REACTOR CALCULATIONS FOR IMPROVING UTILIZATION OF TRIGA REACTOR

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ABSTRACT

A brief review of our work on reactor calculations of 250 kW TRIGA with mixed core (standard + FLIP fuel) will be presented. The following aspects will be treated:

- development of computer programs;
- optimization of in-core fuel management with respect to fuel costs and irradiation channels utilization.

TRIGAP programme package will be presented as an example of computer programs. It is based on 2-group 1-D diffusion approximation and besides calculations offers possibilities for operational data logging and fuel inventory book-keeping as well.

It is developed primarily for the research reactor operators as a tool for analysing reactor operation and fuel management. For this reason it is arranged for a small (PC) computer.

Second part will be devoted to reactor physics properties of the mixed cores. Results of depletion calculations will be presented together with measured data to confirm some general guidelines for optimal mixed core fuel management. As the results are obtained using TRIGAP program package results can be also considered as an illustration and qualification for its application.

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1. INTRODUCTION

A brief review of our work on reactor calculations of 250 kW TRIGA with mixed core (standard + FLIP fuel) is presented. The following aspects are treated:

- development of computer programs,
- optimization of in-core fuel management with respect to fuel costs and irradiation channels utilization.

TRIGAP programme package is presented as an example of computer programs. It is based on 2-group 1-D diffusion approximation and offers possibilities for operational data logging and fuel inventory book-keeping as well.

It is applicable for the research reactor operators as a tool for analysing reactor operation and fuel management. For this reason it is designed for a small (PC) computer.

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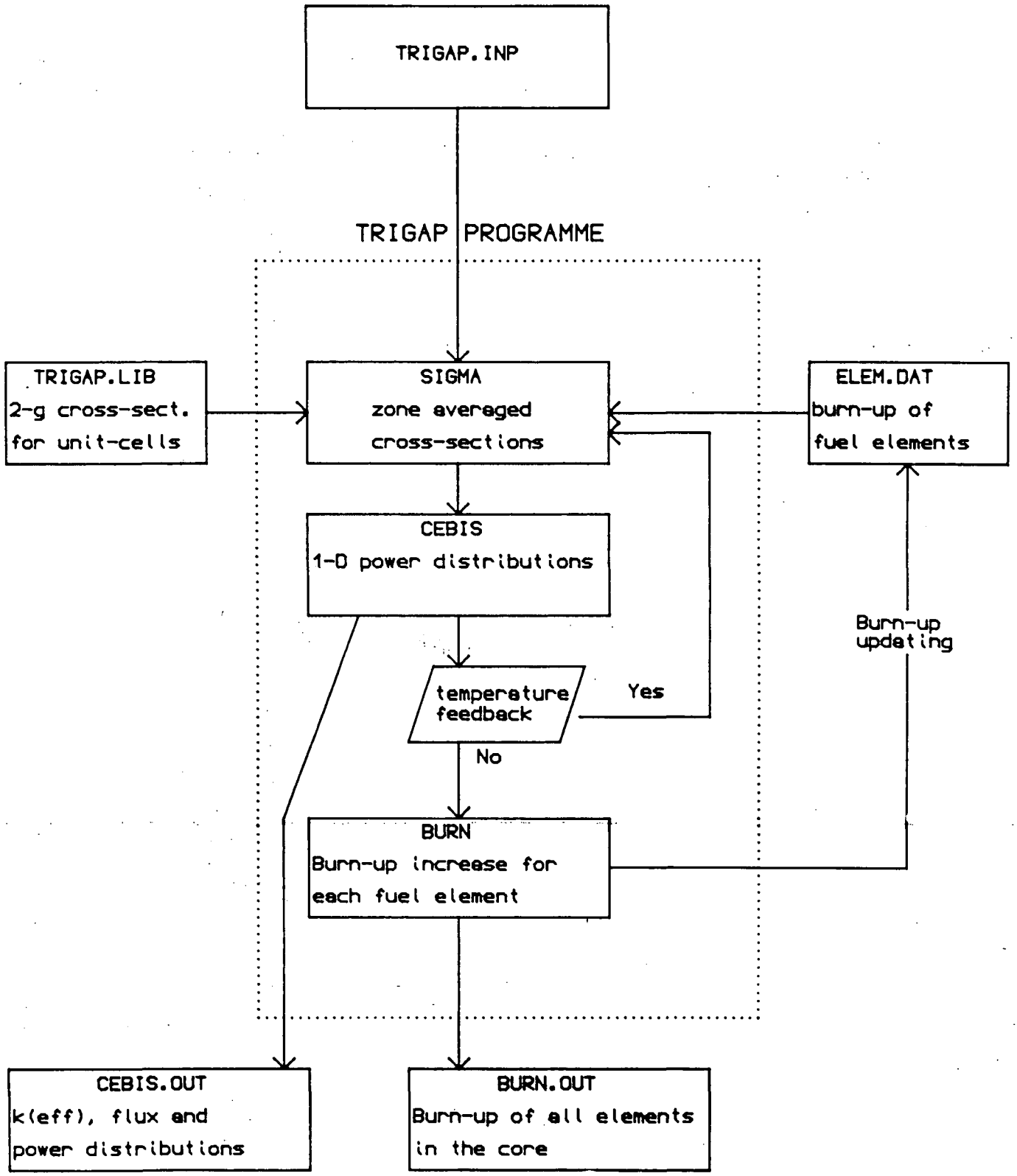
Flow-chart of the programme TRIGAP



2. DESCRIPTION OF TRIGAP PROGRAMME

TRIGAP programme was developed for reactor physics calculations of 250 kW TRIGA reactor. The application for other water moderated reactors is straightforward provided that

- reactor has cylindrical geometry,
- programme is supplied with appropriate data base consisting mainly of the nuclear constants and of the fuel operating history (burn-up),
- the criticality calculations are adjusted to integral experiments.

If these conditions are fulfilled, the programme can be applied for the following purposes:

- criticality predictions,
- power peaking predictions,
- fuel element burn-up calculations and data logging,
- in-core fuel management and fuel utilization improvement.

Expected accurary of the calculations is 0,5 % for absolute criticality, 15 % for power distributions and peakings and 10 % for fuèl element burn-up, which are practically the same values as required from power reactor codes.

TRIGAP programme was originally developed for IBM-PC. VAX version is available as well. Typical running time on IBM-PC is 8 min. Hard disk is not necessary.

The programme consists of the main programme TRIGAP and libraries:

TRIGAP.LIB - effective group constants
ELEM.DAT - fuel element data.

The structure of the main programme is presented on the flow-chart. It is divided into three subroutines: SIGMA, CEBIS and BURN.

Their description is given below.

2.1. Subroutine SIGMA

SIGMA calculates the ring-smeared two-group diffusion constants using the effective 2-g cross-sections for all types of unit cells (fuel and nonfuel) which are stored in the library TRIGAP.LIB as a function of burn-up. SIGMA searches the library for the cross-sections corresponding to the appropriate burn-up for each fuel element in the core. Burn-up of each fuel element is stored in ELEM.DAT. If the burn-up of the element falls between two steps in the library, the effective unit-cell cross-sections are obtained by linear interpolation. The extrapolation of unit-cell cross-sections is not foreseen. If burn-up of an element exceeds the library limits, the program is stopped and message is written on CEBIS.OUT.

The library contains the unit-cell cross sections as a function of burn-up at full power, equilibrium Xe and Sm conditions. For other operating conditions, the cross-sections are obtained according to the following corrections.

2.1.1. Temperature correction (power correction)

We assume that fuel and coolant temperatures vary linearly with power. The cross-sections are tabulated for different types of fuel or non-fuel unit cells only at one (nominal) power (temperature). If the fuel element power is different from nominal (in case of different reactor power or radial and azimuthal power variations), the following correction is performed:

$$\Delta\Sigma^{P}(P,\tau) = \Delta^{P}(\tau) \cdot (1 - P/P^{0})$$

where:

$\Delta\Sigma^{P}(p, \ )$ - power correction to 2-g diffusion constants for unit-cells (D_1, D_2, Σ_{a1}, Σ_{a2}, Σ_{12}, $\nu_1\Sigma_{f1}$, $\nu_2\Sigma_{f2}$)

p - power of the element

p^0 - nominal power of the element

$\Delta^{P}(\tau)$ - difference between cross-section at nominal and zero power

τ - burn-up

Detailed calculations show that the power correction is a function of burn-up. We calculated Δ^P for two fixed burn-up values (τ_0, τ_1) and linearly interpolate for other values:

$$\Delta^P(\tau) = \Delta^P(\tau_0) + \frac{\Delta^P(\tau_1) - \Delta^P(\tau_0)}{\tau_1 - \tau_0} (\tau - \tau_0)$$

Values for $\Delta^P(\tau_0)$, p^0, τ_1 and τ_0 are included in the TRIGAP.LIB, while p and τ enter SIGMA as independent variables for all fuel elements. For preparing the x-sections in SIGMA a guess power distribution must be entered through TRIGAP.INP(e.g. average power for all elements). After that the programme will perform the prescribed number of iterations, until the power density is consistent with the temperature (power) feed-back . For all practical cases two iterations are sufficient.

2.1.2. Xenon correction

Similar to temperature also the Xenon correction to the cross-sections is calculated for every fuel element:

$$\Delta\Sigma^X(p,\tau) = \Delta^X(\tau) \cdot (1 - f(p))$$

$$\Delta^X(\tau) = \Delta^X(\tau_0) + \frac{\Delta^X(\tau_1) - \Delta^X(\tau_0)}{\tau_1 - \tau_0} (\tau - \tau_0)$$

$$f(p) = \frac{1 + c}{1 + c \cdot p/p^0} \cdot \frac{p}{p^0}$$

where:

$\Delta\Sigma^X(p,\tau)$ - xenon corrections to 2-g diffusion constants for unit-cells (D_1, D_2, Σ_{a1}, Σ_{a2}, Σ_{12}, $\nu_1\Sigma_{f1}$, $\nu_2\Sigma_{f2}$)

$\Delta^X(\tau_0)$ - difference between cross-sections at full power, eq. Xe and zero power, no Xe, $\tau = \tau_0$

$\Delta^X(\tau_1)$ - difference between cross-sections at full power eq. Xe and zero power, no Xe, $\tau = \tau_1$

p - element power (kW)

p^0 - nominal element power (kW)

Function f is proportional to equilibrium Xe concentration for given power (well known S-curve). c is a constant, dependent only on the xenon microscopic nuclear constants and fission cross-section of the fuel. It is tabulated in

TRIGAP.LIB for all types of fuel elements. So are $\Delta^X(\tau_1)$ and $\Delta^X(\tau_0)$.

If Xenon correction is calculated, it is always adjusted to the equilibrium xenon at that power. There is a possibility (a parameter for each element in input data) to perform the calculation of reactor core at power and no Xe condition.

2.1.3. Samarium correction

The same way as temperature and xenon correction the samarium correction is performed for each element separately. It takes into account the effect of saturation of Sm after a longer period of shut-down. It was included into the program for special cases which arise after the reactor or some fuel elements were not operating for a longer period (for example: partialy burnt elements which were before insertion stored long enough to reach equilibrium samarium).

$$\Delta\Sigma^S(\tau) = \Delta^S(\tau) \cdot \text{FLAG}$$

For Δ^S we again presume linear dependence of burn-up:

$$\Delta^S(\tau) = \Delta^S(\tau_0) + \frac{\Delta^S(\tau_1) - \Delta^S(\tau_0)}{\tau_1 - \tau_0} \cdot (\tau - \tau_0)$$

List of symbols:

$\Delta\Sigma^S$ - samarium correction for 2-g cross-section (D_1, D_2, Σ_{a1}, Σ_{a2}, Σ_{12}, $\nu_1\Sigma_{f1}$, $\nu_2\Sigma_{f2}$)

FLAG { 0 = equilibrium Sm for nominal power
1 = peak Sm after longer shut-down

$\Delta^S(\tau_0)$ - difference between cross-sections at nominal conditions and conditions with saturated Sm after shut-down

τ - burn-up of the element

2.1.4. Homogenization

After power, Xe and Sm corrections are performed according to the formula

$$\Sigma(\rho,\tau) = \Sigma(\rho_0,\tau) + \Delta\Sigma^{P}(\rho,\tau) + \Delta\Sigma^{X}(\rho,\tau) + \Delta\Sigma^{S}(\tau).$$

Ring averaged cross-sections are calculated by volume weighting, assuming that all unit-cells occupy the same volume V_i:

$$\langle \Sigma_g \rangle = \frac{\sum_i V_i \Sigma_{i,g}}{\sum_i V_i} \qquad g = 1,2$$

$$\left\langle \frac{1}{D_g} \right\rangle = \frac{\sum_i V_i / D_{i,g}}{\sum_i V_i} \qquad g = 1,2$$

2.2. Subroutine CEBIS

In the original form CEBIS is an independent one-dimensional two-group diffusion code. A detailed description of this programme is given in its Manual /1/.

In TRIGAP programme CEBIS is used as a subroutine. Its generality is reduced. It can be used only for cylindrical geometry and adjoint diffusion equation is not solved. No independent input is necessary for CEBIS. All input data come through TRIGAP.INP. CEBIS output record is the same as in independent version of CEBIS except that it is possible to omit the plots of flux and power distributions.

With ring averaged power distributions from CEBIS, corresponding power, Xe and Sm corrections can be calculated. Corrected cross-sections enter the input of CEBIS, new power distribution is obtained and the procedure can be repeated until two successive CEBIS power distributions are equal. The convergence criterion is not built into the program. Experience shows that two

iterations are sufficient for small compact cores like TRIGA. If there are more iterations than one, only the output of the last iteration appears on CEBIS.OUT.

After the iteration procedure is completed, the programme will continue with burn-up calculation.

2.3. Subroutine BURN

On the basis of total energy (in MWh) produced by the reactor and core power distributions, subroutine BURN calculates the burnup of each element in current step.

Power distributions are taken from CEBIS. Azimuthal power variations are taken into account in heterogeneous rings with different types of fuel elements, although they do not influence the average power of the ring. Power correction factors for mixed rings were calculated in advance with 2D diffusion code in R-Θ geometry (see ref. /2/).

Results of BURN are burn-up increments for all fuel elements in the reactor. They are automatically added to the burnup of elements in ELEM.DAT so that ELEM.DAT contains updated burn-up.

There is also an independent output file of BURN where burnups of all elements in the core in MWh and in % of U-235 (together with the identification numbers of the elements) are written for each zone. At the end elements are written again with their burnup in descending order which is useful for incore fuel management calculations.

2.4. File TRIGAP.LIB

TRIGAP library (= TRIGAP.LIB) together with the history of elements (= ELEM.DAT) form the data base for TRIGAP programme. The library is appropriate for 250 kW TRIGA research reactor composed of standard fuel elements (8.5 w/o of U-235, 20 % enrichment), FLIP fuel elements (8.5 w/o of U-235, 70 % enrichment, Er as burnable poison) or LEU fuel elements

(20 w/o of U-235, 20 % enrichment). It contains the effective two-group cross-sections for all types of unit-cells (fuel and nonfuel) in TRIGA reactor. All unit-cells are of equal volume. Fuel unit-cells contain fuel rod + water, nonfuel unit-cells contain a rod of nonfisile material (e.g. graphite, berilium, void, water), surrounded with water. All unit-cell cross-sections were calculated with WIMS-S transport code in 18-group transport approximation. For unit-cells with no fissile material a supercell approximation had to be used (central, nonfuel rod, surrounded with six fuel rods) and at the end only cross-sections over the central nonfuel unit-cell are considered. The cross-sections of fuel unit-cells are calculated at nominal power (different for each type of fuel unit-cell) and tabulated in dependence of burn-up (in % of U-235) from zero burn-up to 35 % for FLIPS and 50 % for LEU and standard elements. All nonfuel unit-cells are calculated as if surrounded by fresh fuel.

2.5. File ELEM.DAT

ELEM.DAT is a file which has to be prepared for each TRIGA reactor in dependence of the operating history of reactor. It should contain the following data for each element: identification number of the element, type of the element and history of the element (energy produced by this element in MWh). ELEM.DAT should contain also the data for all types of nonfuel elements.

2.6. File TRIGAP.INP

All independent input data are entered into TRIGAP through TRIGAP.INP file.

The first part of input data are general, specifying the geometry and other general conditions for solving the diffusion equation. In second part the identification numbers together with flags for xenon and samarium correcti-

ons for each element in the core are written. At the end the ring-averaged power densities must be defined.

2.7. Output Description

Output of TRIGAP programme consists of CEBIS.OUT file and BURN.OUT file (if burn-up calculations is performed).

CEBIS.OUT is described in CEBIS Manual. The only modification is that reactor (core) average group constants are omitted.

BURN.OUT information is the following: first total accumulated energy produced by the core including the last burn-up step is printed, together with energy produced and thermal power of the reactor during the burn-up step. Follows the information about the burn-up of each element in the core. For each zone, (fuel) element identification number is printed together with burn-up in MWh and % of initial U-235. Fuel element thermal power in current burn-up step is printed as well. Follows the list of fuel elements arranged according to their burn-up in % of U-235. The last information is average burn-up for all types of fuel elements.

3. COMPARISON OF 1-D AND 2-D RESULTS OF REACTOR CALCULATIONS FOR TRIGA REACTOR

The computer programmes used for 1-D reactor calculations were described in previous paragraph. The FINELM computer code was used for two-dimensional calculations of TRIGA reactor in R-Θ geometry. The code is tested and verified. Description is given in Ref. (3). Considering the accuracy of FINELM code for TRIGA reactor calculations, the following observations can be made:

- calculations of one-dimensional problems in 2-D approximation with FINELM code yield identical results as our standard 1-D codes used for TRIGA reactor calculations,
- the numerical accuracy of FINELM is of the same order as that of our standard 1-D calculations,
- the numerical accuracy of the code is for 2-D problems below the experimental error for multiplication factor and power distributions.

Two hypotetical core configurations were calculated in two-dimensional approximation:

a) every third fuel element in E-ring was FLIP, all other positions filled with standard fuel elements, including A-ring (Fig. 1),

b) "chess board" distribution of standard and FLIP fuel elements (Fig. 2).

First case roughly simulates an isolated FLIP fuel element in a uniform matrix of standard fuel. Second case is close to periodical lattice of FLIP and standard fuel elements. The problem is not realistic: in general the homogeneous zones do not correspond to integer numbers of fuel elements, except for rings C and E, where each homogeneous zone covers exactly one and two fuel elements, respectively. The heterogeneity of the core is deliberately exaggerated so that the 2-D effects are stressed as much as possible.

Both problems were calculated also in 1-D approximation with homogenized (smeared) ring using our standard calculational procedure (TRIGAP). Results are presented in Tables I. - V.

Table I.: Multiplication factor in one- and two-dimensional approximation

Case	k_{eff}*	
	2-D (FINELM)	1-D (CEBIS)
a.	1.16036	1.16034
b.	1.19626	1.19659

*Axial leakage is zero for both cases.

Table II.: Relative power distribution in 2-D approximation for case a.

Zone	Material	Relative power	Ring average	Relative power / Ring average
A-1	S	1.437	1.437	1.00
A-2	S	1.437		1.00
B-1	S	1.387	1.387	1.00
B-2	S	1.387		1.00
C-1	S	1.276	1.276	1.00
C-2	S	1.275		1.00
D-1	S	1.090	1.071	1.02
D-2	S	1.032		.96
E-1	S	.823	1.064	.77
E-2	F	1.547		1.45
F-1	S	.721	.704	1.02
F-2	S	.670		.95
Volume weighted average		1.000	1.000	-

Table III.: Relative power distribution in 2-D approximation for case b.

Zone	Material	Relative power	Ring average	Relative power / Ring average
B-1	F	1.952	1.353	1.44
B-2	S	.754		.56
C-1	S	.692	1.180	.59
C-2	F	1.668		1.41
D-1	F	1.487	1.072	1.39
D-2	S	.657		.61
E-1	S	.587	.931	.63
E-2	F	1.275		1.37
F-1	F	1.165	.870	1.34
F-2	S	.575		.66
Volume weighted average		1.000	1.000	

Table IV.: Ring - averaged power distribution in 1-D and 2-D approximation for case a.

Ring	Relative power 2-D (FINELM)	1-D (CEBIS)	Relative difference (%)
A	1.437	1.438	- 0.1
B	1.387	1.395	- 0.6
C	1.276	1.281	- 0.4
D	1.071	1.054	+ 1.6
E	1.064	1.080	- 1.5
F	.704	.697	+ 1.0
Volume weighted average	1.000	1.000	

Table V.: Ring-averaged power distributions in 1-D and 2-D approximation for case b.

Ring	Relative power 2-D (FINELM)	1-D (CEBIS)	Relative difference (%)
A	-	-	
B	1.353	1.324	2.1
C	1.180	1.181	- 0.1
D	1.072	1.074	- 0.2
E	.931	.934	- 0.3
F	.870	.871	- 0.1
volume weighted average	1.000	1.000	

Comparison of multiplication factors in Table I. gives a surprising result : multiplication factors calculated in 2-D and 1-D approximation are only slightly different in spite of high azimuthal heterogeneity for both cases. The difference grows with the heterogeneity of the problem. In case of isolated FLIP element (a.) the difference is negligible, while for "chessboard" distribution (b.) grows to $\approx$ 5 ¢. Case b. is extremly heterogeneous and such fuel patterns never occur in practice. So we can conclude that the maximal error in k_{eff} due to 1-D approximation is less than 5 ¢ for all realistic core configurations. If only one or two rings are heterogeneous the error is expected to be even smaller (below 1 ¢) according to the results for case a.

Ring-averaged relative power distributions calculated in 2-D and 1-D approximation are compared in Tables IV and V for both cases. Differences between 1-D and 2-D results are again surprisingly small ($\approx$ 2 %) in spite of large power variations within rings consisting of two types of fuel. The influence of the heterogeneous ring on the azimuthal power distributions of other rings is weak and limitted only to the closest rings as can be seen from the last column in Table II.

The one dimensional representation of TRIGA reactor is a good approximation until only average values of flux and power have to be determined for heterogeneous rings. But, for calculations of fuel element burn-up the detailed power distribution within rings must be taken into account as well. The two-dimensional power distributions presented in Tables II. and III. show large variations of power within rings consisting of standard and FLIP fuel elements. FLIP fuel elements produce much more power than standard elements in the same ring. Ratio between power produced by FLIP element and average power of the ring is typically 1.4 for the rings, loaded with approximately equal number of FLIPs and standard fuel elements. The ratio depends on the ring loading pattern.

Power ratio 1.4 is valid for a single FLIP element, separated from its nearest FLIP neighbour in the ring by one or more standard fuel elements. If FLIPs are loaded in couples, separated from each other by one or more standard elements, the power ratio is 1.37, as can be seen from Table III. For larger groups the power ratio tends to 1., as can be expected.

The FLIP-to-average power ratios derived from 2-D calculations are used in calculations of burn-up for mixed rings in 1-D approximation. The burn-up rate of FLIPs is approximately two times greater than burn-up rate of standard fuel elements in the same (mixed) ring if the power ratios are taken into account. This has strong influence on the core lifetime as can be seen on Fig. 3. k_{eff} is presented on this diagram as a function of core burn-up. 10 FLIP fuel elements are loaded in D-ring, all other positions in D and other rings are filled by standard fuel. Both curves were calculated in 1-D approximation. Power variations within D-ring were taken into account for the upper curve (FLIP-to-average power ratio = 1.4). Lower curve was obtained without 2-D corrections. Upper curve corresponds to loading pattern where FLIPs and standard elements are mixed (one FLIP, one standard, etc.). Lower curve corresponds to the pattern, where they are not mixed. The core lifetime for mixed ring is approx. 5 % longer.

Loading patterns with mixed rings are avoided in practice because of the high power peaking factors. It is recommended that only the type of fuel is loaded in one ring. However, the above results show, that the fuel utilization can be improved if mixed rings were used.

4. OPTIMAL FUEL UTILIZATION IN TRIGA REACTOR

4.1. Homogeneous Core

Our previous experience show that the multiplication factor and flux distributions depend strongly on the fuel loading pattern not only for mixed cores but also for cores, consisting of one type of fuel with high burn-up. So we first performed a set of burn-up calculations for core, initially loaded with fresh standard fuel (20 % enriched, 38 g U-235 per element, no burnable poison). We tried to answer the following questions. Does the core lifetime (time of reactor operation in which the excess reactivity falls to zero and during which no fresh fuel is added to the core) depend on loading pattern changes ? If so, does the optimal fuel loading strategy exists for

initially homogeneous core ?

Burn-up calculations were performed in one dimensional approximation for realistic operating conditions (full power, 250 kW). First the number of fuel elements was determined to give realistic excess reactivity for the beginning of core lifetime ($\approx$ 4 \$, 69 elements). Next the time interval between two successive k-effective and power distribution calculations had to be determined (for burn-up distribution calculation the power shape was considered constant on this interval). The time step was varied for fixed core configuration until no longer influenced the core life-time. Burn-up interval 250 MWh (1000 h of full power operation) was determined and used for all burn-up calculations. Only the first burn-up step in each calculation was taken shorter (50 MWh) to cover the Xe-buildup.

The following three burn-up calculations were performed:

1. The core was burnt without changing the loading pattern until the excess reactivity fell to zero (at approximately 2000 MWh). After that the fuel elements were shuffled, according to their burn-up, so that their burn-up increased with the distance from the centre of the reactor. In other words, the most burnt fuel from the central rings was placed in outer rings and vice versa. Considerable reactivity gain ($\approx$ .3 % or .5 \$) was obtained. Burn-up was continued until excess reactivity again fell to zero at $\approx$ 2450 MWh.
2. The same procedure was applied as in first case, only the fuel elements were rearranged according to their burn-up after every 1000 MWh.
3. Same as 2., except that the rearrangement was performed after every 250 MWh.

Results are presented on Fig. 4. First observation is, that the core lifetime can be increased for more than 10 %, if the fuel is rearranged after certain period of operation. The core lifetime depends on the burn-up interval between two rearrangements, as it is shown on Fig. 5. The best utilization of fuel is obtained, if the interval is as long as possible.

The worst possibility is "permanent" rearrangement of fuel elements (after every 250 MWh).

This case gives the shortest core life-time. Core life-time is approximately proportional to the interval between two rearrangements, so the core lifetime where rearrangements are performed every 1000 MWh, lies between the two limiting cases.

The results of the calculations show, that the most uniformly burnt core does not mean the longest core life-time. Average burnups of different rings for the three cases are presented in Table VI. It can be observed, that the variations of burn-up are the largest for the case with the highest average burn-up and longest core life.

Table VI.: Ring-averaged burnup for case 1. (rearrangement after 2000 MWh), case 2. (rearrangement after 1000 MWh) and case 3. (rearrangement after 250 MWh)

Ring	Burnup in % of initial mass of U-235		
	Case 1.	Case 2.	Case 3.
A.	-	-	-
B.	3.80	4.23	4.47
C.	4.00	4.30	4.43
D.	4.24	4.30	4.35
E.	5.05	4.43	4.29
F.	5.90	4.76	4.28
Average	4.73	4.42	4.34
Core life-time (MWh)	2420	2290	2250

The calculations show, that the multiplication factor is a linear function of burn-up after Xe and Sm reached equilibrium (3 and 100 days of operation on full power, respectively). The reactivity reduction rate (shape of the curve) is independent of burn-up in this region but slightly depends on the shuffling strategy as can be seen in Table VII. It is in good agreement with the burn-up reactivity reduction rate presented in reference (4) for the same type of fuel. Slight difference can be explained by

different core geometries (hexagonal array in reference case, concentric rings in our case) affecting the fuel to water volume ratio and consequently the spectrum.

Table VII.: The burn-up reactivity reduction rate as a function of burn-up strategy

Case	Δk / MWd
1.	-1.80864×10^{-4}
2.	-1.76620×10^{-4}
3.	-1.82688×10^{-4}
Reference (4)	-1.6834×10^{-4}

4.2. Mixed Core

We studied the burnup of reactor core consisting of two types of fuel elements: standard fuel elements and FLIP-s (70 % enrichment, 134 g U-235, Er as burnable poison). The total number of fuel elements was kept the same (69) as in previous case (standard fuel only) to enable the direct comparison of the results. The number of inserted FLIP-s was adjusted recording to the following conditions:

a) realistic core excess reactivity (not exceeding 5 $)
b) realistic power shapes (mixed rings not acceptable)
c) at least one ring filled with FLIPs only.

These conditions are contradictory: in B-ring there are 6 positions and 30 in F-ring. A compromise has to be made. First FLIP-s in B-ring are not considered due to high power peaking and reduction of flux in the central irradiation channel. After trying several schemes with different numbers of FLIPs we accepted the scheme with 10 FLIP-s and 59 standard elements. With this number of FLIP-s second condition is violated (mixed rings can not be avoided in general). So the results must be interpreted mainly

as a comparative study.

We calculated the burnup cycles for four loading patterns:

1) 10 FLIPs in ring C (no standard elements in C)
2) 10 FLIPs in ring D (+ 8 standard elements)
3) 10 FLIPs in ring E (+ 13 standard elements)
4) 10 FLIPs in ring F (+ 2 standard elements, other positions filled with graphite elements)

Initial excess reactivity of these four different cases gives direct insight in the reactivity value of FLIP fuel in different rings. It is given in Table VIII. and compared to standard fuelled core. From the k_{∞} curves (Fig. 7) it could be expected, that the exchange of fresh standard fuel elements with fresh FLIP elements will decrease the reactivity of the reactor. It happens only in the case, when FLIP-s are loaded in D-ring and also for this case much stronger reduction is expected (10/69 * 5000 pcm $\approx$ 700 pcm). Smaller reactivity reduction or even reactivity gain for other rings is explained by reduced neutron leakage from the core due to the flux shapes perturbed by the presence of FLIP-s, as can be seen from Table IX. While the fast neutron radial leakage is not strongly influenced by the FLIP-fuel, the thermal radial leakage exhibits large variations.

Table VIII.: Multiplication factor of mixed cores. Total number of fuel elements is 69 in all cases

Configuration	k_{eff}	difference to standard (pcm)
Standard fuel only	1.03256	-
10 FLIPs in C	1.03270	+ 14
10 FLIPs in D	1.03001	- 255
10 FLIPs in E	1.03355	+ 99
10 FLIPs in F	1.04233	+ 977

The influence on the leakage increases approching with FLIP-s to the core boundaries. There are two radial boundaries of the multiplying part of the

core: outer - core reflector / boundary and inner-central channel / B-ring boundary. This is the reason why the reactivity gain is observed also for FLIP-s in C-ring: leakage from the core through the central channel is reduced. Our previous experience shows that this effect is even stronger for FLIP-s in B-ring.

Table IX.: Integrated fast (J_1) and thermal (J_2) neutron current through the radial surfaces of the active core (relative units)

Configuration	J_1	J_2
Standard	- 404.96	- 62.43
10 FLIPs in C	- 393.27	- 55.52
10 FLIPs in D	- 391.03	- 57.99
10 FLIPs in E	- 413.27	- 44.44
10 FLIPs in F	- 433.03	- 29.62

The effect of reduced leakage is the same also for the burnt fuel, only the reactivity gain is more significant due to the increase of k with burn-up for FLIPs. From the view of reduced leakage we can conclude, that the FLIP fuel elements are best utilized in outer rings of the reactor. But from the aspect of the core life-time it is more convenient to place them in the inner rings. Both effects are competing so it depends on the particular case which of them will prevail. The effect of burn-up is discussed below. The results of the burn-up calculations are shown on Fig.6.

We assume the following burn-up strategy for the calculations. During the burn-up the fuel is not shuffled until the reactivity falls to zero. Then standard elements are shuffled with regard to their burn-up: more burnt fuel is shuffled from the centre to the periphery of the core and vice versa. Position of FLIP fuel is not changed. The burn-up calculations is continued until the excess reactivity falls to zero again.

The multiplication factor of FLIP fuel k_∞ increases with burn-up until burn-up of approximately 30 % is reached. This corresponds to ≈ 15 full power operating years for FLIP-s in the central part (C, D-rings) of

250 kW TRIGA. This means approximately 45 years of normal reactor operating (8 hours per day).

So it may be considered that once the FLIP-s are introduced in a reactor, their reactivity will increase during any practical reactor life-time. Their life is practically limited only by the mechanical integrity.

During the FLIP life-time, the rest of the core which is supposed to consist of standard fuel, has to be reloaded several times. If the FLIP-s are present, the utilization of the standard fuel is improved. Higher burn-up of standard fuel can be achieved due to high reactivity of burnt FLIP fuel, which compensates the reactivity decrease of standard fuel. The best utilization of the mixed core is achieved, if the FLIP-s are positioned in the rings with highest power (C, D), so that their reactivity increases with the highest possible rate. This can be observed on Fig. 6 or in Table X, where the asymptotic reactivity decrease rates (after Sm in equillibrium) are presented. The reactivity decrease for mixed cores is allways significantly smaller than for standard fuelled core, even if it is used in optimal way. It is also evident that although the highest initial reactivity gain is obtained for FLIP-s in F-ring, the reactivity increase due to burn-up prevails and yields the longest core life time for FLIP-s in C-ring. In this case the standard fuel will have the highest burn-up (Table XI) when leaving the reactor. If there are more than 10 FLIP-s in the core, the longest core life-time and the best utilization of standard fuel will be achieved, if they are placed in C and D rings (B excluded due to power peakings and central channel flux depresion).

Table X.: The burn-up reactivity reduction rate

Configuration	Δk / MWd
Standard fuel only	$-18.086 * 10^{-5}$
10 FLIPs in C	$-7.476 * 10^{-5}$
10 FLIPs in D	$-10.071 * 10^{-5}$
10 FLIPs in E	$-13.349 * 10^{-5}$
10 FLIPs in F	$-15.355 * 10^{-5}$

Table XI.: Core life-time and burn-up for mixed cores

Configuration	Core life-time (MWh)	burn-up (4)	
		FLIP	standard
10 FLIPs in C	6255	6.63	10.028
10 FLIPs in D	4620	4.42	7.209
10 FLIPs in E	3970	3.45	7.079
10 FLIPs in F	4315	3.04	8.675
standard fuel only (optimal strategy)	2420	-	4.726

5. CONCLUSIONS

1. Optimal strategy for utilization of the standard fuel without FLIP elements is to operate without shuffling of fuel elements as long as possible if the core was loaded mainly with the fresh fuel. In this case the maximal core life-time and burn-up of the fuel, leaving the reactor, are obtained. These statements seem to be true also for the consequitive fuel cycles, when fresh fuel is added, but need additional verification.

2. Optimal burn-up strategy for the mixed cores is as follows:
   - fresh FLIP fuel should be filled in the rings with the highest power (inner rings, but not B), to get the best reactivity reduction rate and the longest core life-time, until the reactivity of FLIP fuel is increasing with burn-up. In 250 kW TRIGA this means approximately burn-up of 30 % for FLIP-s or 15 full power operating years for the whole reactor;
   - the standard fuel elements should be used in combination with FLIP-s as described in conclusion 1.

The results of the mixed core burn-up calculations are surprising and have to be verified experimentally. Reactor experiment in which the reacti-

vity values of standard and FLIP fuel elements were measured as a function of burn-up and positions, had been performed. Preliminary results show agreement with our assumptions.

6. REFERENCES

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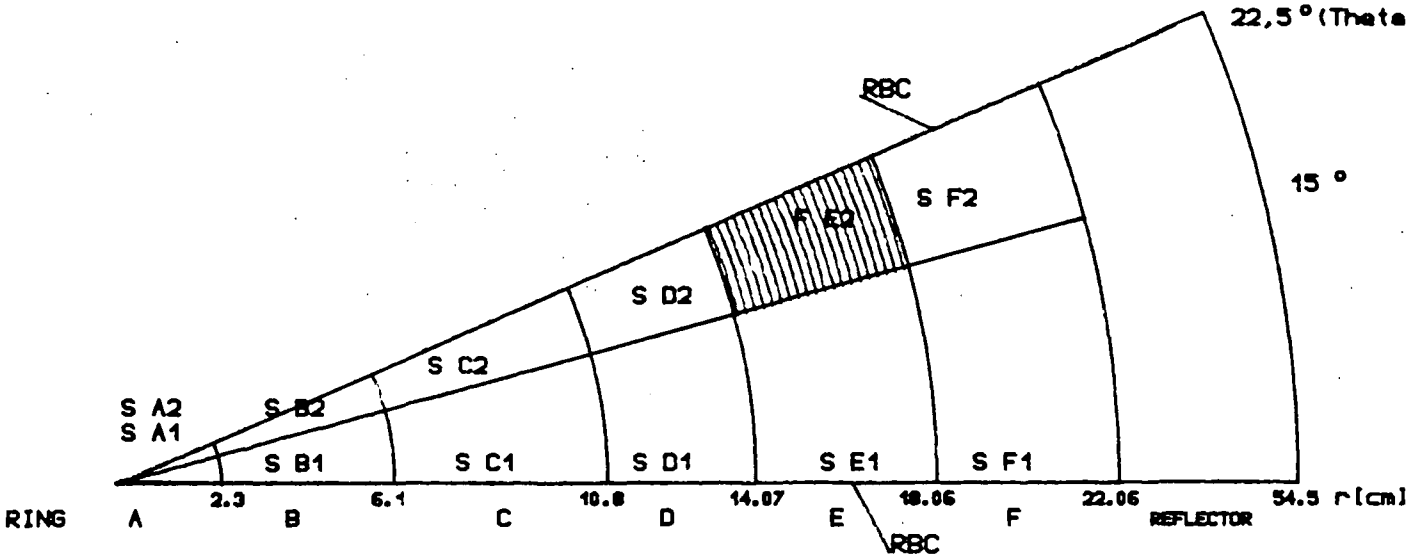

Fig. 1.: Zone geometry and material composition for case a. S = standard fuel, F = FLIP fuel, RBC = reflective boundary condition

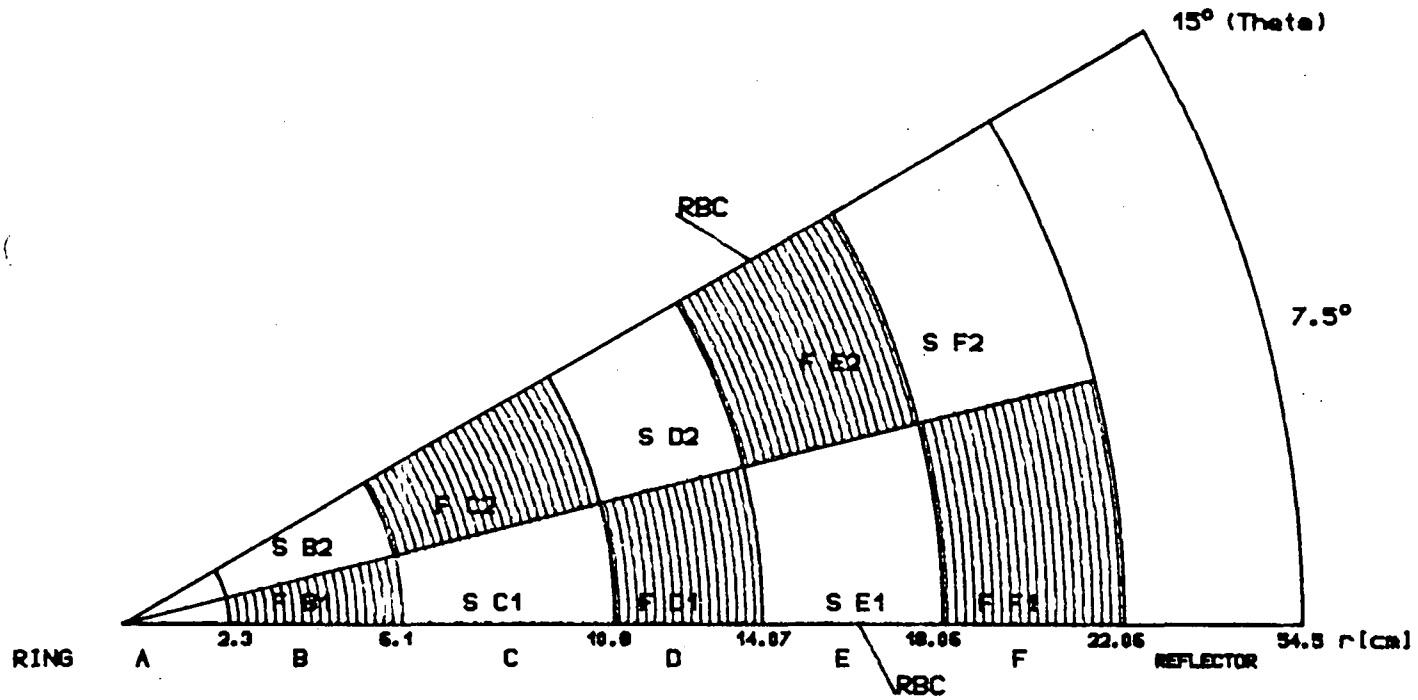

Fig. 2.: Zone geometry and material composition for case b. Ring A does not contain fissile material

Fig. 3.: Comparisons of burn-up curves with and without asimuthal corrections of power distributions

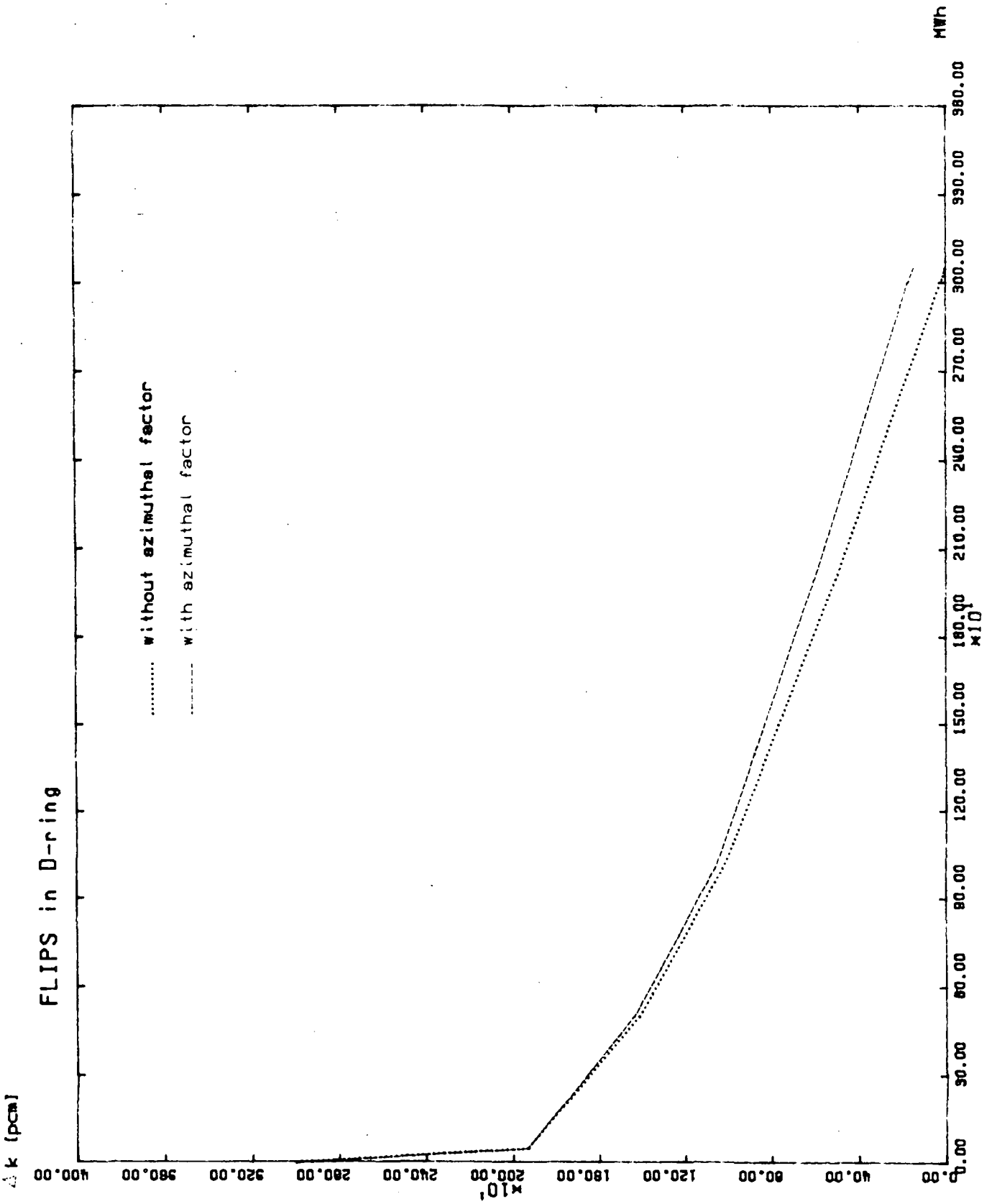

Fig. 4.: Multiplication factor of the reactor loaded with 69 standard fuel elements as a function of burn-up for different burn-up intervals between reshufflings

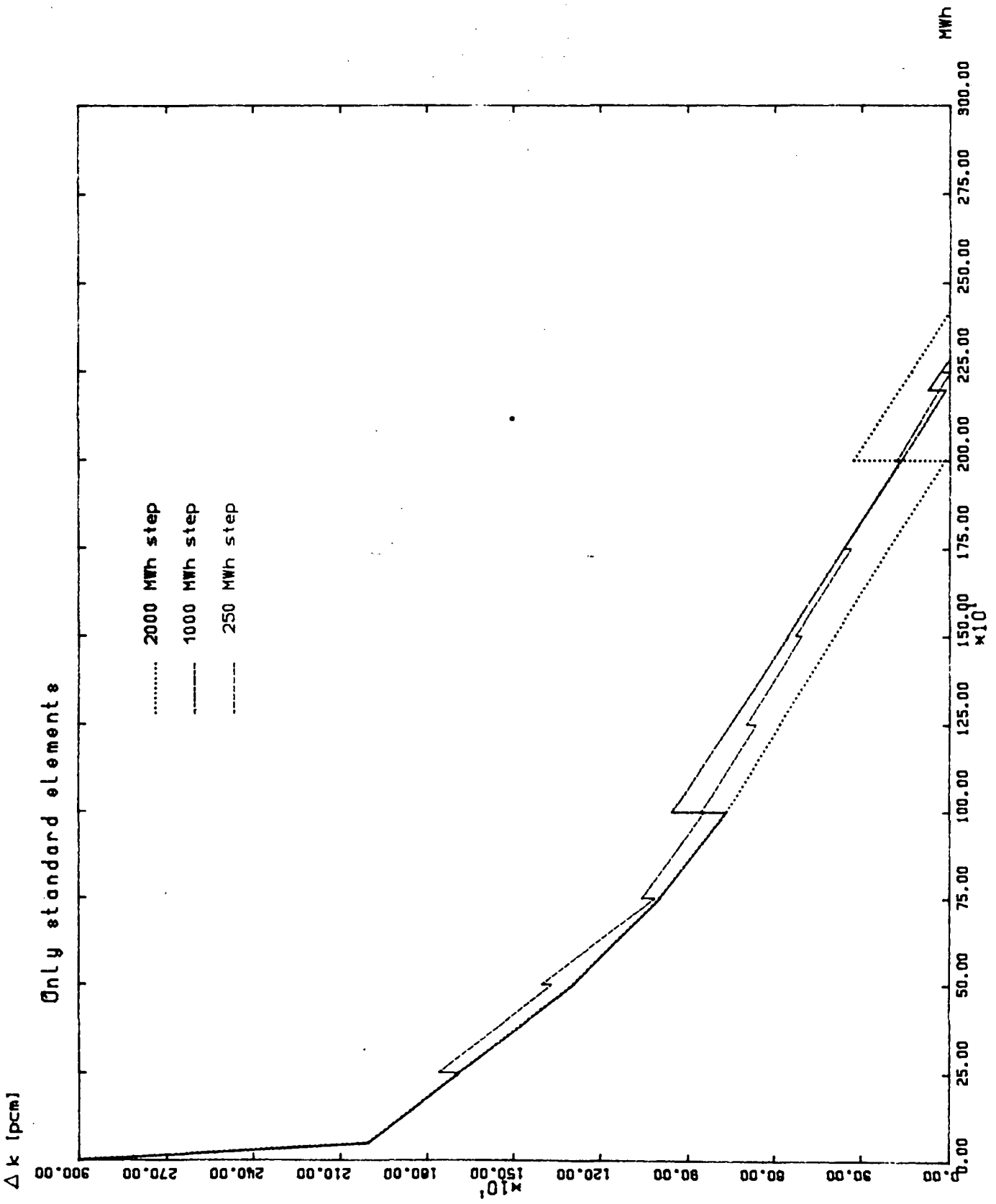

Fig. 5.: Core life-time as a function of burn-up step between reshufflings for standard fuel

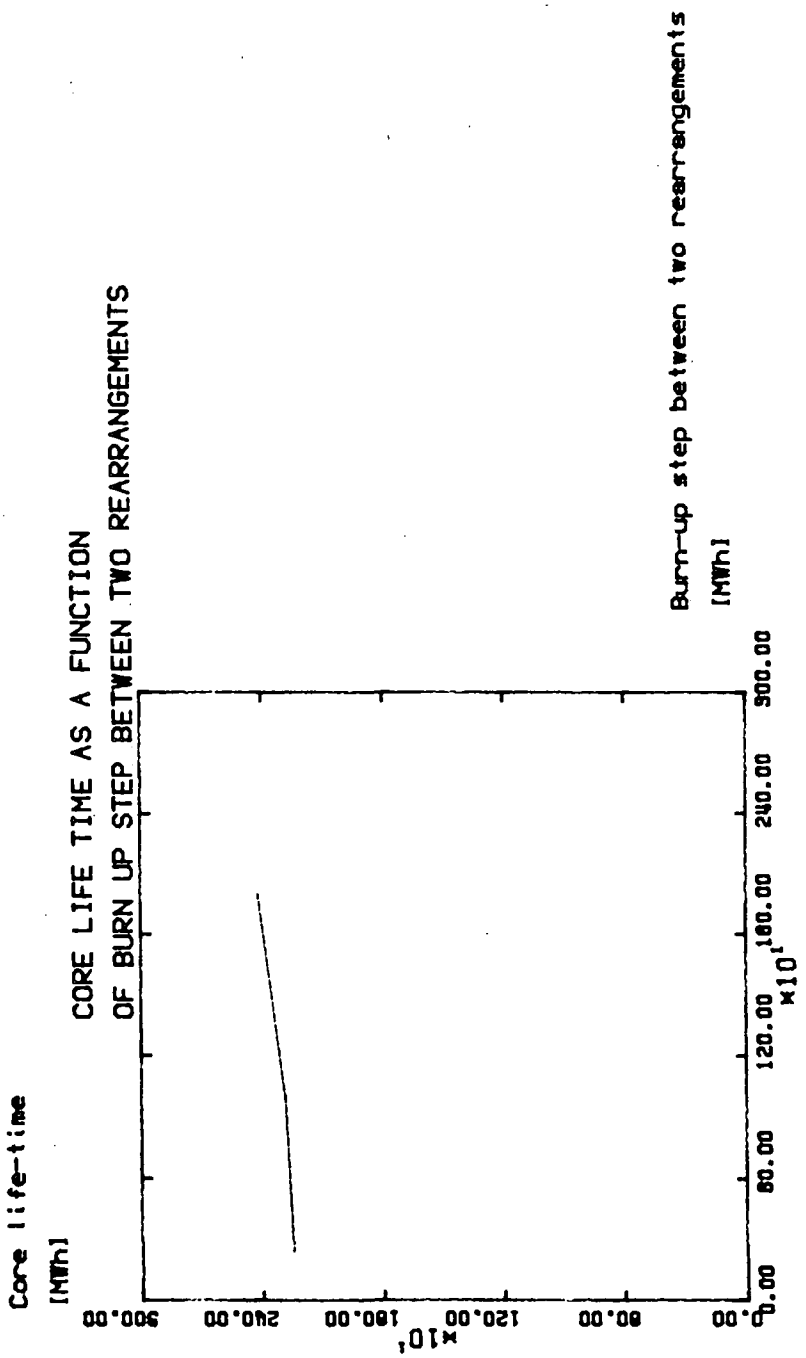

Fig. 6.: Multiplication factor as a function of burn-up for mixed cores

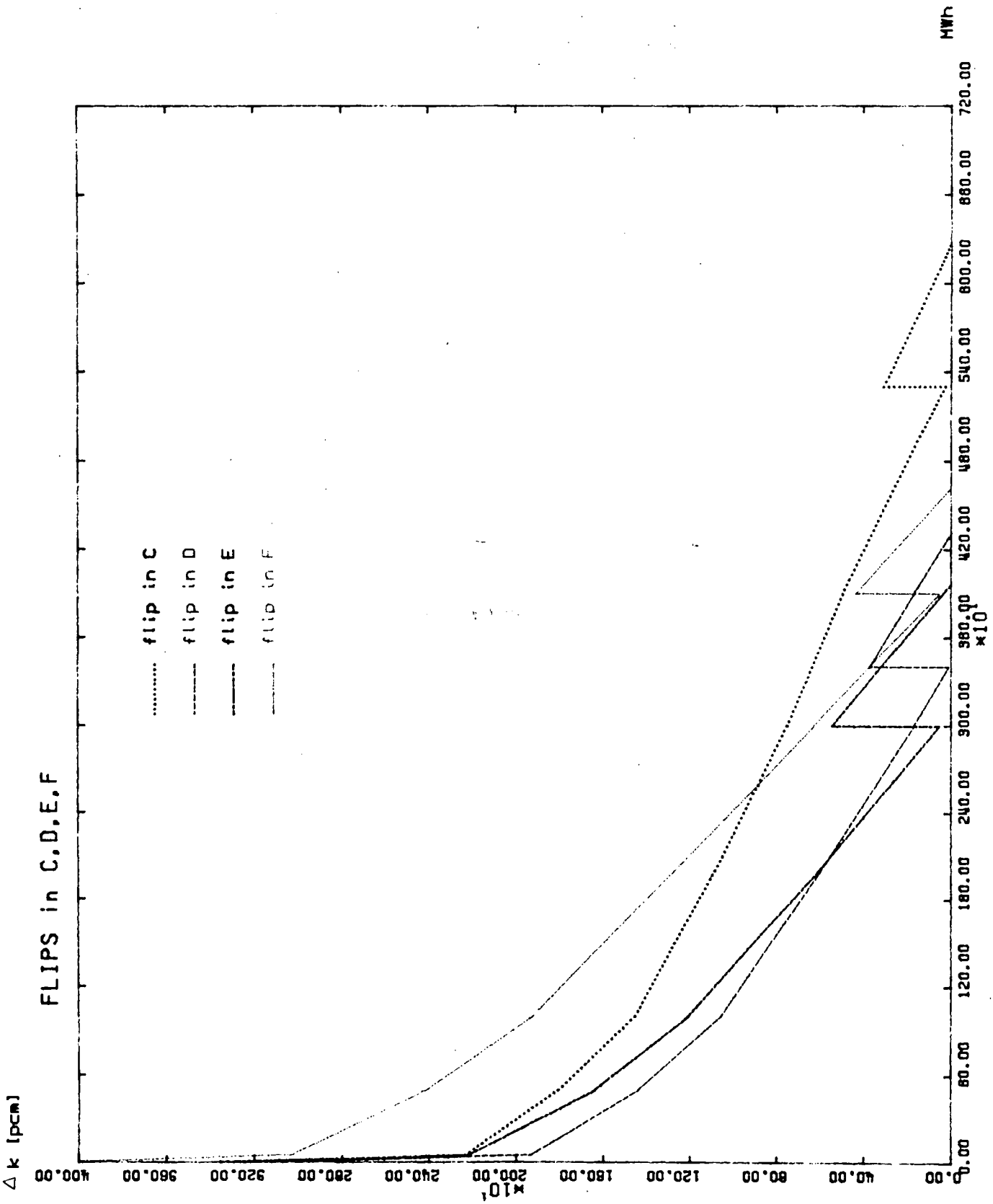

Fig. 7.: k_∞ as a function of burn-up for FLIP and standard fuel element unit cell