STUDIES ON EQUILIBRIUM FUEL MANAGEMENT SCHEMES ON THE DRAGON HTR CORE DESIGN

by

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(3 February 1971)

1. INTRODUCTION

The Dragon Project has recently started investigations on fuel management in HTR's with the assumed Dragon design [1]. A genuine fuel management study must necessarily include the full running-in to equilibrium and the equilibrium fuel management itself by the use of multi-dimensional burnup codes. Such a study is very costly, especially if it involves variation of the many parameters, which have an influence on the core burnup behaviour and power generating costs. In order to reduce the number of detailed studies and to concentrate the effort to fuel management schemes with the greatest prospect potential, we have investigated a number of equilibrium fuel management schemes with the 1-dimensional FLATTER code [2] and calculated the corresponding total power generating costs with the programme TECO.

The main aim with the FLATTER calculations has been to investigate different methods for flattening the radial power distribution, especially for removing the power peak which occurs near the core/reflector interface due to the spectrum softening effect of the reflector.

Although this study was not intended to be an optimisation of the many parameters, we believe that some promising schemes have been found, that are worthwhile investigating with the more detailed methods.

2. PHYSICAL MODELS

The use of FLATTER for these studies involves the adoption of a reactor model in which the core and the radial reflector are subdivided into annular zones. Spectrum and burnup calculations are performed in each core zone taking the proper zone averaged bucklings and fluxes into account. The power distribution is calculated with 6 group diffusion theory assuming that the composition in each core zone is an average smear of fuel of all ages. A point on the power distribution curve thus represents the power production at that radius in an element which has been "average burnt". Due to the nuclide variations during burn up we must multiply this power with a factor, called the agefactor, in order to obtain the maximum power of an element at that radius during its irradiation time.

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The agefactors used in this study have been obtained with the simple "parabolic fit" approach which assumes that the power production of fuel varies as a polynomium of the second degree in the irradiation time, the parameters of the polynomium being determined from the power values at start of life, at end of life and from the time-averaged power production. Check calculations taking into account the exact power variation as a function of time have shown that this simplification tends to underestimate the agefactors by about 5%.

Some of the investigated fuel management schemes have involved a search for the core composition which gives the best possible radial power distribution. In these cases the search has been made in such a way as to flatten the power x agefactor curve because this will tend to give a fuel element at its maximum power producing point in time the same power all over the core.

In the radial FLATTER calculations we have used results from the codes SIGPE (effective potential scatter cross sections), DISA (transport programme, gives disadvantage factors in the fuel cell for average burnt fuel) and FLATTER (axial calculation used to generate axial bucklings).

3. COST ASSUMPTIONS

The assumptions made in the evaluation of the fuel cycle costs are given in Table 1.

Table 1

Cost Assumptions

Interest rate	10%	p.a.
Plant lifetime	25	years
Load factor	0.75	
Uranium ore cost	8	$ /lb
U_3O_8 - UF_6	2.67	$ /lb
Separative work costs	30	$ /SWU
Tail enrichment in diffusion process	0.20%	
Transport for fresh fuel	2.90	$ /kg HM
Transport for spent fuel	8	$ /kg HM
Reprocessing cost	100	$ /kg HM
Pu value	10	$ /g fissile plutonium
Devaluation factor used for value of discharge U	0.80	
Reprocessing losses	2%	
Cooling time for discharged fuel	1	year

4. FUEL MANAGEMENT SCHEMES

In this chapter we will briefly describe each of the investigated equilibrium fuel management schemes and give the main results of each scheme.

4(a) 2-zone Enrichment Flattening. $R_1/R_2 = 0.8$

This is the "standard case" against which all other schemes are compared. In this scheme we have tried to flatten the radial power distribution by dividing the core into two radial zones, the dividing radius being 0.8 times the full core radius and giving zone 1 and 2 different feed enrichments. The difference between the enrichments in zone 1 and 2 was adjusted until the maximum of power x agefactor is the same in zone 1 and 2. The fuel burnup is kept constant in the whole core = 60 GWD/t, which means that the residence time varies inversely proportional to the local power. Fig 1 shows the obtained power distribution, which is greatly influenced by the reflector effect giving a high power peak in the fresh fuel near the reflector. The main results from this case are:

Feed enrichment, zone 1	5.32%
Feed enrichment, zone 2	5.93%
Feed enrichment, average	5.54%
Formfactor	1.18
Formfactor x agefactor	1.28
Total generating costs	4.423 mills/kWh

4(b) 2-zone Enrichment Flattening, varying R_1/R_2

In order to see the influence of the separating radius, we made calculations using the values R_1/R_2 = 0.7 and 0.9 with the following results:

R_1/R_2	0.7	0.9
Feed enrichment, zone 1	5.24%	5.39%
Feed enrichment, zone 2	5.79%	6.15%
Feed enrichment, average	5.52%	5.53%
Formfactor	1.14	1.23
Formfactor x agefactor	1.24	1.34
Total generating costs	4.419	4.424 mills/kWh

The average feed enrichment is the same as in case 4(a) within the accuracy of the calculation, but we see that the difference in enrichment between zone 1 and 2 goes down when the separating radius is made smaller, because now a bigger part of the core with the higher enrichment is helping to increase power in the outer part of the core. This fact reduces the effect of the soft spectrum near the reflector, so that a lower formfactor and product formfactor x agefactor can be obtained. (See Fig 2). The better formfactor for $R_1/R_2 = 0.7$ can be utilised to get a more uniform flowpattern over the reactor core, and therefore a lower pumping power and better overall plant efficiency. This is the reason for the lower total generating costs.

4(c) 3-zone Enrichment Flattening

A means to reduce the power peak near the reflector is to introduce an extra enrichment for the fuel pins which have the reflector as a neighbour. Fig 3 shows the results from such a scheme. The low enrichment fuel pins are simulated with a 9 cm wide annular zone next to the reflector. These pins have in the calculation been given the same residence time as fuel in zone 2 and have therefore a somewhat lower burnup than the 60 GWD/t. R_1/R_3 was kept at 0.8.

The results are:

Feed enrichment, zone 1	5.25%
Feed enrichment, zone 2	6.23%
Feed enrichment, zone 3	5.10%
Feed enrichment, average	5.54%
Formfactor	1.13
Formfactor x agefactor	1.23
Total generating costs	4.437 mills/kWh

The average enrichment is again the same as in case 4(a).

The introduction of the third enrichment has improved the formfactor by 5%, but we see, that the extra costs by having three different enrichments in the fabrication process and many extra types of fuel blocks are so high, that the total generating costs increase with this scheme, which also from a practical point of view (book-keeping of many block types) seems rather unrealistic.

4(d) Different Schemes Reducing Reflector Effectiveness

One might think that the power peak near the reflector occurs because the reflector is too good, and that we can reduce it by reducing the reflector effectiveness with some means or another. We have reduced the reflector effect in two ways: the first was simply to reduce the reflector thickness from 95 cm to 60 cm and the second was to introduce iron poisoning in a 9 cm annular reflector zone surrounding the core in order to let the reflector work as usual for fast neutrons and only use the iron as a neutron trap for thermal neutrons returning from the reflector. The iron was assumed to be smeared in this zone with an atomic density = $9.6\ 10^{-4}$ at/(cm barn).

The results are:

Case	Fe poisoning	60 cm reflector
Feed enrichment, zone 1	5.27%	5.26%
Feed enrichment, zone 2	6.97%	6.81%
Feed enrichment, average	5.88%	5.82%
Formfactor	1.13	1.14
Formfactor x agefactor	1.22	1.23
Total generating costs	4.483	4.471

Both schemes give the desired improvement in formfactors, but the average feed enrichment has in both cases to be increased so much that economics make them unrealistic.

4(e) <u>2-zone Burnup Flattening</u>

In this scheme, we keep the feed enrichment constant over the whole core and vary the burnup in the core so as to produce power flattening. The core is again divided into two zones with $R_1/R_2 = 0.8$, the fuel in zone 1 is allowed to have a higher maximum burnup than in zone 2 thus raising the power in the outer zone. The following results were obtained:

Feed enrichment	5.67%
Burnup, zone 1	64.5 GWD/t
Burnup, zone 2	55.4 GWD/t
Burnup, average	61.2 GWD/t
Formfactor	1.14
Formfactor x agefactor	1.26
Total generating costs	4.414 mills/kWh

Compared with case 4(a), this scheme has the advantage of only using one enrichment. Agefactors in zone 2 are lower due to lower feed enrichment and lower burnup, thus producing a better formfactor x agefactor. These advantages yield lower total generating costs than can be obtained with enrichment zoning.

4(f) <u>2 zone Enrichment Flattening using a Lower Heavy Metal Density in the Outer Core Zone</u>

The difficulties with the power peak at the core edge results from a mismatch between the hard core spectrum and the soft reflector spectrum. A way of reducing the mismatch is to use a lower heavy metal loading in the outer core zone thus softening the spectrum in that zone. The resulting power distribution for such a case is shown in Fig 4, and the other main results are as follows:

Heavy metal density in fuel, zone 1 (g/cm^3)	0.8	0.8
Heavy metal density in fuel, zone 2 (g/cm^3)	0.72	0.64
Feed enrichment, zone 1 (%)	5.23	5.17
Feed enrichment, zone 2 (%)	5.80	5.70
Feed enrichment, average (%)	5.42	5.33
Formfactor	1.15	1.13
Formfactor x agefactor	1.26	1.24
Total generating costs (mills/kWh)	4.407	4.405

With this scheme we obtain a considerable reduction in the unwanted peak, both in size and steepness, and therefore also better formfactors. Due to the softer, overall spectrum we also obtain a lower average feed enrichment without the corresponding increase in agefactor which results if the core as a whole was given a lower heavy metal loading. All these advantages improve the total generating costs.

4(g) 2 zone Enrichment Flattening with Low Heavy Metal Density in Zone 2 and Natural Uranium in the Reflector.

As an extra improvement to scheme 4(f) we have tried to further reduce the power peak in zone 2 by introducing a blanket consisting of a ring of fuel pins with natural uranium in the removable reflector columns. The blanket will act as a trap for thermal neutrons returning to the core from the reflector, but compared with the iron poisoning scheme 4(d), the blanket will improve the overall neutron economy by producing fission neutrons, and it will also contribute to the power production. It is assumed that the removable reflector columns remain in the reactor until the maximum burnup 60 GWD/t is reached in the natural uranium blanket. The obtained power distribution is shown in Fig 5, and other results are:

Heavy metal density, zone 1	0.8 g/cm^3	
Heavy metal density, zone 2	0.64 g/cm^3	
Heavy metal density, zone 3 (Nat.U)	0.8 g/cm^3	
Feed enrichment, zone 1	5.11%	
Feed enrichment, zone 2	6.37%	
Feed enrichment, average (zone 1 + 2)	5.52%	
Formfactor (zone 1 + 2)	1.08	
Formfactor x agefactor (zone 1 + 2)	1.18	
Total generating costs	4.42	mills/kWh

This scheme gives a very nice power distribution and the lowest formfactors of all investigated schemes. However, compared with scheme 4(f) this scheme requires higher feed enrichment in the core, and the extra complications are therefore hardly justified.

4(h) Burnup Self flattening with Low Heavy Metal Density in the Outer Core Region

In this scheme we have combined the advantages of burnup flattening 4(e) and the use of low heavy metal density near the reflector 4(f). Here we have chosen to use the natural self-flattening of power which will be obtained, if all fuel is given the same residence time. The feed enrichment is kept constant over the whole core.

The power distribution is shown in Fig 6. Other results are:

Feed enrichment	5.39%
Formfactor	1.11
Formfactor x agefactor	1.22
Total generating costs	4.399 mills/kWh

This scheme, with very simple methods gives a good power distribution and has the further advantage of a rather low feed enrichment due to the overall softer spectrum. Therefore low costs.

5. CONCLUSIONS

In looking for the "best" fuel management scheme, one could be tempted to chose the one which simply gives the lowest total generating costs. This study has, however, shown that the differences in costs between different schemes are very small. Moreover, the differences are rather uncertain and depend to a large extent on special assumptions made for each type of fuel management scheme.

It seems therefore natural not only to keep an eye on the economics but also to take into account factors like inherent safety and overall simplicity. These factors only make a small impact on the results in our simplified economic models, but they will probably have a large influence on the rate of failures and accidents by fuel handling, and therefore also on the economics, of the real reactor.

In this fuel management study one of our main concerns has been to get rid of the power peak at the core edge. In the simple 1-dimensional model, the peak was allowed to have the same height as the power maximum in the core centre. In practice we would have to apply a safety factor to the peak in order to take into account the uncertainty of the calculated peak height due to calculational errors and the irregular shape of the core edge in the real design.

This problem leads us to prefer fuel management schemes which have a natural tendency to lower the peak at the core edge, and one of the main results of this study has been to show that a simple and effective way of lowering the peak (without spoiling the formfactors) is to use a lower heavy metal loading in the parts of the core near the reflector.

This effect can be utilised in different fuel management schemes for power flattening, such as 2-zone enrichment flattening or the burnup self-flattening scheme. It is interesting to note that the latter, very simple scheme, gives nearly the same results as the best optimisation based on enrichment flattening.

REFERENCES

[1] J Daub: "A Homogeneous HTR Core Design with Hexagonal Blocks and Teledial Fuel Pins", DPTN/65, September 1970

[2] J Pedersen: "Power Distributions in an HTR", DPID/240, May 1970

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FORMFACTOR = 1.18

FORMFACTOR × AGEFACTOR = 1.28

FEED ENRICHMENT	(%)	5.32	5.93
AGEFACTOR		1.09	1.22
POWER DENSITY	(MW/m^3)	8.70	7.56
BURNUP	(GWD/T)	60	60
ρ_{HM}	(g/cc)	0.8	0.8

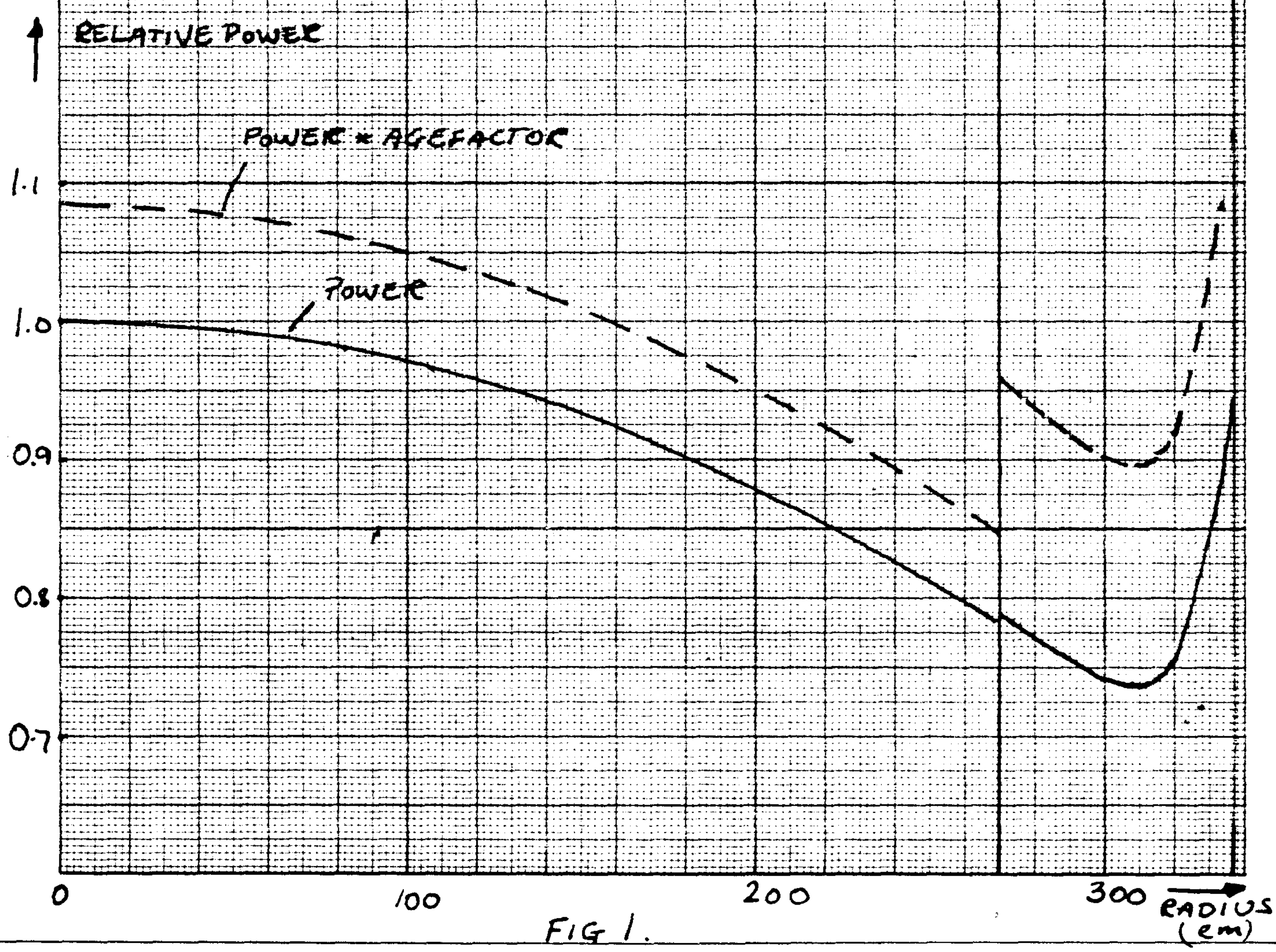

FIG 1.

2-ZONE ENRICHMENT FLATTENING, $R_1/R_2 = 0.8$

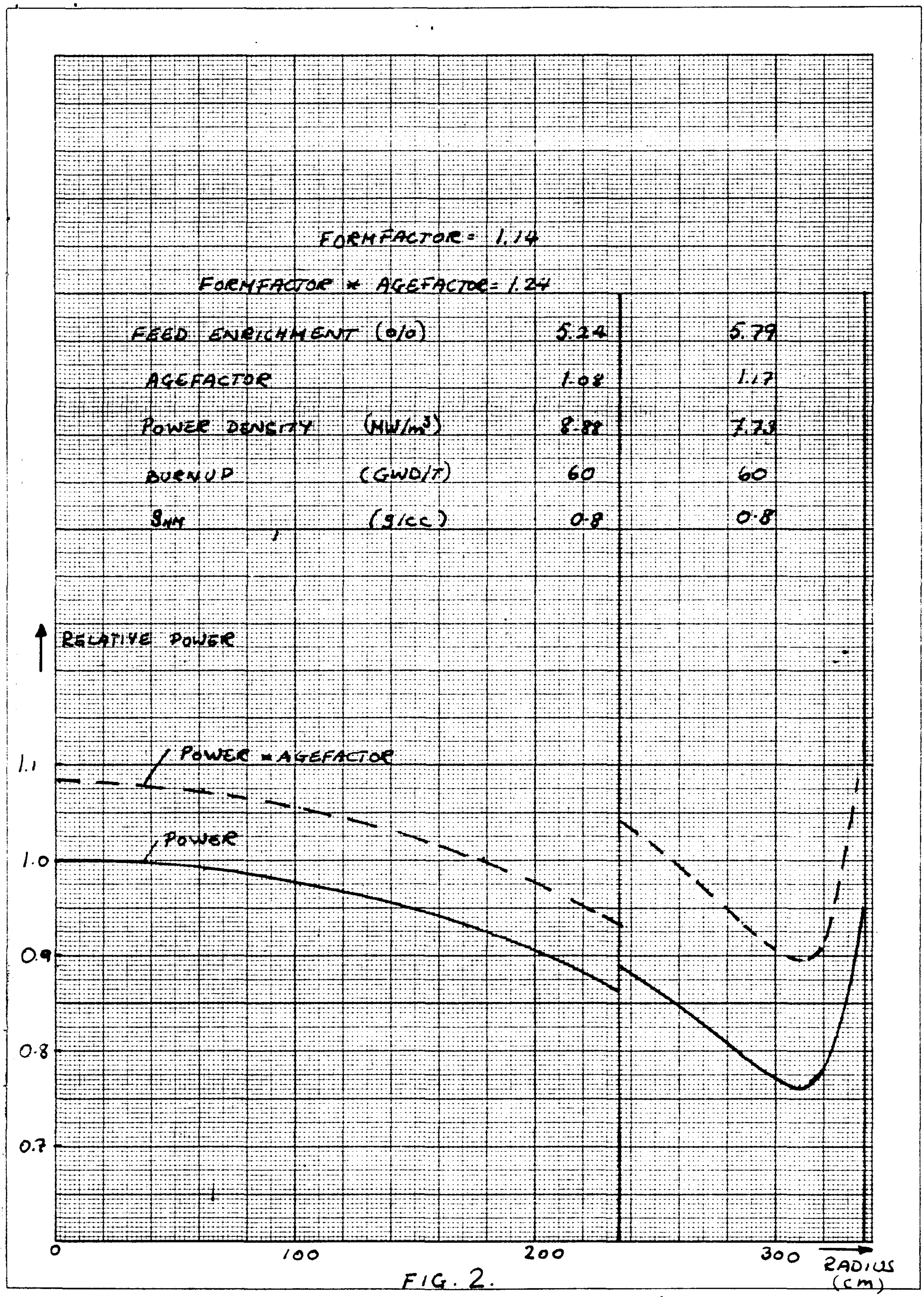

FIG. 2.

2-ZONE ENRICHMENT FLATTENING, $R_1/R_2 = 0.7$

FORMFACTOR = 1.13

FORMFACTOR × AGEFACTOR = 1.23

FEED ENRICHMENT	(%)	5.25	6.23	5.10
AGEFACTOR		1.08	1.17	1.37
POWERDENSITY	(MW/m^3)	8.53	8.01	6.95
BURNUP	(GWD/T)	60	60	52.1
ρ_{HM}	(g/cc)	0.8	0.8	0.8

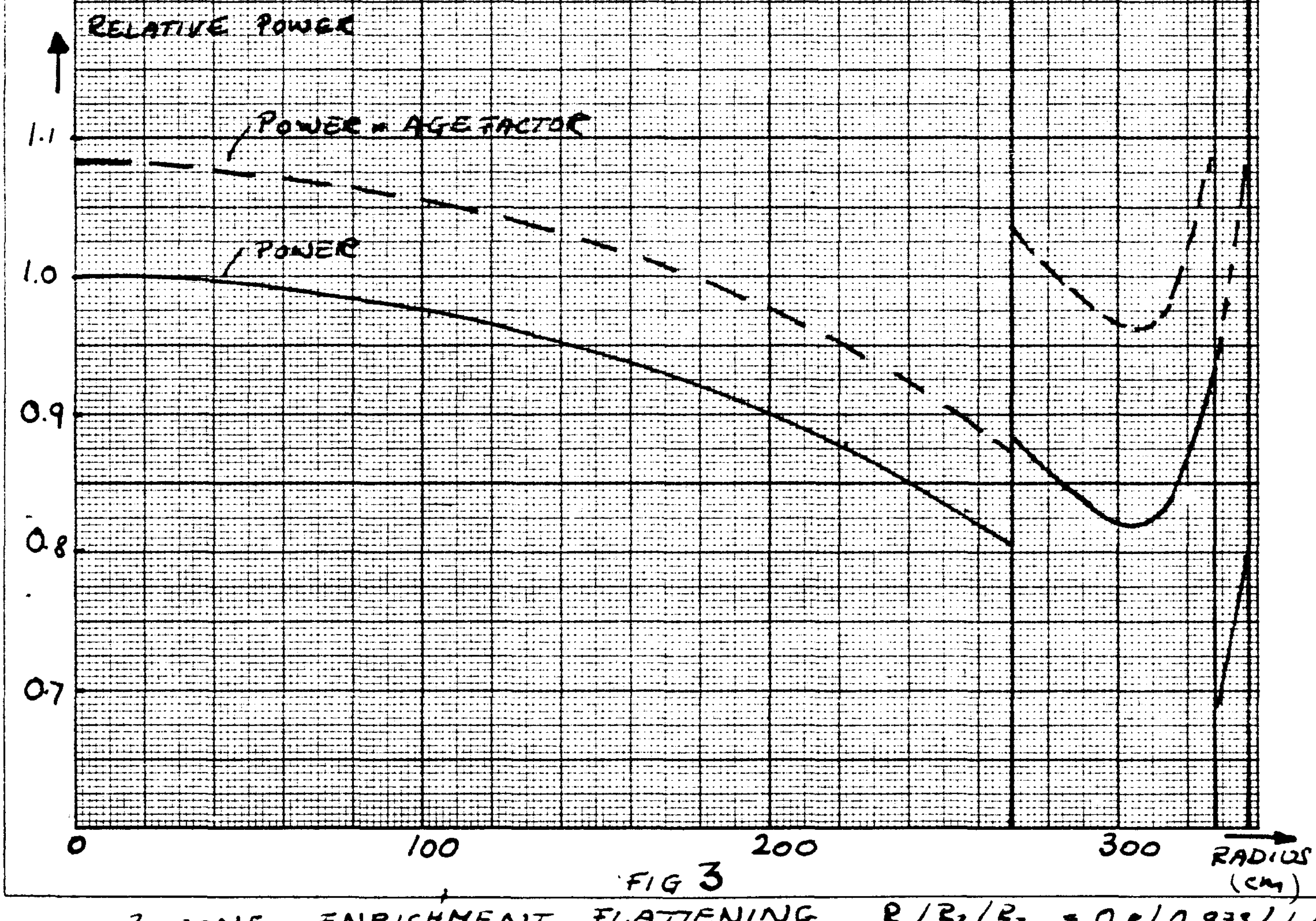

FIG 3

3-ZONE ENRICHMENT FLATTENING, $R_1/R_2/R_3$ = 0.8/0.975/1.00

FORMFACTOR = 1.13

FORMFACTOR * AGEFACTOR = 1.24

FEED ENRICHMENT (o/o)		5.17	5.70
AGEFACTOR		1.10	1.30
POWER DENSITY	(MW/m³)	8.88	7.23
BURNUP	(GWD/T)	60	60
ρ_{HM}	(g/cc)	0.8	0.64

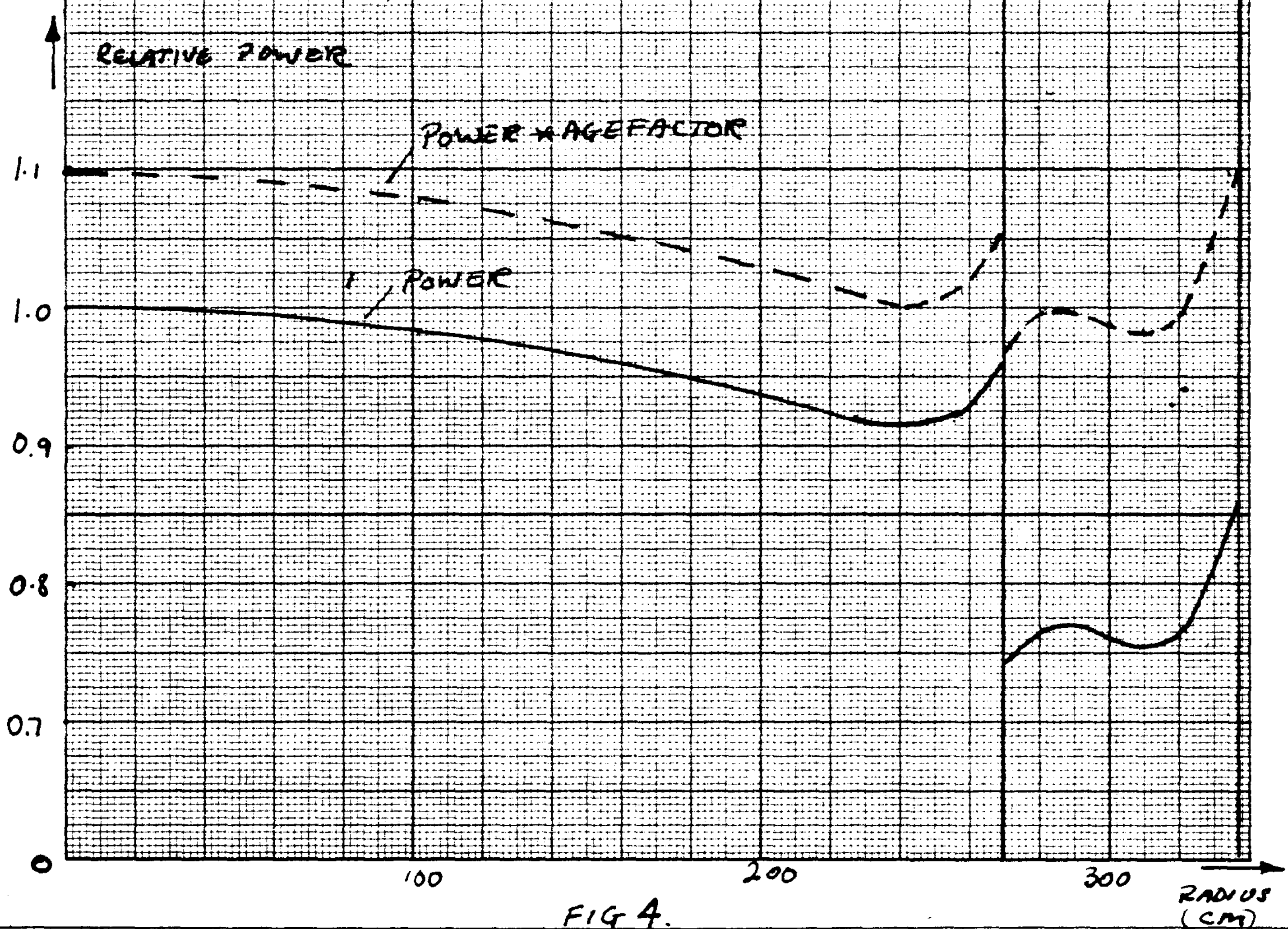

FIG 4.

2-ZONE ENRICHMENT FLATTENING WITH LOW HEAVY METAL DENSITY IN ZONE 2. $R_1/R_2 = 0.8$

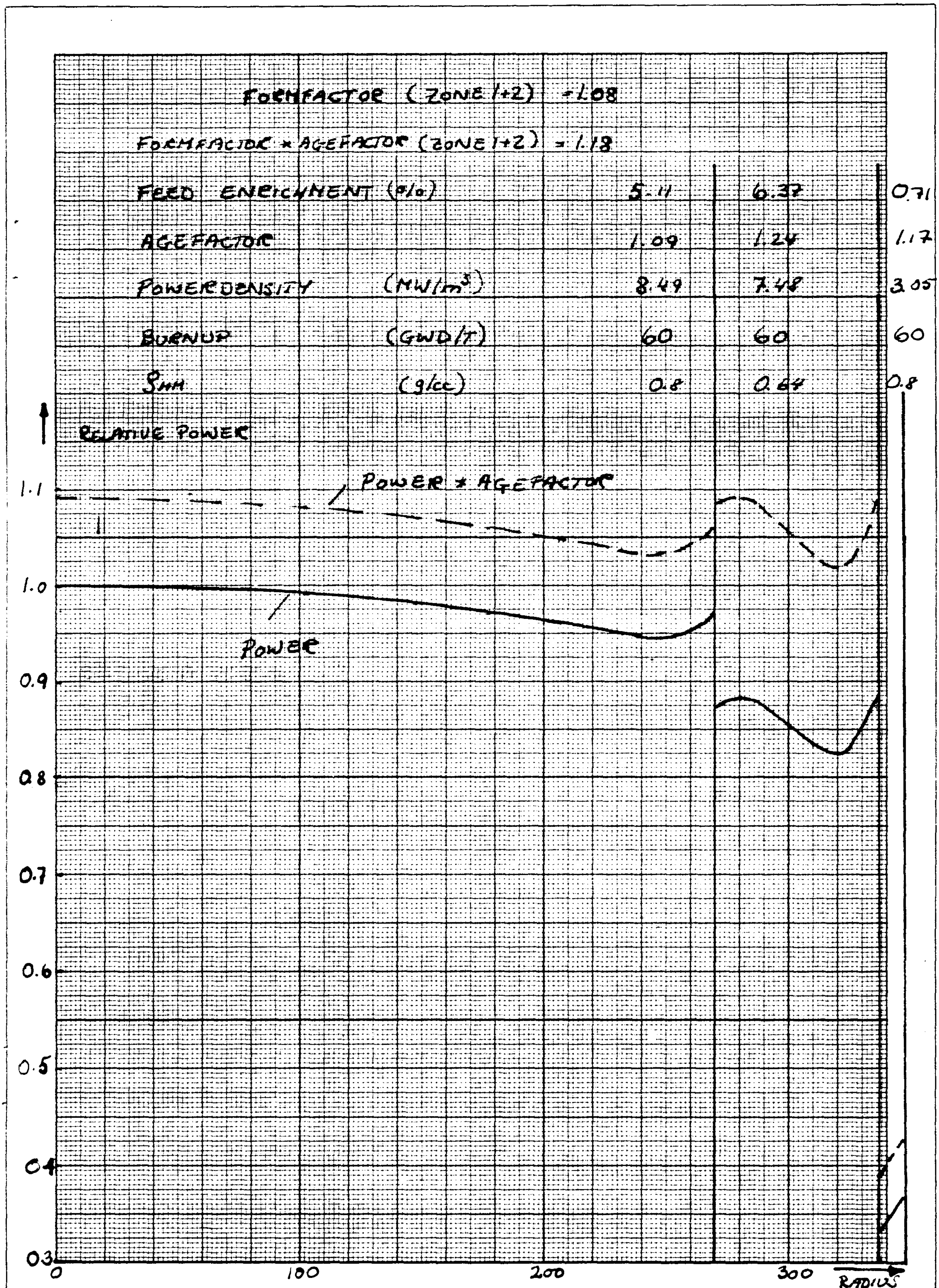

FIG 5.

2-ZONE ENRICHMENT FLATTENING, NATURAL URANIUM FUEL IN 9cm ANNULUS OF REFLECTOR, LOW HEAVY METAL DENSITY IN ZONE 2.

FORMFACTOR = 1.11
FORMFACTOR * AGEFACTOR = 1.22

FEED ENRICHMENT (%)	5.39	5.39	5.39	5.39
AGEFACTOR	1.10	1.10	1.14	1.25
POWER DENSITY (MW/m^3)	9.17	9.00	8.10	7.38
BURNUP (GWd/T)	63.1	61.7	61.8	56.4
S_{HM} (g/cc)	0.8	0.8	0.72	0.72

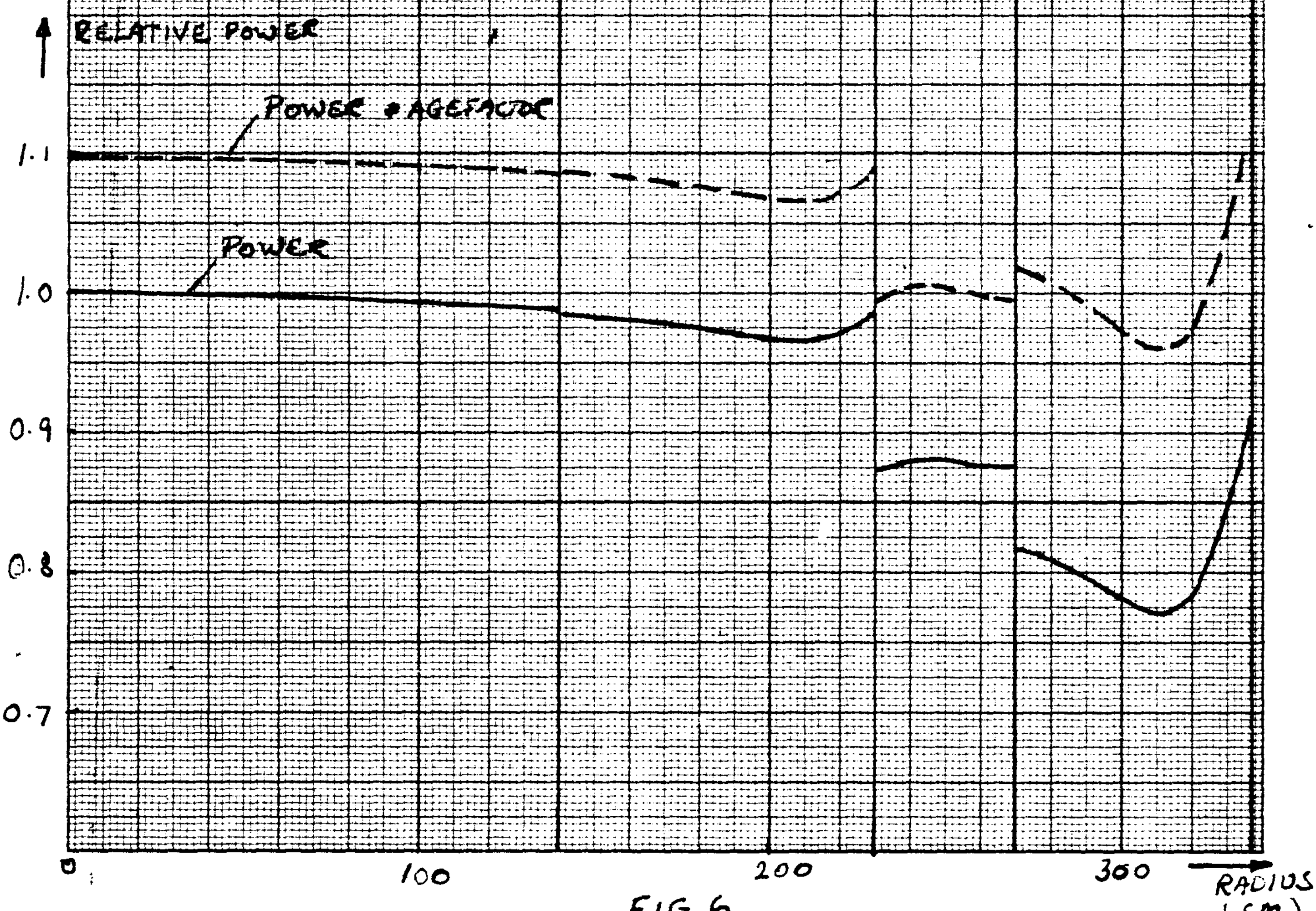

FIG 6.

CONSTANT RESIDENCE TIME = 628 DAYS, SELFFLATTENING LOW HEAVY METAL DENSITY IN ZONES 3 AND 4