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THE HÄFELE-MANNE MODEL OF REACTOR STRATEGIES:
SOME SENSITIVITY ANALYSIS

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Wolf Häfele and Alan Manne [1] consider a linear programming model in which the sum of discounted costs of meeting demand for electrical and non-electrical energy over a horizon of 75 years divided into 25 periods of 3 years is minimized subject to constraints, inter alia, on the total availability of fossil fuel and low cost ($15/lb.) natural uranium. The alternative technologies considered were the following:

(i) conventional coal based plants, light water reactors (LWR) and two types of fast breeder reactors (FBR) for producing electricity; and

(ii) conventional petroleum and natural gas (PETG) and hydrogen for producing non-electrical energy, where hydrogen is produced through electrolysis (ELHY) and chemical water splitting using process heat from a high temperature gas cooled reactor (HTRB) that uses either natural uranium or plutonium generated from FBR's along with thorium as fuels.

It was postulated that FBR's and HTRB's will not become available until 1988 or later and that construction rates of various types of reactors were subject to specified upper bounds for the earlier part of the time horizon.

The final demands for the two forms of energy are determined differently for three "model" societies 1, 2, and 3. Each model society is assumed to have a population of 250 million as of 1970, the initial year of the planning horizon. In model societies 1 and 2, the energy demands are exogenous throughout the planning horizon while in model society 3 the demands are responsive to price. Though, by the end of the planning horizon, the final energy demands were virtually the same in model societies 1 and 2, demands grew rapidly in the first 45 years and remained the same thereafter in model society 1, while in model society 2 the demands grew slowly but steadily throughout the horizon.

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*We wish to thank Professors Häfele and Manne, and Dr. Marchetti for many valuable suggestions. Thanks are also due to Mr. Schrattenholzer for his assistance with the calculation.

The Häfele-Manne model focused on "timing the introduction of new technologies--taking a perspective sufficiently long so as to allow for the eventual exhaustion of oil and gas resources." Also the benefits of new technologies were calculated as variants of base cases, it being assumed that a specified new technology (e.g. thermo-chemical water splitting) is not available in a variant. Thus the additional discounted costs in the variant over the base case will represent the benefits accruing from the availability of the specified technology.

The purpose of this exercise is to explore the sensitivity of the Häfele-Manne results with respect to changes in some of the more crucial parameters and other assumptions. More specifically, we ran the model:

(i) for alternative discount rates of 0%, 5%, and 15% per year. The Häfele-Manne model assumes 10% discount rate;

(ii) for alternative assumptions regarding costs and availabilities of natural uranium;

(iii) allowing for the possibility of installed capacity of a technology to remain underutilized because of obsolescence;

(iv) imposing constraints on the rate at which "new" technologies (nuclear power in the case of electricity, hydrogen in the case of non-electrical energy) can penetrate into the market;

(v) allowing for secular reduction in the capital costs of new technology to reflect the possibilities of cost reduction due to increasing scales of production and learning by doing;

(vi) for an alternative version of model society 3 in which an adaptive form of demand response to changes in price of energy is postulated;

(vii) for an alternative price of petroleum and gas in the range of \$5-\$20/barrel. The Manne-Häfele model assumes \$10/barrel; and

(viii) minimizing the total amount of petroleum and gas consumption under additional constraints on the total discounted costs of meeting the specified energy demand.

The reader is referred to the paper by Häfele and Manne [1] for details regarding the algebraic formulation and numerical specification of the model. We present the results (barring a few exceptions) of our runs for model society 2 with a petroleum and natural gas availability of 3.375 Q.

Variation in Discount Rate

The discount rate is a measure of the cost of capital, i.e. the lower the discount rate the cheaper the cost of capital. Thus lowering the discount rate will make it more attractive to introduce the more capital intensive technologies such as FBR and electrolysis (ELHY) in greater amount and earlier in time. In Figures 1 to 4, the evolution of capacity (= output) of LWR, FBR, HTRB, and ELHY over time are plotted. It is seen that the time pattern of build up of LWR and FBR capacity is similar and fairly insensitive quantitatively for discount rates in the range 5% to 15%. There are two peaks in LWR capacity, the first peak is higher and comes at the same time, while the second peak is lower and occurs at the same time as or later than, the discount rate is reduced from 15% to 5%. At a zero discount rate, there is only one peak and it occurs at the same time as for 5% but reaches far higher.

The first peak in LWR occurs at the last period for which there are binding upper bounds on FBR construction rates (see Table 5 in [1]). In other words, had there been higher upper bounds on FBR construction, it would have been more economical to construct more FBR's and consequently less LWR's so that the peak would have been lower. The second peak in LWR occurs due to the fact that plutonium stocks become a binding constraint on the installation of FBR's and indirectly, HTRB's. As such some LWR's are installed to produce plutonium as well as to supply electricity for electrolytic production of hydrogen. However, at a zero discount rate, enough of LWR's and FBR's are installed earlier that a shortage of plutonium does not appear to warrant the installation of LWR's later giving rise to a second peak.

While decreasing capital costs associated with decreasing discount rate should make FBR's more attractive--and this happens to hold as the discount rate is reduced from 10% to 5% and to 0%--it appears that more FBR's and LWR's get installed when the discount rate is raised from 10% to 15%. A possible explanation of this curious system response, which is contrary to expectations based on partial equilibrium analysis, is to be found in the supply of non-electrical energy. Firstly, increasing capital costs make petroleum a more attractive source of non-electric energy. As can be seen from Figure 5, this leads to more and earlier petroleum consumption as the discount rate increases. In fact, at a discount rate lower than 10%, the available stocks of petroleum are not used up. When the discount rate is 15%, exhaustion of physical supplies occurs earlier as compared to the 10% case, and hence more hydrogen has to be produced in the final years. When, on the other hand, the discount rate falls below 10%, more hydrogen is produced in the final years not because supplies get exhausted but because it becomes uneconomic to use the existing supplies! Thus as we move away from the 10% discount rate in either direction, more hydrogen gets produced in later years, and this means higher demand for either process heat or electricity. Whether process heat of HTRB or electrolysis is used to produce hydrogen depends on breeding gain, cost of electricity, and the discount rate. At zero discount rate, capital is free of cost and electrolysis wins throughout the horizon. As the discount rate is increased, introduction of electrolysis is pushed further into the future, and the demand for hydrogen is met through HTRB. However, in the last 25 years of the horizon, ELHY capacity rises as the discount rate is raised above 5% or lowered to 0%. Taken together with the behavior of LWR capacity, it appears that at a discount rate above 5%, the existence of LWR capacity in increasing amounts makes electricity available for ELHY, while at a zero discount rate FBR's are used to produce electricity for ELHY. The variation in the time path of HTRB capacities as the discount rate is varied needs no further explanation as this is the one side of the hydrogen coin with the other being electrolysis.

The sensitivity with respect to discount rate changes is also affected by the Häfele-Manne assumption that capacity once installed cannot be retired until its service life of 30 years is over. This assumption was relaxed and we permitted underutilization of capacity if it is economical. The results are presented in Figures 5 to 9. First, comparing the two alternatives with and without underutilization possibilities for the 10% discount rate case, it is seen that when underutilization is permitted, capacity creation with respect to ELHY and HTRB is virtually identical in the two cases, while more LWR and less FBR capacity is created in the last 30 years when underutilization is permitted. ELHY capacity is underutilized in the final years of the horizon. What seems to be happening is that when underutilization is permitted, slightly more ELHY capacity is created and part of it is left idle in the final years with petroleum usage correspondingly adjusted.

Turning to the other discount rate, underutilization of ELHY capacity increases at 15% as well as 5% discount rates compared to the 10% case. The explanation of these variations is similar to the case when no underutilization was permitted. At zero discount rate, there is no underutilization of FBR and ELHY capacities while all the existing capacities of LWR's and HTRB's are left idle during the last 30 years of the horizon. The reason behind this is simple: at zero discount rate, we are essentially comparing the operating cost, and the most economical way to meet the energy demand is to use whatever has the cheapest operating cost if it is physically possible to do so. Obviously (see Table B-2 in [1]) the cheapest way here is to use FBR for the supply of both electric and non-electric (via ELHY) energy, and after a certain number of years when we can install enough FBR's, all the electric and non-electric energy is supplied by FBR's and everything else is left idle.

Though permitting underutilization does not bring about significant reduction in the discounted sum of costs except in the 5% and 0% cases, it eliminates some of the anomalies reported in [1]. A typical example is the results in Table 9, where it is reported that the relative merit obtained from advanced FBR is $\$1\text{x}10^9$, $\$13\text{x}10^9$, $\$6\text{x}10^9$ when the petroleum availabilities are 2.250 Q, 3.375 Q, and 4.500 Q, respectively--contrary to our intuition that the benefits should increase as the petroleum availability decreases. However, assuming underutilization, these figures become $\$25.5\text{x}10^9$, $\$15.2\text{x}10^9$, and $\$5.9\text{x}10^9$, respectively, and the anomaly disappears as expected.

Variation with Respect to Current Costs of Operation HTRB

It was suggested that the Häfele-Manne assumption, that current costs of HTRB are twice that of FBR, may need revision in the direction of lower costs. We tried a run with the assumption that these costs are identical: it makes virtually no difference to the time pattern of capacity creation, except that as expected, with lower HTRB operating costs somewhat more of them are installed earlier.

Sensitivity with Respect to Costs and Availability of Natural Uranium

One of the main arguments for the early introduction of FBR has been that it does not require scarce natural uranium as fuel. Scarcity of low cost natural uranium has been built into the Häfele-Manne model through their assumption that only 2 million tons of uranium at \$15/lb are available while unlimited amounts are available at a high cost of \$50/lb. We tried two alternative assumptions: (i) an additional 6 million tons of uranium are available at a medium cost of \$30/lb, and (ii) availability of low cost uranium is increased to 10 million tons, in other words, essentially unlimited amounts of low cost uranium are available. Since even the second assumption did not make much of an impact on reactor strategies, we present the results of this run only in Fig. 10. As expected, abundance of low cost natural uranium results in fewer FBR and more LWR installations. However, the differences are small. Further, the demand for natural uranium seems to be quite insensitive in the price range of \$15/lb to \$50/lb, falling from 5.21 million tons to 4.91 million tons.

It seems likely that the insensitivity with respect to the price of natural uranium arises from the fact that at a uranium cost of \$15/lb and a 10% discount rate, the (static) cost per KW year thermal is $32 for LWR while it is $31 for FBR. Thus at $15/lb, LWR is just barely competitive with FBR. A run with a uranium cost of $10/lb did not alter the picture either. Thus the uranium price has to be set below $10/lb for observing sensitivity.

Market Penetration Constraints

It has been observed, particularly in the chemical industry, that there is a regularity in the evolution over time of the market share of the product (e.g. rubber) that is captured by a newly introduced substitute (e.g. synthetic rubber). This time path turned out to be the logistic curve for a large number of products (see [2]). While economic theory would suggest that this phenomenon implies some regularity in the evolution of the relative price of the substitute and there is no reason to believe that such an evolution of relative prices is an inviolable natural law, it is nevertheless unrealistic to assume that any rate of penetration into a market is feasible. In the context of the Häfele-Manne model, the question of market penetration can be raised with respect to two new sources of energy: nuclear power for meeting electricity demand and hydrogen for meeting non-electrical energy demand. Indeed, in their model, the rate of penetration required is very rapid: model society 2 with 3.375 Q's of oil and gas goes almost 100% nuclear by 2000. In the USA in 1971, only 2% of electricity production came from nuclear plants. Hydrogen captures nearly 70% of non-electric energy demand in 50 years (See Figs. 11, 12).

In order to examine the implications of limits on market penetration, we introduced constraints stating that nuclear power (hydrogen) should not constitute more than a specified proportion of electric (non-electric) energy demand in any period. The specified proportion was assumed to follow a logistic curve, with 1% (0.1%) of electric (non-electric) energy demand being met with nuclear (hydrogen) energy in 1970 and rising to 50% (50%) in 25 (50) years. Compared to the actual penetration of coal and petroleum into the energy market in the past, the specified rates of penetration are indeed optimistic.

It turns out, nevertheless, that if only 3.375 Q's of petroleum and gas are available, it is not possible to meet the market penetration constraints if we want to satisfy the demand. The reason is that, while there is enough coal to produce non-nuclear electricity to the required extent or more, there is not enough petroleum and gas to meet the constraint on hydrogen.

To proceed further, we had to relax the petroleum constraint. This we did by dropping it altogether. It turns out that it requires 4.44 Q's of petroleum (as contrasted with 3.375 Q in the base case 2.60) to meet the hydrogen constraint. It so happens that base case 2.80 (with an upper bound of 4.50 Q of petroleum and an actual consumption of 4.12 Q) can be compared to the case with market penetration constraints. We present the results for this run in Figs. 11 to 14.

It appears that the market penetration constraints are binding only in the early years, the first 25 years in the case of electric energy and the years 1994 to 2015 in the case of non-electric energy. As is to be expected, substantially more coal capacity and less LWR and FBR are installed and used for the production of electricity as compared to the base case. Also more petroleum is used in the years when the hydrogen constraint is binding. The cost of meeting the market penetration constraint is $29 billion in terms of present value. In other words, the minimized present value of costs goes up from $470 billion in the base case 2.80 to $499 billion in the case with the penetration constraint. This itself is a sizable sum, not to mention the fact that 4.44 Q's of petroleum are required as well. The situation is even worse if we consider model society 1 in which both forms of energy demand grow fast in earlier years and not at all in later years. As is to be expected, the cost of market penetration constraints (which, we noted, are binding in earlier years) is $50 billion, and 4.94 Q's of petroleum are required as well. These figures will go up substantially if slower rates of penetration are specified. Indeed, these figures can be considered as illuminating measures of the criticality of the energy situation.

Sensitivity With Respect to Changing Capital Costs

In order to examine the implications of anticipated reduction in capital costs over time due to scale economies and learning by doing in the nuclear industry, we postulated that capital costs of commercially available technology such as LWR, separative work for uranium, and high temperature reactors will go down to 25% of their 1970 values in 75 years, while those of FBR will go down to 50% of the assumed initial value. Given the initial capital cost disadvantage of FBR, the relative cost of LWR to FBR goes down to 0.38 from its initial value of about 0.75 in 75 years.

The results are presented in Figs. 15 to 17. The lowering of capital costs of electricity and nuclear process heat technology makes the cost of electricity (and process heat) go down over time. Also, the relative cheapening of LWR should make it more attractive relative to FBR. On the one hand the falling trend in electricity and process heat costs results in more hydrogen production (through more ELHY and HTRB) as compared to the base case for meeting non-electric energy demand. Thus only 2.60 Q's of petroleum are used from the available stock of 3.375 Q's. On the other hand the increase in demand for electricity or process heat also increases the demand for LWR and FBR as compared to the base case.

Price Responsive Demands: An Alternative Version

In order to examine the implications of making demands for energy responsive to price, Häfele and Manne maximized the following:

$$\sum_{t=1}^{T} \sum_{j=1}^{2} \{a_j^t (q_j^t)^{b_j} - p_j^t q_j^t\}$$

where q_j^t is consumption of energy j at time t (j = 1, 2 represents electric and non-electric energy, respectively) and p_j^t is cost per unit of energy j. It can be shown easily that this implies the following demand curves with constant elasticity

$$q_j^t = \left[\frac{p_j^t}{a_j^t b_j}\right]^{\frac{1}{b_j}-1} \qquad j = 1, 2 \quad .$$

Since the demand at any t depends only on the prices of that period, any sharp changes in prices will result in sharp changes in demand. This is a somewhat unrealistic feature since it is not easy to adapt instantaneously to fluctuation in price of a commodity such as energy which is an input into the production of other commodities. Indeed, in order to avoid this unpleasant feature (and probably to avoid computational difficulties), Häfele and Manne impose an additional constraint that demand grows at least 1% per annum.

We have attempted to bring in adaptive response to prices directly by maximizing the following:

$$\sum_{t=1}^{T} \sum_{j=1}^{2} \left[\lambda_j a_j^t \{ q_j^{t-1} + \frac{1}{\lambda_j} (q_j^t - q_j^{t-1}) \}^{b_j} - p_j^t q_j^t \right]$$

where λ_j is an adjustment parameter which lies between 0 and 1. A value of $\lambda=1$ corresponds to the Häfele-Manne case of instantaneous adjustment to price changes while values of $\lambda<1$ lead to lagged adjustments.

It can be shown that the above maximand leads to the following demand functions:

$$q_j^t = (1-\lambda_j)^t q_j^o + \lambda_j \sum_{t=1}^{t} (1-\lambda_j)^{t-\tau} z_j^\tau$$

$$Z_j^\tau = \left[\frac{1}{a_j^\tau b_j} \sum_{u=\tau}^{T} (1-\lambda_j)^{u-\tau} p_j^u\right]^{1/b_j-1} .$$

Thus all past and future prices affect the demand.

The parameters a_j^t were chosen in such a way that, had λ been equal to unity and had prices p_j^t remained at their assumed 1970 values (of course, the discount factor is also taken into account), demand for both types of energy would have grown at 3% per annum.

With λ=0.9 and p_j^t's determined by marginal costs of production, the following results were obtained. Marginal cost of electricity (per KW year thermal) varied from about $20 to the base year price of $30. And, as such, the demand path for electricity generated by the model remained close to the reference path; that is, demand grew at an annual rate of 3%. The marginal cost of non-electric energy varied between $50 and $81 per KW year thermal as compared to a base year price of $15. As such demand grows initially very slowly, at about 0.5% per annum, and eventually around 2.5% per annum. Thus the ratio of demand along the model path to that along the reference path falls at first from unity to about 0.60 and then rises to about 0.68. This is consistent with expectation since with a price elasticity of -0.3, and a price increasing to a range $50 - $81 from $15, one should expect the ratio of demands to lie between 0.60 and 0.67.

Sensitivity With Respect to Changes in Petroleum Prices

In the Häfele-Manne model, the price of petroleum and gas (PETG) was fixed at $10/barrel for all model societies though they varied the available quantity of PETG considerably from 2.25 Q's to 4.5 Q's. In the current world petroleum situation, it looks very interesting to examine the effect of changes in the petroleum prices, especially for model society 3 where the demand for energy is responsive to price. This variation can be expected to lead to similar results as the variation in discount rate, since lowering the petroleum price has qualitatively the same effect as increasing capital costs associated with a decrease in the discount rate. We parametrized the price in the range of $5 to $20 per barrel. The results for model society 3.60 are presented in Figs. 18 to 22.

It was observed that there is qualitatively not much effect of the price change in the range of $5 to $12; namely, when PETG is cheaper, somewhat more petroleum is consumed in the early period. This leads to earlier exhaustion of available stock of PETG, and hence slightly more HTRB and ELHY are installed in the later period. When, however, the price is raised above $15/barrel, the system shows quite a different response. First of all, though the annual consumption rate of PETG maintains the initial level during the first 12 years (where there is essentially no other way to meet the non-electrical energy demand) it decreases rapidly after 15 years, and only 1.59 Q's and 2.69 Q's are consumed for the $20/barrel and $15/barrel cases, respectively. Had we allowed for under-utilization of existing capacity, the decrease of petroleum consumption after 1985 would have been much faster, especially for the $20/barrel case. Secondly, due to the earlier decrease in PETG consumption, ELHY via FBR and hence LWR comes in much earlier and in greater quantity to substitute for PETG until cheaper HTRB can be constructed to meet the non-electric demand.

One interesting phenomenon is that petroleum consumption jumps from zero to a very high level toward the end of the horizon when $15/barrel for PETG is assumed. The explanation for this is as follows: To meet the demand increase in non-electric energy, we have to use either PETG or hydrogen via HTRB and ELHY. Static comparison shows (see Table 2 in [1]) that hydrogen by HTRB ($47/KW year thermal) is cheaper than PETG ($75/KW year thermal at $15/barrel), but there is not enough plutonium to construct enough HTRB capacities. On the other hand ELHY is more expensive ($84/KW year thermal) than using $15/barrel PETG still available. When, however, the PETG price is $20/barrel ($100/KW year thermal by static comparison) it is more expensive than ELHY and hence is not used at all. The break-even point seems to lie near $17/barrel. Though the configuration of supply pattern of energy changes widely as we vary the PETG price, the total sum of energy consumed is less sensitive.

Minimization of PETG Consumption With Constraints on the Sum of Discounted Costs

Finally we tried to minimize the consumption of PETG with the constraint on the sum of discounted costs.

In other words, we interchanged the role of the equations representing the sum of discounted costs and cumulative sum of PETG consumption. We ran two cases of this version with the sum of discounted costs less than 0.95 and 1.05 times the total sum of discounted costs for the base case 1.60 (which is $850 billion in terms of the present [1970] value).

It turned out that 0.95 case was infeasible; i.e. it is physically impossible to meet the total demand with 95% of the cost given by the base case even if we had an infinite amount of PETG at $10/barrel. This is because the PETG consumption constraint in the base case was only binding in the very late years of the horizon, and the minimum cost thus obtained was almost the same as the minimum cost without the PETG constraint. On the other hand the 1.05 case is obviously feasible, and we found that we can save 0.7 Q's of PETG by allowing a 5% increase in the sum of discounted cost which is $42.5 billion in the present value.

Final Remarks

While the above class of sensitivity analysis is interesting and useful, more work is needed in several directions. First, while the model focused on the time pattern of capacity creation, it virtually ignores the fact that rapid build up and equally rapid dismantling of capacity in the reactor building industry is not possible at constant costs. Either construction costs, which are related to the rate of change of output of the reactor industry, or some constraints on this rate of change in both directions may have to be introduced. Indeed, a rapid build up of capacity initially that may have to be left idle later is itself an indicator of the criticality of the energy situation. Work on building up such an index is under way.

There are other critical parametric variations which may have substantial impact. This is the breeding gain of an FBR. Since it is possible to design FBR's for different rates of breeding gain within a certain range, it is important to know the sensitivity of the reactor strategy with respect to this parameter. This will also be explored in subsequent work.

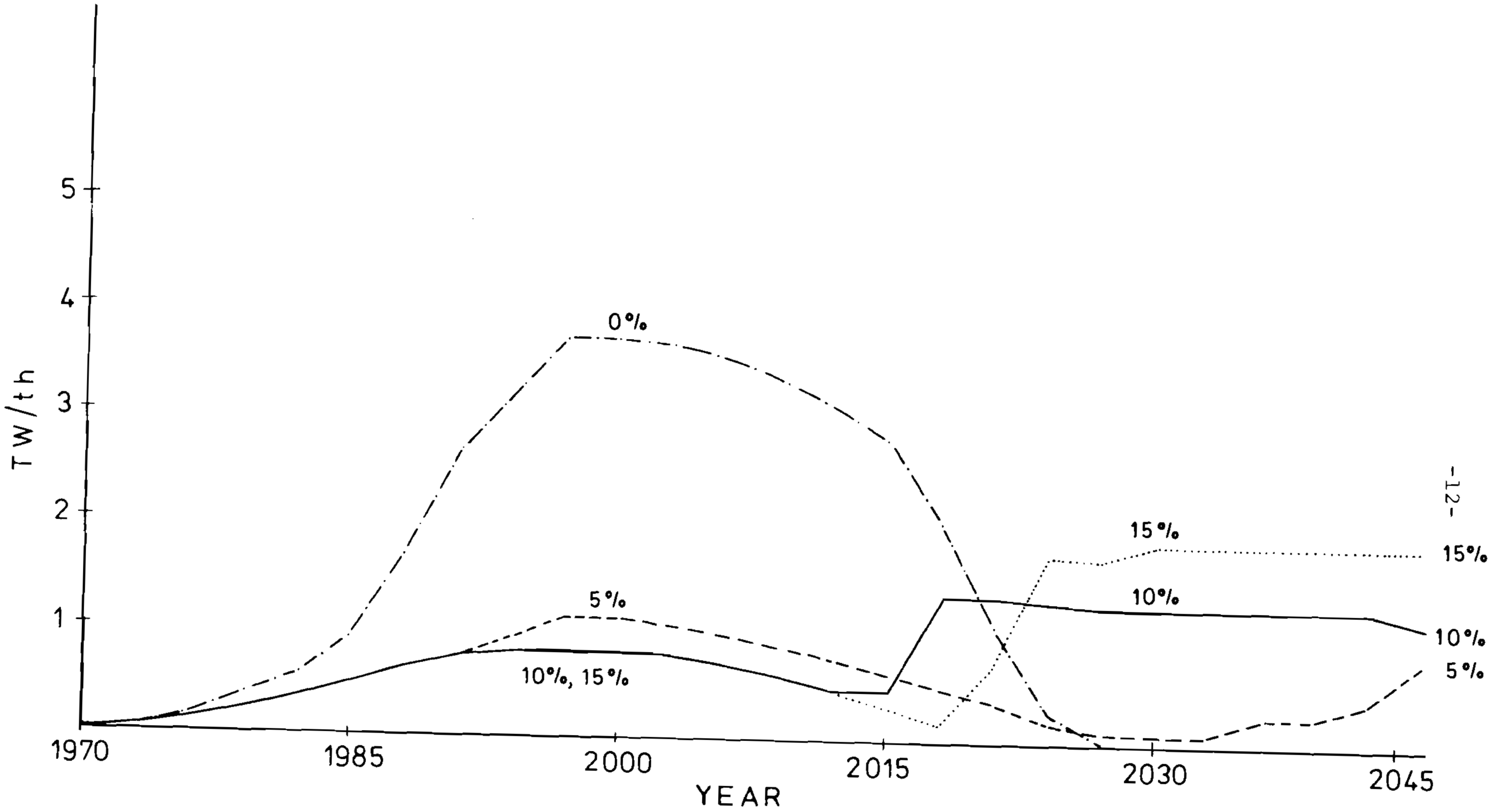


FIGURE 1: LWR CAPACITY RELATIVE TO DISCOUNT RATE.
MODEL SOCIETY 2.60

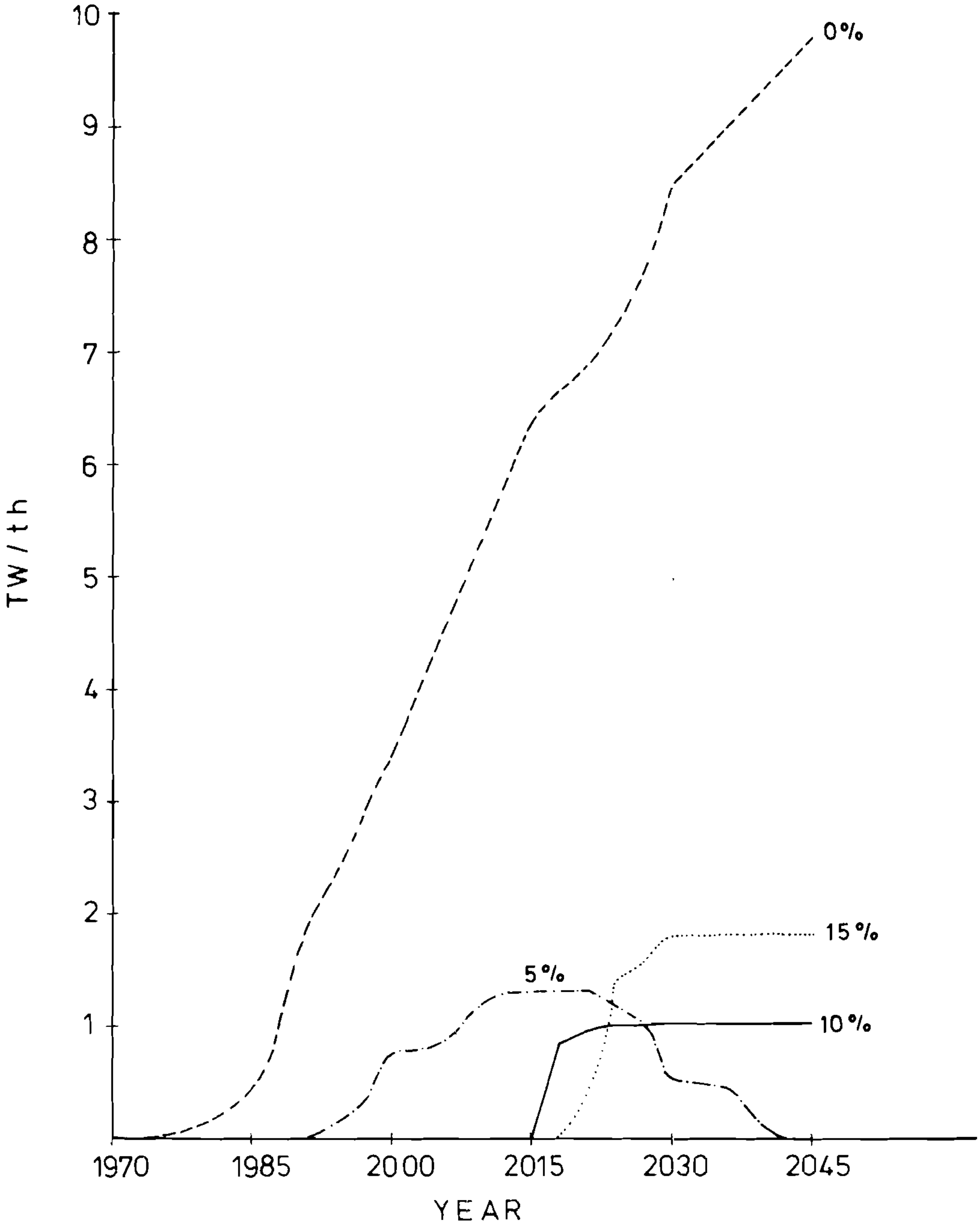


FIGURE 2: ELECTROLYSIS, MODEL SOCIETY 2.60

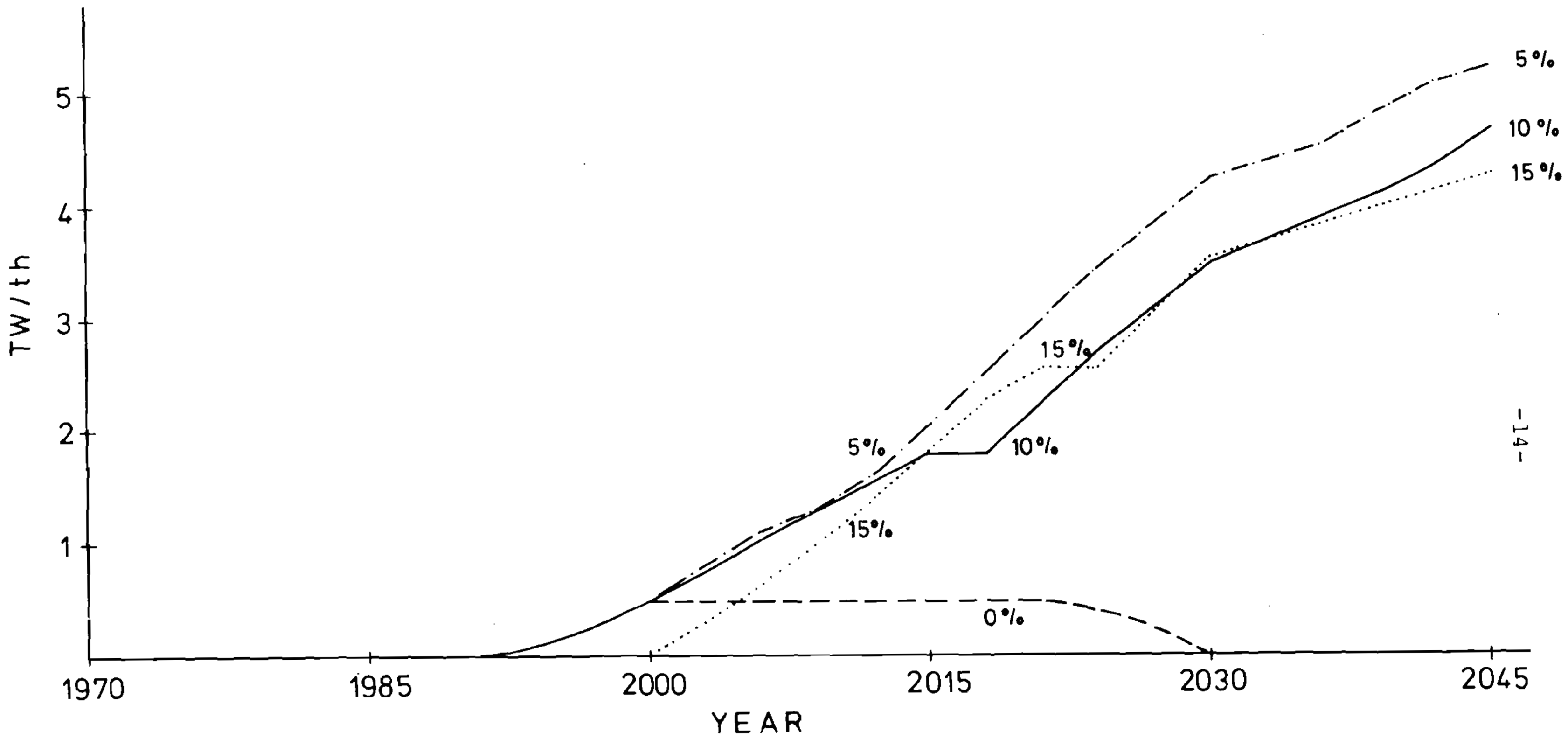


FIGURE 3 : HTRB CAPACITY RELATIVE TO DISCOUNT RATE
MODEL SOCIETY 2.60

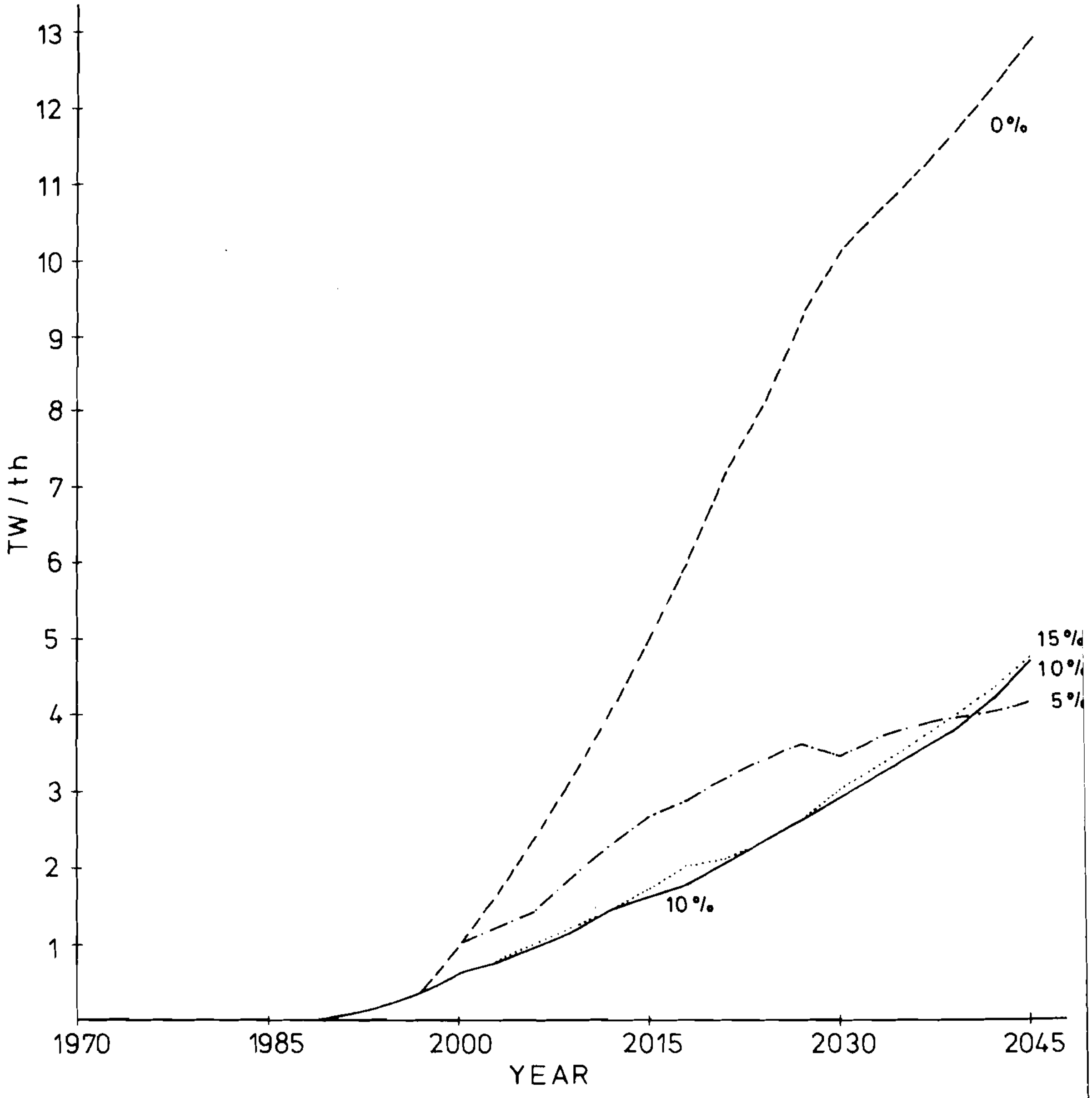


FIGURE 4 : F B R CAPACITY RELATIVE TO DISCOUNT RATE
MODEL SOCIETY 2.60

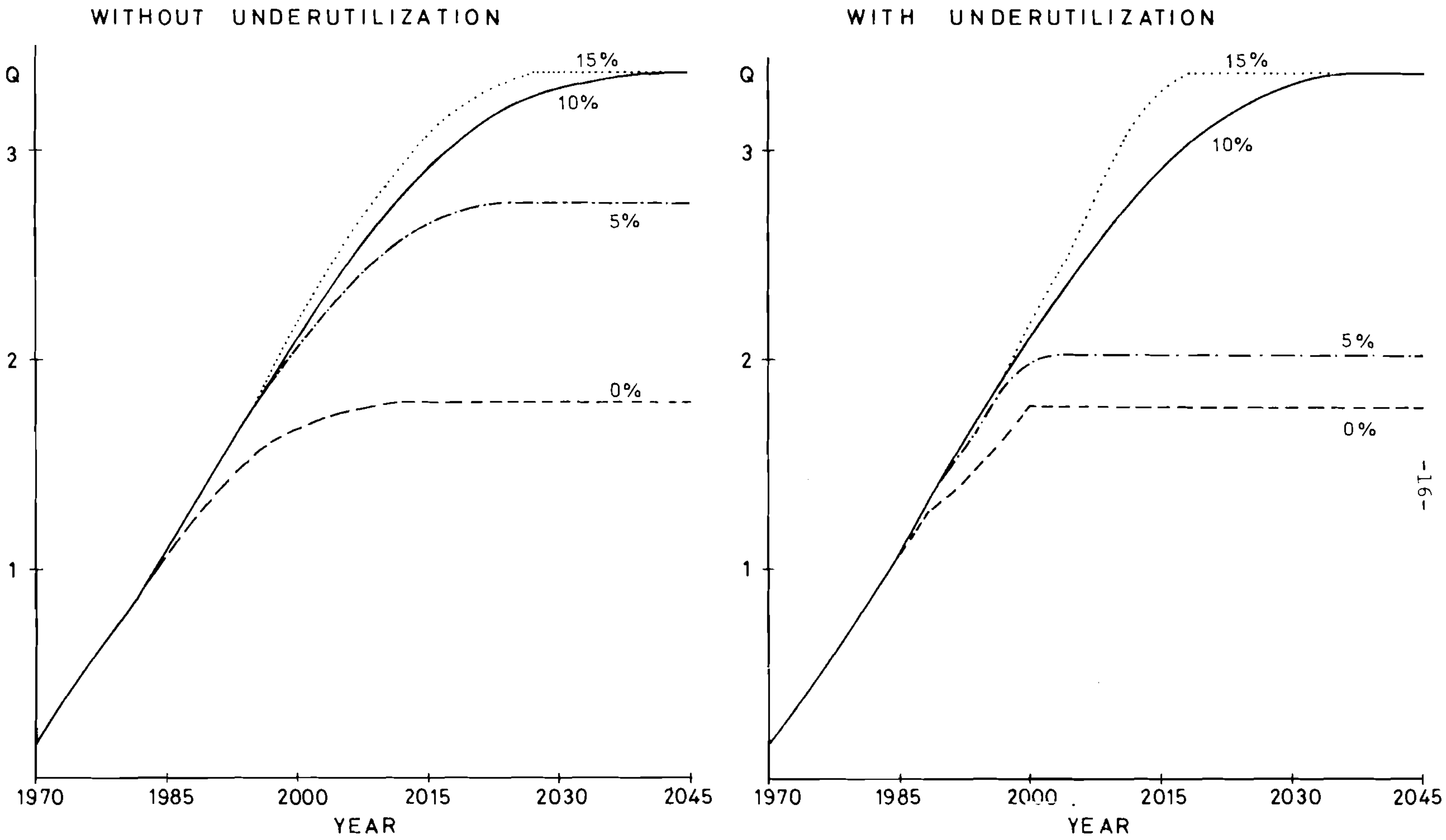


FIGURE 5: P E T G CONSUMPTION RELATIVE TO DISCOUNT RATE
MODEL SOCIETY 2.60

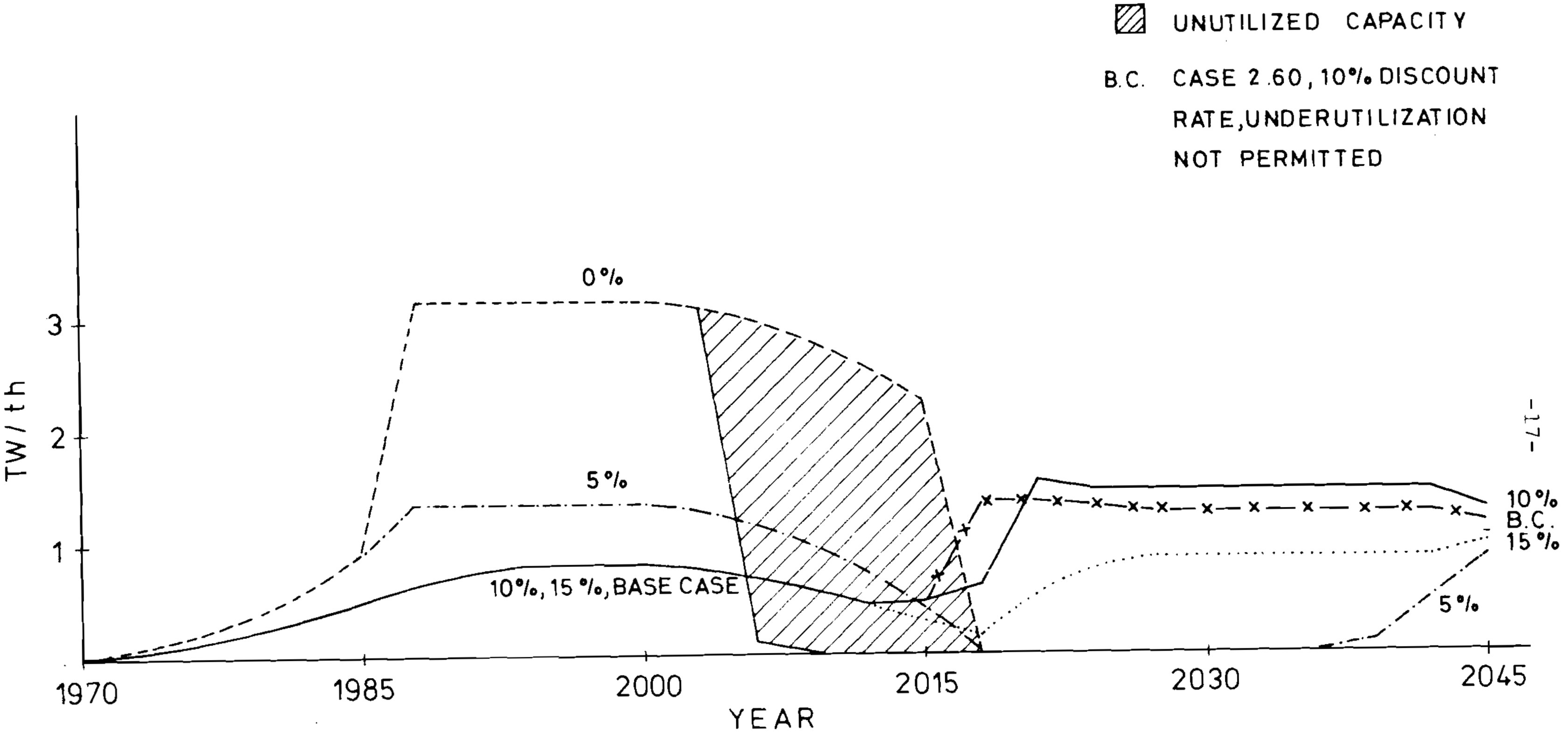


FIGURE 6: L W R CAPACITY RELATIVE TO DISCOUNT RATE WITH UNDERUTILIZATION OPTION; MODEL SOCIETY 2.60

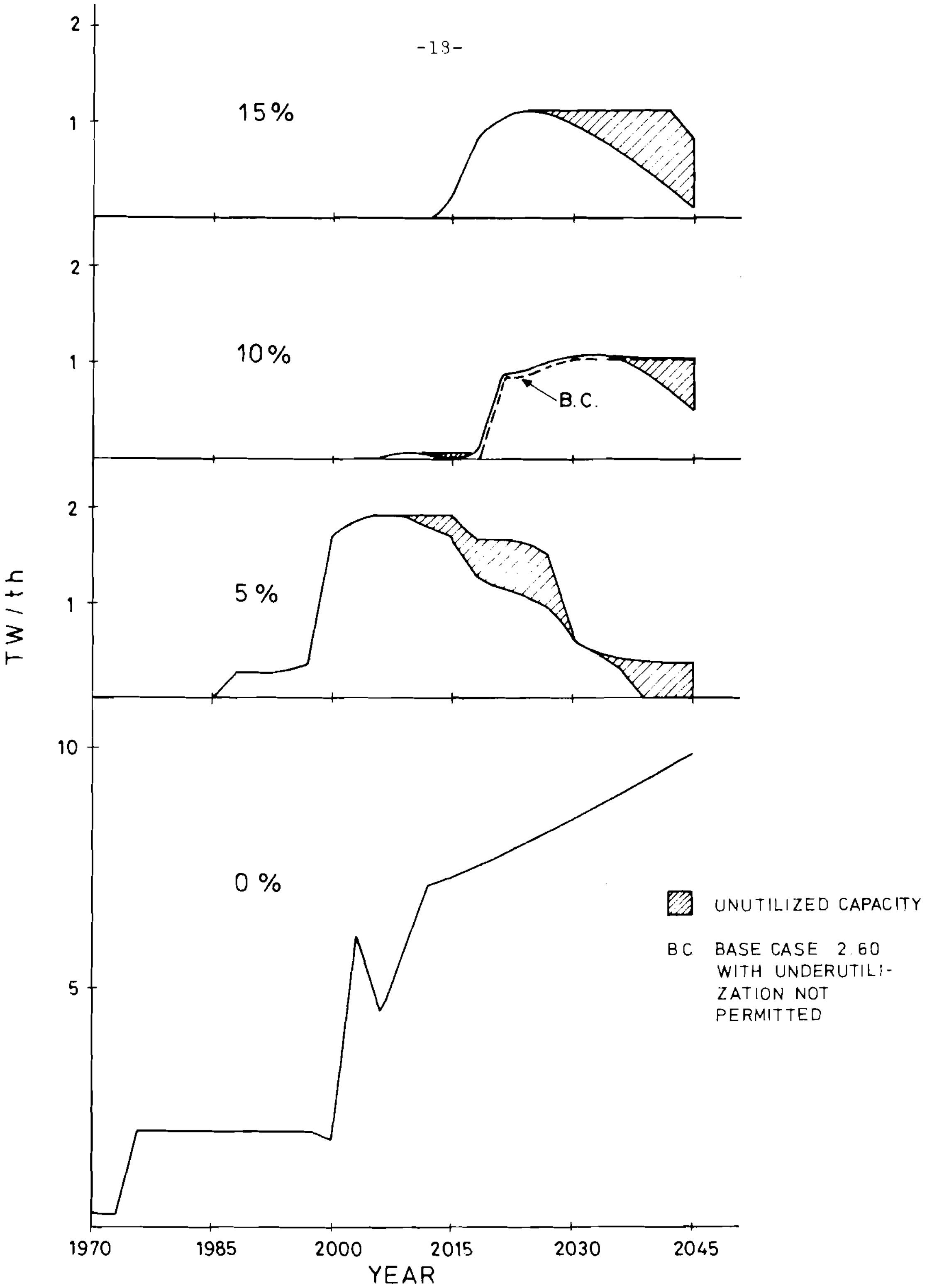


FIGURE 7: ELECTROLYSIS: RELATIVE TO DISCOUNT RATE WITH UNDERUTILIZATION; MODEL SOCIETY 2.60

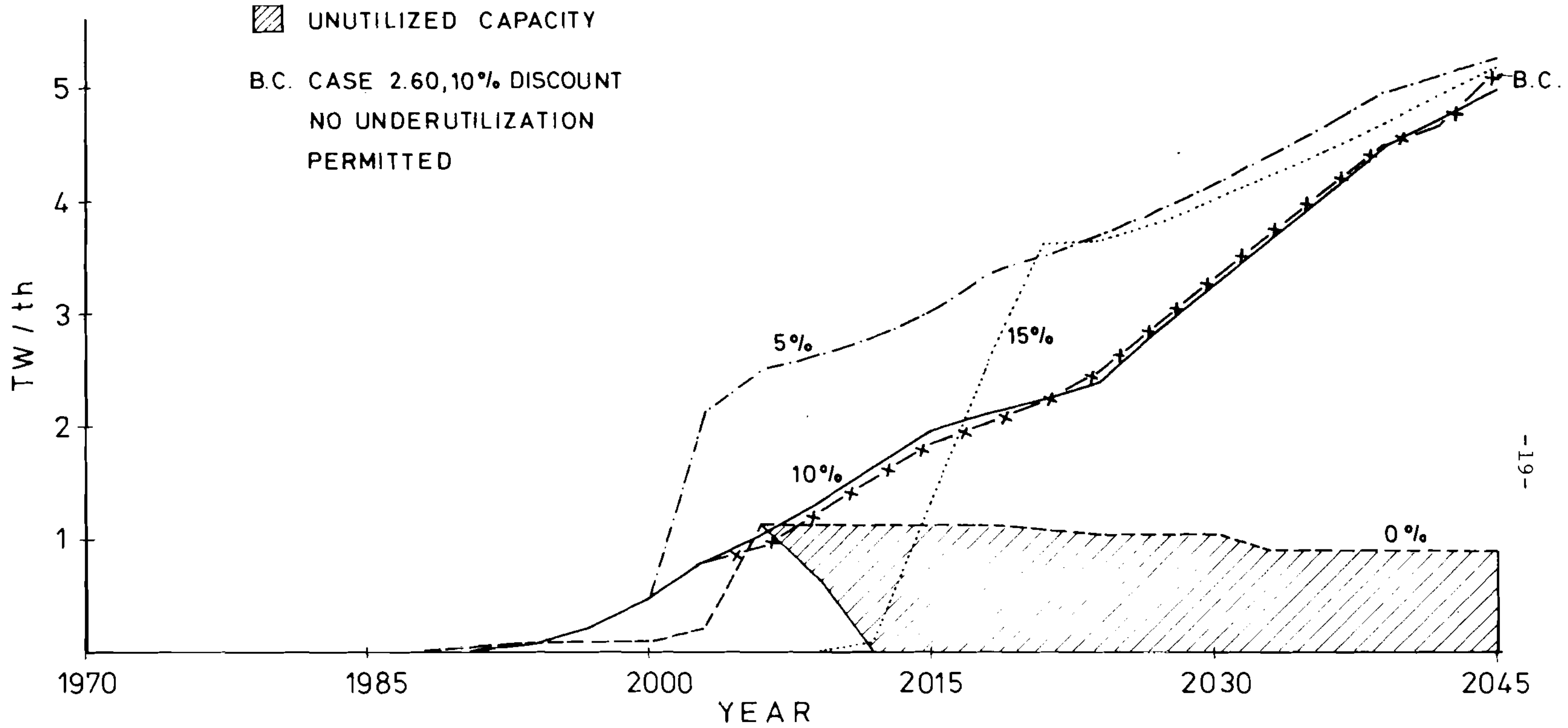


FIGURE 8: HTRB CAPACITY RELATIVE TO DISCOUNT RATE WITH UNDER-UTILIZATION OPTION; MODEL SOCIETY 2.60

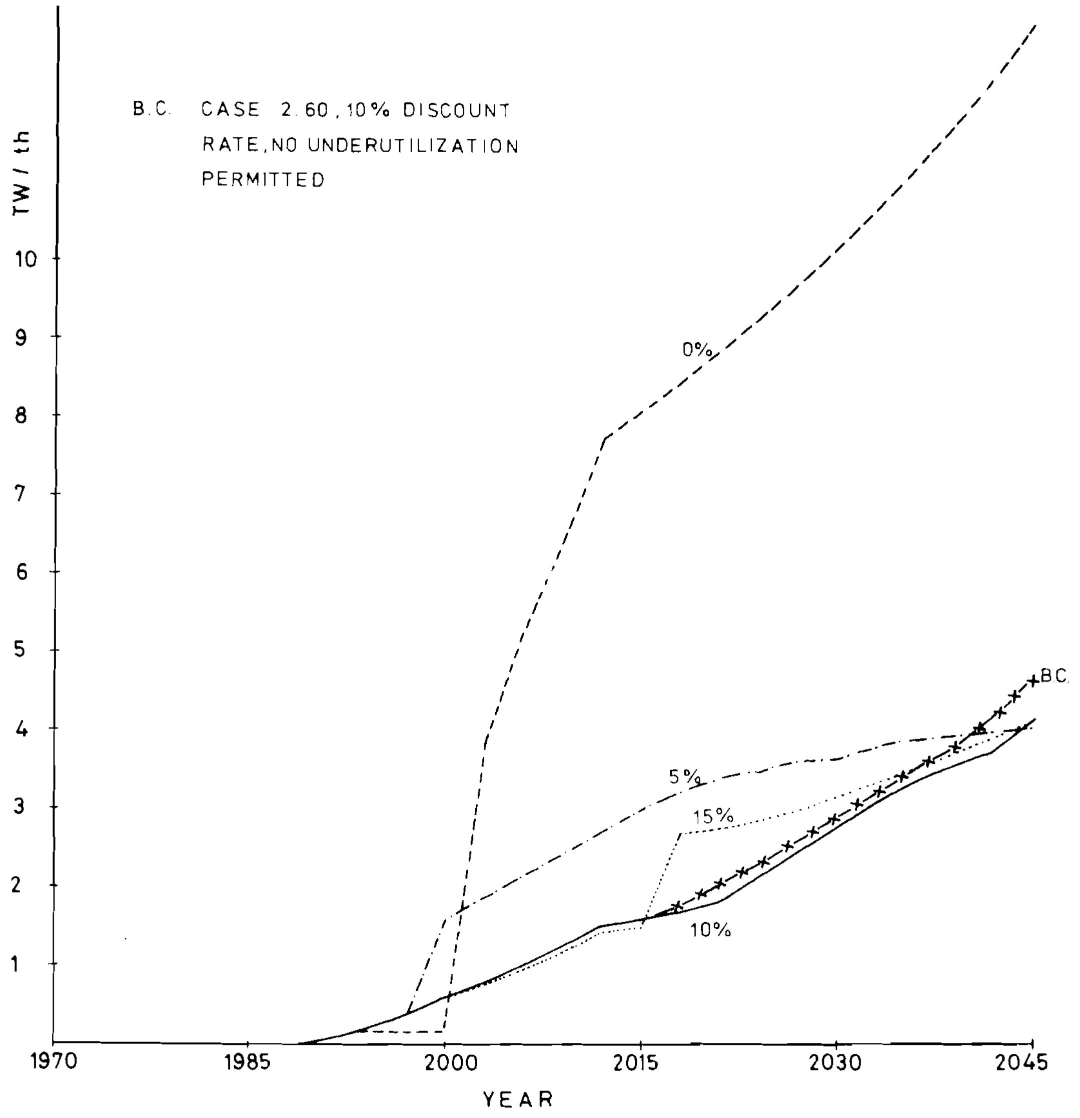
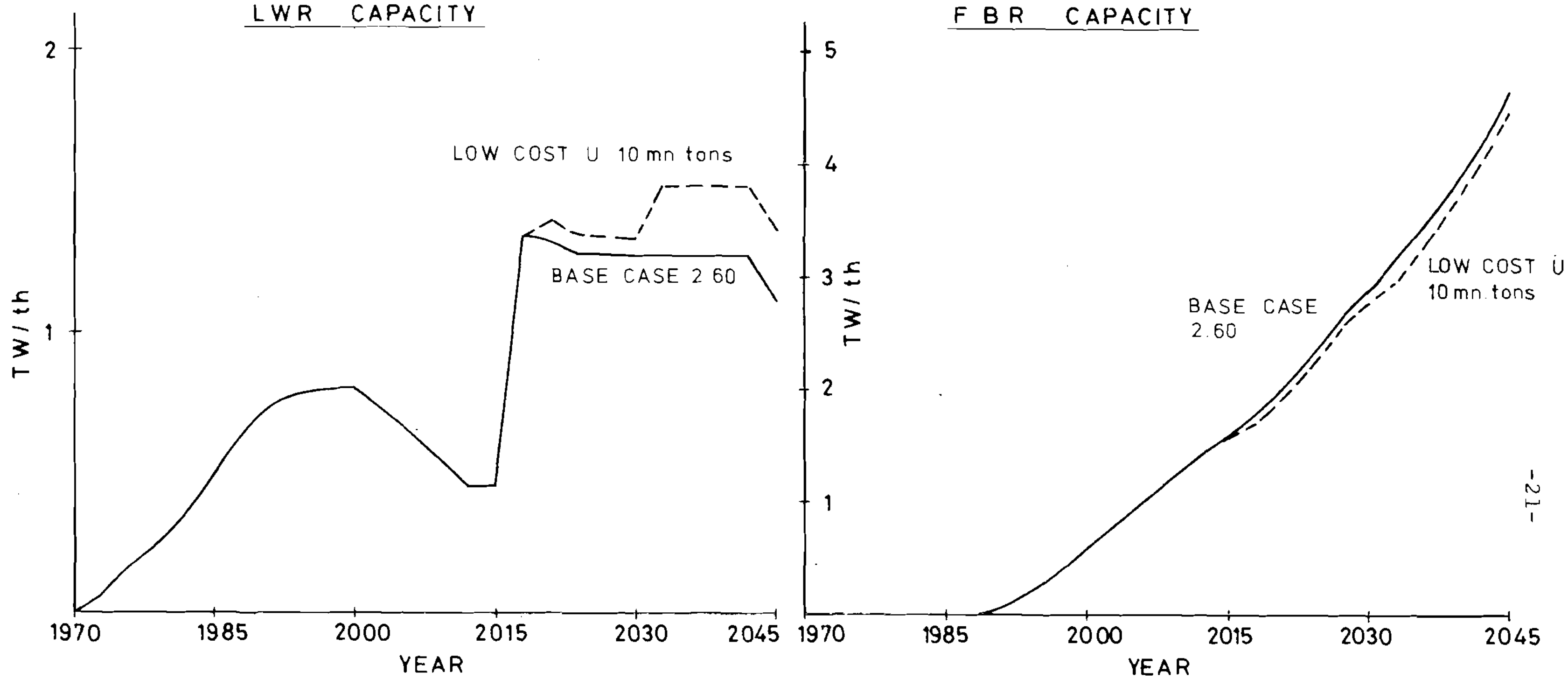


FIGURE 9 F B R CAPACITY RELATIVE TO DISCOUNT RATE WITH UNDERUTILIZATION OPTION MODEL SOCIETY 2.60



	At $ 15/lb	At $ 50/lb	TOTAL
BASE CASE 2.60 (2mn. tons LOW COST U)	2.00	2.91	4.91
ALTERNATIVE (10mn tons LOW COST U	5.21	0	5.21

TOTAL CONSUMPTION OF URANIUM (mn. tons)

FIGURE 10: L W R, F B R CAPACITY AND CUMULATIVE URANIUM CONSUMPTION RELATIVE TO AVAILABILITY OF LOW COST URANIUM MODEL SOCIETY 2.60

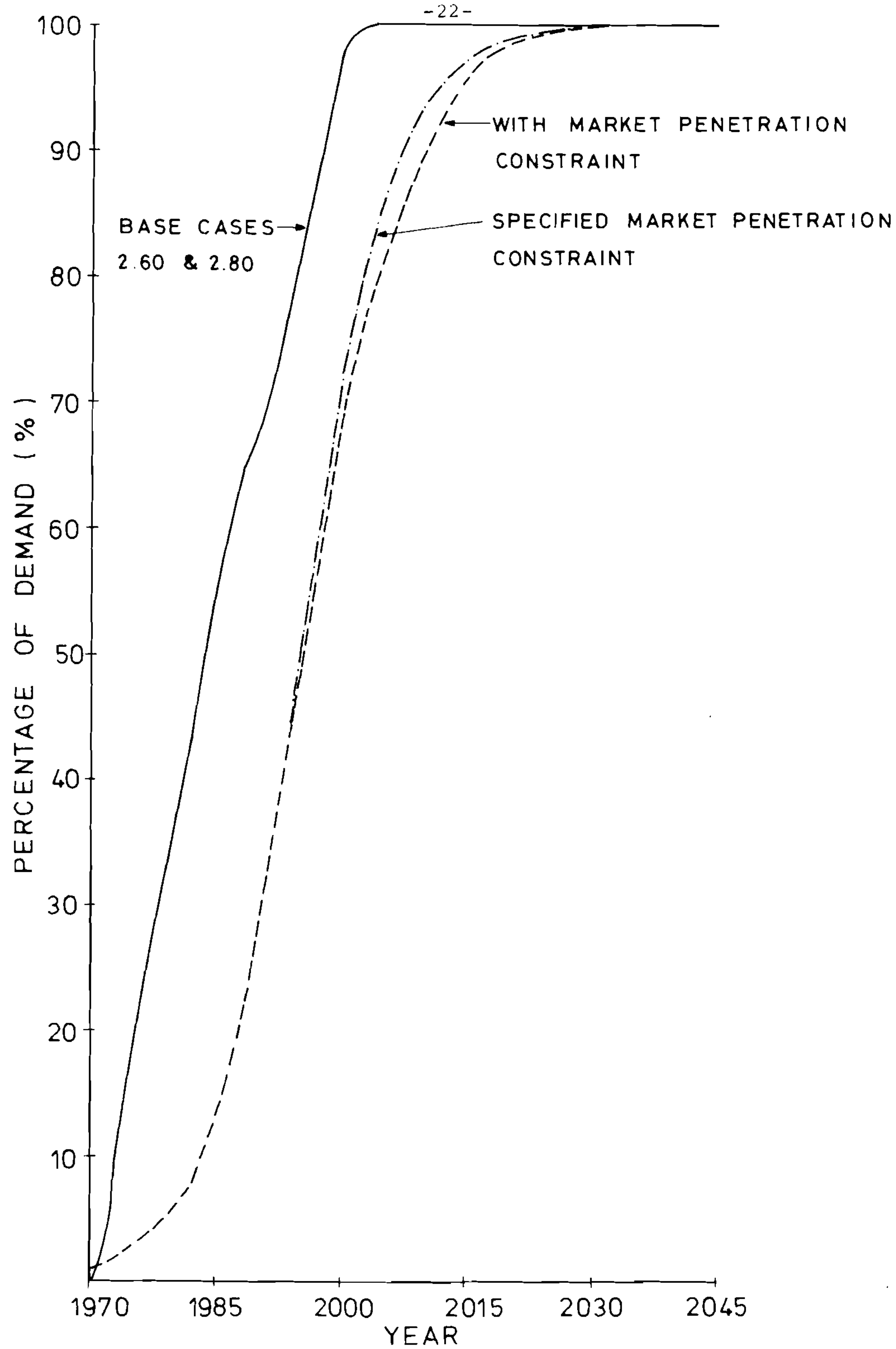


FIGURE 11: MARKET PENETRATION:
NUCLEAR ENERGY

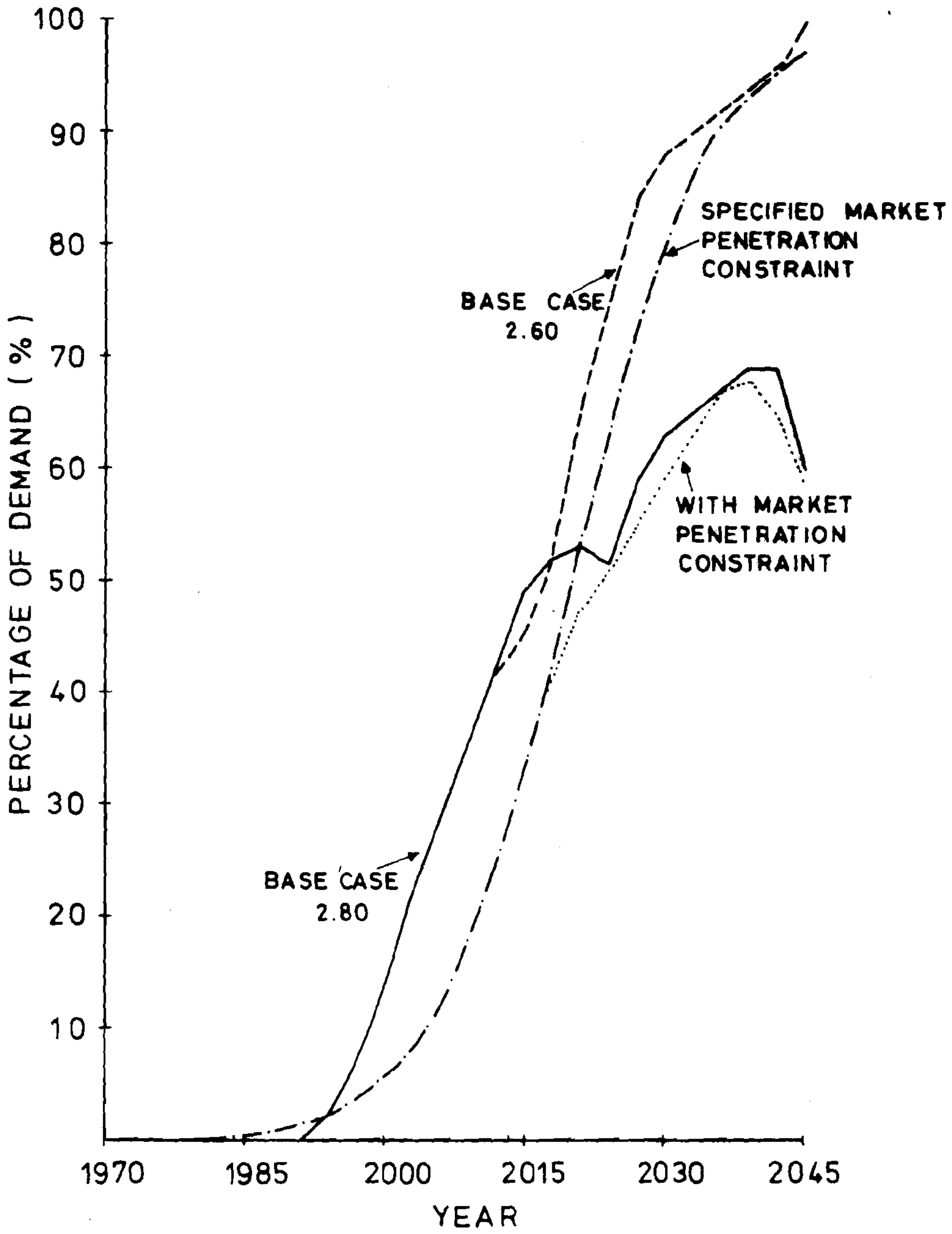


FIGURE 12: MARKET PENETRATION HYDROGEN

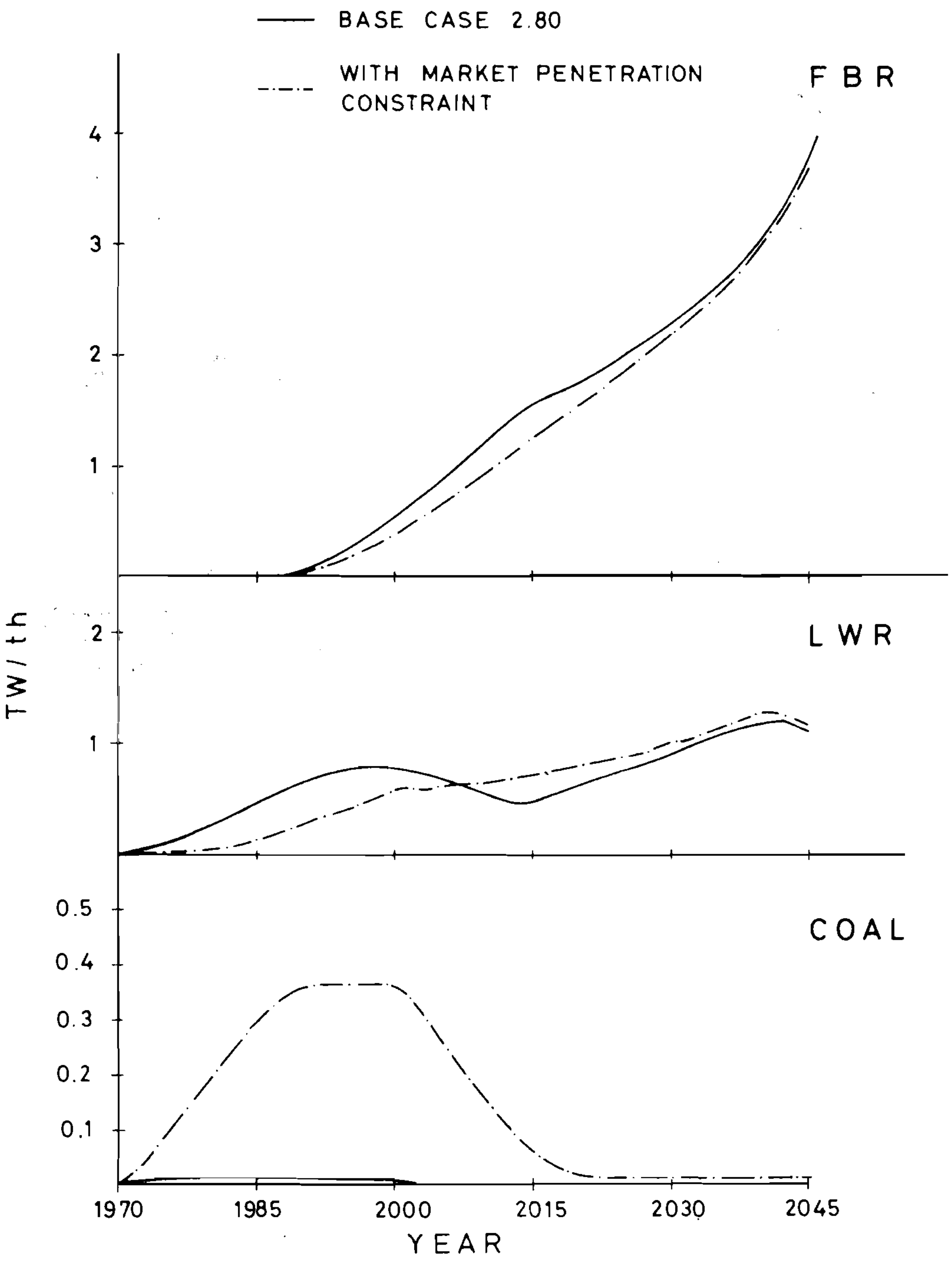


FIGURE 13: MARKET PENETRATION:
ELECTRICITY GENERATION

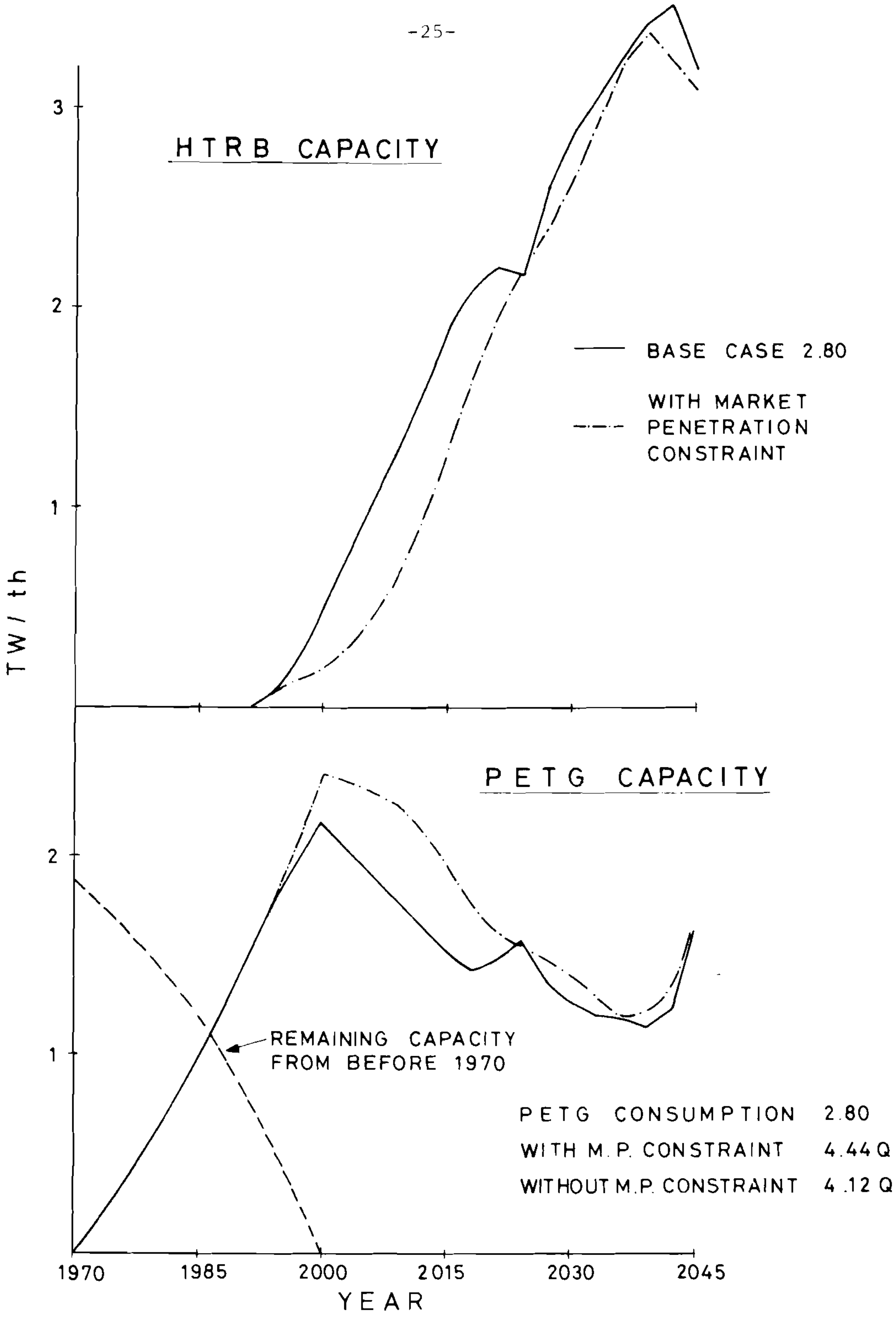


FIGURE 14 : MARKET PENETRATION : NON-ELECTRIC ENERGY

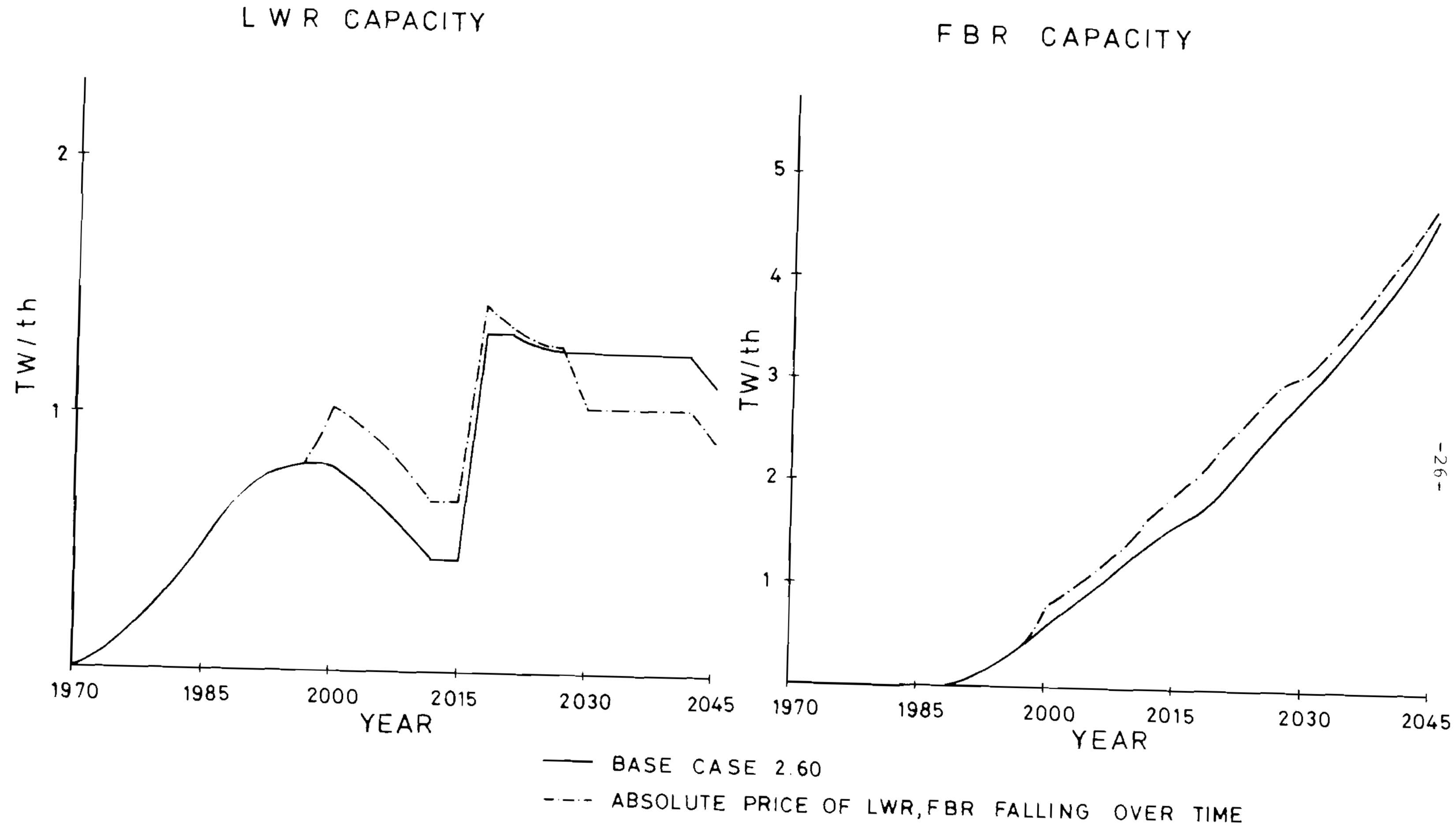


FIGURE 15 : SECULAR REDUCTION OF CAPITAL COST
MODEL SOCIETY 2.60

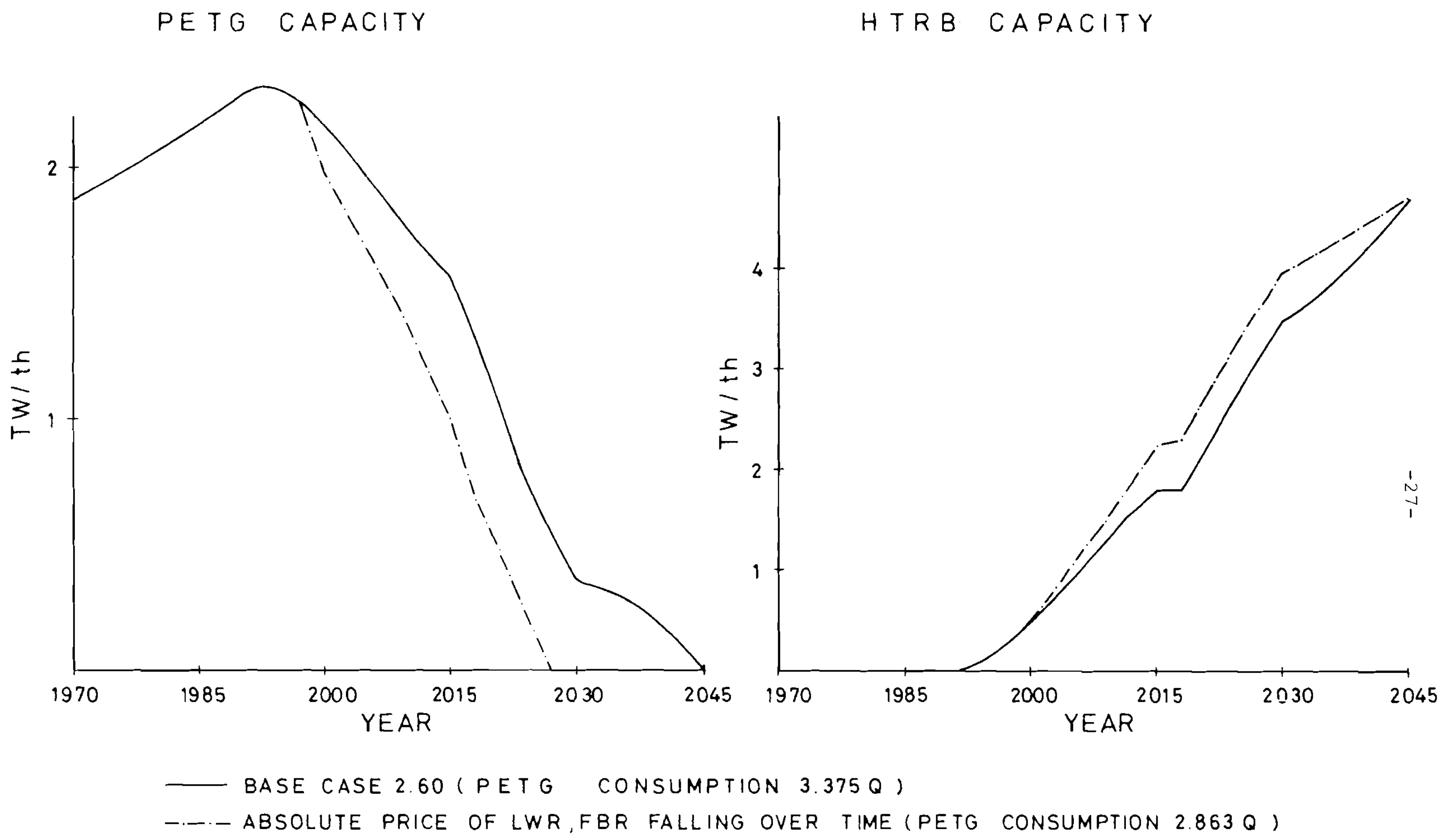


FIGURE 16: SECULAR REDUCTION OF CAPITAL COST
MODEL SOCIETY 2.60

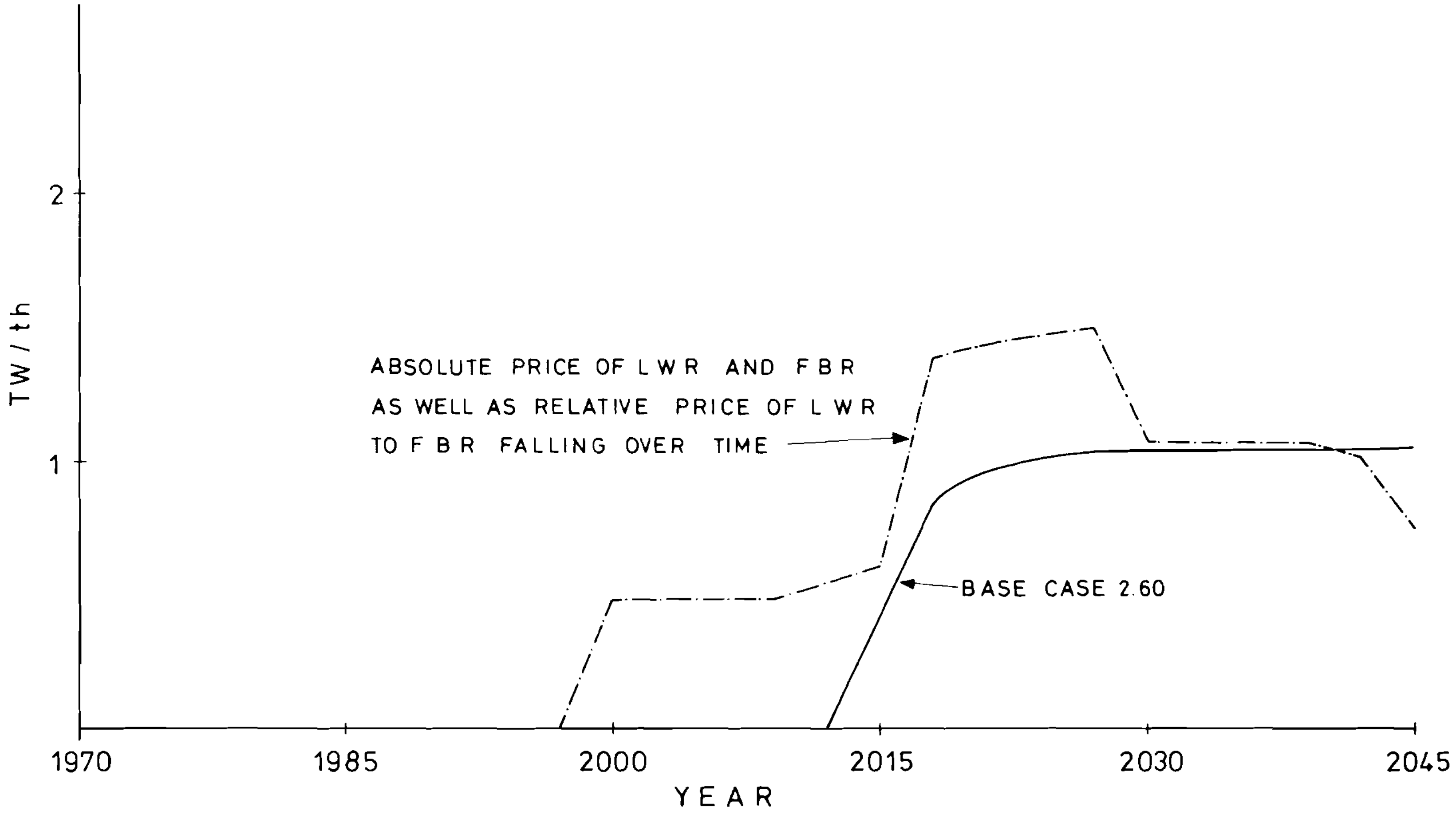


FIGURE 17: SECULAR REDUCTION OF CAPITAL COSTS: ELECTROLYSIS CAPACITY ; MODEL SOCIETY 2.60

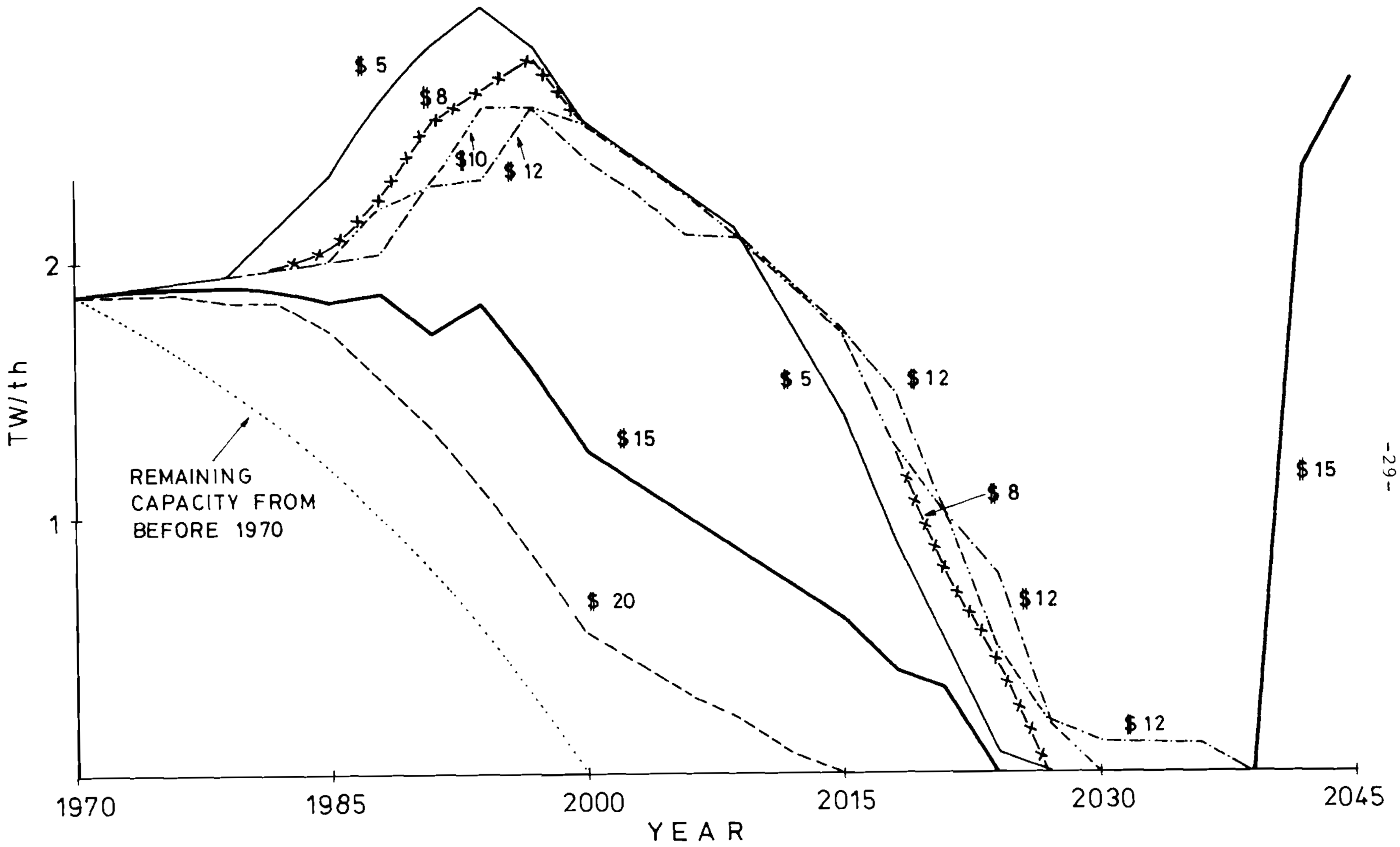


FIGURE 18 : ANNUAL CONSUMPTION OF PETG RELATIVE TO PRICE CHANGE
MODEL SOCIETY 3.60

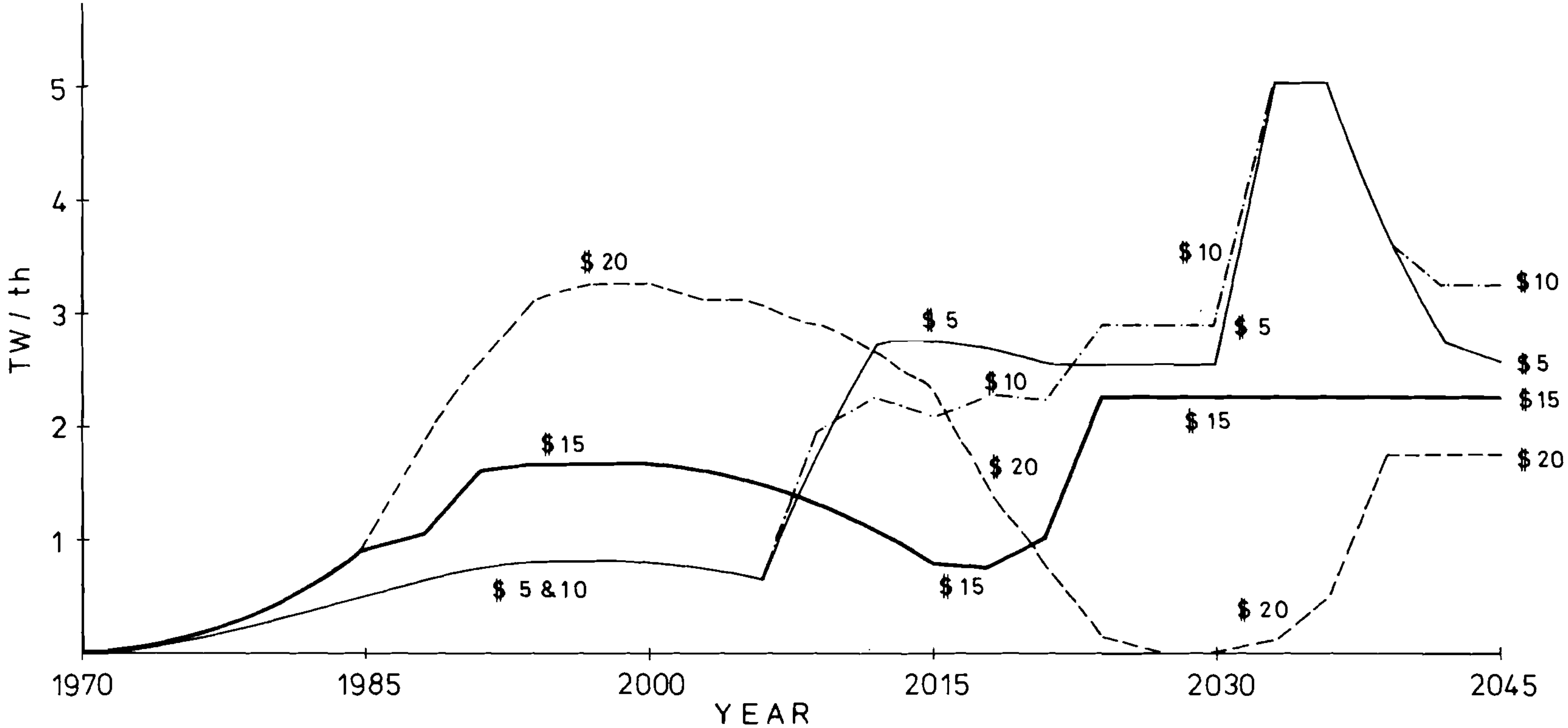


FIGURE 19: LWR CAPACITY RELATIVE TO PETG PRICE CHANGE
MODEL SOCIETY 3.60

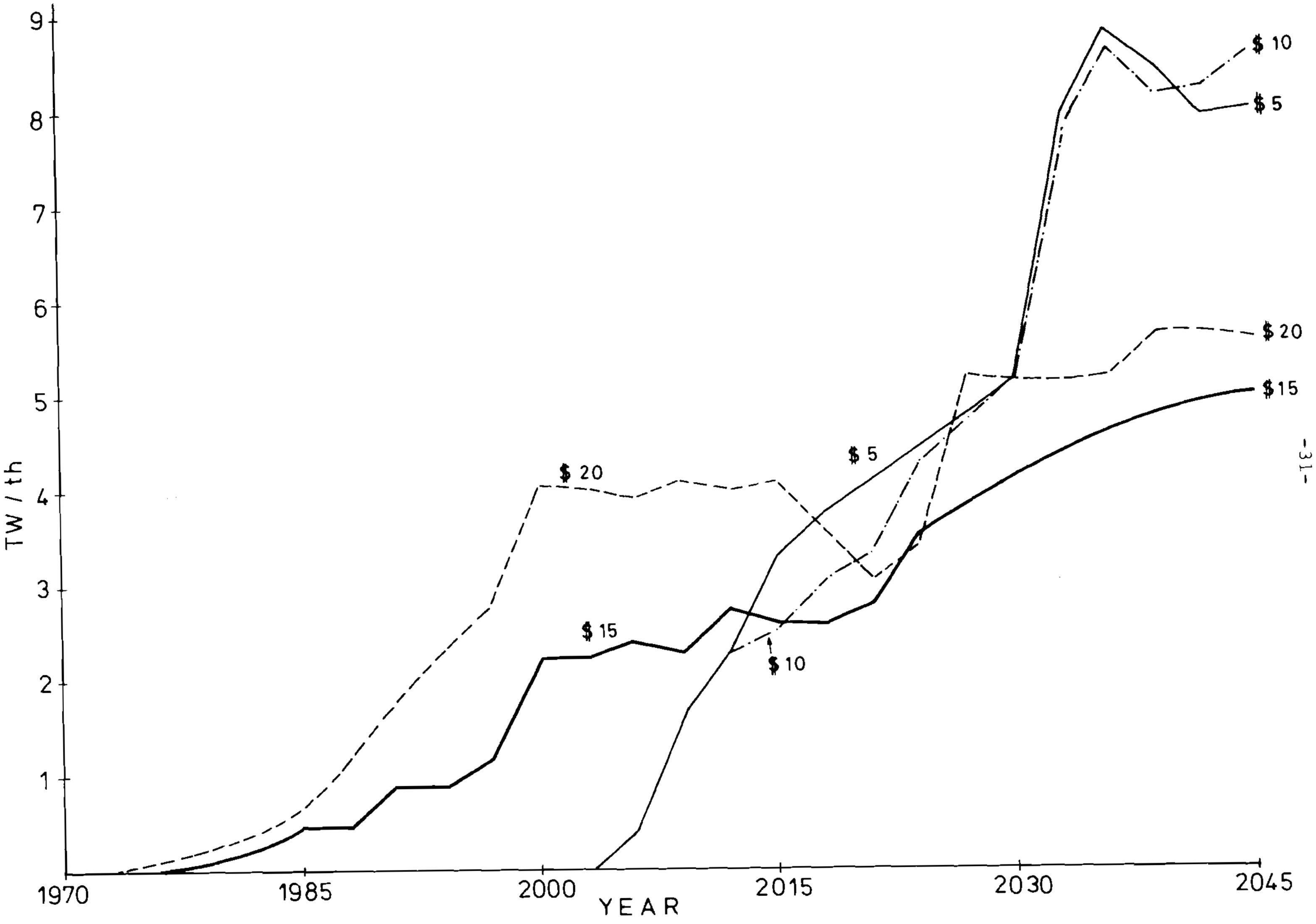


FIGURE 20: ELHY CAPACITY RELATIVE TO PETG PRICE CHANGE

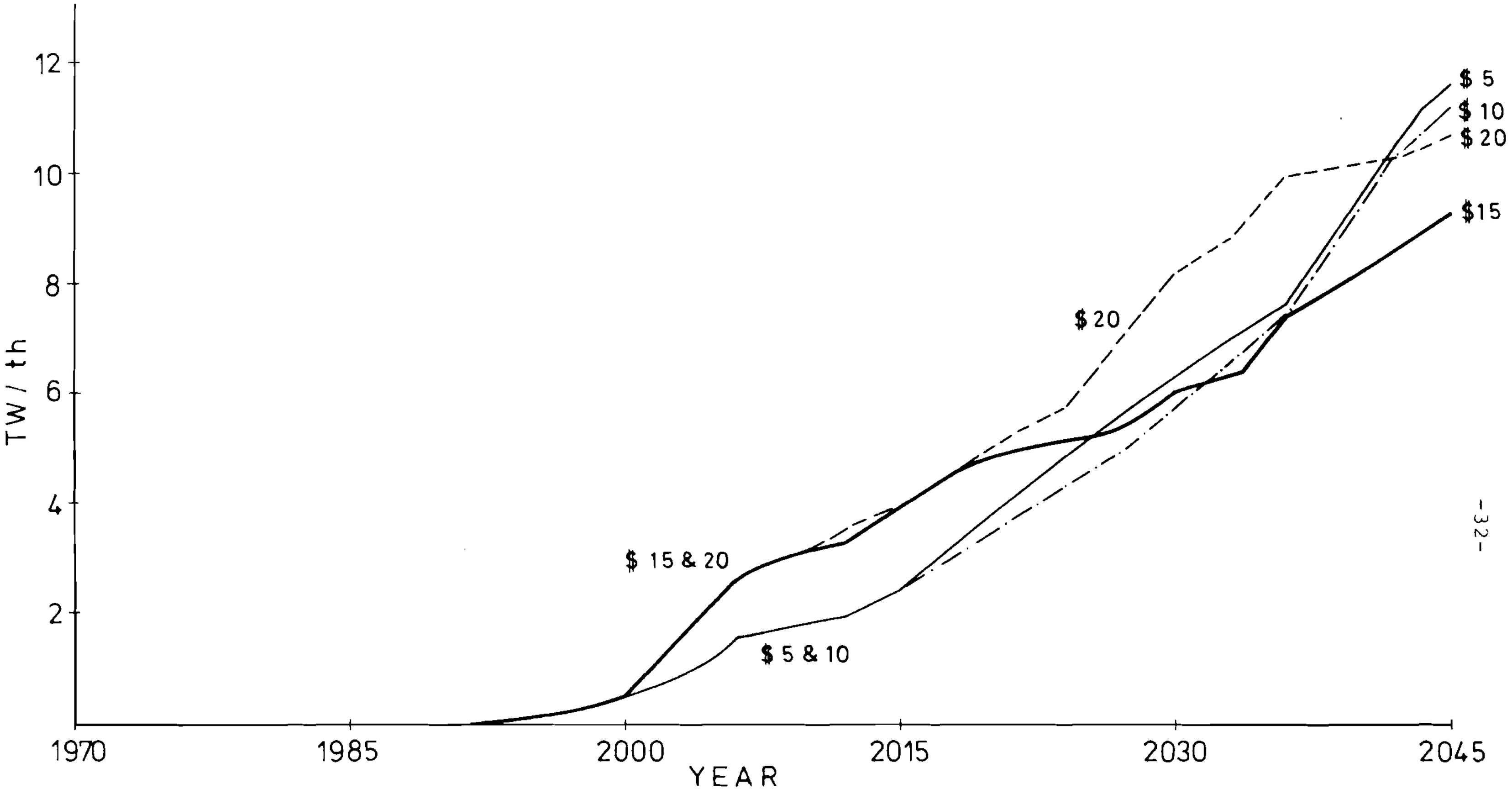


FIGURE 21: H T R B CAPACITY RELATIVE TO P E T G PRICE CHANGE
MODEL SOCIETY 3.60

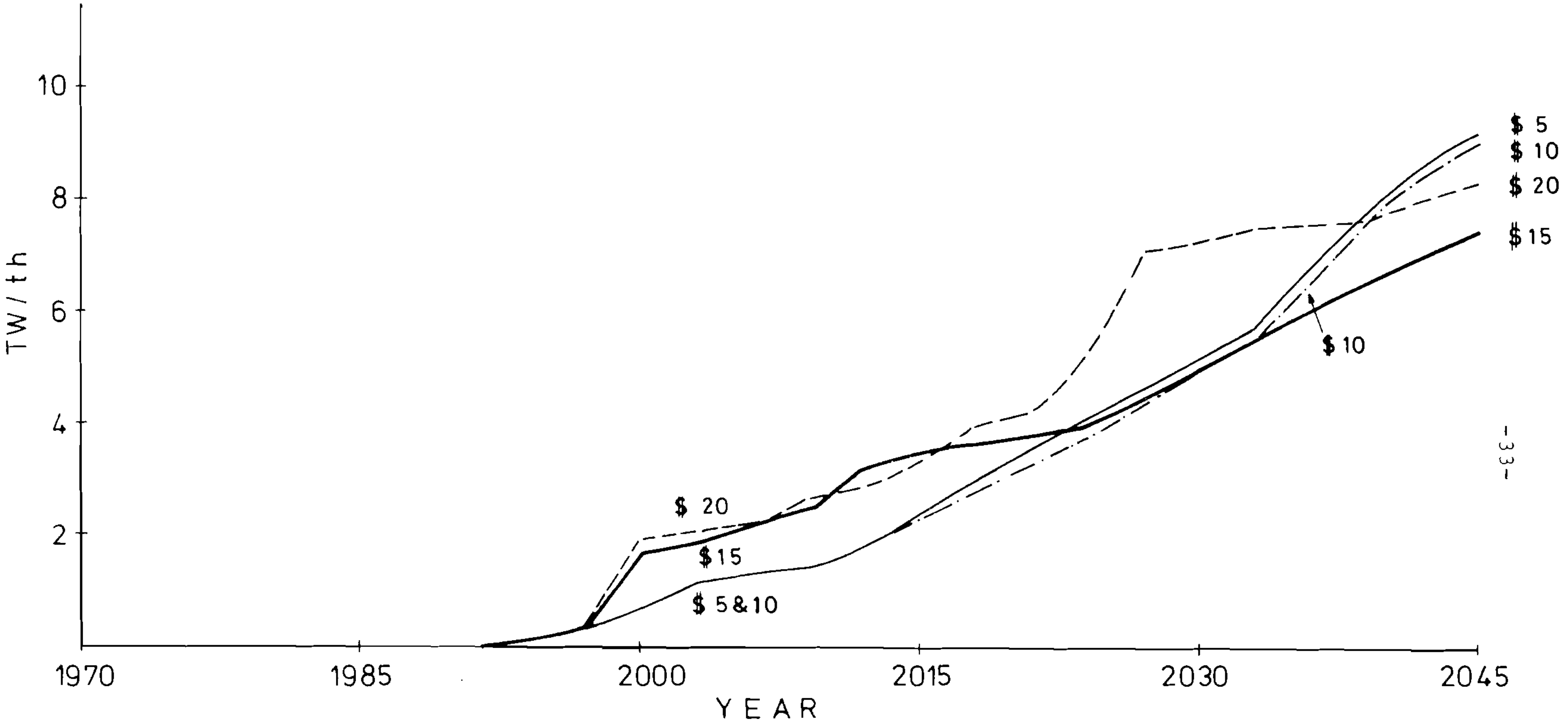


FIGURE 22: FBR CAPACITY RELATIVE TO PETG PRICE CHANGE
MODEL SOCIETY 3.60

REFERENCES

[1] Häfele, W. and Manne, A.S. "Strategies for a Transition from Fossil to Nuclear Fuels." IIASA Research Report RR-74-7.

[2] Fisher, J.C. and Pry, R.H. "A Simple Substitute Model of Technological Change." Technology Forecasting and Social Change, No. 3, 1971.