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Studies of Low Enrichment Targets for ISIS

T.D. Beynon, D.J. Picton and T. Al-Sharify

Department of Physics, University of Birmingham,
Birmingham B15 2TT, England.

ABSTRACT

The paper concentrates on design options for a replacement to the current depleted uranium target on ISIS. The two options under consideration were the use of a variable enrichment to flatten power production, and a change in the shape of the target from a circular to a rectangular cross section.

The results for variably enriched targets must be judged by the available benefits to moderators, rather than overall gains in neutron production. "Flattening" power production by the use of axial enrichment variation would mainly benefit the "downstream" moderators possibly by a factor of two. In contrast, the use of a radially varying enrichment would enchance the performance of all moderators. It is clear that a combination of the two would be a desirable option.

The results for a target with a rectangular cross section were encouraging, in that substantial gains could be achieved at a far lower enrichment.

1. INTRODUCTION

Two basic options for enhancing the ISIS target station are currently under investigation. The present depleted uranium target could be replaced by an enriched target. The replacement target-moderator-reflector configuration would, in practice, be subject to a number of constraints; for example, the size and shape of the target pressure vessel could not be changed. The second option would involve the construction of a completely new target station, for which the conceptual design restrictions would of course be less severe.

This paper concentrates on design options relevant to the replacement of the existing target with an enriched uranium target of similar dimensions. As the title suggests, the concept of a highly enriched 'superbooster' within the available space is not realistic; a replacement target would have to have a relatively low average enrichment, and a peak power density of the same order of magnitude as the current target.

The three design options explored in this paper are: variable enrichment along the axis of the target cyclinder, radially varying enrichment, and a change in target geometry from the present cylinder of radius 4.5 cm to a slab-like target with a rectangular cross section (10x20 cm).

A variable enrichment is suggested because a flattening of power production would allow a target to produce a better neutron production within the constraint of a maximum peak fuel temperature. The use of a modified target shape, enlarged in one direction (without increasing the distance from the moderator to the centre of the proton beam) has a number of obvious advantages for any enriched target. In particular, the degree of enrichment required can be considerably reduced, and (as will be demonstrated later) uniform flattening of power generation over the whole target would be far easier to achieve.

Section 2 presents results for a cylindrical target with axially varying enrichment, and section 3 presents similar results for a slab target. Section 4 contains calculation for a radial variation in enrichment in a cylindrical target.

2. AXIALLY VARIABLE ENRICHMENT IN A CYLINDRICAL TARGET

2.1 Calculational Details

Fig 1 shows the geometry specified for the variably enriched target. The target itself was represented as a cylinder of radius 4.5 cm and length 30 cm, enclosed in a 1 cm decoupler region (represented as 10^{22} atoms cm^{-3} of ^{10}B.) The decoupler was in turn surrounded by a 70 cm cube representing a D_2O cooled Be reflector and consisting of a homogeneous mixture (80% Be, 20% D_2O.)

The target region itself was divided into four zones for which differing degrees of ^{235}U enrichment could be specified. All four zones contained a homogeneous fuel-coolant mixture (80% uranium and 20% D_2O.)

All calculations were performed by the Monte Carlo code MORSE(1), using the DLC-37(2) coupled neutron-gamma library. The fixed source (representing all processes above 15 MeV) was based on a HETC(3) calculation for a pure ^{238}U target assuming a 7 cm proton beam diameter with a parabolic radial distribution. An adjustment was made for the reduced uranium density in this configuration.

In the heterogeneously enriched configuration here and in Section 3, enrichments were adjusted to flatten total neutron production (ignoring capture processes.) A more appropriate parameter to flatten would be the peak (i.e. centre line) power density. However, estimates of the peak power density based on the results in Section 4 suggest that a target with a uniform rate of neutron production per plate would also have a nearly uniform peak power density. This is due to the fact that the relatively flat spatial distribution of the fission source, compared with the primary source, compensates for the higher energy deposition per neutron.

All results presented in sections 2 and 3 consist of production rates in each target zone with the total primary source normalized to 1.0 for the whole target.

2.2 Results and Discussion

Results for the rate of neutron production in homogeneously enriched targets are shown in Fig. 1. It is clear that neutron production in such targets is very non-uniform, and a high proportion (about 45% for a ^{238}U target) are generated in the first 7.5 cm of the target.

Fig. 2 presents the calculated neutron production rates for the heterogeneous configuration designed to produce a uniform neutron production rate. A "flattened" result was found to be hard to achieve for the entire target - in fact the last quarter required an enrichment of 90% to match the performance of the 0% enriched first quarter!

Two parameters of greater importance are shown in Figs 3 and 4 for the heterogeneous target, clearly i.e. net neutron production and estimated power production. Here "net neutron production" exclued all neutrons list in capture processes in the target, including fission capture. Power production was estimated as 30.2 MeV per neutron for the primary source and 61.3 MeV per neutron for the fission source(5). (Note: for this non-thermal system, γ was calculated as 3.08 neutrons/fission.)

Two basic disadvantages of enriched targets are revealed here, and must always be taken into account. Fission deposits more energy per neutron produced than spallation, and also involves the capture of neutrons. Thus the ratio of power production to useful neutron production increases with enrichment, from about 40 MeV/neutron for pure ^{238}U to 100 MeV/neutron for ^{235}U.

The overall advantage the heterogeneous target as compared with a ^{238}U target is rather modest. Net neutron production is increased by only 52%, at the expense of a 135% increase in energy deposition. However, as previously mentioned, the performance of the rear moderaters would be considerably enhanced. A precise estimate of the gain must await calculations in which moderators are included.

3. AXIALLY VARIABLE ENRICHMENT IN A SLAB TARGET

3.1 Calculational Details

Fig. 6 shows the geometry specified for the slab target, which differed from the cylindrical target only in having a rectangular (20x10 cm^2) cross section.

Calculations were again performed by the code MORSE.

3.2 Results and dicussion

Neutron production rates for homogeneous enrichments are given in Fig 7, and results for two heterogeneous configurations in Fig. 8. Figs 9 and

10 contain net neutron production and estimated power production rates respectively.

The modified geometry exhibits the expected strong advantage over the cylindrical geometry. A relatively modest maximum enrichment (45% instead of 90%) is required to achieve a flattened neutron production rate over the whole target, and elsewhere in the target enrichments would be reduced in approximately the same proportion.

The minimally enriched heterogeneous configuration (enrichements 0, 10%, 22%, 45%) gives a 53% increase on net neutron production, at the expense of a 125% increase in power production, when compared with the homogeneous ^{238}U slab target. In this respect its performance is comparable with the heterogeneously enriched cylindrical target presented in section 2. The second configuration (enrichment 20%, 20%, 32%, 53%) increases net neutron production by a factor of 2.38 at the expense by a factor 4.19 in power production, again in comparison with a 0% enriched target.

Precise conclusions on the merits of a modified target geometry must involve a more detailed investigation in which a pure realistic design is adopted, and a full geometry calculation, including the moderators and reflector is performed.

4. INVESTIGATION OF RADIALLY VARYING ENRICHMENT

4.1 Calculational Details

The one dimensional S-N code ANISN(4) was used to calculate the performance of targets with a radially varying enrichment.

The material composition of the target, decoupler and reflector were as described in Section 2. The geometry of the system was similar to the MORSE geometry in Fig. 1, except that all components were represented as a set of concentric infinite cylinders or cylindrical shells.

The target was represented as a cylinder of radius 4.5 cm, subdivided into four zones of outer radii 1.125, 2.25, 2.375 and 4.5 cm. As for the MORSE calculations, the target was surrounded by a decoupler in the form of a 1 cm thick cylindrical shell. The reflector was represented by a cylinder of outer radius 35 cm.

The source used for these calculations had the same average radial distribution as in the MORSE calculations, and was normalized to 1 ns^{-1} cm^{-1}. The ratio of peak to average intensity used here was approximately 1.9. Care must be used in interpreting the results because in practice the source distribution broadens along the axis of the target. In the first few cm of the target the peak to average ratio is about 3 for a 7 cm diameter proton beam.

4.2 Results and discussion

Preliminary results indicated that the power densities in zones 1 and 2 ($0 < r < 1.125$ cm and $1.125 < r < 2.25$ cm) were nearly identical as was the enrichment required to produce a uniform power density throughout. A decision was therefore made to combine zones 1 and 2 in the analysis of results, and to specify the same level of enrichment for both.

Fig. 11 displays the total energy deposition in each target zone as a function of enrichment for uniformly enriched targets. Clearly the proportionate variation in power density is large at low enrichments, (being dominated by the distribution of the primary source,) but becomes small at high enrichments (because of the presence of the reflector.)

Fig. 12 shows the results of a series of calculations in which the enrichments in different zones were adjusted to produce a uniform power density. The enrichments required (three values for zones 1 and 2 combined, zone 3 and zone 4) are plotted against the estimated power density in MeV cm^{-3}.

A similar pattern to fig. 11 is discernable, in that the variation in enrichment required to produce uniform power is larger at low enrichments.

Fig. 13 compares the net neutron production in the target for heterogeneously and homogeneously enriched configurations. Here the net leakage across the surface of the target is plotted against centre zone enrichment. In the absence of moderator calculations, this parameter is the best available indicator of target performance. However, a true comparison of the homogeneous and heterogeneous targets should be made at equal centre-line power densities, rather than enrichments. The slanted lines on Fig. 13, link points of equal power density in the centre zone.

As expected, the proportionate gain in neutron production is greatest at low enrichments. The heterogeneous configuration with zero enrichment at the centre shows a gain of about 25% in the homogeneous target (enrichment 3%) with the same centre zone power density. At higher enrichments, the available gains are relatively poor (about 15% for a centre line enrichment of 50%, falling to ~ 10% for a centre line enrichment of 60%.)

Finally, Fig 14 shows the total energy deposition as a function of centre - line enrichment. Again, the slanted lines link points of equal centre-zone power density.

5. GENERAL CONCLUSIONS

The results for an axially enriched cylindrical target suggest that an overall gain of 52% could be achieved over a ^{238}U target at the expense of an increase of power production from 230 to 540 kW. However, this could only be achieved with an unrealistically high enrichment of 90% for the last quarter of the target. As previously mentioned, the principal gain from the axially enriched target would be a considerably improved source for the rear moderators.

The use of a radially varying enrichment to flatten power production could also improve target performance. The source distribution used here predicts as 25% true gain (at constant peak power density) decreasing with increasing enrichment. However, a more appropriate source distribution would predict a higher available gain (by a factor of about two) near the front of the target. Thus axial and radial enrichment variation are to some extent complementary. The radial variation would mainly benefit the front end of the target, whereas the axial variation would benefit the rear end. Calculations will now be performed for a target which combines both types of enrichment variation. In principle the whole target could be flattened to give a power production of about 1.5 MW; however, a 1 MW target with power density flattened for the first 20 cm of uranium would be more realistic.

The results for a two dimensional target are interesting, in that the same level of neutron production can be achieved with about half the enrichment. However, more detailed calculations are now needed to evaluate the neutron brightness available to the moderator.

Future calculations must also include a realistic moderator and reflector configuration. A major uncertainty must be resolved, i.e. the coupling efficiency of moderators to the fission source in an enriched target. For a number of reasons this source will be harder than the primary spallation source, and it can therefore be expected to couple less efficiently with moderators.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

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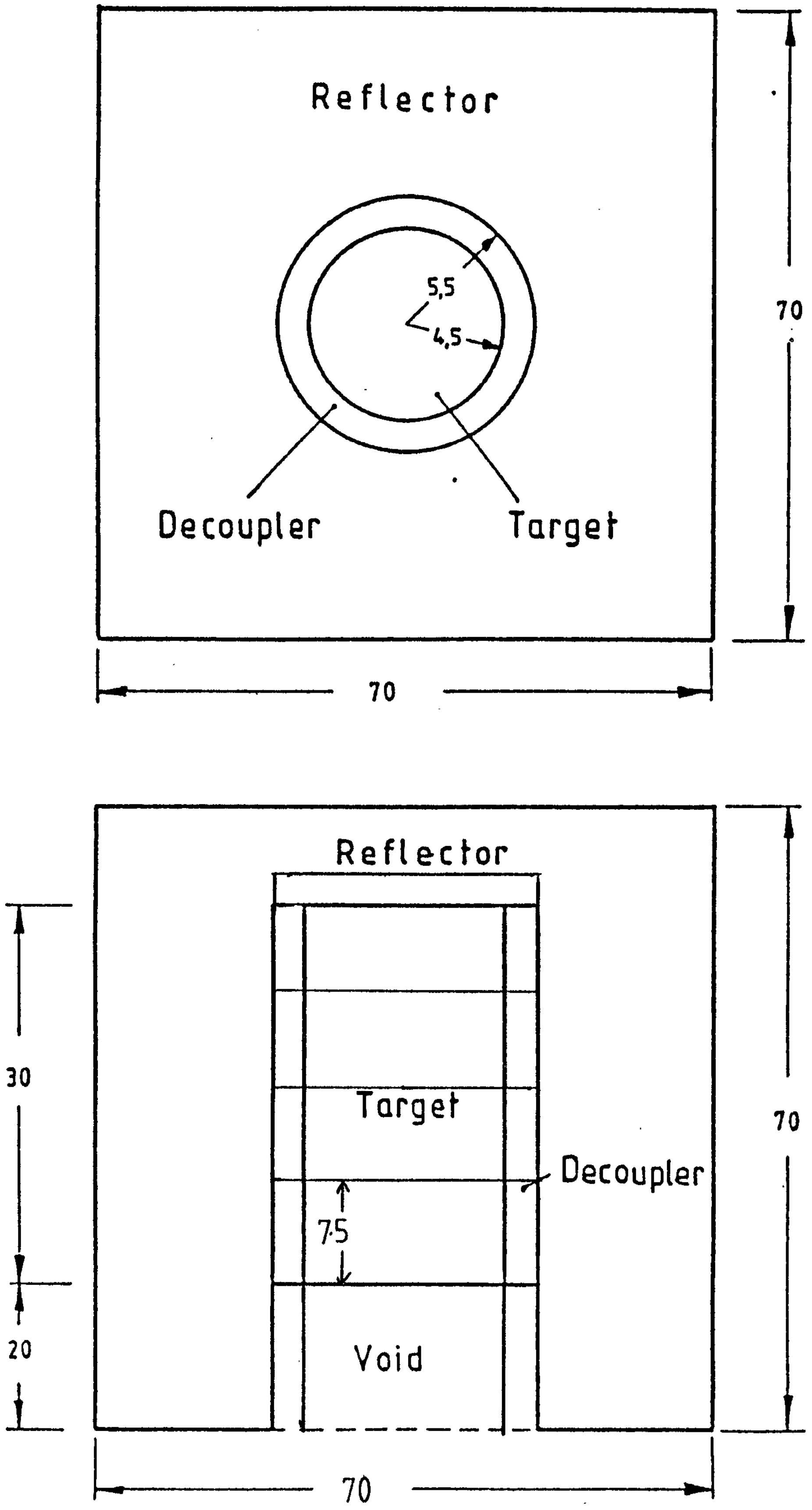

Fig. 1 Geometry specified for the cylindrical target configurations.

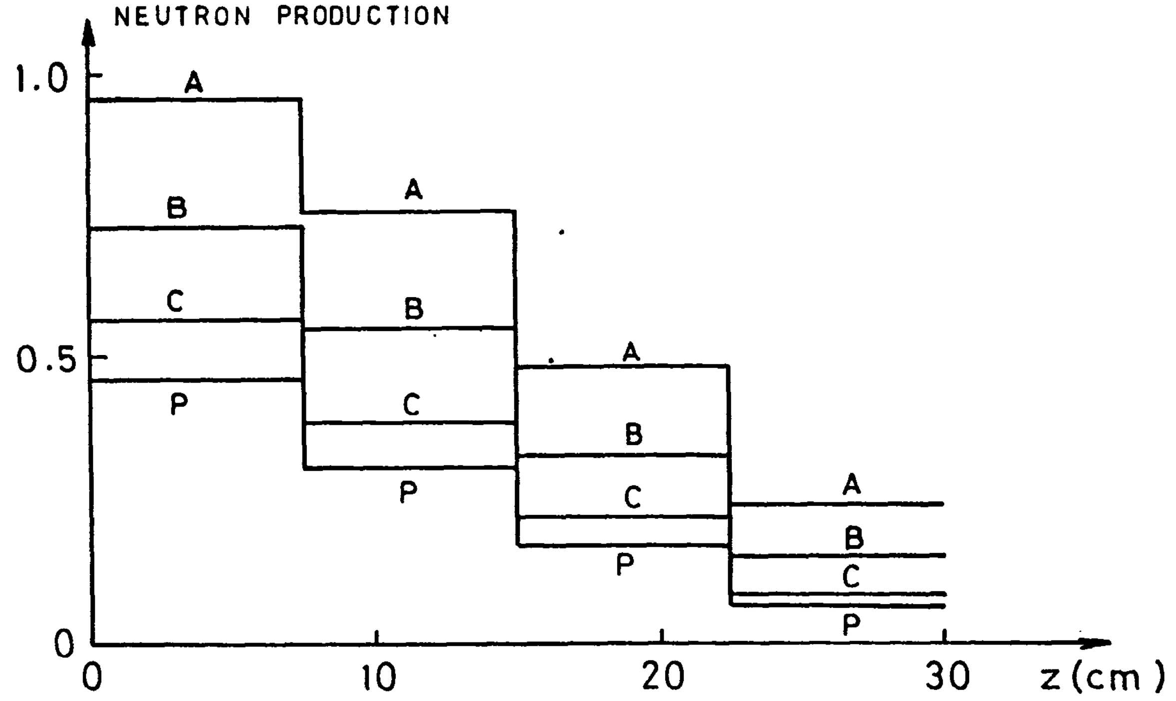

Fig. 2 Total neutron production (per target zone per unit primary source in whole target) in homogeneously enriched cylindrical targets. "P" represents the primary source (normalized to 1.0 for whole target.)

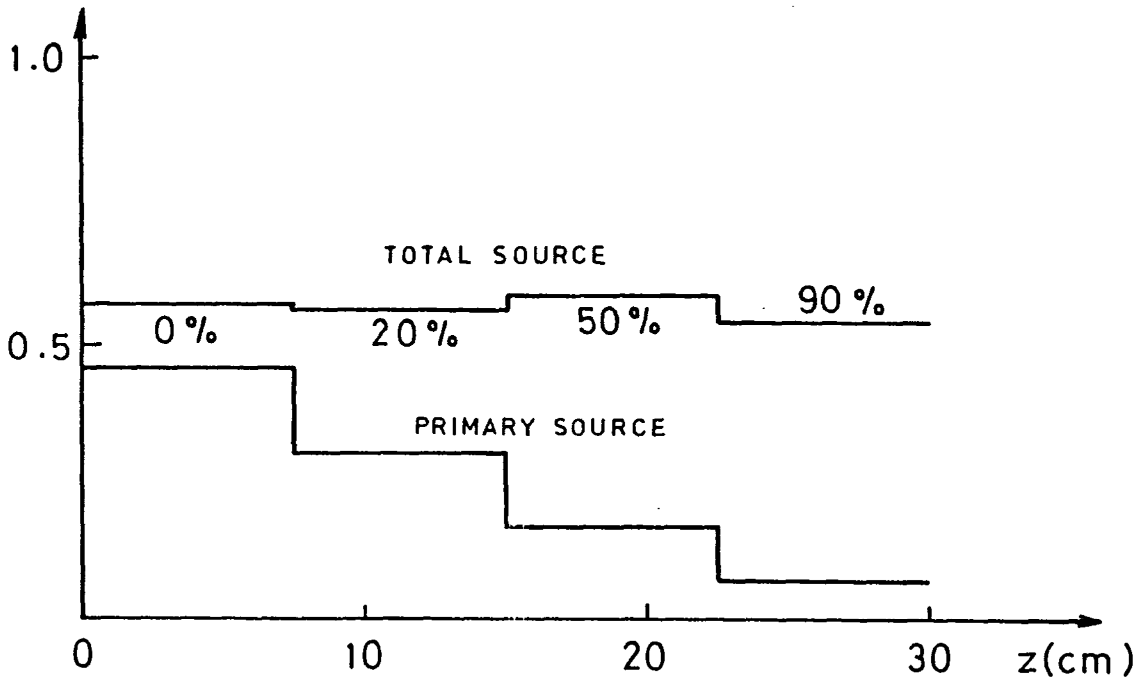

Fig. 3 Neutron production from the heterogeneously enriched cylindrical target. Enrichments are shown.

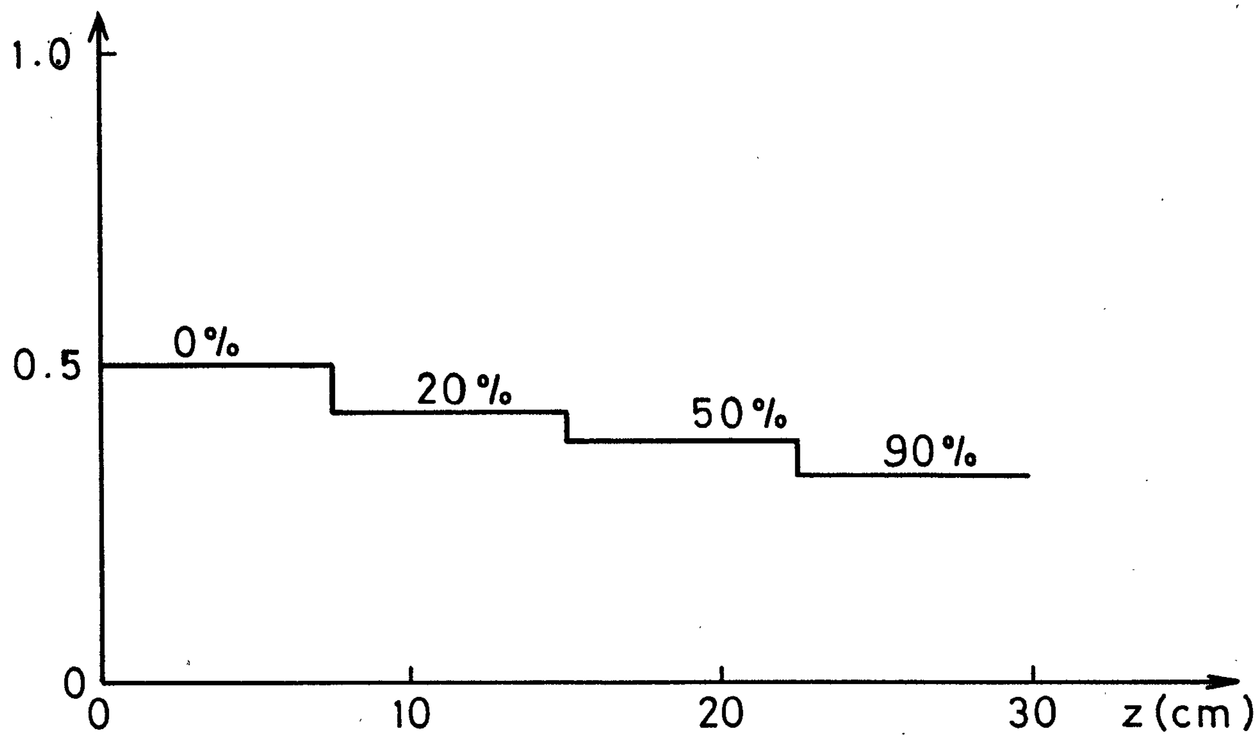

Fig. 4 Net neutron production in the heterogeneously enriched target. (per target zone per unit primary source in whole target)

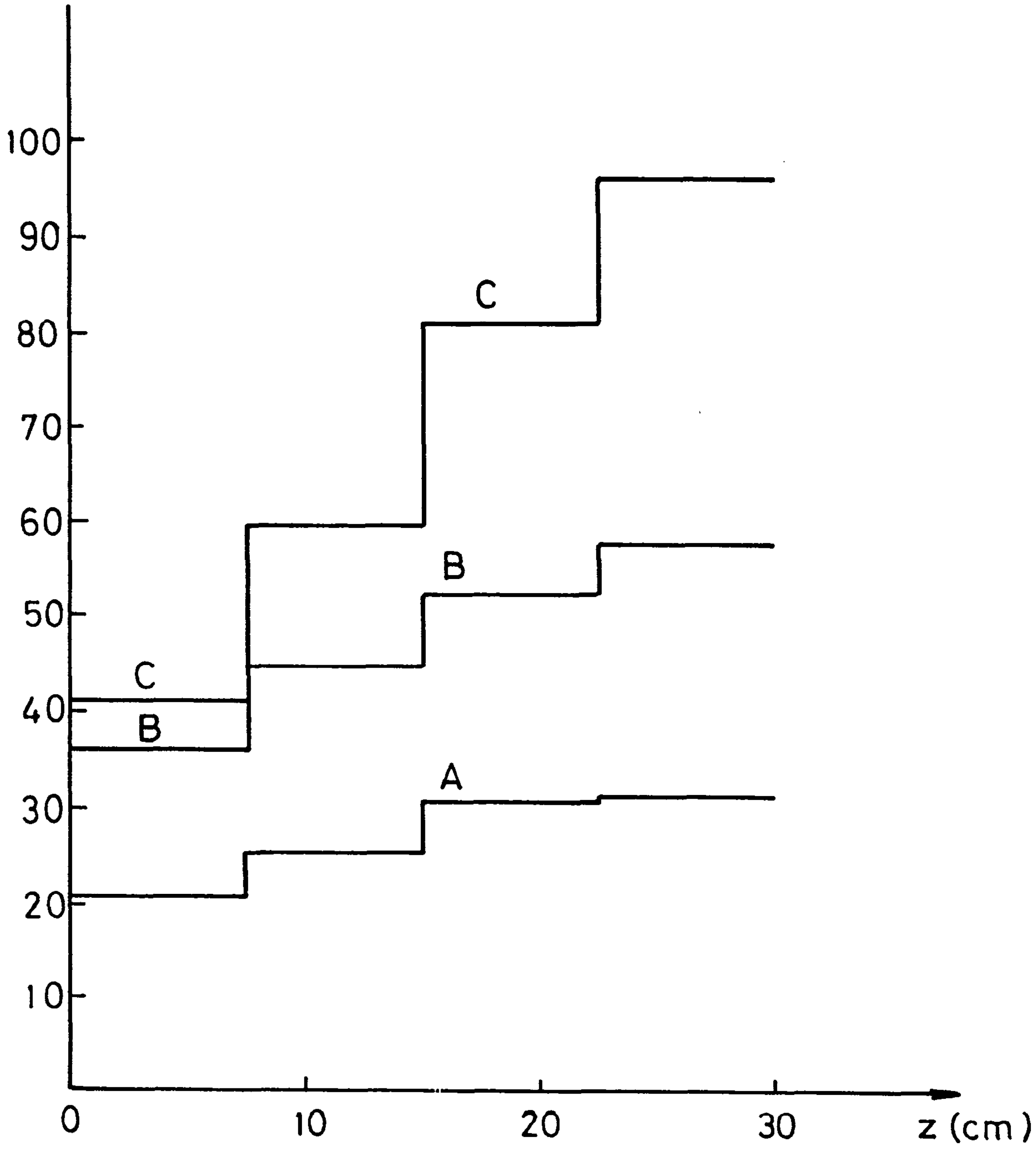

Fig. 5 Estimated power production (per target zone)

A. per unit primary source in whole target (1 MeV per primary neutron corresponds to 4.29 W at 200 µA beam current.)

B. per unit total source in target zone.

C. per unit net neutron production in target zone.

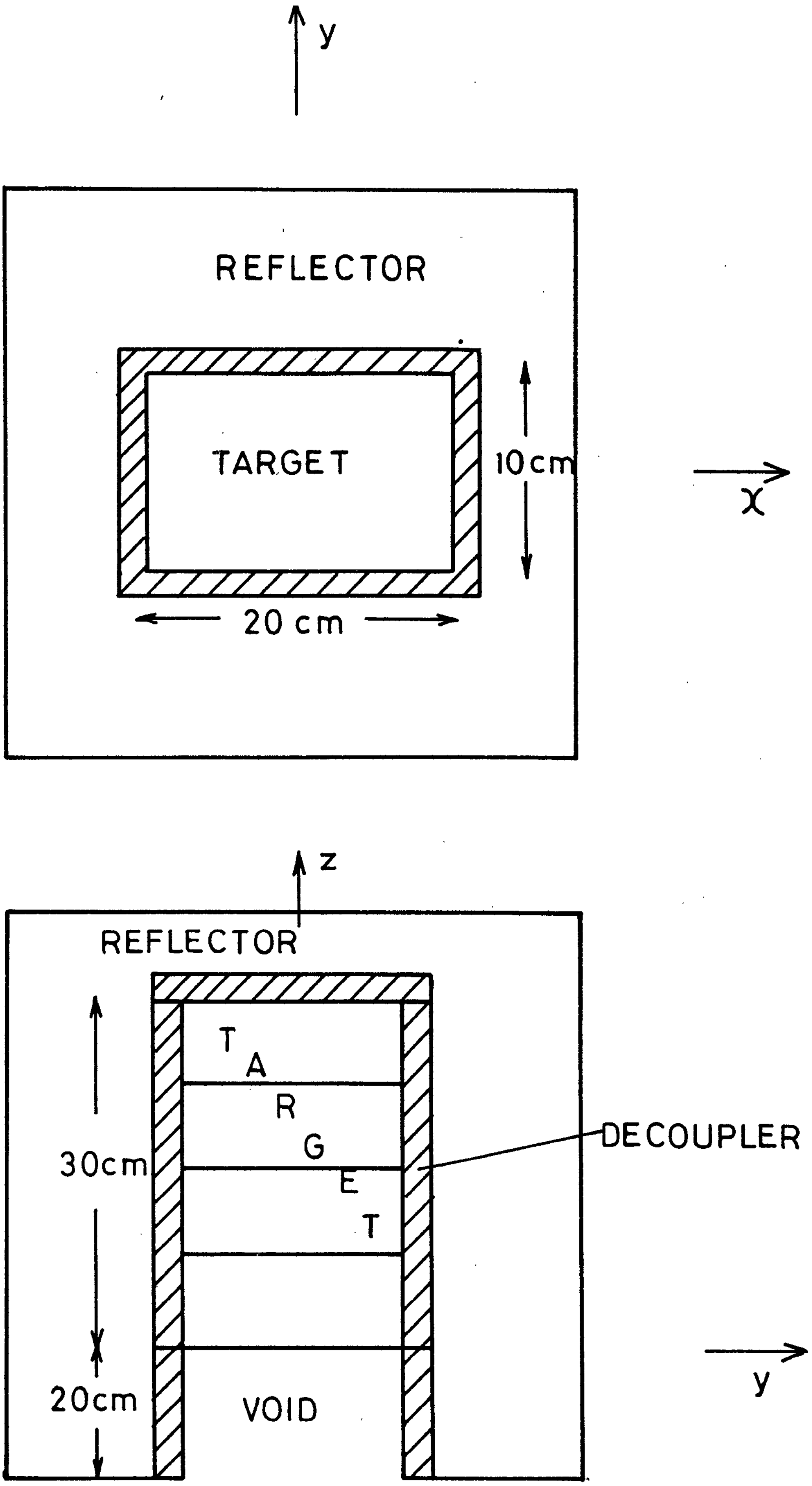

Fig. 6 Geometry of the slab target configuration.

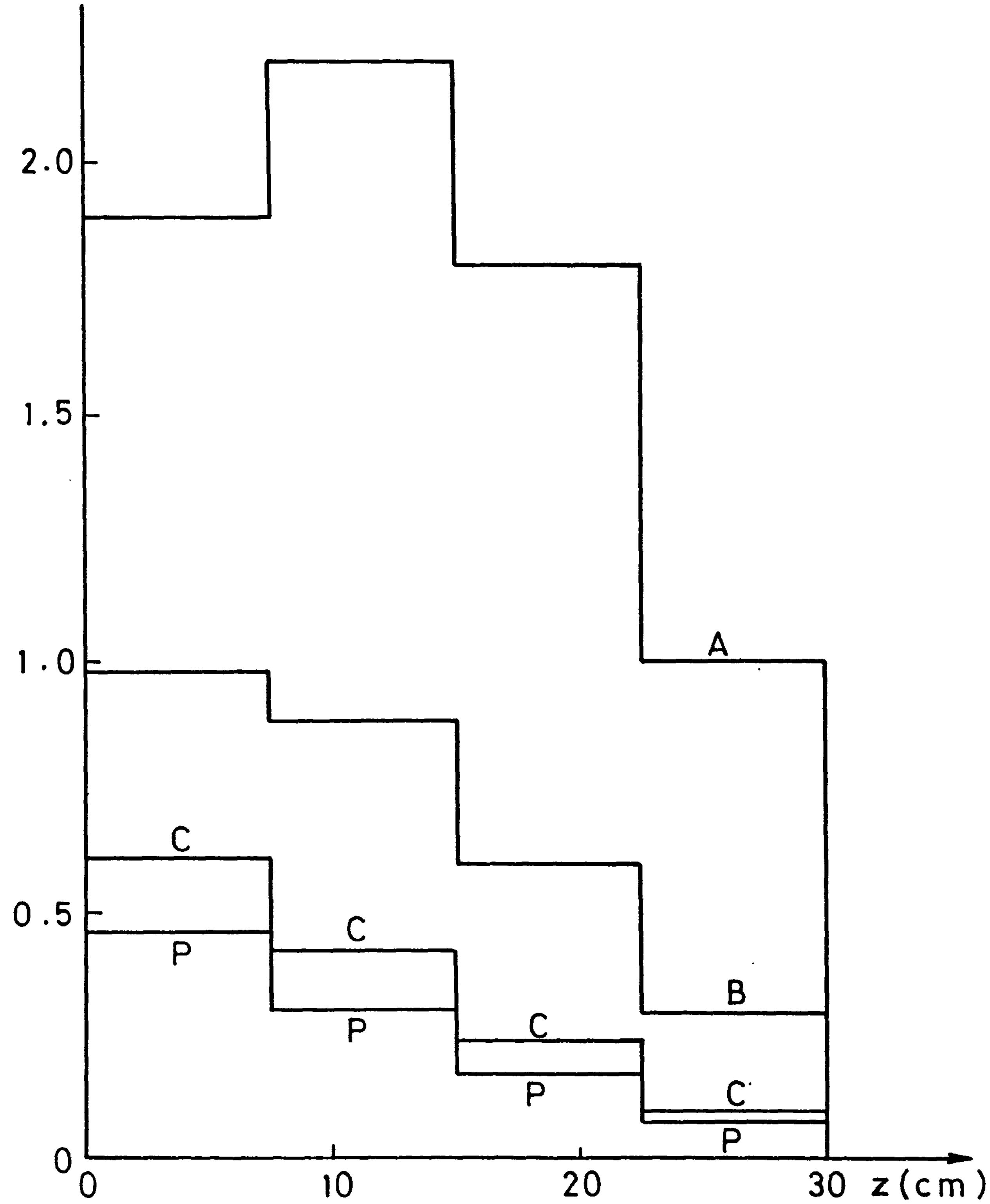

Fig. 7 Total neutron production per target zone in homogeneously enriched cases (per unit primary source in whole target)

A x = 40%   B x = 20%   C x = 0%

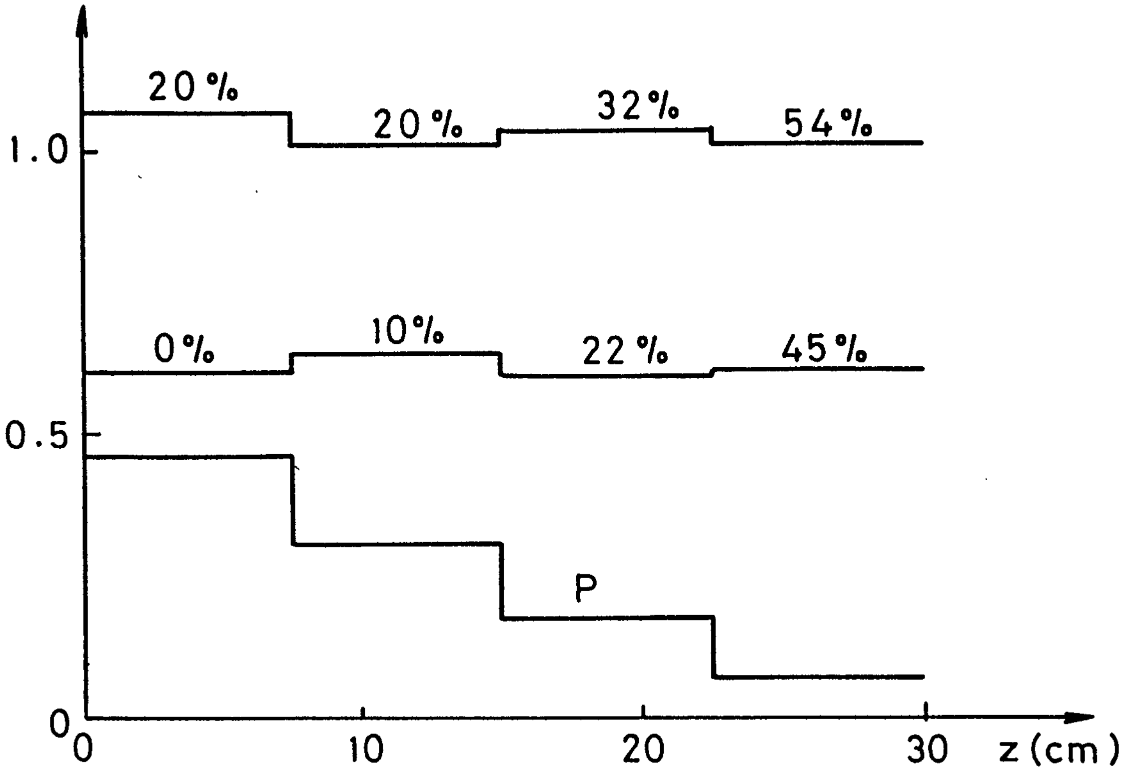

Fig. 8 Total neutron production per target zone in heterogenously enriched slab target configurations. Enrichments are as shown.

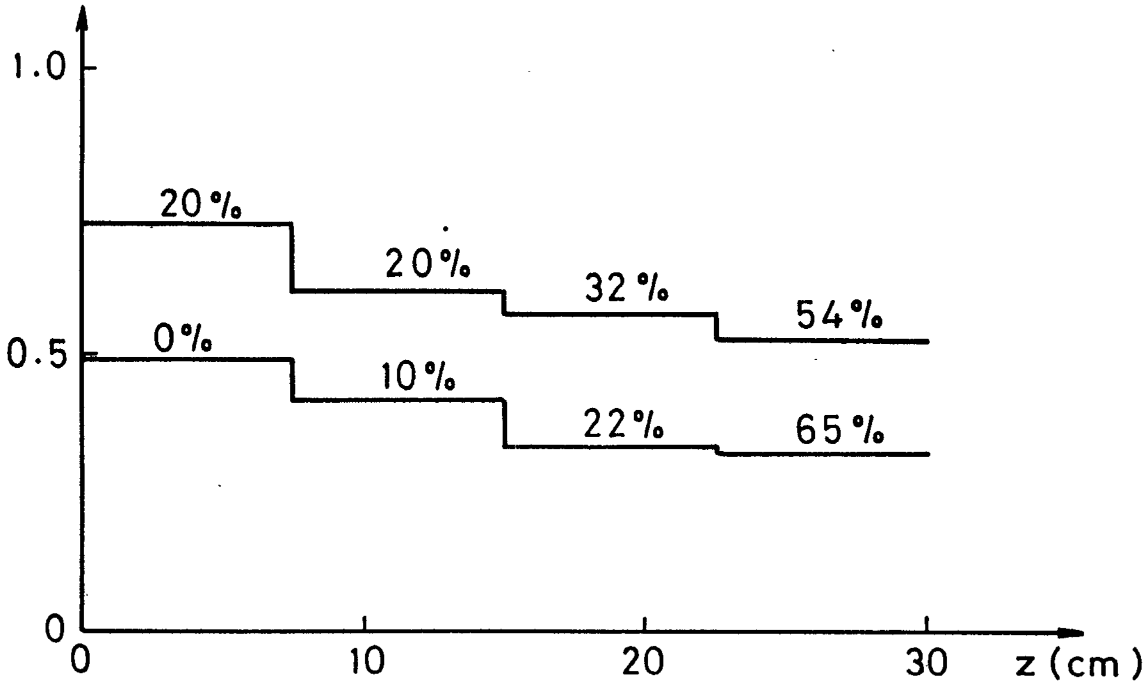

Fig. 9 Net neutron production (per target zone per unit primary source in whole target) for the heterogeneous slab targets.

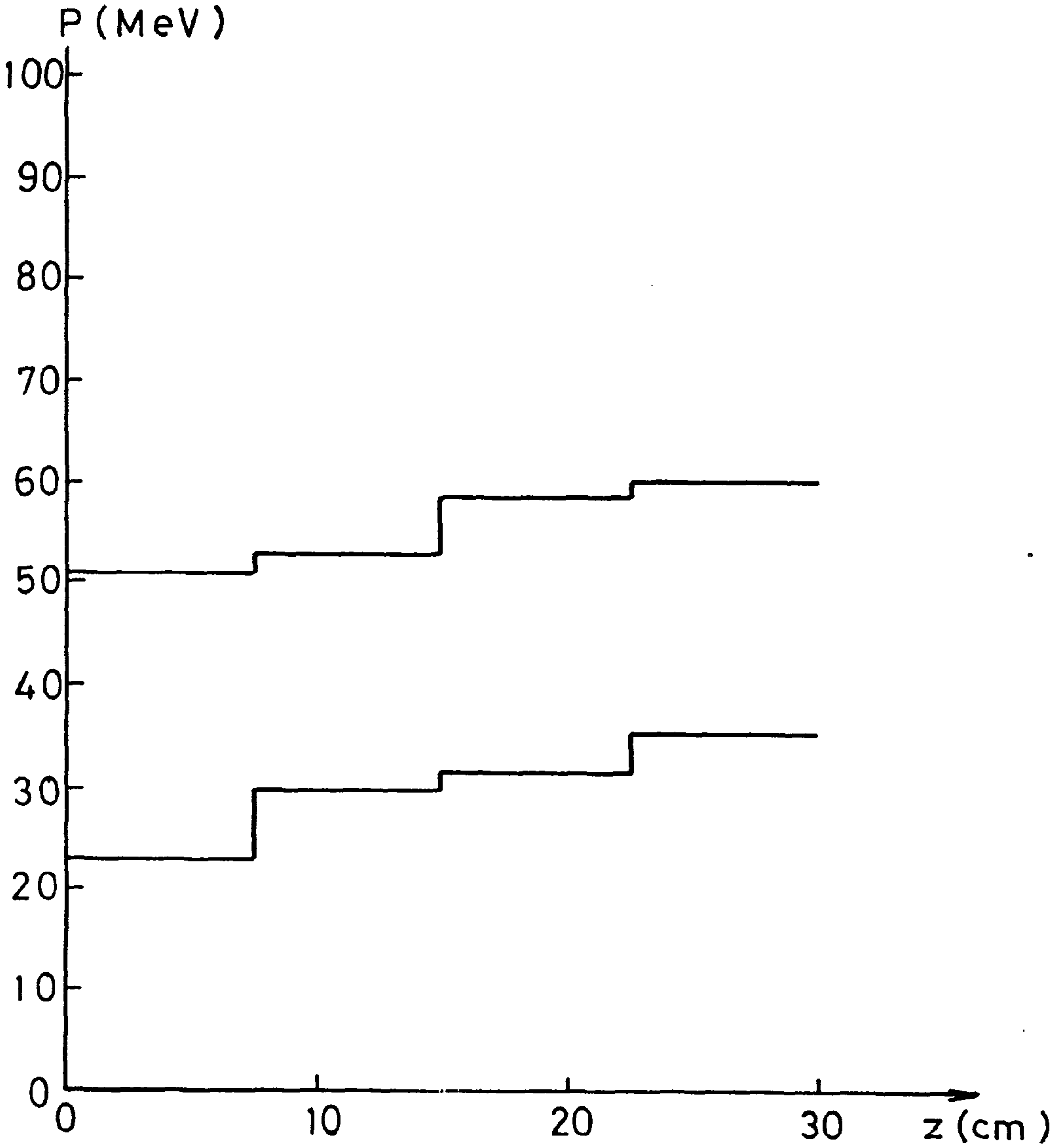

Fig. 10 Estimated power production in heterogeneously enriched slab targets(power in MeV per target zone per primary neutron in whole target.)

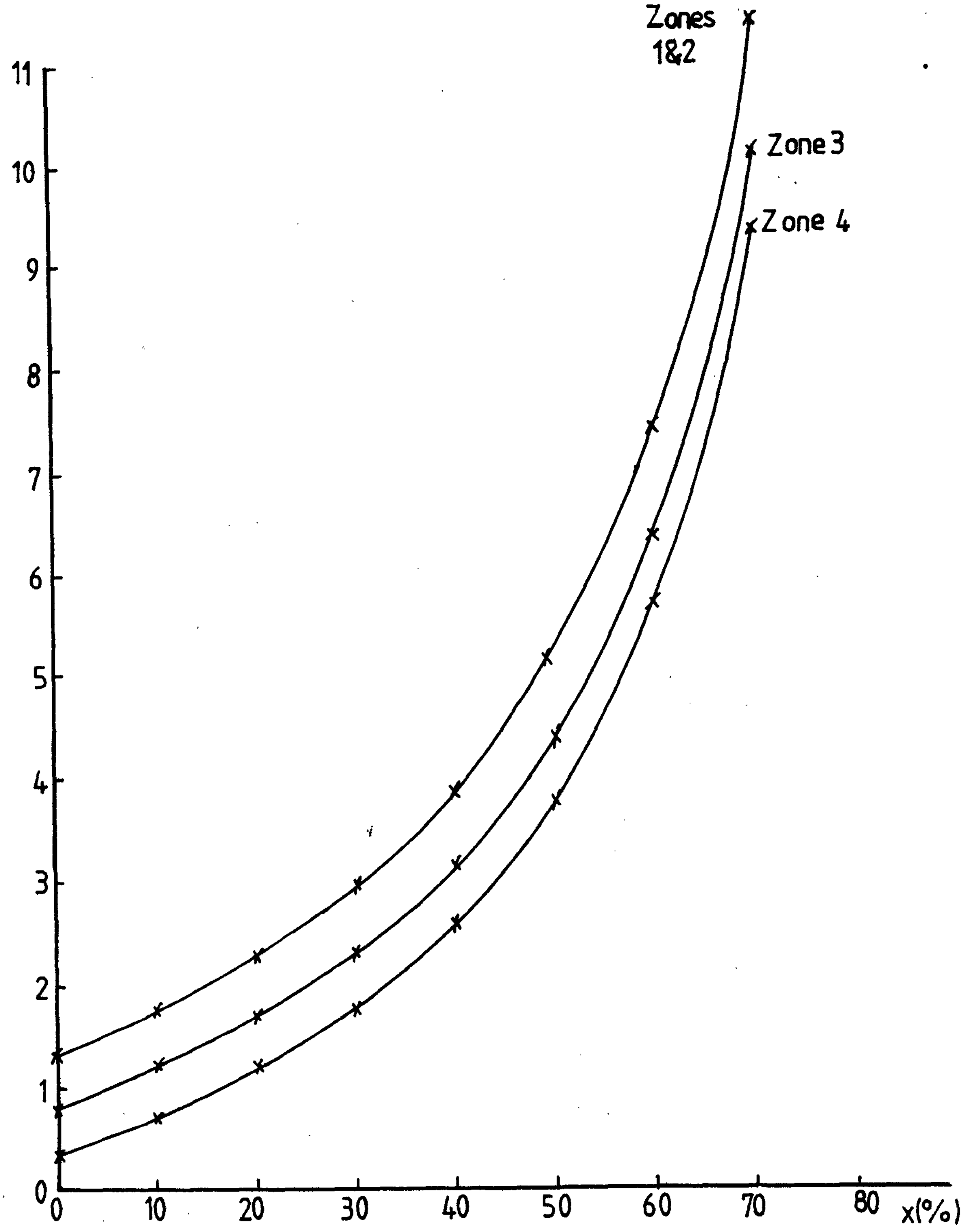

Fig. 11 Power density (in MeV per primary n) in homogeneously enriched targets.

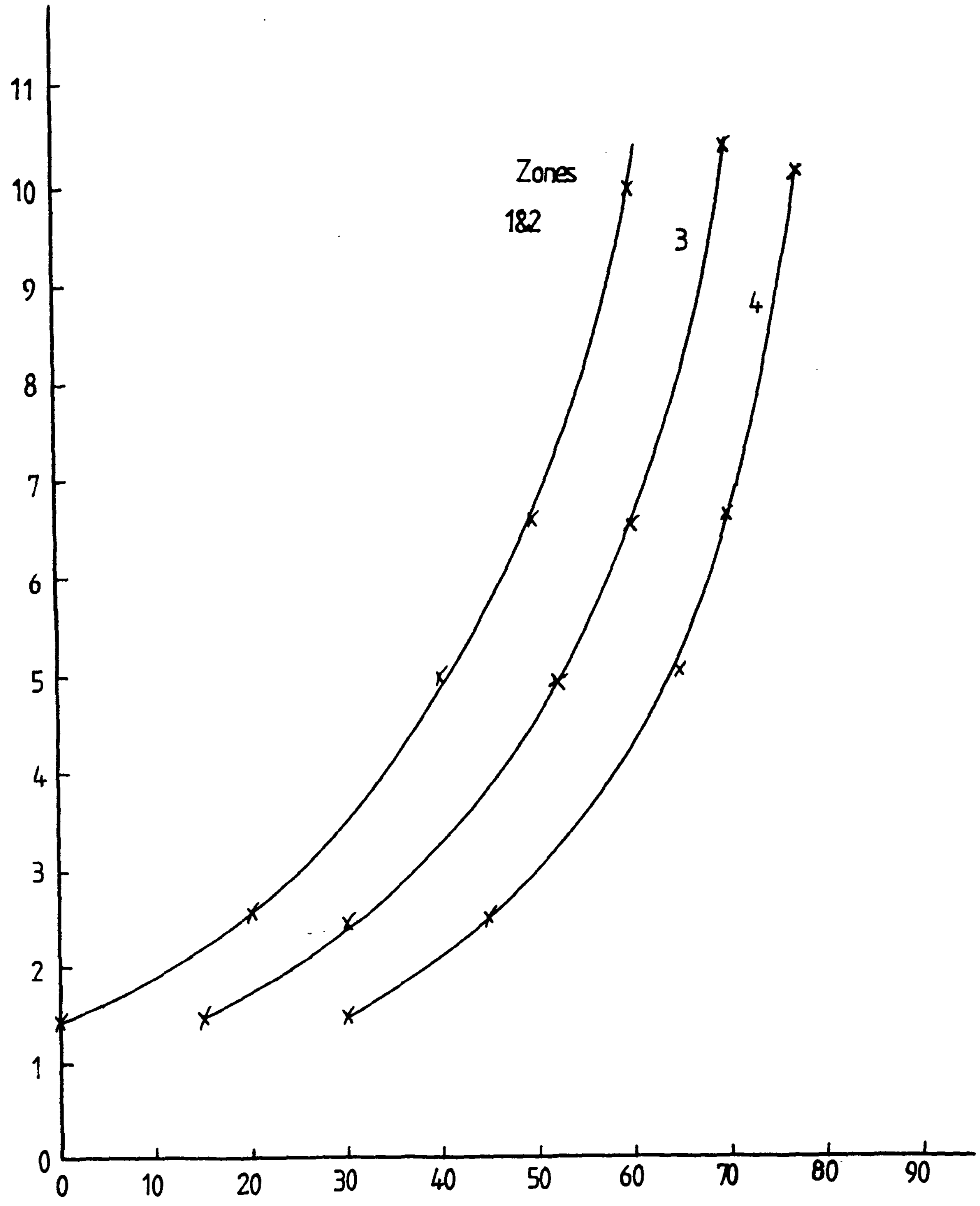

Fig. 12 Power density (MeV) vs enrichment in targets adjusted to produce a uniform power density.

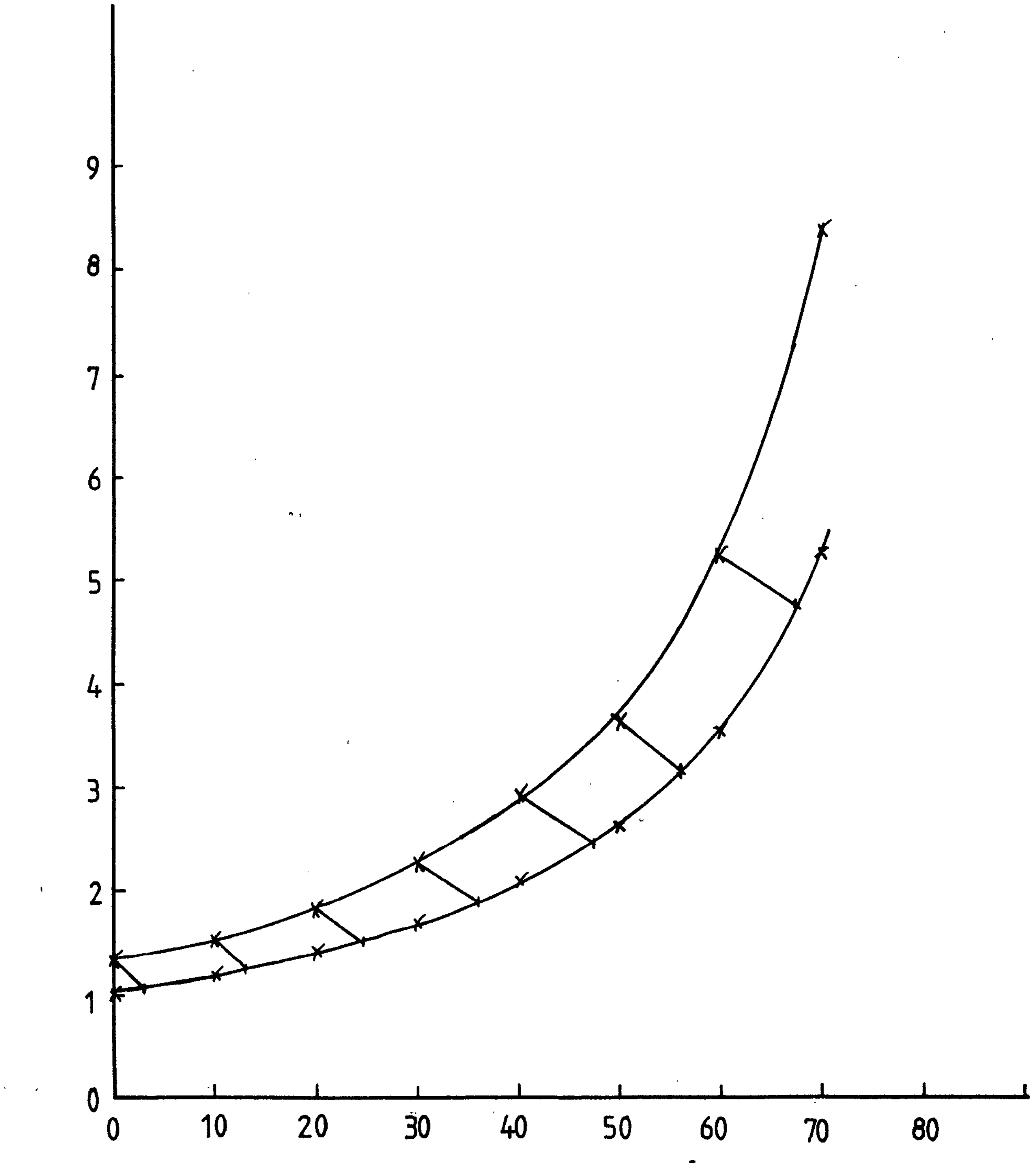

Fig. 13 Net neutron production (per primary neutron)

Upper curve: uniform power density and
Lower curve: uniform enrichment.

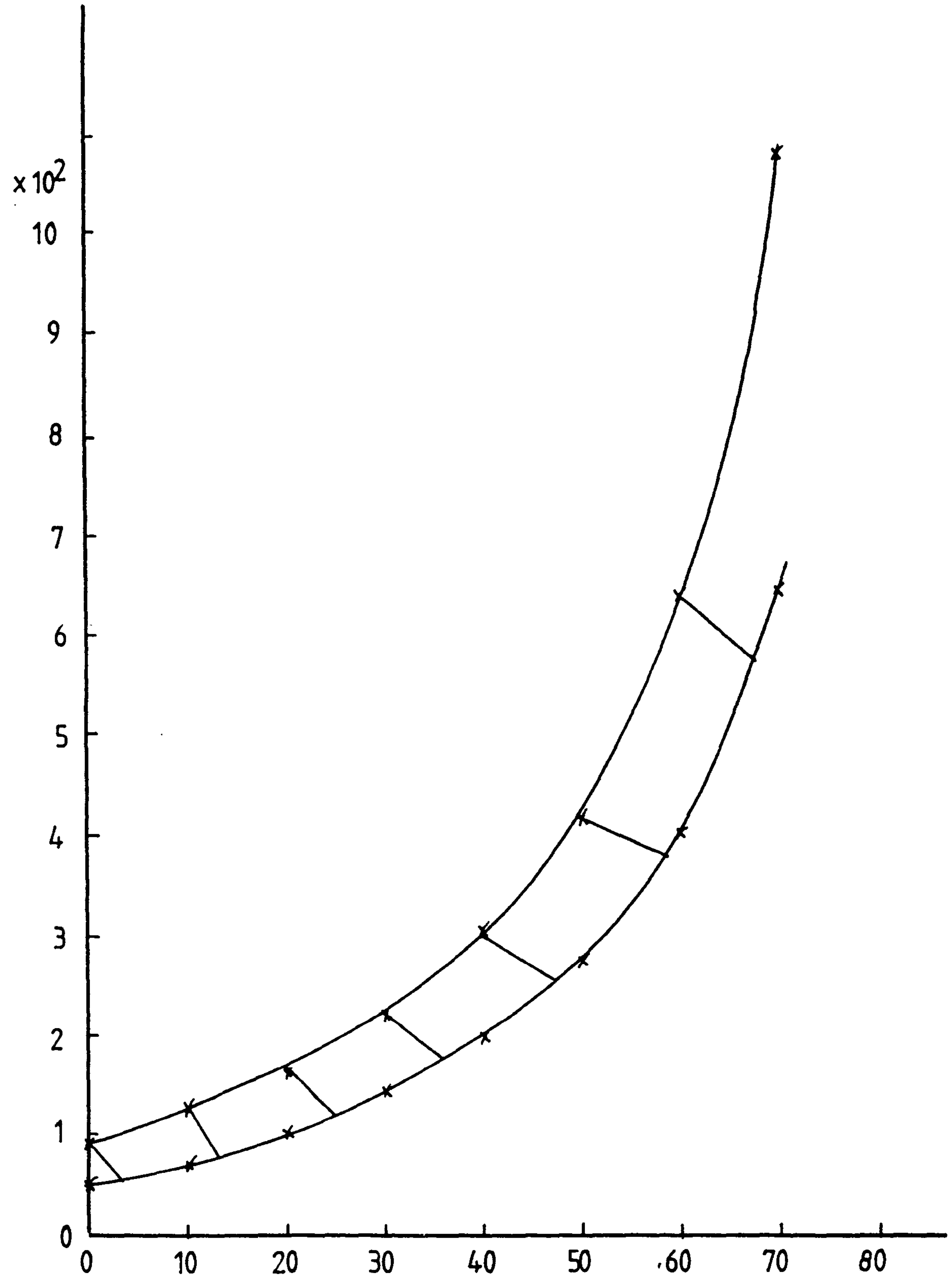

Fig. 14 Estimated power production (per primary neutron).

Upper curve: uniform power density.
Lower curve: uniform enrichment.