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COMMISSION OF THE EUROPEAN COMMUNITIES

APPROACH TO EQUILIBRIUM IN HTR. A COMPARISON BETWEEN THORIUM AND LOW-ENRICHED CYCLE

by

G. GRAZIANI and C. RINALDINI

1973

Joint Nuclear Research Centre
Ispra Establishment - Italy

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CORRIGENDUM

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ABSTRACT

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KEYWORDS

HTGR TYPE REACTORS
POWER REACTORS
FUEL CYCLE
EQUILIBRIUM
R-CODES
COMPUTER CALCULATIONS
THORIUM
ENRICHED URANIUM
ONE-DIMENSIONAL CALCULATIONS

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Introduction

The low-enriched cycle and the Thorium cycle have been compared in the past for the HTR reactors for different geometries of the fuel element, and for different moderation ratios[1, 2]. In these comparisons the fuel cycle during the approach to equilibrium period was not studied in detail, as it depends on many parameters such as control availability and cost, power flattening, local power peaks, etc, which require extensive calculations in order to be taken into account.
The approach to the equilibrium period (or running-in), represents, however, a consistent fraction of the total fuel cycle expenditures and it is responsible of the build-up of the equilibrium fissile inventory. The way in which the running-in contribution is approximated in the economic programme usually employed in the equilibrium calculations at Ispra[3], is to give a "value" to the average equilibrium fissile inventory: the "core value" used is the arithmetic average between the cost of a charge of fresh fuel and that of a discharge of spent fuel.

We do not intend here to carry on a large and detailed comparison between the various possible running-in strategies for the different HTR's fuel cycles. Our purpose is to fix-up a few parameters with which it is possible to define the approach to equilibrium phase, and, with some simplifying assumptions, look at the influence of the running-in on the total fuel cycle cost, both for the Thorium cycle and for the low-enriched cycle.

As a by-product, a more correct calculation of the equilibrium fissile inventory will be obtained for each case.

Brief Outline of the Calculation Method

The calculations were performed using the running-in fuel cycle computer programme RINA and the economic programme ECCO[4]. The programme RINA employs the same approximations as in the equilibrium burn-up programmes usually used at Ispra[5, 3]. Zero and one-dimensional calculations are permitted.

The one group one-dimensional diffusion equation is solved by means of the nodal method[6]. In this way, for a given composition, the average flux levels and power densities in each diffusion region are obtained, without any further calculation of the shape of the power distribution inside each region.

In each of the diffusion regions, the programme considers different burn-up zones, which have, in general, different volumes and compositions. The spectrum employed in the burn-up calculation is a multigroup spectrum, averaged over the refueling interval and over the zones belonging to the same diffusion region. This assumption corresponds to the"scatter load" charging procedure and to a continuous refueling or, in any case, to a refueling strategy in which the burn-up interval between two reloads is sufficiently small that no large changes occur in the average region spectrum.

For a given refueling interval, the programme searches for a single initial fissile concentration, to be attributed to one or more specified zones, needed to obtain the required reactivity at the end of the interval. Alternatively, it may search for the refueling time, when the initial composition is fixed for all zones. A third option is also included: the programme can search both for the fissile concentration and for the refueling time, when the initial and final reactivity values are fixed. When the convergency is achieved, a fraction of the core, specified in the input, is discharged. Fresh fuel of given composition (fixed or guessed, depending on the type of search) is loaded, and the convergency process starts for the new interval.

The possibility of recycling part of the fissile material discharged is taken into account, both in the case in which the fissile is immediately available, as when the reactor considered is in an expanding system of similar reactors, and in the case in which a certain delay time has to be applied due to the cooling, reprocessing plus refabrication times.

In each burn-up zone, the cell heterogeneity is taken into account by means of self-shielding factors, which are given functions of the total absorption cross-section of the zone, according to the coefficients of a fitting previously performed with some Sn calculations over the real cell geometry.

The possibility of introducing burnable poisons in the fresh core, when the reactivity variations due to the depletion can be large, is also considered in the programme employing a routine based on an approximated analytical solution. The radius of the burnable poison pin and the initial concentration of the poisons have to be given in the input. When also the number of pins is given, the code calculates the reduction in the initial and final values of the reactivity. Alternatively, the desired reactivity variation along the interval can be given and the code searches for the number of pins which have to be inserted in the fresh fuel initial charge.

Main Assumptions

The flexibility of the code used and the relatively short computer time requested by each calculation could allow a great deal of different running-in assumptions to be studied. However, the many possible variations in the approach to equilibrium phase may depend on such detailed effects as local power peaks, power flattening requirements, control rod movements, which are far out of the possibilities of analysis of a survey programme like RINA.

The criterium of assuming, as a parameter of the running-in strategy, the lifetime of the first charge was chosen. The following charges present always the same initial composition of the fresh fuel, but different refueling periods, which, after few cycles, were getting stable around an equilibrium value.

The main physical and economical assumptions are reported in Table 1 and 2.

The geometry of the fuel element was the one optimized by GGA[7] for the Thorium cycle. The same geometry for the low-enriched cycle was assumed, without allowing for a re-optimization of the fuel element.

In Table 1, the number of blocks in the core and the number of pins of burnable poison per block, are given according to the GGA design. However, as the number of fuel elements per block is very large, it is reasonable to think that the number of burnable poison pins per block can be doubled, without any important shadowing effect between them. An upper limit for the total number of burnable poison pins in the whole core can be assumed to be 6, 300. The poison chosen was Gadolinium and its reference concentration was the one corresponding to the theoretical density. The diameter of the pin has been varied in the calculations and it is referred to as an equivalent diameter because other sets of burnable poison pin diameter, poison concentration and number of poison pins could be chosen in order to have the same reactivity behaviour of the burnable poisons. For instance, a reference value of the pin diameter of 12, 7 mm could be fixed and the concentration and number of pins adjusted accordingly in each of the cases considered in the following. In order to avoid too lengthy calculations, the fraction of the core discharged at each refueling interval was kept equal to 1/8, a value much higher than the one used in the equilibrium survey (1/40). Higher fissile requirements can then be expected for a given burn-up, or lower burn-up values for the same initial enrichment. The number of energy groups, the source for the multigroup cross-section data and the data on the cell heterogeneity were the same as in the equilibrium cycle survey already mentioned/2/.

Zero-Dimension Calculation

1) Low-Enriched Cycle

Following the running-in strategy outlined, the equilibrium refueling composition of the low-enriched cycle was chosen equal to that of the continuous charge-discharge equilibrium cycle which corresponds to a moderation ratio C/V of 350 and an irradiation of 92 MWd/kg. The burn-up of the first charge was changed parametrically and, consequently, different initial enrichments were obtained.

The burnable poison equivalent diameter was assumed to be 1 mm, with which small absorptions of the burnable poisons at the end of the first charge were obtained (below 2 percent), increasing only slightly the initial fissile requirements as compared to the case in which the burnable poisons are replaced by control rods. Calculations for a higher burnable poison equivalent diameter show an increasing initial enrichment, as it can be seen from the following table.

		Equivalent burnable poison diameter (mm)	
		1	1,4
Burn-up of the first charge = 24 MWd/kg	Initial enrichment (%)	5	6
	Percent absorption of the burnable poison at the end of the first charge	1,2	4,8

Results of the running-in for the low-enriched cycle are reported in figures 1 and 2. In figure 1 the fuel cycle cost averaged over the entire reactor life is plotted as a function of the burn-up of the core at the first reloading. The cost curve increases both for low irradiation values, due to the contribution of the fabrication and reprocessing costs, and for large burn-up values, due to the poorer neutron economy. The influence of the first charge irradiation on the total fuel cycle is small and their cost variations shown in the figure are in the order of percents of a mill. The initial charge with the same initial enrichment of the equilibrium cycle (8.35%) corresponds to an initial batch type irradiation of 47 MWd/kg and to a fuel cycle cost which is 0.02 mills higher than the minimum

In figure 1 the maximum irradiation, which is reached by the last fraction of the first charge before it is discharged, is also reported. Giving a limitation of 100 MWd/kg, due to technological reasons, to this maximum burn-up, the irradiation of the first charge is bounded to values lower than 35 MWd/kg, without any appreciable penalty in the cost.

In figure 2 it is plotted as a function of the burn-up of the first charge, the number of burnable poison pins needed to bring down the excess of reactivity to a value of about 0.09. This last value has been calculated adding to the excess reactivity of the equilibrium cycle (0.05) the initial contribution of Xenon, Xenon override requirements and Samarium.

It is shown by the figure that the limitation of 6,300 in the number of burnable poison pins plays an effective role, as it reduces the maximum permissible average irradiation of the first charge down to a value of 30 GWd/T. However, the penalty in the total fuel cycle cost is negligible.

In the figure 1 the behaviour of the quantities x and x_1, described in reference 8 (see Appendix I), are also reported. They may be used for calculating the excess of fissile material charged and discharged during the running-in as compared to the equilibrium ones for the same energy.

2) Thorium-Uranium Cycle

The equilibrium refueling composition of Thorium cycle was determined to give an equilibrium irradiation equal to the one of the low-enriched cycle, namely 87 MWd/kg. For this irradiation the initial make-up enrichment of the equilibrium fuel was 3.5%. The moderation ratio was defined according to the GGA design (C/Th = 225).

The value of the burnable poison equivalent diameter was somewhat higher than the corresponding value for the low-enriched cycle, as Thorium neutron spectrum increases the depletion of the burnable poison macroscopic cross-section with the irradiation. Values of percent absorption of the burnable poison at the end of the first charge are well below 3% in the range of the lower initial irradiation considered and tend to decrease for large burn-up values. In figures 3 and 4 the results of the running-in for the Thorium cycle are reported. As in the low-enriched cycle, the fuel cycle cost averaged over the reactor life shows very little sensitivity to the burn-up of the first charge in a range of values between 20 and 50 MWd/kg. The constraint on the maximum irradiation (100 MWd/kg) bounds the initial irradiation to values lower than 30 MWd/kg. The fuel cycle cost penalty, however, is almost negligible. The initial enrichment of the first charge is always much higher than the equilibrium make-up enrichment, due to the lack of U-233 recycled.

The recycling of U-233 is performed, without any delay, supposing the HTR reactor in an expanding system of similar reactors employing the same fuel cycle. The taking into account of a delay due to cooling, plus reprocessing and re-fabrication would increase the cost and probably change the picture.

In figure 4 the number of burnable poison pins is plotted versus irradiation, together with the factors x and x_1 mentioned above. The number of burnable poison pins is much lower than for the low-enriched cycle. This is partly due to the better efficiency of the burnable poisons in the Thorium spectrum, but also to the much lower reductions in reactivity between the fresh and the spent fuel in the Thorium than in the low-enriched cycle (figure 5), according to the fact that the latter has a much lower conversion ratio.

Table 3 presents the main physical results and the cost comparison between the optimum cases of the Thorium and of the low-enriched cycle. The cost difference in favour of the Thorium cycle, obtained in the equilibrium calculations (0.18 mills/KWh) is found here again almost unchanged.

3) Comparison with the Equilibrium Calculations

As the economic advantage of the Thorium cycle against the Uranium cycle in the case treated before, is almost the same as it was in the equilibrium calculations (programme MOGA), the question may be put if one can conclude about a general validity of the equilibrium surveys. In particular the approximation of giving a value to the average equilibrium fissile inventory has to be investigated.

Table 4 presents some main physical parameters of the equilibrium cycles and the cost splitting, calculated in the two different ways (programmes MOGA and RINA) for the low-enriched fuel. The equilibrium fresh fuel composition being the same, the equilibrium burn-up was lower in the RINA calculation, as in this case the fraction of the core to be recharged has been assumed to be higher. The small differences in the Uranium and Plutonium fuel enrichments are due both to the burn-up variation and to the differences in the average spectrum and in the calculation of the self-shielding factors. As a matter of fact, in MOGA the self-shieldings are calculated as functions of the average core composition, whilst in RINA there are as many disadvantage factors as the number of different fuels with different irradiations. For each of them, the average composition in the refueling interval considered is the parameter determining the self-shielding factors. The difference, however, is quite small, as for the fuel element type chosen, the cell-heterogeneity is very little. These differences in burn-up values and in fuel compositions reflect on the differences in the fresh fuel consumption costs, in the revenues, in the fabrication and reprocessing costs.

The following two items, fresh fuel storage and out of core inventory, represent the inventories in the fresh and in the spent fuel due to the presence of the fabrication time and of the cooling plus reprocessing time. In the equilibrium calculation they are inversely proportional to the burn-up and directly proportional to the delay times (for example: fabrication time). In the running-in economic calculation they are obtained as the differences between the expenditures (or revenues) actualized and those not actualized to the average time at which the energy is produced, i.e. half of the refueling period. According to this, they are inversely proportional to the burn-up of the cycle, but their dependence on the delay time is obtained through the quantity

$$\left[(1+i)^{\mp(T_D+0.5*T_{RF}/h)}-1\right]$$

- i being the interest value,
- T_D being the delay time considered,
- T_{RF} being the refueling time,
- h being the load factor.

The sign + is used for fresh fuel and the sign - for spent fuel.

Approaching the exponential with a linear solution and neglecting the terms of higher order, the fresh fuel storage and out of core inventory are then proportional to the sum of the delay time considered and half of the refueling time. This difference can explain the relatively large discrepancies in these two items. Summing up the six quantities considered, the equilibrium fuel cycle costs are obtained. The agreement is sufficiently good, the difference being found mainly in the fresh fuel storage and out of core inventory.

The total fuel cycle cost is obtained summing to the equilibrium fuel cycle cost, in one case the inventory cost obtained giving a value to the arithmetic average between charged and discharged fuel, in the other case the running-in contribution plus the last charge revenue. The running-in contribution can vary depending on the running-in strategy considered. In the approach to equilibrium strategy considered here, this cost lies in the range between 0.28 and 0.31 mills/KWh and the agreement with the inventory cost is surprisingly good.

For the Thorium cycle, such a comparison was not carried out, as the initial equilibrium composition and then the equilibrium burn-up values were not the same. However, even in this case, some figures can be quoted, which show that the discrepancy between the inventory cost and the running-in contribution, can hardly be higher than 20%, as it can be seen from the following table:

Thorium Cycle	MOGA Calculation	RINA Calculation
Burn-up (MWd/kg)	68	86
Inventory cost or running-in contribution (mills/KWh)	0.427	between 0.40 and 0.42

One-Dimension Calculations

An analysis of the running-in phase for the low-enriched cycle and for the Thorium cycle has been performed for a radially flattened core. Using the one-dimension routine of the code RINA, the purpose of this analysis was to detect any important factor, which is linked to the more detailed one-dimension calculation, as compared to the zero-dimension calculation described above and which could play a role in the comparison between the low-enriched and the Thorium cycle.

No detailed analysis of the radial power form factor has however been performed and therefore the average power and the total reactor power in the one-dimension calculations have been kept equal to those employed in the zero-dimension calculations. This implies that the results of the one-dimension calculations are penalized by the neutron losses due to the power flattening, without correspondingly ensuring a reduction of the investment costs as it should be allowed by the better power form factor due to flattening. A better power form factor, as a matter of fact, usually allows a higher average power, once the maximum peak power is fixed.

Because of the above reasons, the fuel cycle costs obtained from the one-dimension calculations shall not be compared to the one derived from the zero-dimension calculations. The comparison will be done only between low-enriched cycle and Thorium cycle, both calculated at one-dimension: it will be seen that this more detailed calculation will not change very much the conclusions previously reached.

In the one-dimensional calculations, the core was split into two different diffusion zones, the radius of the inner zone being nearly 80% of the total radius. A reasonably good power shape was assumed to be the one giving nearly 70% of the power in the inner zone. This corresponds to an average power density in the inner region of 1.1 and in the outer region of 0.83 times the average value.

1) Low-Enriched Cycle

The power flattening at equilibrium conditions can be achieved in two ways: either refueling a larger fraction of the external zone with the same initial fissile content of the inner zone, in order to have an average higher fissile content, and consequently a good power shape; or recharging the same fraction in both regions with a higher fissile enrichment in the external region. The first possibility was chosen here: it exploits the insensitivity of the HTR fuel cycle cost over a wide range of burn-up values and avoids the fabrication of two different fuels, for the whole reactor life. Calculations were made for different ratios of refueling fractions, and the results are presented in the following table.

Refueling Fractions of		Power Fraction in inner region (%)	Equilibrium burn-up (MWd/kg) of	
inner region	outer region		inner region	outer region
12	4	58.5	106	44
10	6	65.5	95	53
9	7	70	91	55

For the refueling fractions in the ratio 9/7 the power shape assumes the desired value and the irradiations reached by the fuel elements in the two regions are just in the range of acceptable values.

In the first charge, two different initial enrichments were considered to give approximately the same power shape as for the equilibrium cycle. As it was done for the zero-dimensional calculations, the average burn-up of the first charge was assumed as the parameter of the running-in, and at the end of the first charge 1/9 of the inner region and 1/7 of the outer were discharged and replaced with the equilibrium composition, and so on.

The equilibrium composition was the one obtained in the zero-dimensional calculation. Burnable poisons were allowed in the first charge, the burnable poison pins being spread uniformly through the whole core. The effective diameter of the burnable poison pins was reduced from 1 mm to 0.8 mm in these calculations, in order to avoid large burnable poison absorption at the end of the first charge, and consequently an increase of the initial fissile requirements. The increase of final burnable poison absorption at the end of the first cycle is due to the hardening of the spectrum, according to the higher average fissile content than in the zero-dimensional calculations.

Figures 6 and 7 show the results obtained for the running-in of the low-enriched cycle in the one-dimensional approach. In figure 6 the initial enrichments of the first charge are reported and the fuel cycle cost which reaches its minimum value at about the same average irradiation of the first discharged fraction as in the zero-dimensional calculations. Due to the different refueling fractions in the two zones, the maximum burn-up limitation plays here an important role. Actually, already for an average irradiation at the first reload of 19 MWd/kg, the last fraction of the inner zone has an irradiation of 100 MWd/kg before it is discharged. This limitation implies an increase in the total fuel cycle cost of 0.02 mills/kWh over the entire reactor life.

In figure 7 the number of burnable poison pins is plotted versus the average irradiation of the first charge, together with the quantities x and x_1. These last two items do not change very much passing from one to two zones core. The number of burnable poison pins, however, increases both because of the reduction of the effective diameter and for the hardening of the spectrum. The limitation to 6,300 of this number gives an irradiation value which is about half of that obtained in the zero-dimensional calculation: the burn-up of the fuel first discharged is here bounded to values lower or equal to 15 MWd/kg, with a further increase in the total fuel cycle cost of 0.012 mills/kWh.

2) Thorium Cycle

In the Thorium cycle the possibility to obtain an equilibrium power flattening equal to that of the low-enriched cycle was also investigated. As a result of the calculation, however, the numbers of refueling fractions in the two radial zones were found to be in the ratio 12 to 4, giving for the equilibrium irradiation the values of 130 and 29 MWd/kg in the two regions. Even if the technological limitation could be extended to include the value of 130 MWd/kg, the penalty in the fuel cycle cost would be in this case too severe, as the values calculated are too far from the region of insensivity of the cost to the burn-up variations.

The introduction of two equilibrium enrichments is then necessary to obtain the flattening ratio desired in the equilibrium cycle. The initial enrichment of the inner region was kept equal to that used in the zero-dimensional calculations, the outer enrichment resulting 25% higher. The equilibrium burn-up values are different, according to the different average power densities in the two regions. The following table shows the economical advantage of flattening by two zone enrichments in the Thorium equilibrium cycle, instead of flattening by differential burn-ups. No penalty in the fabrication cost has been considered for the enrichments case, but the fabrication unit cost should increase from 120 to 270 $/kgHM in the case of the two enrichments, to obtain the same fuel cycle cost as in the case of a single enrichment.

	Inner zone	Outer zone	Inner zone	Outer zone
Number of refueling fractions	12	4	8	8
Initial enrichment (%)	3.5	3.5	3.5	4.35
Burn-up (MWd/kg)	130	29	87.5	67.5
Equilibrium fuel cycle cost (mills/kWh)	1.35		1.17	

In the first charge two different initial enrichments were also considered to give approximately the same power shape as for the equilibrium cycle. As in the other cases, the average burn-up of the first charge was assumed as the parameter of the running-in. At the end of the first charge 1/8 of the inner region and 1/8 of the outer region were discharged and replaced with the equilibrium fuels. Burnable poisons were allowed in the first charge. The effective diameter of burnable poison pins was reduced from 1.4 mm to 1 mm to avoid the large absorptions at the end of the first charge.

Figure 8 and 9 show the results obtained for the running-in of the Thorium cycle in the one-dimensional approach. In Figure 8 the total fuel cycle cost is plotted versus the average burn-up at the first charge together with the initial enrichment of the first charge and the maximum irradiation. No severe penalty is introduced by the limit on the maximum burn-up. Optimum fuel cycle cost occurs for a burn-up of about 30 MWd/kg, but the irradiation is bounded to values below 23 MWd/kg. This limitation introduces an increase of fuel cycle cost which is however, of one order of magnitude smaller than the corresponding increase for the low-enriched cycle.

In figure 9, the number of burnable poison pins as a function of the burn-up is given, together with the quantities x and x_1. These two items do not change passing from one radial zone to two radial zones calculation, and they are also quite independent from the irradiation of the first charge. Their values are more or less typical of the type of the cycle investigated and of the running-in strategy assumed.

The number of the burnable poison pins is well below its limiting value of 6,300. In figure 10 the reactivity shift between fresh and spent fuel for the first charge in the non-poisoned core is reported together with the single burnable poison pin efficiency for the Thorium and for the low-enriched cycle. Mainly the large differences in the reactivity shifts for the two cycles are responsible of the much lower values of the number of pins for the Thorium cycle.

Optimum Cases

The main parameters of the optimum running-in case for the low enriched cycle are shown in table 5, where the refueling interval, the power fraction in the first zone, the reactivity to be controlled with control rods, and the maximum age factors in the two regions are reported. As the number of charges increases, each of these quantities tends to reach its equilibrium value. The variations of the refueling interval, of the fresh-spent fuel reactivity shifts and of the power fractions are smooth and do not introduce any difficulty.

The age factor, on the contrary, changes drastically as soon as some Plutonium is building up in the reactor and, particularly in the inner core where the irradiations are larger, reaches values much higher than the equilibrium ones. This does not mean that the running-in considered is not feasable, as the age factor remains anyway lower than the equilibrium age factor of the Thorium cycle (see Table 6). It indicates only a reduction of the eventual advantages, which could be achieved in the low-enriched cycle with a proper fuel element design.

The optimum running-in of the Thorium cycle is described in table 6. Apart from the Uranium-233 recycled quantity, the equilibrium values are reached here some charges before and the parameters oscillations are smaller, which can introduce a further advantage to the Thorium cycle.

A comparison between the two cycles is shown in table 7, where two fuel cycle costs are quoted for the Thorium. They correspond to two different fabrication changes, nominal and increased by 20%, in order to take into account the penalty due to the fuel element fabrication with different enrichments, for the entire reactor life. The results of the table indicate that, even in this case, the low-enriched cycle is more expensive than the Thorium one, the difference being of the same order of that found in the equilibrium zero-dimensional calculations.

Final Remarks

The approximations of the calculation method and the limited investigation of the parameters of the two fuel cycles do not allow to draw a final conclusion on the advantage of one cycle on the other. Different running-in approaches can be studied, different fuel geometries, moderation ratios and equilibrium burn-up values have to be introduced.

Some interesting results can, however, be summarized:

- The running-in costs are more or less the same of the inventory costs obtained in the equilibrium zero-dimensional calculation. Most of the conclusions of the previous surveys can then be maintained.
- Both the zero and one-dimensional calculations show a higher number of burnable poison pins, required by the low-enriched cycle.

The limitation on this number plays an effective role in determining the minimum cost. The influence of fabrication cost of the burnable poison pins should be taken into account in the economic evaluation.

- Too low irradiations of the first charge are not economically attractive, because of the high fabrication charges.
- The limitation on the maximum burn-up is effective only for Thorium cycle.
- In the running-in of the low-enriched cycle, the age factor is much higher than that of the equilibrium cycle and is of the same order of that of the Thorium cycle.
- The power flattening of the equilibrium cycle can be achieved varying the burn-up values of the two regions. This is attractive only for low-enriched fuel.
- The quantities x and x_1, which represent the excess of fissible charged and discharged during the running-in, as compared to the values at the equilibrium and normalized to the same energy, are not very sensitive to the running-in approach and to the type of calculation (0-D or 1-D). They are typical of the fuel cycle of the reactor considered.

Appendix I

In order to interpret the results of the running-in survey studies in terms of different consumption or production of fuel, relative to the equilibrium cycle, the conclusions of the work performed by ENEA[8] can be used. In fact, in the running-in period, the fuel charges are usually less effective than equilibrium fuel, e.g. they achieve lower burn-up values if the composition is the same.

This can be compensated by an additional amount of fuel, xk for the new fuel or x'c for recovered fuel, where k and c are the equilibrium charge and discharge, respectively.

If the whole running-in period would have the same uranium requirements, k and c for new and spent fuel, no transition term would be needed.

If, however, the first fuel charge has values k_1, c_1 and B_1, then the increase in the uranium consumption will be as follows.

xk = (uranium in first charge) - (uranium requirement with equilibrium fuel over the irradiation period of the first charge) =

$$k_1 - k B_1 / B$$

and for the whole running-in period

$$xk = \frac{1}{N} \quad \mathrm{Sum}_i \, k_i - k \, \mathrm{Sum}_i B_i / B$$

$$\text{hence} \quad x = \frac{1}{N} \left[\frac{\mathrm{Sum}_i}{k} k_i - \frac{\mathrm{Sum}_i \, B_i}{B} \right]$$

Similarly, the component arising from the spent fuel is

$$x' = \frac{1}{N} \left[\frac{\mathrm{Sum}_i \, C_i}{C} - \frac{\mathrm{Sum}_i \, B_i}{B} \right]$$

Table 1

MAIN REACTOR AND PHYSICS CHARACTERISTICS

1. Electrical power	1000 MW
2. Thermal efficiency	0.40
3. Power density	8 W/cc
4. Axial buckling	$2.15 \,.\, 10^{-5}$ cm^{-2}
5. Control rod investment	100% Xe override
6. Number of refueling regions	8
7. Core height/core diameter ratio	0.835
8. Fuel pins:	
Rod diameter	12.7 mm
Length	36.5 cm
Number of rods per block channel	2
Height of channel plugs	3 cm
Heavy metal loading	variable
Graphite matrix density	1.7 g/cc
9. Hexagonal block:	
Graphite density	1.8 g/cc
Distance across flats	360 mm
Height	790 mm
Fuel holes: number	210
diameter	12.7 mm
Coolant holes: number	108
diameter	15.9 mm
Burnable poison holes: number	6
diam.	variable
Block handling hole: length	395 mm
equivalent diameter	50 mm

Table 2

ECONOMIC DATA

Interest rate	11%
U-233 value	14 $/g
Pu-fissile value	10 $/g
U-235 (93% enriched)	12 $/g
Thorium value	30 $/kg
Fabrication delay	180 days
Reprocessing delay	360 days
Load factor	0.75
Reprocessing cost:	
Uranium	100 $/kg HM
Thorium	120 $/kg HM
Fabrication cost:	
Uranium	212 $/kg HM
Thorium	190 $/kg HM
Graphite cost	9 $/kg

Table 3

ZERO-DIMENSIONAL SCHEME

Comparison between Thorium and Low-Enriched Cycle

OPTIMUM CASES

with the limitations in maximum burn-up (100 MWd/kg) and in the number of burnable poison rods (6, 300)

	Thorium cycle (U-233 recycled)	Low-enriched cycle (Pu sold)
Burn-up of first charge (MWd/kg)	30	30
Initial make-up enrichment (%)	5	5.9
Maximum burn-up (MWd/kg)	100	100
Equilibrium make-up enrichment (%)	3.5	8.35
Fuel cycle cost (mills/kWh)	1.479	1.691
Equilibrium fuel cycle cost (mills/kWh)	1.090	1.420
Running-in cost (mills/kWh)	0.389	0.271
Number of burnable poison rods	2,300	6,300
x	0.55	0.5
x_1	0.18	0.0

Table 4

LOW-ENRICHED CYCLE

Comparison between an Equilibrium MOGA-calculation and a RINA-calculation which include a zero-dimensional approach to equilibrium phase

	MOGA calculation	RINA calculation
Refueling fraction	1/40	1/8
Equilibrium burn-up (MWd/kg)	92	86
Equilibrium critical enrichment (%)	8.35	8.35
Equilibrium Uranium final enrichm. (%)	1.92	2.03
Equilibrium Plutonium final enrichm. (%)	1.48	1.45
Cost splitting (mills/kWh)		
Fresh fuel consumption	1.017	1.051
Fabrication (fuel + mod.)	0.407	0.435
Reprocessing	0.114	0.121
Revenue	- 0.280	- 0.323
Fresh fuel storage	0.077	0.112
Out of core inventory	0.020	0.024
Equilibrium fuel cycle cost (mills/kWh)	1.355	1.420
Inventory (mills/kWh)	0.324	-
Running-in contribution (mills/kWh)	-	0.281
Last change revenue (mills/kWh)	-	- 0.011
Total fuel cycle cost	1.679	1.691

Table 5

OPTIMUM RUNNING-IN FOR THE LOW-ENRICHED CYCLE

Charge number	Refueling time (days)	Power fraction in the first zone	Maximum age factor		ΔK_{eff}	Discharged fissile Pu enrichment
			Region 1	Region 2		
1	150	70.6	1	1	9.2	0.56
2	134	67.2	1.51	1.12	8.1	0.84
3	92	67.5	1.47	1.12	5.8	0.97
4	79	68.2	1.42	1.11	5.0	1.06
5	81	68.6	1.37	1.10	4.9	1.13
6	85	68.6	1.33	1.08	5.0	1.19
7	89	68.4	1.29	1.07	5.1	1.24
8	92	68.1	1.25	1.05	5.2	1.27
9	96	68.3	1.22	1.05	5.3	1.28
10	97	68.7	1.19	1.05	5.2	1.31
11	99	69.3	1.18	1.05	5.3	1.33
12	98	69.4	1.17	1.05	5.2	1.34

Table 6

OPTIMUM RUNNING-IN FOR THE THORIUM CYCLE

Charge number	Refueling time(days)	Power fraction in the first zone	Maximum age factor	ΔK_{eff}	U-233 enrichm. (%)
1	312	71.	1.15	9	-
2	168	69.2	1.36	5.4	1.24
3	117	69.2	1.55	4.6	1.74
4	130	69.4	1.60	5.2	1.94
5	136	69.5	1.61	5.5	2.04
6	143	69.6	1.62	5.7	2.11
7	156	69.5	1.62	6.2	2.16
8	156	69.4	1.60	6.1	2.19
9	156	69.3	1.60	6.1	2.23
10	156	69.3	1.59	6.1	2.25
11	156	69.3	1.59	6.0	2.27
12	156	69.3	1.58	6.0	2.28

Table 7

ONE-DIMENSIONAL SCHEME

Comparison between Thorium and Low-Enriched Cycle

OPTIMUM CASES

with the limitations in maximum burn-up (100 MWd/kg) and in the number of burnable poison rods (6, 300)

		Thorium Cycle		Low-Enriched Cycle
Burn-up of first charge (MWd/kg)		23		15
Initial make-up enrichment (%)	inner core	4.6		5.1
	outer "	5.85		7.5
Maximum burn-up (MWd/kg)		100		92
Equilibrium make-up enrichment (%)	inner core	3.5		8.35
	outer "	4.35		8.35
Fuel cycle cost (mills/kWh)		1.592	1.667*	1.867
Equilibrium fuel cycle cost (mills/kWh)		1.223	1.280*	1.556
Running-in cost "		0.370	0.387*	0.311
Number of burnable poison rods		3,800		6,300
x		0.56		0.48
x_1		0.21		- 0.07

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* The fabrication charges are increased by 20% as compared to the nominal value.

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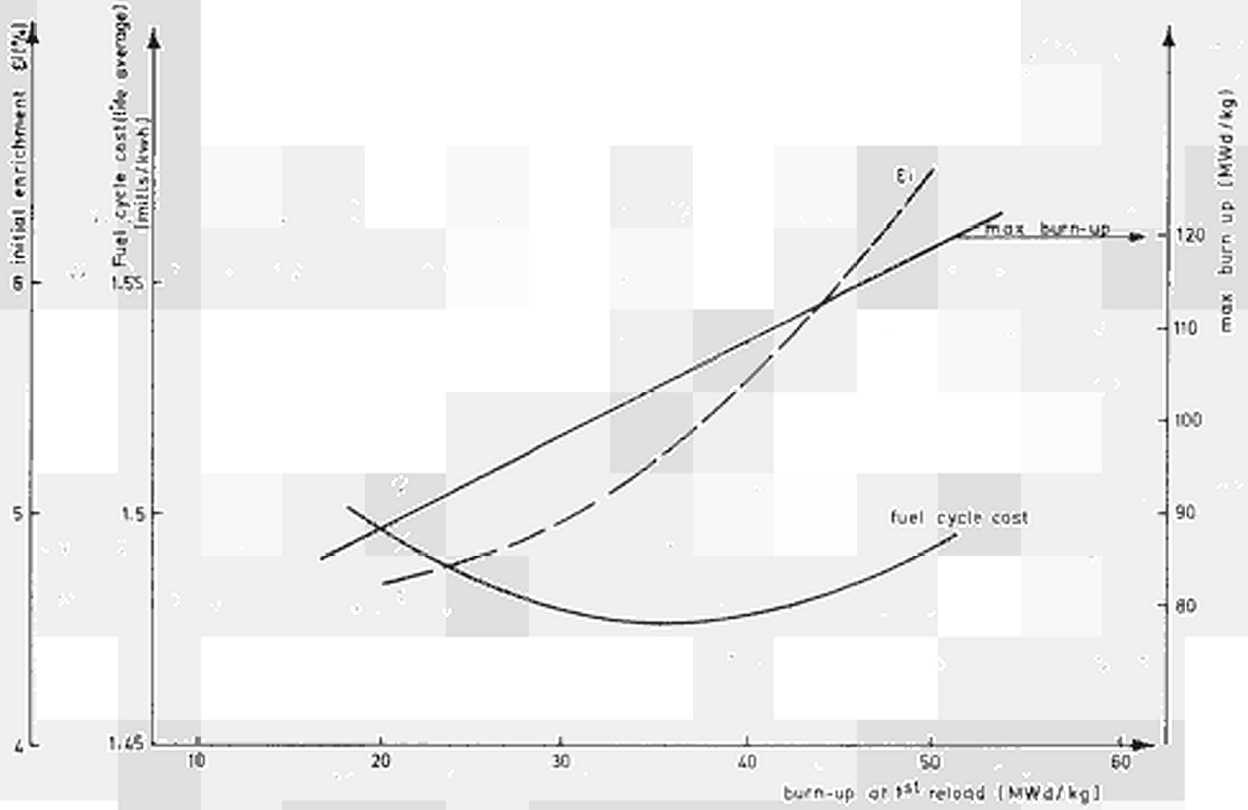

Fig. 3 - THORIUM-URANIUM CYCLE ZERO-DIMENSIONAL CALCULATION

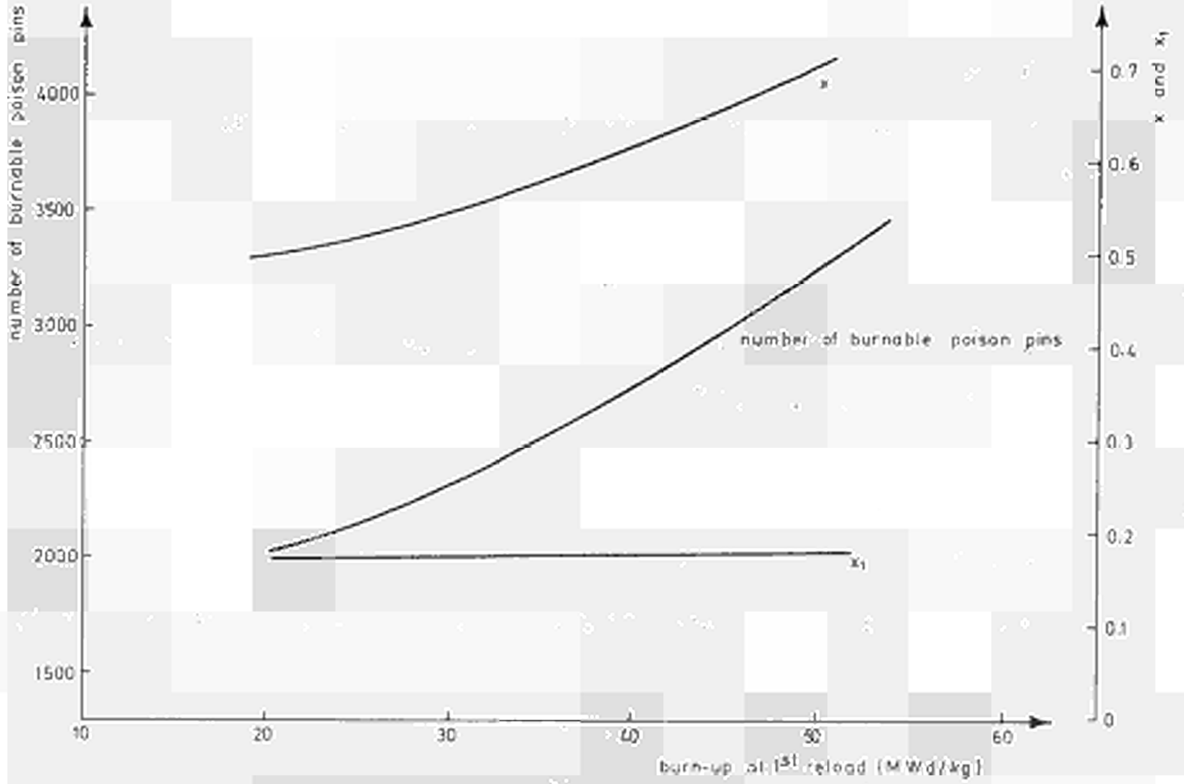

Fig. 4 - THORIUM-URANIUM CYCLE ZERO-DIMENSIONAL CALCULATION

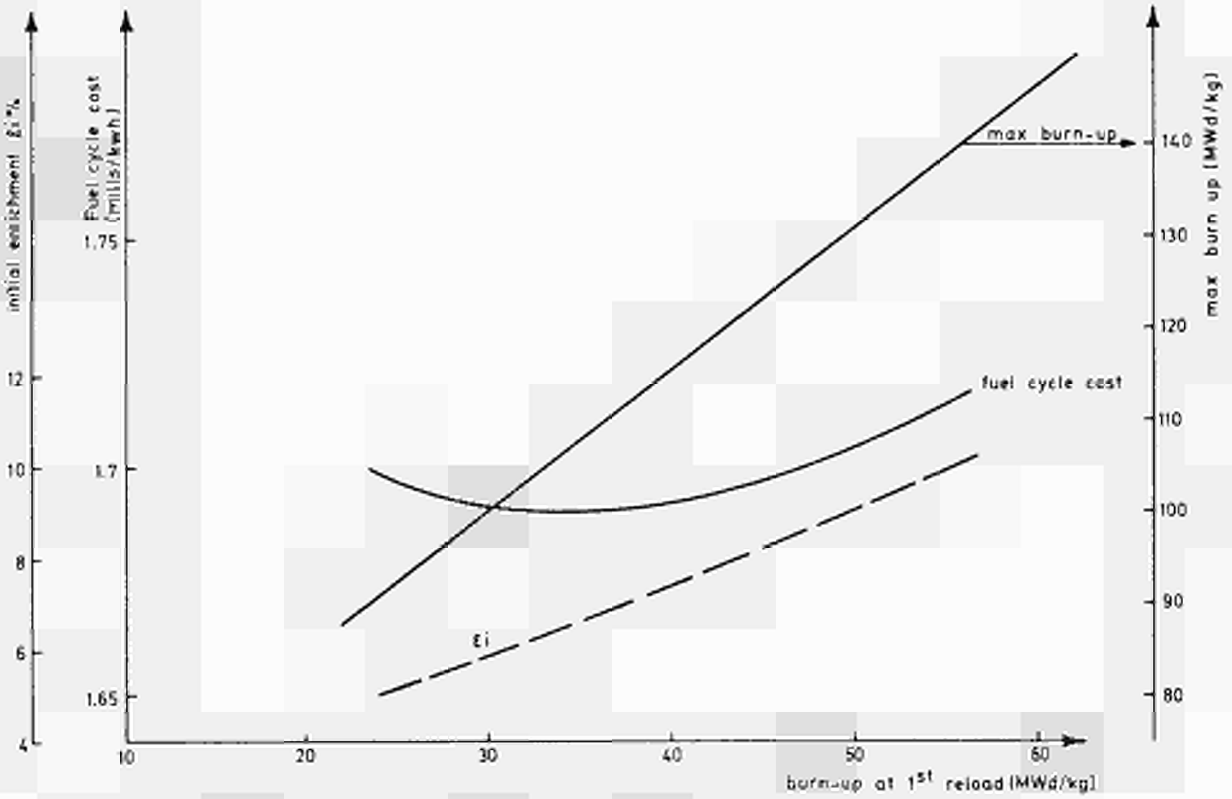

Fig. 1 - LOW-ENRICHED CYCLE ZERO-DIMENSIONAL CALCULATION

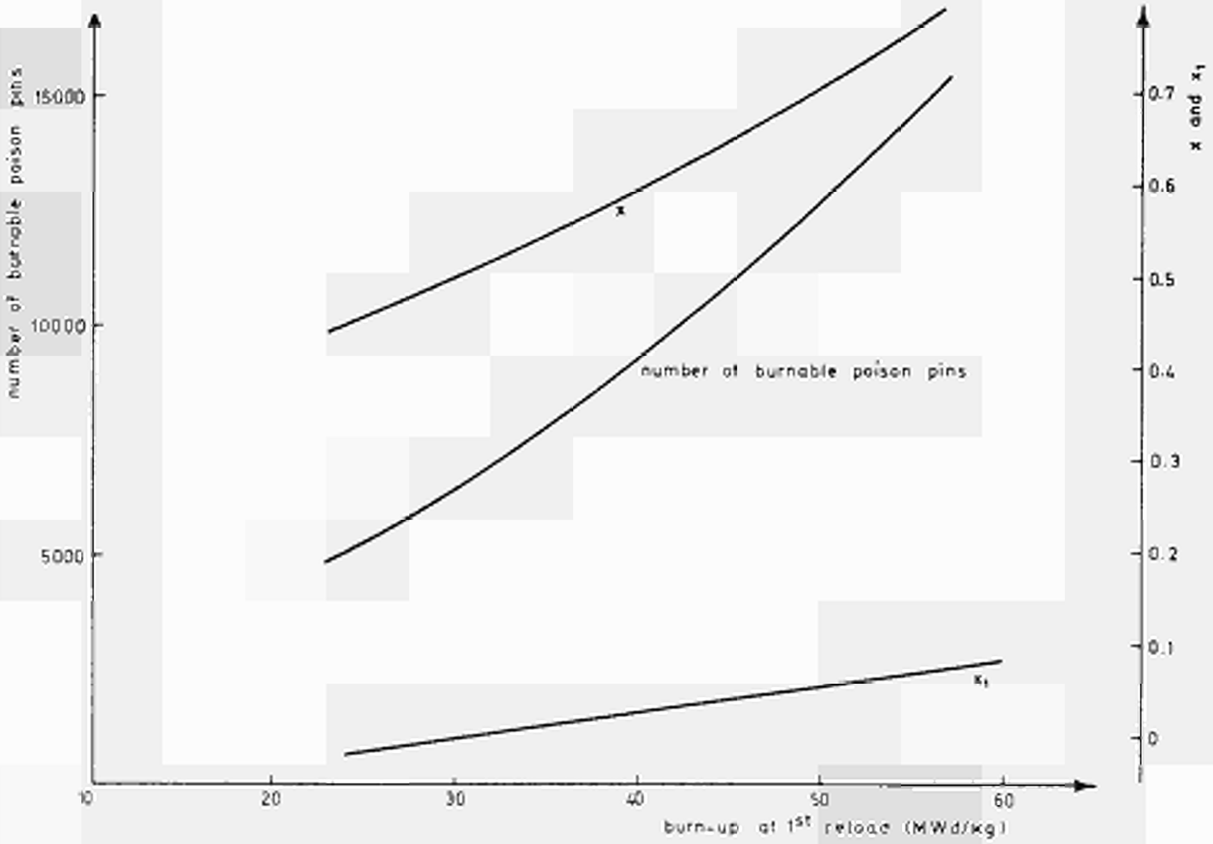

Fig. 2 - LOW-ENRICHED CYCLE ZERO-DIMENSIONAL CALCULATION

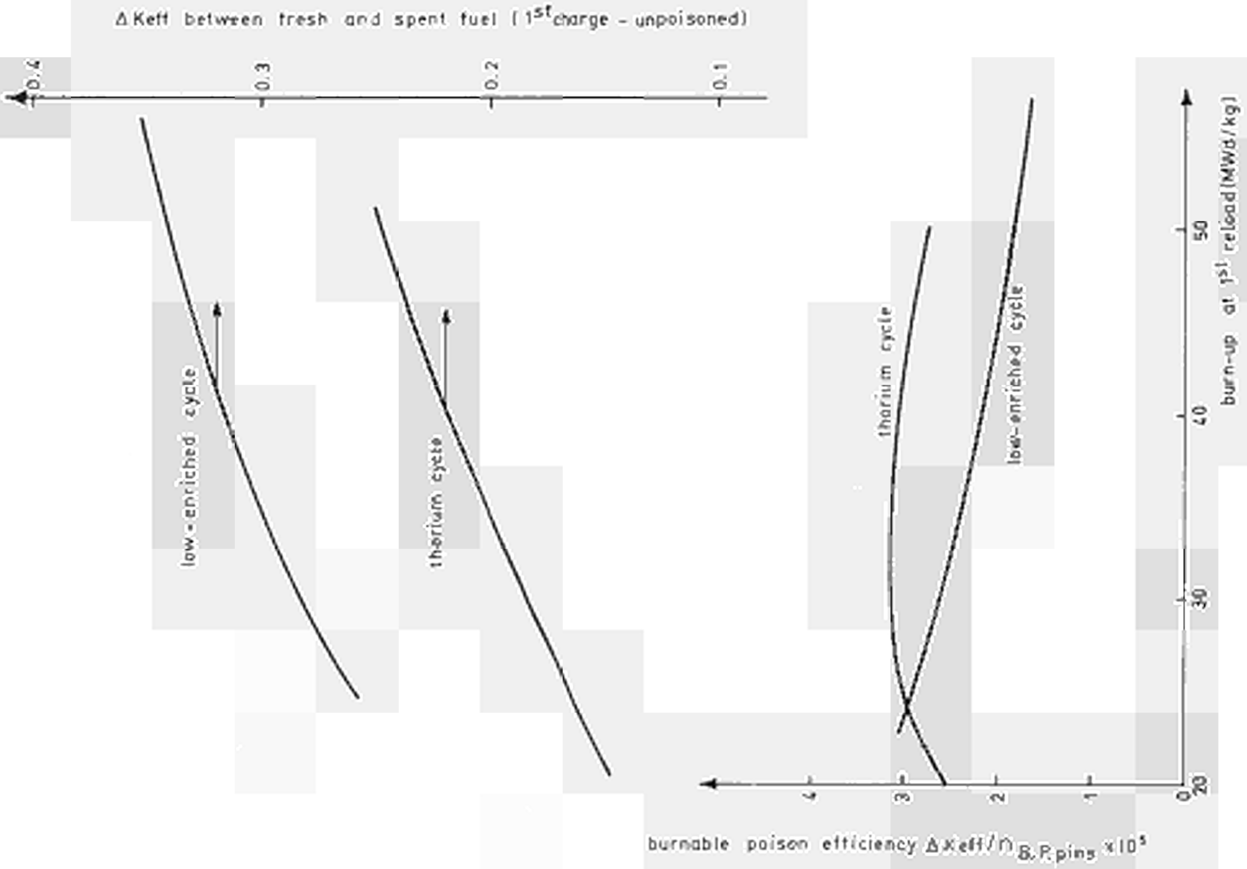

Fig. 5 - ZERO DIMENSIONAL CALCULATION

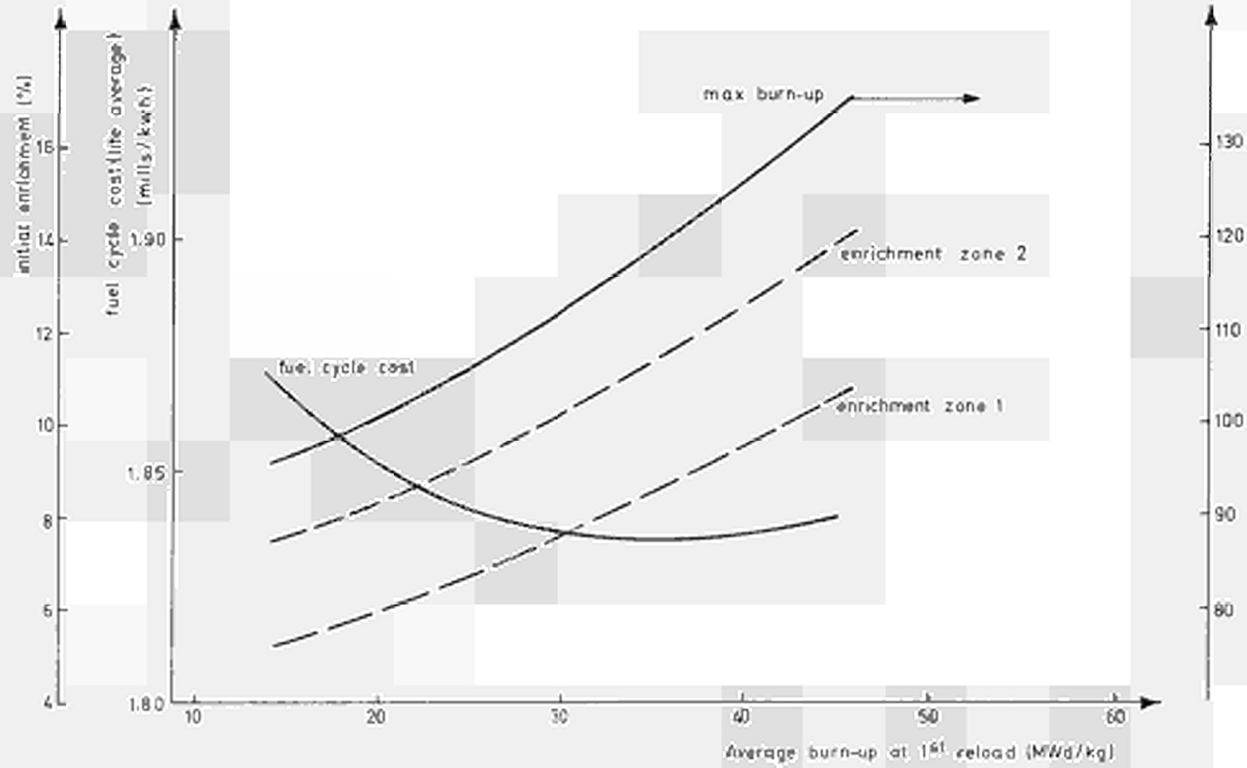

Fig. 6 - LOW-ENRICHED CYCLE ONE-DIMENSIONAL CALCULATION

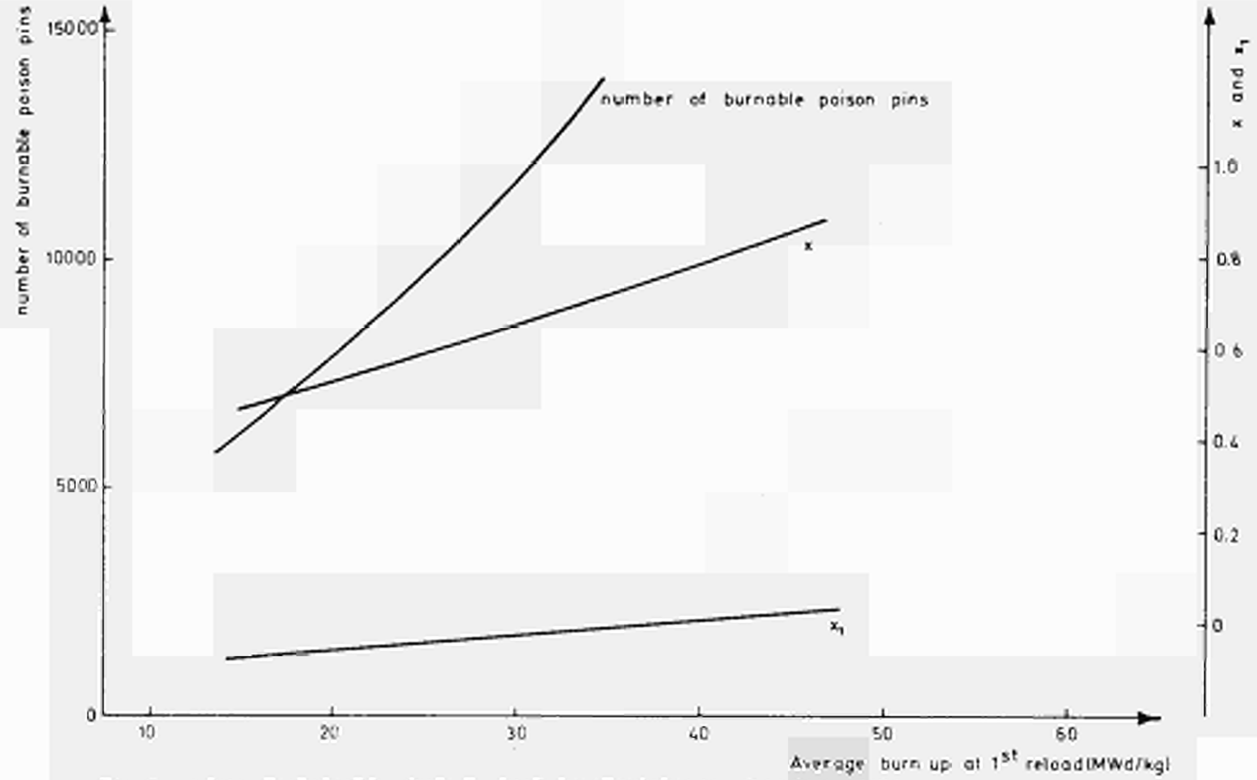

Fig 7 - LOW-ENRICHED CYCLE ONE DIMENSIONAL CALCULATION

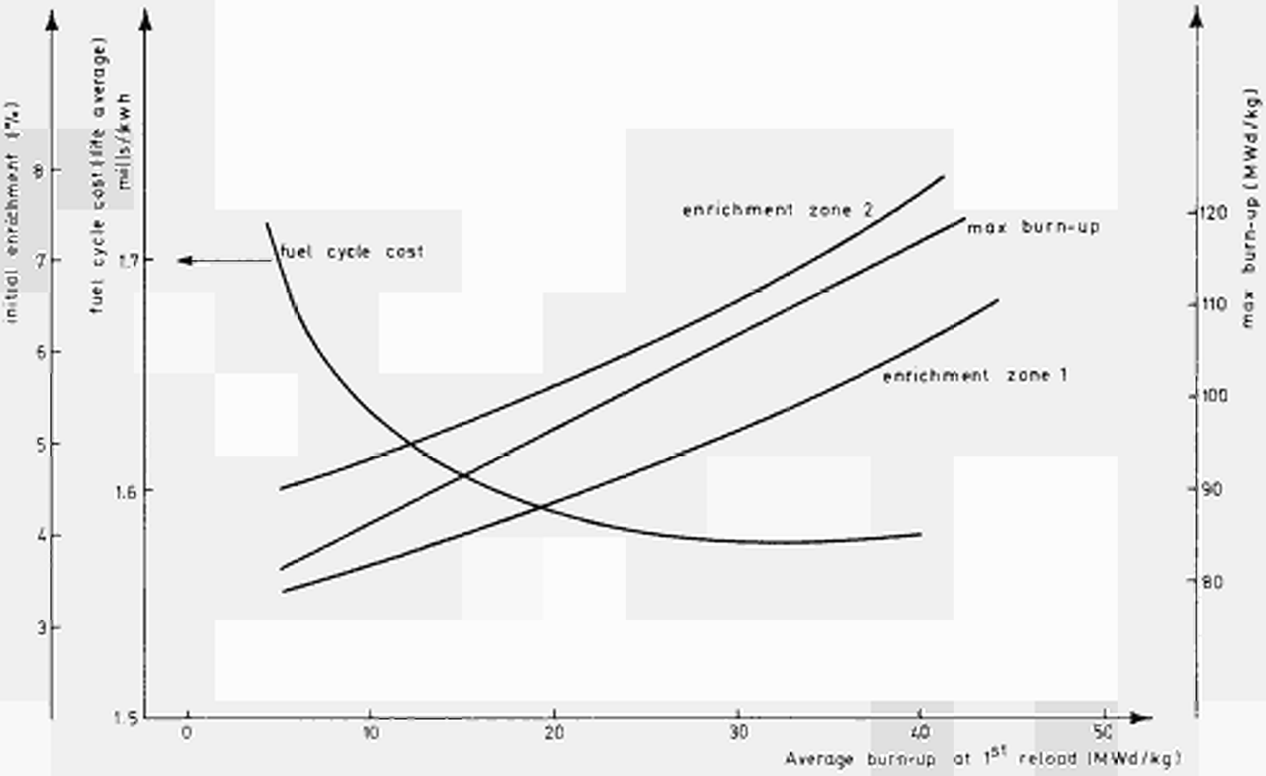

Fig. 8 - THORIUM-URANIUM CYCLE ONE-DIMENSIONAL CALCULATION

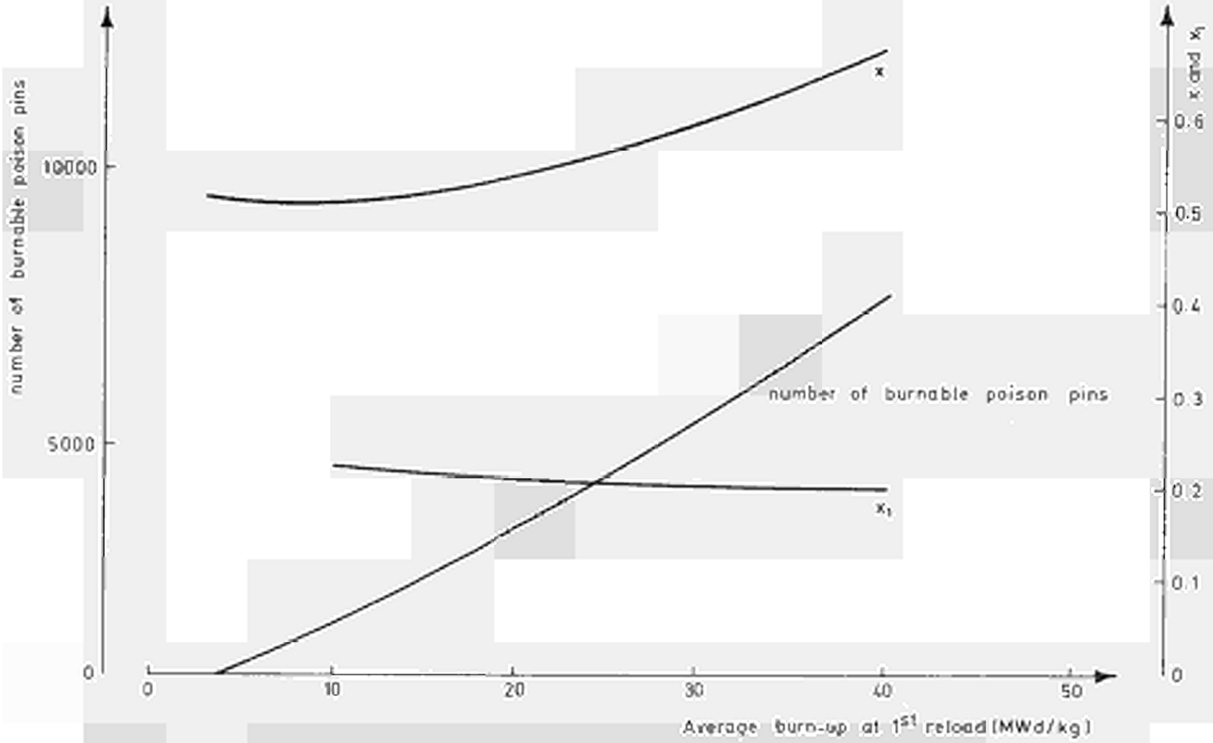

Fig. 9 - THORIUM-URANIUM CYCLE ONE-DIMENSIONAL CALCULATION

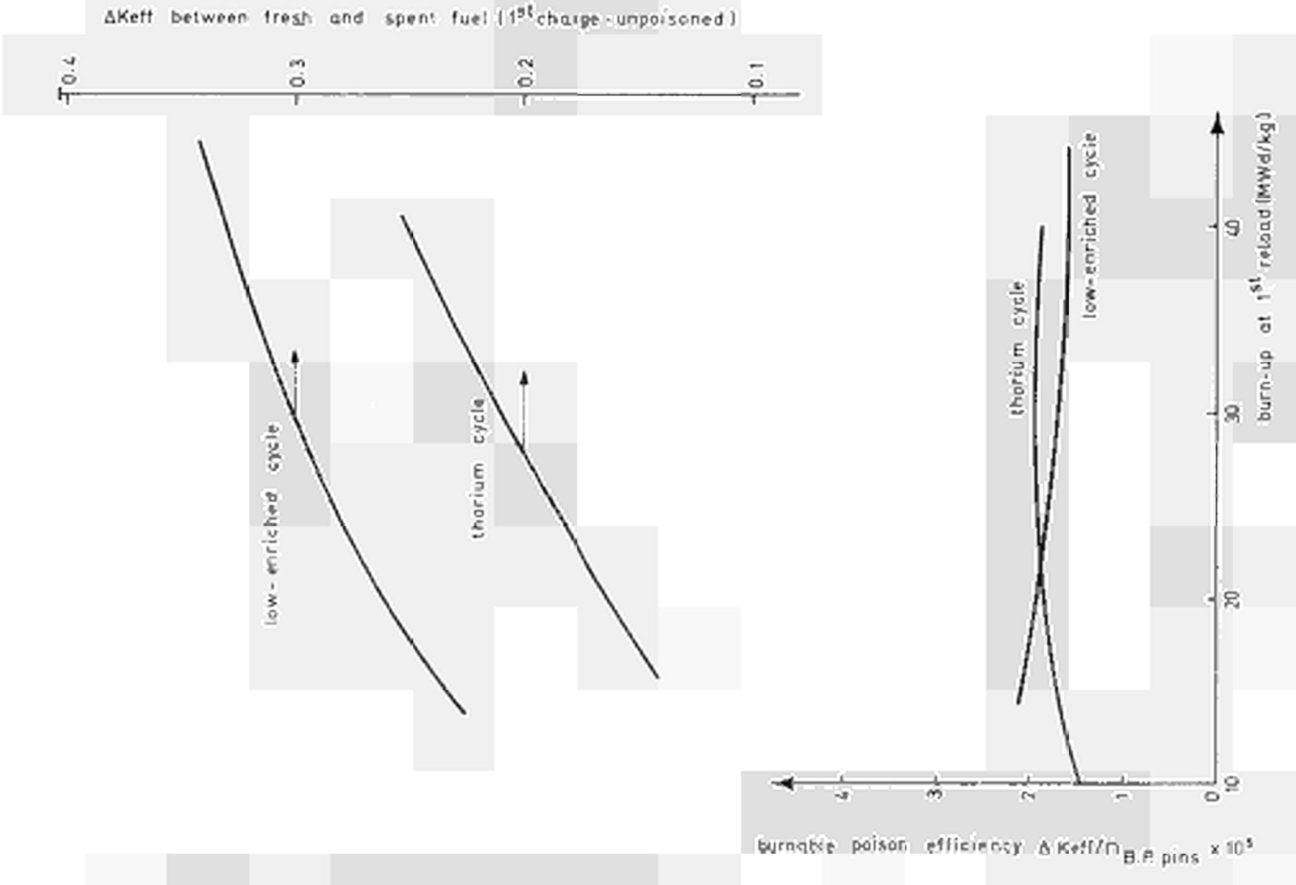

Fig. 10 - ONE-DIMENSIONAL CALCULATION

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To disseminate knowledge is to disseminate prosperity — I mean general prosperity and not individual riches — and with prosperity disappears the greater part of the evil which is our heritage from darker times.

Alfred Nobel

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