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ECONOMIC CONSIDERATIONS OF PLUTONIUM UTILIZATION IN THE NUCLEAR POWER STRATEGY OF FINLAND

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1. INTRODUCTION

The prospect of diminishing uranium resources has motivated a number of studies on the impact of plutonium in the global supply of fissile material. We are discussing the topic from the viewpoint of a single power production system. This system is not capable of exerting any major influence on the global capacity and therefore it can be optimized separately while assuming that reasonably reliable estimates on the global trends are available. In all practical calculations we have chosen Finland as an example. However, most of the discussion is applicable to any power utility which has its own responsibility of planning and financing.

The anticipated nuclear share of the future production capacity is taken from more general considerations. Hence we are given a rough estimate of the nuclear programme to be optimized for LWR and LMFBR. Due to the long lead times the programme is fixed for the next 10-15 years. Thereafter we allow parallel upper and lower growth estimates.

In the subsequent chapters the principles of the comparative method are outlined. The work is based on the minimization of the total discounted financial requirements. In order to be able to incorporate the major aspects of the national energy policies we have reserved a possibility to weigh the domestic part of the investments. The model will separate the domestic and import expenditures and the suggested scenario is chosen by the cost minimum where the domestic share is given a reduced value. The reduction factor is a free input parameter.

2. PRINCIPLE OF THE DISCOUNTED COST MINIMIZATION

Given the part of the total nuclear energy demand the supply is thought to be increased by steps of 1000 MWe. Each unit can freely vary between uranium and mixed oxide fuelled LWR's and LMFBR's. Based on the 1976 prices the plant investment cost of the LWR is assumed to increase annually by the percentage corresponding to inflation. The investment cost of the LMFBR is taken to be 15% higher than that of the LWR. The cost difference is assumed to decline to 12% by the year 1995.

In addition to the constant inflatory increase of the raw uranium price we assume an upward trend in the real price relative to the present level. The uninflated uranium price in the year 2000 is supposed to vary between $ 100-130/lb. The cost of separative work is dealt similarly. The price band of $ 120-180/kg SWU is estimated for the year 2000.

Since the plutonium recycle reduces the LWR fuel costs we suggest that recycle is commenced as early as it would be technically feasible. In the calculations the year 1985 is taken as the starting point. Afterwards the extent of the recycling is set to correspond to the self-generated plutonium amount that is available. The plutonium recycle is terminated early enough to guarantee the availability of plutonium for the LMFBR programme.

Whenever a new plant is introduced the choice between the LWR and the LMFBR is made by calculating the total investment and running costs which are discounted to the beginning of the plant operation by the factor $P_{n,r} = (1+r/100)^{-n}$ where r is the rate of interest. Similarly, the cost escalation is dealt with by the factor $P_{-n,e}$ where e is the predicted rate of inflation.

The discounted running costs are split into two components, total fuel costs TFC and other operating costs TOC. Letting TIC denote the investment cost, the plant type s is decided upon minimizing the discounted total cost TC

$$TC = \min_{s = \text{LWR or LMFBR}} \{(TIC_s+TFC_s+TOC_s)\} \quad (1)$$

over the entire plant lifetime.

Supposing that the type s includes a domestic share DS in the investment cost where a reduction factor RF is accomodated then TIC_s is obtained from

$$TIC_s = (1-DS_s+RF\cdot DS_s)\cdot IC_s\cdot P_{-n,e} \quad (2)$$

IC_s denotes the present (1976) investment costs which are escalated by the factor $P_{-n,e}$ until the startup in 1976+n.

The reduction in the domestic investment share is motivated by the individual energy policy. It will evidently increase from the initial fraction IF when the number of plants of the type s is increased. If MDS is the maximum DS can conceivably obtain we have used an exponential relation

$$DS_s = IF_s + (MDS_s-IF_s)(1-e^{-K_s}) \quad (3)$$

where K is the number of plants of the type s installed earlier.

The fuel costs are based on the present price FC. The trends in the unit raw uranium and enrichment costs are taken into account by weighing their fractions in FC and letting them develop according to U(t) for raw uranium and E(t) for the enrichment. Consequently, TFC for the LWR is obtained from

$$TFC = \sum_{i=0}^{A-1} FC \cdot P_{i,r} \cdot P_{-n-i,e} U(n+i) E(n+i) \tag{4}$$

where A denotes the operating lifetime of the plant which is normally 30 years. In case the plutonium recycle is started during this period FC is reduced by 10% for that part of the time interval.

In case the LMFBR we allow a separate cost trend for plutonium. The unit price is based on the estimate FC(i) on an annual basis. If FC(i) is given in terms of its real present value then TFC for the LMFBR is determined by

$$TFC = \sum_{i=0}^{A-1} FC(n+i) \cdot P_{-n-i,e} \cdot P_{i,r} \tag{5}$$

The other operating costs are given a constant real value OC in case of the LWR while for the LMFBR they can vary according to an estimate OC(i). Eq. 5 can be applied when TFC and FC are changed to TOC and OC, respectively.

In order to calculate the cost of energy the capital investment is amortized by applying a fixed annuity. The annual payment is therefore $IC/S_{A,r}$ where

$$S_{A,r} = 100 \cdot \frac{P_{-A,r} - 1}{r\, P_{-A,r}} \, . \tag{6}$$

The unit cost of energy EC(t) during a given year t is now obtained from

$$EC(t) = \frac{\sum_i [IC/S_{A,r} P_{-n,e} + (FC(t) + OC(t)) P_{-t,e}]_i}{8760 \cdot L \cdot P(t)} \tag{7}$$

where the sum is extended over all the operating plants. P is their total nominal power output and L denotes the load factor.

3. PLANNING ALGORITHM

A simplified flow sheet of the algorithm is shown in Fig. 1. The total energy demand allotted to nuclear power is given in the input. In case no new capacity is required the work boils down to deciding only whether and when recycle is initiated.

Given the capacity scenario we proceed to solve the types of the installed plants. The total costs are calculated for the two alternative plant types along the lines presented in the previous chapter.

Once the comparison block is traversed one is ready to edit the integral quantities of the strategy, i.e. the total revenue requirement, temporal development of the fissile material flow and the production cost of electricity.

4. COST AND DEMAND ASSUMPTIONS

The values employed for the investment, fuel and operating costs are summarized in Table I. The LMFBR investment cost is assumed to be 15% higher than that of the LWR [1], while the annual fuel cost of the LMFBR is 50% of the LWR fuel costs [2]. In other operating costs the corresponding ratio is 1.10. In other operation costs the corresponding ratio is 1.10 declining to 1.05 by the year 1995.

As far as the real raw uranium price is concerned we use a higher and a lower estimate which vary from $ 40/lb in 1976 to $ 100 and $ 130/lb in 2000, respectively [3,4]. The trends are depicted in Fig. 2. Similarly, we have an upper and lower trend for the enrichment cost as shown in Fig. 3 [5,6].

Just as our calculational model can tolerate any conceivable price variation the energy demand development can be given rather arbitrarily. The following discussion will be based on a given forecast on the system demand of nuclear power. This prognosis shown in Fig. 4 is relevant in the case of Finland. After a period of fixed programme implementation we allow again an upper and lower installation forecast after the year 1993. The combinations of demand forecasts and cost trend assumptions are selected according to Table II. For both demand alternatives we consider separately the higher and lower fuel cost trends. Consequently, there are four different cases A, B, C and D.

Since a massive introduction of LMFBR's can be reasoned to increase the market value of plutonium the fuel costs of the LMFBR are predicted to be doubled during the period 1990-2010 from their present value given in Table I. This is in addition to the general inflatory escalation discussed in Chapter 2. The annual rate of interest is fixed at 10% and the rate of inflation at 7%.

5. RESULTING STRATEGIES

The results of the strategy calculation are summarized in Table III. In case the higher energy demand curve would materialize there would not be enough domestic plutonium available to support any recycle in the LWR's. The installation of the LMFBR's in 1997-99 would require all the plutonium to be stored. In the case of the lower power demand estimate in the 1990's the plutonium recycle would be permitted in 1985-91 on self-generated basis in all plants installed.

The accumulation of domestic plutonium appears to be too low in order to allow the advent of the LMFBR on purely economic grounds of competitiveness. In all cases the domestic plutonium backlog will support the installed LMFBR's not earlier than 1997 while they could be economic already in the late 1980's.

Some of the financial figures are also shown in Table III. The discounted capital required is of the order $ 12-14 billion the plutonium recycle savings of $ 114-150 million are somewhat marginal. Finally, the annual average production cost of electricity is shown in Fig. 5 for the case A. After a monotonous increase until 1997 the introduction of fast reactors will imply a clear reduction.

6. SENSITIVITY ANALYSIS

The stability of the final strategies is studied with respect to changes in the rate of interest, inflation and some LMFBR parameters. If the rate of interest is raised from 10% to 15% there will be no change in the strategy. At 10% the LMFBR investment cost can be 110% higher than for the LWR and the LMFBR is still favoured. At 15% the corresponding marginal is 51%. This is for the low LWR fuel cost cases B and D.

A change of ±1% in the inflation rate changes the total revenue requirement about 0.5% more than a ∓1% change of the interest rate does. The increase and decrease of inflation effects 15.9% and 13.5%, respectively.

In the basis calculation we have assumed the LMFBR/LWR fuel cost ratio of 0.5. If this is increased to 0.7 the LMFBR investment cost marginal reduces to 78%. These were some examples of the stability analyses. Other items can be edited easily from our algorithm.

CONCLUSIONS

Our method was based upon separating the predicted nuclear capacity from the rest of the power production system. The calculated material flows and financing requirements can be fed back to the overall energy planning system in order to consider if any major changes would be recommendable. At the present time the power growth estimates are declining globally and this may lead to reductions in the nuclear power programme at least in the 1990's. Our lower demand estimate appears therefore more relevant and, consequently, the incentives to the plutonium recycle are enhanced.

The outlook for the plutonium recycle in the late 1980's depends heavily, c.f. Table III, on the increase of demand of nuclear power in the 1990's. Therefore the recycle decisions are to be made within this perspective. Because we tend to rely more on the lower demand estimate, the starting of the plutonium recycle appear favourable as soon as it is seen technically feasible.

Maintaining the principle of self-generated plutonium use alleviates the speculation of free plutonium market in the future. Assuming that the recycle would reduce the LWR fuel cycle costs by some 7-10% [7] one obtains readily the pertinent plutonium price which makes the plutonium import competitive. Over the entire period until the year 2000 the plutonium recycle would in our case reduce the total fuel costs by some 2.5%.

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TABLE I

LWR AND LMFBR COST COMPONENTS
LOAD FACTOR 0.75

	Investment Cost $/kWe	Annual Fuel Costs $/kWe/a	Other Operating Cost $/kWe/a
LWR	817	35.5	11.8
LMFBR	940	17.8	13
LMFBR/LWR	1.15	0.50	1.10

TABLE II

DIFFERENT CASES STUDIED

		POWER DEMAND ESTIMATE	
		Higher	Lower
RAW URANIUM PRICE AND SEPARATIVE PRICE ESTIMATES	Higher	A	C
	Lower	B	D

TABLE III

SUMMARY OF RESULTING STRATEGIES

	Plutonium Recycle	Introduction of the LMFBR	Total Revenue Requirement Discounted to 1976, M$			Savings due to Pu Recycle Discounted to 1976, M$
			Investment	Fuel	Total	
A	Plutonium stored for the LMFBR programme	1997	7700	7250	15700	-
B		1997	7700	5550	14000	-
C	1985-1991 on self-generated basis in all plants installed	1997	6250	6640	13500	151
D		1997	6250	5140	12000	114

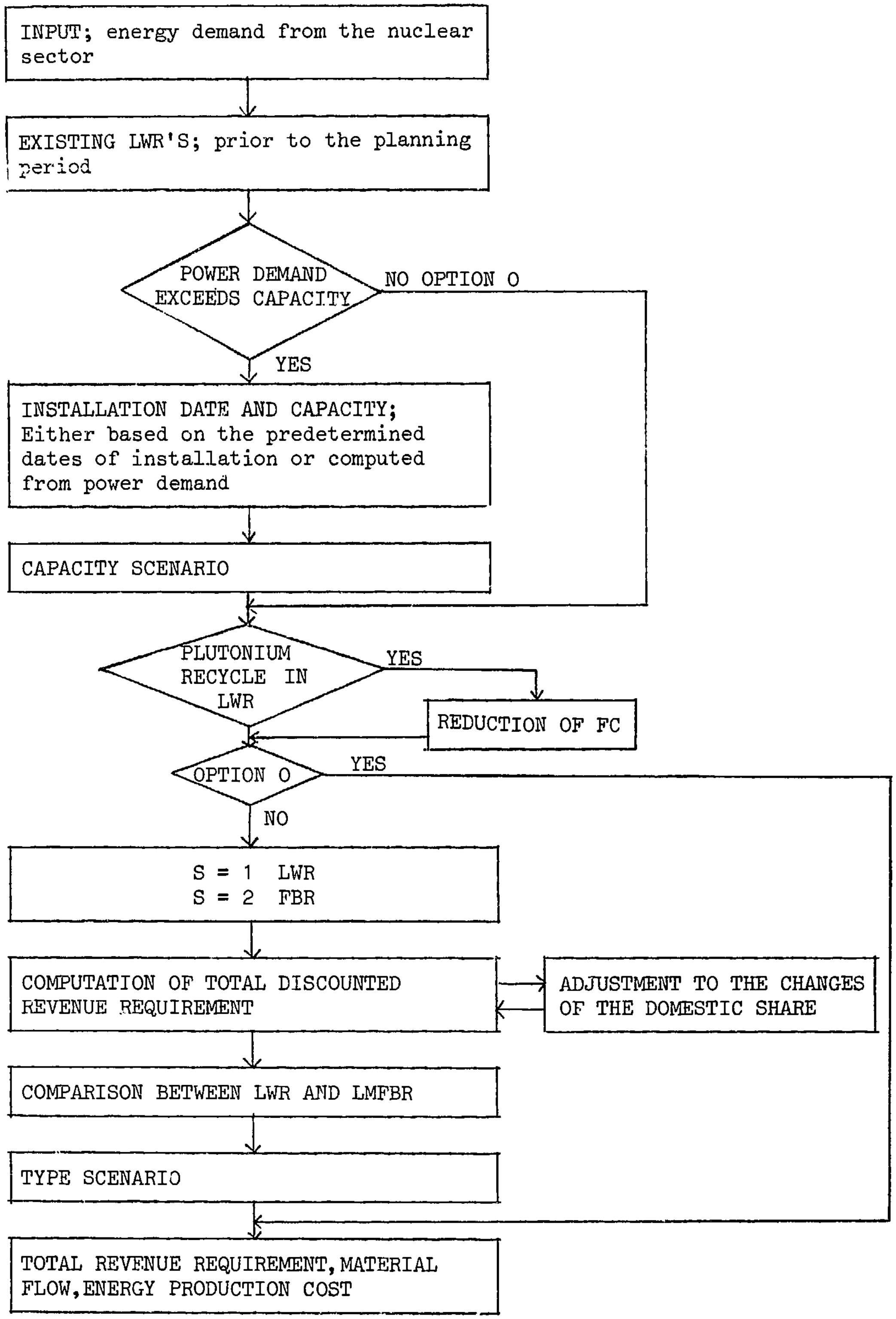

Fig. 1. FLOW SHEET OF THE PLANNING ALGORITHM

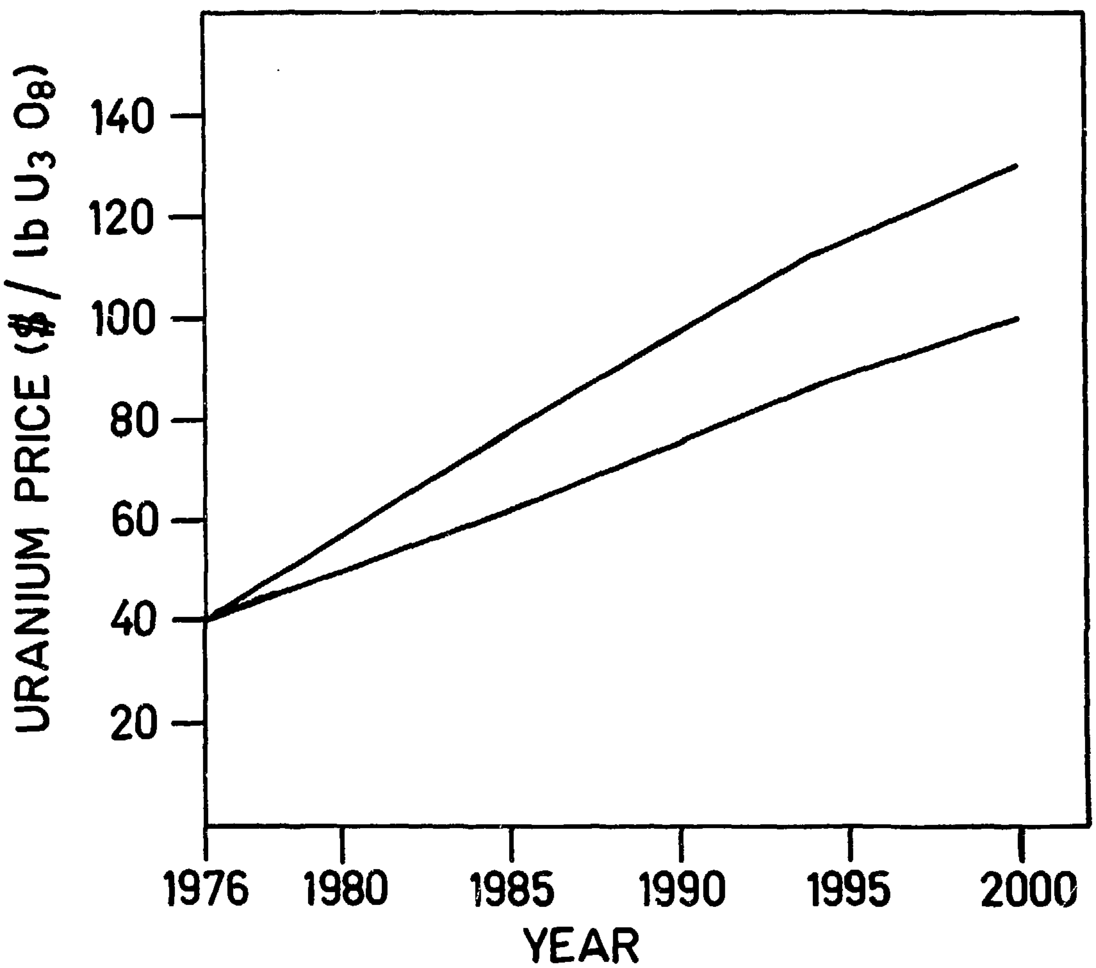

Fig. 2
TRENDS FOR THE URANIUM PRICE

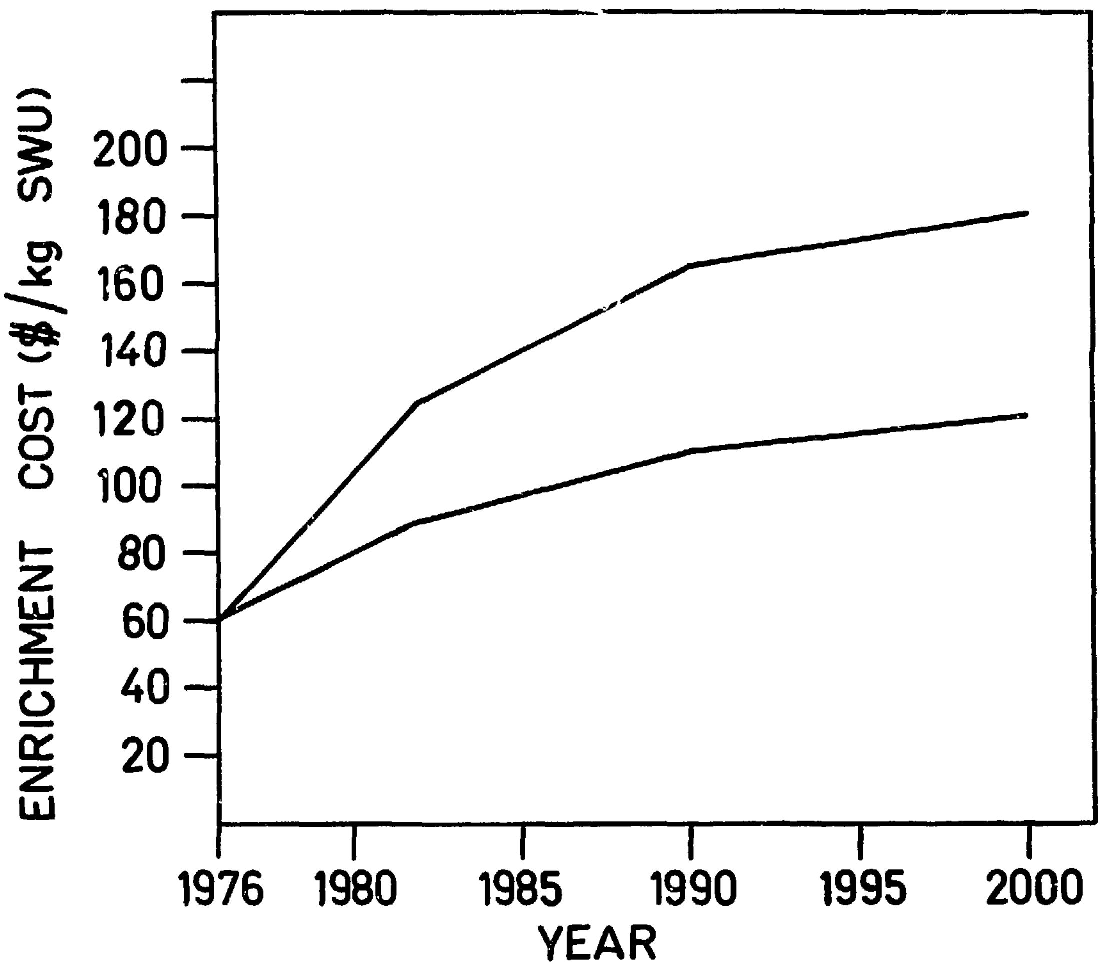

Fig.3
TRENDS FOR THE ENRICHMENT COST

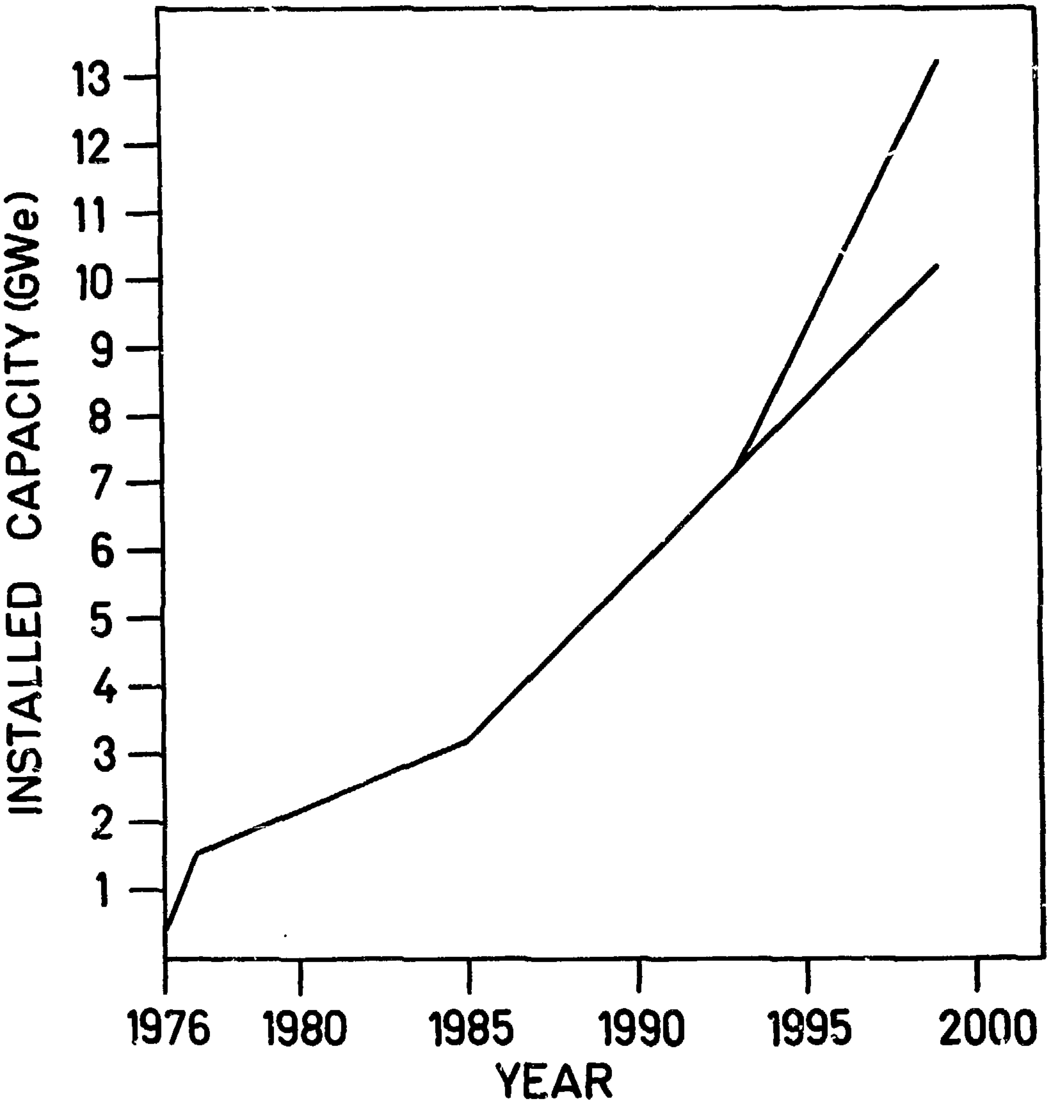

Fig. 4
NUCLEAR POWER GROWTH

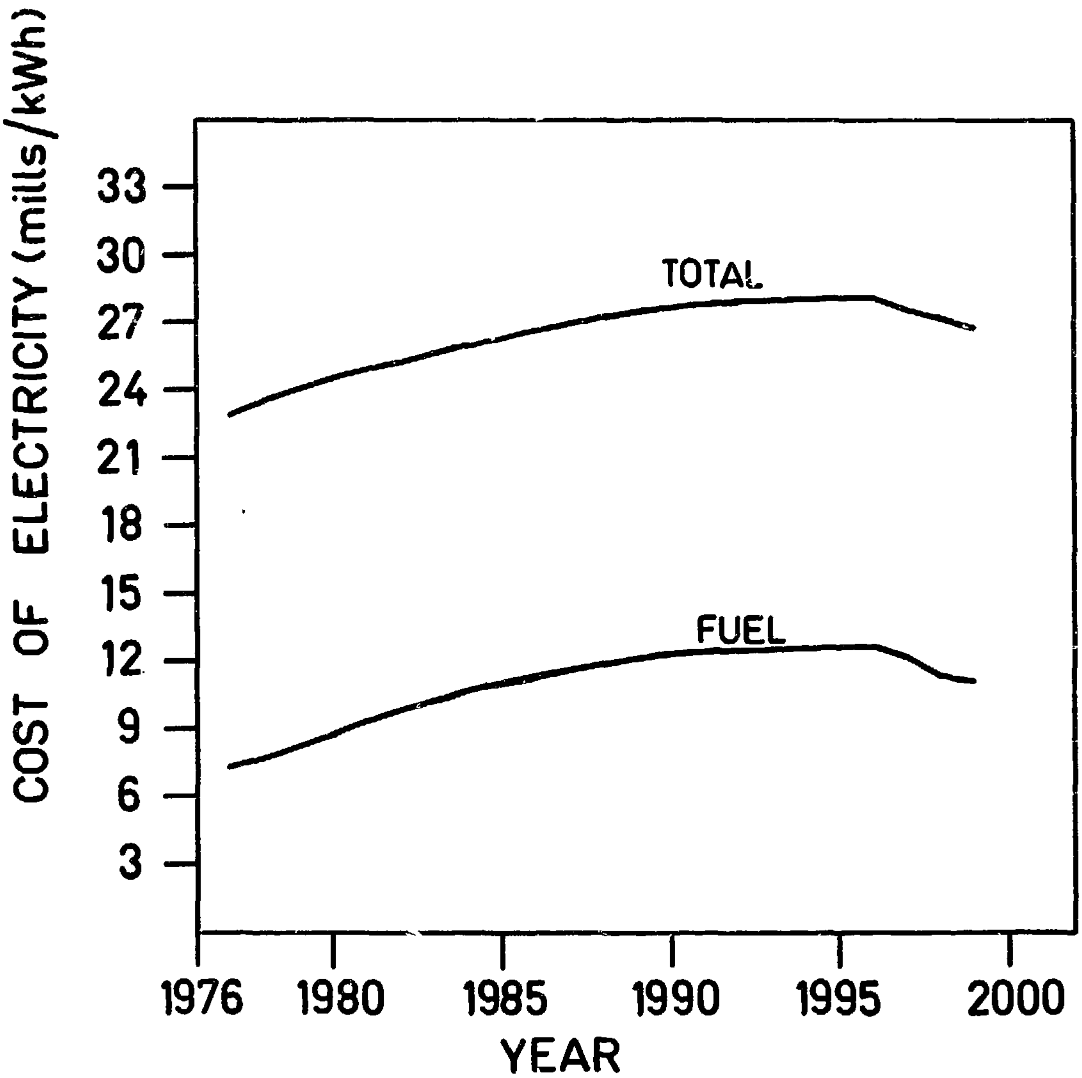

Fig. 5

TOTAL COST OF ELECTRICITY AND ITS FUEL COST COMPONENT