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Dragon Project Report

BURN-UP IN A LARGE HIGH TEMPERATURE GAS COOLED REACTOR

by

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1. INTRODUCTION

The Dragon Project has just started to study the burn-up of Thorium-Uranium systems in a large power reactor. In order to determine core compositions of interest earlier results, obtained in studies by the U.K.A.E.A. [1] are used as a basis for the present investigations.

In this paper equilibrium compositions are discussed which can be achieved either by a complete replacement of the core or by a continuous charge discharge operation when the fuel is reprocessed. These two simplified recharge methods were chosen because the uncertainty in the fuel fabrication costs is such that a more detailed fuel cost study involving partial reloading schemes appears to be inappropriate at present. On the other hand a wide range of fuel production costs has been considered and core compositions leading to minimum fuel costs under various conditions have been established.

2. THE BURN-UP OF THORIUM-URANIUM SYSTEMS

The basic nuclear cross sections for Thorium-Uranium-Graphite systems are reasonably well known and the calculational techniques have been developed during the last years to match the accuracy of the nuclear data. Using high-speed digital computers with large storage capacities, multi-group diffusion equations are generally employed for determining the physical properties of such systems.

Multi-group methods are used because of the complicated shape of the neutron spectrum and its change with irradiation as illustrated in Fig. 1. The epithermal part deviates considerably from a 1/E dependence with sudden drops owing to neutron absorption in Thorium resonances. The irradiated core shows additional resonance absorption from the Uranium isotopes U-233, U-234 and U-236 which have been built up. The absorption in Thorium is smaller since some of it has been burnt. As to the thermal part of the spectrum, this does not show a Maxwellian distribution. Owing to the smaller macroscopic thermal absorption cross-section of the depleted core its thermal peak is higher than that of the unirradiated one.

The effective cross-sections, used for calculating the burn-up, must reflect these spectral changes. For some important isotopes the relative change of the absorption cross-section with burn-up is plotted in Fig. 2. It shows that cross-sections generally increase with time as the spectrum softens. Isotopes with near thermal resonances as U-233 and U-235 produce a smaller change, because an increase of the thermal cross-section is partially balanced by a smaller resonance absorption. In the case of Protactinium the latter effect is stronger at first and for U-236 with its strong 5.5 eV resonance one even finds a steady decrease at all times. For calculations on long irradiated cores it is therefore essential to follow these changes as accurately as possible which can adequately be done only with multi-group methods.

The semi-homogeneous nature of the fuel elements on the other hand makes

diffusion theory an appropriate tool; the size of large power reactors further reduces the importance of spacial effects. For survey calculations, a zero-dimensional multi-group burn-up programme is therefore suited best, whereas a more detailed analysis of selected cases is better carried out with a one-dimensional diffusion programme in few energy groups [2], whereby the spectrum is recalculated in many more groups at appropriate time intervals.

The general character of a burn-up curve for Thorium-Uranium systems is given in Fig. 3. The effective multiplication constant K_{eff} without control rods drops immediately after start-up as Xe-135 and Sm-149 build up rapidly. Equilibrium is reached within a few days. During the next 100 days the Protactinium comes to equilibrium and causes K_{eff} to drop faster during that period than later, when the decrease is governed mainly by the depletion of fissile material, and partly by the build up of the low cross section fission products.

The influence of the slow and non-saturating fission products cannot be seen readily from these curves. A few burn-up calculations, however, with reduced fission product yield to simulate a partial release of fission products have been carried out [3]. The outcome is that a complete release of Xe-135 and Sm-149, 151 as well as a 20% release of the slow and non-saturating fission products increases the specific burn-up only by about 30%. According to a study of Pointud [4] on small particles, the assumed 20% reduction in the absorption cross section of the slow and non-saturating fission products seems to be the utmost one can hope for, namely a complete loss of Krypton, Zirconium, Indium, Iodine, Caesium and Xenon.

Fig. 3 gives two burn-up curves which differ in the degree of moderation only as expressed by the S-value, the number of moderator atoms per fissile atom. Although the N-value, defined as the number of fertile to fissile atoms, is the same for the two cores shown, core B has a higher conversion factor and achieves, therefore, a higher specific burn-up (MWd/kg U-235) making a better use of the invested U-235. Its conversion factor is higher because this core is less moderated leading to relatively more resonance capture than thermal capture.

Before the burn-up of Thorium-Uranium fuel cycles is discussed for one particular reactor we would like to comment on one other question, that of the power density for these systems. By comparing optimum burn-up for different power densities Beliaev and Bruneder [5] have shown that the maximum specific burn-up does not change appreciably with power density. When it is increased from 5 to 15 kW/litre the optimum burn-up decreases only by about 15%, this reduction being largely due to increased neutron absorption in Protactinium, which also lessens the overall conversion factor. On the engineering side, smaller pressure vessel costs are compensated by higher blower costs and decreased net electrical output [1]. From these studies it emerges that a power density around 10 kW/litre is a realistic figure bearing in mind that other factors such as the mechanical stability of the fuel element at high temperatures and its fabrication cost are likely to determine ultimately an appropriate power density.

THE THORIUM-URANIUM FUEL CYCLE

So far only some principle features of the Thorium-Uranium system have been mentioned and we shall now discuss in more detail the Thorium-Uranium fuel cycle proper. The importance of an optimisation of the fuel cycle lies in the fact that

for a high temperature graphite moderated reactor fuel costs contribute between one-third to one-fourth of the total electricity generating costs. Because of the complex balance between Uranium make-up costs, interest rates, fabrication and reprocessing costs it is not feasible to optimise on purely physical grounds as any statement like trying to achieve maximum burn-up or a high conversion ratio is oversimplified and may lead to a wrong answer. Furthermore, some of the main cost parameters, such as fabrication and reprocessing costs, are very uncertain at the present stage so that a survey ought to cover a wide range of costs. One also has to bear in mind that so decisive a value as the Uranium cost, although known at present, may change significantly in the future.

The whole subject is further complicated by the number of parameters to be varied even when reactor specifications like dimensions of core and reflector, design of fuel element, power density and temperatures are determined by other considerations. To name but a few: initial loading, composition of feed elements and which fraction of the core should be reloaded in which time interval are those which should be covered in a systemmatic survey.

As a first step in establishing principles which would lead to fuel cycles with minimum fuel costs under various conditions, earlier burn-up calculations by Brinkworth [1] could be used. They refer to a 1055 MW(t) reactor with a power density of 11.6 kW/litre.

Two different loading procedures, the complete core replacement and the continuous charge discharge have been studied. These two cases can be regarded as two extremes, the actual loading procedure being somewhere in between. It was assumed that reprocessing costs would be such that separation would be worthwhile and recycled fuel could be burnt. The analysis is based on the equilibrium or near equilibrium core compositions, as they determine mainly the fuel costs. Already after the first third of the reactor's life constant fuel costs are observed [1].

As mentioned above it is convenient to define a core composition by firstly the ratio of fertile to fissile atoms, the N-value and by secondly the ratio of moderator to fissile atoms, the S-value. For burn-up studies it is appropriate to use time averaged values, since the moderator ratio as well as the fertile to fissile atomic ratio increases with time (the conversion factor is less than one). In the case of continuous charge discharge the so defined N- and S-value can be regarded as the time average for one fuel element or as the core average which is independent of time. In this way every point in a S-N diagram represents one particular core composition (see Figs. 4 and 5). Reactors with the same Uranium loading lie on parallels to the N-axis and those with the same Thorium loading on straight lines through the origin.

In the plots, contours of constant fifa-value and conversion factor are drawn. Fifa is understood as the number of fissions per initially invested fissile atoms, whereas the conversion factor is being used as the ratio of average production to average destruction of fissile atoms. For a given S-value the running time of one loading and, therefore, fifa increases first by adding Thorium because of the increased conversion of fertile to fissile isotopes, but drops later since the gain in conversion is offset by the decrease in lifetime. When one keeps the N-value constant, a well moderated system (high S-value) will exhibit a large η-value but will yield less conversion because the effective Thorium cross-section is reduced and the Uranium cross-section increased. The curves for constant conversion need little explanation, points on straight lines through the origin have the same effective Thorium resonance integral and, as long as changes in the Uranium

cross-section and the thermal absorption cross-section of Thorium can be neglected, they also have the same conversion factor.

The maximum fifa values obtained are about 1.98 for continuous reloading and 1.12 for complete core replacement, and both procedures lead to N-values around 9 and S-values around 3,400. The fifa values quoted are high; one has, however, to remember that recycled fuel is burnt containing much U-233 which is a superior fuel to U-235. When comparing fifa values of the two reloading schemes for the same core composition a continuous charge discharge operation can almost double the specific burn-up.

In both cases the conversion factor achieved is about the same for equal S- and N-values. This could be expected as the conversion is not primarily dependent on running time but on the actual core composition. By using time averaged values the influence of different running times has been reduced still further. The effect of the control poison on neutron economy, especially on the conversion, however, is noticeable. As Blomstrand [6] has shown, and the same is confirmed by this analysis, the conversion factor is directly related to the initial reactivity so that small conversion factors are equivalent to high initial reactivities. In the case of a complete core replacement a conversion factor of 0.6 is equivalent to 20% excess reactivity initially which has to be taken away by absorption in control rods. This loss of neutrons is reflected in the plot. Lines of constant conversion factor lie, for larger initial reactivities, increasingly lower when complete core replacement is compared with continuous charge discharge. The conversion itself is not very high, the reason is presumably that recycled fuel, besides the advantage of consisting partly of U-233, has the disadvantage of considerable parasitic absorption in U-234 and U-236.

So far only the burn-up of various core compositions for two different loading procedures has been discussed. In order to establish areas of fuel cycle compositions which may lead to minimum fuel costs a very simplified cost evaluation has been attempted. It should be emphasised in this connection that this fuel costing is of a very preliminary nature and is only intended to indicate certain trends and to limit the range of parameters which could be varied. No opinion is being expressed on the feasibility of such cost parameters which are kept constant, nor of the probable value of those which are varied.

The fuel costs are calculated according to:-

$$K = \frac{\alpha}{LP} \left\{ P_u(\gamma U_i - U_f) + P_t (\gamma T_i - T_f) + P_f(U_i + T_i) + \gamma P_f' C + P_s(U_f + T_f) \right\}$$

$$\gamma = 1 + i\, L/l$$

whereby $U_{i,f}$ denote respectively the initial, final Uranium loading, $T_{i,f}$ the equivalent Thorium investment, C the weight of the core graphite, L the running time at full power, P the net electrical output and α a factor for unit conversion.

The following parameters are kept constant:-

Price of 93% enriched Uranium P_u	5,000 £/kg
Price of Thorium P_t	15 £/kg
Cost of core graphite (including fabrication) P_f'	1 £/kg
Interest Rate i	5.5%
Load factor l	75%
Efficiency (net electrical to total thermal)	40%

The fabrication costs P_f for the fuel and the separation costs P_s are varied as they constitute the most uncertain parameters at present. They are assumed to be proportional to the amount of heavy metal, that is Uranium and Thorium, as the use of coated particle fuel was envisaged. The graphite material and fabrication costs seem to be very small as the better retention capabilities of coated particles should facilitate the utilisation of cheap graphites. Hold up interests are neglected.

With the above formula fuel costs have been obtained and those compositions determined which led to minimum fuel costs when fabrication and reprocessing costs of the fuel were altered. The result is plotted in Figs. 4 and 5 as a thickly drawn curve. The arrow indicates increasing fabrication and reprocessing costs which were assumed to vary proportionally in the ratio three to four. In the case of a continuous charge discharge the curve starts at the minimum for no fabrication and reprocessing costs at all (point "A"), whereas such minimum could not be established for the complete core replacement as it is outside the range of reactors considered. Two further points are marked on these curves, "B" for 20 £/kg separation and 15 £/kg fabrication costs and "C" for costs ten times as high. The minimum fuel costs under these conditions are listed in the Table below:-

Case	Fabrication Costs £/kg	Separation Costs £/kg	Continuous Charge Discharge	Full Core Replacement
A	0	0	0.051	< 0.055
B	15	20	0.065	0.076
C	150	200	0.112	0.150

Minimum fuel costs (d/KWh) depending on production costs.

Before discussing these curves in detail it is worthwhile considering how the various cost factors are influenced by the physical parameters, the N- and S-value and the derived quantities, the conversion factor C and the fifa-value F. The Uranium make-up costs per KWh produced is found to be proportional only to (1-C), the complement of the conversion factor. The cost for interest on the invested Uranium is inversely proportional to the S-value (1/S). The fabrication

and reprocessing costs per KWh depend essentially on the Thorium loading and the running time, or on the ratio of the N-value to the fifa-value (N/F), as the Thorium is not markedly depleted during life.

With these simple rules one can now qualitatively explain the course of the minimum fuel cost curve. For fabrication and reprocessing costs in the order of 150 £/kg and above, these two items excel in importance all other cost factors. The curve, therefore, follows the lowest gradient of the (N/F) surface in the N-S diagram or approximately the ridge of the fifa surface, so reducing the N-value and at the same time gaining in fifa. As the curves for constant conversion factor run in this area nearly parallel to the ridge, minimum fuel costs are achieved as a balance only between fabrication and reprocessing costs on the one side and Uranium interest on the other. Higher production costs force the balance towards higher Uranium investment.

In the case of very low fuel production costs, the Uranium investment and necessary make-up are the dominant factors. It is, however, necessary at least to consider the cost of the core graphite; otherwise no cost factor dependent on running time is involved and a core composition with very heavy Thorium loading and consequently negligible lifetime would result.

To keep the cost of Uranium low a high conversion factor for reducing the make-up fraction and a high S-value for decreasing the inventory charges are desirable. This, however, is not compatible with the demand for long running times, as can indirectly be seen from the diagrams: the life of one core loading can be expressed somewhat artificially as being proportional to the ratio of the fifa- to the S-value (F/S). In the case of negligible fuel production costs the wish for long running times does not carry much weight. Therefore, points A and B are situated in an area which exhibits high S-values and high conversion factors and takes only little notice of a low fifa.

When one compares the minimum fuel cost curves of the two recharge procedures one finds lower S- and N-values for the complete core replacement than for the continuous one, equal specific fuel production costs presumed. The change in the N- and S-value is mainly brought about by an increase in the Uranium loading. This can be understood when one realises that a complete core replacement puts more emphasis on fuel production costs which depend on the ratio (N/F) than on interest charges being proportional to (1/S), so that lower N- and higher fifa-values are favoured. The make-up costs do not change significantly in the two cases as the conversion factor remains about the same.

Finally, Fig. 6 shows in more detail the dependence of minimum fuel costs with the specific fabrication costs of fuel. Here the separation costs are fixed at 200 £/kg. The fraction of fabrication costs on the total fuel costs is higher in the case of a complete core replacement and, therefore, the slope of its fuel cost curve steeper. The difference is about 30%, being somewhat smaller for lower specific fabrication costs (< 150 £/kg).

SUMMARY

As a first step in establishing Thorium-Uranium fuel cycle compositions which would lead to low electricity generating costs the physical behaviour of various equilibrium compositions of recycled fuel and their respective merits concerning fuel costs are discussed. To, somewhat extreme, reloading procedures,

the complete core replacement and the continuous exchange of fuel elements, are compared as it is felt that any technically feasible reloading procedure would be easier to determine once limits of what one can achieve with these systems are known. Furthermore, the present uncertainty in the specific production costs outweighs the differences in core composition which can possibly be encountered between a partially reloaded core and a continuous or completely reloaded one. It is, therefore, desirable that production costs should be specified more accurately as they add considerably to the uncertainty of present fuel cost estimates. It also would facilitate the task of an optimisation on such a broad basis and enable further more detailed studies on more realistic partial reloading procedures.

The analysis shows that fifa-values between 1.12 for complete core replacement and 1.98 for continuous charge discharge can be reached for core compositions with a moderator ratio of $S \approx 3{,}400$ and a fertile to fissile atomic ratio of $N \approx 9$. More interesting is the fact that over a wide range of fabrication and separation costs core composition with an S-value between 3,500 and 5,000 and an N-value between 10 and 15 are the most promising ones. Low production costs are related to high N-values.

The transition from one loading scheme to the other is mainly brought about by a change in the Uranium investment, so that the smaller the parts of the core being recharged the higher the S- and N-values. Fuel costs can be reduced by about 30% when one goes from a complete core replacement to a continuous one, as compared with an increase from 0.07 d/KWh to 0.13 d/KWh, when production costs increase from 35 £/kg to 350 £/kg of heavy metal (fabrication and separation).

5. ACKNOWLEDGMENTS

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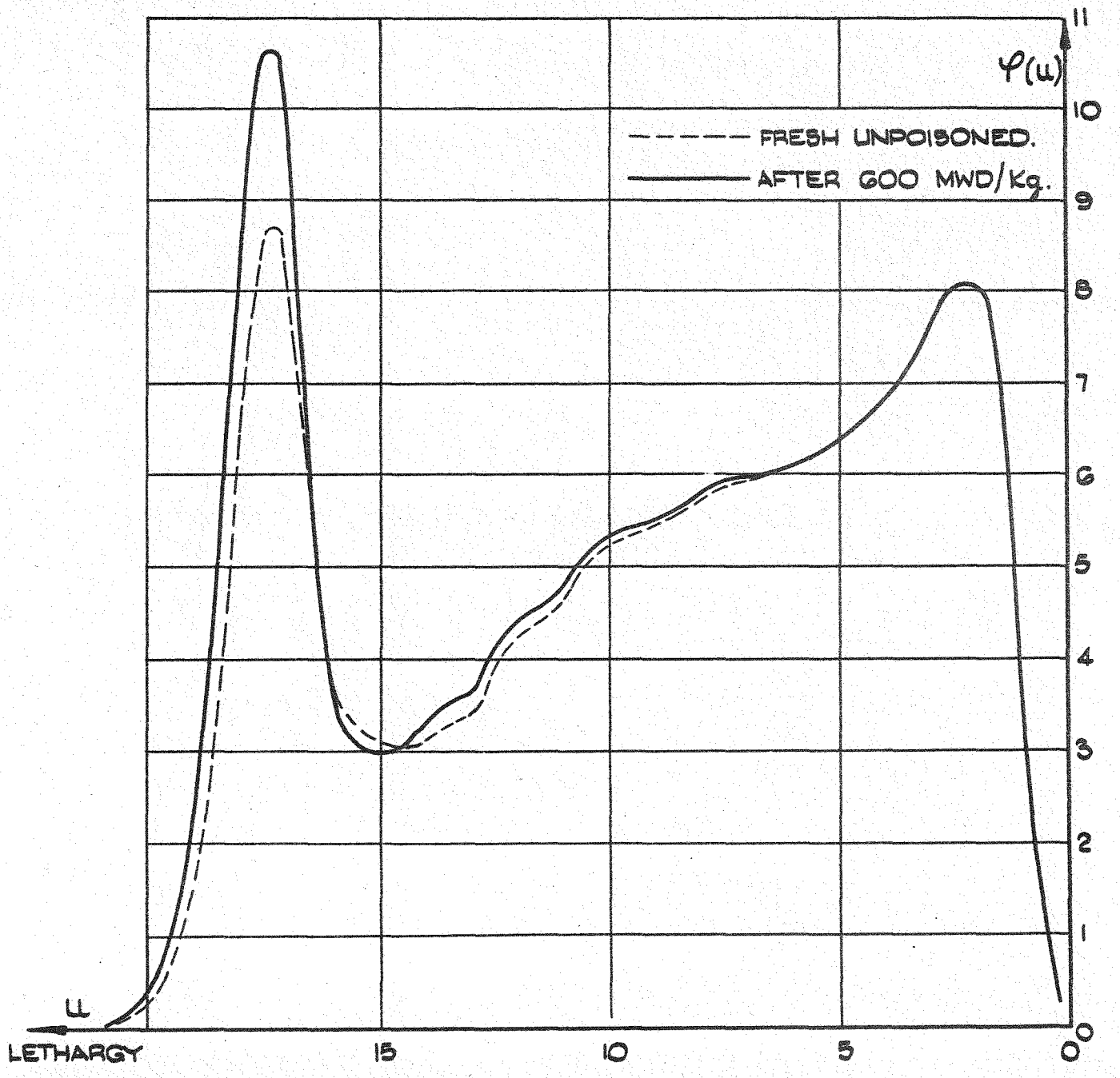

FIG. 1 NEUTRON SPECTRUM AT BEGINNING & END OF LIFE.

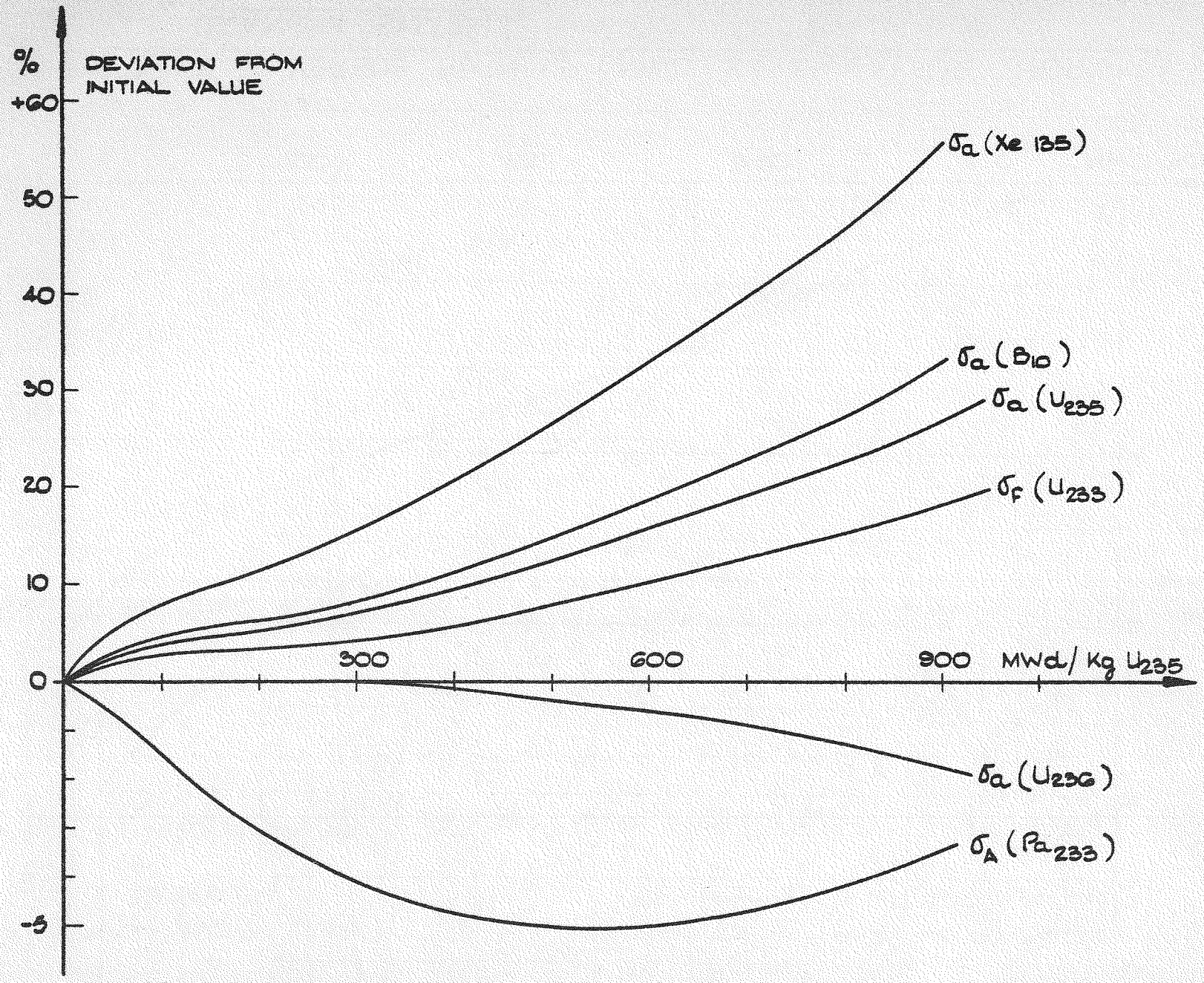

FIG. 2 THE RELATIVE CHANGE OF EFFECTIVE CROSS-SECTIONS WITH IRRADIATION.

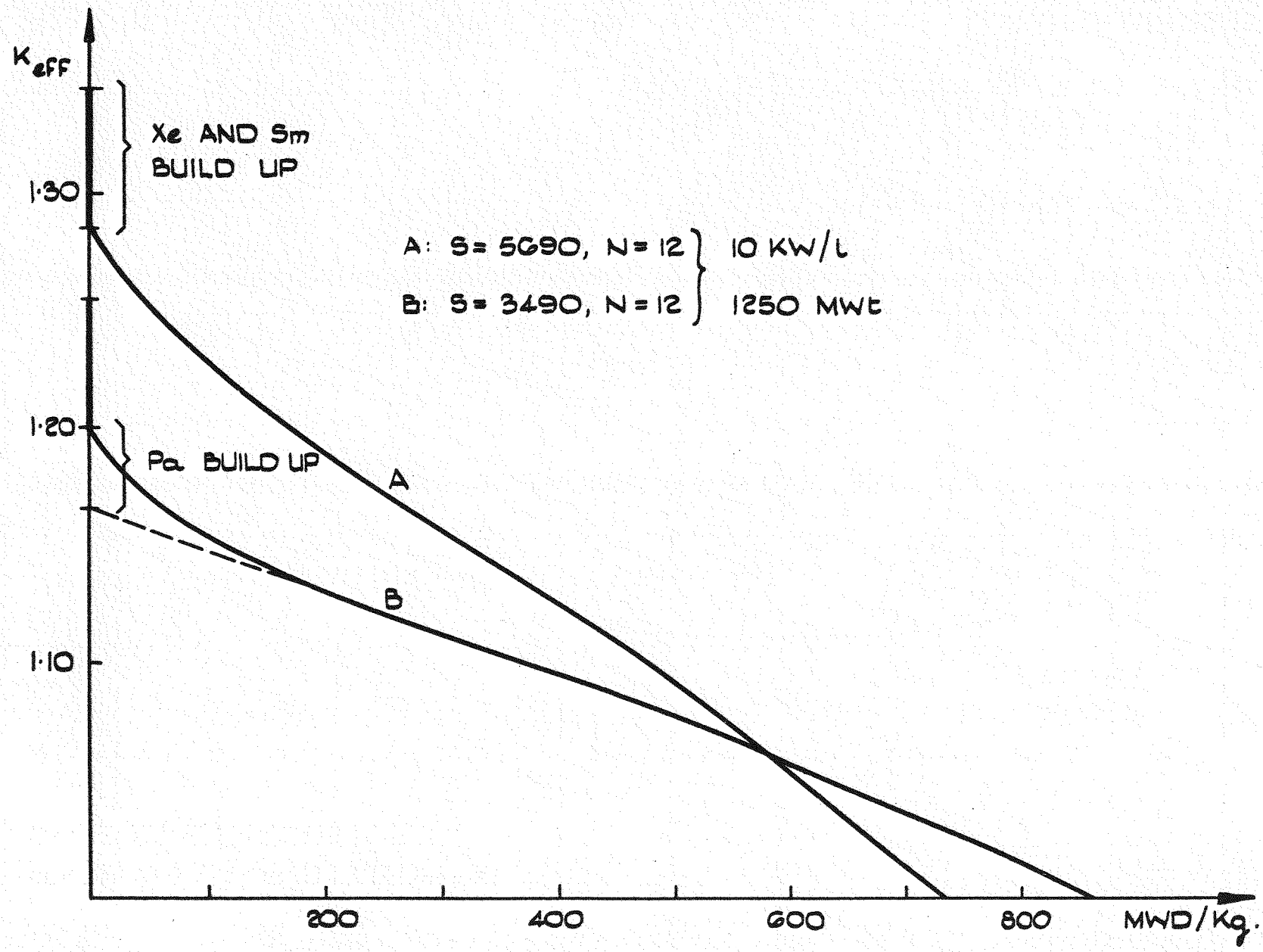

FIG. 3 K_{eff} VERSUS BURN UP (MWD / Kg U_{235}) FOR THORIUM URANIUM SYSTEMS.

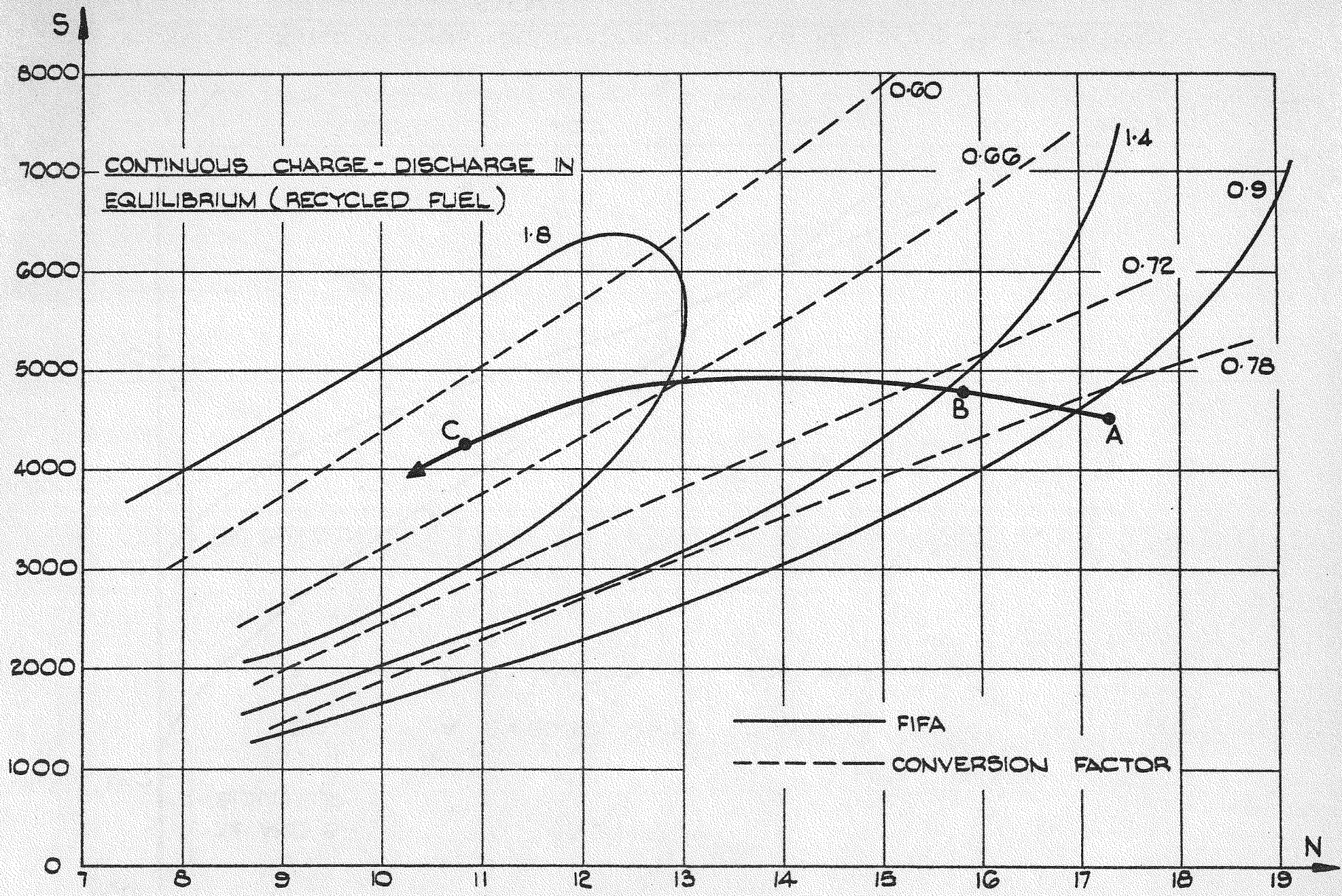

FIG. 4 FIFA VALUE AND CONVERSION FACTOR VERSUS CORE COMPOSITION.

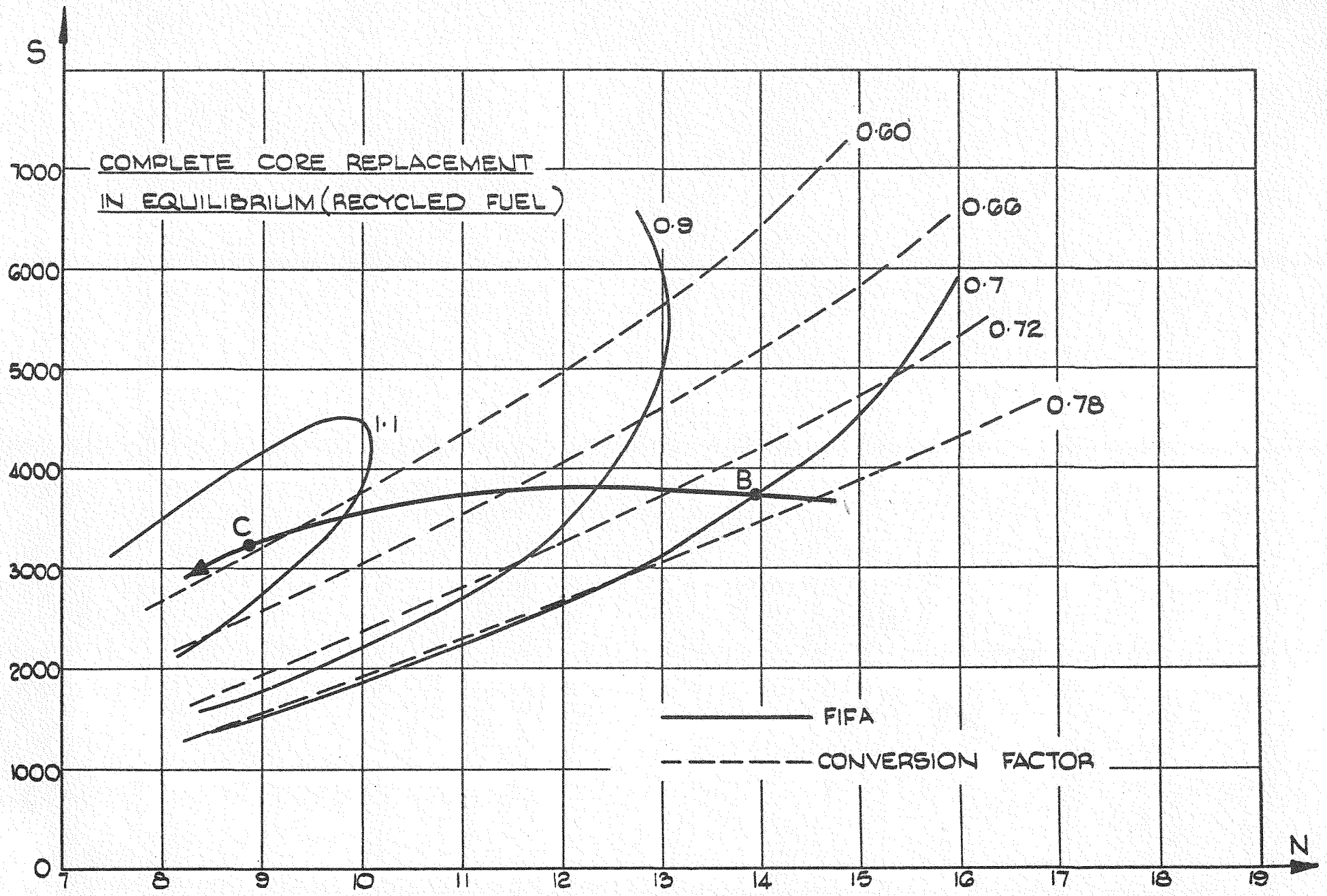

FIG.5 FIFA VALUE AND CONVERSION FACTOR VERSUS CORE COMPOSITION.

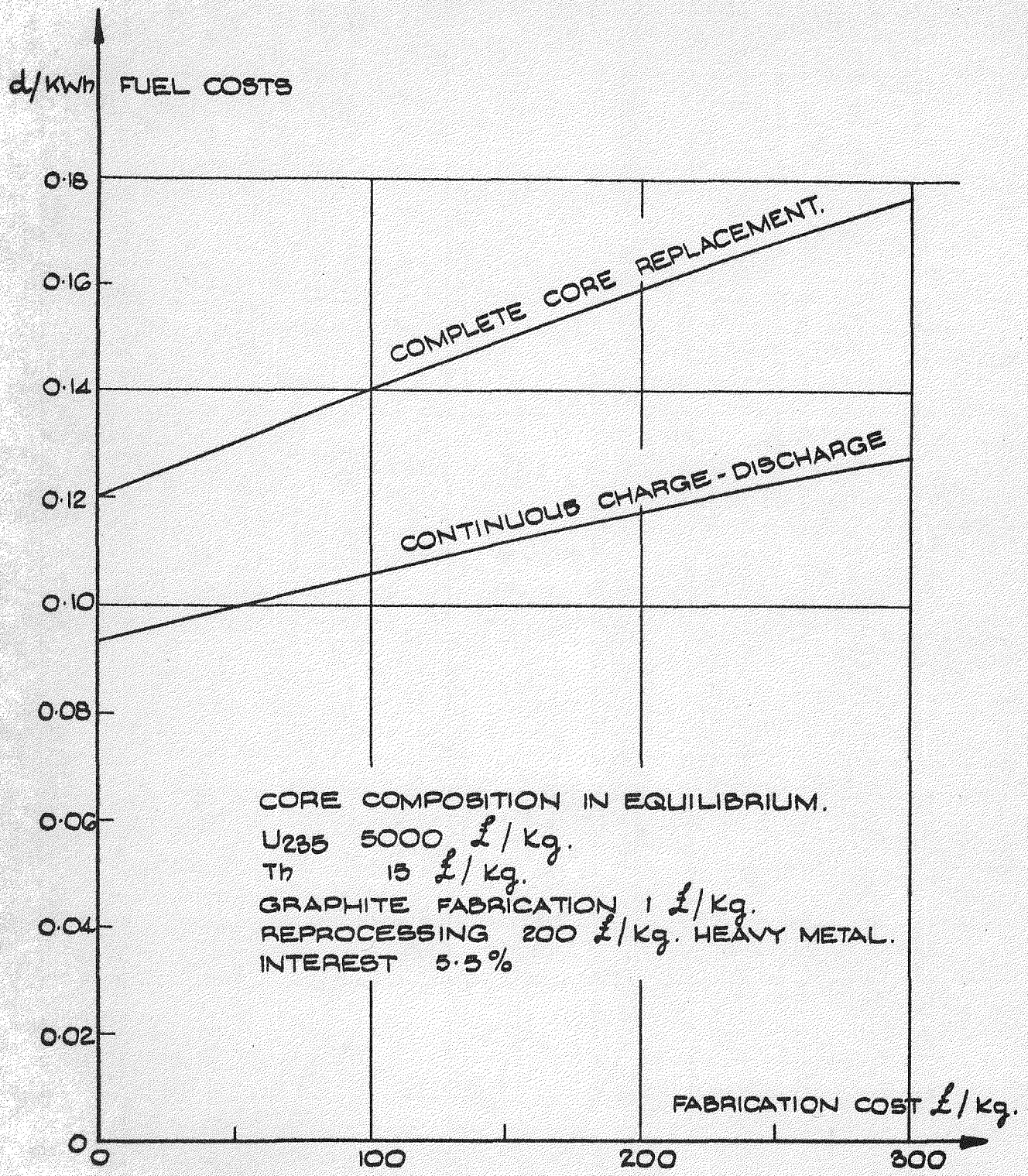

FIG.6 FUEL COSTS VERSUS FABRICATION COSTS (£/Kg HEAVY METAL)