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EVALUATION OF ELECTRICAL ENERGY PRODUCTION PATTERNS

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F. CONTI , G. GRAZIANI , R. VISEUR and C. ZANANTONI

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EUR 5336 e

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Published by the Commission of the European Communities Directorate General „Scientific and Technical Information and Information Management"

29, rue Aldringen

Luxembourg (Grand-Duchy)

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* Joint Nuclear Research Centre
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and
** General Direction Energy - Brussels

ABSTRACT

The code is used to evaluate the physical and economical consequences of electrical power station installation policies.
The input data are:
— the time-dependent electrical energy demand and its load duration curve.
— the physical and economical characteristics of the power stations.
— the splitting of the energy between the various types of station, apart from the energy produced by a Plutonium burner and Plutonium producer, which is calculated by the code.

The output includes:
— costs
— fuel consumption
— separative work requirements.

CONTENTS

Introduction

It is one of the obvious tasks of the Commission to prepare forecasts and to propose targets concerning the future energy production, in particular of electrical and nuclear energy. This work requires the evaluation of the consequences of such a production on consumptions, investments etc..
A particular, but not secondary, aspect of this activity is the establishment, at regular intervals, of a Target Programme (Art. 40 of the Rome Treaty).

The two main aspects of the problem, i.e. a critical analysis of the demand growth and the evaluation of its consequences, could be included into a single frame, i.e. an "energy model" for the Community.
Even if this broad view of the problem is taken, it is -as a first step- useful to consider only a part of the model, i.e. to pragmatically assume a certain demand growth and analyze its consequences.
This is the approach for which the program TOTEM was written for the Energy Directorate.
This report concerns a brief description of the program and of its possible applications.
For a more detailed description, see :

"TOTEM - A computer program for the evaluation of power station installation policies", Version 1, by F. Conti, G.Graziani.

1. Effects of the future electric energy demand. Main features of the code TOTEM.

This report is not concerned with an evaluation of the reasons underlying the demand growth and its yearly distribution (load diagram). On the contrary, they are assumed to be given, and our first concern is to evaluate the consequences of such hypotheses.
Of course, as is typical of this type of study, the hypotheses are varied in order to evaluate a set of possible future developments. The consequent range of variation of the results is therefore studied, particular importance being attributed to those results which are little affected by variations of the hypotheses.
The code TOTEM is used to evaluate fuel consumption and production, separative work, fabrication and reprocessing capacity requirements, expenditures and capital investments consequent to any given production patterns.

TOTEM is not an optimization code, i.e. it does not optimize the installation policy concerning the various types of station. The splitting of the total energy production between various types of station is assumed to be given (with the exception of an option, described below, where a certain degree of freedom is left to the fast breeders in order to make full use of the available Plutonium).
We do not want to enter here into a discussion of whether optimization studies concerning such a partition are advisable. In any case, an optimization code is available at the J.R.C..
In the course of optimization studies, TOTEM can be used to evaluate strategies other than the theoretical optimum, i.e. to perform a "sensitivity analysis".

What does TOTEM basically do ?

Its first task is to deduce from the energy requirements given as input the power to be installed in order to satisfy that demand.

This calculation is not straightforward, for a number of reasons, e.g. :

1. The energy required is distributed in time according to a given load-diagram (load duration curve)

2. The maximum utilization (load factor) of any type of station is a function of its age (load factor history)

3. A minimum power reserve must be provided (+)

TOTEM splits the load diagram amongst the various stations, divided by type and age-group (++) . The splitting is performed according to the following rules :

- for a few types of station the position in the load diagram (average load factor) is given (hydraulic stations, privileged base-load stations, peak-load stations). They are called here "FATAL" stations.

- for the other stations the allocation in the load diagram is performed according to a given priority list (per type and age-group), established according to economical competitivity (example in table 2).

Having done this, the code knows, for each year of the period investigated, the number of power stations installed and existing for each type of station, their age and their load factor.

(+) the reserve is defined here as the percentual difference between installed power and peak demand. In other words, the percentual increase of the ordinate of the production load diagram compared to the demand load diagram.

(++) age-group means all stations having age included between two limits.

From the physical and economical characteristics of the power stations it can therefore calculate information such as fuel consumption, capital investments etc. (see next point).

A few main options are worth mentioning :

a) Plutonium balance

If the energy produced by each type of station is given in input, the Plutonium produced does not necessarily match with the Plutonium consumed. Therefore there will be a positive or negative Plutonium stock. An alternative way to operate the code is possible, in case the system is considered to be closed (no Pu sale or purchase) : a part of the energy demand is left free for the Fast Breeders (or any Plutonium burner) to satisfy it, according to Plutonium available, starting year and industrial constraints (maximum installation rate).
The rest will be filled by another type of station defined in input : in case this can not be installed at the necessary rate, the other types of station contribute to satisfy the demand, according to a given preference list and to constraints on their maximum installation rates.

b) Decision not to install new power stations of a certain type after a given year

A typical use of this option is to evaluate the maximum increase of nuclear stations installation, if conventional power stations are not built any more after a given year.
A minimum production of energy by the other types of station is given as an input. The difference to the total, resulting from the going out of service of the conventional stations, is distributed among the other stations according to a preference list and to constraints on their installation rate.

c) Energy storage by pumping water into reservoirs

Having performed an estimation of the available reservoirs, it is possible to give as an input the energy provided by them and its position in the load diagram.

This being a "secondary" form of energy, the corresponding area of the load diagram is actually not directly required from the system, and it is shifted to another part of the load diagram, as much as is permitted by the existence of non-utilized capacity. In other words, the load diagram is modified, a flatter i.e. more convenient shape being obtained.

d) <u>Input correction</u>

This is actually not an option, but a permanent feature of the code.
The installation policy conceived as an input may be unsatisfactory, since a few details cannot be appreciated without previous calculations:

- the installation required for one (or more) type of station may be larger than admissible, taking into account the minimum doubling time. In this case more energy is attributed by the code to other types of stations, following a given preference list: the next type is charged with a larger demand as far as is compatible with installation constraints, then the next type and so on.

- The variation with time of the energy demand from a type of station may be such as to imply one year the installation of new power, the next year an incomplete utilization of that power. This can occur as a consequence of the shape of the load factor history given in input (stations installed one year may be assumed to be capable of producing much more the next year).
  In these cases the input is corrected by the code, as much as necessary to allow full utilization of the already existing stations. (+)
  A correspondingly lower amount of energy will be produced by other types of station, according to the preference list.

(+) Full utilization means working according to the input load-factor history, but only as far as compatible with given load diagram and reserve (see above)

2. A few details on the calculations performed by TOTEM

For each type of power station the physical and economical characteristics are given, e.g. :

- fuel consumption
- fuel inventory
- plant cost
- fuel fabrication and reprocessing costs
- various delays, e.g.mine-enrichment plant-fabrication plant-storage-core residence-cooling-reprocessing.

The cost of fuel can be constant or variable with time.

The code can perform many calculations, based on the basic evaluation concerning the number of power stations existing per year, type and age-group and their utilization hours ; e. g. it calculates, for each year :

- consumption of various types of fuel
- fuel inventory due to new installations
- running costs
- capital investments

The expenditures can be actualized, the discount rate being one of the input data.

Taking into account the various delays, the code evaluates the ore requirements, the separative work and consequently the enrichment plant capacity required, the capital investments as a function of time, etc..

3. Examples

An indicative list if problems which can be investigated with TOTEM is reported here, followed by the detailed description of two cases.

3.1. Typical problems

- Given energy demand, load diagram and required reserve, calculate the necessary power installation.
- Effect of the load diagram shape on installations, capital investments etc.
- Effect of the demand growth rate on the installation rate of new power stations, related fuel and capital requirements.
- Effect of the load factor history (maximum utilization as a function of life) on the required installations.
- Effect of a given development of pumping stations on the installed power requirements.
- Effects of different ways of splitting the demand among various types of station: on costs, ore requirements etc...
- Sensitivity studies around the optimum installation policy evaluated by an optimization code.

3.2 Analysis of a typical installation policy

3.2.1 Input Data

The main input data are summarized in figs. 1 to 4 and tables 1 to 3.

Energy requirements

The total energy required from 1975 to 2030 is given by fig. 1 and table 1.
The partition of this energy amongst hydraulic, conventional thermal (oil, coal, gas) and HTR is given in fig. 2-a and table 1. The code is left free to choose how to split the rest of the energy demand between LWR and FBR, giving preference to FBR installation if compatible with constraints and Pu availability.

In the tables and figures, the station types are indicated as follows:

FATAL = peak-and base-hydraulic, nat.gas etc.

C = conventional

L = light water reactor

H = hight temperature reactor

F = fast breeder reactor

The assumption concerning the HTR penetration is rather rough, but typical of a parametric investigation into the effects of HTR introduction.
The HTR is assumed to be introduced in 1985 (2Gwe) and to grow according to table 1 (a) and fig. 2 (a) up to 30% of total energy production in the year 2000.
The FBR installation starts in 1990 with 2 Gwe and is limited, apart from Pu availability, by a power doubling time greater than 2 years.
The required partition will be accepted by the code only if the LWR and FBR are capable of coping with the input demand and if the input energy demand of any station type does not imply a reduction of its load factor below that already required by the load diagram shape (see point 1-d).

Load diagram

The shape of the load diagram, variable with time, is reported in fig. 3.

Allocation of the stations in the load diagram, maximum availability, preference list, reserve

The maximum load factor admissible for each type of station as a function of its age is given in fig. 4 (load factor history).
This does not mean that the utilization of the power stations will follow these curves: it can be lower, if the allocation of the stations in the load diagram requires a further load factor reduction.

This allocation is performed according to the preference list given in table 2.
The minimum reserve is 20%

Note Table 2 and fig. 4 refer only to conventional and nuclear stations. This applies only to this example. In general, this input can be given for each type of station.

Physical characteristics of the stations + Delay times

A few physical data concerning nuclear power stations are reported in table 3.
The typical delays affecting the evaluations reported in table 5 are as follows :

time from the mine to the enrichment plant	(y)	1
time from the enrichment to the fabrication plant	(y)	0.25
Enrichment delay	(y)	1
time from the reprocessing to the fabrication plant	(y)	0.25
time from the reprocessing to the enrichment plant	(y)	0.25
time from the enrichment to the conversion plant	(y)	0.5
fabrication + storage time	(y)	0.4
cooling + reprocessing	(y)	1.0 (0.75 for FBR)

Life of stations : 30 years

Tails enrichment : 0.25%

3.2.2 Evaluations performed by the code

The code calculates, year by year, the energy produced by existing stations. Then, it calculates the new installations according to the preference list and to the energy required in input. There is an option according to which some freedom of choice is lefte to the code, e.g. two types of station can cover the difference between the input energies and the total required energy. This is usually done for a fuel producer (LWR) and a fuel consumer (FBR), as in the example reported here : the FBR is installed as much as permitted by the available Plutonium and by its maximum installation rate. The LWR covers the rest of the demand, if permitted by its maximum installation rate.
In the case reported here there are no difficulties in installing enough LWR to cope with the input demand of fig. 2 -(a); otherwise additional installations would have been provided by the code according to the given preference list and to constraints (e.g. first HTR, then conventional stations).
A small correction to the energy produced by conventional stations is performed in some of the last (+) 5 years, otherwise the considerable number of conventional stations installed in the previous year would not be utilized as much as the load diagram and their load factor history would allow.
The resulting energies are reported in fig. 2 -(b) and table 1-(b). The installed power is reported in table 4 and its percentual splitting between various types of station is reported in fig. 5. The load factor of each station type as a function of time can be deduced by tables 1 and 4.
Finally, on the basis of this policy, the evaluations concerning consumption, demands, inventories and costs are performed. A few typical data are reported in table 5.

(+) The correction occurs in alternative years : the energy produced by conv. stations is increased by roughly 10%.

<table>
<tr><th colspan="2">NUCLEAR</th><th rowspan="2">A G E
(years)</th><th colspan="2">CONVENTIONAL</th></tr>
<tr><th>PREFER. ORDER</th><th>A G E GROUP</th><th>A G E GROUP</th><th>PREFER. ORDER</th></tr>
<tr><td rowspan="2">1</td><td>1</td><td>1</td><td>1</td><td rowspan="2">1</td></tr>
<tr><td>2</td><td>2</td><td>2</td></tr>
<tr><td rowspan="24">2</td><td rowspan="24">3</td><td>3</td><td rowspan="6">3</td><td rowspan="6">2</td></tr>
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<tr><td>25</td></tr>
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<tr><td rowspan="4">3</td><td>4</td><td>27</td></tr>
<tr><td>5</td><td>28</td></tr>
<tr><td>6</td><td>29</td></tr>
<tr><td>7</td><td>30</td></tr>
</table>

TAB. 2

Example of priority order for the allocation in the load diagram, according to type and age-group.

INPUT						OUTPUT	
YEAR	TOTAL	FATAL	CONV.	HTR	LW + FB	LWR	FBR
1975	1 160.-	134.9	907.2	-	117.8	117.8	-
1980	1 640.-	150.7	1 150.-	-	339.3	339.3	-
1985	2 400.-	161.8	1 150.-	6.-	1 082.2	1 082.2	-
1990	3 600.-	164.3	1 150.-	88.-	2 197.7	2 191.7	6.-
1995	5 000.-	166.8	1 150.-	650.-	3 033.2	2 974.8	58.4
2000	7 000.-	170.5	1 150.-	2 100.-	3 579.5	3 330.3	249.2
2005	9 500.-	170.5	1 150.-	2 850.-	5 309.5	3 920.1	1 409.4
2010	12 500.-	170.5	1 150.-	3 750.-	7 429.5	3 479.9	3 931.6
2015	16 000.-	170.5	1 150.-	4 800.-	9 879.5	2 265.8	7 613.7
2020	20 000.-	170.5	1 150.-	6 000.-	12 679.5	1 072.6	11 606.9
2025	24 000.-	170.5	1 150.-	7 200.-	15 480.	645.1	14 834.4
2030	28 000.-	170.5	1 160.-	8 400.-	18 279.4	169.3	18 099.7

TAB. 1 Demanded and calculated energy production $\left(\frac{\text{TW h}}{\text{year}}\right)$.

I T E M		UNIT	LWR	HTR (U)	FBR (carb)
nat. U EQUIVALENT	CHARGE	kg/TWh	29.7	20.8	0.05
	DISCHARGE	kg/TWh	4.8	3.7	0
	INVENTORY	kg/MWe	443.	555.	0.7
DEPLETED U	CHARGE	kg/TWh	-25.4	-19.7	2.1
	DISCHARGE	kg/TWh	- 0.6	- 2.7	1.94
	INVENTORY	kg/MWe	-337.	-494.	39.5
SEPAR. WORK	CHARGE	kg/TWh	17.4	16.0	0
	DISCHARGE	kg/TWh	0.24	1.6	0
	INVENTORY	kg/MWe	228.	417.	0
FISSILE P U	CHARGE	kg/TWh	0	0	0.089
	DISCHARGE	kg/TWh	0.028	0.0145	0.135
	INVENTORY	kg/MWe	0	0	1.91

TAB. 3 Physical characteristics of nuclear power stations.
(Tail enrichment 0.28%)

YEAR	TOTAL	FATAL	FBR	HTR	LWR	CONV.
1975	255.5	46.5	-	-	19.1	189.8
1980	358.4	53.-	-	-	59.9	255.0
1985	520.2	58.-	-	2	188.6	283.4
1990	798.3	60.-	2.-	18.6	366.4	339.2
1995	1 106.-	62.-	11.3	128.4	468.3	416.3
2000	1 543.-	65.-	48.2	359.2	542.4	498.
2005	2 079.8	65.-	272.9	453.8	659.6	588.5
2010	2 742.7	65.-	733.	599.8	619.	590.5
2015	3 492.9	65.-	1 263.3	773.6	490.2	672.
2020	4 365.3	65.-	1 889.8	1 071.0	312.	726.7
2025	5 202.5	65.-	2 393.-	1 406.0	206.7	802.
2030	6 067.6	65.-	3 003.0	1 615.0	129.1	817.5

TAB. 4 Generating capacity (GWe)

YEAR	nat (10^3 T)	SEP.WORK (10^3 T)	Pu STOCK (T)
1975	8.2	3.6	0.5
1980	95	43	5.6
1985	305	155	46
1990	688	375	197
1995	1 260	741	512
2000	2 024	1 257	890
2005	2 863	1 855	940
2010	3 717	2 472	940
2015	4 510	3 077	1 108
2020	5 356	3 694	2 195
2025	6 265	4 416	4 204
2030	6 641	4 910	8 613

TAB. 5 Integrated Uranium consumption, separative work requirement, Plutonium stock

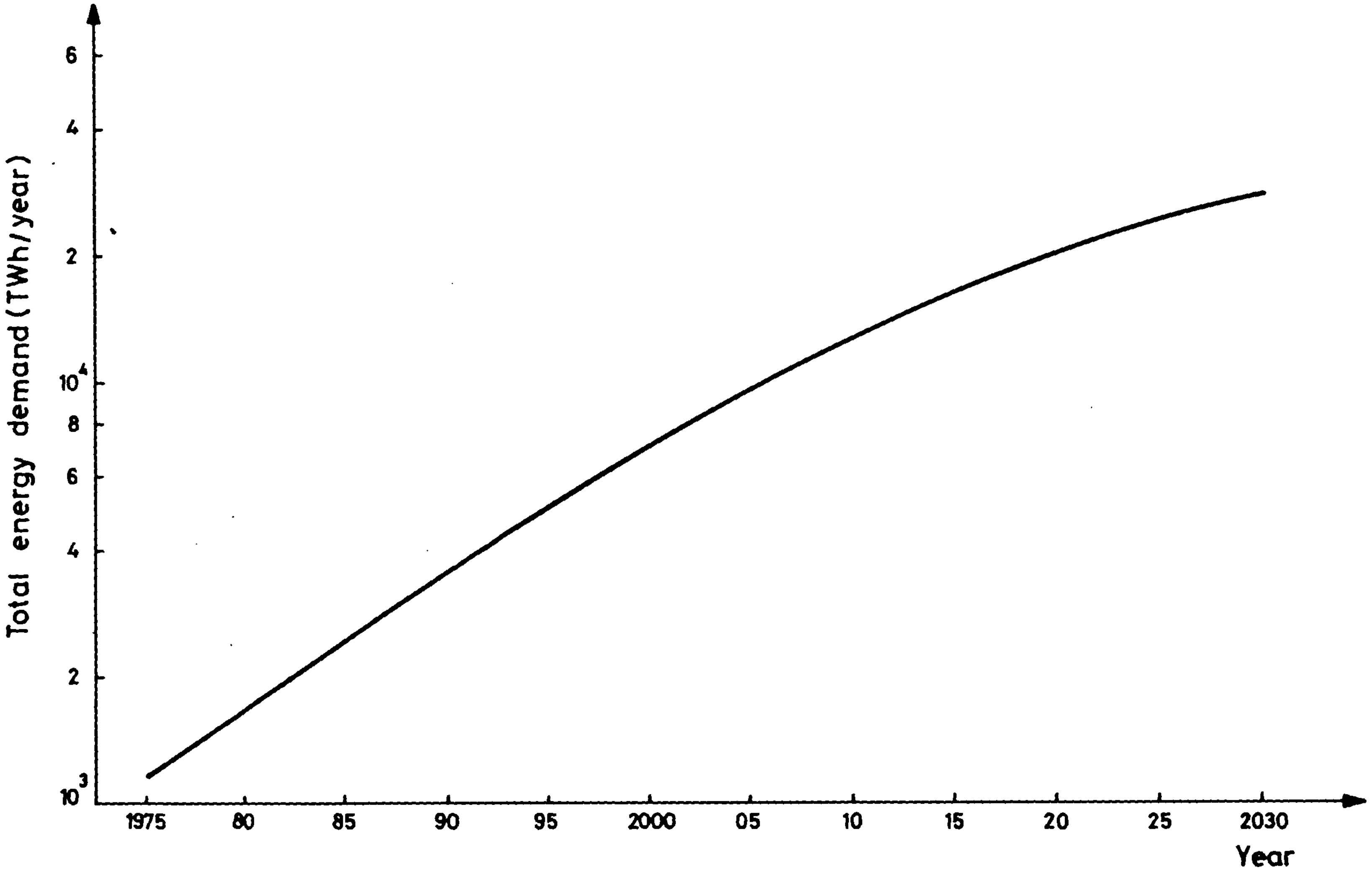

Fig. 1 - TOTAL ENERGY DEMAND

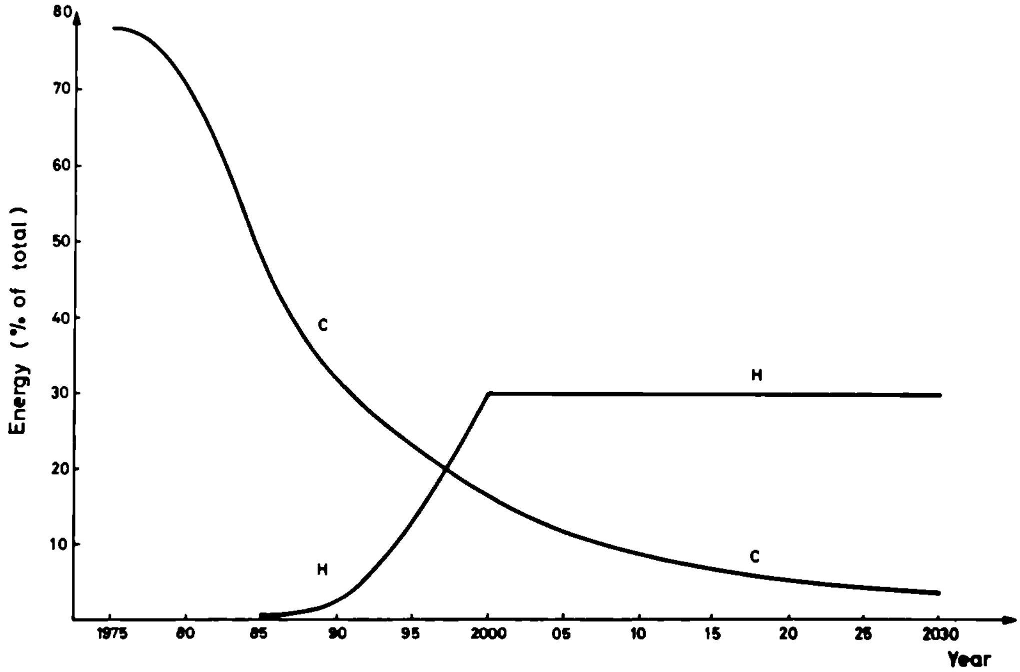

Fig.2-(a)-% ENERGY DEMANDED FROM CONVENTIONAL AND HTR STATIONS

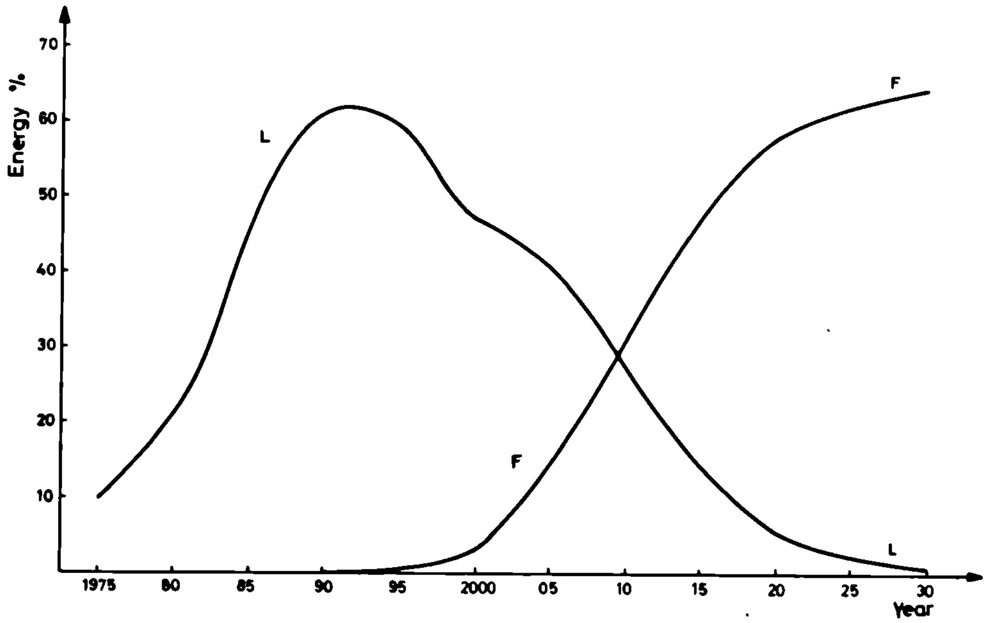

Fig. 2-(b)-% ENERGY PRODUCED BY FBR AND LWR

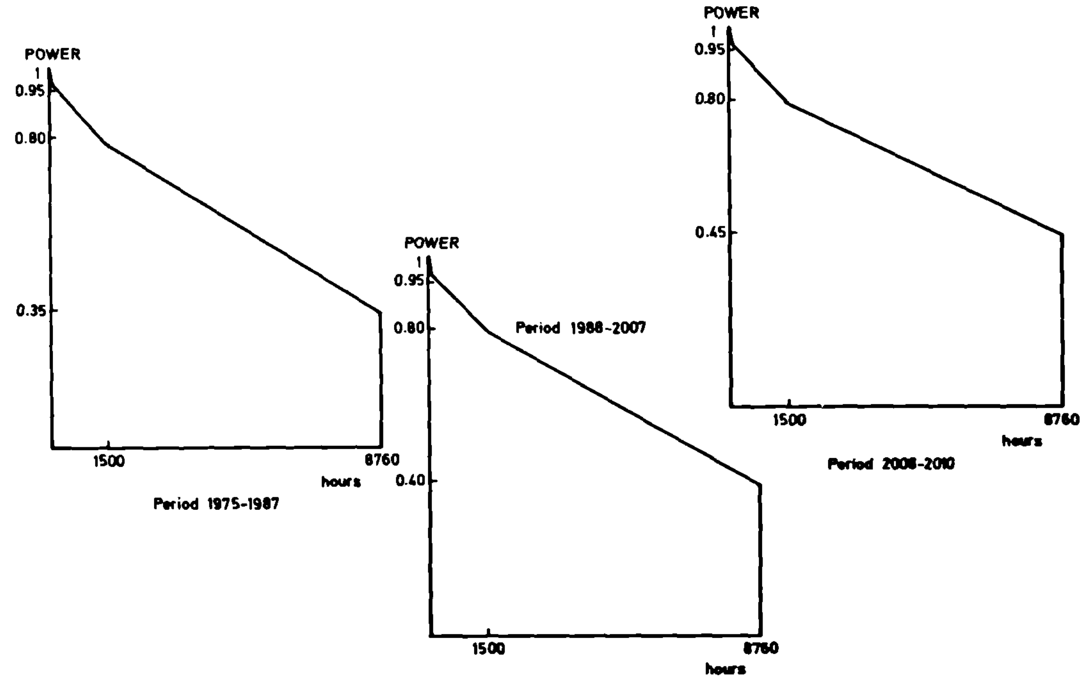

Fig. 3 - LOAD DIAGRAM

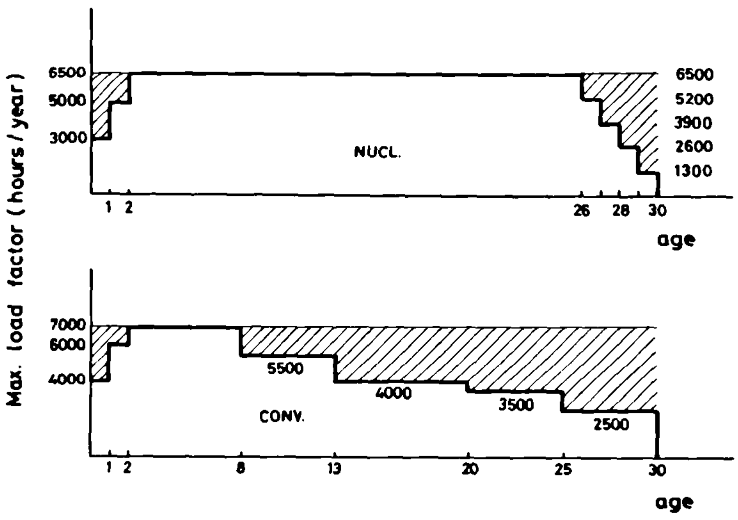

Fig. 4 - LOAD FACTOR HISTORY FOR CONVENTIONAL AND NUCLEAR STATIONS

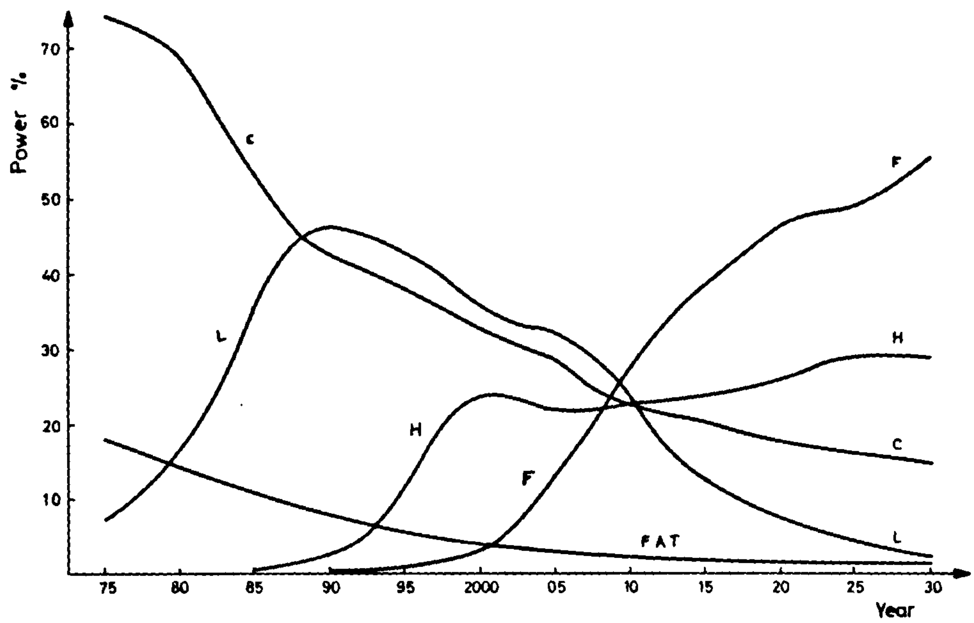

Fig. 5 - INSTALLED POWER

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