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ASPECTS GOVERNING THE SELECTION OF GENERATING PLANT

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NOTE: This text is subject to editorial revision.

CONTENTS

/1. General

1. General

The designer of generating plant repeatedly finds himself faced with the task of having to select from the various possible station designs the system most suitable for the local conditions. All factors which are to be considered will be dealt with in detail for the following types of generator prime movers:

(A) Natural sources of energy
  1. Water turbines
  2. Wind-driven turbines

(B) Fuels
  1. Heat
    (a) Steam engine (steam turbine)
    (b) Hot-air turbine
  2. Internal-combustion energy
    (a) Diesel engine (petrol engine)
    (b) Gas turbine
    (c) Free-piston engine
  3. Compound processes

(C) Nuclear energy

Only permanent installations will be dealt with, having an output of upwards of 1 MW. The upper limits of capacity vary, but in practice only steam turbines are considered suitable for a high output level per unit.

As the most essential quantity for the purpose of comparison, the cost per kWh, referred to the annual costs, will be dealt with at first, followed by the special features of each type of prime mover listed above.

All figures stated are correct only as regards the order of magnitude and for normal conditions and must be determined exactly in each particular case.

2. Cost of energy

Basis of comparison is the cost of energy per kilowatt-hour generated, computed from the annual costs. It gives the cost of producing energy taking into account the amortization of the invested capital, fixed expenses

/and cost

and cost of fuel. The cost of energy is computed in accordance with the following formula:

$$s = \frac{k}{v}\ a + \frac{b}{\eta} + z$$

where

s	Energy cost in cents/kWh
k	Specific construction costs in Us-$/kW
a	Annual percentage of capital (see 3 below)
v	Full-load operating hours per annum
b	Specific fuel cost in cents/860 kcal
η	Per-unit overall efficiency
z	Other costs in cents/kWh (lubricants, special costs with nuclear power stations etc.)

The energy cost is influenced so much by the individual terms of this formula that their effects must be dealt with in further detail.

(a) Specific construction costs

These comprise:

a) Costs of mechanical and electrical equipment

b) Costs of civil engineering work

c) Costs of ancillary installations

For purposes of comparison, it may be as well to examine solely the costs of the power generating unit under consideration and to make proportionate allowance for ancillary installations, such as cooling-water intake structure, chemical water treatment plant, coal and ash handling equipment, workshops, laboratories etc., as these installations usually serve several units. On the electrical side, only the costs of the electrical auxiliary service system should be considered. The unit or step-up transformer, the outdoor switching station and the starting and regulating transformers are to be regarded as belonging to the grid, as the size and therefore the costs of these installations may vary considerably.

The costs of the generating unit are referred to the maximum terminal output of the generator and it is assumed that the auxiliary service requirements are tapped off after the generator terminals. The efficiency of the prime mover may be lower than this common-base output which corresponds to the so-called "installed capacity". The power fed into the

/grid is

grid is equal to the power generated reduced by the auxiliary service requirements.

The specific construction costs can, therefore, be calculated from

$$k = \frac{A}{N}$$

where

k .... Specific construction costs in dollars per kW

A .... Unit construction cost in dollars

N .... Total unit power output including auxiliary service requirements in kW (installed capacity)

(b) Capital interest per annum

Every year, a certain percentage of the invested capital is taken as amortization of the installation. It is called "annuity" and includes the period of depreciation as well as capital interest. The period of depreciation should be approximately identical with the service life of the equipment. Capital interest is dependent upon the conditions attached to credits and depreciations. The following formula is used:

$$a' = 100 \times \frac{\left(1 + \frac{p}{100}\right)^n \times \frac{p}{100}}{\left(1 + \frac{p}{100}\right)^n - 1}$$

where

a' .... Percentage annuity

n .... Operating time in years (working life)

p .... Percentage capital interest per annum

Capital interest at a rate of 6 per cent per annum is normally assumed in the Federal Republic of Germany.

(c) Incidental costs

The depreciation charges per annum ($\frac{a'}{100} \times A$) are independent of the actual operating time of the equipment during the course of the year, so they affect the energy cost in accordance with its utilization. To these charges are to be added incidental expenses, such as repairs, personnel, insurance, tax etc. This method is not quite accurate, since repair costs,

/for instance,

for instance, may bear a certain relation to the operation time. However, this error may be neglected. Normally, various power stations are compared with each other on the basis of similar operating conditions and furthermore, the incidental costs are usually small compared with the cost of depreciation. The total percentage of the capital may therefore be stated as

$$a = a' + a''$$

where

a .... Percentage capital per annum
a' .... Percentage annuity per annum
a'' .... Percentage incidental costs per annum

(d) Utilization

The number of full-load operating hours indicates the degree of utilization of the power station. It is the number of hours which the plant would have to be run at the installed capacity to deliver the energy for the year under varying load conditions. This is expressed by the formula

$$v = \frac{L}{N}$$

where

v .... Full-load operating hours per annum
L .... Generator terminal energy per annum, in kWh
N .... Installed capacity, in kW

Dividing the full-load operating hours by 8,760 (total number of hours per year) gives the so-called "utilization factor".

(e) Fuel costs

Fuel costs are of importance with all those power stations where the required energy is produced by burning purchased fuel. Fuel costs are generally given per ton or kilogram of fuel. In economy calculations it is usual to convert the costs to a common base in thermal units of the calorific value, e.g. 10^6 kcal. However, basing the cost on 860 kcal, the cost is obtained of the fuel required for the generation of one kilowatt-hour at 100 per cent efficiency. This value is used in the further calculations:

/b =

$$b = 860 \times \frac{P}{H_u}$$

where

b .... Specific fuel costs in cents/860 kcal

P .... Fuel costs in cents/kg or in dollars per 100 kg

H_u .... Lower calorific value of the fuel in kcal/kg

To give an idea of the order of magnitude of the fuel costs the following figures are listed for 1959 ex-colliery or refinery, referred to conditions in the Federal Republic of Germany:

Fuel	Specific fuel costs in cents/860 kcal
Coal (lignite - anthracite)	0.12 - 0.24
Fuel oil (heavy - light)	0.20 - 0.40
Diesel oil	0.85 approx.
Petrol	1.30 approx.
Nuclear fuels depending on degree of enrichment	0.06 - 0.12 approx.

Transport charges have a marked influence on the cost. They are the higher, the greater the distance involved and the more inferior (low calorific value) the fuel. This must be considered when choosing a site for a power station. For this reason, the above-mentioned figures give only a rough indication and must be determined exactly for all fuels in question and for a particular power station site.

(f) <u>Efficiency</u>

Basis for determining the average annual efficiency is the overall efficiency of the equipment from the fuel handling plant to the generator terminals at optimum load without considering the electrical auxiliary service requirements. The efficiency can be represented or rather expressed in several ways, for instance,

(i) as a percentage or per-unit quantity of power output compared with the power input required, as for instance with hydroelectric power stations the output power at the generator terminals against the input power which is equal to the product of water quantity multiplied by net head;

/(ii) as

(ii) as consumption of heat, i.e. the amount of heat which must be expended to produce one kilowatt-hour. With steam-turbo generator sets, for instance, the amount of heat consumed per kilowatt-hour at the generator terminals;

(iii) as fuel consumption necessary to produce one kilowatt-hour at the generator terminals, as with Diesel power stations, for instance.

In some cases, combinations of these three definitions are encountered, as shown by the example of the steam power station. Boiler efficiency is here stated in per cent, whereas for the turbo-generator set with its regenerative feed heating plant heat consumption is the governing factor. The overall efficiency can be expressed in accordance with any one of the three definitions.

For the purpose of comparing the various types of generating plant the percentage efficiency is used. Therefore, quantities expressed otherwise must be converted to percentage efficiency to which the following formula applies:

$$\eta' = \frac{86,000}{W}$$

where

η' .... Percentage efficiency at optimum load

W .... Heat consumption at optimum load in kcal/kWh

$$W = \frac{b' \times H_u}{1,000} = 1.36 \times \frac{b'' \times H_u}{1,000}$$

where

b' .... Fuel consumption at optimum load in g/kWh

b'' .... Fuel consumption at optimum load in g/HPhr (metric) = $1.36 \times b'$

H_u .... Lower calorific value in kcal/kg

$$\eta' = \frac{86 \times 10^6}{b' \times H_u} = \frac{63.2 \times 10^6}{b'' \times H_u}$$

The efficiency at optimum load must now be further qualified by introducing various factors to reflect the actual operating conditions:

f_E .... Factor for auxiliary service requirements.

/It reduces

It reduces the generator terminal output by the power requirements of the unit auxiliaries as well as by the portion consumed by the ancillary installations (as indicated under the relevant detailed description).

f_T .... Part-load factor

It can be computed, if the load schedule of the relevant unit and the relationship of the part-load efficiencies to the full-load efficiency is known, in accordance with the following formula:

$$f_T' = \frac{\eta_1 h_1 + \eta_2 h_2 + \eta_3 h_3 \,.......\, \eta_n \; h_n}{100 \; h}$$

where

$h = h_1 + h_2 + h_3$ ....

$\eta_1, \eta_2, \eta_3 \cdots \eta_n$ Part-load efficiencies for optimum load = 100 per cent

$h_1, h_2, h_3 \ldots h_n$ Operating time in hours at the respective part-load efficiencies

h .... Total period in hours of a cycle of the operating schedule .

f_A .... Factor for start-up and shut-down

It can be assumed that the losses incurred when starting-up and shutting down are dependent on the necessary starting time or rather on the ratio of starting time to operating time.

Therefore

$$f_A = \frac{h_B}{h_B + h_A}$$

where

f_A .... Factor for start-up and shut-down

h_B .... On-load time in hours

h_A .... Starting time in hours

f_U ...., Factor for inadequate (boiler) stability and contamination

If the plant is operated continuously but with varying load, additional losses are incurred which are dependent on the type, magnitude and frequency of the load variations as well as on the degree of contamination and these can only be roughly estimated.

/The efficiency

The efficiency determining the energy cost can therefore be stated as

$$\eta = \frac{\eta'}{100} \times f_E \times f_T \times f_A \times f_U$$

where

η............ Per-unit overall efficiency averaged over the year and referred to the generator capacity

(g) Other costs

There are various stations and sites where additional costs are incurred which have a marked influence on the cost of energy. For instance, an increased consumption of lubricating oil may develop or the cooling water must be taken from the public water supply system and consequently paid for.

With nuclear power stations, the loan charge for the fissionable material and the gain from the breeding effect as well as the cost of replacing the core are also to be considered.

3. Comparison of the various types of generating plant

The values and data necessary for the evaluation of a power generating plant are stated for each type under consideration in accordance with the following classification:

(i) Description and method of operation
(ii) Design considerations
(iii) Output range
(iv) Cost of construction
(v) Amortization
(vi) Incidental and other costs
(vii) Source of energy
(viii) Efficiency
(ix) Advantages and disadvantages
(x) Application and characteristics

(a) Water turbines

(i) Description and method of operation

The following types of water turbines are mainly used:

Free-jet turbines (Pelton wheels)	$n_s < 40$
Francis turbines	$n_s = 40-400$
Propeller-type turbines	$n_s > 400$
Kaplan turbines	

/With all

With all types, water power is converted into mechanical energy delivered by a water wheel which drives the generator.

(ii) Design considerations

Which type is to be used is determined by the net head available and the capacity of the unit. A characteristic feature is the specific speed which is

$$n_s = 36.8 x n \times \frac{\sqrt{N_o}}{\sqrt[4]{H^5}}$$

where

n_s .... Specific speed
n .... Speed in RPM
N_o .... Turbine output in MW for = 100 per cent

The quantity of water discharged results in a turbine output of

$$N_T = \frac{Q \times H \times \eta_T}{102}$$

where

N_T .... Turbine output in MW
Q .... Quantity of water discharged in cu.m/sec.
H .... Net head in metres
η_T.......... Per-unit turbine efficiency

Substituting in the formula for specific speed the output by the above formula using the value of $_T = 1$ it can also be expressed as

$$n_s = 3.65 x n \times \frac{\sqrt{Q}}{\sqrt[4]{H^3}}$$

Here, the power output has been eliminated and the specific speed determined by the water discharge, the net head and the speed.

(iii) Output range

All types of turbines mentioned are now designed for a unit output of up to 100 MW, sometimes even of 200 MW.

The Pelton turbine is exclusively used for heads exceeding 300 m and for those less than 300 m, if the speed would be too high for the Francis turbine or if the dimensions of the water wheel would be too small because of the danger of choking.

/Francis turbines

Francis turbines are built for heads of up to 300 m.

Propeller-type turbines with fixed blades are used up to a head of 30 m approx., Kaplan turbines up to about 20 m.

(iv) Cost of construction

The costs for the erection of a hydroelectric power station are subject to severe fluctuations, especially on the construction sector. The matter of the costs in each particular case is preferably gone into from the opposite end by calculating the maximum permissible cost of the plant on the assumption of a fixed energy cost level and definite conditions of amortization and operation. As only the first term of the formula need be used for computing the kWh cost, the following relation exists

$$k = s \times \frac{v}{a}$$

where

k .... Maximum permissible construction costs in dollars
s .... Highest permissible energy cost in cents/kWh
v .... Full-load operating hours per annum
a .... Annual percentage of capital

Frequently, the entire erection costs need not be charged with respect to the generation of power, as a dam or a river weir may assist in irrigation, control of floods and rivers in general and facilitate shipping.

(v) Amortization

Normally, depreciation is based on a period of 40 years, at least as regards the civil engineering part. The mechanical and electrical equipment is often written off in 20 years.

(vi) Incidental and other costs

Incidental costs are very low and generally do not exceed 1 per cent of the investment costs per annum.

(vii) Source of energy

Water is the source of energy and is collected as rainfall in the drainage area of the impounded river. Planning requires statistical data regarding the run-off over long periods. The ultimate capacity of a plant can be determined, for instance, for the stream flow which is maintained for 9 months of the year.

/Under favourable

Under favourable conditions, tidal movements can also be utilized for the generation of power.

(viii) Efficiency

If the most suitable type of turbine is chosen for given conditions, the efficiency at the optimum point is almost equal in the various cases. A tendency can merely be noted of larger units having a higher efficiency which is quite obvious. Modern turbines have optimum-load efficiencies which lie between 84 and 94 per cent. Those of the associated generators are between 96 and 99 per cent which results in overall efficiencies ranging from 80 to 92 per cent.

The electric auxiliary requirements are negligible and need not be considered. Furthermore, these requirements are often supplied by a station service generator. The consumption also fluctuates a great deal and is of only short duration (for instance operation of gates).

The part-load performance characteristics of the various turbine types are shown in figure I.

(ix) Advantages and disadvantages

Advantages

Water, the source of energy, costs nothing and is inexhaustible.

Impounding of rivers can also be used for irrigation and river control.

The efficiency is high.

Storage power stations are most suitable for varying and intermittent loads (peak-load operation).

Disadvantages

The construction costs are high and the project is only economical under favourable local conditions.

Where the storage capacity of the reservoir is low the power output of the station is dependent on the seasonable variation of the run-off.

(x) Application and characteristics

Hydroelectric power stations are built as storage stations, run-of-river stations (frequently as a cascade of power stations) and also as pumped-storage stations. Their main function is the solution of transport problems (shipping), irrigation and flood control etc. The possible

/utilization of

utilization of water power is limited by the number of sites worth developing. But, taking the world as a whole, only an average of 30 per cent of the water power available for this purpose has been tapped.

Furthermore, projects are under consideration for the harnessing of tidal and wave energies of the sea.

(b) Wind turbines

(i) Description and method of operation

The output of wind-electric power stations is comparatively low and, at present, lies below 1 MW. However, they are to be dealt with here for the sake of giving a complete picture.

Basically, such an installation consists of a tower on which a multi-vaned wind wheel is pivoted. The generator is coupled directly with the wheel.

(ii) Design considerations

For the most effective use, power output should set in at the lowest possible wind speed which requires vanes of great length. On the other hand, it is important to safeguard the installation in stormy weather. Special control mechanisms are needed when feeding into a system. Methods have already been developed to this effect, making fully automatic operation possible.

(iii) Output range

The installations at present have a capacity of 100 to 300 kW and it should be more economical to install several mass-produced standard types in this capacity range than to develop larger units. However, project studies exist for units with ratings of up to 4 MW approx.

(iv) Cost of construction

System-connected self-regulating wind-electric plants with a capacity in the order of 100 to 300 kW cost approximately 150 to 180 dollars per kW in mass production.

(v) Amortization

The depreciation period of a wind power plant may be taken as 15 years approximately, for the sake of comparison.

/(vi) Incidental

(vi) Incidental and other costs

As the plant is fully automatic and otherwise requires a negligible amount of consumable material, only repair costs need be considered which may not exceed 1 per cent per annum of the invested capital (excluding emergencies).

(vii) Source of energy

Local wind conditions govern the choice of a wind power station site. It is stated that the average annual wind speed should not be less than 6 m/sec. to feed surplus power into an existing system. Independent units operating under special conditions may have different economy limits.

(viii) Efficiency

The efficiency of modern vane shapes is around 60 per cent. However, this is not as important from the point of view of economy as being able to start at the lowest possible wind speed. Wind speed for starting generally is around 5 m/sec., however, equipment has been brought on the market, starting at a speed as low as 2.5 m/sec.

(ix) Advantages and disadvantages

Advantages

Wind, the source of energy, costs nothing and is inexhaustible.

The plant requires only very little servicing.

Disadvantages

Output is dependent on wind conditions.

(x) Application and characteristics

With isolated installations in, for instance, remote districts the wind-electric plant can fairly compete with the Diesel generating unit, if wind conditions are favourable. This applies in particular if a battery must be provided in either case to afford sufficient storage of energy to meet excessive demands.

Most problems arising with a group of installations feeding into existing supply networks have already been solved and their use may be considered in areas with favourable wind conditions.

(c) Steam turbines (steam engines)

(i) Description and method of operation

Steam power stations consist mainly of steam generators and turbo sets

/(small installations

(small installations have steam engines). Heat is supplied to the steam generator (boiler) by way of fuel combustion evaporating the water contained in the boiler tubes which is fed as steam to the turbine where it expands and imparts its energy to the turbine rotor. Unless the exhaust steam is not used otherwise (for heating purposes, for instance), the heat released during steam condensation must be dissipated. To reduce this loss part of the steam is bled off from the turbine at several points after expansion and is used to heat the condensate (regenerative feed heating). With higher live steam conditions, the last stages of the turbine would have to operate in a region of excessive steam wetness which would cause erosion. Because of this and also for reasons of better utilization of the heat content of the steam, especially in the case of large units, the steam is re-heated in the boiler after having passed through the first turbine part (reheating). This may also be repeated several times in succession.

If the exhaust steam is fed into a district heating system instead of a condenser (back-pressure turbine), the heat of condensation can be used to advantage. Losses due to cooling in the condenser can be avoided and the amount of heat consumed in the generation of power alone is reduced which means obtaining cheap energy (primary energy, district heating generation stations).

Steam at constant pressure is sometimes extracted from the turbine and supplied to process equipment (extraction turbine).

(ii) Design considerations

The live steam conditions ahead of the turbine inlet characterize the design of a steam plant. Conditions must be chosen which ensure that the last turbine stages are not subjected to excessive steam wetness (limit of 12 to 14 per cent).

The material to be used for the most highly-stressed parts of boiler and turbine is mainly determined by the live steam temperature. At temperatures from 530 to 565° C it is still possible to use ferritic steels, whereas higher ranges (at present up to 650° C) require the application of very expensive austenitic steels. After the temperature has been determined and the condenser vacuum computed from the cooling-water temperature, a certain inlet pressure must not be exceeded to avoid

/excessive final

excessive final wetness of the steam. Therefore, the choice of the live steam conditions also depends on the cooling-water temperature. Figure 2 gives the most essential standardized design conditions as a function of the output (ASME-USA, VDEW-Germany, IEC-International).

(iii) Output range

The steam engine is often used for small outputs (below 1 MW). However, it generally suffers from the disadvantage that the exhaust steam is contaminated with oil as a result of cylinder lubrication. But models already exist with labyrinth-sealed pistons which are not affected by this and can also be run on superheated steam. For larger power generating units, however, the steam turbine is to be preferred. Large units are brought into service more and more as a result of the rising power requirements and the large interconnected grids. In Europe the largest single-shaft (tandem-compound) turbo set under project has a rating of 250 MW, whereas units are already being designed in the United States of up to 750 MW as multi-shaft (cross-compound) sets.

(iv) Cost of construction

The specific costs may vary considerably and they depend a great deal on the conditions involved. A few major factors are mentioned in the following.

Costs are increased by:

fuel: coal, especially with low calorific value, high water and ash content and appreciable sulphur content;

oil of a high vanadium content in the case of oil-fired boilers;

high live steam conditions (austenitic tube material); low cooling-water temperatures (less than 12° C); hydrogen cooling of the generator;

cooling water intake structures very remote from the power house, with recovery turbines and weirs in the case of great differences in water level;

water re-cooling systems (cooling towers or cooling ponds);

extensive chemical water treatment plants;

large coal storage yards with equipment for unloading and distribution;

/poor subsoil;

poor subsoil;

opening up of the site (roads, bridges, railway sidings);

bringing under cover all parts (no outdoor installations).

Therefore, the exact values must be determined in each particular case. To give an idea, values are shown in figure III which have been taken mainly from United States publications. Corresponding European costs are up to 20 per cent lower.

(v) Amortization

The depreciation period for the mechanical equipment is generally in the region of 15 to 25 years. The building part is often written off over 40 years.

(vi) Incidental and other costs

Incidental costs such as wages, salaries, social contributions, costs of general administration, repairs and materials etc. for steam power stations usually lie between 2 and 4 per cent *per annum* of the invested capital.

(vii) Source of energy

A steam power station can be designed to burn all kinds of fuels and offers a wide range of possibilities in this respect. To mention some of them:

Coal (peat, lignite, hard coal, anthracite, coke)
Wood
Oil (fuel oils, shale oil, tar sands, waste oils)
Gas (natural gas, coal gas, blast-furnace gas, waste gas from chemical processes).
Sulphite liquor from paper and pulp mills
Refuse

(viii) Efficiency

The overall efficiency of a steam power station increases with the size of the units and varies with the type of fuel, as the boiler efficiency considerably depends on the fuel used. Figure III shows the values for average conditions as a function of unit output. The values refer to optimum load. Figure I shows the performance under part-load conditions whereby the optimum load was assumed to be 80 per cent of the overload

/capacity. For

capacity. For a different value, the load percentage must be converted in the ratio of the percentage for optimum load.

The station auxiliary service requirements can be taken from the following table:

Electrical service requirements in per cent of the installed capacity:

Boiler plant	High-pressure	Low-pressure
Furnace	0.6 - 1.3	0.4 - 1.0
Fans	1.0 - 1.2	1.1 - 1.6
Boiler feed pumps	1.8 - 2.7	1.0 - 1.5
Turbine plant	**Fresh water**	**Recooled water**
Cooling-water pumps etc.	1.5 - 2.0	2.3 - 4.0
Other station service requirements	0.5 - 1.5	
Total	4.0 - 9.0	

(ix) Advantages and disadvantages

Advantages

Almost any kind of fuel may be used.

Particularly good part-load performance.

Suitable for large units.

Moderate operating noise.

Disadvantages

Long start-up time (120 - 180 minutes)

High water consumption, unless a water re-cooling system is employed.

(x) Application and characteristics

The range of application is very wide due to the fact that it is possible to burn the most varied fuels. It extends from small auxiliary drives and industrial turbines up to very large units. The following mean values were obtained from field installations:

/Water consumption

Water consumption

Fresh water cooling requires about 200 l/kWh of screened water, the re-circulating system (cooling tower) about 10 l/kWh and air-cooled condensers require no water at all. In all three cases, an additional amount of about 1 to 2 l/kWh of the purest possible water (well water) is required.

Floor-space requirements

It comes to about 0.02 to 0.06 sq.m/kW for the power station building alone, depending on the size of the unit. For units below 20 MW capacity, it amounts to 0.06 to 0.2 sq.m/kW. Added to this are the areas needed for storing fuel and dumping ash as well as those required for auxiliary installations such as water-intake structure, workshops, office buildings, garages, stores etc.

Building-space requirements

These amount to about 0.5 to 1.8 cu.m/kW for the power station building itself without auxiliary installations, depending on the size of the unit. Units with less than 20 MW capacity require 1.8 to 2.5 cu.m/kW.

Storage quantities

Generally, provision is made for the oil and coal stores to last a month under full-load conditions and the oil tank for a day's requirements or the coal bunkers for 16 to 24 hours full-load operation.

Steam raising capacity of the boiler

For straight-condensing plants of normal design, the maximum continous boiler rating in t/h can be roughly calculated by multiplying the maximum generator terminal output in MW by the following figures:

1 MW	10 MW	50 MW	100 MW	150 MW
7.5	5	4	3.5	3

Site conditions

The altitude of the site has no major bearing on the lay-out, although it must be considered. With a turbo set, the cooling-water temperature governs the choice of the turbine model and it also affects the efficiency.

Staff requirements

The staff requirements, expressed in men/MW, are about 0.3 for large units, about 1 for 50-MW units and more for smaller ones.

/(d) Hot-air

(d) Hot-air turbines

(i) Description and method of operation

It is similar in principle to the steam cycle except that air is used as working substance. Heat is conveyed to the air in a fuel-fired heater with a separate combustion chamber. The hot air expands in a turbine and via a heater exchanger to the water-cooled precooler. It is compressed in a compressor with intercooler, pre-heated in the heat exchanger and fed to the heater. Turbine, compressor and generator are directly connected with each other.

The output is controlled by adjusting the pressure level in the air cycle without varying the temperatures.

(ii) Design considerations

The air temperature on the turbine inlet side is 600° to 700° C and the pressure in the system is maintained at 28 to 30 kg/cm^2 absolute (maximum pressure: 32 to 36 kg/cm^2 absolute).

The cooling-water temperature affects the efficiency and the maximum continuous output. However, with warmer cooling water normal output can be achieved by increasing the pressure level.

(iii) Output range

For permanent installations, there are standard sizes of 2,5, 10 and 20 MW normal output.

(iv) Cost of construction

The approximate amount of the invested capital is shown in figure III.

(v) Amortization

Exact details regarding the service life are not available to date, since existing installations have not been in operation long enough. The period of amortization can be taken as 15 years approximately.

(vi) Incidental and other costs

Repairs will be more expensive than will steam power stations due to the high cost of the air heater made mainly from austenitic steel. Figures based on experience are not available. 3 to 5 per cent of the invested capital per annum may be assumed.

/(vii) Source

(vii) Source of energy

Apart from gaseous fuels, coal of not too inferior a quality may be burned. Very heavy fuel oils may only be used subject to limitations in respect of the high tube wall temperatures and consequent high-temperature corrosion. Furthermore, the air temperatures must be reduced, thereby lowering the efficiency.

Pure air is circulated which need not be treated in any way and does not cause corrosion.

(viii) Efficiency

The efficiency depends on the cooling-water temperature (see (x)below) and is stated in figure III for normal conditions.

The electrical station service requirements are between 3 and 6 per cent depending on the type of fuel used.

Figure I shows the performance under part-load conditions.

(ix) Advantages and disadvantages

Advantages

No corrosion caused on the air side, not even when shut down;
Heater can be mounted outdoors, resulting in small space requirements;
Rapid load changes are effected at constant temperature by varying the pressure level and do not cause any appreciable stresses in the material;
Suitable also for coal of reasonable quality apart from gaseous fuels;
Good performance under part-load conditions;
Effective output is independent of ambient temperature and altitude above sea level.

Disadvantages

Not suitable for use of fuel oil due to high-temperature corrosion caused in the air heater;
Output and efficiency are much dependent on the cooling water temperature;
Long time taken for start-up (about 180 minutes);
Considerable operating noise;

/Expensive heat

Expensive heat exchanger (made from austenite).

(x) Application and characteristics

Hot-air turbines may be used in small power stations for continuous operation (because of long start-up time). Good performance under part-load conditions permits considerable variations in the load.

The manufacturers give the following main data for standard sets:

Maximum continuous output (kW)	2,300	6,000	12,000	25,000
Rated output (kW)	2,000	5,000	10,000	20,000
Inlet temperature (in °C)	600 to 700			
Maximum pressure in the system (kg/cm^2 abs.)	28-32	30-36	30-36	30-36
Speed (RPM)	13,000	8,600	6,000	
Number of inter-coolers	1	1	2	2
Thermal efficiency referred to generator coupling (per cent)	26-28	28-30	30-32	
Cooling-water temperature (°C)	15			
Mean cooling-water requirements (cu.m/h)	230	500	1,000	

Water requirements

About 100 l/kWh are required. To use the water-recirculating method is advisable only in exceptional cases because of the high cooling-water inlet temperature involved and the consequent reductions in output and efficiency.

Floor-space requirements

This amounts to about 0.05 to 0.15 sq.m/kW. Added to this are auxiliary similar as with the steam power station.

Building-space requirements

Assuming that the air heater is mounted outdoors, the building-space requirements are about 0.5 to 1.2 cu.m/kW. This is possible, as there is no danger of freezing-up.

Storage quantities

As regards the fuel stores, the same applies as under 3 (c) above.

Site conditions

Each 10° C increase of the cooling-water temperature above 15° C reduces the efficiency to about 95 per cent. This drops the output to

/about 94

about 94 per cent, unless the pressure in the air cycle is increased. This is of particular significance in tropical regions with cooling-water temperatures lying around the 30° C mark.

Staff requirements

No figures are available, but fewer attendants should be required than with steam power stations of equal size.

(e) Internal combustion engines (petrol engines)

(i) Description and method of operation

Diesel engines are piston engines where the fuel is directly injected into the air which has been drawn in and compressed by the piston. With the petrol engine, the fuel is volatilized before it enters the cylinder where it is compressed and subsequently ignited by an electrical spark. Both types of engines may operate on the two-stroke or four-stroke cycle principle, depending on whether only one or two crankshaft revolutions are required for each cycle. Several pistons work on one crankshaft which directly drives the generator through an interposed flywheel.

(ii) Design considerations

For units intended for continuous operation, it is advantageous to select engines with a low piston speed. High-speed engines can be used for peak-load units.

The output of the engine considerably depends on the altitude of the site, which must be given due consideration when selecting the engine. This disadvantage can be offset by pre-compressing the air, e.g., by an exhaust gas turbine (supercharging).

(iii) Output range

Diesel engines are normally used for driving generators with a unit rating of 6,000 kW. Larger engines are built for ship propulsion and are not normally used for stationary generating sets. The speed ratings range between 150 and 3,000 rpm.

(iv) Cost of construction

The costs of construction are shown in figure V

(v) Amortization

Depreciation times of 10 to 15 years are normally assumed for calculating the amortization of the capital investment.

/(vi) Incidental

(vi) Incidental and other costs

The incidental costs amount to 4 to 6 per cent of the construction costs per year. Where the lubricating oil is expensive, consideration should be given to the fact that about 2.5 grams per kWh are required. The other costs are calculated according to the following formula:

$$z = \frac{o}{10} \times P_o$$

where

z = Other costs in cents/kWh

o = Consumption of lubricating oil in grams/kWh

P_o = Price of lubricating oil in US-$/kg.

(vii) Source of energy

Diesel oil is normally used as fuel. Heavy oils can be used for normal Diesel engines only after they have been treated. Special types of engines are available for operation on gaseous fuel (dual-fuel engines).

(viii) Efficiency

The optimum-load efficiencies are shown in figure V.

The electric auxiliary service requirements are normally between 3 and 5 per cent of the terminal output, but may amount up to 8 per cent if treatment of heavy oil is required.

The part-load performance is very favourable as can be seen from figure I.

(ix) Advantages and disadvantages

Advantages

The units are ready for service within a minimum of time.

High efficiency.

Disadvantages

Large amount of spare parts required; high maintenance costs.

The output varies with the altitude of site and is dependent on the cooling-water temperature.

(x) Application and characteristics

The range of applications covers power generating stations with a total output of up to 15 MW. Owing to the high efficiency and the immediate availability for service, the Diesel-generating sets are particularly suitable for peak-load operation and as stand-by units.

Water consumption

If fresh water is used for cooling, approximately 35 to 40 litres are required per kWh. In the case of the water being re-circulated through coolers (cooling tower or spray ponds), 2 litres per kWh are sufficient.

Floor-space requirements

An area of 0.05 to 0.1 sq.m/kW is required.

Building-space requirements

For the power-station building, about 0.5 to 0.8 cu.m per kW are required.

Site conditions

As a general rule, the reduction to be made to the ratings is 1 per cent per 100 m of site altitude above sea level, and per 2° C above 20° C of the cooling-water temperature.

(f) Gas turbines

(i) Description and method of operation

With the normal open-cycle turbines, the air is compressed in a compressor and conveyed into a combustion chamber. The combustion gases expand in a turbine and escape into the atmosphere. The compressor is directly driven by the turbine, and the generator which takes the differential power, is connected to the same shaft.

In order to improve the efficiency, the heat of the turbine exhaust can be recovered and used for preheating the air to be compressed (gas turbine with regenerator).

The part-load performance can be improved by providing a separate power turbine; the compressor is driven by a turbine which operates independently of the speed of the power turbine, the latter driving the generator at a uniform speed (gas turbine with separate power turbine).

Large turbines use intercoolers for the combustion air.

(ii) Design considerations

Assuming favourable fuel conditions (furnace gas or natural gas) and the availability of vanadium-free fluid fuels, turbine inlet temperatures as high as 750° C may be reached. With heavy fuel oils the present stage

/of turbine

of turbine development calls for inlet temperatures below 650° C, since higher temperatures may involve corrosion of the turbine blades by the vanadium contained in the oil residues. The gas inlet temperatures of turbines built so far mostly range between 600° and 650° C. Output and efficiency depend on the ambient air temperature and the altitude of the site.

(iii) Output range

Open-cycle turbines are built for outputs up to about 20 MW, and up to approximately 40 MW if intercoolers are used.

Gas turbines with regenerators have been built for up to about 30 MW unit ratings, intercoolers being used for turbines with outputs of about 10 MW upwards.

(iv) Cost of construction

These costs can be seen from figure IV, the lower range applying to gas turbines of the open-cycle type, the upper range to gas turbines with regenerator.

(v) Amortization

Modern, stationary gas-turbine plants are designed for a long service life. 10 to 15 years are taken as a basis for calculating the amortization rate of the capital invested.

(vi) Incidental and other costs

The incidental costs are low and amount to 1.5 to 3 per cent of the annual construction costs.

(vii) Source of energy

Oil and gas are used as fuel exclusively.

(viii) Efficiency

The values of efficiency are shown in figure IV, the lower range applying to open-cycle turbines without regenerator, the upper one to turbines with regenerator.

The electric power requirements for the auxiliaries range between 0.8 and 2 per cent of the terminal output.

The part-load performance can be seen from figure I, in which the lower curve has been plotted for open-cycle gas turbines without regenerator, the centre curve for turbines with regenerator and separate

/power turbine,

power turbine, and the upper curve for multiple-shaft gas turbines with intercoolers, reheater and regenerator.

(ix) Advantages and disadvantages

Advantages

Simple construction and small space requirements.

Low first costs.

Short starting times (8 to 15 minutes without regenerator, 20 to 30 minutes with regenerator).

Negligible cooling-water requirements.

Low electric-power requirements for auxiliaries.

Disadvantages

Reduction of efficiency and oil absorption by deposits on the blading if ash-containing fuel is used.

Danger of corrosion as a result of the combustion of oil residues.

Output and efficiency are dependent on the ambient air temperature.

With open-cycle turbines without regenerator, the efficiency is low and the part-load performance unfavourable.

Great noise in operation.

(x) Application and characteristics

Owing to their short starting time, open-cycle gas turbines are particularly suitable for peak-load operation.

Gas turbines with regenerator have given satisfactory service in continuous operation in medium-sized plants.

Water consumption

Approximately 4.5 litres/kWh are required for cooling.

Floor-space requirements

Gas-turbine plants without regenerator require an area of about 0.03 to 0.07 sq.m/kW, gas-turbine plants with regenerator about 0.04 to 0.08 sq.m/kW.

Building-space requirements

0.5 to 0.9 cu.m/kW are required for plants without regenerator, and 0.6 to 1.0 cu.m/kW for plants with regenerator.

Site conditions

In the case of plants without intercoolers and without regenerators,

/the conversion

the conversion factors determined by the air temperature are as follows:

A temperature variation of 10° C within the range of -10° to +30° C causes a variation of output of 12 per cent and of efficiency of 5.5 per cent, the reference values being those applicable at 20° C.

Altitude of site:

Every 300-m change in altitude involves a 3.5 per cent output variation, while the change in efficiency remains negligible.

(g) Free-piston engines

(i) Description and method of operation

A free-piston plant comprises one or more gas generators with a gas turbine in series. The gas generator corresponds to the combustion chamber with compressor of the gas turbine. The fuel is injected at the dead point between two opposed pistons, forcing the pistons apart; the outer pistons build up an air cushion, while fresh air is drawn in at the other side. The combustion gases escape through ports which are opened before the outer dead point is reached. In the course of the return motion of the pistons, which is effected by the compressed air cushion, the drawn-in fresh air carries out the scavenging action and is compressed until the piston again reaches a dead point. Combustion takes place with a high air surplus, so that the combustion gases contain about 80 per cent of air. The pistons are connected only by a synchronizing mechanism.

(ii) Design considerations

The gas generator affords gas turbine inlet conditions of 3 kg/cm^2 gauge and 455° C. The turbine operates with atmospheric back pressure.

The only gas generator which has so far been put into practical operation is the French type GS.34, which is suitable for a turbine output of about 1,000 metric h.p. Other sizes are, however, being developed.

(iii) Output range

The spacing of ratings is determined by the size of the gas generator. 7 or 8 gas generators are provided for the largest units of about 6 MW built so far.

(iv) Cost of construction

The costs of construction are shown in figure V.

/(v) Amortization

(v) Amortization

The depreciation time is comparable to that given for Diesel power stations, i.e., 10 to 15 years.

(vi) Incidental and other costs

The incidental costs amount to 4 to 6 per cent of the costs of construction per year.

Since a large amount of oil is required for cooling and lubricating the pistons, the other costs are comparable with those calculated for the Diesel engine. The specific consumption is about 3.2 grams/kWh of lubricating oil, and about 0.55 grams/kWh of cooling oil (for the formula, see under 3 (e)).

(vii) Source of energy

Free-piston plants can be operated only with fluid fuels. Owing to the high air surplus and the low turbine inlet temperatures, even heavy oils can be used.

(viii) Efficiency

The values of efficiency at optimum load can be seen from figure V. They vary only slightly with the size of the unit.

Figure I shows the part-load performance characteristics for turbines with 2 and 8 gas generators.

The electric-power requirements for the turbine auxiliaries amount to 2 to 4 per cent of the terminal output.

(ix) Advantages and disadvantages

Advantages

High efficiency
Short starting time (20 to 30 minutes)
Small space requirements
Heavy oils can be burned

Disadvantages

Can only be operated with fluid fuels
Output and efficiency are dependent on the pressure and temperature of the atmospheric air
High oil consumption for lubrication and cooling
Poor part-load performance if only a few gas generators are used per turbine

/Additional cooling-

Additional cooling-water requirements, great noise in operation
Large amount of spare parts required; high maintenance costs.

(x) Application and characteristics

Free-piston plants will be economical for peak-load operation and small power stations if heavy oils can be used.

Water consumption

In addition to the cooling-oil system, the gas generator requires cooling water at a rate of about 35 litres/kW

Floor-space requirements

An area of about 0.06 to 0.08 sq.m/kW is required for the power-station building.

Building-space requirements

0.7 to 0.9 cu.m are required per kW.

Site conditions

Air temperature:

If the air temperature changes by 10° C, the output will vary by 3.2 per cent and the efficiency by about 2.3 per cent.

Altitude of site:

A 300-m change in altitude involves an output variation of about 1.5 per cent.

The values of output and efficiency are normally referred to sea level and an air temperature of 10° C.

(h) Compound processes

All the cyclic processes described in sections 3 (c) - (g) can be improved with a view to adapting them to the ideal Carnot cycle, and their thermo-dynamic efficiency can be improved by increasing the temperature range. The measures to be adopted for improving the processes have been referred to in the respective sections (e.g., the use of regenerative feed heating in steam power stations, exhaust gas turbines for Diesel engines, regenerators for gas turbines, etc.). The thermo-dynamic efficiency can further be improved by combining two or more cycles, so that a compound process is obtained, the essential methods being the following:

/Utilization of

Utilization of waste heat

This widely applied method utilizes the waste heat resulting from a cyclic process. The heat recovered no longer constitutes a loss for the basic process, the efficiency is improved and the costs of power generation are reduced.

Compounding of processes

The actual compound cycles are characterized by the fact that two or more systems are combined, either directly or through heat exchangers, with a view to increasing the temperature range and to improve the efficiency. It is obvious that the expenditure and thus the costs of construction for compound plants are higher than those of one-cycle installations, which offsets the gain in efficiency. Many combinations have been proposed, but none of these processes has so far been accepted in practice. Nuclear power stations may, however, provide a field of application for such plants.

(i) Nuclear energy

(i) Description and method of operation

The basic thermal energy is generated in a reactor, where various processes take place, of which a simplified description is given in the following.

The fuel (uranium in most cases) is exposed to neutron irradiation, which splits the uranium isotope U 235 (of which only 0.7 per cent are contained in natural uranium): during this process, 2.5 further neutrons are freed on an average. Part of these neutrons are captured by other nuclei or are otherwise lost for the process. If, however, more than one free neutron causes a further fission, a chain reaction takes place. In the thermal reactors used mostly, the action of the neutrons is improved by a moderator so that a continuous chain reaction can be maintained. Part of the neutrons are captured by the nuclei of the non-fissile uranium U 238 (of which 99.3 per cent are contained in natural uranium), which is converted into plutonium Pu 239: this has fissile properties similar to those of U 235. Where the plutonium production is greater than the consumption, the reactor is called a breeder reactor. The fuel is introduced into the reactor in the form of elements which must be replaced when they are depleted.

/In order

In order to reduce the reactor dimensions and to extend the reaction period, enriched uranium (U 235 content above 0.7 per cent) can be used instead of natural uranium.

During fission, energy is produced in the form of heat, which is supplied via a coolant to a closed cycle in which the turbine driving the generator is incorporated.

(ii) Design considerations

The great number of types of atomic power stations which are under construction or in the stage of planning makes it impossible to give a detailed description of each type.

Of the many possible combinations, the reactor types listed below are - in the present stage of development - being given serious consideration for the actual use in power generation:

1. Thermal reactors
    (a) Gas-cooled reactors
        Natural-uranium graphite-moderated reactors
        Heavy-water reactors
    (b) Water-cooled reactors
        Light-water reactors
        Heavy-water reactors
    (c) Reactors with an organic coolant
    (d) Reactors with liquid-metal coolant
        Sodium-graphite reactors
    (e) Steam-cooled reactors
        Superheater reactors
2. Fast breeder reactors
    (a) Liquid-metal breeder reactors

In the case of boiling-water reactors, the coolant is expanded directly in the turbine. If other types of coolant are used, one or two more circuits are connected in series through heat exchangers. Gaseous coolants, which are expanded directly in the turbine, are used in small plants only.

/(iii) Output

(iii) Output range

Experimental reactors and power plants for the training of personnel are built for a low power only. For power generation, the economical minimum generator rating is normally 50 MW. The capacity of the largest atomic power station presently under construction is 550 MW.

(iv) Cost of construction

The costs of construction of United States and United Kingdom stations (excluding experimental plants) differ widely and vary between 250 and 450 dollars per kW, depending on the size and the type of the reactor. It is expected, however, that - by 1970 - the construction costs can be reduced to 180 - 270 dollars per kW.

(v) Amortization

A depreciation time of 20 years can be used as a basis for atomic power stations.

(vi) Incidental and other costs

At the present time, the incidental costs vary between 1.5 and 3 per cent of the construction costs. Contrary to generally accepted assumptions, the removal of ash involves only little cost, which is included in the percentages given.

The procurement of fuel elements for the first charge, including spare elements, involves additional costs. In many cases (in the United States), the fuel elements are supplied by the Atomic Authority on a loan basis only, and a lending fee is charged.

The costs are calculated on the basis of the following formula:

$$z = \frac{P}{l \times \eta} \times \frac{a_b}{v}$$

where

z = Incidental costs in cents/kWh

P = Price of fuel in US-$kg (see point 7)

l = Specific capacity of reactor in MW, reactor capacity per tonne of fuel charge (MW/t)

η = Per-unit efficiency at generator terminals, referred to the thermal capacity of the reactor

a_b = Annuity or lending fee for fuel elements in per cent per year (4.5 per cent normally)

v = Full-load operation hours per year in hr.

/The specific

The specific capacity of a natural-uranium reactor is about 2 to 7 MW/t, and 10 to 30 MW/t in the case of thermal reactors using enriched fuel. The values obtained with fast breeder reactors are considerably higher.

(vii) Source of energy

The most important fuel is U 235, of which 0.7 per cent is contained in natural uranium and which is also available in enriched form. A criterion for the amount of heat released is the degree of burn-up, which is expressed in MWD/t (megawatts per day per tonne). With natural uranium, the relevant value is 7,000 MWD/t, and 10,000 to 20,000 MWD/t in the case of enriched uranium (up to 4 per cent). If plutonium is produced during the burn-up (breeder reactor), the plutonium may be sold, which reduces the fuel costs. The latter are calculated according to the following formula:

$$b = \frac{P - c \times P'}{0.24 \times H}$$

where

b = Specific fuel costs in cents/860 kcal

P = Price of fuel in US-\$/kg
(including processing and transportation)

c = Plutonium produced in grams/kg of fuel
(this is in the order of some grams, and does not exceed 10 grams even with enriched uranium)

P' = Price of plutonium sold in US-\$/gram
(the present figure is about 12 US-\$/gram)

H = Burn-up per tonne of fuel in MWD/t

The price "P" of the fuel depends on the degree of enrichment, the approximate figures being as follows:

Enrichment in per cent	0.7	1	2	3	4
"P" in dollars per kg,	80	130	320	500	700 approx.

(viii) Efficiency

Recently completed atomic power stations operate with an efficiency of over 28 per cent, referred to the terminal output of the generators, using the thermal yield in the reactor as a basis.

/The electric-

The electric-power requirement for the auxiliaries amount to 5 to 16 per cent, depending on the reactor type.

The part-load performance is determined by the type of the closed-cycle employed.

(ix) Advantages and disadvantages

Advantages

High energy yield of the fuel.

High efficiency.

New source of energy after exhaustion of fossile fuel in the world.

Disadvantages

High costs of construction for the time being.

Radiation hazards, requiring special provisions for shielding equipment.

Expensive production and processing of fuel.

(x) Application and characteristics

It is expected that some of the atomic power stations which are being developed at present will operate economically already in the near future. Reactor types are, however, being developed by means of which the energy cost can be reduced below the values obtaining with conventional power stations.

The characteristic data are not stated, since they vary within wide limits. A factor to be considered is the high water consumption (about 50 per cent more than with steam power stations of the same size).

FIGURE I

GRAFICO I

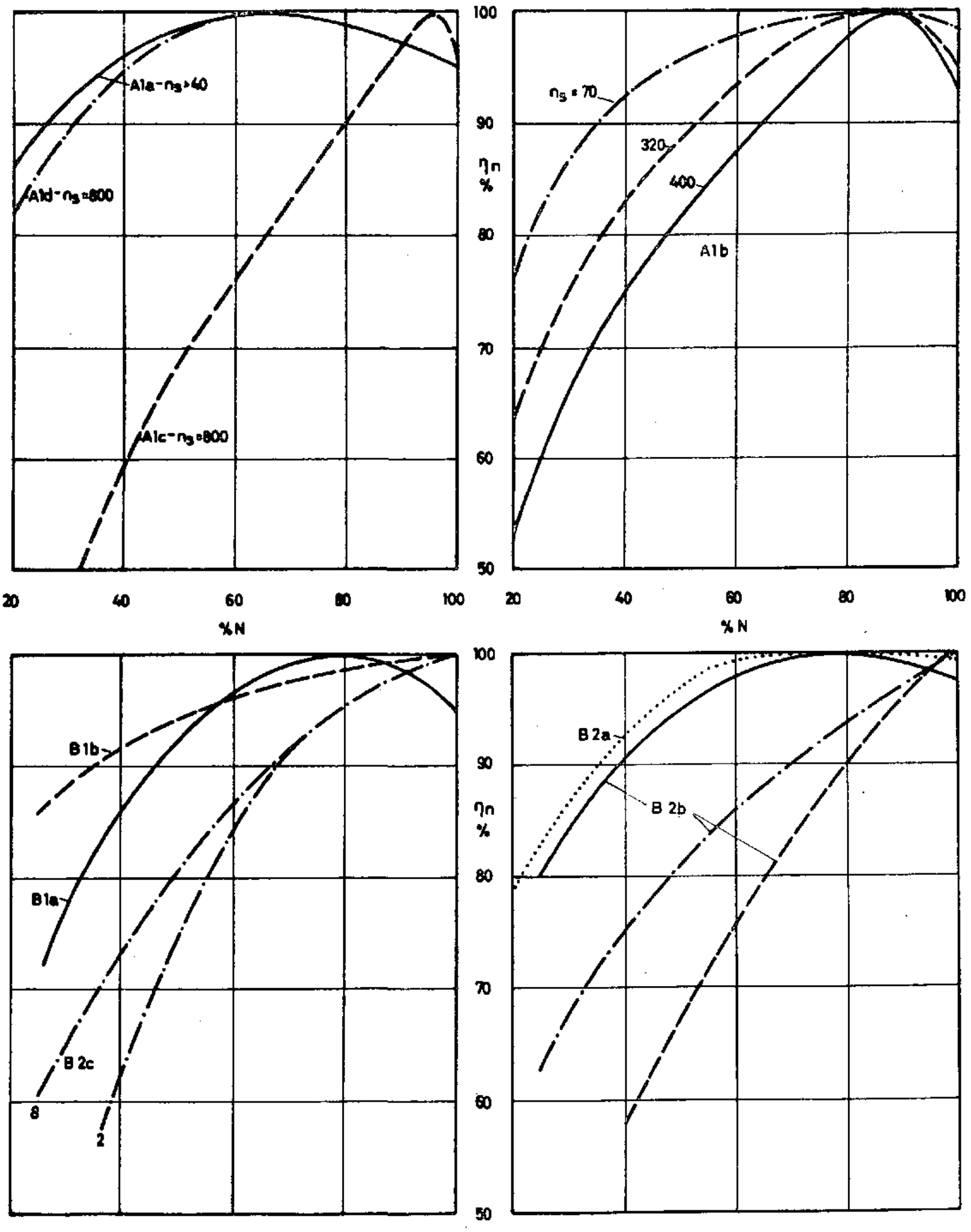

FIGURE 11
GRAFICO 11

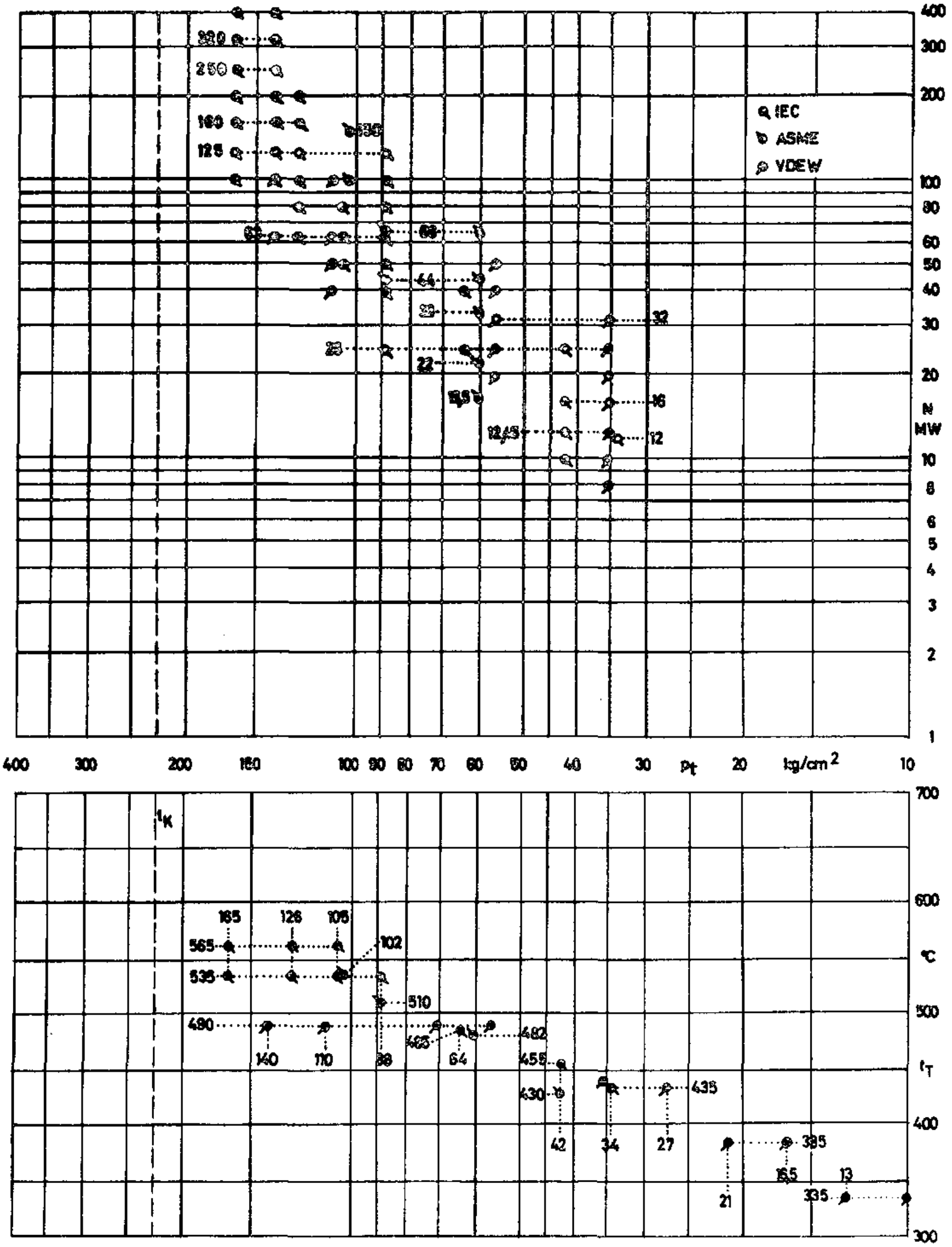

FIGURE III

GRAFICO III

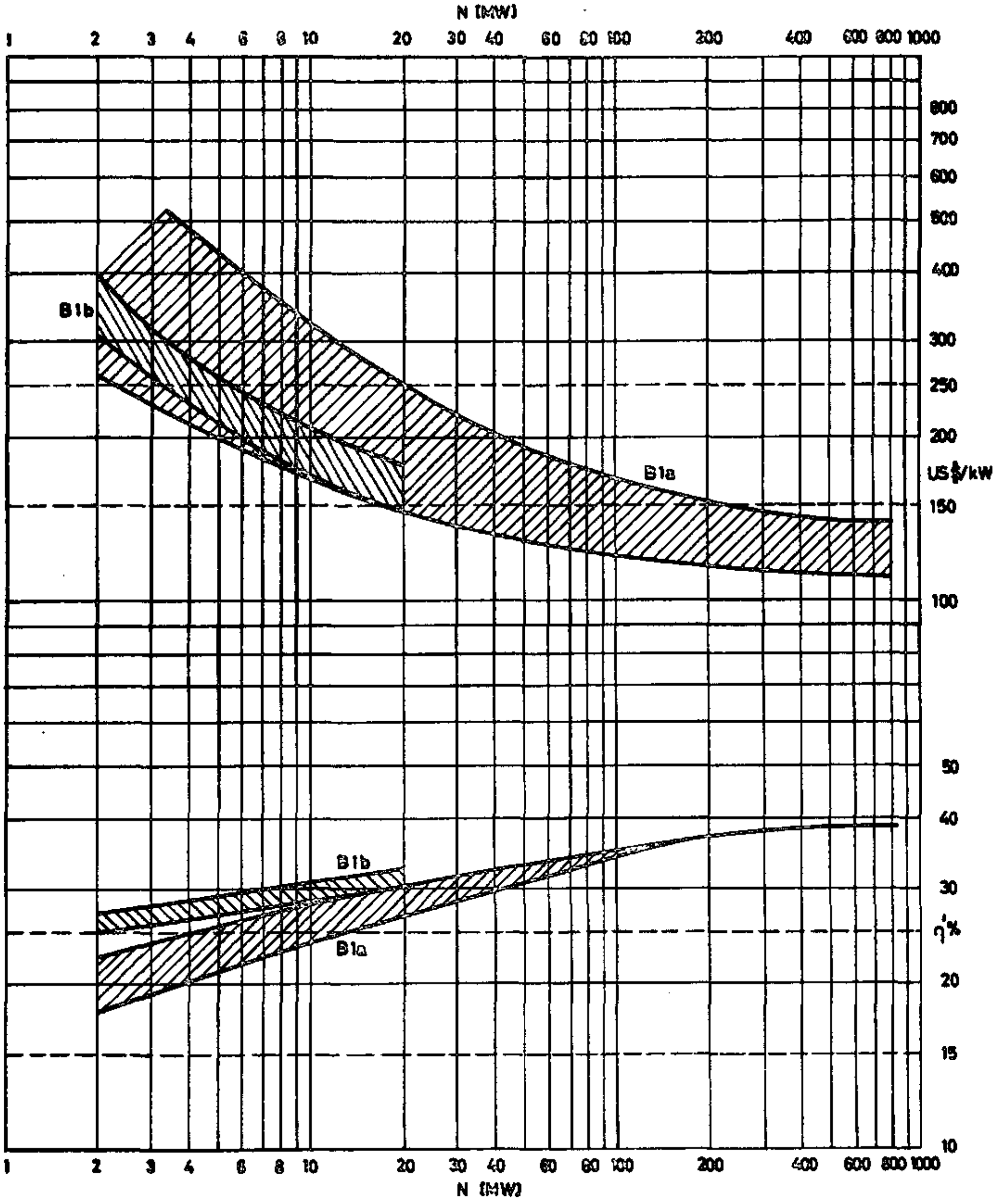

FIGURE IV

GRAFICO IV

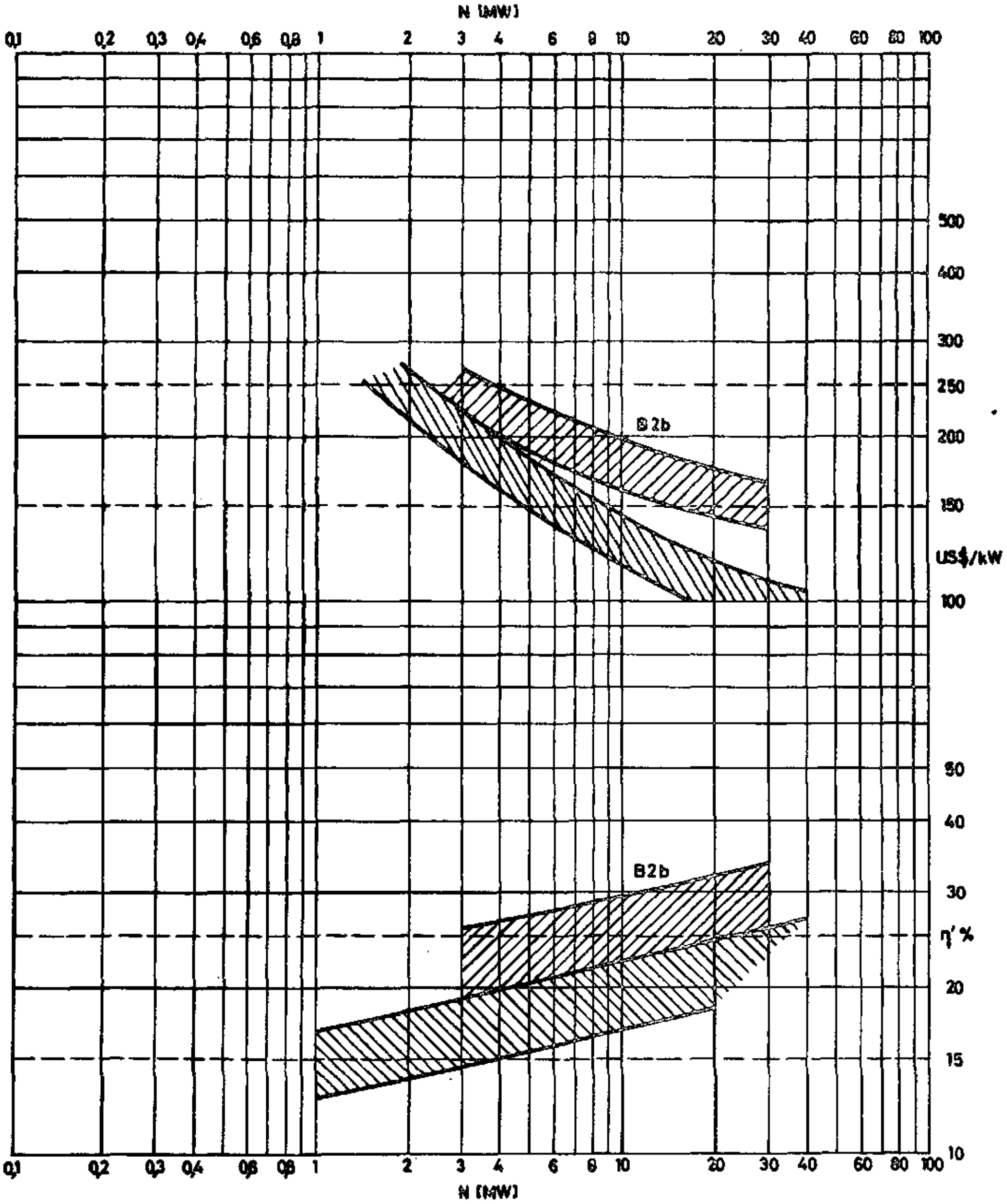

FIGURE V

GRAFICO V