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CAN THORIUM COMPETE WITH URANIUM ? AN ASSESSMENT FOR HEAVY-WATER AND GRAPHITE MODERATED REACTORS

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G. GRAZIANI, C. RINALDINI, C. ZANANTONI, J.J. DEVOS and M. PARUCCINI

1969

Joint Nuclear Research Center
Ispra Establishment - Italy

Reactor Physics Department
Reactor Theory and Analysis

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Printed by Smeets
Brussels, May 1969

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The comparison between the fuel cycle costs of the uranium and thorium cycle shows a slight advantage for thorium under present economic conditions. The economic conditions which should be realized in order to make thorium more competitive are investigated by means of a parametric survey of the cost of fabrication, reprocessing, ore and separative work.

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ABSTRACT

The cost of thorium fuel cycles with fully enriched uranium make-up and of natural and enriched fuel cycles was investigated for D_2O moderated pressure tube and pressure vessel reactors and high-temperature gas-cooled reactors.

The fuel cycle cost was optimized by a parametric investigation of burn-up, specific power and moderation ratio. A continuous charge-discharge fuelling was assumed, with full recycle, partial recycle and segregation schemes.

The comparison between the fuel cycle costs of the uranium and thorium cycle shows a slight advantage for thorium under present economic conditions. The economic conditions which should be realized in order to make thorium more competitive are investigated by means of a parametric survey of the cost of fabrication, reprocessing, ore and separative work.

Note

A preliminary version of this work was presented at the IAEA Panel on Thorium Utilization in Power Reactors, Vienna, June 4 to 8, 1968.
Since then, a number of changes have been brought in, mainly :

a) The calculations have been repeated with an adjourned (1967) cross section library. This has resulted in a slight shift in favour of thorium cycles.
b) All calculations have been carried out with a control poisoning corresponding to the so-called "40% xenon override" requirements.

KEYWORDS

THORIUM
URANIUM
FUEL CYCLE
COST
NATURAL URANIUM FUEL
HEAVY WATER MODERATOR
PRESSURE TUBES
PRESSURE VESSELS
REACTORS
GAS COOLANT
HTGR
ECONOMICS

CONTENTS

Manuscript received on 14 January 1969.

1. LIST OF SYMBOLS AND DEFINITIONS

SP	SPECIFIC POWER[o] (W/g=MW/T)	= Thermal power per unit metal weight - HTGR Thermal power per unit fuel (oxide) weight - ORGEL
PD	POWER DENSITY[o] ($W/cm^3=KW/lt=MW/m^3$)	= Thermal power per unit core volume
	RATING[o] (MW/Kg)	= Thermal power per unit fissile material weight in the reactor
	FISSILE INVENTORY (Kg/MW)	= $(\text{Rating})^{-1}$
R	REPROCESSING COST ($/Kg)	= Per unit fuel (oxide) weight - ORGEL Per unit metal weight - HTGR
F	FABRICATION COST ($/Kg)	= Same units as the reprocessing cost. For the HTGR, a graphite manufacturing cost per unit graphite weight was added
BU	BURN-UP[o] (MWD/T)	= Thermal energy extracted from unit fuel (oxide) weight - ORGEL metal weight - HTGR
	ENRICHMENT (Usually quoted for fresh fuel (%))	= Atomic ratio: $\frac{\text{fissile}}{(\text{fissile} + \text{fertile})}$
$\bar{c}$	CONVERSION RATIO[o]	= Fissile produced/Fissile destroyed. It is the value corresponding to the life-average fuel composition
$\bar{\bar{\eta}}$	THERMAL FISSION FACTOR	= Relative to the average concentration of all fissile isotopes
$\begin{cases} C/Th \\ C/U8 \end{cases}$	ATOMIC RATIO CARBON TO THORIUM (HTGR)	= Parameter used as moderation ratio for HTGR
Vm/Vf	VOLUME RATIO MODERATOR TO FUEL (D_2O)	= Parameter used as moderation ratio for D_2O Reactors
PPf	POWER PEAK FACTOR	= It is not the total power peak factor that would be found in a

[o] These quantities are always to be intended as averaged over the core or over the fuel element life (space-average being the same as time-average in the homogeneous continuous-charge-discharge scheme).

true reactor, as space-effects are not considered in our zero-dimensional calculations. It is sometimes called age factor as it represents the ratio between the power density in the fresh fuel and the average power density in our zero-dimensional calculations

FISSILE CONSUMPTION (g/MWD) = (Fissile content per unit fuel weight in fresh fuel - same in spent fuel)/Burn-up

C FUEL-CYCLE COST (mills/KWh) = Includes all items relative to the core and to the fuel treatment. Investment in heavy water and channels is included

40% XENON OVERRIDE = Enough control poison is permanently in the core as to be able to restart the reactor soon after a shut-down from 100% to 40% load

DEFINITION OF THE TYPES OF FUEL-CYCLE MENTIONED IN THIS PAPER:

Once-through = The fuel is either thrown away or sold after discharge. The results presented here refer to the case with sale of the discharged fuel

Full recycle = All the discharged fuel is reprocessed and the reprocessed Uranium is fed back again with the fresh fuel, together with a Uranium or Plutonium make-up, bought on the market

Segregation = The fuel is segregated into "seed particles" and "breed particles". When the fuel is fabricated all Uranium is fed into the seed particles, and the breed particles contain only Thorium. After irradiation, all Uranium isotopes are present in the breed particles, but very little U236 has built up in them. Instead, a considerable quantity of U236 has accumulated in the seed particles, and they are thrown away or sold to get rid of U236. The breed particles are recycled into the

seed particles: in a real case they would partly be recycled into breed particles, in order to smoothen out the power distribution in the reactor. But using either scheme would lead to small differences in the fuel-cycle cost on a theoretical basis, so this was not done in this paper

2. LIST OF THE MAIN TECHNICAL AND ECONOMICAL ASSUMPTIONS

Reactor thermal power	1500 MW, PHWR 1100 MW, HTGR	
Plant thermal efficiency, PHWR	32%	
HTGR	43%	
Maximum specific power, PHWR Th fuel	50 W/g	
U fuel	40 W/g	
Standard case { ore cost (U308)	17.6 $/Kg	
Standard case { cost of separative work	27.8 $/Kg	
Standard case { tails enrichment	0.253 %	
Standard case cost of 93% enriched Uranium	11.16 $/Kg	
Enriched Uranium cost (USAEC standards):	see fig.2	
Sale's price of discharged fissile Plutonium	8 $/g	
Fabrication cost, PHWR	50 $/Kg	(oxide)
Reprocessing cost, HTGR	30 $/Kg	(oxide)
Fabrication cost, HTGR		
U-Th homogeneous fuel (ref. 5): fissile	800 $/Kg	(metal)
fertile	55 $/Kg	(metal)
Enriched Uranium homogeneous fuel	75 $/Kg	(metal)
Enriched Uranium heterogeneous fuel	75 $/Kg	(metal)
Reprocessing cost, HTGR	100 $/Kg	(metal)
Manufactured graphite cost	6 $/Kg	
Fixed graphite structure resid. time	6 years	
D_2O cost	40 $/Kg	

Constant out of reactor D_2O inventory	175 Kg/MWe
Reflector thickness, PHWR: radial	50 cm
axial	21 cm

Densities:

Core average carbon density, homogeneous HTGR	1.4 g/cm^3
Maximum matrix density, heterogeneous HTGR	2.0 g/cm^3
Fuel density, Th PHWR	8.0 g/cm^3
U PHWR	9.0 g/cm^3
D_2O density, PHWR	0.87 g/cm^3

Temperatures:

fuel, PHWR	1200°C
D_2O, PHWR	300°C
fuel, HTGR	1500°C
graphite, HTGR : fuel graphite	1200°C
permanent graphite	800°C

Interest rate on fuel	6%/year
Interest rate on permanent moderator	10%/year
Out-of-reactor residence time	240 days
Plant load factor	7000 hours/year

3. INTRODUCTION

A large number of investigations on the use of Thorium in thermal reactors has been carried out during the last 10 years. However, it is not easy do draw from the published work any conclusion on the economic competitivity of Thorium against Uranium.

One of the reasons for this is that the assessments were usually made for a Th fuel cycle only and had to be compared with Uranium fuel cycles studied by different authors.

Moreover, the optimization studies were often performed for the whole power plant, which is of course the best thing to do in principle but makes comparison between the results of different authors very difficult.

In this paper the assessment of Thorium fuel cycles is made in the same type of reactor, so that the comparison of Thorium against Uranium can be made on a fair basis.

The fuel cycle cost only (') is considered, as the plant power is the same in both cases. A fraction of the plant's cost depends on the type of fuel, namely vessel, shields and containment: the variations of this fraction with the type of fuel and with the core size , although small, are taken into account separately, when necessary.

Of course care is taken that:

1. The fuel cycles are optimized,
2. The economic assumptions concerning:
   a) fuel fabrication and reprocessing cost
   b) fissile material cost

   are not unfair,
3. The optimum specific power and burn-up calculated for Thorium and Uranium cycles are technically achievable, or, in case these technical limitations are determinant for the optimization of the fuel cycle, their choice has been fair.

The analysis was carried out for heavy water moderated reactors and for high temperature graphite moderated reactors. They are the most promising users of Thorium besides the Molten Salt Reactor. For the D_2O reactors the pressure

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' See list of definitions

vessel type (PHWR) was considered, as it is the best user of Thorium fuel due to its good neutron economy ('). For the HTGR, a quasi-homogeneous arrangement with prismatic fuel was studied with the Th-cycle, the heterogeneous multi-annular fuel element as well as the quasi-homogeneous were studied with the enriched Uranium cycle. Data on the fuel elements are reported in Table I.

A parametric variation of the most important economic factors was performed.

An investigation was made of future economic conditions which could favour the use of Thorium, like

- increase of the ore cost
- decrease of the cost of separative work
- availability of cheap Plutonium.

4. CALCULATION METHOD

The physics calculations relative to the fuel cycle were performed with a 15-group zero-dimension scheme, taking the leakage and its variation with core size into proper account with group-dependent bucklings. One-dimensional details of power and burn-up distribution do not play any important part in favour of either Thorium or Uranium.

The same can be said of the type of loading. A continuous charge-discharge scheme was considered, disregarding the loss of neutrons due to the control rods, which is true if the number of fractional reloads is so large as to approach a continuous charge-discharge.

A 40% Xenon override control (see definitions), was accounted for, although it has little effect on the comparison of Thorium against Uranium.

A great deal of accuracy was put in the evaluation of the effective cross sections as a function of the fuel composition during burn-up and in the description of the fission product chains. The multigroup reactivity calculations were performed using the 1967 General Atomic cross-section library (GAM+GATHER) and the codes MOGA or BACON which calculate the continuous

(') Calculations carried out for ORGEL reactors have shown that Thorium is not a very attractive fuel for pressure tube reactors (Ref.3). Those calculations have not been repeated, however, with the most adjourned cross-section library, which would make Thorium look better than before, but, we feel, not better than Uranium for pressure tube reactors.

charge-discharge equilibrium conditions.

The effects of heterogeneity and spectrum on the effective cross-sections are represented in these codes by self-shielding factors which are fitted by simple formulae to the cell macroscopic cross-sections. They are therefore a function of the fuel composition.The evaluation of the self-shielding factors was performed with the code WRETCH, incorporating WDSN.

The energy partition used for the burn-up calculations is reported in Table III. As one can see from this table, the HTGR calculations were performed with 20 groups, of which 12 thermal, 5 fast groups being added with respect to the partition used for D_2O reactors evaluation; they were introduced in the HTGR calculations because of the much harder spectrum.

The fission product chain used in all calculations is given in Table II. The error in reactivity induced by the simplification implied by this chain does not exceed 0.2% in any case (1).

The effect of specific power (i.e. of reactor size) on the neutron economy was taken into account with power density dependent bucklings. A single buckling was used for D_2O reactors, whereas different bucklings for four groups were used for HTGRs. This is due to the fact that leakage is more important for HTGRs than for HWRs, and the epithermal spectrum in the energy range where Thorium absorptions are important is more sensitive to moderation ratio and leakage in the HTGR than in the HWR.

As for the economic assessment, the method which was followed could be called the "direct method", as compared to the "present worth" technique. That is, the "running in" period is not described, therefore an assumption must be made concerning the value of the capital invested in the core. If the "running in" was known, the present worth technique would allow the exact evaluation of this capital investment, but this approach-to-equilibrium phase is not uniquely determined and it should be carefully optimized. Therefore the assumption was made in this paper that the capital invested in building up the equilibrium charge of the core can be assessed as a "core value", attributing to each fuel element a worth equal to the average between the fresh fuel and the spent fuel.

For a more detailed description of this method see Ref. 6. The value of the U233-U235-U236 mixtures contained in the recycled fuel were assessed by comparing the use of such mixtures with the use of U235 as a make-up for Thorium fuel cycles. Details on this point were published in an internal report, which can be made available on request.

5. CHOICE OF THE FUEL ELEMENT

PHWR

A homogeneous lattice of Th-U oxide rods with Zircalloy cladding, cooled and moderated by pressurized heavy water, is considered in this paper. It is certainly the most suitable type of D_2O lattice with Thorium fuel, due to the low neutron absorption and the possibility of tight lattice arrangements. Details are given in Table I.

The same fuel element was assumed for the Uranium cycle: this assumption favours Thorium, because an increase of the rod diameter and clustering of the rods could improve the situation for Uranium.

HTGR

A quasi-homogeneous prismatic type of fuel was assumed for the evaluation of Thorium cycles. The fuel element optimization is unnecessary in this case, as the small degree of heterogeneity makes it possible to treat the core as homogeneous. The fuel heterogeneity was taken into account only for the evaluation of the power peak factors.

The evaluation of Uranium fuel cycles requires a more detailed consideration of the fuel elements dimensions, as heterogeneous lattices are needed to reduce resonance absorption by U238. The calculations were carried out for a multi-annular fuel element (Fig. 1) and for a solid rod fuel identical to that considered for the Thorium cycle. Details are given in Table I.
It turned out (Par. 9) that the latter is not more "homogeneous" than the former.

6. CHOICE OF THE CYCLING SCHEME

D_2O cycling schemes

Uranium cycles: With our economic assumptions the once-through cycle with reprocessing and sale of the discharged Uranium and Plutonium is about 0.03 mills/KWh cheaper than the Plutonium recycle scheme

(Fig.7), therefore the former scheme is chosen as representative of the Uranium cycles. Clustering of the rods into bundles would improve the cost, but this was not taken into account in the present paper.
The full recycle scheme is not reported in Fig. 7, as it would be much worse than the Plutonium recycle scheme, due to the build-up of U236 and Np237.

Thorium cycles: The best scheme is full recycle. Segregation schemes do not pay because the optimum burn-up is not large enough, consequently there is too much good fissile material in the discarded fuel. With Pu-Th cycles, the cheapest scheme is recycling of Uranium only, as the recycled Plutonium would have a poor composition.

HTR cycling schemes

Uranium cycles: The optimum scheme with our economic assumptions is the once-through with reprocessing and sale of the discharged fuel.
Both kinds of once-through cycle, i.e. the one just mentioned and the throw-away type are cheaper than the Plutonium recycle scheme, and this in turn is cheaper than the full recycle scheme. This is due to the large optimum burn-up and to the consequently poor composition of the discharged Uranium and Plutonium.
It is worth pointing out that, due to its hard thermal spectrum, the HTR is a good burner but a bad producer of Plutonium.

Thorium cycles: The segregation cycle was chosen, whereby the "breed particles", containing initially Thorium only, are recycled and the "feed particles", containing initially the recycled fuel plus make-up U235, are thrown away or sold after discharge.
Other types of segregation, like recycling into the breed particles, would be about equally expensive on the paper and are not considered here.

7. PARAMETRIC OPTIMIZATION OF THE FUEL CYCLE

The following parameters were changed:

- Fuel rod diameter (D_2O)
- Moderation ratio ($\frac{Vm}{Vf}$ for D_2O, $\frac{C}{Th}$ or $\frac{C}{U8}$ for HTGR), hence lattice pitch
- Specific power (per unit fuel weight, D_2O)
  (per unit core volume, HTGR)

The optimization was repeated for several values of the ore cost, of the cost of separative work and of the fabrication and reprocessing cost, as will be described later on.

The tails enrichment was optimized as a function of the ore cost and separative work cost according to the USAEC ground-rules. The cost of U235 as a function of the enrichment for an ore cost of 8 $/lb and three values of the separative work is quoted as an example in Fig. 2.

8. RESULTS FOR D_2O REACTORS (PHWR)

Optimum moderation ratio

The optimum moderation ratio (Vm/Vf) is about 16 for Uranium cycles as well as for Thorium cycles. This is shown for a case without Xenon override in Fig. 3, where the optimized fuel cycle cost is reported as a function of the moderation ratio. The influence of the D_2O cost is shown by comparison with Fig. 4.

The question of the optimum Vm/Vf is rather important, both because many authors have found lower optimum moderations for the Thorium cycle and because a lower optimum moderation ratio would lead to some saving in plant costs due to the smaller vessel size.

As this behaviour of the fuel cycle cost remains also with the new cross section set it is perhaps worthwhile to repeat with the new data the explanation already given to the IAEA Panel: an increase of moderation ratio leads to a higher η value due to the softening of the neutron spectrum, therefore to a higher conversion.

This higher conversion leads to a higher concentration of U233 and this in turn improves η.

The reduced concentration of U235 leads to a lower U236 + Np237 concentration.

Moreover, the softening of the spectrum leads to a reduction of the U236 and Np237 effective cross section.

These statements are supported by the example given in Table IV.

Optimum specific power

The fuel cycle cost shows a very flat minimum as a function of specific power. Figs. 3, 7 and 10 show that the optimum specific power is about 40 W/g for both Thorium and Uranium fuel cycles. A higher specific power (50) was assumed to be achievable with Thorium fuel, due to the better metallurgical properties of ThO_2 as compared to UO_2. But the neutron balance does not allow to take full advantage of these better properties: the optimum specific power of 40 W/g is due to the effect of the leakage (and to a less extent to the Protoactinium absorption).

In spite of the equality of the optimum specific power for Thorium and Uranium cycles, a lower specific power (30) was chosen for the representative Uranium cycle quoted in Table V. This leads perhaps to a more conservative attitude towards the Uranium fuel than towards the Thorium fuel.

The reader may be surprised by the fact that the theoretical optimum specific power is not higher for the Thorium cycle than for the Uranium cycle, as many authors find it convenient in order to reduce the fissile material inventory cost. Of course this optimum depends on the interest rate; in our case the increase of leakage arising from a higher specific power was more important than the inventory reduction. The increase of leakage leads to a reduction of the conversion ratio which leads to a larger increase of the fuel consumption in the Thorium cycle than in the Uranium cycle, because the former has a higher conversion factor.

Plant costs

The objection was raised by a few Panel members that consideration of the fuel cycle cost alone is not sufficient for the choice of the best fuel cycle: the choice of the core power density and of the moderation ratio affects the vessel, shielding and containment costs.

This is qualitatively true, but the actual amount of this effect is small.

For the PHWR, it has been often stated that the consideration of pressure vessel and containments would

a) shift the optimum moderation ratio to values considerably below 16
b) bring an additional advantage in favour of the Thorium cycle, due to its higher power density.

Let us assume that the figure which is affected by the reactor size (mainly the cost of the vessel) amounts to 5 $/KWe. Let us assume that this figure is proportional to the core volume (in reality it is less sensitive to core size). Then:

A) The core volume changes less than 35% if the moderation ratio is decreased from 16 to 10. This means a change of 1.7 $/KWe of the plant cost, that is a change of 0.025 mills/KWh at 10% interest rate.
This effect is not such as to change the behaviour of the curves quoted in Fig. 3.

B) Assuming that the specific power is 30 with Uranium, 50 with Thorium (according to our results they should instead be both about 40) the core power density is 16 W/cc for Uranium, 23.5 for Thorium.
This, with the assumptions mentioned in A, leads to a cost difference of 0.023 mills/KWh in favour of the Thorium plant. This would mean a small advantage for Thorium, only noticeable because we are dealing with small differences (see Figs. 3 and 10): in fact, according to Fig. 10, this would make specific powers 30, 40 and 50 about equally expensive.

Optimum burn-up

The fuel cycle cost exhibits a very flat minimum as a function of burn-up. This minimum is obviously due to the opposite effects of fabrication and reprocessing cost on one side, fission product build-up on the other side. Therefore it depends on economic assumptions and on the accuracy to which the fission product chain is described.
According to Figs. 7 and 10, 30,000 MWD/T can be chosen as the optimum burn-up for both Uranium and Thorium cycles. Thus the capability of the Thorium fuel to withstand a higher burn-up than the Uranium fuel can not be exploited.

Conversion, fissile isotopes' consumption, enrichment

Details are given in Figs. 5 and 6 for the Uranium cycles, 8 and 9 for the Thorium cycles.

Fuel cycle cost

The best Thorium cycle is about 0.02 mills cheaper than the best Uranium cycle. Details on the physics of the representative cycles and the fuel cycle cost splitting are given in Table V.

The reasons why Thorium does not perform any better are the following:

1) It uses a very enriched, hence expensive, fuel (see Fig. 2) and requires large fissile investment;

2) Because of fabrication and reprocessing costs, the optimum burn-up can not be as low as to exploit the potentiality of Thorium, that is to produce large quantities of U233 and therefore improve the η value and the conversion factor, thus reducing the fuel consumption.

For both reasons (1) and (2), hopes for Thorium can be searched in:

a) a decrease of the cost of separative work,

b) an increase of the ore cost.

Both (a) and (b) would reduce the cost difference between low-enrichment and high-enrichment Uranium.

These possibilities have been investigated by reoptimizing both fuel cycles for each set of economic assumptions and the results are reported in Figs. 11 and 12.
In these figures a reduction of the cost of separative work by a factor 3/4 and 1/2 and an increase of the ore cost by a factor up to 3 have been envisaged over today's values: 27.8 $/Kg cost of separative work
8.0 $/lb U308 ore cost.

The comparison of Figs. 11 and 12 shows that a 25% reduction of the cost of separative work and a 50% increase of the ore cost would make the Thorium cycle cheaper by about 0.15 mills/KWh.

Final remarks on D_2O cycles

The comparison between Uranium and Thorium cycles presented here should be considered with due caution, bearing in mind the simplifications introduced in our scheme, the effect of the economic assumptions, the inaccuracies of the cross sections set.

For instance, the uncertainty on fabrication and reprocessing costs is probably such as to lead to uncertainties on the fuel cycle cost of the same order of the differences we are talking about. If the fabrication and reprocessing cost were 15% higher for Thorium than for Uranium, which is quite a reasonable assumption, the Uranium fuel cycle would become about 0.4 mills/KWh more expensive as shown by Fig. 10.

If the fuel rods were lumped into clusters, the Uranium fuel cycle cost could be decreased. An optimization of such fuel elements has not been performed yet, but preliminary estimates suggest a reduction of 0.02 mills/KWh. On the other hand, our calculations for the Thorium cycle have been somewhat pessimistic because they assume an infinite recycle, hence a too high concentration of U236 + Np 237.

Indeed, U236 builds up rather slowly; typical values for a D_2O reactor are given in the following table, which reports the average U236 concentration over n years as a % of its infinite recycle value:

n(years)	20	30	40	60
relative concentration (%)	51	63	71	90

Depending on economic assumptions, it could be cheaper to recycle the fuel only a limited number of times, and to sell it or even to throw it away, than to allow full build-up of the U236.

An evaluation was performed with our calculation scheme, where a U236 and Np237 recycle factor ξ was introduced. ξ was calculated in such a way as to yield in our infinite recycle scheme a U236 concentration equal to the average over any given number of years, after which the fuel was assumed to be disposed of. The problem was then to determine, after how many years the fuel should be thrown away to reach the optimum economic compromise between the loss of fuel and the reduced U236 and Np237 concentration. An

optimum was found at 40 years, corresponding to a recycle factor 0.94. The fuel cycle cost is then reduced by 0.04 mills/KWh (see Fig. 10). A 15% increase of fabrication and reprocessing cost for the Thorium cycle as compared to the Uranium cycle would be enough to compensate the effect of the recycle factor, as shown in Fig. 13.

RESULTS FOR HTR REACTORS

As already mentioned in Par. 5, the calculations for the Uranium cycles were carried out for two types of fuel element, a so called "heterogeneous" and a "quasi-homogeneous" one.
The former is a multi-annular fuel element described in Fig. 1 and Table I, the latter is the traditional Dragon type of fuel, as originally conceived for the Thorium cycle, (see Table I). The "heterogeneous" fuel is arranged in a hexagonal lattice within a "fixed" graphite structure: this graphite is assumed to stay in the core longer than the fuel, the reference residence time being 6 years.
The "quasi-homogeneous" fuel, for which also the Thorium cycle calculations were performed,is a single fuel matrix rod surrounded by the moderator which is removed with the rod. The fuel matrix consists of coated particles with an oxide kernel coated by pyrolitic graphite.

The self-shielding due to the microscopic heterogeneity was disregarded in the resonance calculations, as it would have a minor effect on the resonance integral.
The macroscopic heterogeneity was evaluated with the SN method as described in Par. 4, apart from the U238 resonance calculations which were performed with the code GAM II, using Dancoff corrections evaluated with the first flight collision probability method (code SHOCK, Ref. 9).

The cycling schemes investigated with Uranium were Plutonium recycle and once-through with reprocessing and sale of the discharged fuel.
The latter resulted to be cheaper, due to the high burn-up and to the consequently poor composition of the discharged Plutonium.
The cycling schemes investigated with Thorium were full reprocessing and segregation; the latter one is consistently cheaper, but the former is also reported as a term of comparison.

Heterogeneitv effects on Uranium cycles

The heterogeneity was changed in this survey: for the multi-annular fuel, keeping its dimensions constant but varying the matrix density and the lattice pitch; for the solid rod fuel, keeping its matrix density constant (1.7 g/cm^3) but changing the lattice pitch.

A preliminary survey, made with a Plutonium recycle scheme, showed that the fuel cycle cost with the multi-annular fuel markedly decreased with increasing lattice pitch, reaching a minimum at an equivalent cell radius of 26 cm (Fig. 14). A practical minimum was considered to be at a cell radius of 24.15 cm (square pitch= 44 cm) for which the rest of the survey was performed. All the data reported here refer to cell radius 24. The radius 24 was preferred to 26, in order to reduce stresses in the graphite.
With such a pitch, the relationship between the heavy metal density in the fuel matrix and the moderation ratio C/U8 is as follows:

density	0.8	1.1	1.4	1.7	g/cm^3
C/U8	530	390	305	250	

A first interesting result to be mentioned is that two types of fuel element are about equally "heterogeneous" in spite of their very different size: the fact is that there is a large quantity of moderator mixed with the fuel in the multi-annular design, and this reduces the effective lumping relative to U238 resonances. The largest differences are perhaps in the thermal self-shielding factor. Therefore, as can be deduced by Figs. 18, 19, 21, 22 and Table VI, the optimum enrichment and moderation ratio are about the same for both fuel elements.

Optimum power density

There is a very flat minimum of the fuel cycle cost as a function of power density.

- Uranium cycles:

  During the early stages of this work, the minimum was found to be around 7 W/cm^3 for Uranium cycles, as suggested by the comparison between Fig. 15 (5 W/cm^3) and Fig. 16 (7.5 W/cm^3). Practically the same optimum power density would be found if the vessel cost were taken into account.

All the rest of the survey on Uranium cycles presented here was carried out for a power density of 7 W/cm^3.

- Thorium cycles:

Results for three power densities are reported. The best value is again 7, if vessel costs are taken into account.

Display of the results of the survey

The results are reported as follows:

- For Uranium cycles:

Conversion, enrichment, fuel cycle cost as a function of burn-up for each type of fuel and each cycle scheme. A set of such curves is quoted with the moderation ratio as a parameter. The moderation ratio is altered by changing the matrix density in the multi-annular fuel, the lattice pitch in the solid rod fuel, which is assumed to have a constant density 1.7: it would not pay to repeat the survey with other densities, as the most significant parameter is the moderation ratio C/U8.
Figs. 17, 18 and 19 refer to multi-annular fuel, once-through cycle;
Figs. 20, 21 and 22 refer to solid rod fuel, once-through cycle.

- For Thorium cycles:

Conversion, enrichment, fuel cycle cost for three moderation ratios are given:
in Figs. 23 to 28 for the full recycle scheme;
in Figs. 29 to 34 for the segregation scheme.

In Fig. 35 the cost with segregation and sale of the discarded seed particles is reported, because it seems fair to compare this one with the Uranium cycles, for which sale of the discharged Uranium was envisaged.

Fuel cycle cost

The fuel cycle cost for both Thorium and Uranium cycles have a very flat minimum as a function of either power density or moderation ratio or burn-up. Therefore, the "optimum" cases quoted in Table VI should be intended only as an indication of design trends, and it is wiser to speak of ranges for the

various parameters: for this reason a large number of curves is presented.

The best Thorium fuel cycle (segregation) is about 0.2 mills/KWh cheaper than the best Uranium cycle with a solid rod fuel.
The Uranium cycle with multi-annular fuel is cheaper than with solid rod fuel because of the longer residence of the graphite in the core; but it is not clear whether its plant cost should not be higher, due to the larger number of penetrations in the vessel for single channel access. Moreover, the fabrication cost for such a fuel is uncertain. Due to these uncertainties, both fuel elements are considered in this paper.

Variation of fuel cycle cost with the cost of ore and of separative work

Figs. 36 to 40 report the variation of the cost for the several cycles considered here, as a function of the ore cost increase factor C and of the separative work decrease factor S (the fuel cycle was reoptimized for each C and S value).
The reader can draw his conclusions from the figures.

It may perhaps be worth remarking that Thorium is more competitive against Uranium in the HTR than in D_2O reactors, mainly due to the higher enrichment required by the Uranium cycles in the HTR.

10. Pu-Th FUEL CYCLES

Calculations carried out for D_2O and HTGR reactors using as a make-up a typical Plutonium discharged by modern light water reactors (73% Pu239, 15% Pu240, 12% Pu241) have shown that the value of this fissile Plutonium as make-up for Thorium cycles would be (Ref. 6) about 13 $/Kg for D_2O reactors, 11 $/g for HTGR's.

If a cheap Plutonium was available, the Pu-Th cycle could be attractive.

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TABLE I

Fuel element data

PHWR

	Thorium cycle	Uranium cycle
Fuel material	ThO_2	UO_2
Canning material	Zirconium	Zirconium
Fuel density (g/cm^3)	9.0	8.0
Fuel rod diameter (cm)	1.09	1.09
Can thickness (cm)	0.04	0.04
Lattice pitch (cm)	4.0	4.0
Vm/Vf (moderation ratio)	16	16

HTGR

"Heterogeneous" fuel

Type of fuel element	annular
External radius	13.0 cm
Number of fuel annuli	5
Dimensions	see Fig. 1
Fuel material	UO_2 coated particles
Fixed graphite structure density	1.6 g/cm^3
Graphite density in the fuel matrix	0.4 "
Max. fuel density in the fuel matrix	2.0 "
Cell radius	2.6 "

"Quasi-homogeneous" fuel

Type of fuel element	solid rod
Core average graphite density	1.4 g/cm^3
Fuel material	UO_2 coated particles
Fuelled zone radius	0.892
Fuel matrix density	1.6 g/cm^3

TABLE II

HEAVY ISOTOPES AND FISSION-PRODUCT CHAIN

NUCLIDE	ISOTOPE	CAPTURE PARENT 1	CAPTURE PARENT 2	DECAY PARENT	DECAY CONST.	FISSION YIELDS (%) FROM: U233	U235	Pu239	Pu241
1	Th232	-		-	-	-	-	-	-
2	Pa232	1	-	-	2.9279E-07	-	-	-	-
3	U233	-	-	2	-	-	-	-	-
4	U234	2	3	-	-	-	-	-	-
5	U235	4	-	-	-	-	-	-	-
6	U236	5	-	-	-	-	-	-	-
7	U238	-	-	-	-	-	-	-	-
8	Pu239	7	-	-	-	-	-	-	-
9	Pu240	8	-	-	-	-	-	-	-
10	Pu241	9	-	-	1.664E-09	-	-	-	-
11	Pu242	10	-	-	-	-	-	-	-
12	Np237	6	-	-	-	-	-	-	-
13	Mo95	-	-	-	-	6.22	6.27	5.0	4.0
14	Tc99	-	-	-	-	4.96	6.06	6.1	6.2
15	Rh103	-	-	-	-	1.60	2.90	5.6	6.2
16	Xe131	-	-	-	-	3.41	2.93	3.8	3.4
17	Xe135	-	-	-	2.0928E-05	5.84	6.41	7.2	6.5
18	Cs133	-	-	-	-	5.88	6.59	6.9	6.0
19	Nd143	-	-	-	-	5.91	6.03	4.6	5.6
20	Nd144	19	-	-	-	5.91	6.03	4.6	5.6
21	Nd145	20	-	-	-	3.38	3.98	3.1	3.6
22	Nd146	21	-	-	-	2.58	3.07	2.6	2.8
23	Pm147	22	-	-	8.4479E-09	1.93	2.36	1.92	2.2
24	Pm148	23	-	-	1.4857E-06	-	-	-	-
25	Pm148M	-	23	-	1.976E-07	-	-	-	-
26	Sm149	25	24	-	-	0.77	1.13	1.32	1.2
27	SM150	26	-	-	-	-	-	-	-
28	Sm151	27	-	-	2.747E-10	0.35	0.44	0.80	0.5
29	Sm152	28	-	-	-	0.22	0.28	0.6	0.3
30	Eu153	29	-	-	-	0.15	0.18	0.34	0.2
31	Eu154	30	-	-	1.3728E-09	-	-	-	-
32	Eu155	31	-	-	5.495E-09	0.03	0.03	0.16	0.10
33	Gd155	-	-	32	-	-	-	-	-
34	Gd156	33	-	-	-	0.01	0.014	0.10	0.07
35	Rh105	-	-	-	5.34 E-06	0.5	0.9	5.5	5.8
36	U AGGR.	-	-	-	-	100.	100.	-	-
37	PuAGGR.	-	-	-	-	-	-	100.	100.

TABLE III

GROUP PARTITION FOR BURN-UP CALCULATIONS

	HTGR		D_2O	
GROUP	MINIMUM ENERGY	MAXIMUM LETHARGY	MINIMUM ENERGY	MAXIMUM LETHARGY
1	5.5×10^5 eV	2.9	8.65×10^4 eV	4.75
2	2.61×10^3 "	8.25	1.585×10^3 "	8.75
3	353. "	10.25	1.86 "	15.5
4	79. "	11.75	1.2 "	15.94
5	29. "	12.75	0.91 "	16.21
6	10.7 "	13.75	0.414 "	17.
7	5.04 "	14.50	0.16 "	17.95
8	1.86 "	15.50	0.1 "	18.42
9	1.15 "	15.97	0.06 "	18.93
10	1.07 "	16.05	0.04 "	19.34
11	0.97 "	16.148	0.0253 "	19.80
12	0.70 "	16.47	0.015 "	20.32
13	0.35 "	17.168	0.01 "	20.72
14	0.27 "	17.427	0.005 "	21.42
15	0.16 "	17.95	-	∞
16	0.085 "	18.58		
17	0.06 "	18.93		
18	0.03 "	19.62		
19	0.015 "	20.317		
20	0.0 "	∞		

TABLE IV

EFFECT OF THE MODERATION RATIO ON THE NEUTRON BALANCE

U235-Th cycle, no Xe override

Specific power = 40 W/g

burn-up = 40,000 MWD/T

moderation ratio Vm/Vf	10	13	16
% absorption: U236	3.82	3.00	2.64
Np237	1.78	1.35	1.18
2 x Pa233	2.20	2.10	2.03
Total, Non Fertile Heavy Metals (NFHM)	7.80	6.46	5.85
Leakage	2.65	2.60	2.55
Structures	0.43	0.53	0.59
Fission Products	8.02	8.16	8.26
$\bar{\eta}$	2.105	2.144	2.162
A = $\bar{\eta}$ x NFHM	0.1641	0.1384	0.1264
B = $\bar{\eta}$ x (Leak + Struc.)	0.0638	0.0670	0.0680
C = $\bar{\eta}$ x F.P.	0.1691	0.1754	0.1793
Average conversion ratio C = $\bar{\eta}$ -1-A-B-C	0.708	0.760	0.783
$\bar{\eta}$ 233	2.158	2.174	2.183
$\bar{\eta}$ 235	1.874	1.916	1.936
$\overline{U233}/\overline{U235}$	1.230	1.686	1.966
Initial enrichment %	3.89	3.27	3.03
Make-up enrichment %	1.64	1.31	1.19
U235 consumption (g/MWD)	0.366	0.284	0.264
σ_{abs}U236/ σ_{abs}U235	0.192	0.135	0.109

TABLE V

PHWR FUEL CYCLE DATA:

	THORIUM CYCLE Vm/Vf=16 spec.pow.=40 W/g b.v.=30,000 MWd/T (full recycle)	URANIUM CYCLE Vm/Vf=16 spec.pow.= 30 W/g b.v.=30,000 MWd/T (once-through)	(Pu recycle)
Fissile investment (Kg/MWh)	0.507	0.380	0.448
Enrichment make-up (%)	0.98	2.20	1.66
Enrichment initial total (%)	2.75	2.20	2.44
Conversion ratio	0.798	0.672	0.665
Fissile consumption (g/MWd)	0.245	0.477	0.499
Power peak factor	1.26	1.38	1.47
Fifa	1.26	1.58	1.43
Residence time (d)	750	1000	1000
Xe override control absorption (%)			
Cost splitting (mills/KWh)			
Fresh fuel consumption	0.345	0.620	0.502
Fuel fabrication	0.210	0.210	0.210
Reprocessing	0.126	0.126	0.126
Core inventory	0.180	0.087	0.089
Out-of-core inventory	0.049	0.011	0.012
Revenue	0.0	-0.144	0.0
Fuel-cycle cost without D_2O	0.910	0.911	0.940
Moderator inventory	0.225	0.244	0.244
Total cost	1.135	1.155	1.184

HTGR FUEL CYCLE DATA

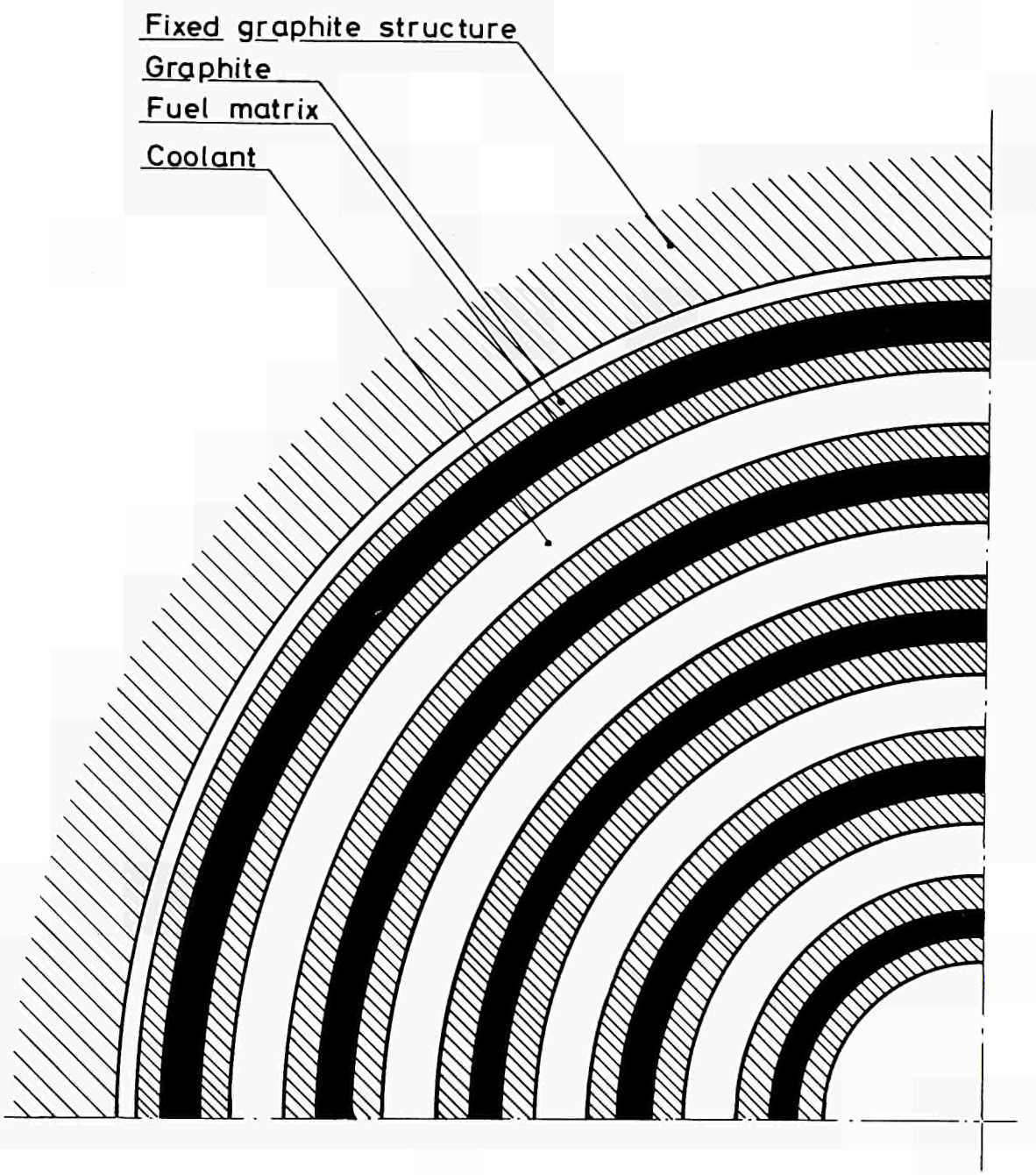
	U235/Th quasi-homogeneous full recycle	U235/Th quasi-homogeneous segregation with sale	U235/U238 heterogeneous once-through $\rho = 1.4$	U235/U238 quasi-homogeneous once-through
Power density (W/cm)	7.0	7.0	7.0	7.0
C/U8 (C/Th)	150	150	310	250
S-Average	4700	6100	10300	7750
Burn-up (MWD/Kg)	57.4	58.	66	78.4
Initial enrichment (%)	4.43	3.46	5.32	6.28
Make-up enrichment	2.45	1.65	5.32	6.28
Conversion ratio	0.733	0.810	0.60	0.567
Fiss. Consumption (g/MWD)	0.33	0.232	0.500	0.577
Xe override control absorption (%)	0.50	0.71	1.02	0.69
Fifa	1.36	1.75	1.31	1.31
Fissile rating (W/g)	1245	1585	2590	1965
Fabrication cost ($/Kg)	88	81	75	75
Power peak factor	1.338	1.345	1.269	1.446
Cost splitting (mills/KWh)				
Fresh fuel consumption	0.357	0.307	0.693	0.715
Fuel fabrication	0.238	0.223	0.120	0.191
Fuel reprocessing	0.169	0.167	0.146	0.123
Fuel inventory	0.255	0.213	0.074	0.122
Mod. inventory (6 years)	-	-	0.08	-
Revenue	-	-0.065	-0.121	-0.086
Total cost	1.019	0.845	0.989	1.065

TABLE VII

PHWR: FUEL CYCLE DATA WITH REVISED CROSS SECTIONS

	Thorium cycle Vm/Vf=16 (full recycle) spec.pow. = 40 W/g b.u.= 30000 MWD/T	Uranium cycle Vm/Vf=16 (Pu recycle) spec.pow. = 40 W/g b.u.= 30000 MWD/T
Fissile investment (Kg/MWth)	0.390	0.293
Enrichment make-up (%)	0.69	1.63
Enrichment initial total (%)	2.57	2.37
Conversion ratio	0.833	0.675
Fissile consumption (g/MWd)	0.203	0.487
Cost splitting (mills/KWh)		
Fresh fuel consumption	0.287	0.480
Fuel fabrication	0.210	0.210
Reprocessing	0.126	0.126
Core inventory	0.171	0.065
Out-of-core inventory	0.046	0.011
Total fuel-cycle cost	0.843	0.894
Moderator inventory	0.225	0.214
Total cost	1.068	1.108

FIG. 1 HTGR heterogeneous fuel element



Scale 1 : 1

FIG. 2 U-235 Cost as a function of enrichment

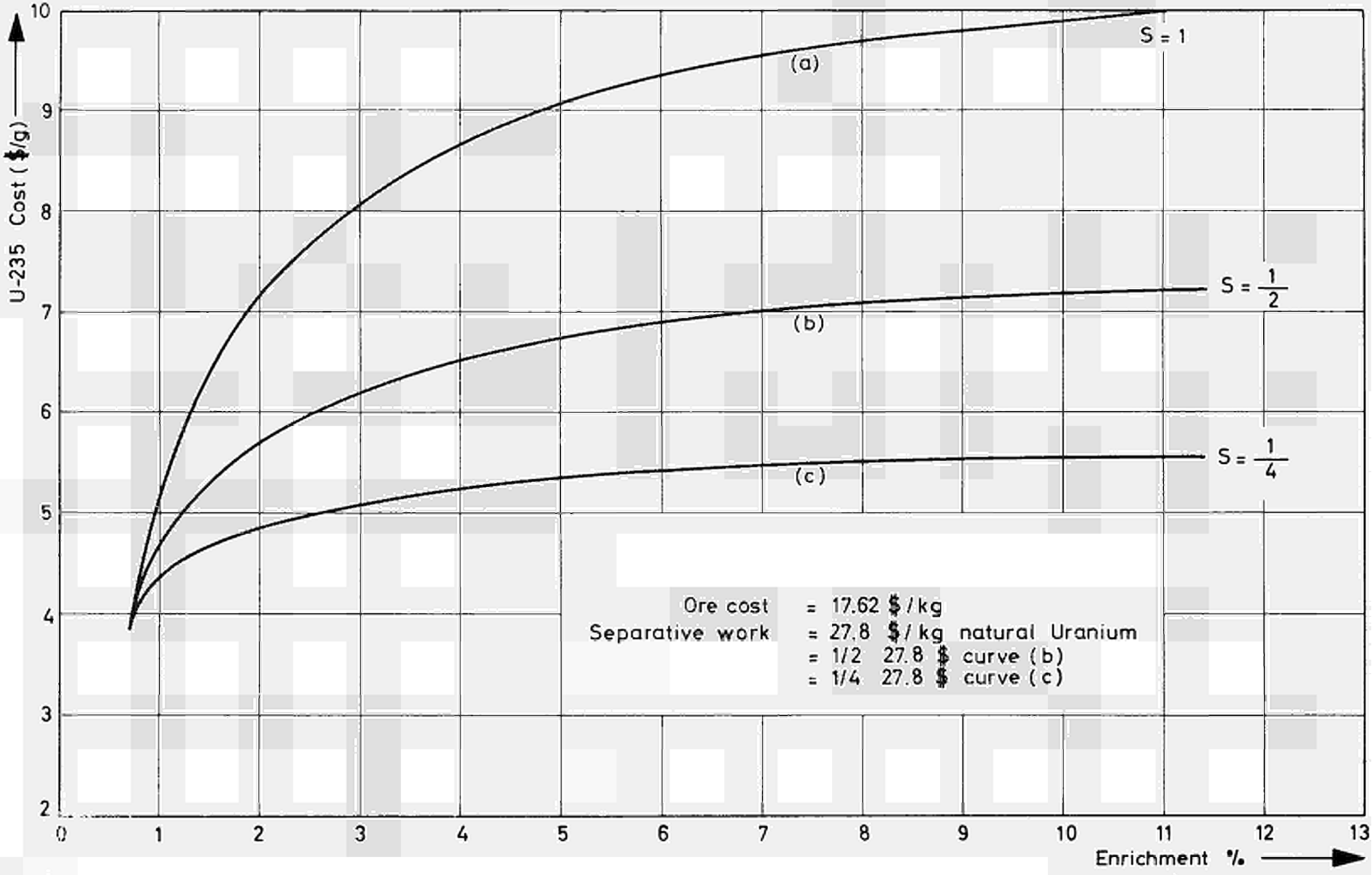


FIG. 3 PHWR
burn-up : optimum for each case
plutonium recycle
No Xe override

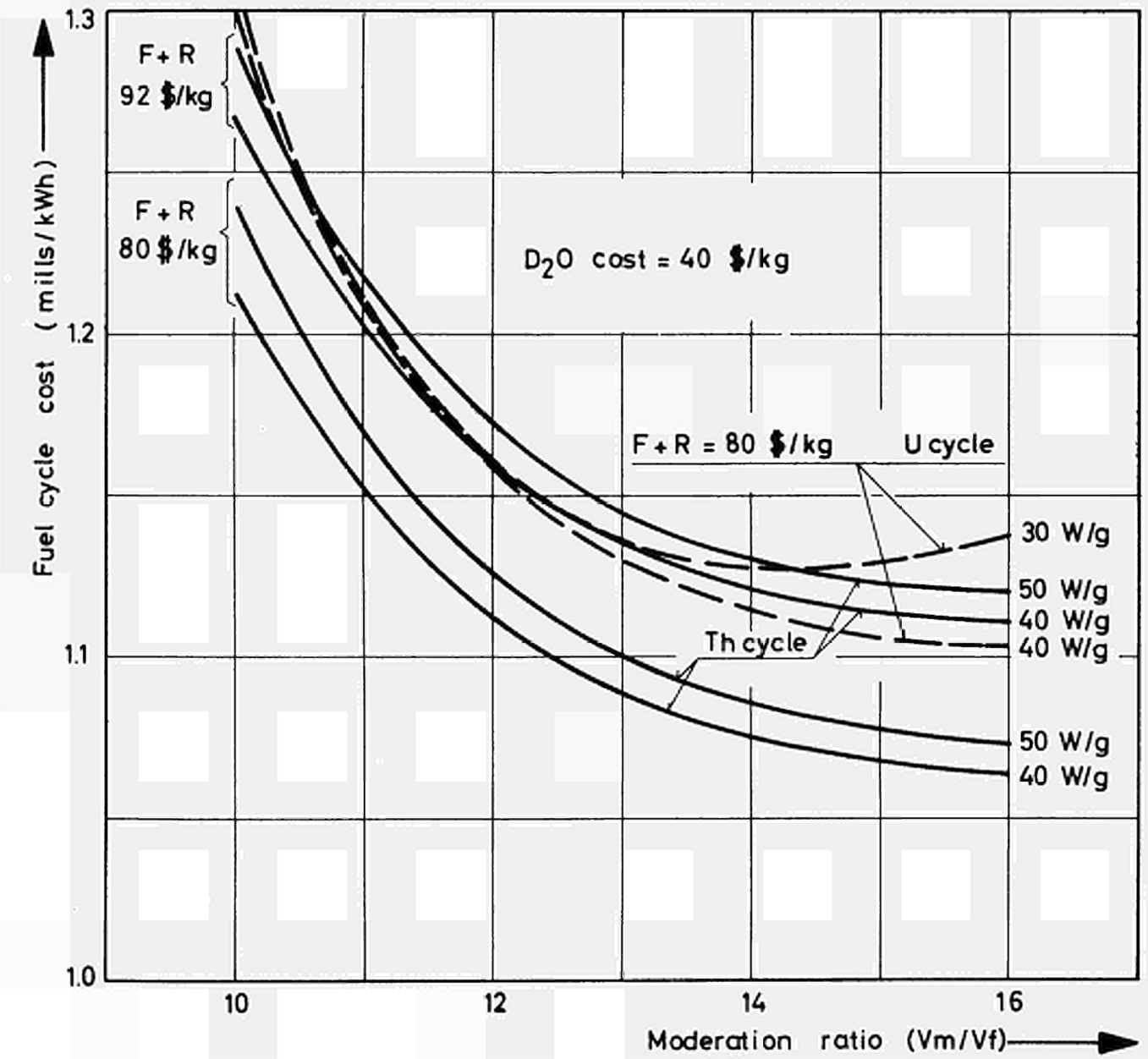
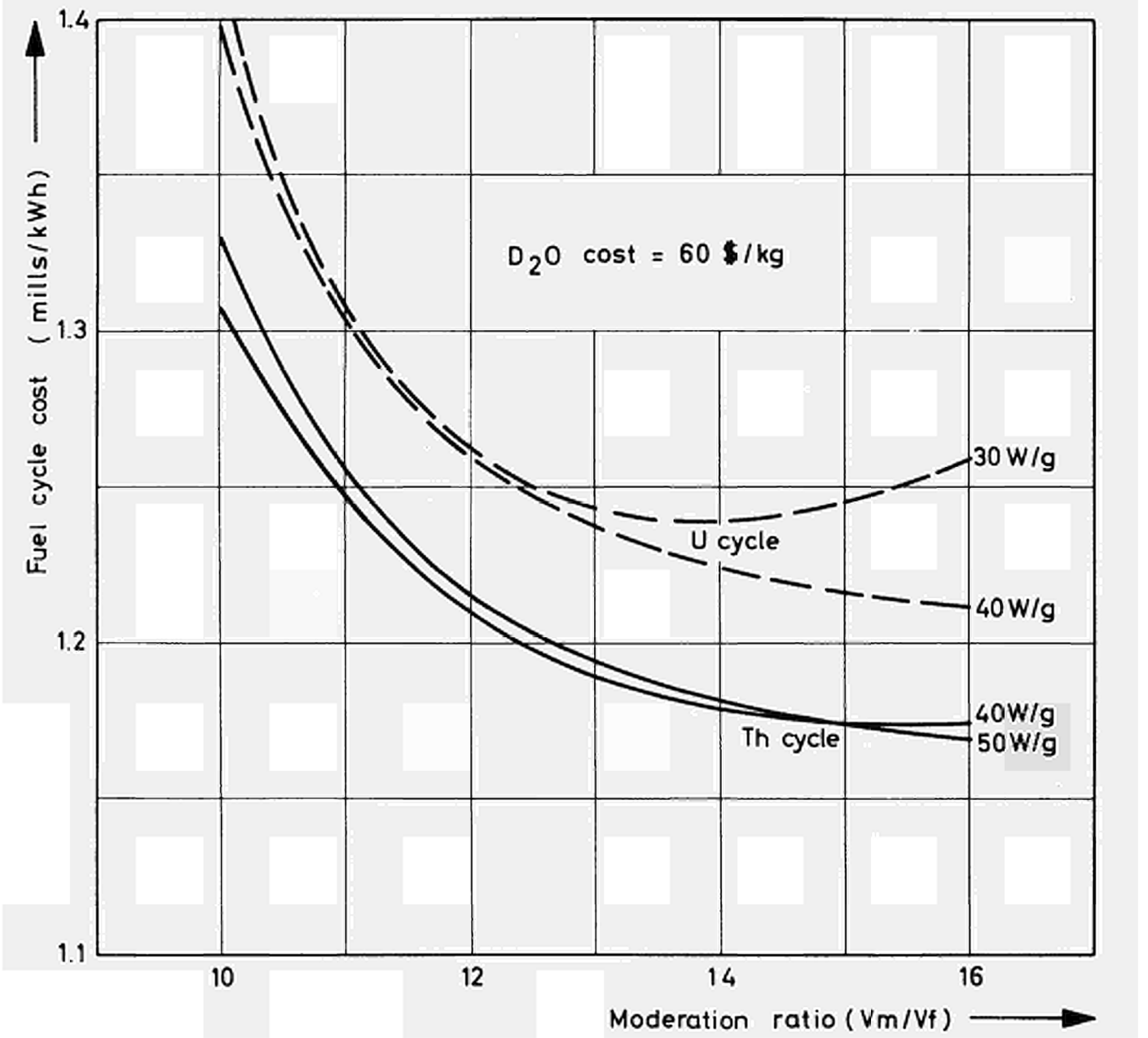


FIG. 4

PHWR
burn-up : optimum for each case
plutonium recycle
No Xe override



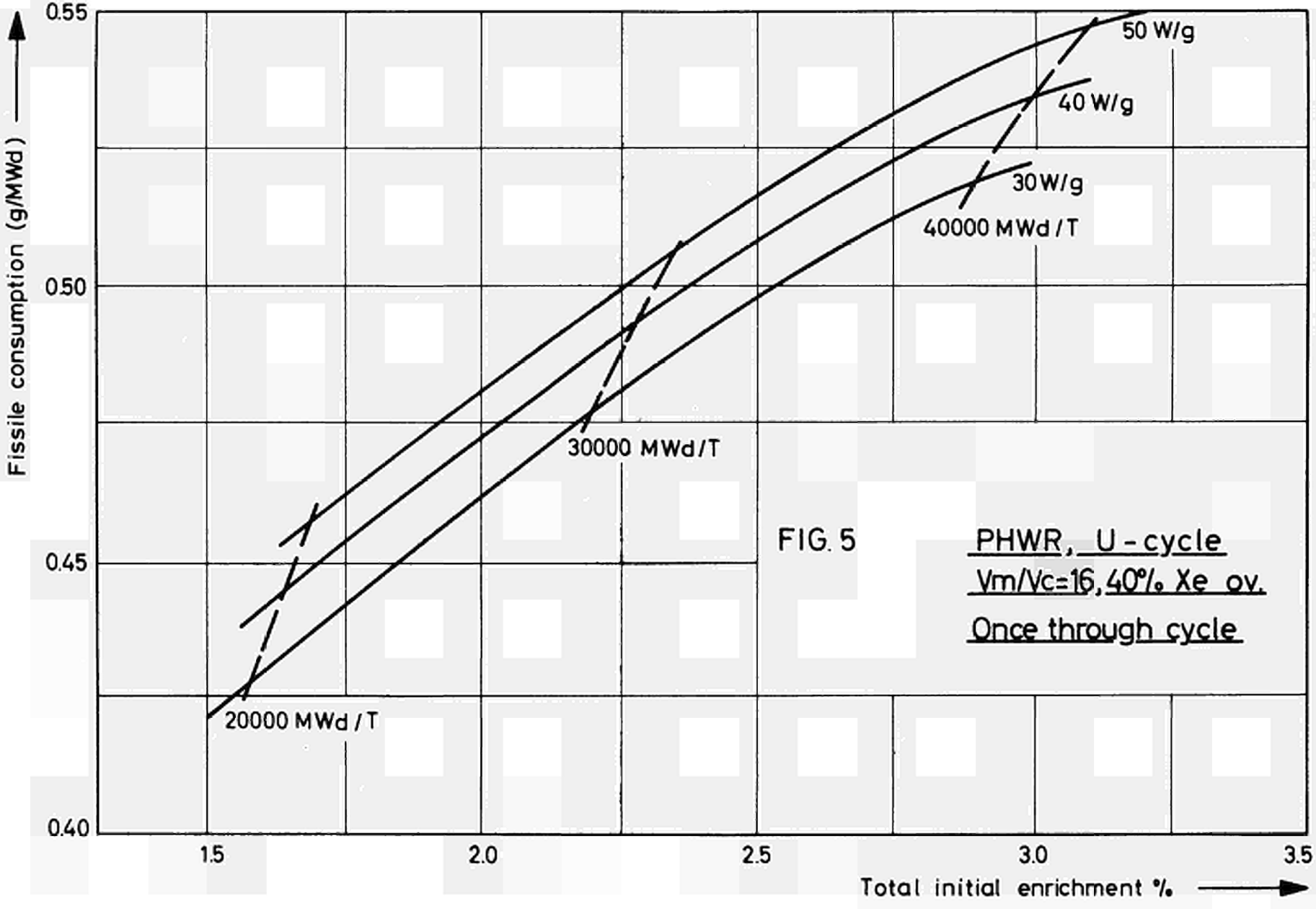

Fissile consumption (g/MWd)
0.55
0.50
0.45
0.40
1.5
2.0
2.5
3.0
3.5
Total initial enrichment %
50 W/g
40 W/g
30 W/g
40000 MWd / T
30000 MWd/T
20000 MWd / T
PHWR, U - cycle
Vm/Vc=16, 40% Xe ov.
Once through cycle

FIG. 5

FIG. 6

PHWR, U - cycle
Vm/Vc = 16, 40% Xe ov.
Once through cycle

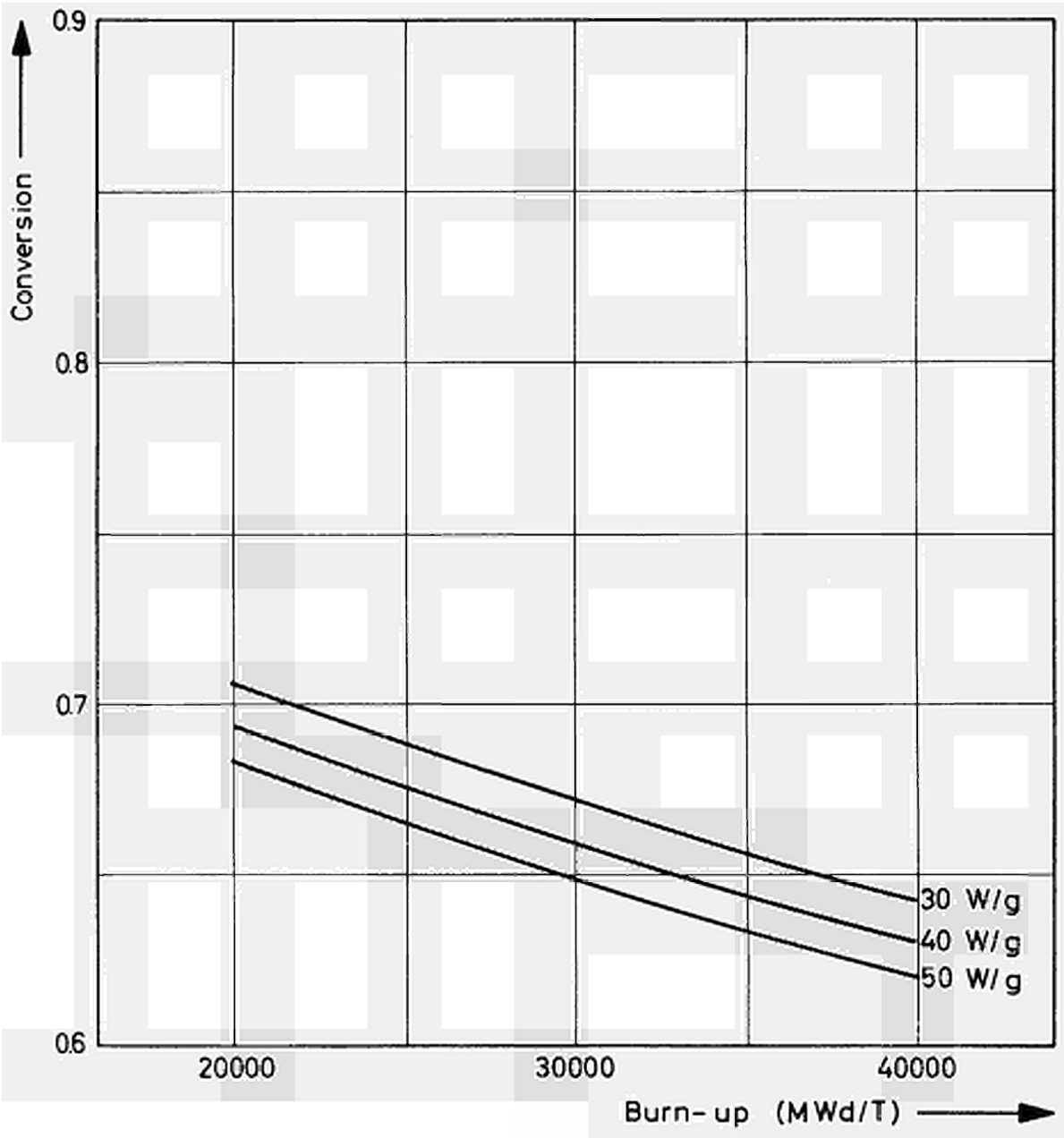
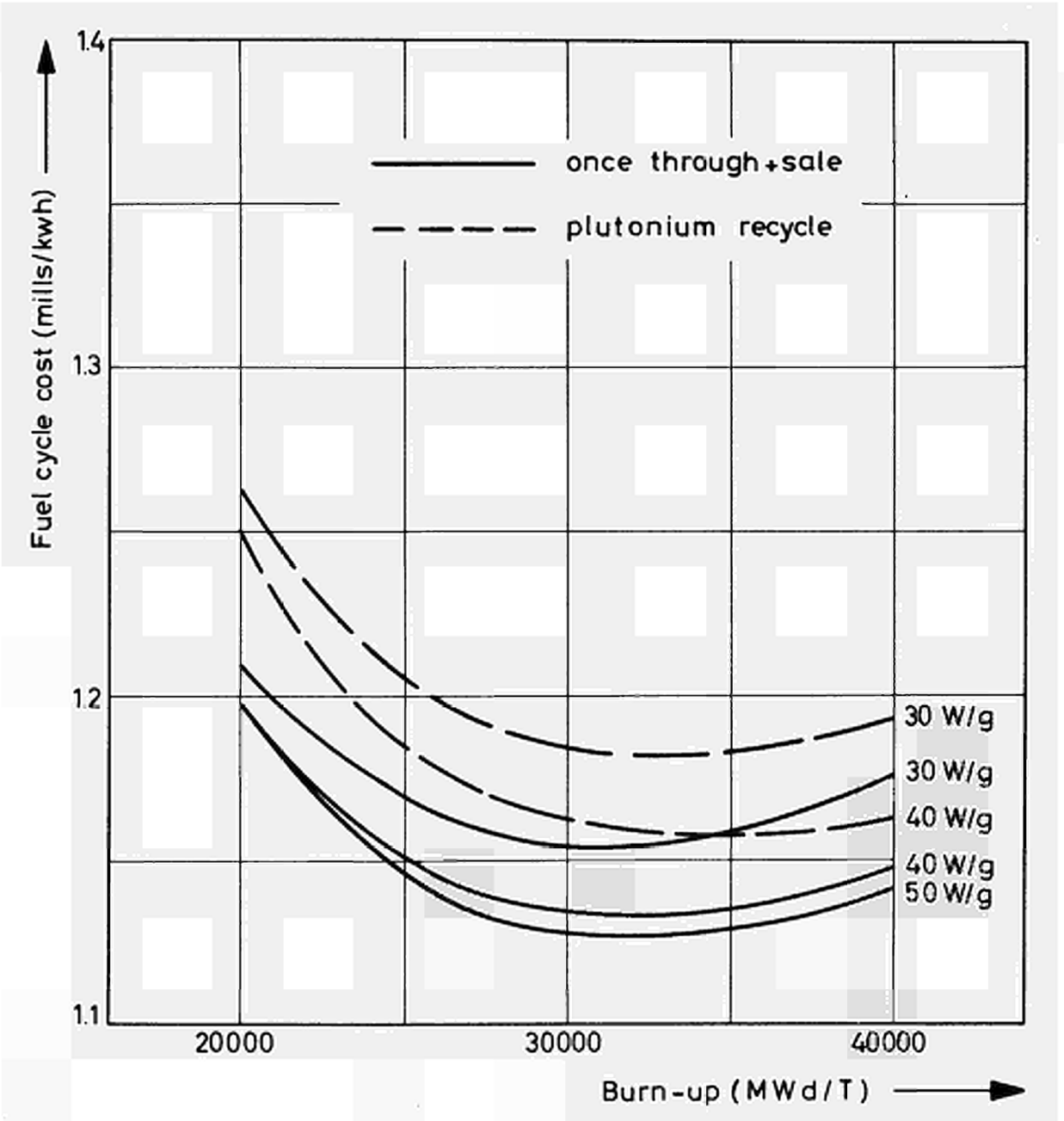


FIG. 7 PHWR, U - cycle
Vm/Vc = 16, 40% Xe ov.



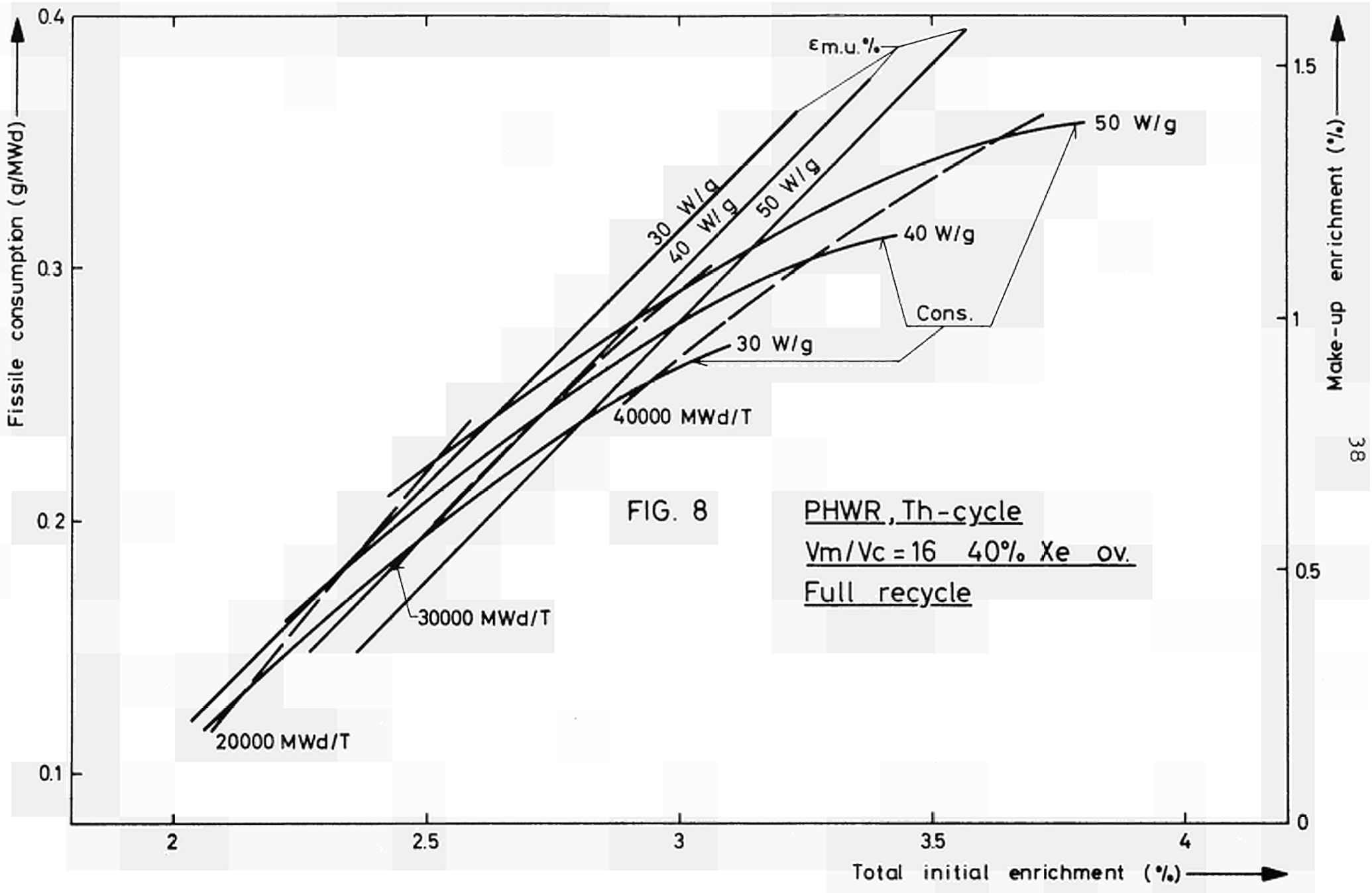


FIG. 8

PHWR, Th-cycle
Vm/Vc = 16 40% Xe ov.
Full recycle

FIG. 9

PHWR , Th-cycle
Vm/Vc = 16 , 40% Xe ov.
Full recycle

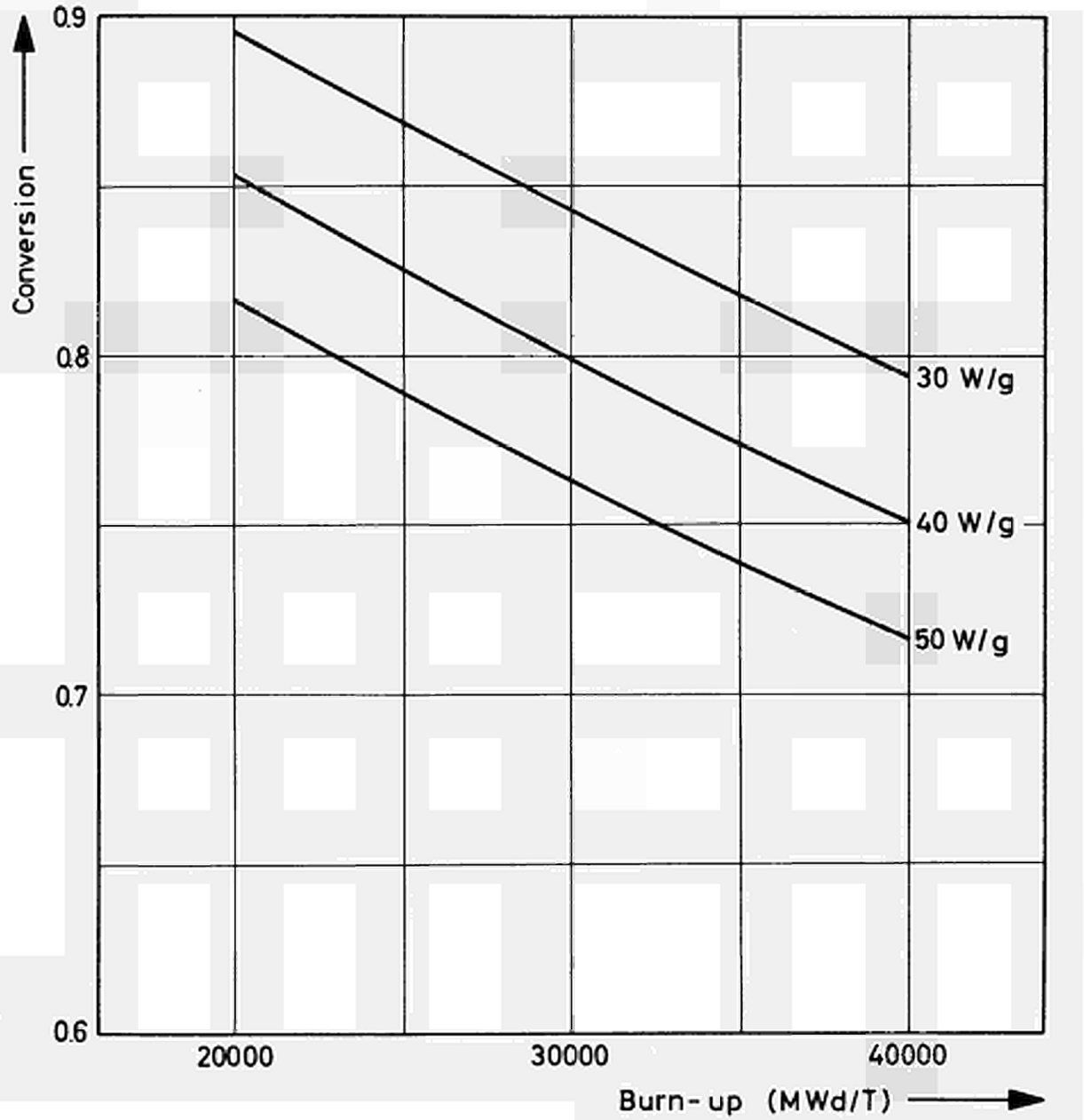


FIG. 10

PHWR, Th - cycle
Vm/Vc = 16, 40% Xe ov.
full recycle

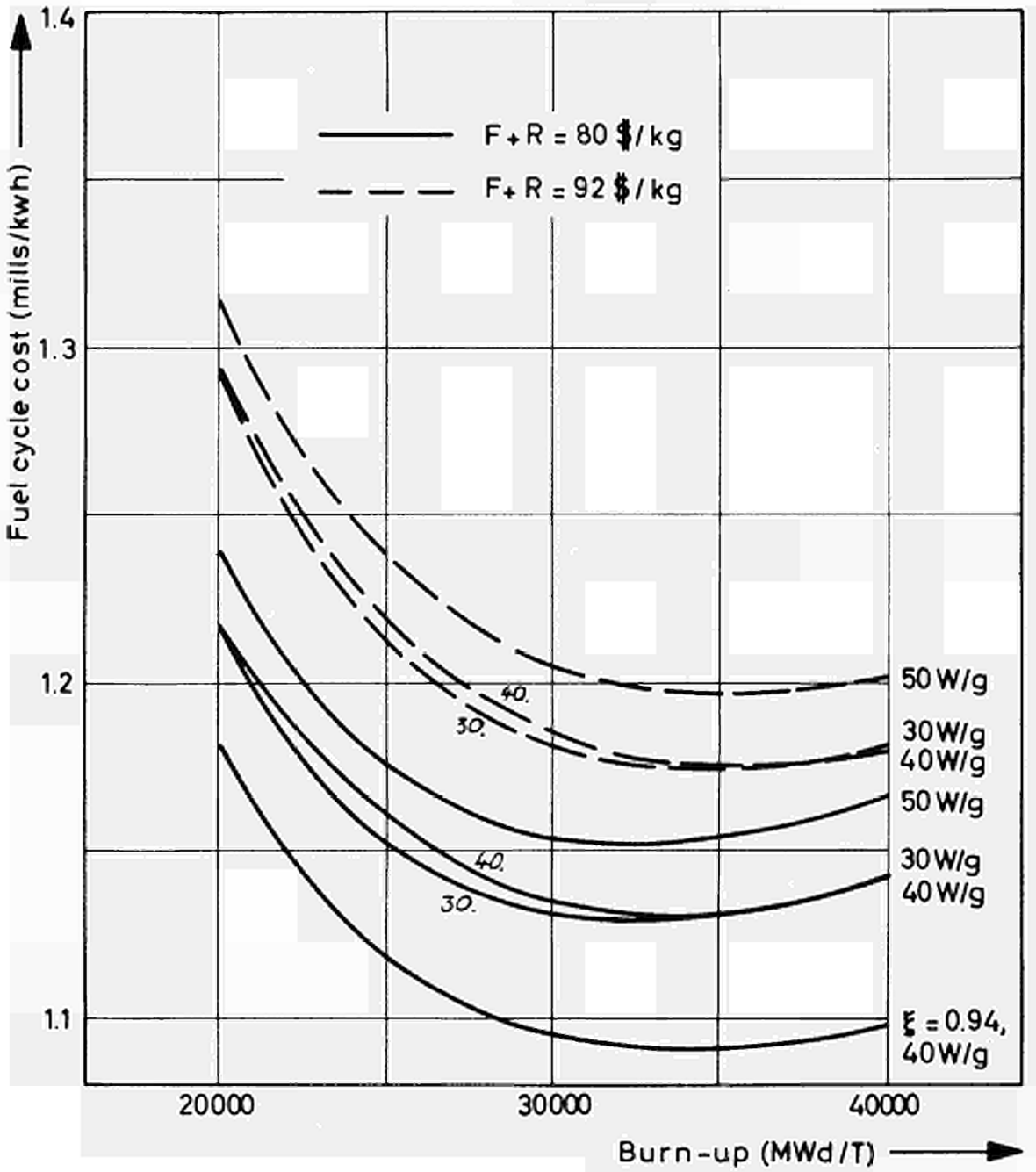


FIG. 11

PHWR , U - cycle
Vm/Vc = 16, 40% Xe ov.
F + R = 80 $/kg
burn-up = optimum for each case
Once through with sale, 30 W/g

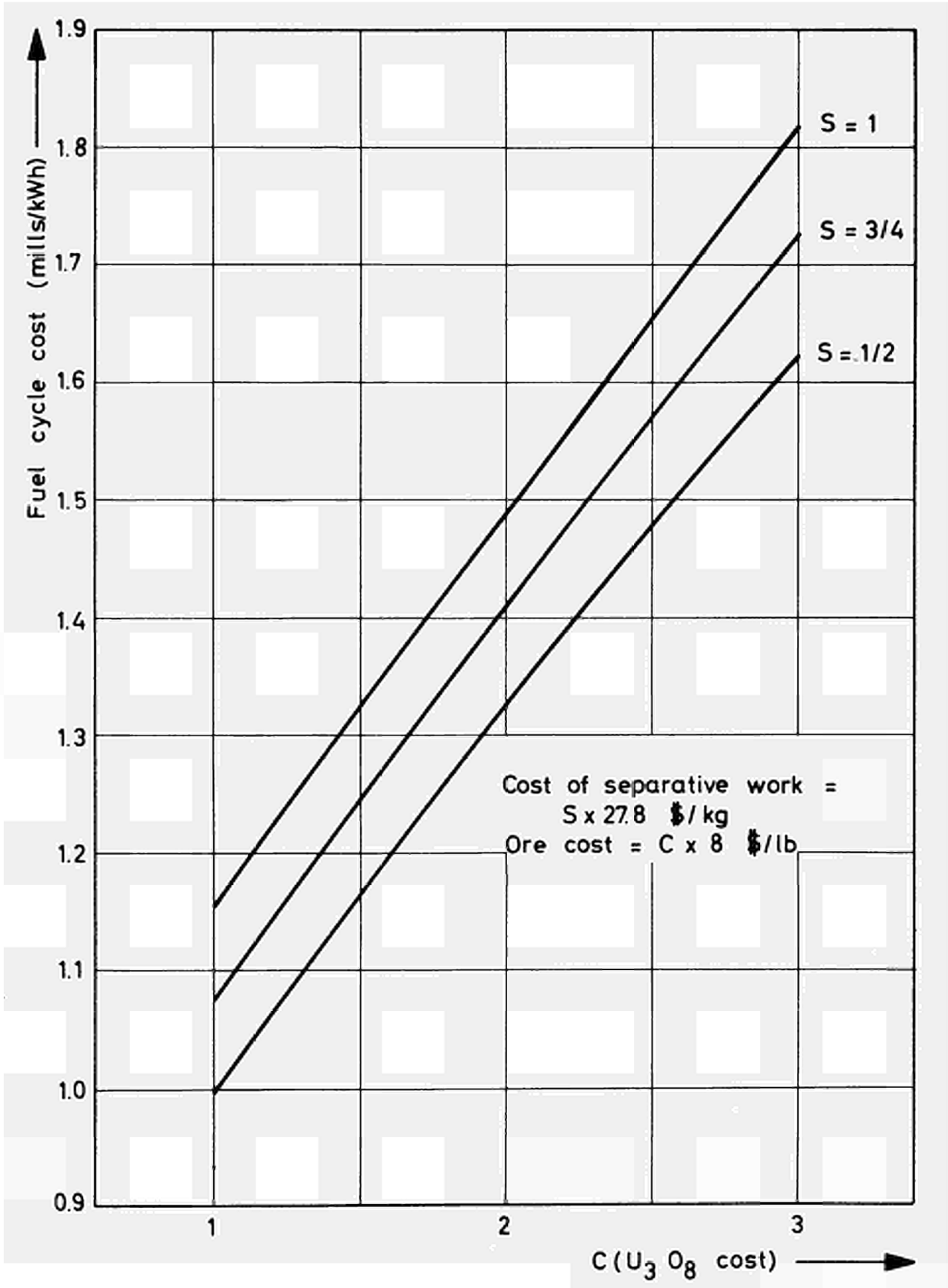


FIG. 12

PHWR , Th - cycle
Vm/Vc = 16 40% Xe o.v.
F + R = 80 $/kg
burn-up = optimum for each case
Full recycle , 40 W/g

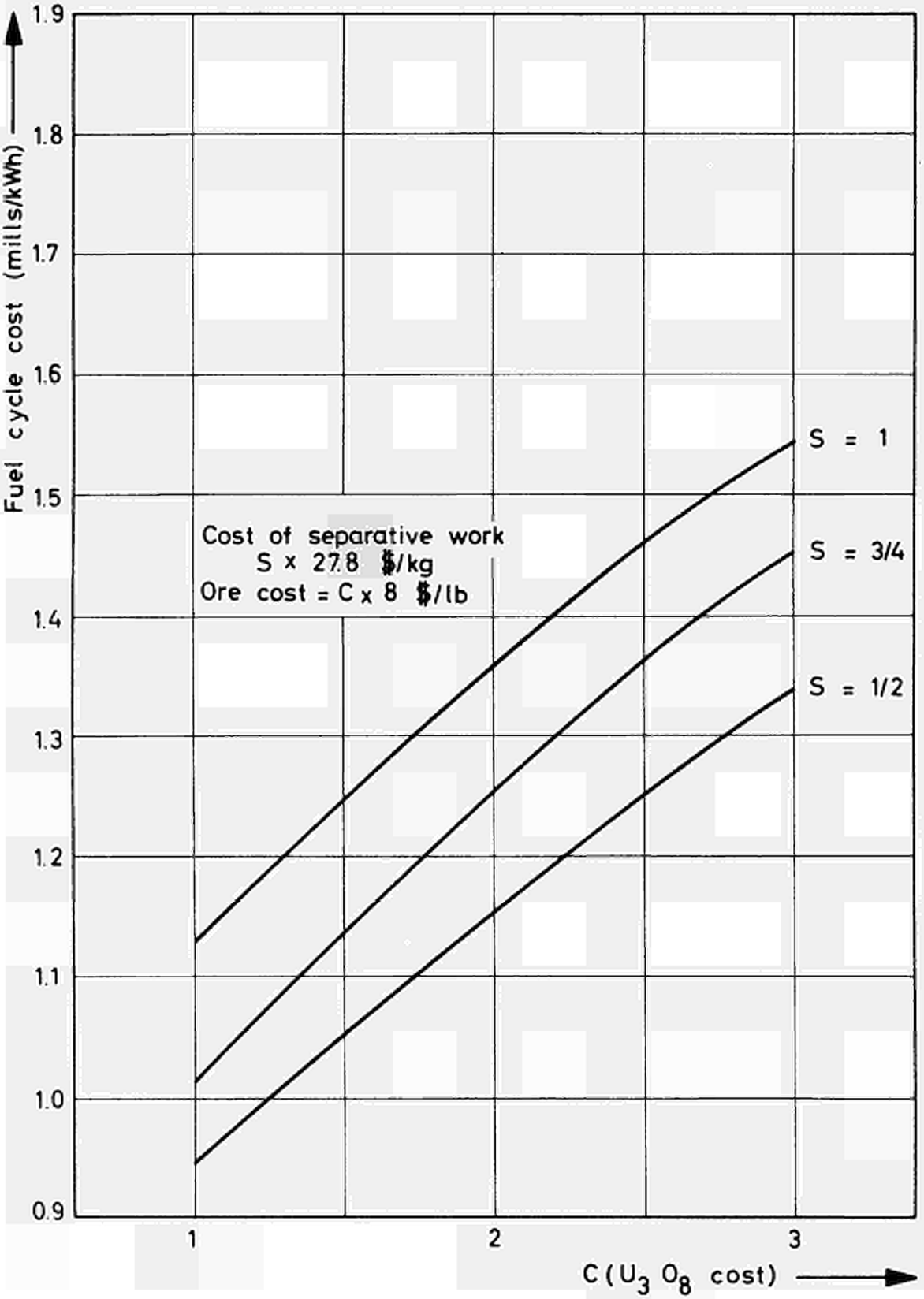


FIG. 13

PHWR
F+R = 80 $/kg

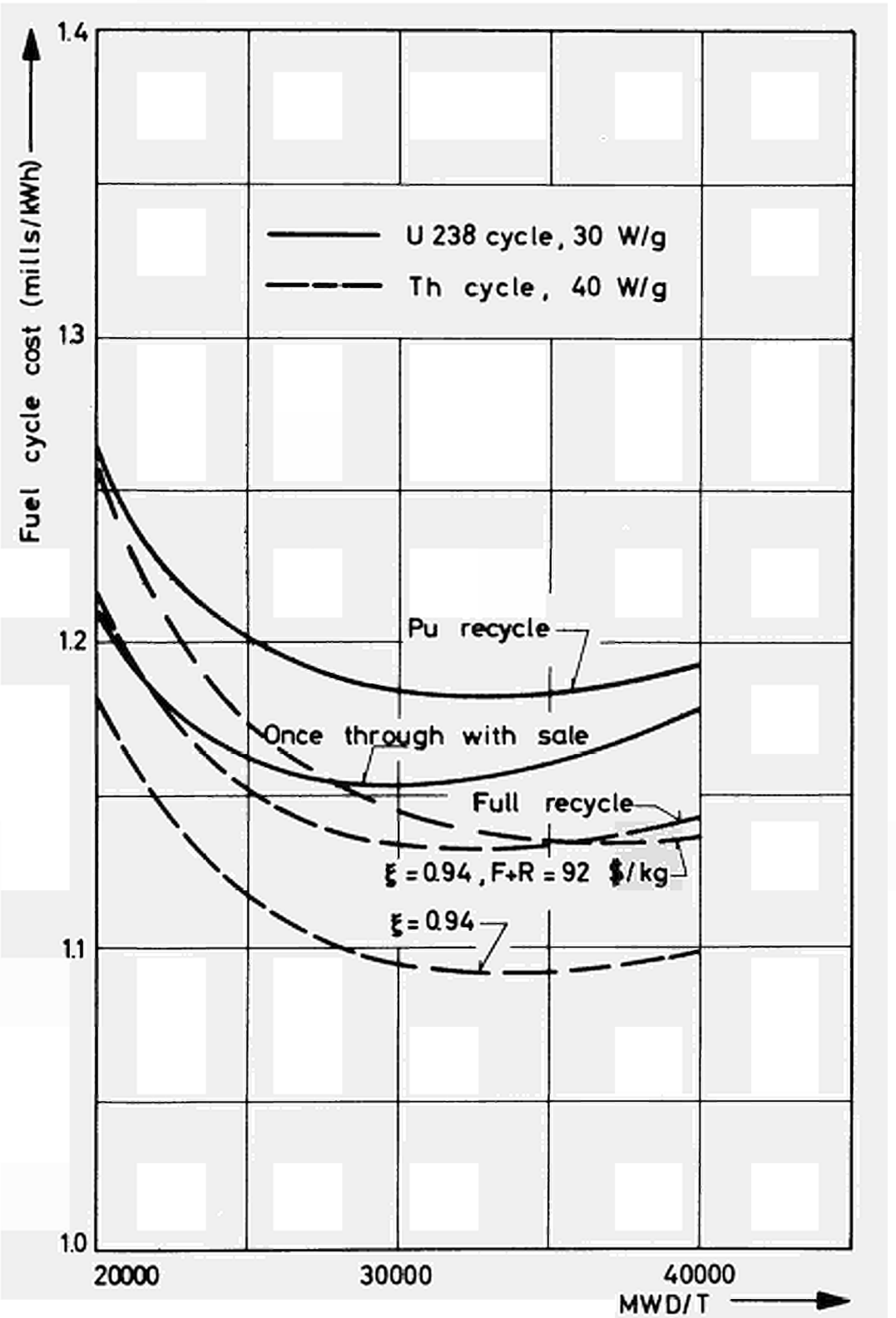


FIG.14 HTR, U-cycle
multiannular fuel
Pu recycle, No Xe ov.
Power density 5 W/cm^3
heavy metal density = optimum for each case

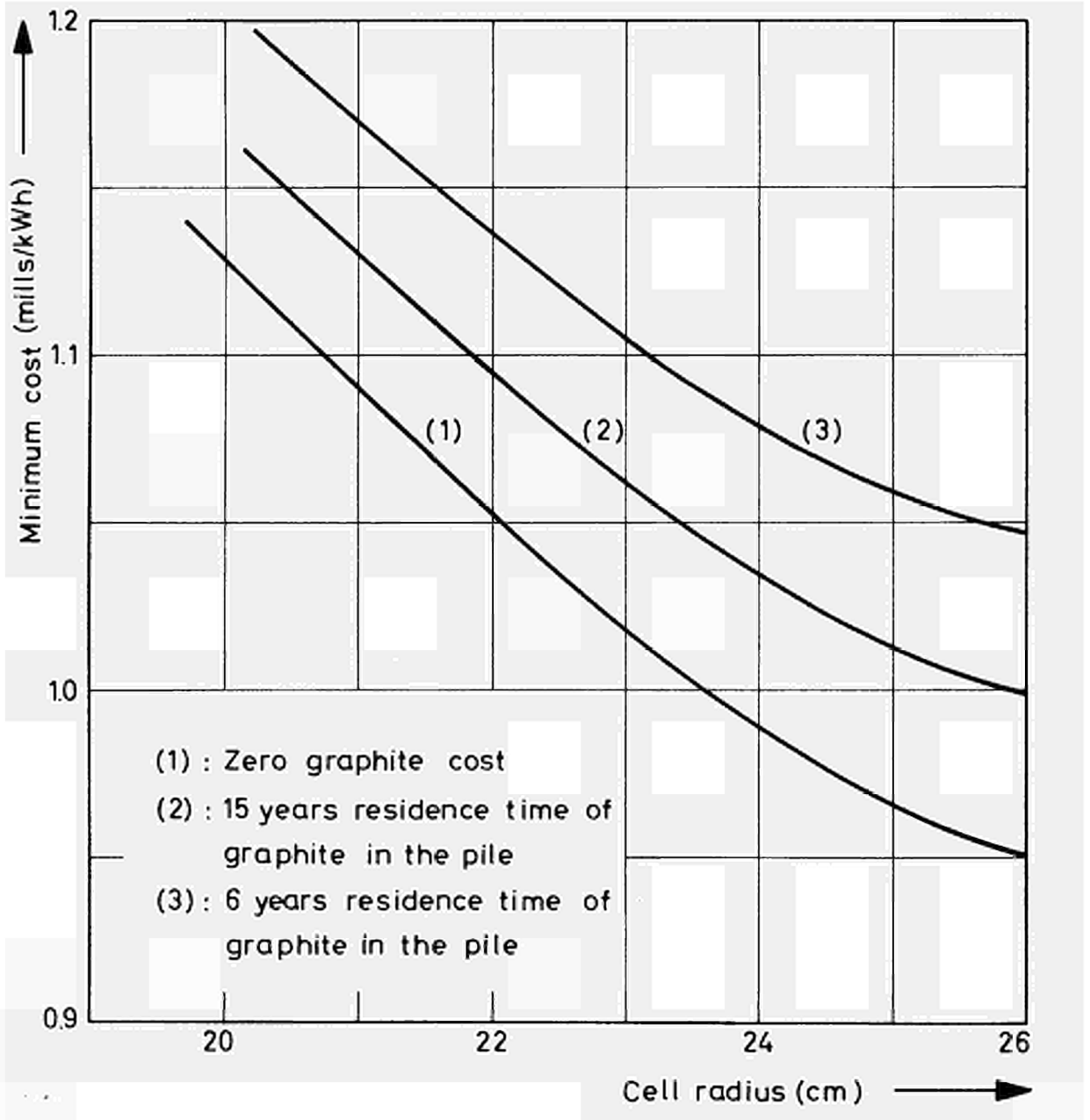


FIG. 15

HTR, U - cycle
multiannular fuel
Pu recycle
No Xe ov.
Power density = 5.0 W/cm^3
Cell radius = 24.15 cm.

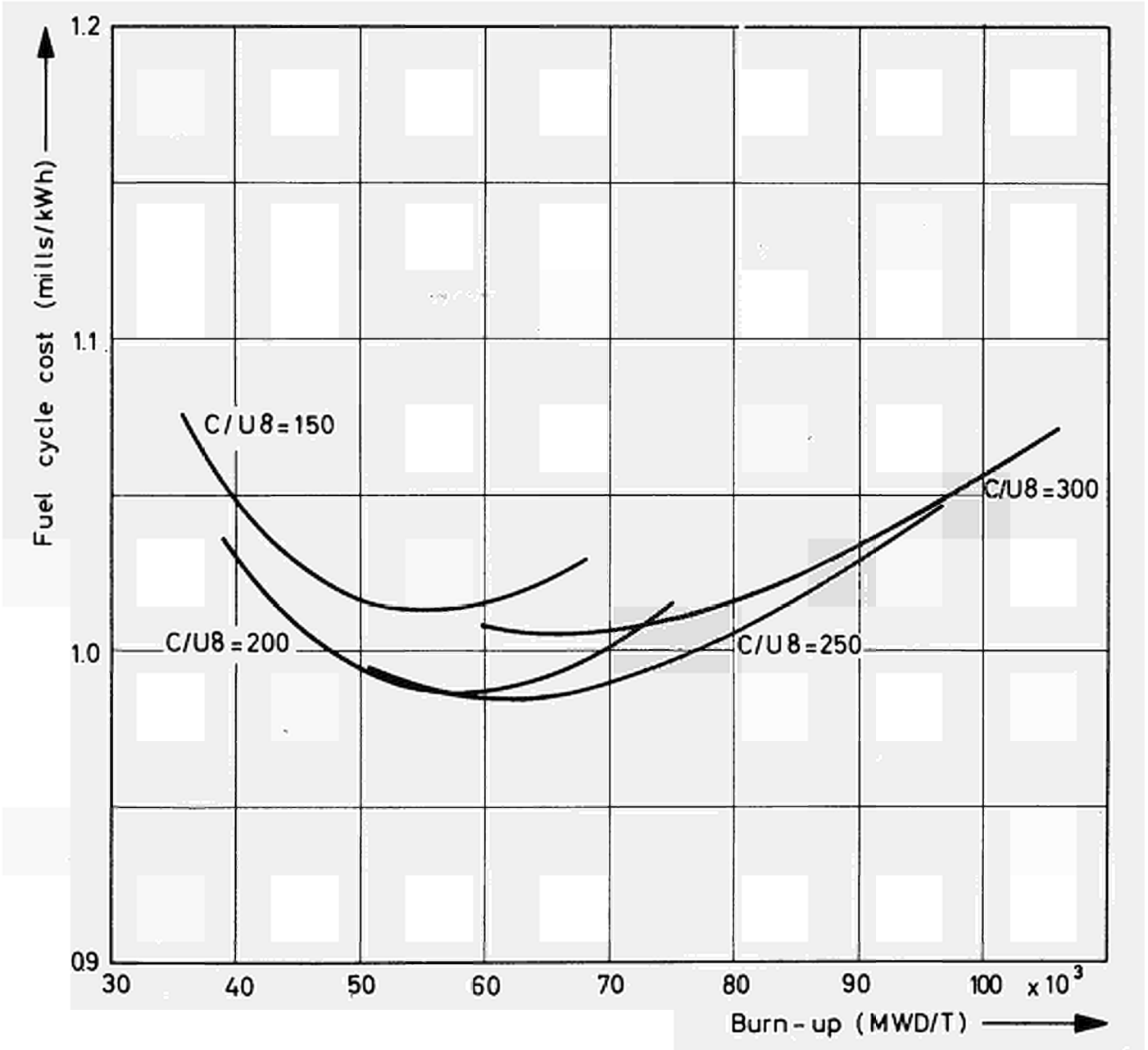


FIG. 16

HTR, U - cycle
multiannular fuel
Pu - recycle No Xe ov.
Power dens. = 7.5 W/cm^3
Cell radius = 24.15 cm

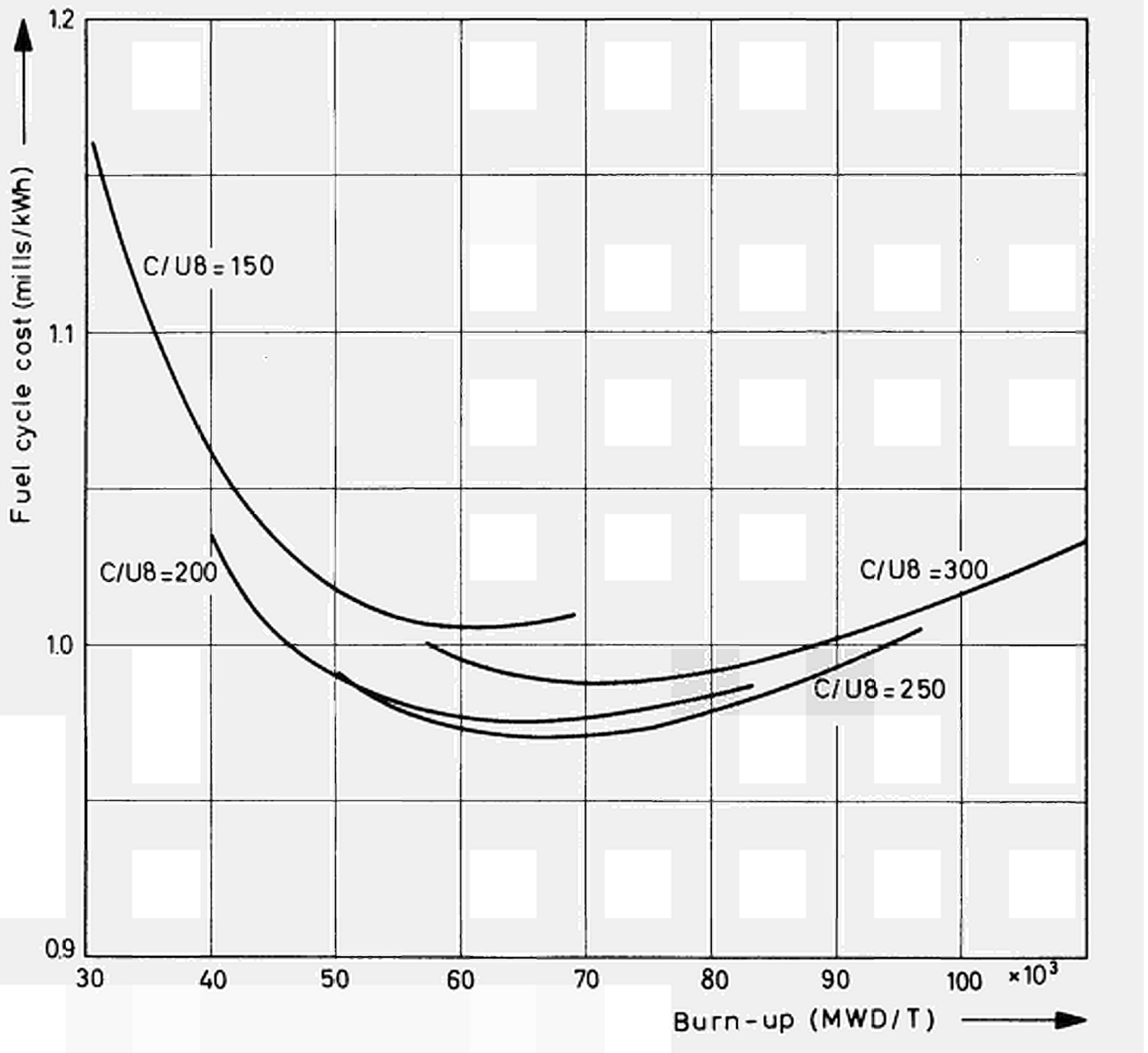


FIG.17 HTR, U-cycle multiannular fuel once-through cycle 40% Xe ov. Power density 7 W/cm³ Cell radius 24cm

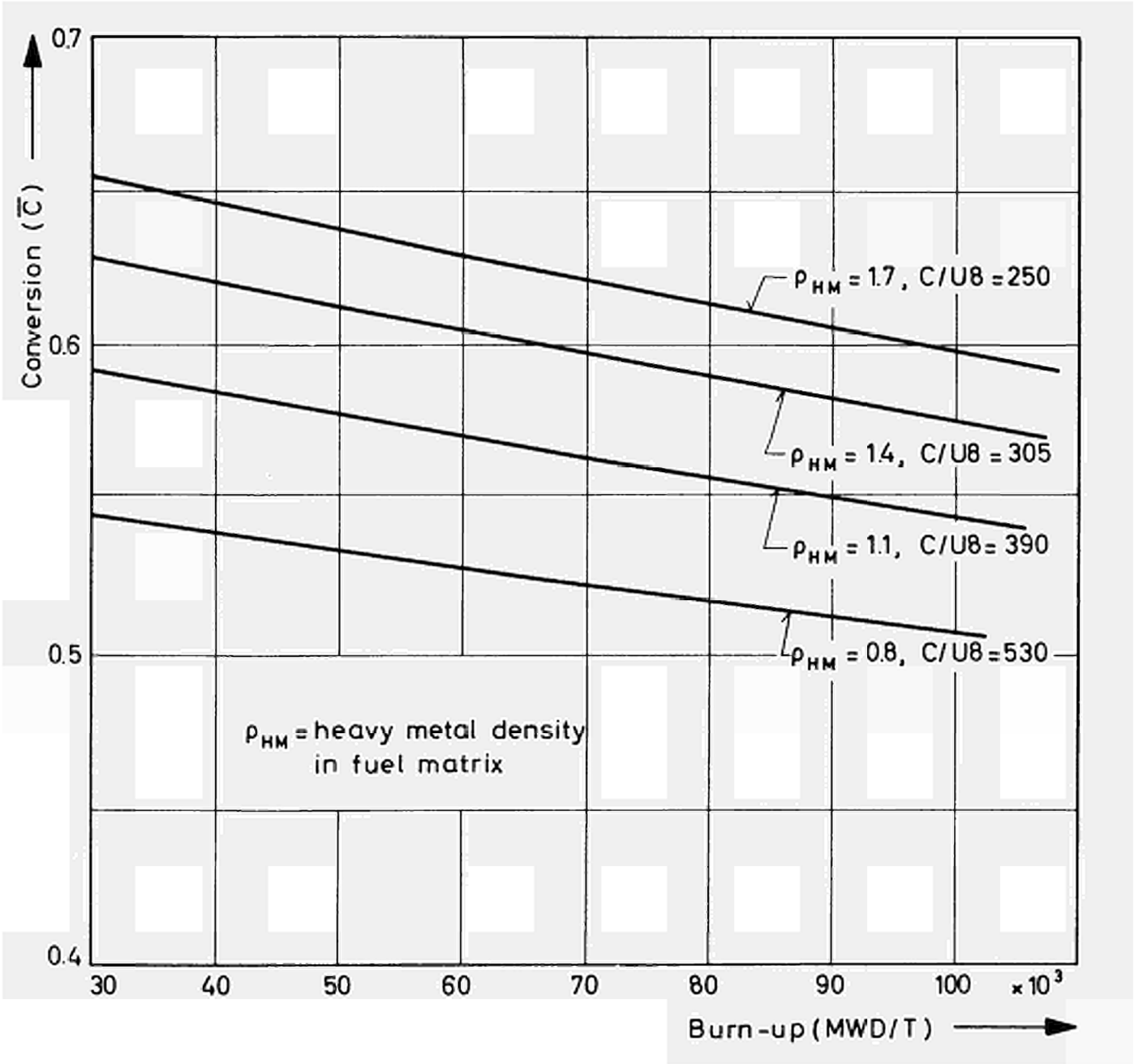


FIG. 18

HTR, U - cycle
multiannular fuel
once - through cycle
40% Xe ov.
Power density 7 W/cm^3
Cell radius 24 cm.

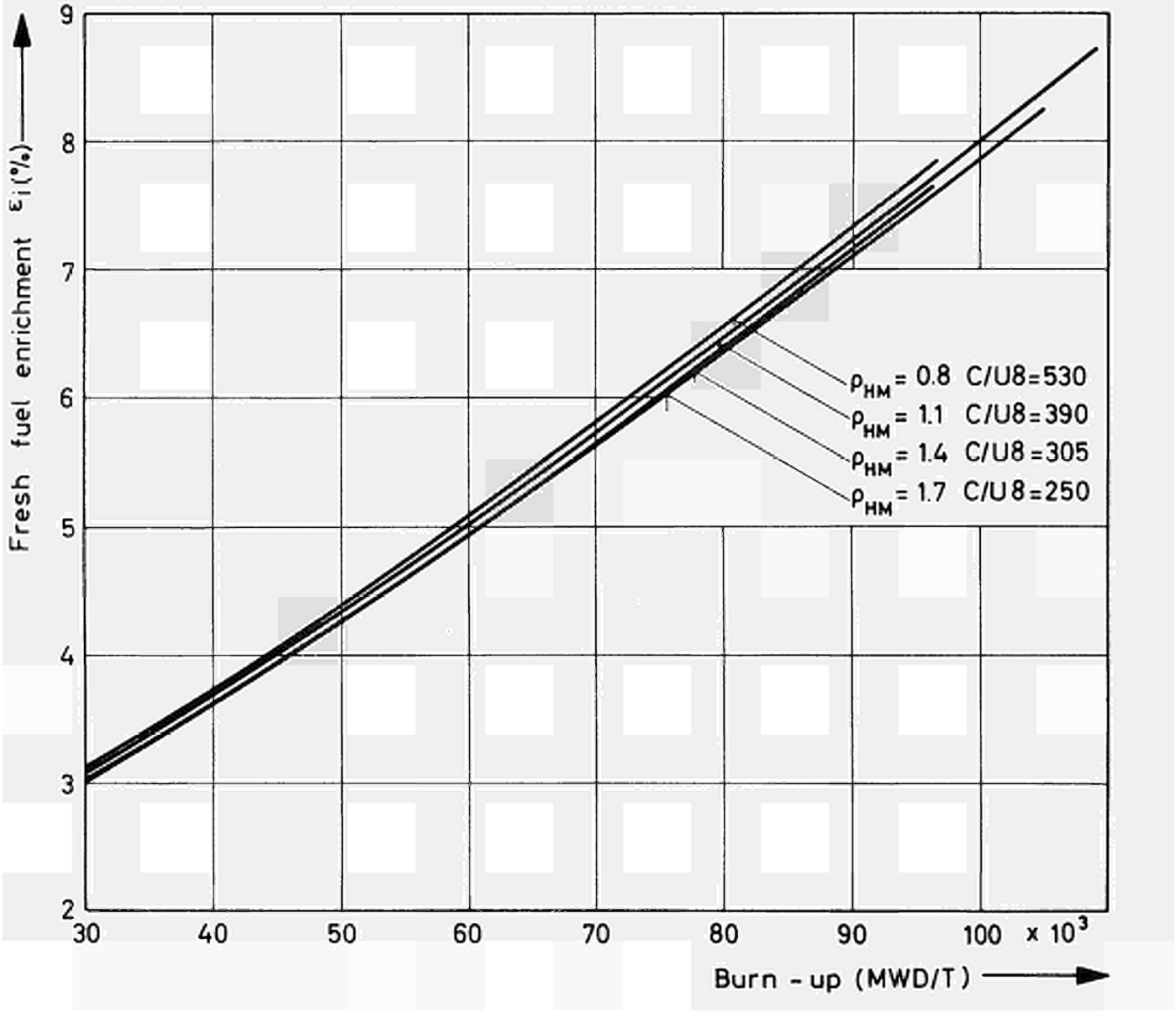


FIG. 19

HTR, U - cycle
multiannular fuel
once - through with sale
40% Xe ov.
Power density 7 W/cm^3
Cell radius 24 cm.

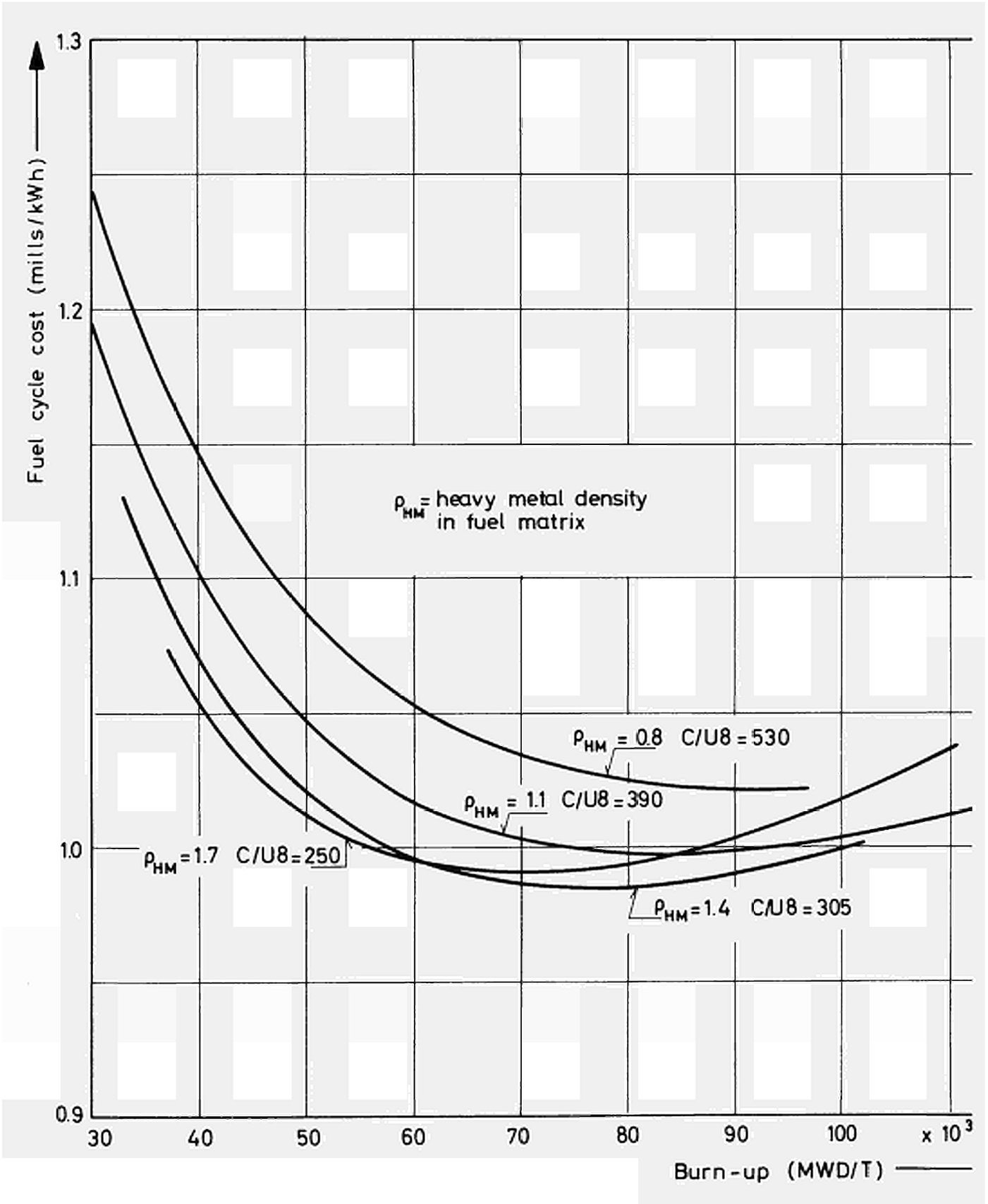


FIG.20 HTR, U-cycle
solid rod fuel
once-through cycle
40% Xe ov.
Power density 7 W/cm^3

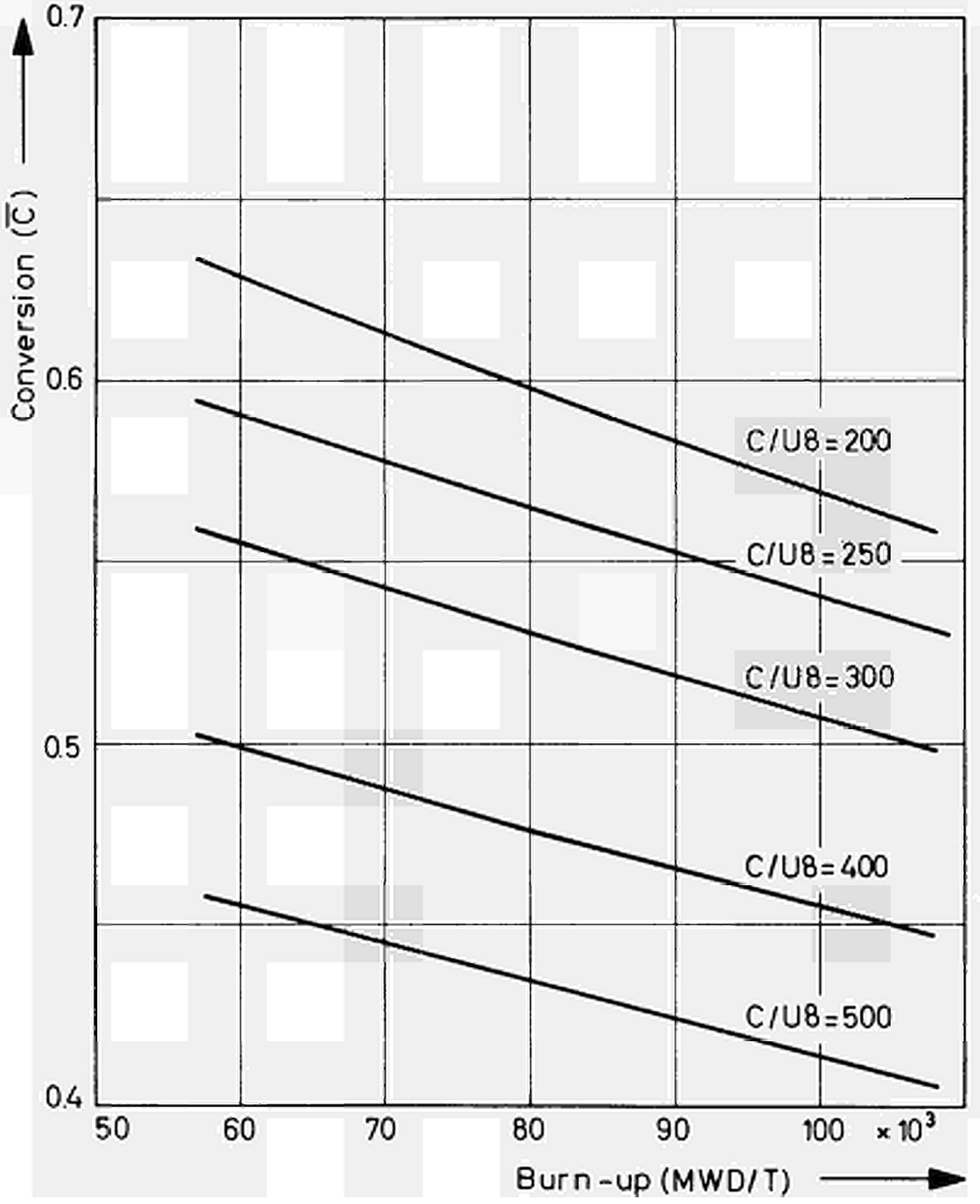


FIG. 21 HTR, U-cycle
solid rod fuel
once-through cycle
40% Xe ov.
Power density 7 W/cm³

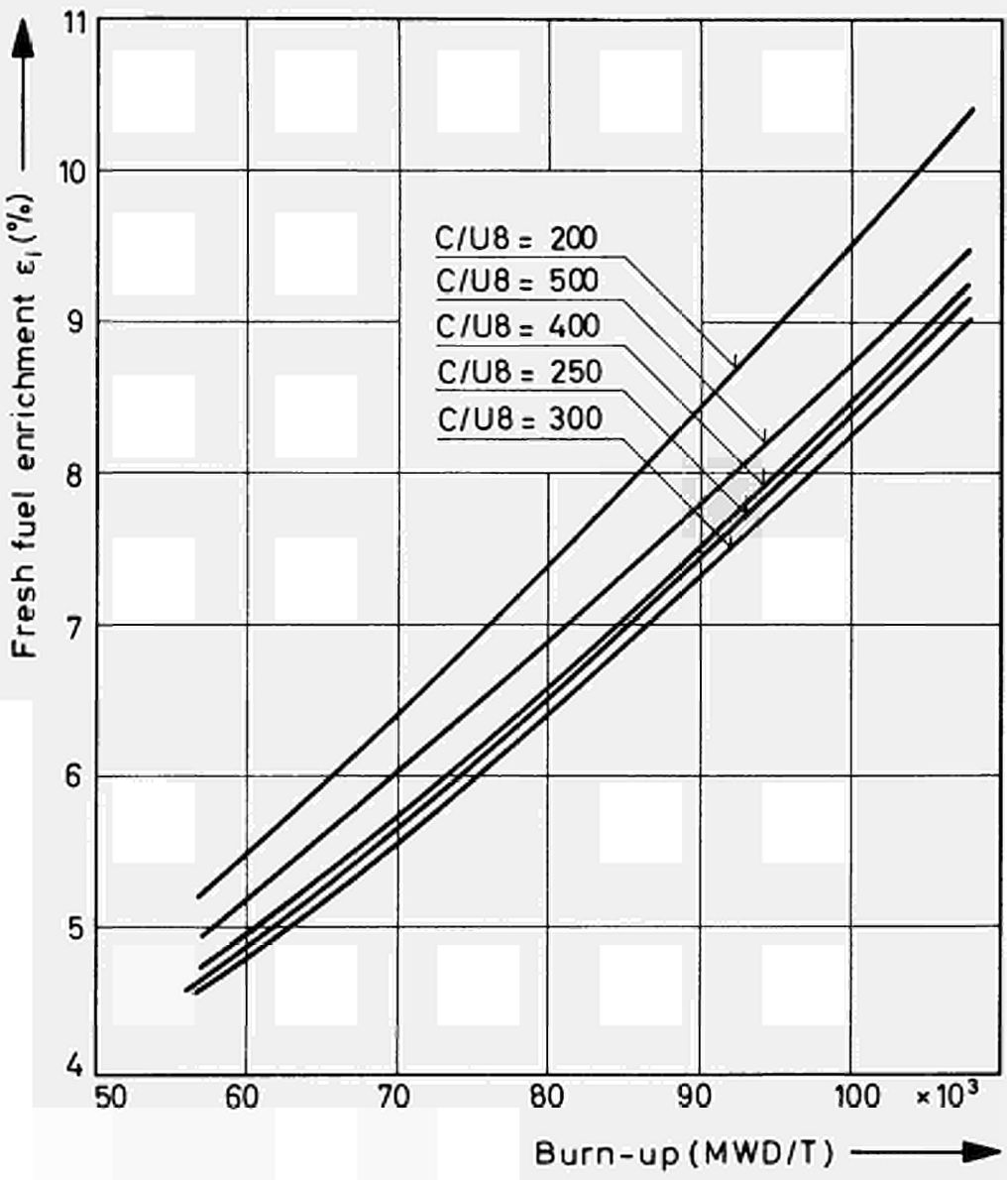


FIG. 22

HTR, U - cycle
solid rod fuel
once - through with sole
40 % Xe ov.
Power density 7 W/cm^3

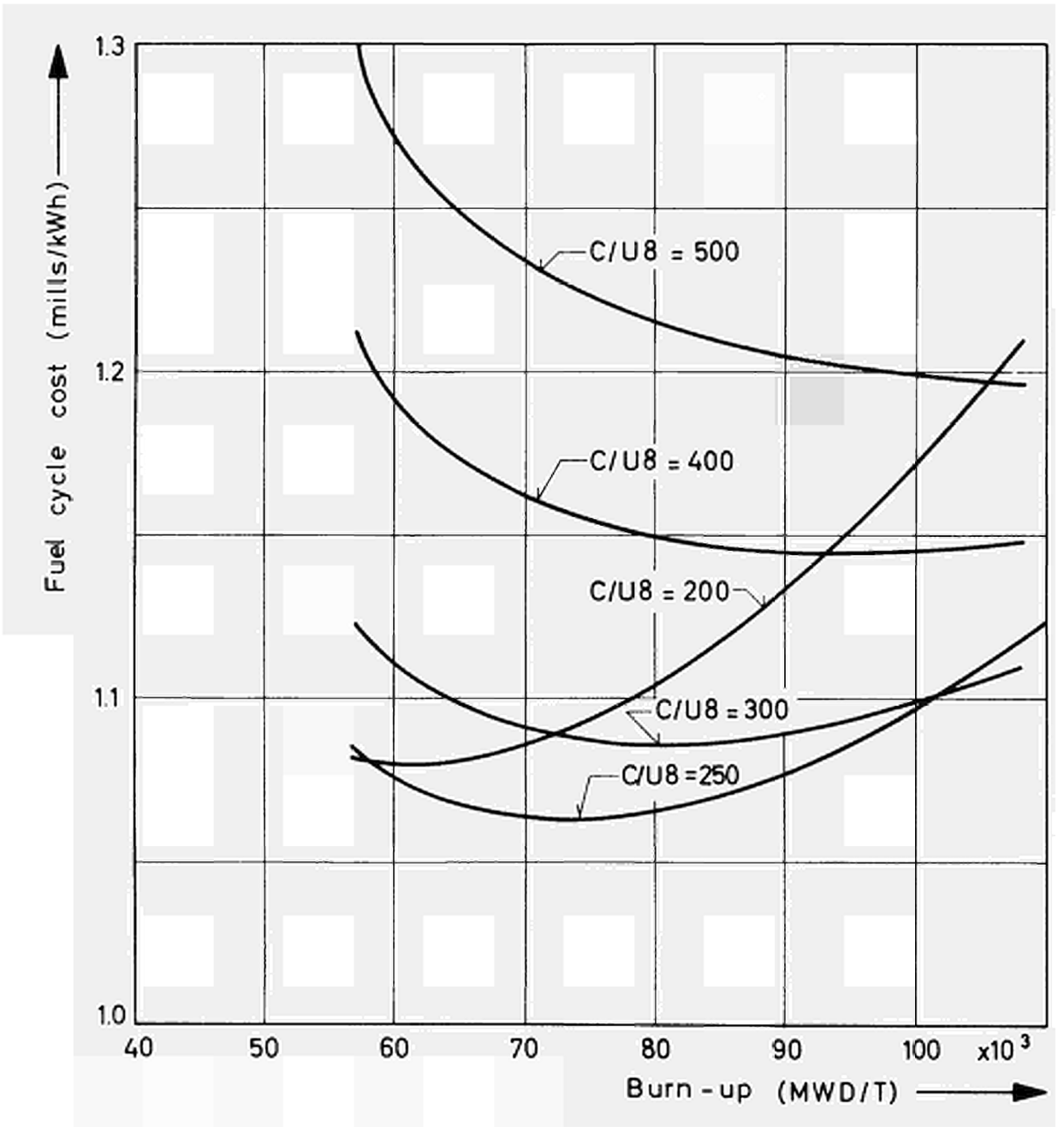


FIG. 23 HTR, Th - cycle
Full recycle, C/Th 150

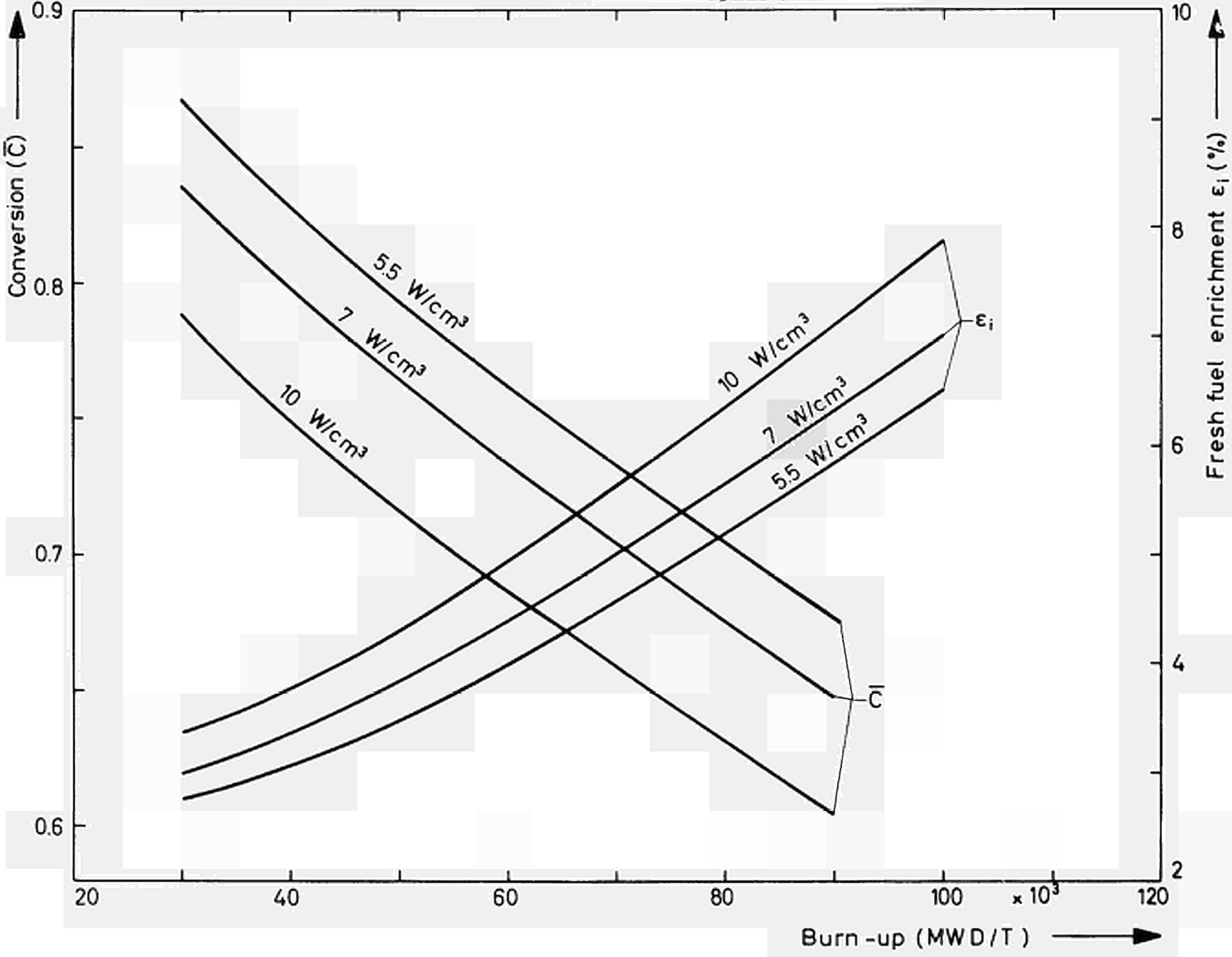


FIG. 24 HTR, Th - cycle
Full recycle, C/Th 200

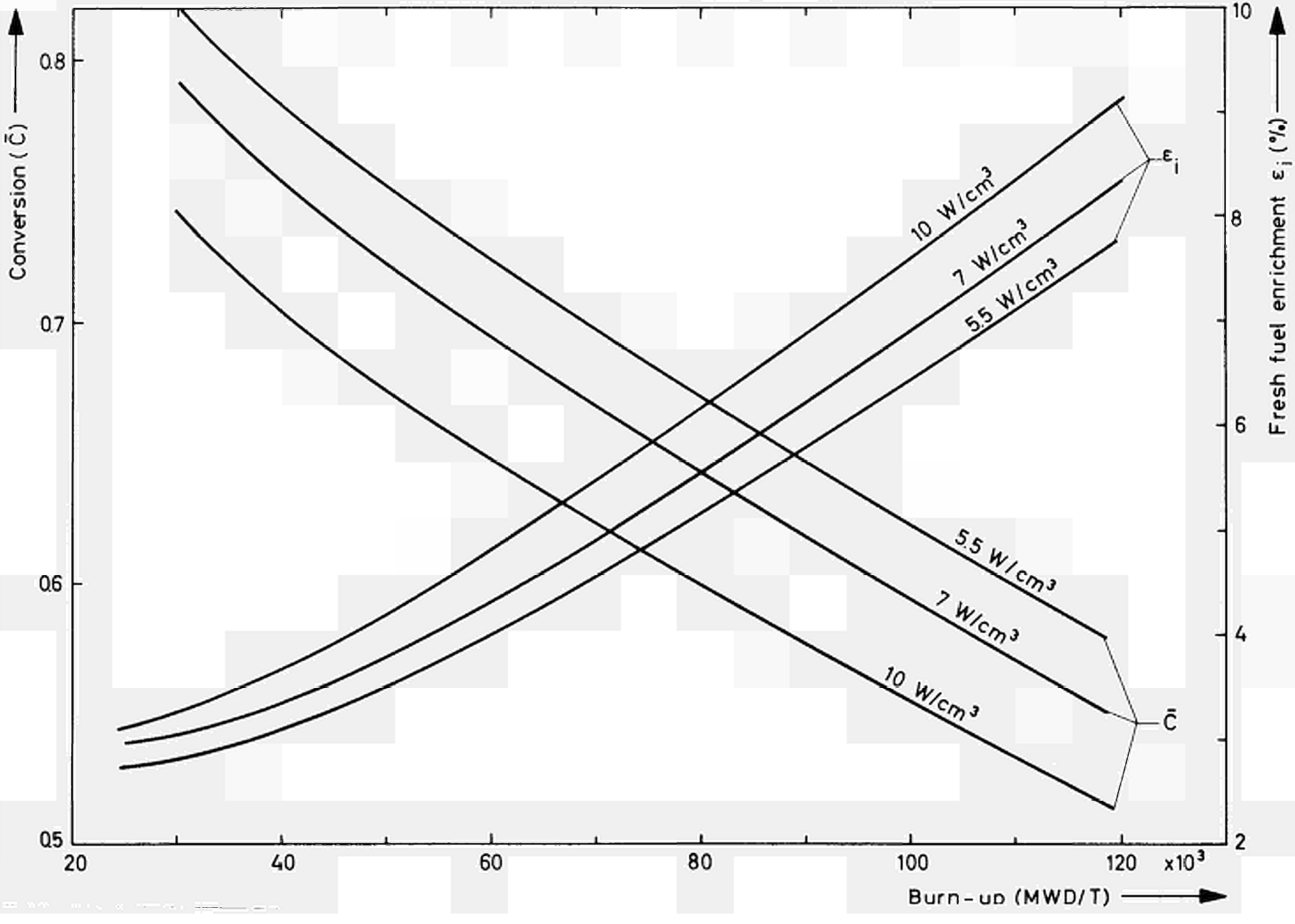


FIG.25 HTR, Th-cycle
Full recycle, C/Th 250

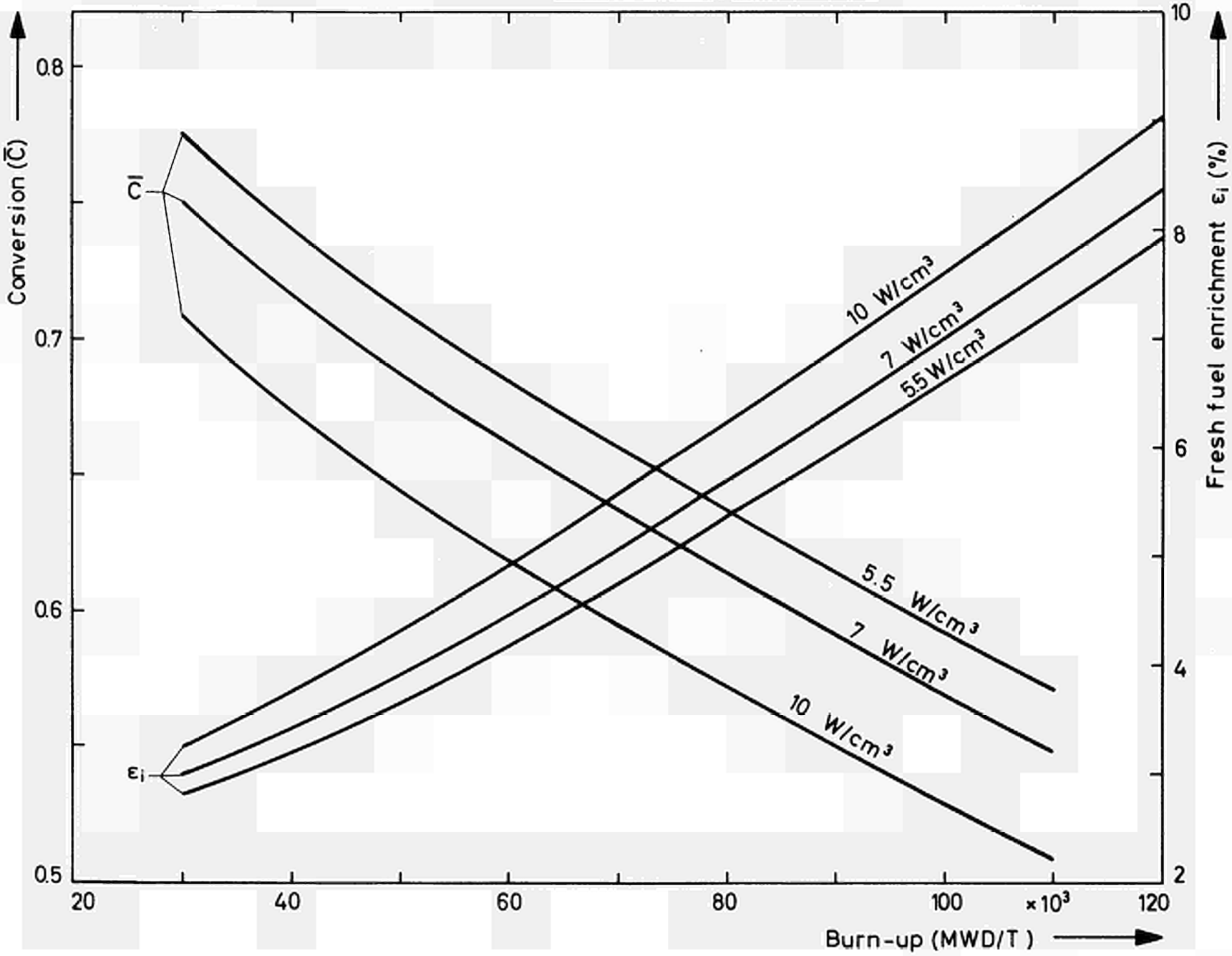


FIG. 26

HTR, Th-cycle
full recycle
C / Th = 150

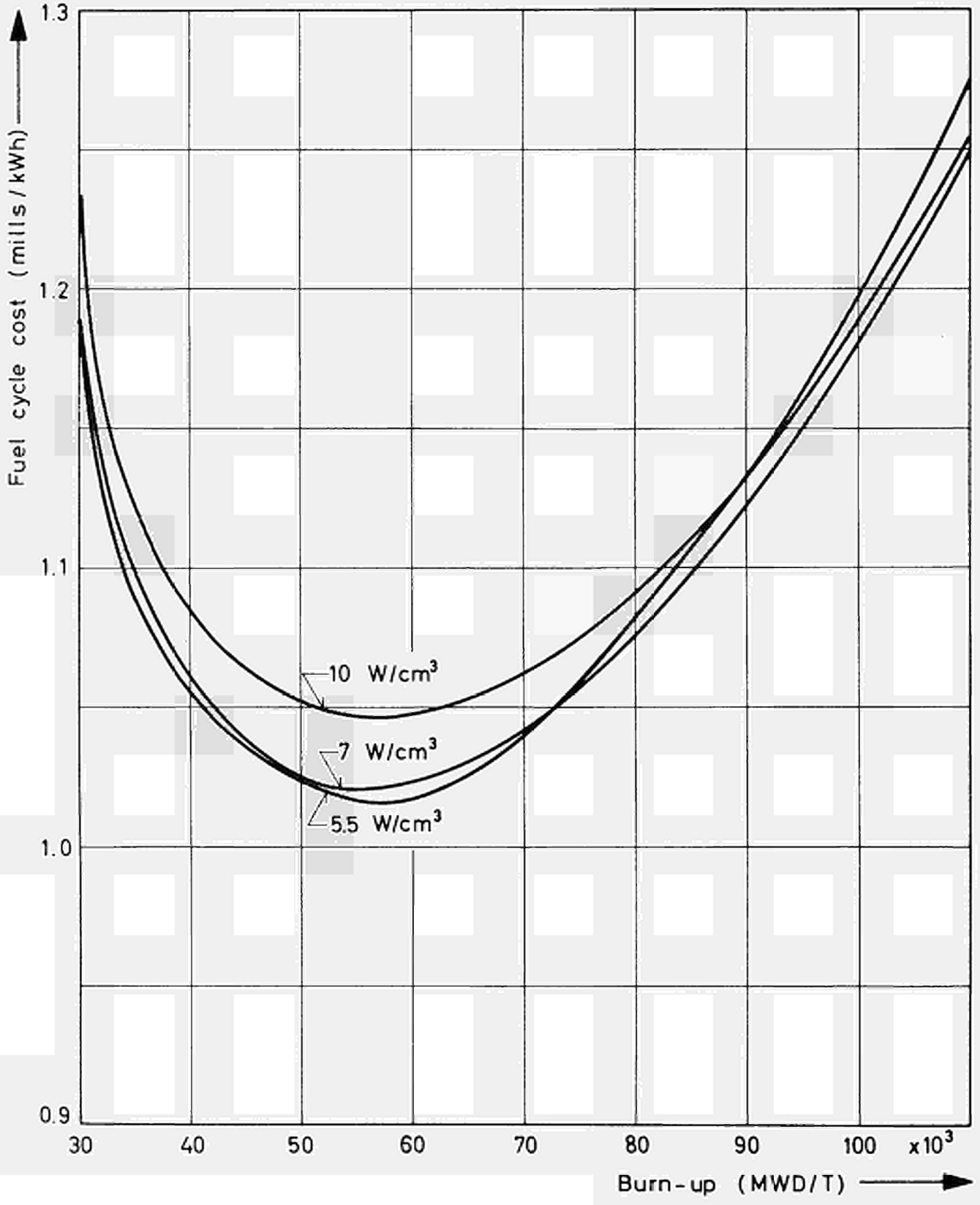


FIG. 27 HTR, Th - cycle
full recycle
C/Th = 200

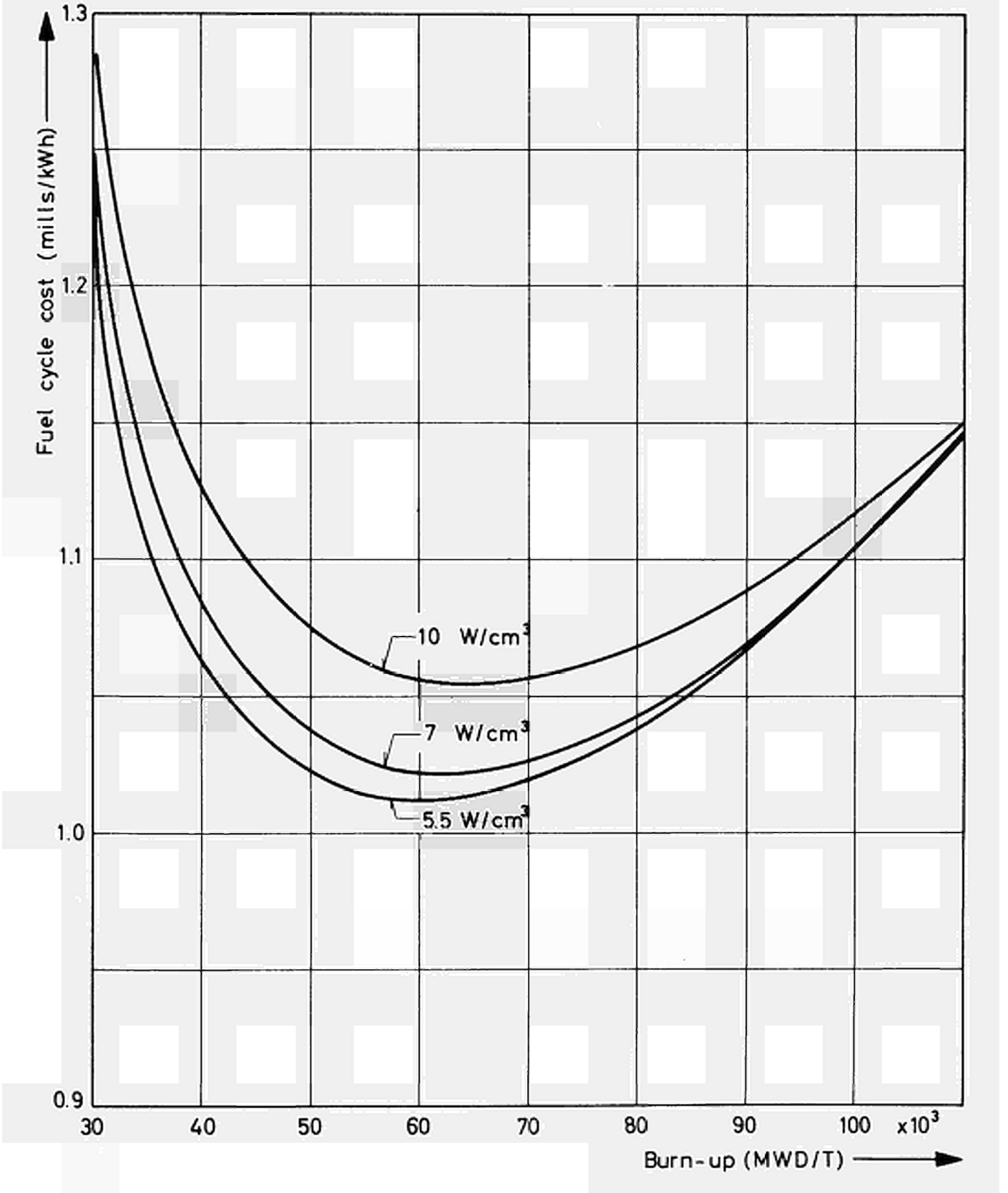


FIG. 28

HTR, Th - cycle
full - recycle
C/Th = 250

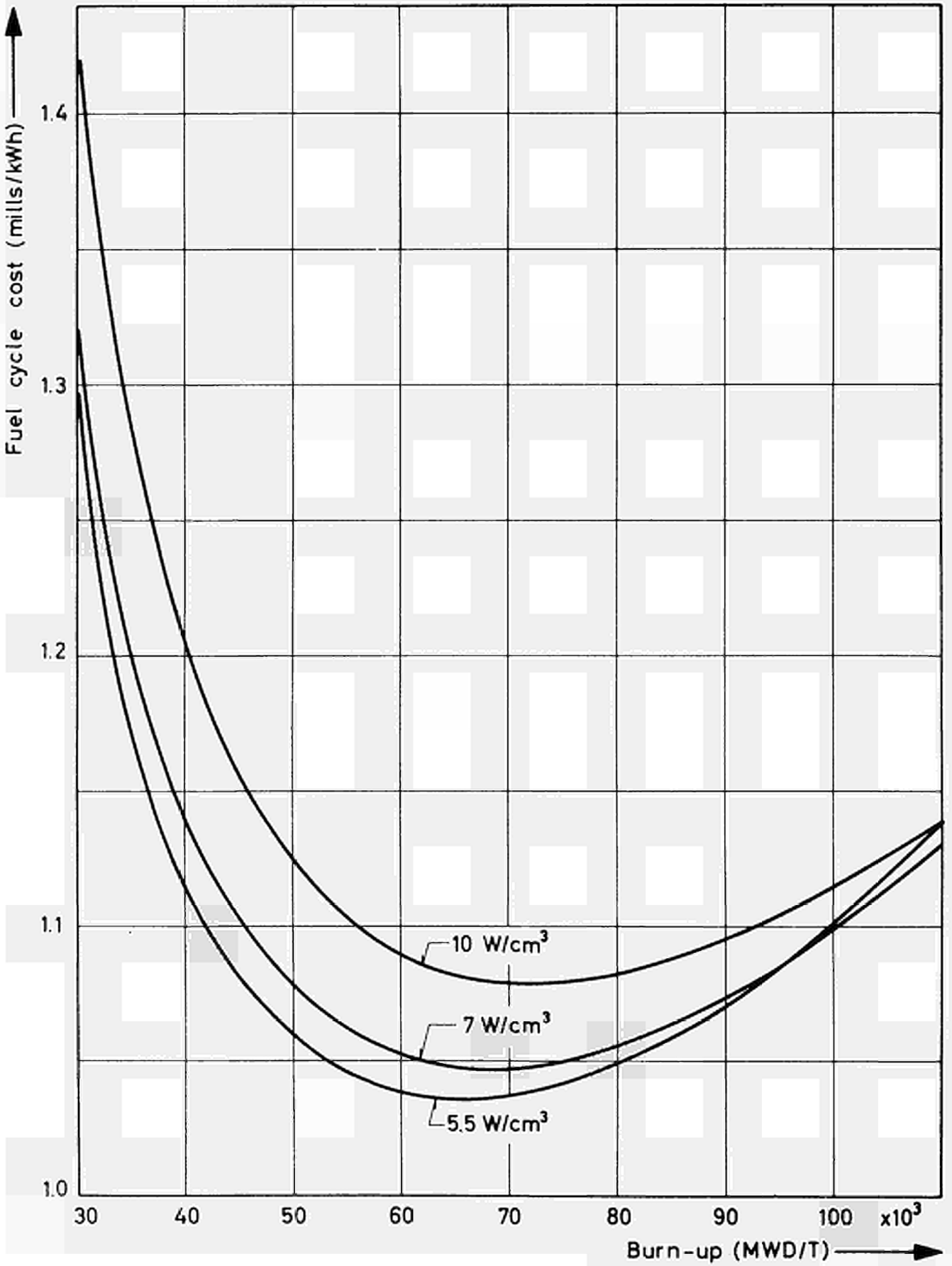


FIG. 29 HTR, Th-cycle
Segregation, C/Th=150

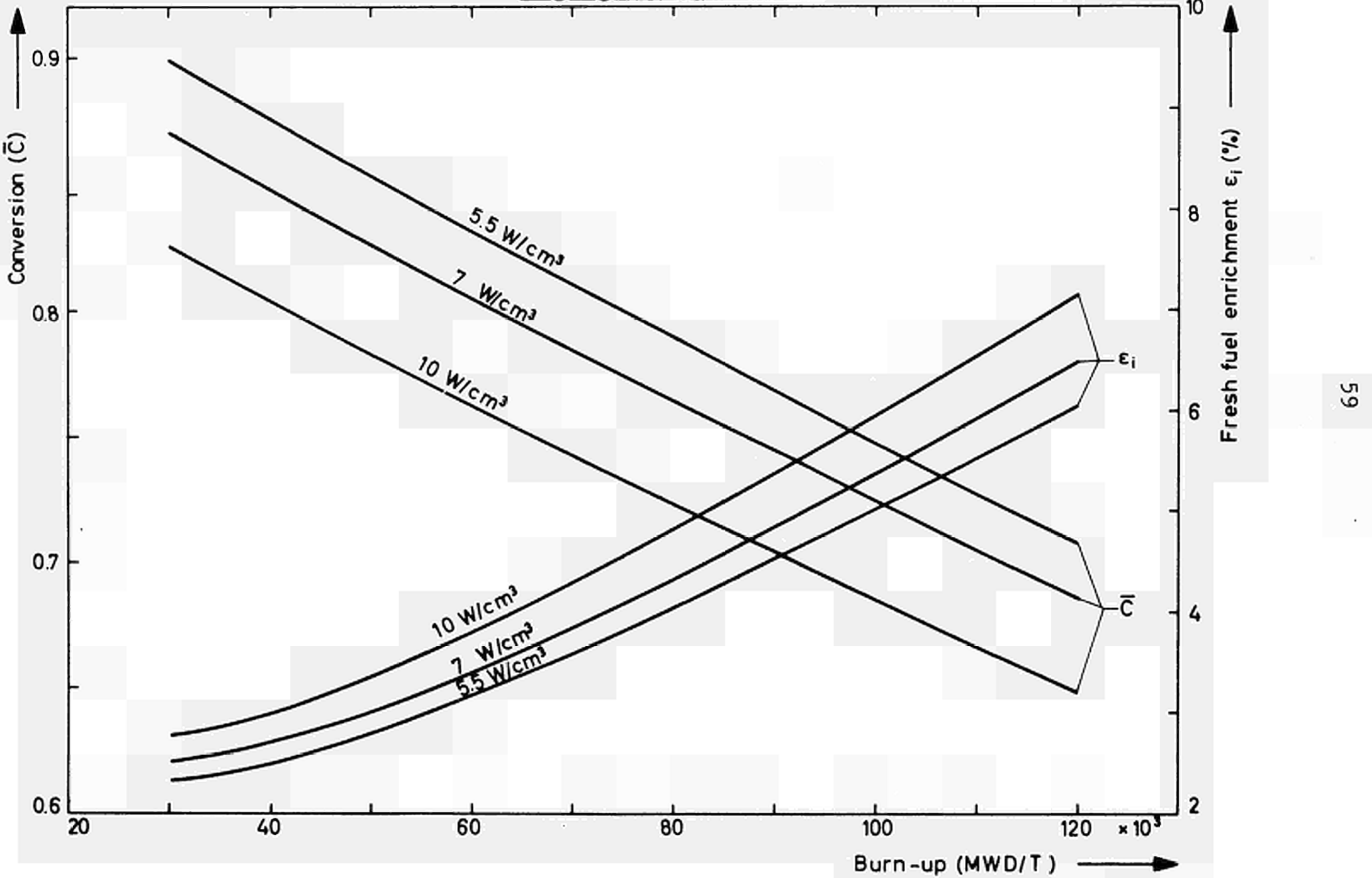


FIG. 30 HTR, Th-cycle
Segregation, C/Th=200

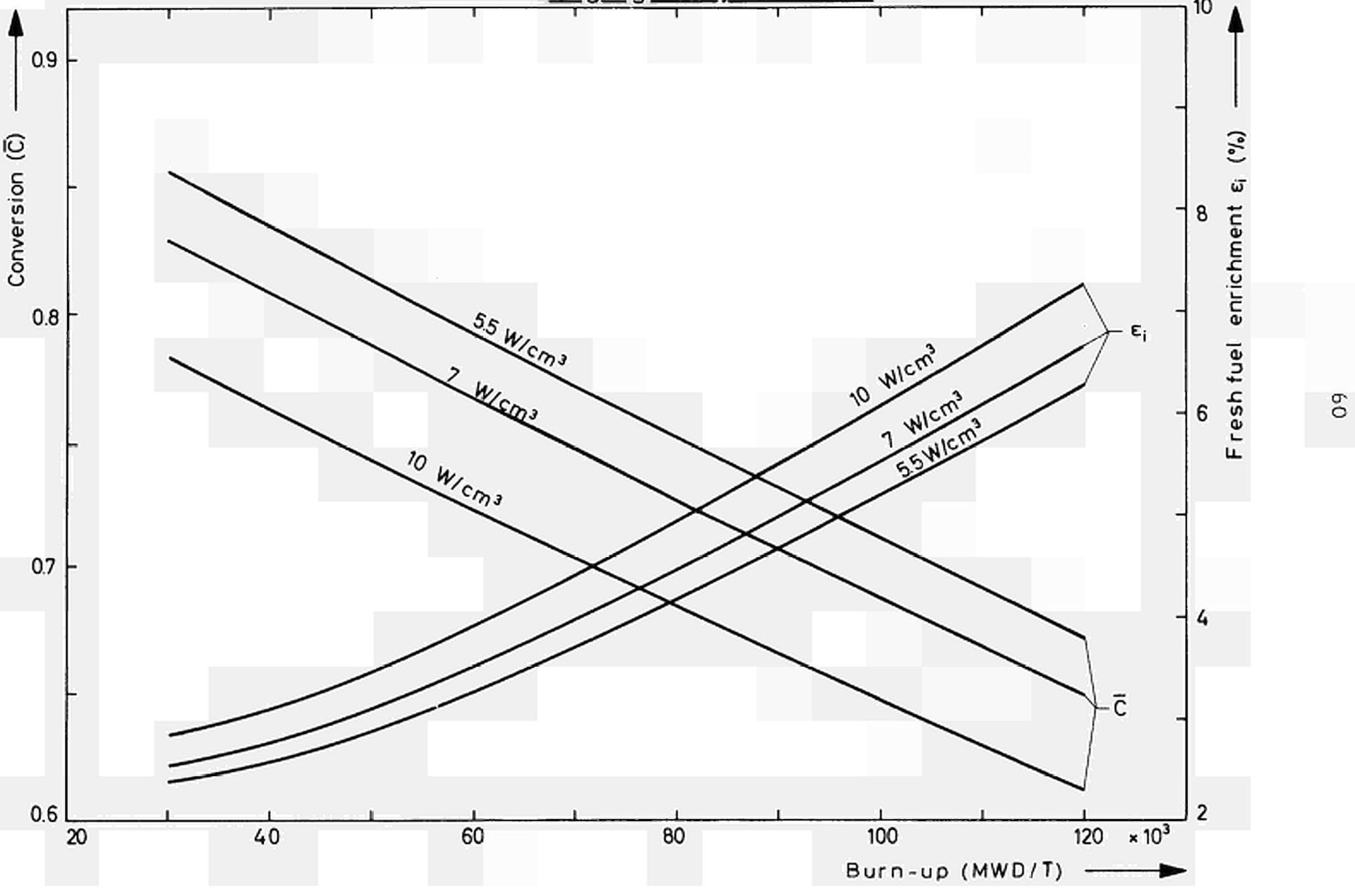


FIG. 31 HTR, Th-cycle
Segregation, C/Th = 300

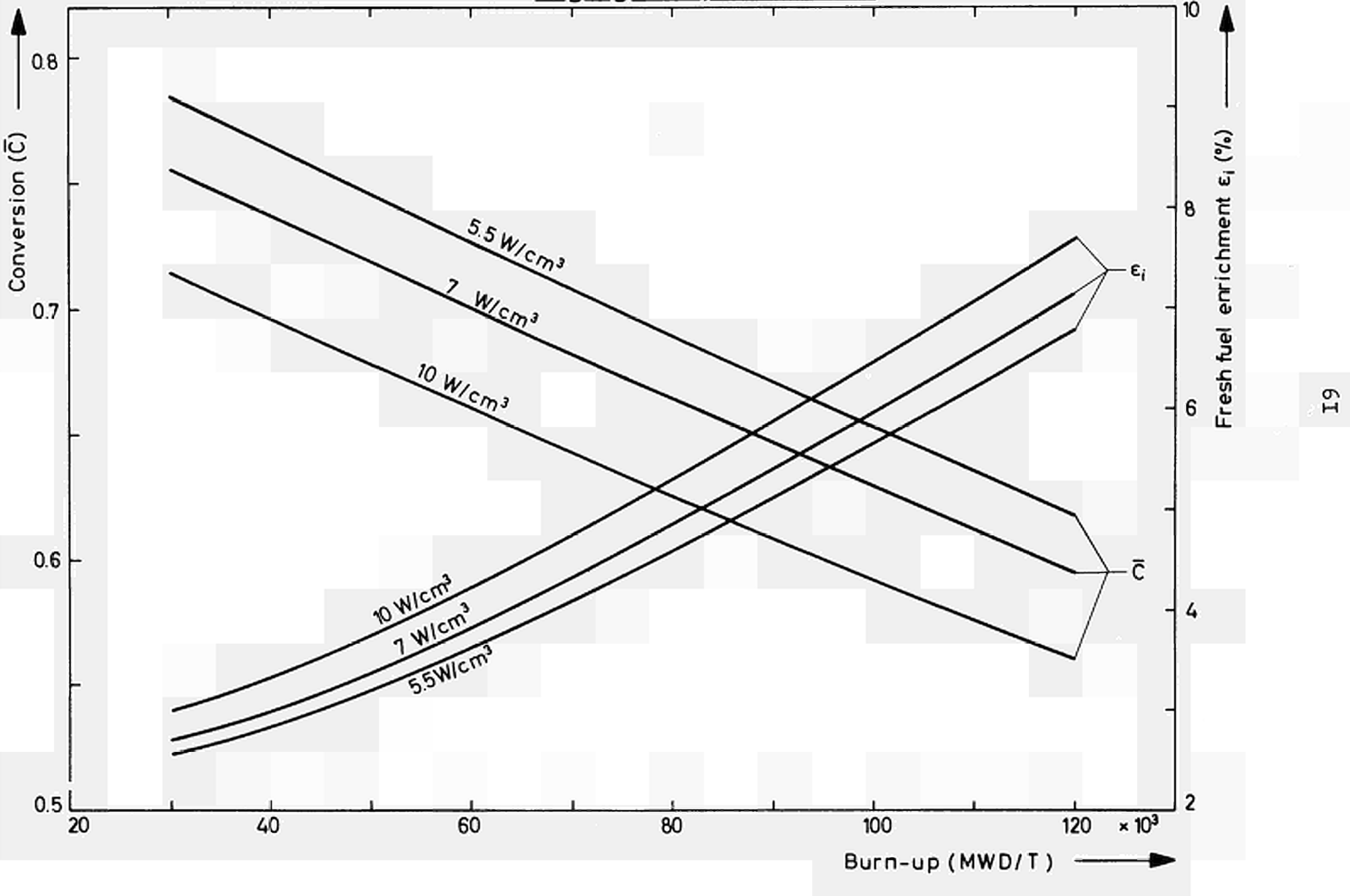


FIG. 32

HTR, Th - cycle
segregation
C/Th = 150

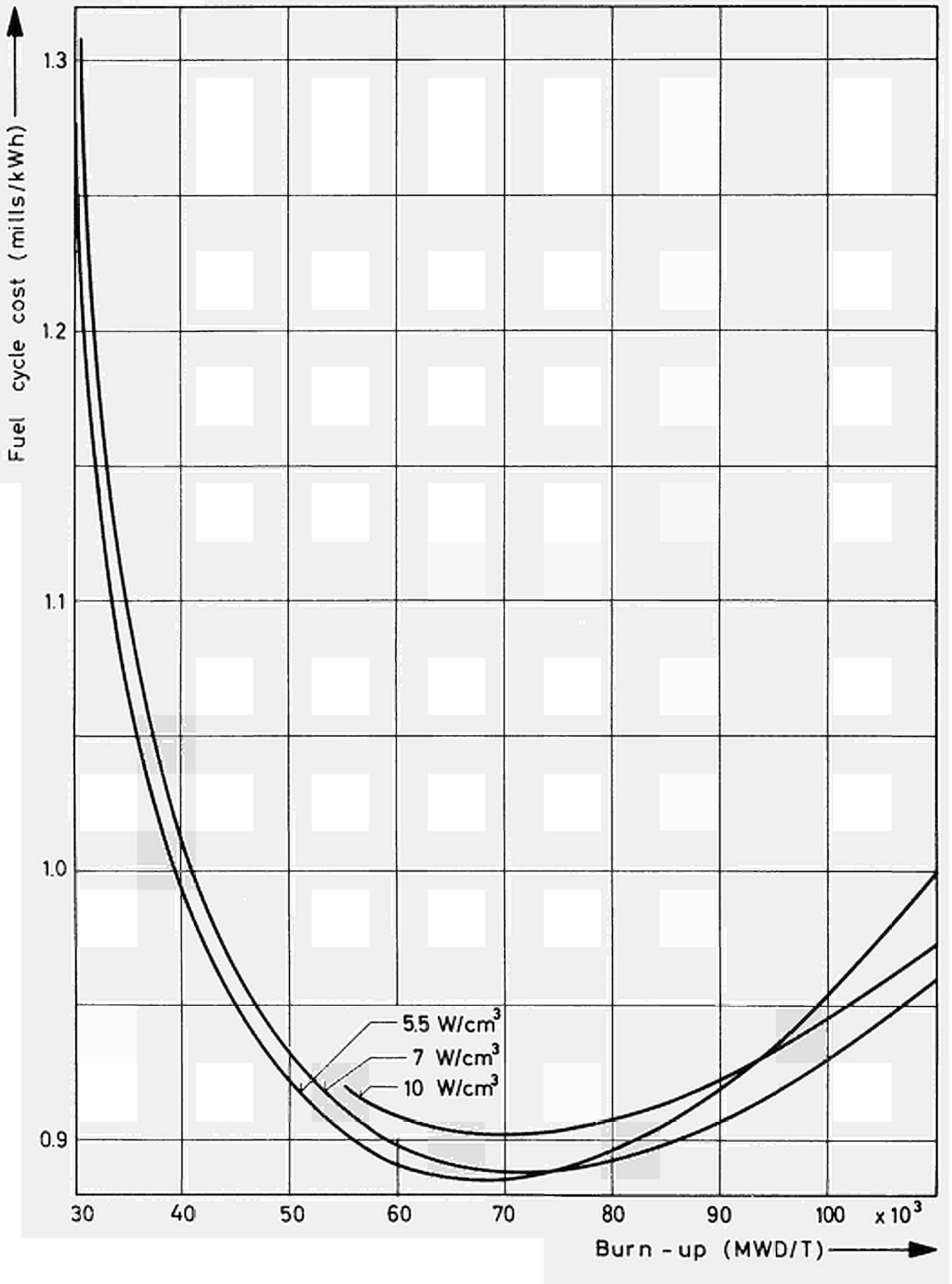


FIG. 33 HTR , Th - cycle segregation C/Th = 200

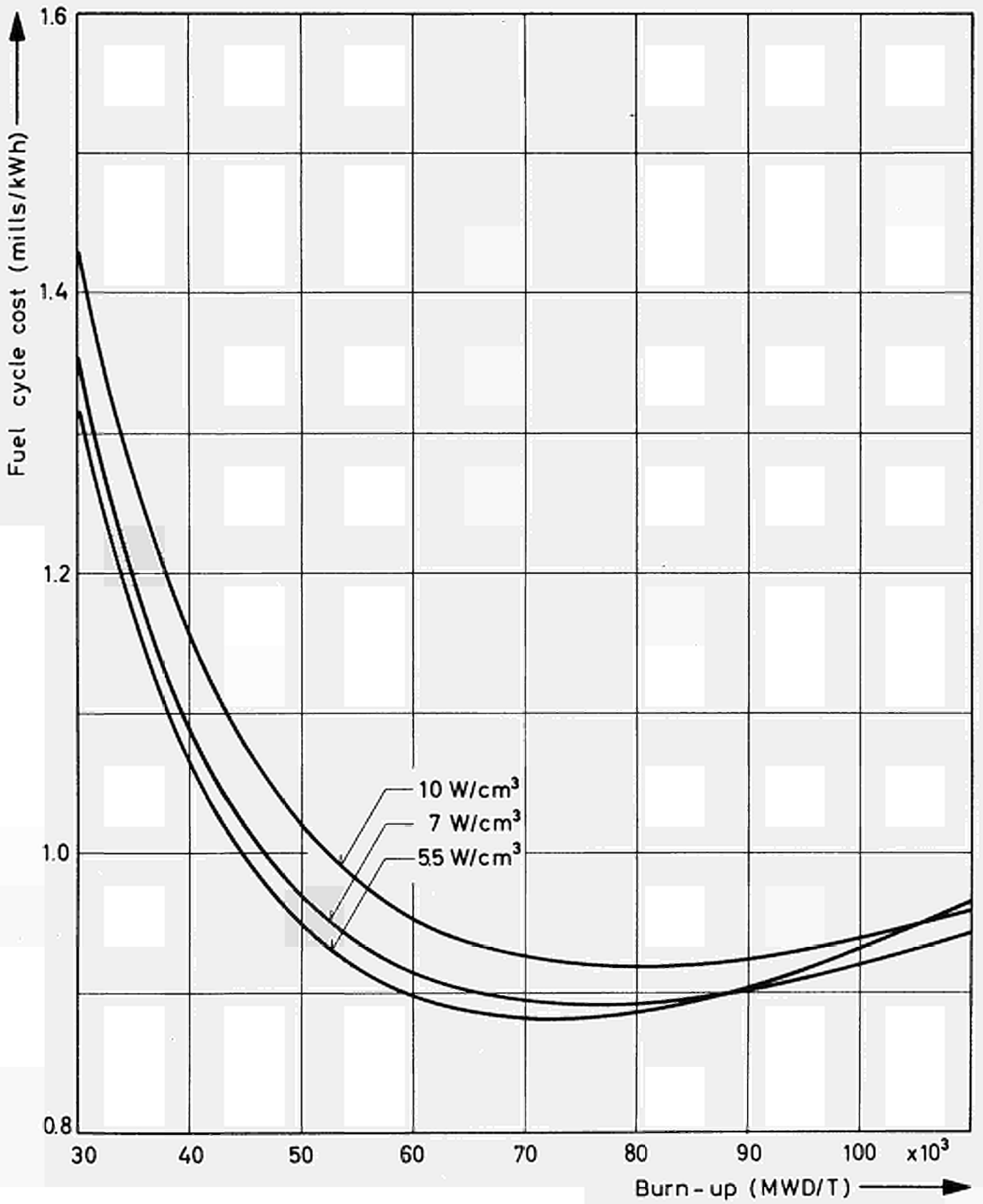


FIG. 34

HTR, Th-cycle segregation C/Th=300

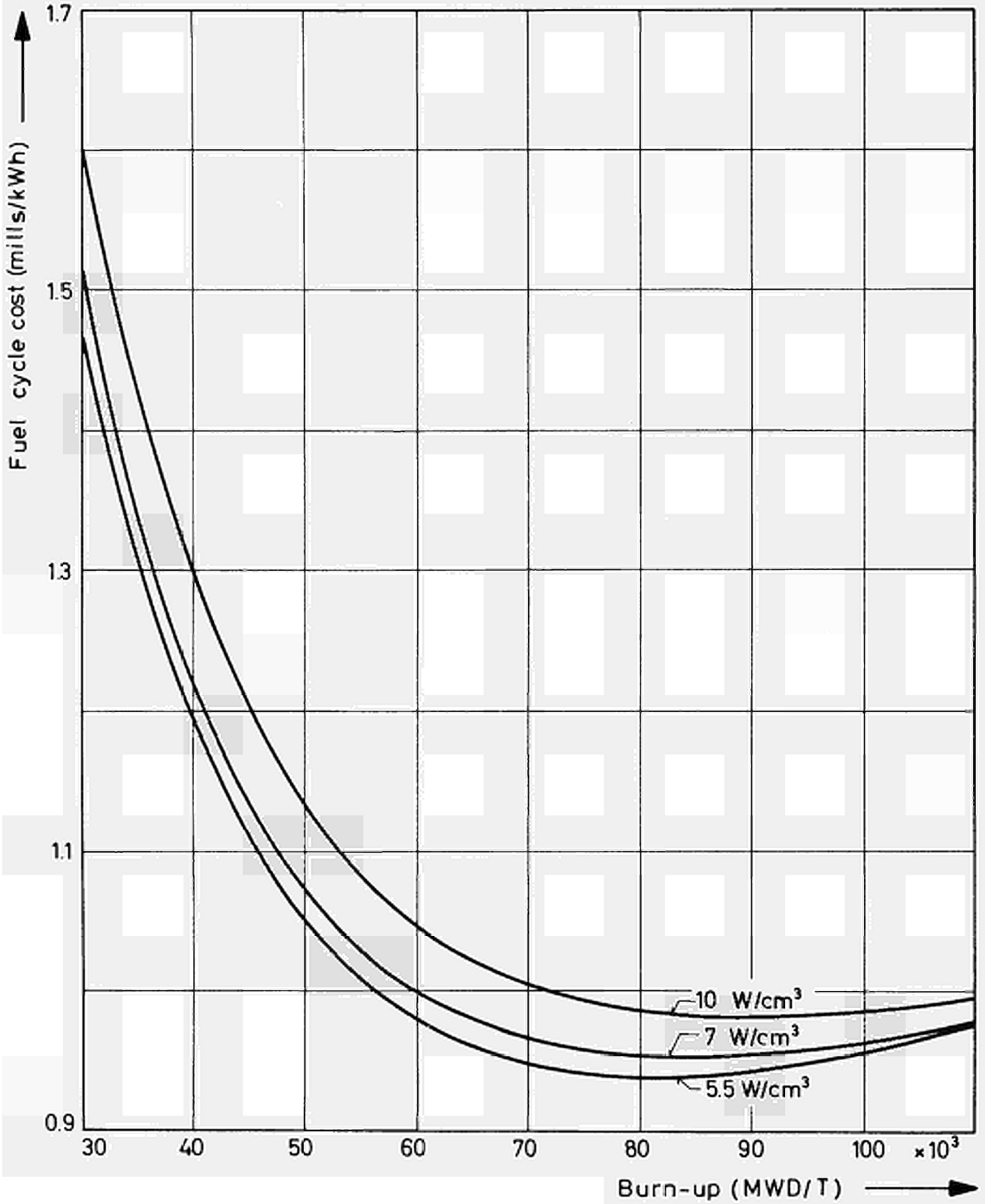


FIG.35 HTR, Th-cycle segregation with sale Power density 7 W/cm³

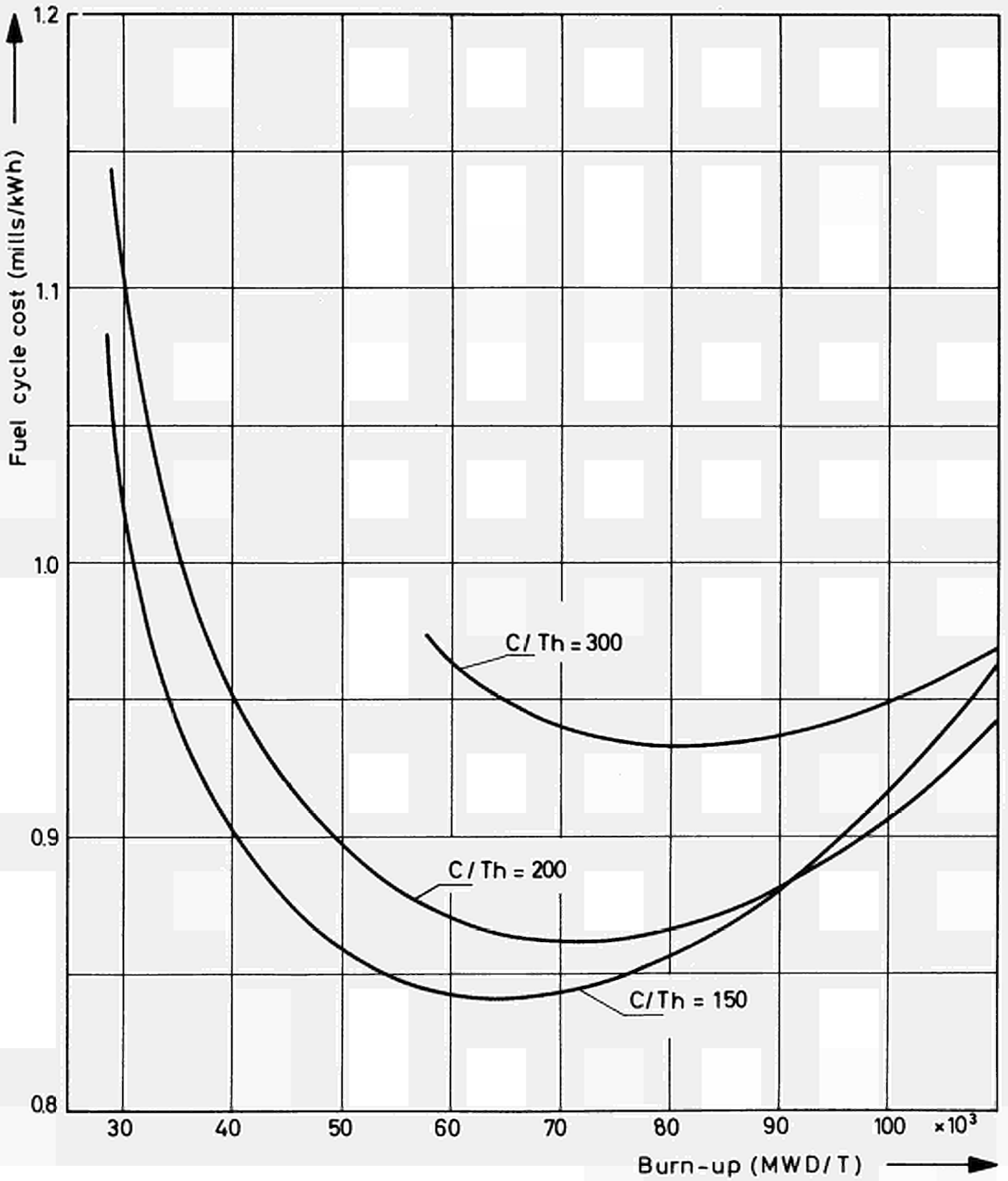


FIG. 36 HTR, U - cycle multiannular fuel once-through with sale Fabrication cost 75 $/kg

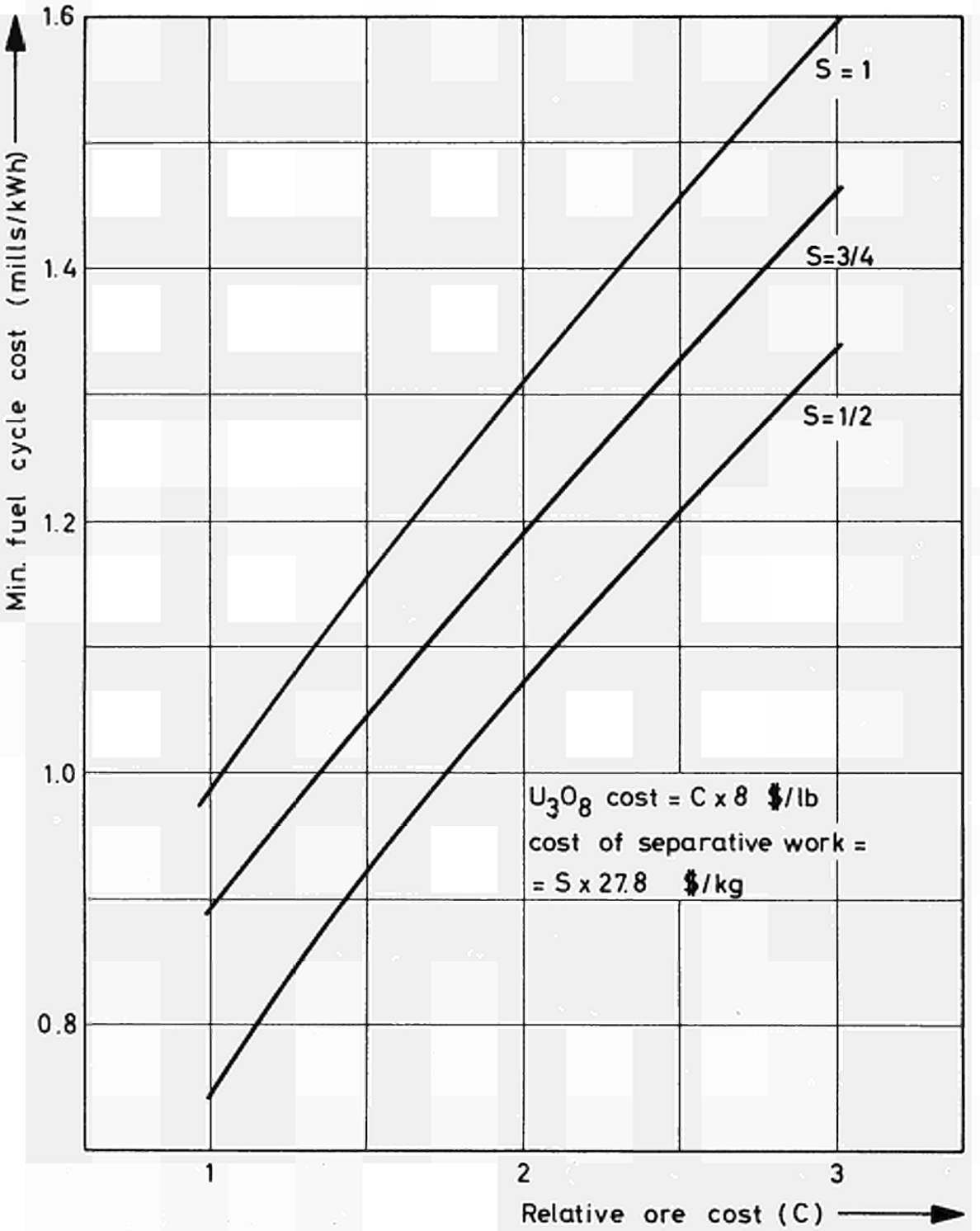


FIG. 37 HTR, U-cycle multiannular fuel once-through with sale Fabrication cost 125 $/kg

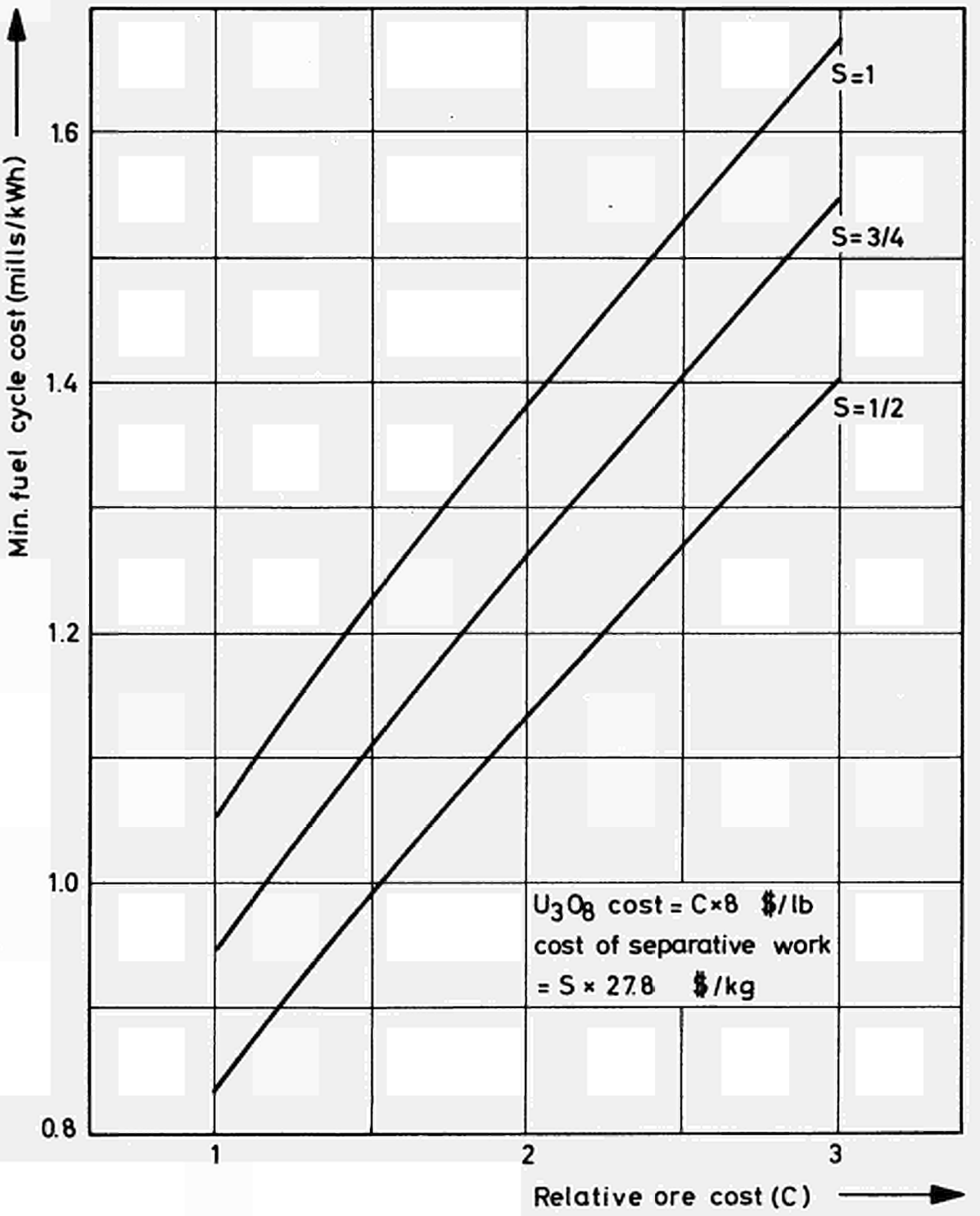


FIG. 38 HTR, U - cycle
Solid rod fuel
once - through with sale
Fabrication cost 75 $/kg

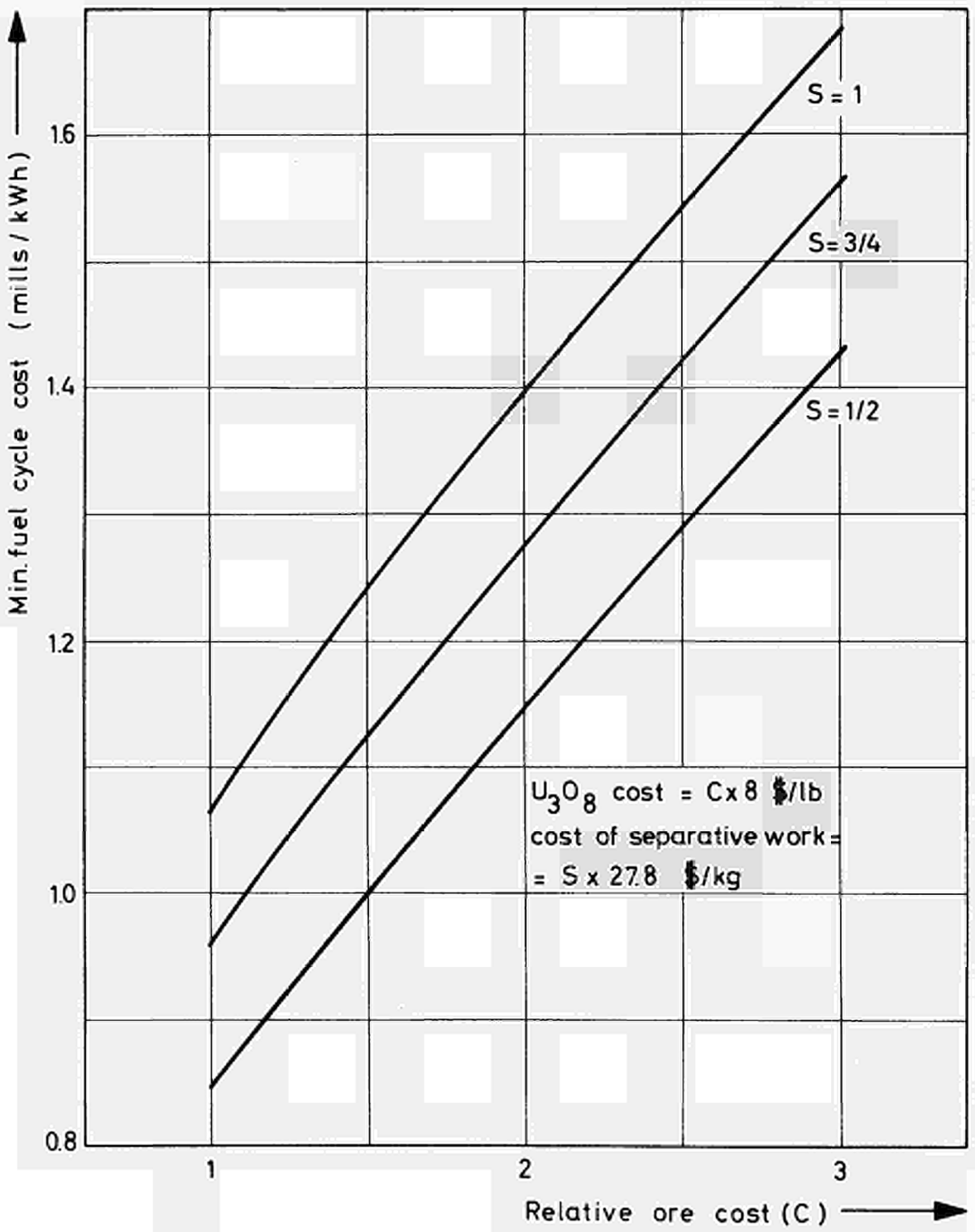


FIG. 39 HTR, Th-cycle full recycle

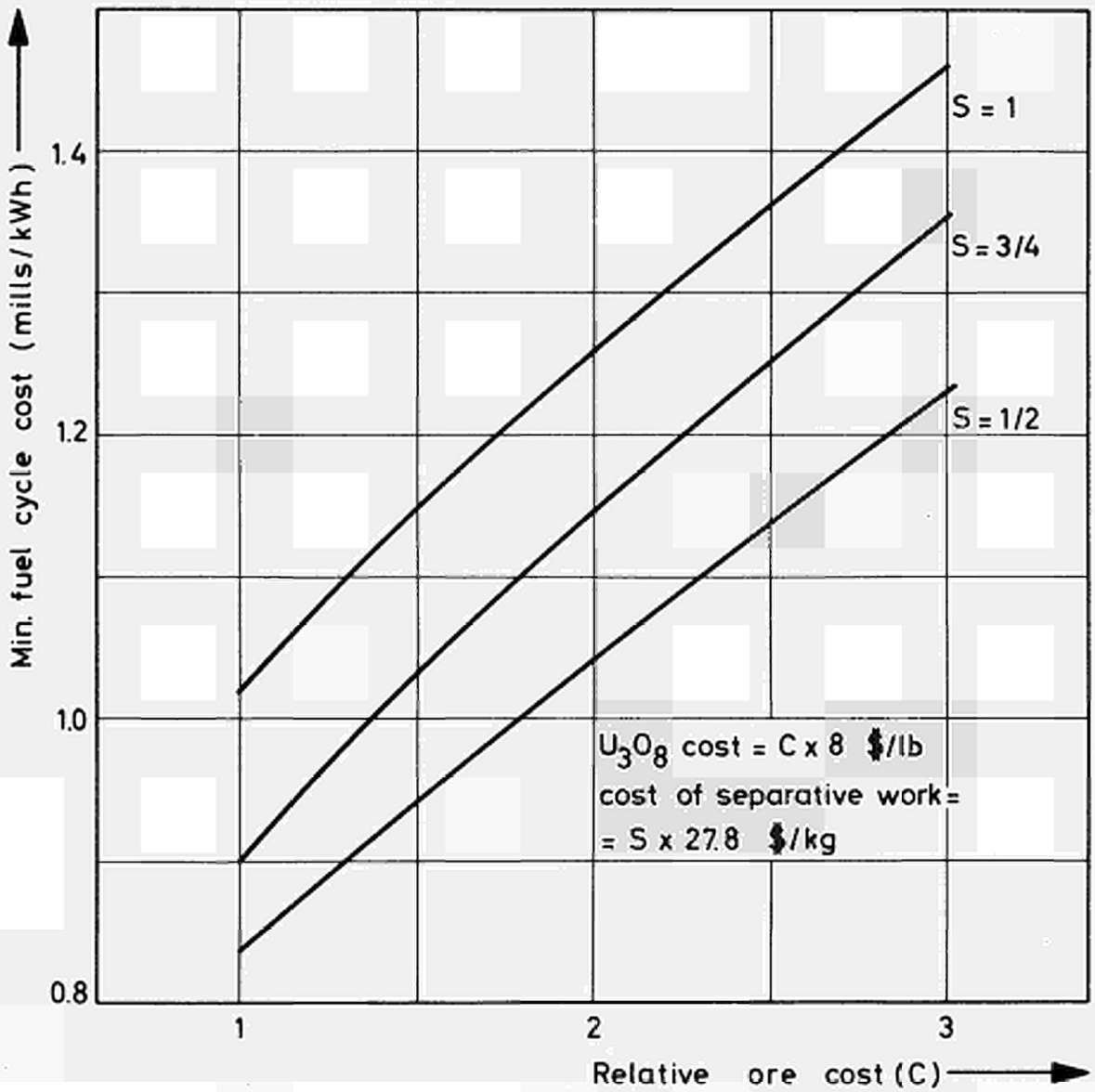
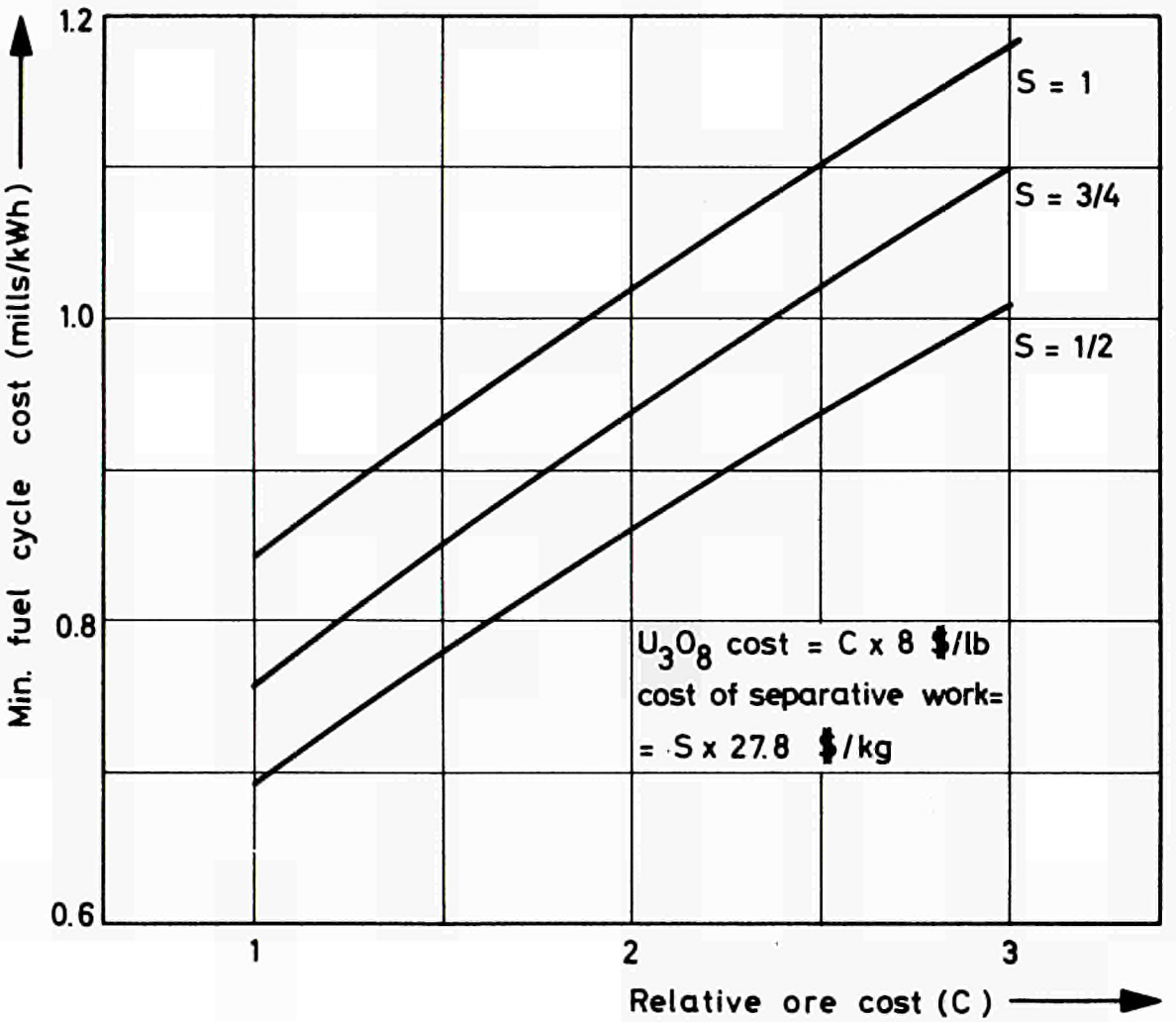


FIG. 40 HTR, Th - cycle segregation with sale



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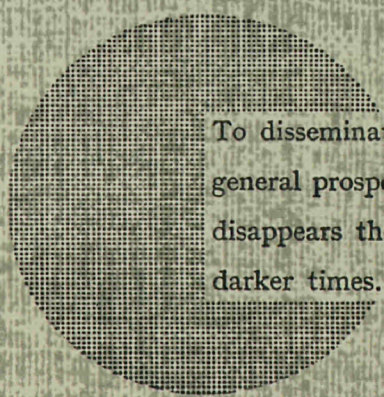

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Alfred Nobel

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