PROGRES TECHNIQUE DE L'ENERGIE NUCLEAIRE : PERSPECTIVES DANS LES DOMAINES DE L'ECONOMIE ET DE L'ENVIRONNEMENT

RESUME

Evolution des performances des réacteurs électronucléaires dans le monde : mise en évidence du retour d'expérience.

La compétitivité du nucléaire en France : les résultats expliqués par le contexte de la réalisation du programme nucléaires français.

Pour favoriser un nouveau développement nucléaire dans le monde : les perspectives techniques et économiques des réacteurs et du cycle du combustible ; les avantages vis à vis de la pollution atmosphérique à terme.

17 th annual international energy conference
May 25-27, 1994, Stavanger, Norway

TECHNICAL PROGRESS OF NUCLEAR ENERGY : ECONOMIC AND ENVIRONMENTAL PROSPECTS

Gilbert NAUDET, Economics Head - CEA - France

INTRODUCTION

Nuclear power is a recent energy source. Its expansion has been very rapid - so rapid that it represents an unique example in the history of energy technology. The first demonstration of the self-sustained nuclear fission reaction was achieved on December 1942 in Chicago, only 43 months after the international patents related to nuclear power were taken out in Paris. The first nuclear electricity was produced in 1951 ; the worldwide industrial expansion of nuclear energy began before 1960 and has been increasing for 30 years at the average rate of at least 20 % a year.

This expansion is now slackening down for many and well-known reasons : mainly cancellations in the U.S. as soon as the early seventies, due to regulatory obstacles and consequently economic difficulties, general decrease in energy demand growth rate, moratoria in many countries after Chernobyl accident, and, more generally, the fear, in public opinion, of long-lived radioactive waste.

Today, nuclear power represents about 5 % of world primary energy consumption, and its contribution to power generation reaches 17 %. The present stagnation in nuclear power plant construction entails a foreseeable decrease in the nuclear share in energy supply within the two or three coming decades [1]. The restoration of nuclear share to the present level will be possible thanks to a renewal of nuclear programs. This is a desirable objective because nuclear power is one of technology options available to meet the increasing energy demand in the long term future.

We know the obstacles which have to be overcome in order to reach this objective. Solutions do exist. They are revealed by learning lessons form the successes observed through the operating and economic performances of nuclear power. Other solutions will be found ; they will result from improvements due to new R & D efforts, and we cannot doubt it if we bear in mind the youth of nuclear power and its rapid expansion enabled by the R & D programs of the fifties and sixties.

LESSONS FROM OPERATING PERFORMANCES

The 431 nuclear power plants which are today operating in the world and the 31 already shut down units have produced by the end of 1993 an accumulated energy of 25 300 TWh, representing an operating experience of 7350 reactor-years. These results allow a detailed and useful analysis of operating performances. However it is not sufficient to illustrate the good performances of reactors by only calculating their average load factors, and by observing for example it reaches around 70 % for PWRs worldwide. We have to examine how these performances evolve and what lessons can be drawn for the future [2].

Considering the average cumulative load factor of PWRs in the world (except French reactors which operate too far from base-load generation), a steady increase depending on the accumulated operating experience is observed (fig. 1) for small and medium size reactors and large ones as well. This observation is valid also for BWRs.

A partial explanation is given by the learning effect and particularly by the improvements achieved in the U.S. after Three Mile Island accident. Another explanation results from a more detailed statistical analysis for the same PWR population distributed into the three following gross power ranges, knowing that a different power distribution yields similar conclusions :

100 MWe - 800 MWe
800 MWe - 1000 MWe
beyond 1000 MWe

For each range, there is a correlation between the average cumulative load factor observed at the end of 1992, and the date of connection to the grid. An illustration of this result is given in figure 2 where histograms represent the average load factor depending on various operating durations. (The first 3 years after connection to the grid are excluded to eliminate teething deases).

Moreover, another analysis shows that 90 % confidence interval of load factor is decreasing year by year both for PWRs and BWRs.

The conclusion is as clear as obvious : designers and operators have learnt lessons from past experience, technological progress can be evidenced and evaluated, so that new progress can be expected owing to the youth of nuclear energy. Consequently projected load factors for nuclear power plants to be built at the beginning of next century must be based only on statistics related to more recent nuclear units and not to the whole units.

LESSONS FROM ECONOMIC PERFORMANCES

Economic assessments of power generation are periodically carried out by OECD-NEA in order to compare nuclear plants with fossil fuel-fired ones. The last study shows that nuclear power is competitive in most industrialized countries at least for a 5 % discount rate, and the French nuclear generating cost is among the cheapest [3].

In France, every three years, the Ministry in charge of Industry makes up its mind about power plants to be commissioned ten years later. Its last study was issued in May 1993 [4], and will be summed up as follows :

Power generation options are compared within a precise framework ; its main parameters are given in table 1.

Table 1 : Economic parameters of comparison of power generation option

Constant money		FF 01/01/93
Commissioning date		2003
Discount rate		8 %
Exchange rate		1 $ = 6,6 FF
Lifetime	Nuclear	30 years
	Coal	30 years
	Gas	25 years

The main technical features of plants under consideration are presented in table 2.

Table 2 : Main technical features of power generation options

OPTION	NUCLEAR	COAL		GAS
Type	Advanced N4	Circulating Fluidized-Bed	Pulverized with scrubbers	Combined Cycle
Capacity (MW)	1450	2 x 300	600	700
Order date	1996	1998	1998	1999
Commissioning date	2003	2003	2003	2003

Nuclear units are N4 type improved to take into account foreseen safety requirements regarding foundation raft and containment structure.

Three types of fossil fuel-fired units are considered :

- an advanced plant, based on circulating fluidized bed technology (CFB) ; however, according to present development, a 600 MWe capacity unit is unlikely to be available in 2003 : two 300 MWe units are therefore considered.

- a conventional plant fitted out with scrubbers.

- a gas combined-cycle plant.

The fuel prices for the long term future are assumed to evolve most of time between two assumptions, high (H) and low (L), as given in table 3.

Table 3 : Assumptions for fuel prices

		2000	2010	2020	2030	2040
URANIUM	H	30	30	30	30	30
[$93/lbU308]	L	20	20	20	20	20
COAL	H	50	55	60	60	60
[$93/tPCS]	L	40	41.5	43	43	43
GAS	H	4.2	4.5	4.7	4.7	4.7
[$93/MBTU]	L	3.0	3.3	3.5	3.5	3.5

Investment cost is assessed with implementation conditions relating to the French experience : the cost of a nuclear unit refers to a pair of units built on a four unit site, and, more precisely, to the mean value between the first and the second pair of units and between a sea-side and a river-side site. In addition, this cost refers to units being ordered every eighteen months which matches the foreseeable program at the beginning of next century. .

Assessment of interests during construction is based on an expenditure-time profile using the discount rate of 8 % in constant money ; this rate is taken into account for the planning of any large equipment in France ; interests during construction amount to 27% of construction cost for nuclear, 18.3 % for coal and 10.8 % for gas.

Investment costs also include pre-operation expenditures and discounted decommissioning costs. Decommissioning costs refer to dismantlement of the plant, which amounts to 15 % of total investment cost - a very prudent estimation considering comparable international ones. It is to be noticed this estimation corresponds to 50 % of nuclear island investment. Associated expenditure is assumed to be paid 10 years after phasing out the reactor, which is a rather pessimistic hypothesis. Discounted decommissioning costs are less than 1 % of investment costs.

Table 4 : Investment costs of power generation options, in F93/kWe

OPTION	NUCLEAR	COAL		GAS
		Pulverized	CFB	
Construction	7528	7361	6852	4006
Interests during construction	2032	1348	1255	431
Others	1031	725	625	243
TOTAL	10591	9434	8732	5680

Availability assumptions are related to planned and forced outages, depending on annual operating time ; the overall availability factors for base-load generation are as follows :

nuclear	74.5 %
coal	74.5 %
gas	80 %

The breakdown of levelized generating costs for base-load generation are given in table 5 in cF 93/kWh.

Table 5 : Levelized generating costs for base-load generation in cF93/kWh

OPTION	NUCLEAR	COAL (CFB)	GAS
Investment	13.6*	11.3	5.9
Operation	5.6	5.8	2.4
Fuel	4.5 / 6.2**	11.7 / 17.7	21.1 / 27.4
R & D	0.4		
TOTAL	24.1 / 25.8	28.8 / 34.8	29.4 / 35.7

* of which 0.1 cF/kWh is for decommissioning

** of which 0.1 cF/kWh is for waste treatment and storage

The nuclear fuel cost covers all steps of fuel cycle evaluated according to either market prices as experienced in France or national and international estimates regarding disposal of high-level waste. It includes also investment for two underground disposal laboratories.

The portion of nuclear R & D expenditures which is not directly taken into account in kWh cost through supplier prices and which covers own CEA and EDF R & D activities has been included ; it corresponds to 1.6 % of nuclear generating cost.

Insurance premiums for nuclear risk have been estimated according to various methods with many uncertainties. However, all of them give an order of magnitude of less than 1 % of kWh cost, similar to calculation uncertainties.

It should be noticed that for nuclear option all related costs are rather conservative estimates so that its competitiveness, as established, cannot be questioned.

The results of the study are summed up as follows :

- for base-load generation, nuclear electricity is the cheapest (roughly 25 % less than CFB coal),

- for annual operating times of 4000 hours or more, nuclear remains competitive even with conservative assumptions,

- for lower times, it competes with coal (CFB) and gaz (combined cycle) as shown in table 6. However, the break-even very much depends on fuel price assumptions and on uncertainties associated with those technologies as detailed hereafter. Its low value explains the increasing gap between availability and load factors as nuclear power capacity was rising in France, as shown in fig. 3.

Table 6 :Generating costs for annual 3000 hour operating time, in cF93/kWh

OPTION	NUCLEAR	COAL (CFB)	GAS (Combined cycle)
Total cost	55 / 57	55 / 61	48 / 55

Because CFB is an advanced technology, related costs are uncertain, therefore a limited power capacity was considered in this study. Conventional pulverized coal plant with desulphurisation, even if less economic according to these calculations, is presently an experienced technology.

Huge storage capacities are needed for combined cycle gas units in intermediate load generation ; limited development of such capacities is expected from now until around 2010 so that, for practical reasons, their extension should be limited as well.

As a conclusion, a remarkable aspect of nuclear power is that it has always been taking on the responsibility for treatment and disposal of its waste, and the corresponding costs have always been included in its generating cost. Moreover, considering the assessment of its R & D expenditures and insurance premiums for risks, one can underline that nuclear energy is the only primary energy source which integrates all its external costs.

Another important point is the stability of nuclear generating cost (fig. 4). Investment cost of nuclear power plants has been stabilized for around 10 years although a slowdown of nuclear construction. At the same time, nuclear fuel cost has been decreasing for several reasons. Market price of natural uranium has been reduced so that the corresponding item in the generating cost breakdown is lower and lower. Other steps of nuclear fuel cycle involve industrial activities which are fully mastered, and the related costs are consequently stabilized, and even tend to lower because of international competition. A last, the upward trend of nuclear fuel burn-up becomes the major reason of the decreasing of fuel cost.

Thus, nuclear option in the French energy supply system is obviously justified by generating cost assessment. It is all the more justified since its macroeconomic impacts are outstandingly favorable for the country as it has been already assessed [5].

Due to the importance of economics issues for a revival of nuclear energy worldwide, it appears necessary to recall the favorable conditions of the French nuclear program implementation, which entailed the good economic performances above mentioned, and to draw lessons from them.

First, the organization of French nuclear industry is characterized by a small number of actors : only one utility, only one nuclear boiler supplier, only one nuclear fuel operator, and an experienced R & D organism.

Second, a constant and strong political will has been maintained. The successive governments have been aware of the interest of nuclear energy for the security of supply because of the lack of national energy sources ; this political attitude has entailed a large enough acceptance by public opinion.

Third, French regulatory processes for licensing are well adapted to ensure a high level safety without hindering the construction of power plants.

Forth, as a consequence, a well-planned program is characterized by the implementation of several series of nuclear power plants according to multi-annual contracts between utility and suppliers. The series effect and its associated standardization have already been quantified as far as capital cost is concerned [6] ; they also allow to enhance feedback experience. So, their impact on the cost effectiveness of French nuclear plants has been very significant.

FUTURE DEVELOPMENT AND ASSOCIATED ECONOMIC PROSPECTS FOR NUCLEAR POWER

Technical improvements which can be expected form current R & D programs must meet the requirements expressed by public opinion for an enhanced safety of reactors and a reduced environmental impact of waste ; at the same time, they must ensure the competitiveness of nuclear power plants. Nuclear development has to be examined in the light of these two prerequisites for a revival of this energy source.

As far as reactors are concerned, the new design jointly developed in Europe by Siemens and Framatome corresponds to an evolutionary type-reactor. This choice allows to take full benefit from operating experience accumulated up to now in order to enhance safety based on the concept of defence in-depth ; it also allows to benefit from the economies of scale on capital, operating and maintenance costs, and to master the development costs from previous construction experience. However, this project is not only designed to reduce further the risk of a core meltdown, but also to mitigate the consequences of such an accident by strongly limiting releases ; for this purpose, additional safety features are necessary and entails a few per-cent overcost of plant investment.

This overcost is to be compensated by a better reliability of the plant associated with a better safety. Preventive maintenance and in-service inspections will also contribute to improve availability, so that the impact of an enhanced safety on generating cost will be limited.

Concerning fuel cycle, technical improvements are expected at various stages. Enrichment R & D in the U.S., France and Japan has focused on Atomic Vapour Laser Isotope Separation for 10 years (AVLIS in the US and Japan and SILVA in France). The economic gain could be significant depending on the size of the plant ; for large capacity plant, the cost per SWU could be about $75 to be compared with current selling price of $120. This laser technology could be commercially deployed before 2010.

Fuel assembly development is still ongoing. Cost decrease in this field arises from advanced designs aiming at better thermal efficiency and using more efficient structural materials. Thus a better use of uranium will be obtained, and, especially, further burn-up extension is expected up to 55 or 60 GWd per tonne ; in this regard, the experienced extension from 33 to 42.5 GWd per tonne entailed a fuel cost reduction of 10 %.

In reprocessing, feedback experience will continue to be a major factor of plant cost effectiveness. For the long term, improvements are foreseeable ; they will be based on new chemical extraction processes which are currently developing . Automation and advanced monitoring will reduce operation costs.

Countries as France and Japan which are determined to pursue their nuclear program must have a strategic vision over the long term and consequently a coherent policy for the management of spent fuel. In this respect, reprocessing appears as the optimal option : fissile materials are recovered and can be reused and the various categories of waste are conditioned under the most appropriate forms.

Although burial of long-lived waste in underground disposal is considered safe by related authorities, it seems preferable, for the long term, to develop a technical option able both to minimize plutonium stockpile and to destroy major part of long lived waste. Long-lived waste are essentially minor actinides which are artificial heavy elements produced by fuel irradiation in reactors. According to ongoing investigations, they could be partitioned thanks to specific chemical processes in reprocessing plants and then incinerated in high flux reactors, that is to say transformed into fission products. A promising technology for both actinide incineration and plutonium stockpile regulation consists in liquid metal reactors (LMR) with specific core concept.

Transmutation of artificial actinides is a very old idea, but nowadays we are in position to develop this waste management option and to give a preliminary estimates.

Additional workshop investments for actinide partitioning in LWR fuel reprocessing plants are already estimated on basis of La Hague plant investment cost and owing to necessary adaptation for envisaged processes.

Concerning LMR, economic assessment is derived from a previous study [7] especially for reactor investment and operation. Fabrication and reprocessing costs have been modified because of new fuel element types and core options. Sensitivity studies have been carried out in order to take into account uncertainties about some technical data or possible strategic options. Nevertheless, the overcost related to the overall levelized discounted generating cost of the French nuclear power system as a whole should not exceed 3 or 5 % the current generating cost.

CONCLUSION

Today nuclear programs are pursued or launched only in countries where necessary conditions related to energy policy, safety and economics are met. In other words, nuclear power is presently deploying only if it represents an energy source essential for the country, if there is a sufficient industrial infrastructure associated to a high safety culture level in order to build and operate nuclear plants, and, at last, if a political will strong enough and lasting exists to implement a coherent program.

Under these conditions, nuclear power plants are undoubtedly competitive with fossil fuel-fired plants, and ensure a high level safety. They are all the more attractive for energy supply because their generating cost integrates their external costs, and they contribute efficiently to air quality improvment, as it has been assessed in France [8], either locally by avoiding sulphur or nitrogen oxides emissions, or globally by reducing carbon dioxide emissions from the energy sector. Extending the results obtained in above quoted study [1], a significant but nonetheless possible nuclear power renewal would contribute around 2030 to a worldwide carbon dioxide emission reduction which is estimated between 10 and 15 per cent.

To cope with the increasing demand for safety enhancement and reduction of the long-term radiological impact of waste, new reactor designs are developed and new waste management options are envisaged. Current development and preliminary economic assessment show that nuclear competitiveness will be maintain. All the conditions will be met for a revival of nuclear power and for a significant increase of its contribution to a safe, economic and sound energy supply in the world.

REFERENCES

[1] G. NAUDET - J.M. CAPRON
"Nuclear power prospects up to 2020 in global energy context"
IAEE - Nusa Dua - Bali, Indonesia, July, 1993.

[2] J.P. QUAEGEBEUR - N. PINEAU
"Analyse statistique des performances des centrales électronucléaires dans le monde".
CEA report, France, April, 1994.

[3] "Projected costs of generating electricity" - OECD/NEA.
Update 1992 - Paris.

[4] "Les coûts de référence : production électrique d'origine thermique "- Edition 1993 - Ministère de l'Industrie, des Postes et Télécommunications et du Commerce Extérieur - Paris, France.

[5] A. CHARMANT - N. LADOUX
"Nuclear energy in France : assessing its impacts on the economy and the environment through an integrated model. Senior Expert Symposium on Electricity and the Environment"
Helsinky, Finland, May 1991.

[6] C. VINCENT
"The series effect : impact on capital cost of the standardization of PWR plants".
IAEE - Tours, France, May, 1992.

[7] G. NAUDET - C. SATRE - J. MARTIN - L. DUCHATELLE
"The trend to the competitiveness of FBRs in Europe" .
International Conference on Fast Reactors and Related Fuel Cycles .
Kyoto, Japan - October-November, 1991.

[8] A. CHARMANT - N. LADOUX - M. VIELLE
"An Assessment of the impacts of the French Nuclear program on the environment".
IAEE - Honolulu, 1991.

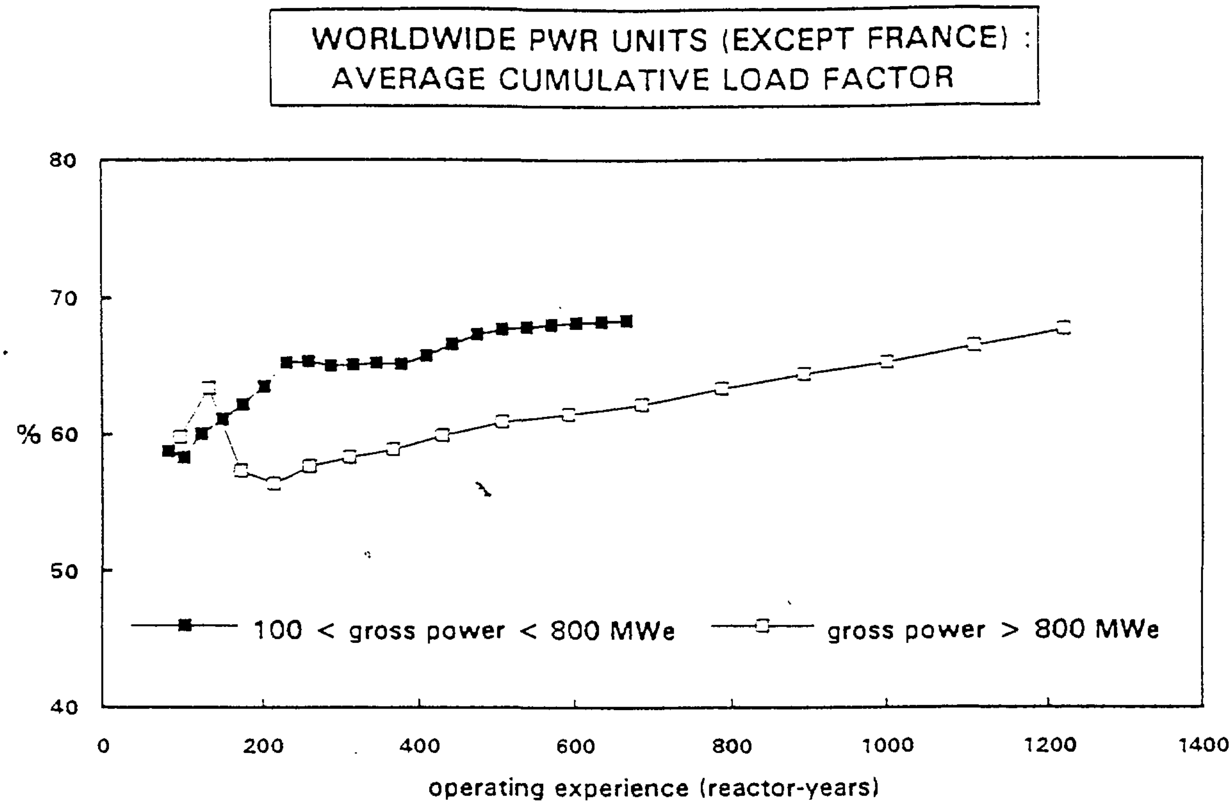


Figure 1

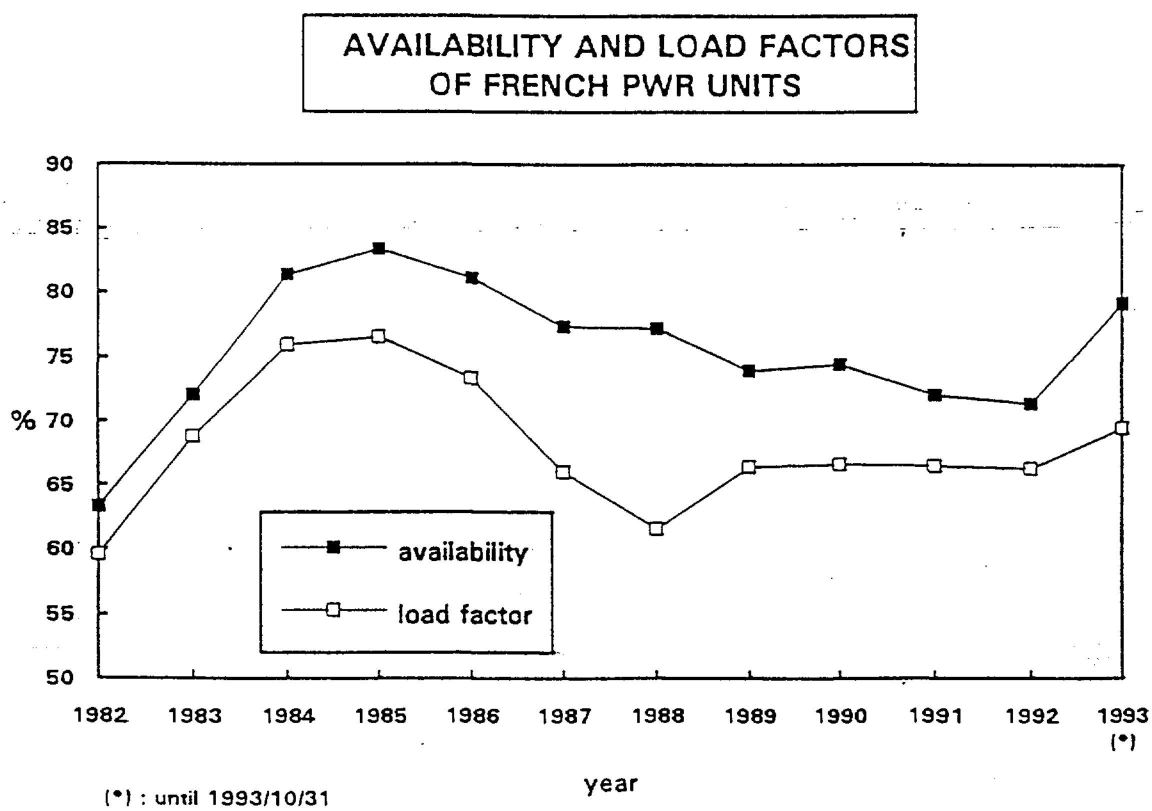


Figure 3

WORLDWIDE PWR UNITS (EXCEPT FRANCE) :
AVERAGE CUMULATIVE LOAD FACTORS (%)

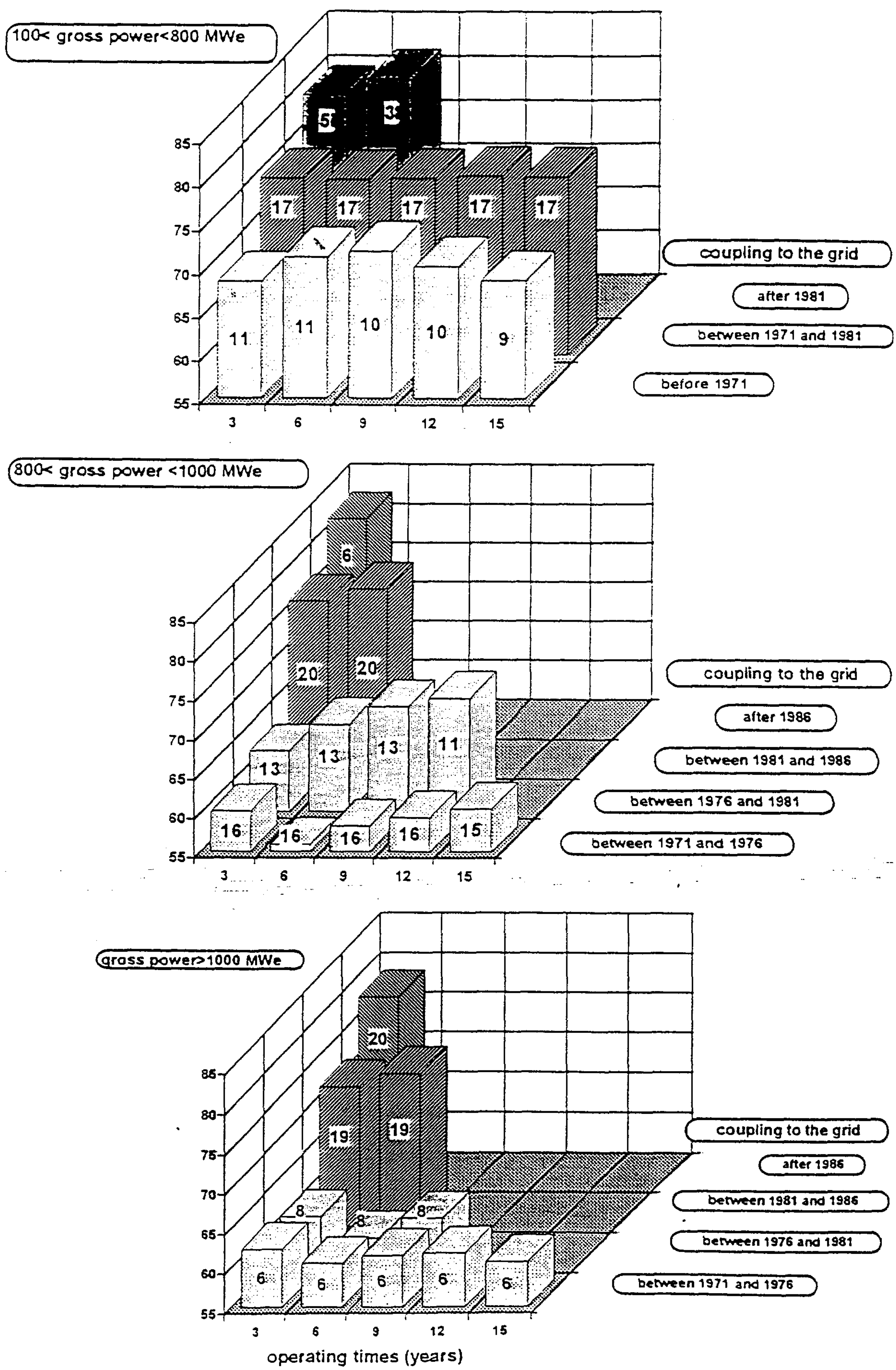
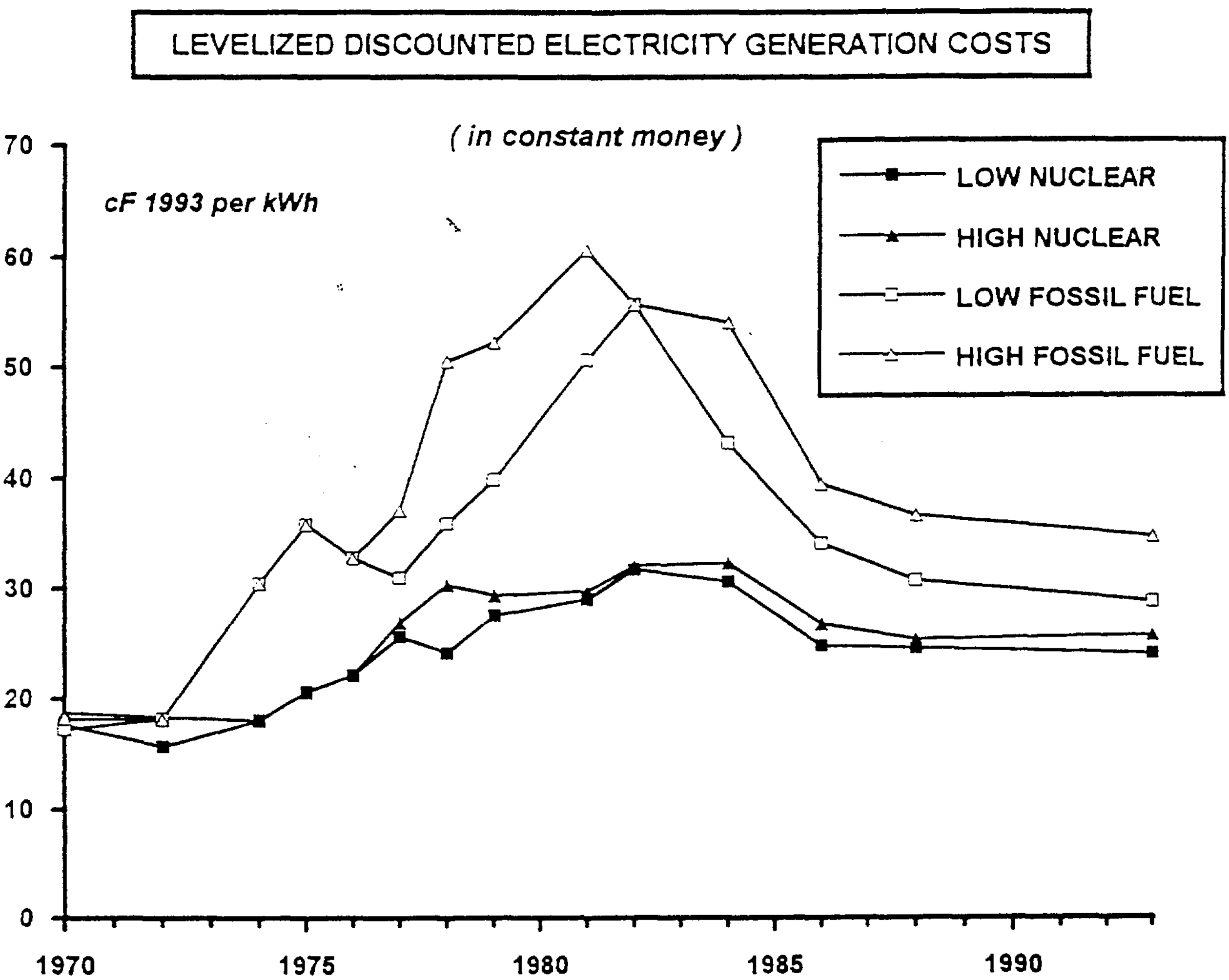


Figure 2

Figure 4


LEVELIZED DISCOUNTED ELECTRICITY GENERATION COSTS
(in constant money)
cF 1993 per kWh
LOW NUCLEAR
HIGH NUCLEAR
LOW FOSSIL FUEL
HIGH FOSSIL FUEL
70
60
50
40
30
20
10
0
1970
1975
1980
1985
1990