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by

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Abstract

The use of slightly enriched uranium as a fuel in CANDU-reactors is studied in a simple parametric way. The results show the possibility of

(1) about 30% savings in natural uranium consumption

(2) about 35% increase in the utilization of the natural uranium

(3) a decrease in fuelling costs to about 70 - 80% of the normal case of natural uranium fuelling.

Angereichertes Uran als Brennstoff für CANDU-Reaktoren

Zusammenfassung

Die Auswirkungen der Verwendung von leicht angereichertem Uran als Brennstoff in CANDU-Reaktoren werden in einer Parameterstudie untersucht. Wichtige Ergebnisse sind:

(1) Der Natururanbedarf kann um etwa 30% gesenkt werden.

(2) Die Nutzung des Natururans kann um etwa 35% verbessert werden.

(3) Der Brennstoffkostenanteil kann auf 70 - 80% der Kosten für die Beschickung mit Natururan gesenkt werden.

C o n t e n t s

1. The CANDU Nuclear Power Station

When introducing nuclear energy quite a number of countries prefer reactor types operating on natural uranium as the fuel. Above all Canada decided in favor of this reactor type and advanced a development of their own. It resulted in the CANDU Nuclear Power Station which is now commercially available.

Four large nuclear power units of this type have been operating as commercial nuclear power stations (Pickering A, units 1 through 4 of 540 MW_e each in Ontario, Canada) and two smaller units (RAPP-1, 220 MW_e, in India, and KANUPP, 137 MW_e in Pakistan).

Ten CANDU nuclear power stations from 220 MW_e to 787 MW_e are under construction and orders have been placed for another 13 power stations /1/.

These figures demonstrate that from experience gathered in operation the customers have been convinced of the technical concept and economy of CANDU facilities.

2. Possible Improvements

The prerequisite of using natural uranium as the fuel in CANDU reactors is that heavy water is both the moderator and coolant in this reactortype. The natural uranium fuel is introduced on load into the reactor pressure tubes as short fuel elements (50 cm in length) and at the same time spent fuel elements are unloaded. After the original CANDU concept had been developed to its commercial maturity other possibilities were included into

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the studies in order to improve CANDU under economical and technical aspects. So, boiling light water and organic substances as coolant media were investigated. In addition, different modes of fuel loading were studied. They centered around plutonium recycling and charging with highly enriched uranium-235 in thorium with and without reprocessing as a substitute for the usual natural uranium fuelling scheme without reprocessing.

Advantageous combinations of these types of loading with the different cooling media were selected. These investigations aim at finding a new reactor concept which would offer more advantages regarding its economy and/or technology than the old CANDU concept and would be related but loosely with the latter.

By contrast, a possibility will be indicated in this paper how to improve the economy of CANDU nuclear power stations without essentially modifying the CANDU concept proper.

The common drawback of all reactors operating on natural uranium lies in their narrow criticality margin, which calls for charging under load and entails the low burnup values below 10 MWd/kg. This drawback can be eliminated by use of enriched fuel. Only low enrichement values are tolerated so that the original CANDU concept is not interfered with in its technical realization.

This way of improving the reactor features has been successfully realized with other reactors operating on natural uranium and demonstrated by extensive computations, respectively: Since the middle of 1974 enriched uranium has been used to refuel MZFR

(Karlsruhe, 51 MW_e net power) and this has substantially increased the discharge burnup /2/.

Computations were made for the Atucha Nuclear Power Station /3,4/, which show that the use of enriched fuel would result in a considerably improved economy. Therefore, it is quite obvious to consider the use of enriched uranium as the fuel also for CANDU reactors. The positive outcomes of this measure will be roughly sketched in this report.

Detailed computations on burnup as for MZFR /5/ have not been performed. A rough estimate was made of the relationship existing between enrichment and burnup, which was based on results of burnup computations on plutonium recycling in CANDU reactors /6/ and results of burnup calculations for a CANDU-BLW /7/. Since the relationship between enrichment and burnup is also influenced by the mode of reactor operation, the results being dependent on burnup and enrichment have been calculated as a function of two independent variables and plotted accordingly.

The calculations and their results are based on the assumptions which roughly correspond to the conditions prevailing in the Pickering Generation Station /8/. The details have been listed in Table 1.

Table 1 Basic Values for Computations

Nuclear power stations:		
Thermal power	1 743.5	MW_{th}
Net efficiency	0.291	MW_e/MW_{th}
Load factor	7000	h/a

Table 1 cont'd

Fuel:

kg fuel per fuel element	20 kg
Losses	
during conversion	0.6 %
during fabrication	3 %
Tails assay (enrichment)	0.25%

Costs:

Natural uranium	US$ 35 per lb U_3O_8
Conversion	US$ 3 per lb U in UF_6
Enrichment	US$ 70 per kg SWU
Fabrications costs	US$ 30-60 per kg U in the fuel element

3. Consequences of the Use of Enriched Fuel

The direct consequence of the higher burnup achieved with enriched fuel (as compared to natural uranium fuel) consists in the r e d u c t i o n o f t h e a n n u a l f u e l e l e m e n t d e m a n d .

Doubling the 8 MWd/kg U discharge burnup - a typical value of natural uranium - to 16 MWd/kg U - a value easily achieved with enriched uranium - implies a reduction by 50% of the annual fuel element demand. On the other hand, this means that now the fuel element fabrication plant can provide twice the number of reactors with fuel elements without extending its capacity.

Using the burnup value of 20 - 22 MWd/kg $U_{enr.}$, probably a more realistic value for enriched fuel, Fig. 1 shows that the annual demand of fuel elements drops to 37.5% of the amount needed for natural uranium fabrication. This means that one fuel element fabrication plant, which can supply natural uranium fuel elements to three CANDU nuclear power stations, will be sufficient to supply eight nuclear power stations of the same size provided that enriched fuel is used instead of natural uranium.

Whereas the annual demand of fuel elements exclusively depends on the burnup, other important characteristics are functions of b o t h the burnup a n d the enrichment. To get a plain survey and to avoid introduction of a special enrichment-burnup relationship depending on many prerequisites, these other variables are plotted as level lines over an enrichment-burnup plane. The important part of this plane, i.e. the range in which the achievable enrichment-burnup combinations lie, is set off by shading.

The a n n u a l d e m a n d o f n a t u r a l u r a n i u m has been depicted in Fig. 2. It is shown that the use of enriched uranium as the fuel implies savings in uranium consumption. Savings of approximately one quarter in uranium consumption seem to be feasib.e. Considering today's uranium prices this reduction entails quite a substantial decrease in operating costs. But it must be seen under economic aspects as considerable uranium reserve stretching as well. This favorable effect has been represented separately in Fig. 3 where the effective uranium utilization has been plotted. The thermal energy in MWd_{th} released in the reactor is related to the amount of natural uranium to be mined in order to obtain this energy. It is noted that this variable, based on 8 MWd_t/kg U for natural uranium loading can be increased to about one and one third which means that the amount of natural uranium required to operate three CANDU nuclear power stations is sufficient to operate four CANDU nuclear power stations having the same power if enriched fuel is substituted for natural uranium.

A comparison with uranium utilization in li^ht water reactors where it amounts to roughly 5 MWd_{th}/kg U clearly shows the good utilization of natural uranium in heavy water reactor as well as the degree of possible improvements through enrichment.

Fig. 4 shows the a n n u a l d e m a n d o f s e p a r a t i v e w o r k in case of changeover to enriched fuel. It amounts to 10 tonnes of SWU per year or less. Compared to this, an LWR of the same power needs for annual refueling about 55 tonnes of SWU, i.e., more than five times this amount.

Use of enriched uranium as the fuel in CANDU reactors will be seriously considered only if, in addition to the advantages mentioned above, - better utilization of uranium reserves, better utilization of fuel element fabrication plants and possibly improvements and simplifications, respectively, in the operation of the nuclear power reactor - marked improvement of economy can be demonstrated as well.

According to publications, expenditures for f u e l c o s t s of the CANDU power station range about 1 mill/kWh or less. This value compares very favorably e.g. with fuelling costs of LWR stations, and is attributed to the low fabrication costs of CANDU fuel elements. These costs can be kept low because of the simple design of the CANDU fuel elements and their convenient dimensions.

The favorable cost values /9/ published by Canada are frequently regarded with some scepticism. Evidentlv, the cost advantages derived from the utilization of enriched uranium will increase with increasing fabrication costs. Therefore, the fabrication costs have been varied in the discussion about economy.

Figs. 5, 6, 7 and 8 show the total fuelling costs in percent, related to the case of natural uranium loading (U_{nat} - fuelling = 100 %). For the computation of the results shown in these figures the costs of fuel bundle fabrication were taken to be $ 30/kg fuel in Fig. 5, $ 40/kg fuel in Fig. 6, $ 50/kg fuel in Fig. 7, and $ 60/kg fuel in Fig. 8. These values cover the range of actual fabrication costs. The cost comparison within each figure was made in relation to the natural uranium fuelling scheme (U_{nat} - fuelling = 100 %) assuming the same fabrication costs for fuel bundles containing natural uranium or enriched uranium. The favorable economic advantages demonstrated in these comparisons should remain even if fabrication costs for the fuel bundles containing enriched material should be slightly higher than for natural uranium fuel e.g. on account of criticality monitoring..

According to Canadian estimates /6/, as published in 1968, the increase in fuel fabrication costs should be of the order of 15% when enriched uranium is used instead of natural uranium. To show that substantial savings in total fuelling costs are to be anticipated - even when extra costs for handling enriched material plus contingencies are explicitely taken into account - another comparison was made between total fuelling costs, when enriched fuel is used, and the respective costs for natural uranium fuel, cf. Fig. 9. In this calculation the fabrication costs for the fuel bundles containing natural uranium were assumed to be $ 35 per kg, while the fabrication costs for fuel bundles containing enriched uranium were assumed to be 50 % higher, i.e., $ 50 per kg. Even with this large penalty for the handling of only slightly enriched material, substantial savings can be achieved in the total fuelling costs. In Fig. 9 - just as in Figs. 5 to 8 - the total fueling costs for the enriched fuel scheme including this 50 % penalty are plotted as percentage values of the natural uranium fuelling costs. Still, this part of the burnup-enrichment plane which is most promising for our purposes (around 1.1% U-235 enrichment and 20 MWd/kg of burnup), shows relative fuelling cost values of about 80 %, indicating the possibility of a 20 % saving or more in comparison to natural uranium fuelling.

Figs. 5 - 9 prove the opportunity of considerable cost reductions as a result of alternative fuelling. This should warrant a large economic incentive to change to the use of enriched fuel in CANDU reactors.

4. Possible Savings in Planning Nuclear Power Plant Extensions

The use of natural uranium instead of enriched uranium evidently calls for the provision of enrichment services. The annual demand of separative work of one single power station has been indicated in Fig. 4. To give a rough idea of the total demand of separative capacity required, we refer to information about extension plannings in Canada (cf. Fig. 4; Prospective Canadian nuclear plants to AD 2000 in /9/). Fig. 10 shows the planned cumulative nuclear power capacities planned in Canada until 1990. We can see from Fig. 10 that about 10 tonnes of SWU are required every year to fuel a 500 MW_e CANDU nuclear power station. This relationship considering refuelling only and not the requirements for the first core gives the annual demand of separative work, which can be read from the ladder on the right side of Fig. 10. The future demand of separative work represented in Fig. 10 is based on the assumption of a 100 % changeover of all Canadian CANDU power stations to loading with enriched uranium. This is certainly not a realistic assumption. However, an extrapolation to possible realistic cases implying that about 1/4 or 1/10 of all CANDU power stations are charged with enriched fuel, can be made easily by reducing accordingly the values of separative work demands on the ladder. This allows simple estimates to be rapidly made.

In fact, the transition to the use of enriched material in Canadian nuclear power stations could take the following course: In 1988 a prototype enrichment plant with a capacity of 250 tonnes of SWU/a will start operation. In the steady-state case this plant would be able to supply roughly 10.000 MW_e of CANDU nuclear power capacity. To gather experience with the new mode of power station operation, only part of the power stations operating as from 1988 will be run on enriched uranium. The necessary preliminary studies, i.e., irradiation of single fuel element bundles for test purposes, licensing procedure, etc., could be terminated until 1988. During the period from 1988 to 2000 more than 90.000 MW_e nuclear power capacity in total will be commissioned in Canada according to planning /9/.

About one fourth to one fifth of this added capacity will be available for trial operation with enriched material so that in the year 2000 about 20.000 MW_e will be installed in CANDU nuclear power stations operating on enriched fuel. The entire production of the prototype enrichment plant (capacity 250 te SWU/a during the 12 years from 1988 to 2000, i.e., total production 3000 t SWU) would approximately meet the total enrichment requirement for a trial operation of this order of magnitude.

The consequences of trial operation to the extent described above would be:

- Generation of roughly 100.000 MW_ea according to this new mode of operation and gathering experience in the technical and economic fields.

- Savings in natural uranium consumption of about 10 million lbs of U_3O_8.

- Considerable financial savings which in the last year of trial operation alone, when 20.000 MW_e of CANDU power station capacity will be supplied with enriched uranium, would amount to more than 60 million $.

These figures underline the advantages offered by this mode of operation from the economic and industrial point of view. Another fact must be underlined, namely that the CANDU concept is not impaired by charging with enriched uranium: If necessary, these nuclear power stations can return at any time to natural uranium operation.

5. Summary

According to this estimate the consequences of utilization of enriched uranium in CANDU reactors can be judged in a positive way under economic and industrial aspects so that a more detailed study seems to be quite advisable.

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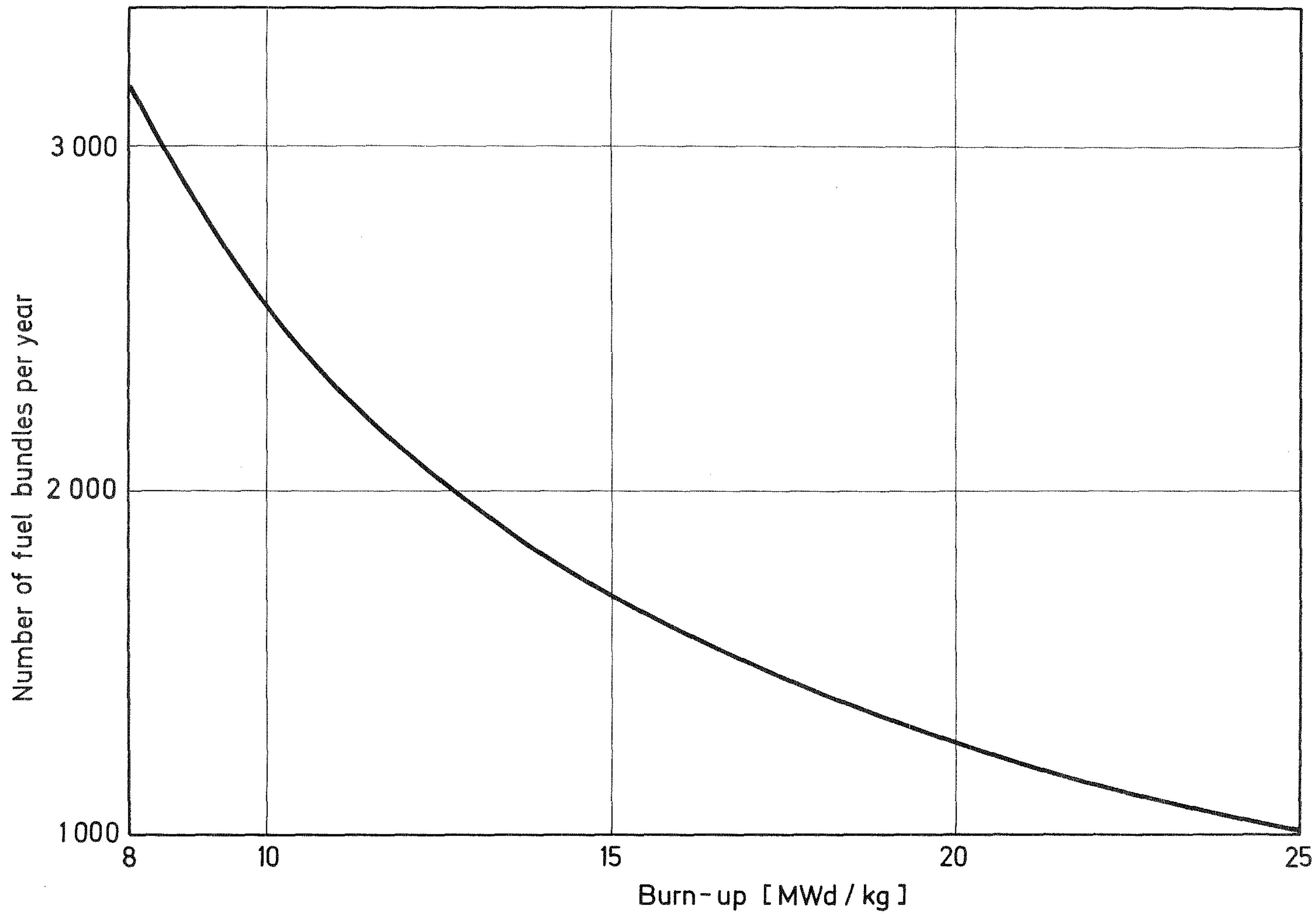

Fig.1

ANNUAL DEMAND OF FUEL BUNDLES FOR A SINGLE 500 MW_e -CANDU vs. BURN - UP

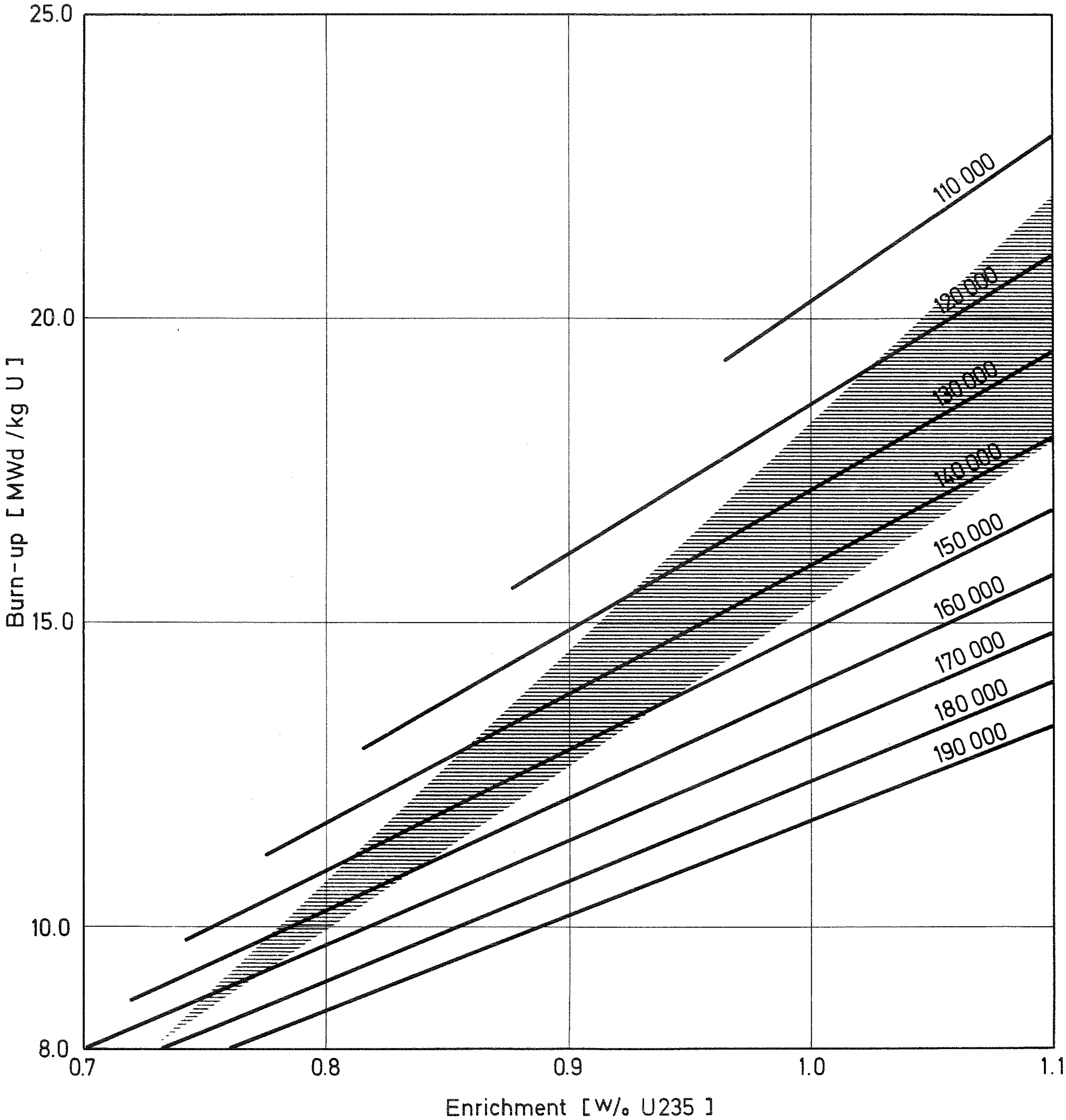

Fig. 2

Annual demand of natural uranium in lbs U_3O_8 for fuelling

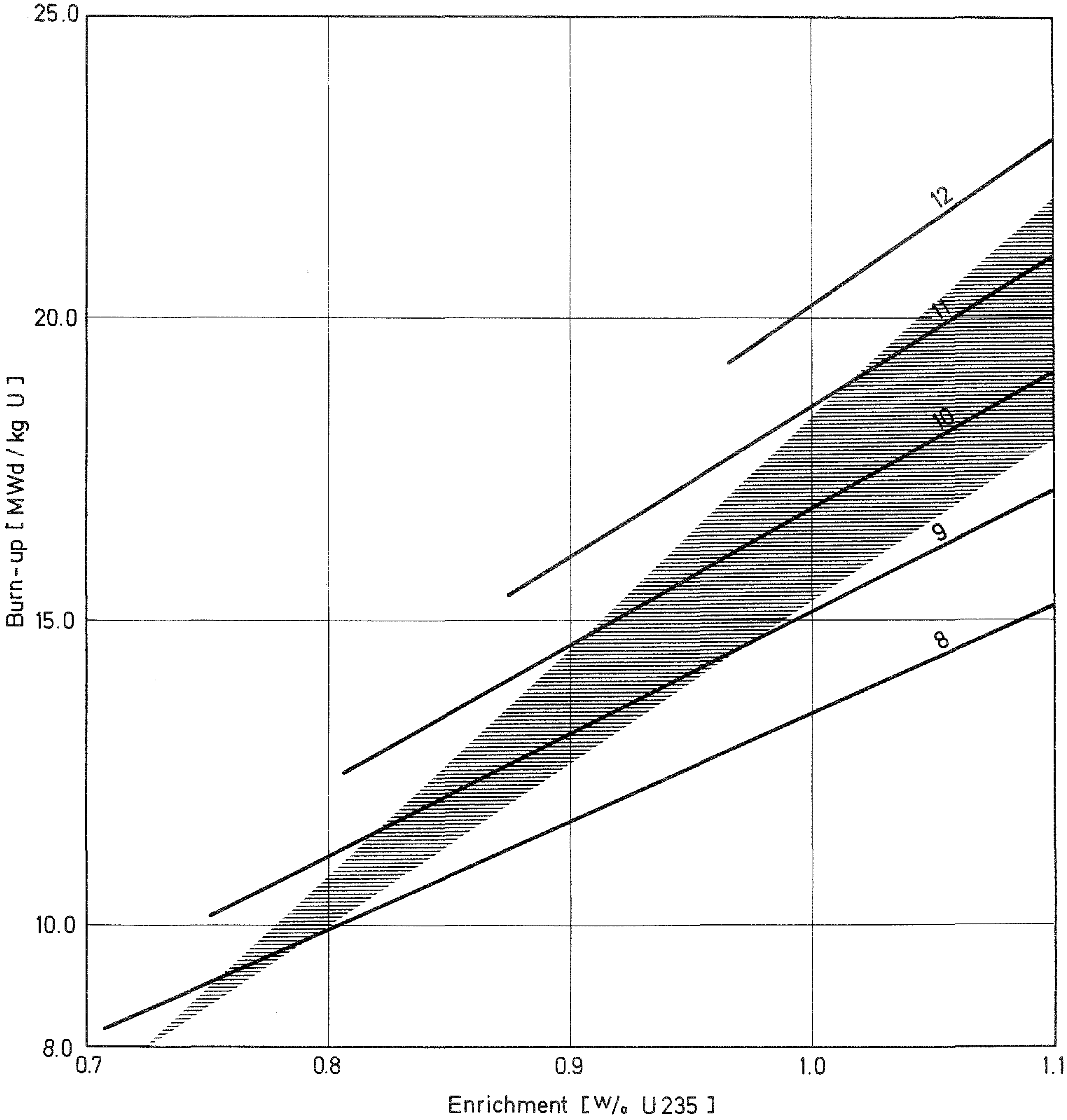

Fig. 3

Uranium utilization in MWd_{th} per kg natural uranium mined

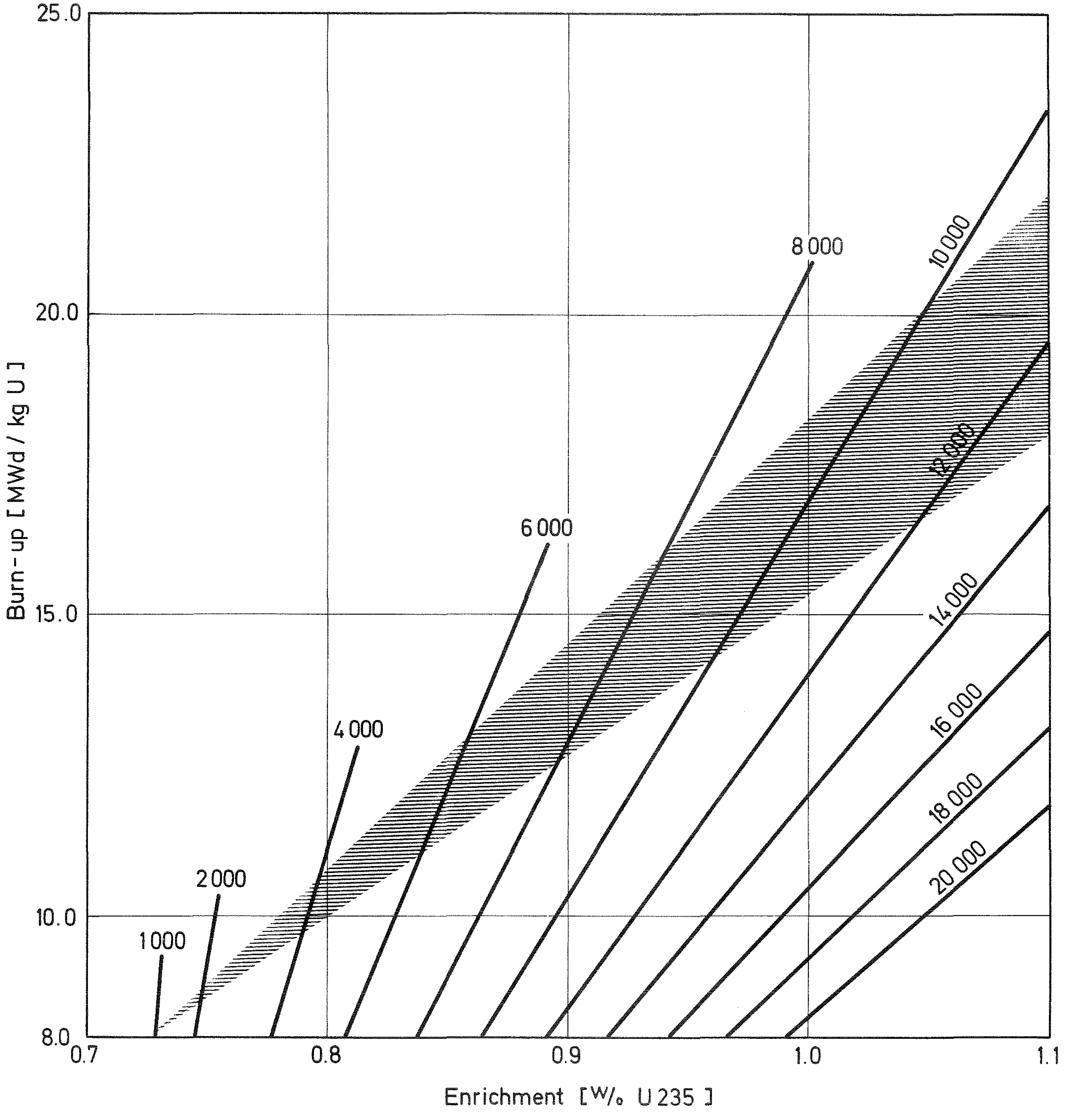

Fig. 4

Annual demand of separative work in kg SWU

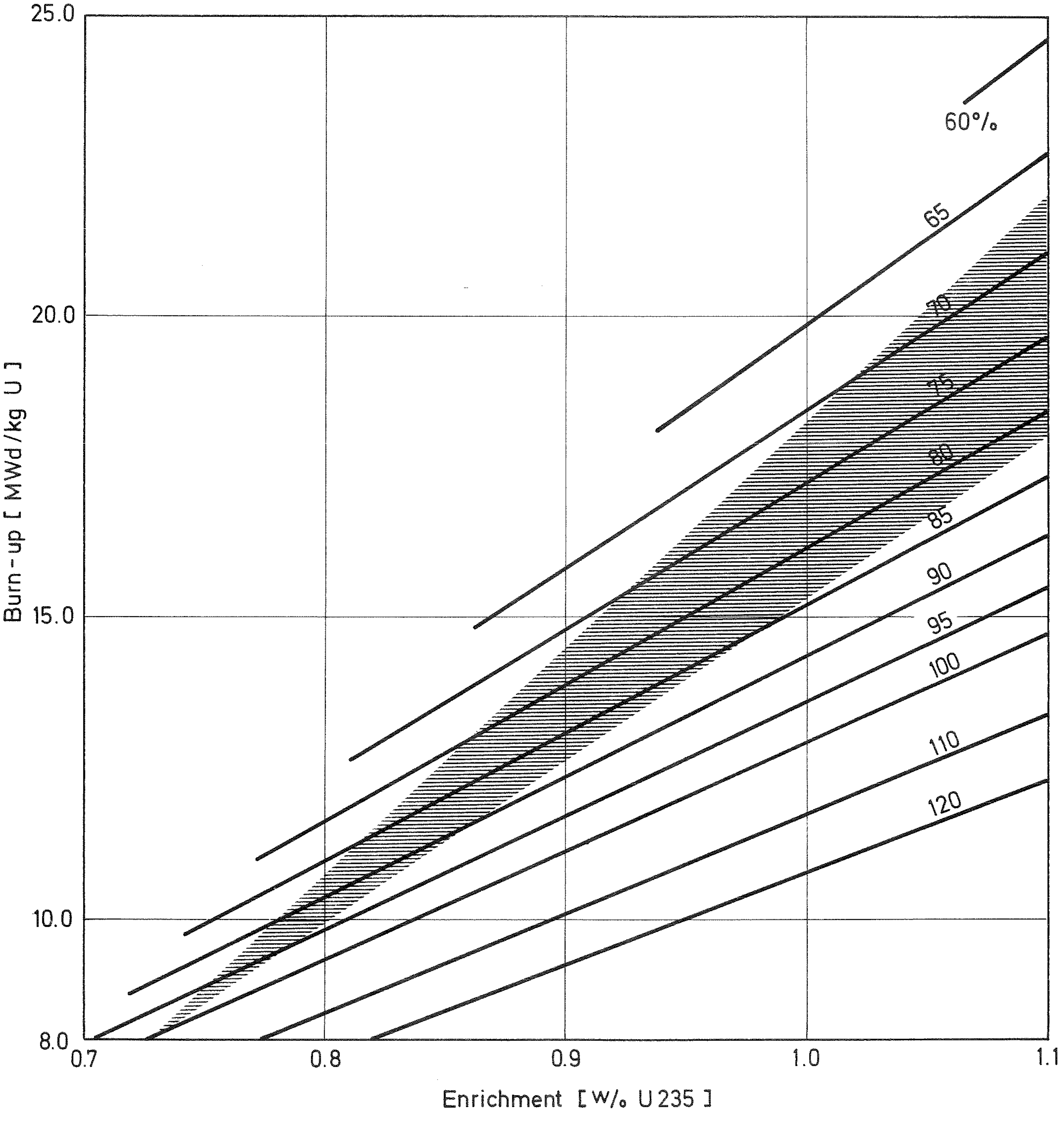

Fig. 5

Total relative fuelling costs in percent compared to U_{nat}-fuelling = 100%

Fuel bundle production costs were assumed to be 30 US-$/kg fuel.

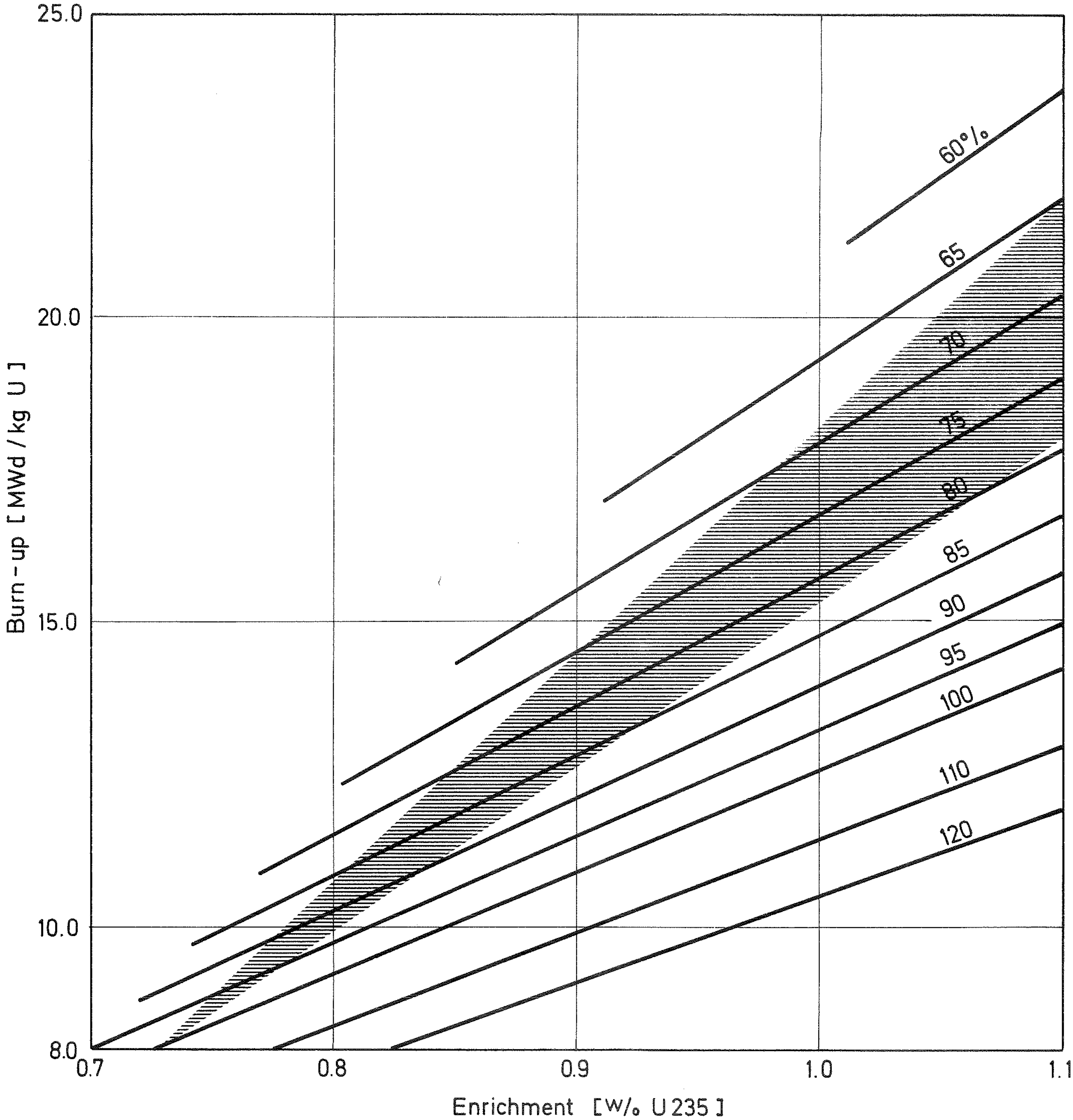

Fig. 6

Total relative fuelling costs in percent compared to U_{nat}-fuelling = 100%

Fuel bundle production costs were assumed to be 40 US-$/kg fuel.

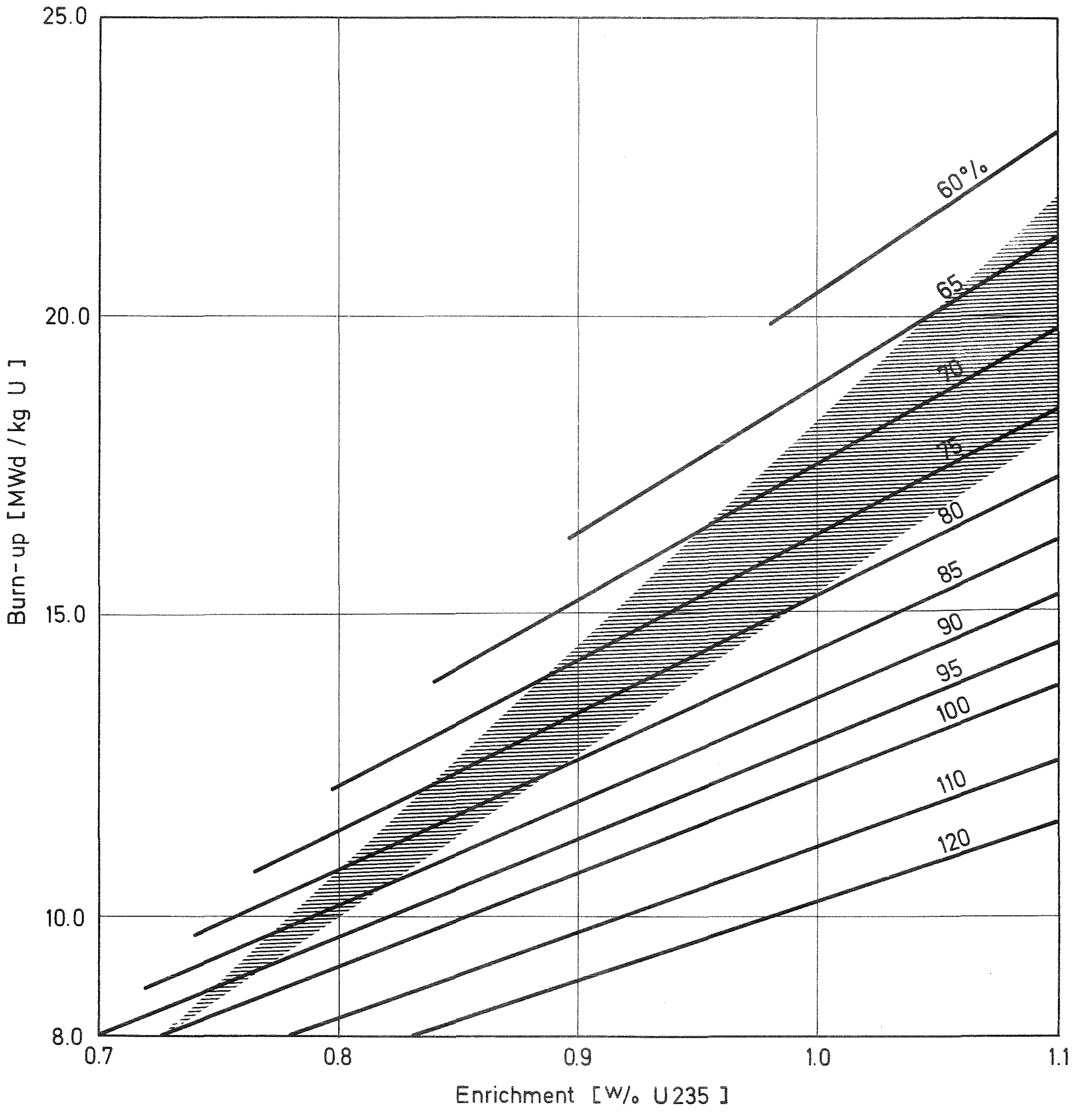

Fig. 7

Total **relative** fuelling costs in percent compared to U_{nat}-fuelling = 100%

Fuel bundle production costs were assume to be 50 US-$/kg fuel.

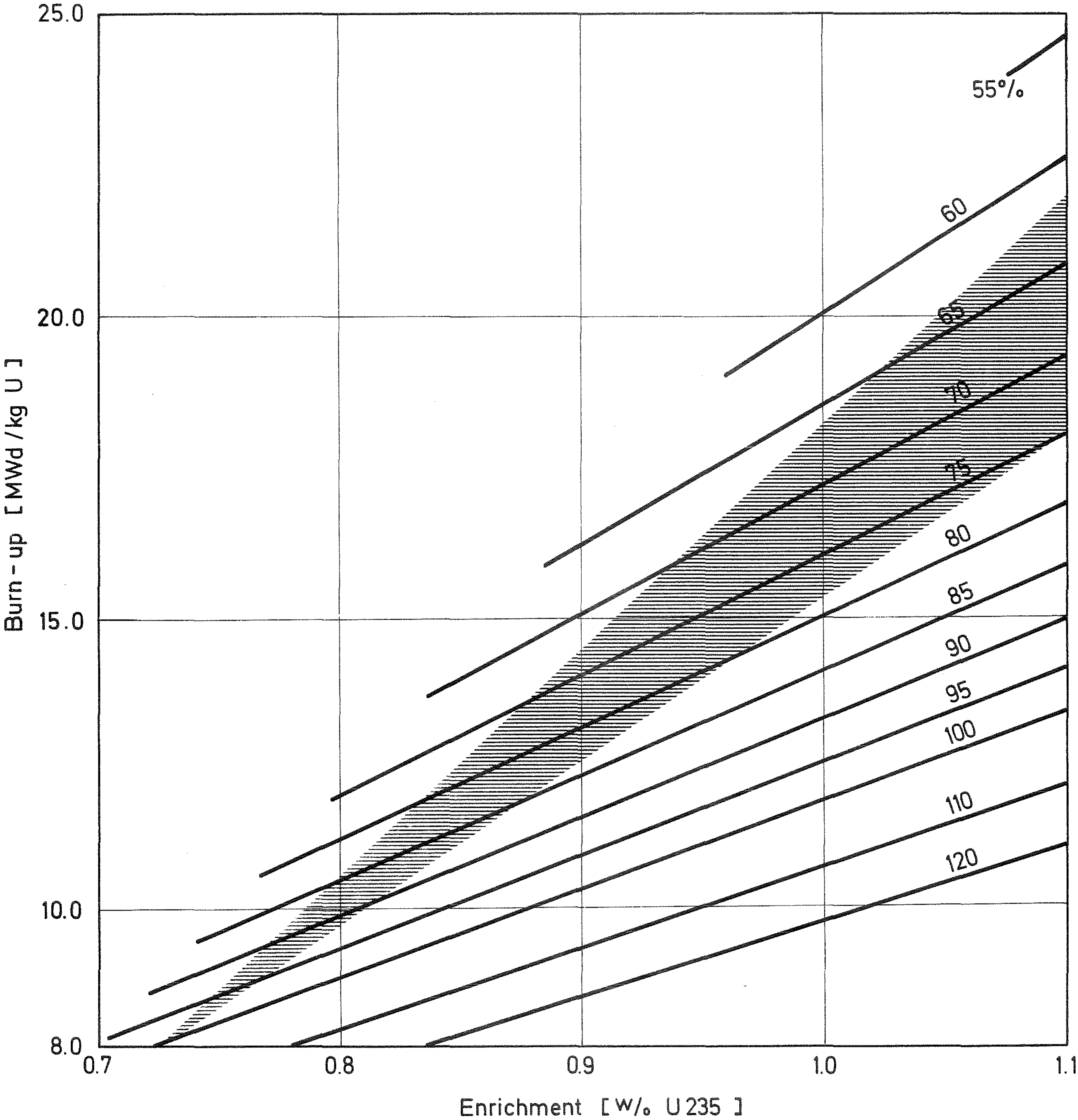

Fig. 8

Total relative fuelling costs in percent compared to U_{nat}-fuelling - 100%.

Fuel bundle production costs were assumed to be 60 US-$/kg fuel.

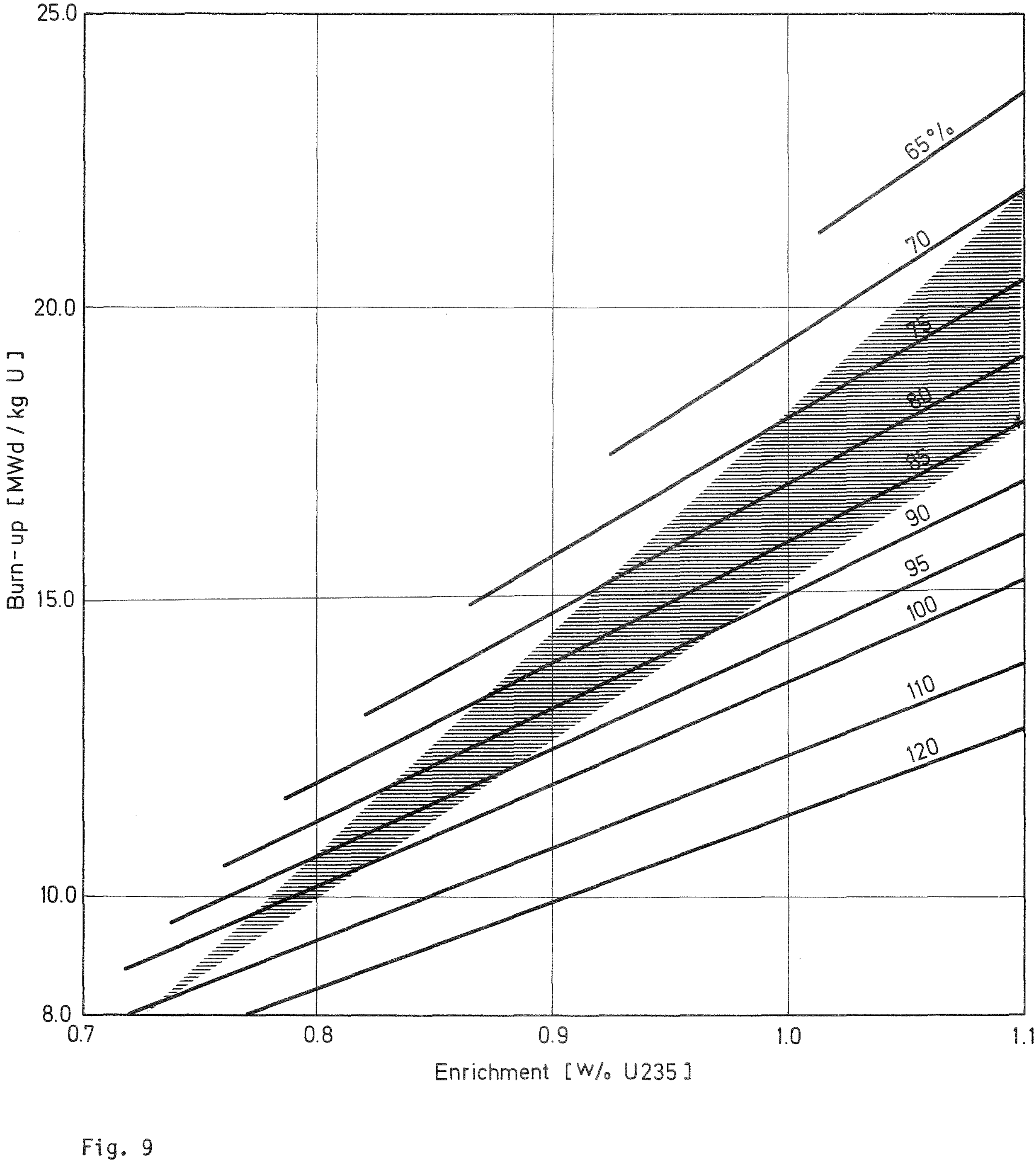

Fig. 9

Total relative fuelling costs in percent compared to U_{nat}-fuelling = 100%
For this comparison fuel bundle production costs were assumed to be 35 US-$/kg U_{nat} fuel for the natural uranium loading but were raised to 50 US-$/kg for enriched uranium fuel fabrication.

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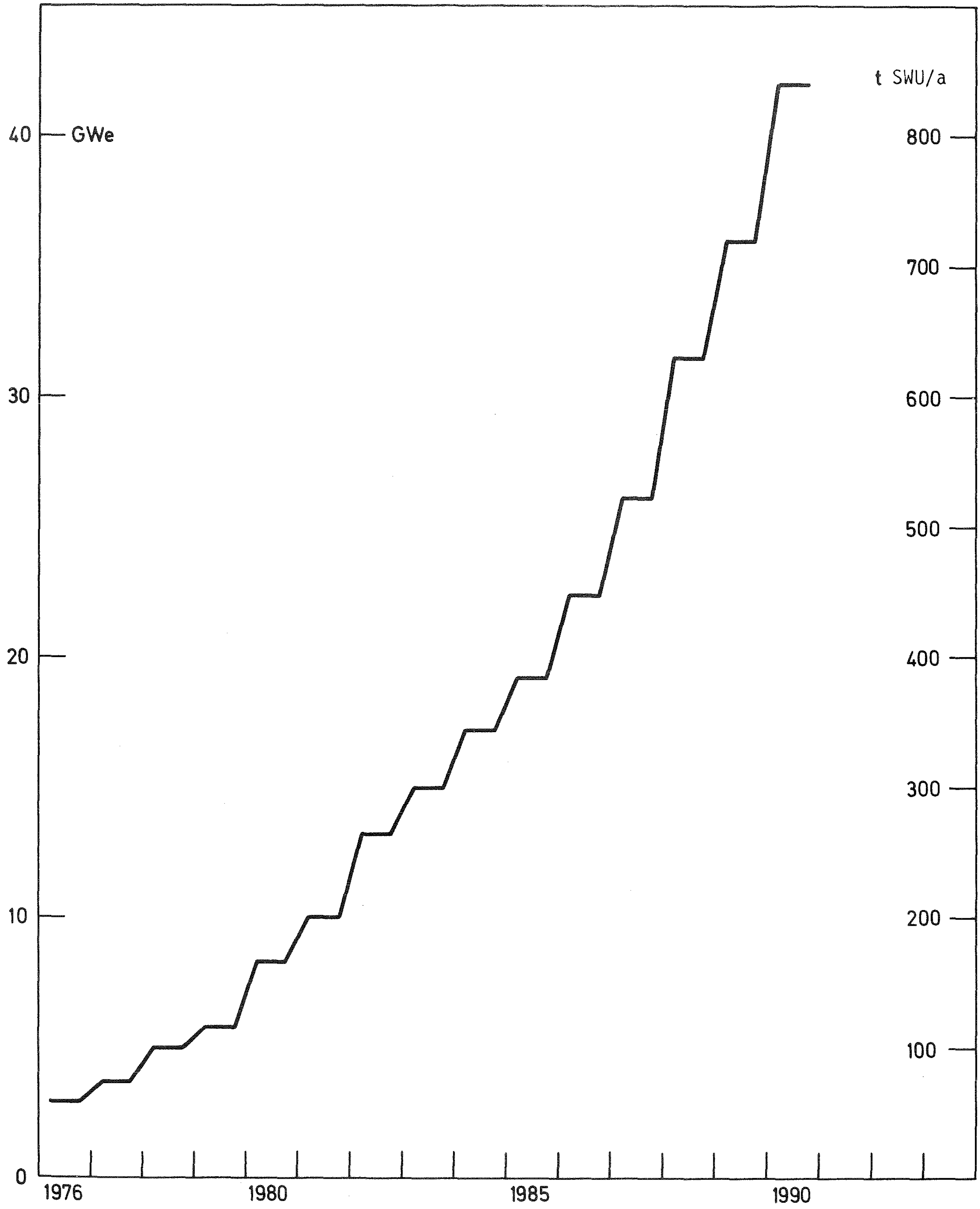

Fig. 10
Canadian nuclear power planning and separative work demand if all CANDU-reactors were to use 1% U-235 enriched fuel.