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Production Cost Parameter Analysis for Fast Reactor Fuel Elements

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PRODUCTION COST PARAMETER ANALYSIS FOR FAST REACTOR FUEL ELEMENTS +)

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CONTENTS

1. INTRODUCTION

In the development of fast breeder reactors for power production the economy of the fuel cycle significantly influences the total energy production cost. Therefore many investigations are related to the technical and economic elements of the fuel cycle. One such element is the fabrication of the fuel pins. This paper shall deal with the economic aspects of such a fabrication in industrial scale, taking into account a sensitive dependence of the unit costs on various technical and economic parameters.

Up to now various schemes concerning the pin fabrication costs were used in the calculational optimization of the fuel cycle. One of the first pin cost evaluations was carried out by Collins [1], who calculated already the parameter dependence using proper numerical examples. Often the single pin cost were assumed to be a constant figure [2]. This is equivalent to the hypothesis of a relative cost decrease with the square of increasing fuel diameter. More recent investigations specified the input data for optimization work with additional details [3,4,5]. The very recent fuel cycle optimization of Gupta [6] now considers fully the principles of this work, as far as the detailed parameter dependence is concerned.

All the present results refer to oxide type fuel. The background for the evaluation are fuel pin test production within the framework of our overall fuel development program, which we described elsewhere [7]. In this connection extensive numerical cost data were supplied by the Alkem and Nukem companies [8] which is gratefully appreciated here.

2. OBJECTIVES AND ASSUMPTIONS

2.1 Scope of Problems

For the fuel cycle optimization it is necessary to have the pin production costs in units per contained uranium and plutonium element. If we principally assume an "integrated" pin design with fuel zone, axial blanket regions and fission gas plenum, we have to divide the production costs in two independent portions:

- F are the specific costs for the fuel zone of the pins, expressed in DM per kg U and Pu contained in this zone. Here all reasonably applicable cost contributions are included as for
  - fuel production
  - cladding tubes and end plugs
  - pin production out of fuel and cladding.

  The figure F contains also the cladding tube costs for the fission gas plenum, but not the tube for the axial blankets.

- B are the additional specific costs for the axial blankets in DM per kg U in the blanket zones. It contains the production of the fertile material and additional tube costs. It does not contain any contributions to end plugs and final pin testing. These and similar expenses are also due to pins without any axial blanket and hence attributable to F.

A fundamental assumption for the whole analysis is - as mentioned above - the integrated pin design. For the evaluation of the numerical cost data the pin features of a 1000 MWe fast reactor reference design ("Na1") were used [9]. The typical length distribution of the various parts is sketched in Fig.1. The typical fuel is pelletized mixed oxide with about 15 % PuO_2 and a smeared density of 85 % of the theoretical value.

Summarizing the objectives of this paper: It is intended to establish the pin production costs F and B, respectively, in their analytical relationship to technical and economic parameters.

2.2 Parameter Evaluation

The following parameters are considered in the cost analysis:

- Fuel and fertile material diameter d (in mm)
- Fuel length L_F (in mm)
- Axial blanket length L_B (in mm)
- Production capacity C_F of Pu-containing fuel (in tons of UO_2-PuO_2 per year)

In an integrated pin design, fuel and fertile material diameter are assumed to be identical. The values of d are defined to be the nominal internal diameter of the cladding tubes (not the outer diameter of pellets). For fast reactor purposes it is appropriate to consider the

diameter range of $5.0 \leqq d \leqq 8.0$ mm.

The fuel length L_F is defined to be the pure length of the fuel zone within the pin. Although the costs of end plugs and fission gas plenum are attributed to the fuel pin costs, their length is not included in L_F. Current fast reactor reference designs suggest to take into account a

fuel length range of $400 \leqq L_F \leqq 1200$ mm.

The axial blanket length is again the pure length of fertile material in the pin. It includes both parts (if present) of the blanket zone, below and above the fuel. A reasonable variation gives an

axial blanket length range of $300 \leqq L_B \leqq 900$ mm.

The production capacity must be oriented towards the expected necessities. The lower limit of a production facility is the need of one large fast reactor power station. This corresponds to about 10 tons of UO_2-PuO_2 fuel per year. An upper limit may be at about 100 tons of mixed oxide throughput, taking into account on the one side the supply of fast reactor populations in the future, on the other side the increasing transportation costs of centralized larger production units. Hence we have to consider a

fuel production capacity range of $10 \leqq C_F \leqq 100$ tons mixed oxide per year

If we should consider the supply of the necessary blanket fuel out of a facility related directly to the Pu pin production unit, there would be, of course, a decrease of specific blanket costs with increasing capacity of that additional facility. The already established market for fabricated UO_2, however, induces to have supplied the necessary UO_2 pellets for the blanket by large facilities which are economically optimized due to the large needs of UO_2 for other reactor systems.

2.3 Accessory Assumptions

Of course there could be envisaged a lot of other parameters, which influence the calculations, as e.g. the material type and wall thickness of tubing, the uranium and plutonium source material price, the Pu losses, the production time, the rate of interest and the utilization of capacity. As it is not possible to handle such a complex system in full generality, the following accessory assumptions rule out such variations, defining:

a) For the tubing, commercially available austenitic stainless steel with a wall thickness of about 0.35 mm is assumed.

b) The cost data are only production costs, they do not contain the price of uranium and plutonium source material.

c) There is no increment included in F, which covers the value of Pu losses during production. But the considered production routine is managed in such a way as to loose less than 1 % of the Pu.

d) There are not included any charges and interest for the Pu in the production facility. Hence there is also no special incentive concerning production time.

e) The production is completely continuous and the utilization of the plant capacity is assumed to be 100 %. No allowance is made for startup and adjustment difficulties.

f) All calculations are based on present general cost and price level and also on the presently available fabrication techniques.

3. PARAMETER ANALYSIS OF FUEL PIN COSTS

3.1 Cost Increments and Numerical Data

For the production of the pin with the fuel zone the total specific costs F are divided in 8 increments:

- F_1 Supply of sinterable UO_2 powder (without uranium source material value)

- F_2 Fabrication of sinterable PuO_2 powder (without plutonium value)
- F_3 Fabrication of mixed oxide pellets
- F_4 Costs for chemical and isotopic analysis of the Pu content and composition
- F_5 Supply of tubes, end plugs and other accessories
- F_6 Fabrication and finishing of the fuel pins inclusive the weighing, drying and filling steps, the final welding and decontamination
- F_7 Control costs for the supplied tubing and the end control of the finished pins
- F_8 General costs, which include costs for active and inactive stores, supply and maintenance, inactive laboratories, workshops, library etc., health and safety.

It should be mentioned that the general costs do not contain overheads, calculational interest etc., because these general items are already properly distributed to all the increments.

The basis for the further synthesis of the analytical relationships are now a set of commercially calculated numerical data which were supplied by the industry /‾8_7, as already mentioned. This set contains the cost increments for all parameter combinations out of

fuel diameter	d =	5; 6; 7 mm
fuel length	L_F =	525; 955 mm
production capacity	C_F =	20; 100 tons UO_2-PuO_2/year

The data are presented in TABLE I. It must be emphasized that they are calculated separately, that means without applying hypothetical relationship.

3.2 The Terms for the Cost Increments

The analytical investigation is carried out separately for both calculated production capacities. Hence the increments F_1, F_2 and F_4, which are independent of fuel diameter and length, need not to be further treated. For the increment F_3 a mathematical form is chosen, which includes the old approach of constant pin costs plus a proper correction. "Constant pin costs" would ask for

$$F_3 \cdot d^2 = a = \text{constant}$$
$$\text{or} \qquad F_3 = \frac{a}{d^2} \tag{1}$$

As the calculated numerical data do not fit to that simple assumption, a corrective addition, which is reciprocal to the diameter, is added, resulting in:

$$F_3 = \frac{a}{d^2} + \frac{b}{d} \tag{2}$$

The constants a and b are determined using the numerical "boundary" values for d = 5 and 7 mm and slight adjustments to get integers. For the case of 20 tons/y-capacity the result is

$$F_3 = \frac{892}{d^2} + \frac{1637}{d} \tag{3}$$

As it can be verified, the greatest difference between the "source data set" and the analytical term is less than 1 %.

The other cost increments, however, need a double treatment. The procedure shall be demonstrated here for the increment F_6 (pin production), again at 20 tons/y capacity. At first an expression F_6' - analogous to F_3 - is derived using the numerical data for L_F = 525 mm. Result:

$$F_6' = \frac{8872}{d^2} + \frac{1090}{d} \tag{4}$$

Now it can be stated that the relation between the numerical values of both calculated lengths are fairly constant. Example:

$$\left.\begin{aligned} 344/569 &= 0.604 \\ 262/438 &= 0.598 \\ 205/334 &= 0.614 \end{aligned}\right\} \text{Average: } 0.605$$

Assuming that the costs are in linear dependence upon fuel length, the expressed average value of this relation allows to include the interconnection to the fuel length into the formula as follows:

$$F_6 = F_6' \left\{ 1 - 9.19 \cdot 10^{-4} (L_F - 525) \right\} \qquad (5)$$

The same procedure can be applied to all (non-constant) cost increments successfully, both in the 20 ton/y- and in the 100 ton/y-capacity case. The result is a complete set of analytical terms for the cost increments. TABLES II and III bring the compilation of those terms. A detailed numerical recheck showed that in all cases the differences between analytical terms and "source data set" remain below a few DM per kg. Such small deviations are completely unessential, as the inacuracy in the calculated source data set is certainly somewhat higher.

3.3 The Generalized Cost Formula

The next task now is to condense the cost increment terms of TABLE II and III into single expressions for both calculated plant capacities, respectively. The longish but principally simple algebraic treatment leads to the following intermediate results

- for C_F = 20 tons per year:

$$F = \sum_r F_r = 271 + \frac{3505}{d} + 3072 \left(\frac{1}{d} + \frac{5.88}{d^2} \right) \left(1 - \frac{L_F}{1557} \right) \qquad (6)$$

- for C_F = 100 tons per year:

$$F = \sum_r F_r = 145 + \frac{1932}{d} + 1454 \left(\frac{1}{d} + \frac{7.06}{d^2} \right) \left(1 - \frac{L_F}{1470} \right) \qquad (7)$$

The last terms in the expression (6) and (7) are already quite similar, which - of course - had to be expected. In order to generalize the system further, the coefficients in the brackets are numerically averaged without undue effect to the accuracy, resulting in:

$$\left(\frac{1}{d} + \frac{6.5}{d^2} \right) \left(1 - \frac{L_F}{1500} \right) \qquad (8)$$

This modification and an additional slight adjustment of the other numerical coefficients in the "raw" formulae (6) and (7) bring up a generalized combined formula for both production capacities:

$$F = P \left\{ 150 + \frac{1925}{d} + 1470 \left(\frac{1}{d} + \frac{6.5}{d^2} \right) \left(1 - \frac{L_F}{1500} \right) \right\} \tag{9}$$

where the factor P has the single values

- for C_F = 20 tons per year: P = 1.904
- for C_F = 100 tons per year: P = 1.000

The advantage of the generalized formula (9) is that the dependence upon plant capacity could be expressed in the separated "capacity factor" P. This suggests now a final investigation with respect to the influence of the plant capacity.

3.4 The Dependence upon Production Capacity

Commonly accepted calculational rules in industry and chemical engineering - for details see e.g. the very subtle and extensive monography of Kölbel/Schulze [10] - recommend that the total costs R (per year) for a production follow a simple potential law if the plant capacity C changes:

$$R = R_o \left(\frac{C}{C_o} \right)^m \tag{10}$$

The "degression exponent" m is mostly in the range of 0.6 to 0.7. The specific costs F (per kg of produced goods) are derived in dividing R and R_o by the related capacities. Thus:

$$F = F_o \left(\frac{C_o}{C} \right)^{1-m} \tag{11}$$

If we identify now (11) with the cost formula (9) we get the relationships:

$$F_o = \left\{ 150 + \frac{1925}{d} + 1470 \left(\frac{1}{d} + \frac{6.5}{d^2} \right) \left(1 - \frac{L_F}{1500} \right) \right\} \tag{12}$$

C_o = 100 tons per year; $C = C_F$

and hence

$$P = \left(\frac{100}{C_F} \right)^{1-m} \tag{13}$$

In order to determine the exponent 1-m the numerical value of P for C_F = 20 tons/y is introduced into (13) with the result

$$1-m = \frac{\log 1.904}{\log 5} = 0.40 \; ; \quad m = 0.60 \tag{14}$$

The introduction of (14) and (13) in (9) produces the generalized end formula:

$$F = \left(\frac{100}{C_F}\right)^{0.4} \left\{150 + \frac{1925}{d} + 1470\left(\frac{1}{d} + \frac{6.5}{d^2}\right)\left(1 - \frac{L_F}{1500}\right)\right\} \tag{15}$$

This expression may be used in the capacity range between 10 and 100 tons mixed oxide per year.

To get a clearer understanding of the degression exponent m, applicable in this case, the "commercial" elements R_r of the total costs R are investigated. Developing (10) to the relation

$$R = R_o \left(\frac{C}{C_o}\right)^m = \sum_r R_r = \sum_r R_{or} \left(\frac{C}{C_o}\right)^{m_r} \tag{16}$$

one gets the single degression exponents m_r by

$$m_r = \frac{1}{\log (C_o/C)} (\log R_{or} - \log R_r) \tag{17}$$

Introducing the considered capacities C_o = 100 tons/year and C = 20 tons/year the expression (17) becomes specifically

$$m_r = \frac{1}{\log 5} \left(\log R_r^{(100)} - \log R_r^{(20)}\right) \tag{18}$$

According to total cost data produced by Alkem/Nukem [8] the elements R_r can be defined as follows:

- R_1 for buildings and equipments
- R_2 for salaries and wages
- R_3 for supply of base material (UO_2 and cladding)
- R_4 for energy and auxiliary material
- R_5 for research and development
- R_6 for administration and sale
- R_7 for interest and profit

This scheme is now applied to the special parameter constellation $d = 7$ mm, $L_K = 955$, see TABLE IV, which is typical for all cases. One realizes that the single degression exponents are quite different. A proper averaging procedure on the basis of equation (16) leads then to the value of m, which we have already calculated in (14) directly. (The slight difference is due to the fact that in (14) a value for P was used, which was already averaged for the different pin dimensions.)

4. ADDITIONAL COSTS FOR AXIAL BLANKETS

4.1 Available Numerical Data

The additional specific costs for axial blankets B (in DM per kg U contained) do not depend upon blanket length L_B, because there are only expenses for UO_2 and additional tube length, which both are strongly proportional to L_B. We distinguish as "cost increments"

- B_1 Supply of sinterable UO_2 powder (without U value)
- B_2 Fabrication of UO_2 pellets
- B_3 Allocable part of the cladding

The "source data set" in TABLE V was calculated in the same manner as the data for the fuel zone costs. According to the Na1 design the capacities for the axial blanket material must be about the same as for the fuel zone itself. This is only significant for the increment B_3 (cladding), while B_1 and B_2 (UO_2 pellets) are assumed to be constant and established by a large UO_2 market. It should be mentioned that B_1 is equivalent to F_1, the different figures result from the difference in the U content.

4.2 The Parameter Dependent Analytical Expression

As TABLE V demonstrates, there is no major influence of blanket production capacity on the total specific blanket costs. We therefore drop this dependence and consider only the relations versus diameter. As a (more optimistic) rule we propose to apply the 100 jato costs for all blanket designs and fuel zone capacities. In any case these figures indicate the lowest costs which could be expected.

For establishing an analytical expression the same principles as for the fuel zone costs F are applied. It is rather easy to work out a formula as follows:

$$B = \frac{934}{d} - \frac{1243}{d^2} \tag{19}$$

Here B means DM per kg uranium in the blanket and d is the diameter (in mm) of the fertile material.

5. INTERPRETATION OF RESULTS

5.1 Application of the Final Formulae

The end formulae (15) and (19) for both parts of an integrated fuel pin design are repeated in the following final set:

$$\begin{aligned} F &= \left(\frac{100}{C_F}\right)^{0.4} \left\{150 + \frac{1925}{d} + 1470\left(\frac{1}{d} + \frac{6.5}{d^2}\right)\left(1 - \frac{L_F}{1500}\right)\right\} \\ B &= \frac{934}{d} - \frac{1243}{d^2} \end{aligned} \tag{20}$$

They produce separately the specific costs for the fuel zone and for the blanket, respectively. If the average specific costs K per kg U and Pu contained in fuel and fertile material are required, a simple procedure leads to:

$$K = p \cdot F + (1-p)\,B \tag{21}$$

where p is the weight fraction of the fuel zone and hence 1-p the fraction of the fertile material in the pin. If fuel and fertile density are equal that fractions can also simply be expressed by the lengths:

$$p = \frac{L_F}{L_F + L_B} \tag{22}$$

As a numerical example let us calculate the production costs for a pin, taking as parameter constellation:

$d = 5.5$ mm

$L_F = 750$ mm
$L_B = 2 \times 300$ mm } smeared density 85 % of th.d.

$C_F = 50$ tons UO_2-PuO_2 per year

The specific fuel zone costs are:

F = 1046 DM/kg U+Pu in the fuel

and the additional specific costs for the axial blankets:

B = 129 DM/kg U in the blanket

With an actual value of $p = 750/(750+600) = 0.556$ the average costs are according to (21):

K = 639 DM/kg U+Pu total.

To get the costs for a single pin, we evaluate the (U+Pu)-amount in the pin to be about 263 g of U+Pu. Hence the single pin costs are

about 168 DM/pin.

5.2 Interpretative Graphs

As a comprehensive demonstration of the final results in (20), some graphs showing the most interesting parameter ranges for fast reactor purposes are attached. Fig.2 brings the specific fuel zone costs F at the reference capacity 100 tons of mixed oxide per year. If another plant capacity is relevant, one has to apply the proper capacity factor P out of Fig.3 onto the specific cost values of reference capacity. Finally Fig.4 shows the additional specific costs for axial blankets.

6. CONCLUSIVE REMARKS

In view of these results and also considering the requirements for the economic analysis of a fast reactor fuel cycle we may outline some remarkable features and the applicability of our cost formulae with some conclusive remarks as follows:

a) It is most obvious that in the cost formulae the terms proportional to $1/d^2$ are of minor influence than the terms proportional to $1/d$. Therefore the hypothesis of "constant costs per pin" is only a very rough approach.

b) The absolute accuracy of the results depends mostly upon the numerical input data, of course, there might be future changes due to increasing experience and newly developed techniques. The relative accuracy for, say, a comparison between different fuel diameters is certainly much higher.

c) The reference Pu content in the fuel was 15 wt.% PuO_2. There should not be any significant changes in our results, if a slightly different Pu content (in the range between 10 and 20%) is assumed. It is also assumed that there is no difference taking either natural or depleted uranium as fertile material.

d) The reference cladding material was of stainless steel type. If another material must be included in a calculation, e.g. a Nickel base alloy for steam cooling purposes or an advanced type without well established market, there might be a significant increase in the cladding cost increments F_5 and B_3.

e) The reference oxide fabrication type was pelletized fuel. In preliminary estimates also the vibrocompaction technique was evaluated to some extent. The first indication was that there might not be major differences. However, the development still to come may produce new possibilities, e.g. in the very cost sensitive production steps of the oxide powder for vibration.

f) The reference utilization of the calculated production facilities was 100 %. It might happen that - due to non continuous power production schemes (reloading of reactors mostly in summer time!) - the utilization is significantly lower, e.g. only 70 or 80 %. This would, of course, influence the cost situation adversely.

g) The final assemblage of the fuel pins is not included in our formulae. It is emphasized that this step involves an essential expense which could amount up to 50 % of the pin costs.

h) At a fast reactor fuel cycle in asymptotic condition the higher Pu isotopes are markedly increased. The "refabrication" technique therefore may differ from the presently evaluated fabrication technique in some steps taking into account the higher dose rates of "dirty" plutonium. It is expected that the cost situation will not be influenced very much.

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TABLE I Numerical Source Data Set for the Fuel Pin Costs F in Deutsche Mark (DM) per kg U and Pu

		20 tons of mixed oxide per year						100 tons of mixed oxide per year					
	Fuel Production Capacity C_F	20 tons of mixed oxide per year						100 tons of mixed oxide per year					
	Fuel Length L_F (mm)	525			955			525			955		
	Fuel Diameter d (mm)	5	6	7	5	6	7	5	6	7	5	6	7
F_1	Supply of UO_2 Powder	35	35	35	35	35	35	35	35	35	35	35	35
F_2	Fabrication of PuO_2 Powder	152	152	152	152	152	152	59	59	59	59	59	59
F_3	Fabrication of Pellets	363	300	252	363	300	252	171	152	131	171	152	131
F_4	Pu Analyses	84	84	84	84	84	84	50	50	50	50	50	50
F_5	Supply of Cladding	179	129	97	152	111	83	133	96	73	114	82	62
F_6	Pin Fabrication	569	438	334	344	262	205	322	240	188	193	146	113
F_7	Control Costs	215	162	127	122	93	72	111	83	66	60	46	38
F_8	General Costs	257	239	223	229	215	205	100	92	86	93	82	79
$F = \sum_r F_r$	Total	1854	1539	1304	1481	1252	1088	981	807	688	775	652	567

TABLE II Fuel Pin Cost Increment Terms for 20 tons/year Capacity

$$F_1 = 35$$

$$F_2 = 152$$

$$F_3 = \frac{1637}{d} + \frac{892}{d^2}$$

$$F_4 = 84$$

$$F_5 = \left(\frac{139}{d} + \frac{3780}{d^2}\right)\left\{1 - 3.37 \times 10^{-4} (L_F - 525)\right\}$$

$$F_6 = \left(\frac{1090}{d} + \frac{8872}{d^2}\right)\left\{1 - 9.19 \times 10^{-4} (L_F - 525)\right\}$$

$$F_7 = \left(\frac{424}{d} + \frac{3255}{d^2}\right)\left\{1 - 10.0 \times 10^{-4} (L_F - 525)\right\}$$

$$F_8 = \left(\frac{2251}{d} - \frac{4830}{d^2}\right)\left\{1 - 2.23 \times 10^{-4} (L_F - 525)\right\}$$

TABLE III Fuel Pin Cost Increment Terms for 100 tons/year Capacity

$$F_1 = 35$$

$$F_2 = 59$$

$$F_3 = \frac{1072}{d} - \frac{1085}{d^2}$$

$$F_4 = 50$$

$$F_5 = \left(\frac{126}{d} + \frac{2695}{d^2}\right)\left\{1 - 3.40 \times 10^{-4} (L_F - 525)\right\}$$

$$F_6 = \left(\frac{581}{d} + \frac{5145}{d^2}\right)\left\{1 - 9.23 \times 10^{-4} (L_F - 525)\right\}$$

$$F_7 = \left(\frac{230}{d} + \frac{1627}{d^2}\right)\left\{1 - 10.29 \times 10^{-4} (L_F - 525)\right\}$$

$$F_8 = \left(\frac{857}{d} - \frac{1785}{d^2}\right)\left\{1 - 2.02 \times 10^{-4} (L_F - 525)\right\}$$

TABLE IV Commercial Cost Elements for Pin Production (without Blanket) at $d = 7$ mm, $L_F = 955$ mm

Cost Elements	Cost per year $R_r^{(20)}$ (10^6 DM)	$R_r^{(100)}$ (10^6 DM)	Degression Exponent m_r
R_1 - Buildings and Equipment	3.139	8.935	0.650
R_2 - Salaries and Wages	5.280	14.192	0.614
R_3 - Base Material	1.844	7.100	0.838
R_4 - Energy and Auxiliaries	3.020	6.639	0.489
R_5 - Research and Development	1.144	1.800	0.282
R_6 - Administration and Sale	2.472	4.855	0.419
R_7 - Interest and Profit	2.535	6.528	0.588
$R = \sum_r R_r$ - Total Costs	19.434	50.049	0.588

TABLE V Source Data Set for the Additional Blanket Cost B in Deutsche Mark (DM) per kg U

Blanket Production Capacity	20 tons UO_2/year			100 tons UO_2/year		
Fertile Material Diameter (mm)	5	6	7	5	6	7
B_1 Supply of UO_2 Powder	41	41	41	41	41	41
B_2 Fabrication of Pellets	51	48	42	51	48	42
B_3 Cladding	61	45	34	45	33	25
$B = \sum_r B_r$ Total	153	134	117	137	122	108

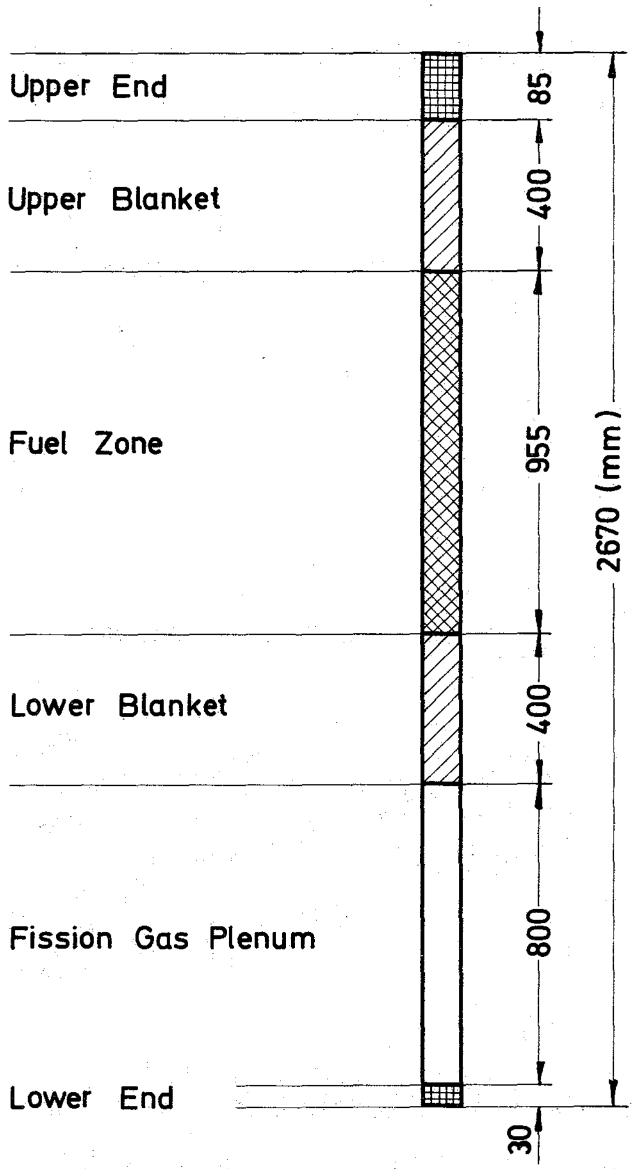

Fig. 1 LENGTH DISTRIBUTION IN "Na 1" PIN DESIGN

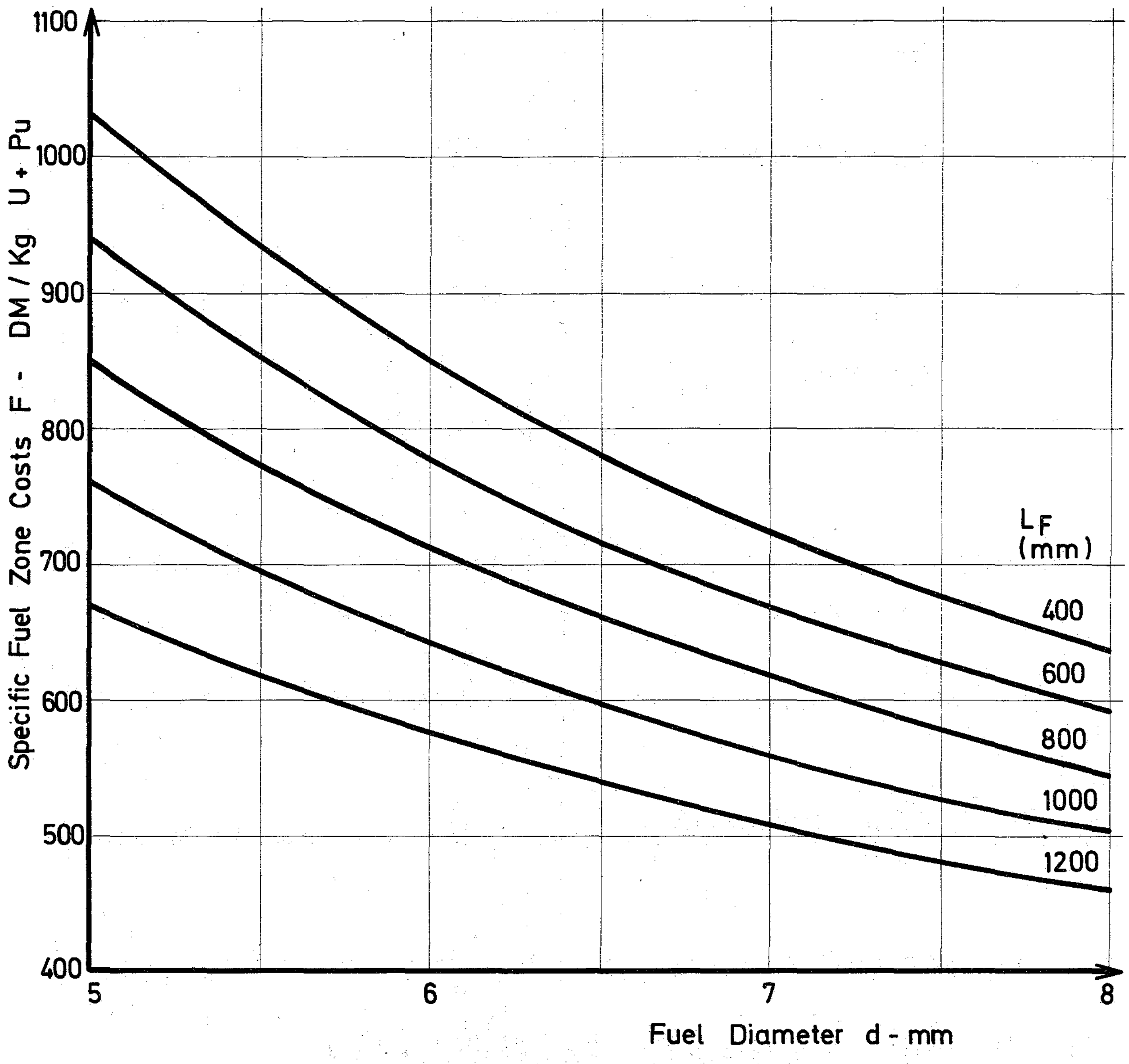

Fig. 2 SPECIFIC FUEL ZONE COSTS AT FABRICATION CAPACITY 100 TONS OF UO_2 -PuO_2 PER YEAR

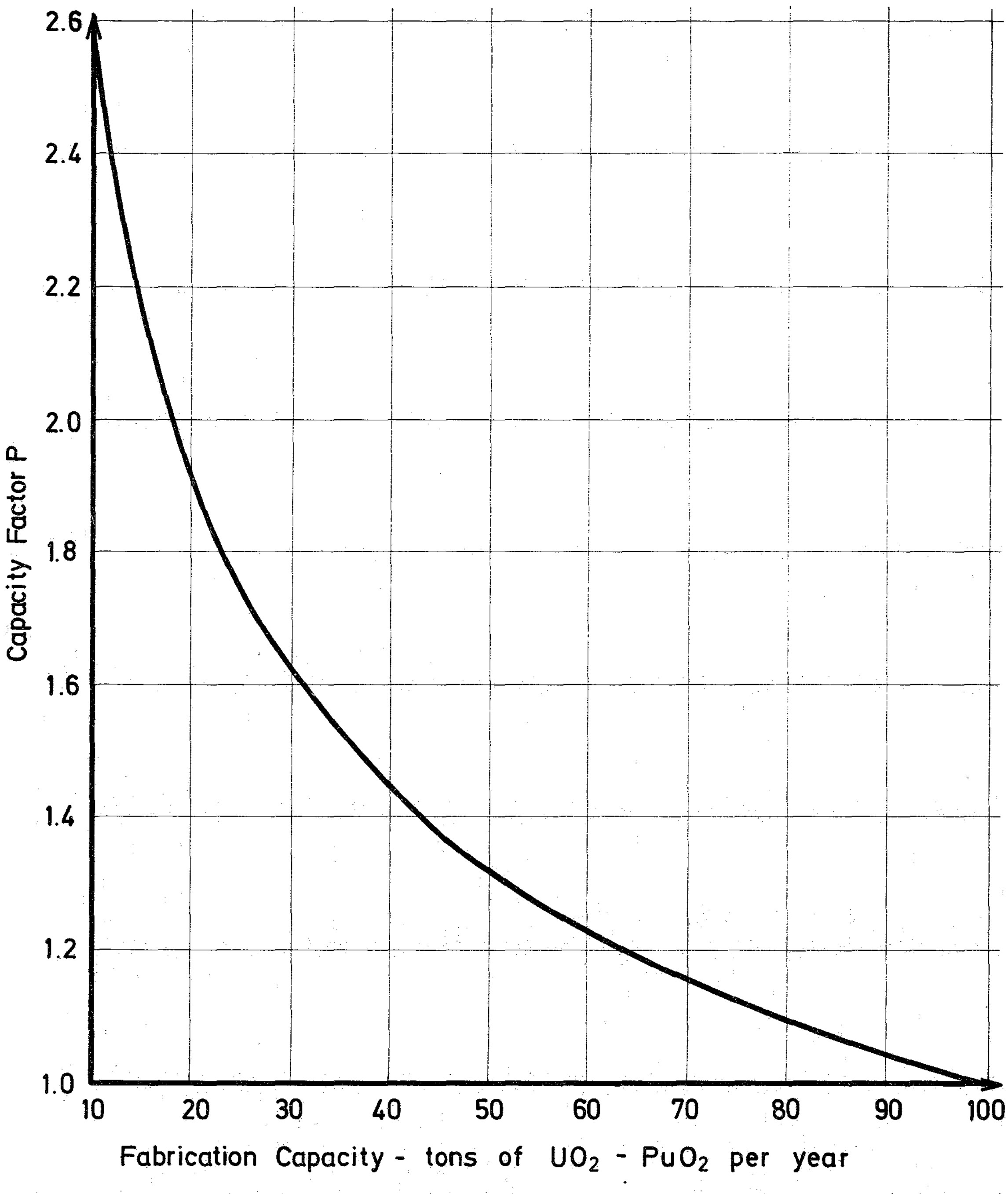

Fig. 3 CAPACITY FACTOR P FOR THE SPECIFIC FUEL ZONE COSTS

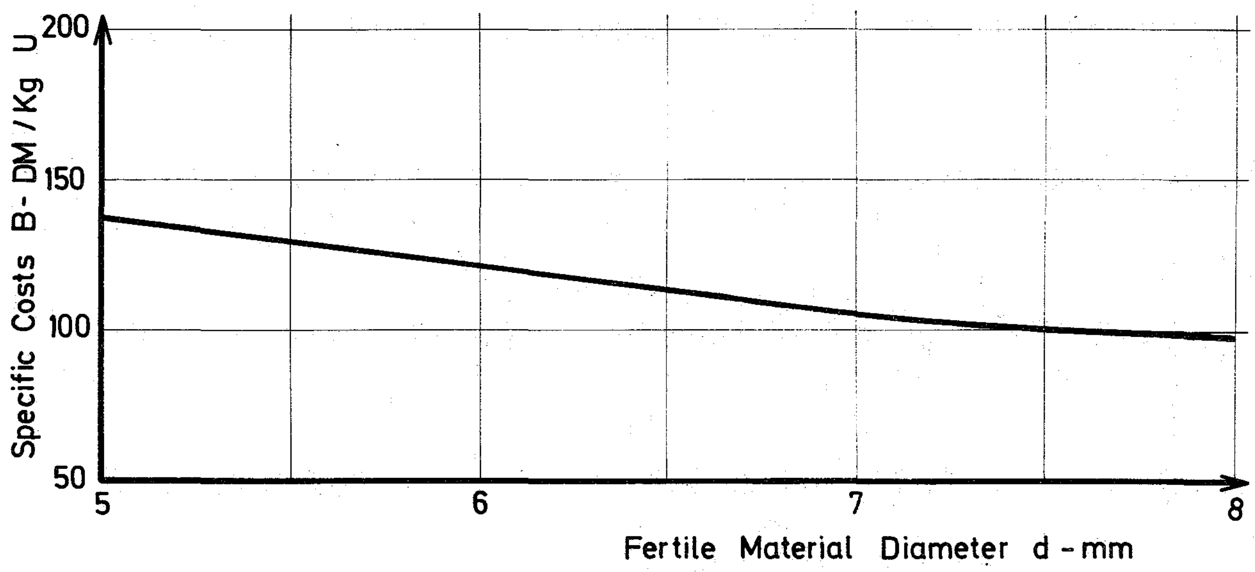

Fig. 4 SPECIFIC COSTS FOR AXIAL BLANKET ZONES