GAS COOLED SOLAR TOWER POWER PLANT (GAST)
KWU APPROACH TO A 20MW HYBRID SYSTEM

by

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0. Introduction

When we talk about energy we normally mean electricity for general use. At present this is mainly produced by the conversion of mechanical energy in generators. The majority of generators are in turn driven by thermal machines such as steam and gas turbines or diesel engines. From this we can see that the generation of electric energy concentrates on the acquisition & economic utilization of thermal energy. The viability of a particular energy source is determined by the following criteria:

- its availability
- acquisition costs
- easy conversion into other forms of energy (e.g. mechanical)
- minimum disturbance of the environment due to acquisition and conversion.

Up until recently these criteria could be applied to solid, liquid and gaseous fossil fuels.

However the increasing demand for these fuels and their limited availability have led both to price increases and to an intensified search for alternative sources.

The most important alternative energy source available to us today, which is based on proven power generation technology is without doubt nuclear energy. However, inspite of a mature technology and consequent high availability the peaceful use of nuclear energy is still handicapped by requirements such as highly qualified operating personnel, stricter safety regulations etc. In addition unsettled questions of waste disposal, as well as memories of the destructive power of nuclear energy have led to an aversion to nuclear power within some countries. This naturally has an impact on the choice between the various types of energy on a global scale and the question of an alternative energy source remains open.

The sun with its almost limitless supply of energy is one of the main alternatives. It fulfils two of the abovementioned criteria but problems arise when trying to bring about an economic conversion of the solar radiation into utilizable (mechanical) energy. Plans for a solar power plant have to take into account fluctuations in the radiation onto a given area of the earth's surface, as well as a relatively low specific irradiation. Solving these problems entails a considerable technical and therefore also financial outlay.

To compensate for this it is necessary to create an extremely economical power generation plant to achieve effective conversion of this expensively acquired thermal energy into electric energy.

Through its subsidiary Interatom KWU is taking part in a joint project supported by the Federal Ministry for Research and Technology, together with such reputable firms as Dornier, MAN and MBB.

It is intended to construct this power plant on a site in the southern European reg

Based on its many years of experience in the field of power plant construction, KWU will provide the power generating equipment.

The high efficiency of the chosen system design and the reliability of the components both guarantee the necessary economy of operation and availability for power generatior Full application of proven technology in the field of power generation is the objective

1.0 Heat Flow System

In the planned solar tower power plant a field of heliostats focusses the solar radiation onto a receiver which transfers the thermal energy to the cycle medium. In the cycle the thermal energy is then converted into mechanical and thereafter into electric energy.

The following criteria were taken into consideration in the selection of a suitable cycle:

- economy of operation
- technology
- reliability
- simple operation
- dependence on water
- adaption to fluctuations in solar energy supply

1.1

Steam, gas turbine and combined cycles were included in the evaluation. In view of the relatively small part played by the power generator in the production costs of the overall plant, the thermal efficiency - i.e. utilization of heat arising in the receive is decisive in the choice of cycle.

On the basis of the design criteria mentioned for the cycle, the following variants wer considered:

a) steam turbine with regenerative feed water heating
b) open gas turbine cycle
c) closed gas turbine cycle
d) open gas turbine cycle with downstream waste heat utilization (GUD)

Schemes for these cycles can be taken from Fig. 1. They contain tried and tested components which have been proved in conventional power plant construction

All the plants are designed as hybrid systems, so as to compensate for the differences between the solar energy supply and the power grid demand. This means that if the heat energy in the system is insufficient due to fluctuations in the solar energy supply the gap is then filled by heat produced in a fossil-fueled combustion chamber connected series to the receiver. The design requirements for the cycles can be taken from Ta

Explanation of cycle variations:

In the conventional steam cycle (a) the receiver replaces the boiler. Auxiliary firing ensures full output even when solar radiation is insufficient.

In the gas turbine process the air is compressed in a compressor with intermediate cooling and is then routed to the receiver via a recuperative preheater. The medium heated in the receiver or in the combustion chamber downstream is expanded in the turbine and the energy released drives the shaft. The expanded air is partly cooled in the recuperator. At this point the working medium is either discharged into the environment (open process-b) or it is routed back to the compressor after further cooling (closed process-c).

In the closed process the pressure level in the system can be set independent of the pressure ratio of the turbine generators; this is an additional design variable.

Utilization of the waste heat from the gas turbine processes in the downstream steam cycle leads to a considerable increase in efficiency, thereby improving the power plant's economy of operation (d).

The comparison in Table 2 shows the optimum cycle.

1.2

The evaluation used the same criteria as mentioned under 1.0.

1.2.1

The open GUD plant (d) is characterised by maximum utilizable output with low plant costs. These low plant costs result from the use of a relatively small number of simple, conventional components, as well as low system pressure.

The disadvantages of variants b and c are the high cost of the air/air recuperator as well as the resulting double pressure loss. The closed cycle (c) is characterised by its indirect heat input, a factor which is particularly significant, for example, with erosive combustion products or with working mediums containing no oxygen.

Air has been chosen as working medium for the solar power plant. Air is not only ubiquitous but as a carrier of oxygen can also be used in the combustion of auxiliary fuel. Compared with helium, for example, the specific dimensions of the machines are considerably smaller, which in turn means that tried and tested components can be used (d).

1.2.2

The technology of the power generation systems under consideration (Fig. 1) is conventional with the exception of the receiver; i.e. the circuits and components have already been used in a number of power plants. The experience gained with these systems played an important role in the evaluation of the cycle variants.

The steam cycle is based on many years of experience. Hybrid systems which make up any lack of heat through combustion of a fossil fuel must in addition incorporate a steam boiler connected in parallel. A relatively complex condensation plant together with other peripheral systems result in high specific costs which are not justified by the relatively low output.

The simple gas turbine cycle in variants (b) and (c) includes recuperative preheating of the combustion air. Without changing the heat input (60 MW) this recuperative preheating increases the unit output of the gas turbine generator set. With current receiver outlet temperatures of about 800 $^{\circ}C$ the use of a recuperator requires that an intermediate cooler be used in the compressor. The high temperature on the air-side of the recuperator outlet decreases the receiver efficiency and requires an increase in its dimensions.

The so-called GUD process makes better use of the exhaust heat from the gas turbine. This simpler design favours the open cycle (d).

1.2.3

The availability of the plant is determined by the number of components, auxiliary cycles and functional groups within the system. Many years of experience have also minimized the number of teething troubles which can be expected in the plant.

As well as variant (a) the open gas turbine cycle with a downstream waste-heat boiler and steam turbine (d) also fulfils the aforementioned conditions. Both variants have been used in a number of plants.

1.2.4

Output of the plant during solar operation is determined by the prevailing solar radiation. The speed with which the power generation system adapts to fluctuations in the solar power supply is one of the essential criteria for the circuit. Circuit (d is characterised by a direct connection between the receiver and the gas turbine. This guarantees an immediate turbine reaction to any fluctuations, which does not occur in other circuits where the reaction is delayed by the cooler, recuperator and boiler.

1.2.5

The water requirement is an important aspect in the design of a solar power plant circuit. Even if the cooling water can generally be replaced by air, make-up water for steam generation must nevertheless be provided for in a steam cycle. In view of the fact that water is less plentiful in countries with a large amount of sunshine and as water treatment increases internal power consumption, thereby reducing efficiency, a low water requirement is an important factor in the choice of a particular system. A combined plant (d) is characterised by its relatively low make-up water requirement for steam generation, as the output of the steam turbine in these circuits only makes up about 30 % of the unit output.

1.3

After assessment of the criteria (Table 2) the combined cycle (d) was chosen as the method with optimum utilization of the solar heat captured in the receiver.

1.3.1

In summary the following reasons were seen as being decisive:

- maximum output i.e. better efficiency in comparison with the other variants.
- possible improvement of efficiency through an increase in the process temperature
- lower specific cost
- conventional technology with tried and tested components, therefore higher availability
- simple control by means of head input
- rapid adaption to fluctuations in solar energy supply
- short startup time
- high part-load efficiency
- a relatively low water requirement for cooling and steam generation.

1.3.2

The chosen cycle is based on the experience gained by KWU in the design of similar plants. As the plant is to operate without storing any energy, great emphasis was placed on the part-load behaviour of the plant, and two gas turbines working in parallel were provided (see Fig. 2 and Table 3). The reasons for these two turbines will be discussed again in this presentation. The relatively low efficiency is a result of the high air and water temperatures. At an ambient temperature of 15 °C this efficiency would be 40 %. This is true for all gas turbine processes.

2.0 Description:

2.1

First the overall construction of the plant; Fig. 3 shows the arrangement of the tower in the array of heliostats.

In this solar tower power plant about 3000 heliostats (individual mirrors each with a reflective surface area of 40 m^2) concentrate the sun's rays onto two receivers. A receiver is a heat exchanger situated at the top of a 200 m high tower. The solar radiation heats up the working medium air in these receivers to a temperature of 800 °C.

The energy absorbed is then fed to an open gas turbine process with a downstream steam turbine cycle. This combined gas and steam process corresponds to the GUD combined cycle developed by KWU. Maximum unit output is obtained by using an auxiliary system for firing fossil fuel in place of a passive energy storage system.

The 3000 heliostats are arranged in a kidney shape around the tower. The total reflective area is about 120 000 m^2 and the plant requires roughly 500 000 m^2 of land.

A tower of reinforced concrete was found to be the optimum design. The tower is of a design similar to that of conventional telecommunications towers. Apart from the two receivers the turret also contains the gas turbines for the energy conversion system.

The steam section of the plant with the steam turbine is situated at the foot of the tower.

In view of the fact that a specific site has not yet been chosen for the plant a number of factors have been assumed in its design. For example the design of the plant assumes that the site will be at 30 ° north latitude. Solar radiation at this location was assumed to be 960 W per m^2 on June 21, 12.00 hours midday. A maximum air temperature of 50 °C was assumed at 20 % relative air humidity. The cooling water temperature was assumed to be 35 °C. The plant must be able to operate exclusively on solar energy and must also be able to maintain a constant output for 24 hours through the auxiliary firing of fossil fuel. If these design conditions are fulfilled it will be possible to adapt the operation of the power plant in principle to any requirements of the plant operators.

2.2

As stated above the power generating equipment is located in the turret and at the foot of the tower.

Figure 4 shows the configuration of the gas turbines with the connected waste heat boiler in the turret. Location in the tower is advantageous in terms of the process design and cost due to short hot gas lines.

At first glance it can be seen that these are conventional components. However, adaption to solar energy requirements must in addition be taken into consideration. These include, for example, hot gas lines with appropriate valves, variable air temperature at the combustion chamber inlet as well as the resulting control probl---.

The design incorporates KWU gas turbines of type V.4, whose combustion chambers are ideally suited to connection to the receiver. The gaseous waste from the gas turbine is routed to a waste-heat boiler via a mixing line. The steam produced in the boiler is routed to the steam turbine (Fig. 5) via a line passing through the tower shaft. The condensate is fed back into the boiler in the same way. The heat routed to the gas turbine determines the output of the entire combined unit.

Using the gas turbine as an example we will now see how the design of conventional components must be modified when fossil fuel is replaced by solar energy.

2.3

The gas turbine shown in Figs. 6 to 8 is basically the same as a standard KWU gas turbine. However, the following requirements must be met;

a) The steel receiver design leads to a drop in the turbine inlet temperature from about 1000 °C to 800 °C. It would therefore be possible to dispense with blade cooling.

b) The receiver is connected in the vicinity of the combustion chamber. KWU combustion chamber design affords easy connection to the receiver due to the large cross-sectional area of both chambers and their physical separation.

c) Control of the turbine must be compatible with both types of heat input - i.e. solar and fossil -. The configuration shown in Fig. 4 provides enough space for the necessary control elements.

Now lets briefly look at the gas turbine (Figs. 6 to 8).

General

KWU gas turbines are single-shaft machines of single-casing design. They are suitable for driving generators in base-load and peak-load plants and for mechanical drive applications. They can be used in combined gas-steam cycles and for district heating. They can burn liquid fuels, such as light or heavy fuel oils, or gaseous fuels with different calorific values, such as natural gas or blast-furnace gas.

Internal and External Construction

The compressor and turbine, the principal components of a single-casing single-shaft gas turbine, have a common rotor. It is supported in only two bearings which are located outside the pressurised region of the unit. This provides the basis for constant good alignment and excellent running qualities.

Rotor

The rotor is built up from a number of discs, each carrying one row of blades, and three hollow shaft sections all held together by a central tie bolt.

The turbine rotor is internally cooled. A small percentage of the compressed air i bled off from the main flow at the end of the compressor and admitted to the interior of the rotor through holes in the centre hollow shaft.

Combustion Chambers

The two combustion chambers are arranged vertically on either side of the turbine and connected to lateral flanges on the turbine casing. This design makes possible concentric gas and air paths from the compressor to the combustion chambers and from the combustion chambers to the turbine involving relatively low flow velocities and thus a minimum pressure drop.

This combustion chamber arrangement offers great flexibility in dimensioning and combustion system configuration and also provides the prerequisites for good accessibility of all components for inspections as well as for easy assembly and disassembly. In addition, it makes possible the simple connection of a regenerator or of other heating systems, such as pressurised furnace boiler, fluidised-bed combustion, solar receiver, etc.

Installation

The turbine/compressor is a compact unit which is assembled at the manufacturer's works. This eliminates the need for any clearance adjustment during field erection.

3.0 Power Plant Operation

The specific operating problems of the solar power plant are a result of the discrepancy between the duration and intensity of the radiation and the demand from the connected grid.

Fig. 9 shows the curve of the heat input Q_{REC} to the receiver during the day on June 21. Q_{SOL} is then routed from the receiver to the gas turbine.

The useful electric power P_{SOL} is then available to the grid in a very short length of time. This characteristic determines the mode of operation of the solar power plant. In principle the power plant can be operated either

- according to the amount of solar radiation, or
- according to the demand from the grid.

Depending on the site the first mode permits 1500 to 2500 hours of operation annually. This type of plant is used as a fuel saver in conjunction with fossil-fueled plants.

The high investment costs for solar power plants have led to attempts to increase the number of hours of operation. This can be achieved either by energy storage or by auxiliary firing of fossil fuel.

The number of hours of operation can be increased depending upon the choice of solar multiple (SV) - i.e. the relationship between receiver and turbine output. For example with SV = 2 and approx. 7 full-load storage hours per day the number of full-load gas turbine hours can be doubled. However the heliostat array must be increased accordingly.

The firing of fossil fuel provides a simpler solution to the problem of utilization. The plant can deliver a constant output as required by the grid demand. The plant should be seen as one step in the development toward complete independence from fossil fuel. This also applies to the hybrid GAST plant discussed in this presentation.

Fig. 9 shows the necessary amount of heat from fossil fuel for a specific turbine terminal output.

Hybrid operation of the solar power plant allows the temperature limit of 800 °C to be exceeded and the gas turbine to be run at the full temperature of 1000 °C. This increases the unit output but increases the amount of fossil fuel required.

3.1

Part-load behaviour is an important factor to be considered in the assessment of a power plant unit. Part-load behaviour was also given careful consideration in the development of the GAST project as the turbine generator set, when operated exclusi on solar energy, only reaches full load at 12.00 hours on June 21. Output and efficienc always depend upon the turbine inlet temperature. The selected configuration of two gas turbines connected in parallel improves on the part-load behaviour of a turbine generator set as shown in Fig. 10. The receivers and turbines are connected in such a way that if the unit load is reduced to approx. 50 %, one of the turbines is shut down and the other is brought up to full load (800 °C).

3.2

It is planned to use the fossil fuel during startup and shutdown of the plant. This would take full advantage of the gas turbine which has a very short startup time. The startup curve for the GUD-system is shown in Fig. 11. The steam produced in the waste-heat boiler is routed to the steam turbine, which is then connected to the electric grid after a certain delay.

4.0 Availability of the GAST power plant

It was possible to precisely determine the **reliability** of the power generating equipment for the GAST plant because the performance of nearly all the components has been evaluated in plants which have been operating for years.

The assessed **reliability** refers to solar operation. The time **reliability** obtained for this is more than 99 %.

5.0 Summary

The gas cooled solar tower power plant with a hybrid solar-fossil heating system in the form given here represents a significant step towards the industrial use of solar energy. The transition from fossil fuels to solar energy can be facilitated for the power plant operators if the transition is gradual and if conventional technology is used.

Using solar energy and with a turbine inlet temperature of 800 °C the GAST power plant reaches an output of approx. 20 MW and a thermal efficiency of approx. 40 % referenced to the heat supplied by the receiver.

In the absence of solar radiation the plant can be operated exclusively on fossil fuel. Increasing the turbine inlet temperature to 1000 °C enables an efficiency of about 47 % to be reached in the GUD cycle.

5.1

The GAST plant as the first step in the transition from fossil to solar energy must be followed by further developments in the field of solar power.

- To meet the requirements of a given grid the plant size can be increased b factor of up to 5. Increases within this range would not alter the charact istics of the basic model.
- The use of a ceramic receiver would enable the gas turbine inlet temperature to be increased, which in turn would lead to an improvement in thermal efficiency.

- Development of an optimum storage system would improve the utilization of the solar energy throughout the day. In this way fossil fuel would then become unnecessary.
- The receiver - gas turbine circuit can be simplified by using a single large gas turbine in the GUD cycle. This system should be able to make more effective use of the favourable characteristics of the KWU combustion chamber configuration.

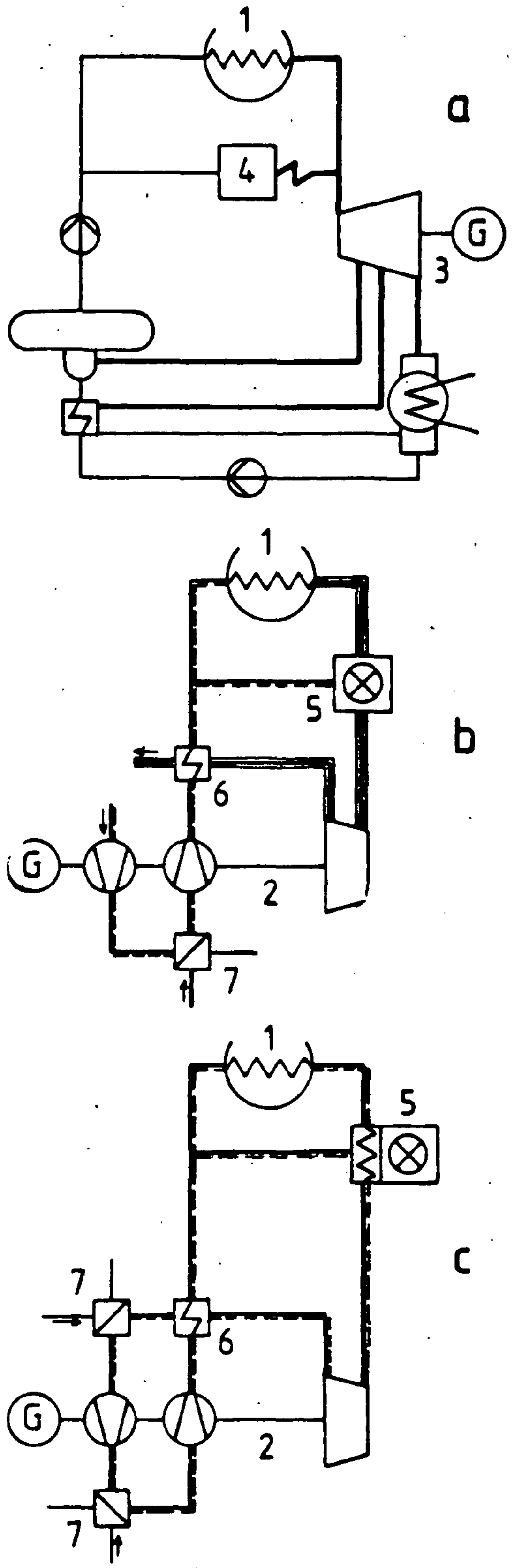
Industrial manufacture of solar collectors and improvement of the efficiency of conversion from solar to thermal energy will at the same time help to bring the costs of solar power generation into line with those of other power generation systems.

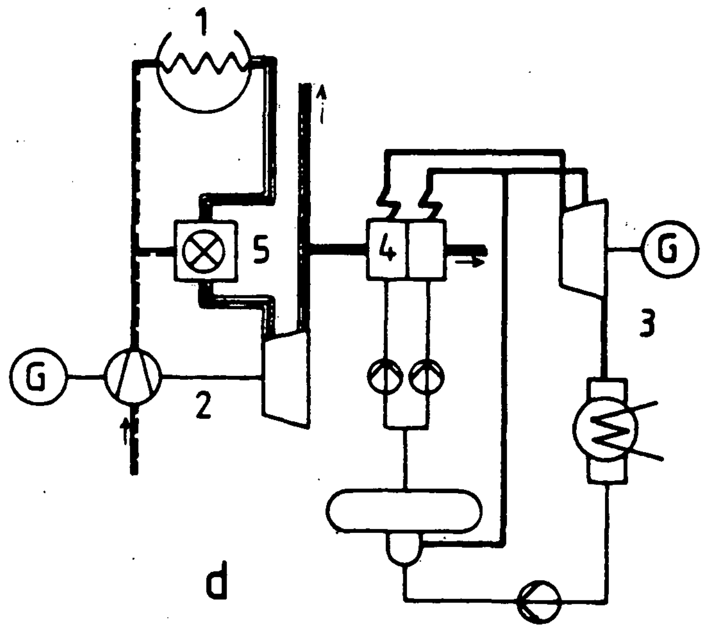
6.0 References

1. S. Kostrzewa: Überblick über das 20 MWE - gasgekühlte Sonnenturm-Kraftwerk
   1. Statusseminar GAST, Köln-Porz (Germany), 13. Mai 80
2. J. Feustel: Wirtschaftliche Perspektiven gasgekühlter Solar-Kraftwerke
   1. Statusseminar GAST, Köln-Porz (Germany), 13. Mai 80
3. H. Finckh: Kreislaufkonzept und Komponenten
   1. Statusseminar GAST, Köln-Porz (Germany), 13. Mai 80
4. E. Franck & Cons.: Solar Tower Power Plant 20 MWE with Gas Turbine Cycle
   International Symposium on Solar Thermal Power Systems Marseille (France), June 15 - 20, 1980

List of tables and diagrams

FIG. 1





1 Receiver
2 Gas turbine
3 Steam turbine
4 Boiler
5 Combustion chamber
6 Recuperator
7 Cooler

21th of June 12.oo midday

Thermal energy transfered from the receiver to the cycle	6o MW
Receiver outlet temperature	8oo°C
Ambient temperature	5o°C
Ambient pressure	1 bar
Ambient air humidity	2o %
Cooling water temperature	35°C

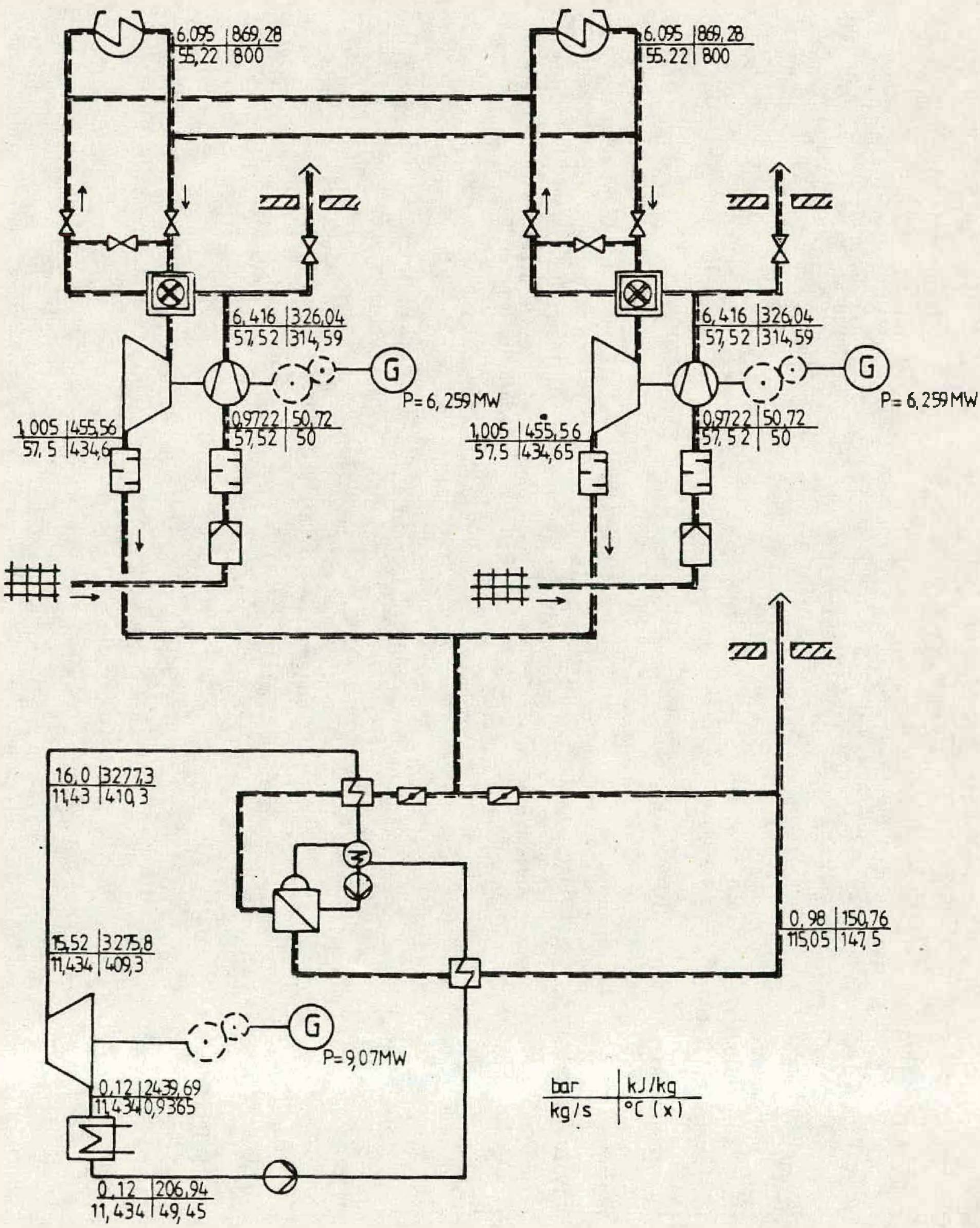
CRITERIA OF SELECTION

Cycle (Fig. 1)	a Steam	b Open GT-cycle	c Closed GT-cycle	d Open GUD-cycle
Economy				
Receiver output MW		6o		
Net cycle output MW	2o,o	2o,1	2o,7	21,6
Net cycle efficiency %	33,4	33,5	34,6	36,o
Investment cost	High	Low	Medium	Medium
Technology		Conventional		
Typical components	Boiler Feed water preheating Make-up water system	Intermed.cooler Recuperative preheater	Precooler Intermed. cooler Recuperative preheater	Waste heat recov. boiler Steam turbine Make-up water sytem
Operation				
load variation	Steam mass flow Pressure and temperature	GT-inlet temperature	GT-inlet temperature Cycle pressure level	GT-inlet temperature
		Alternative control with fossil fuel		
Start-up	Long	Short	Medium	Short
Availability		High		
Water requirement	High	Low	Low	Medium

GAST
THERMAL SCHEME

Reference design of a GUD-plant
scheme of a plant with two gas turbines

FIG. 2



Reference design of a GUD plant main plant data

Gas turbine:

Manufacturer	KWU
Type	V4
Number of units in the plant	2
Turbine inlet temperature	8oo°C
Net unit output	6,25 MW
Air mass flow	57,5 kg/s
Turbine outlet temperature	435°C

Steam turbine:

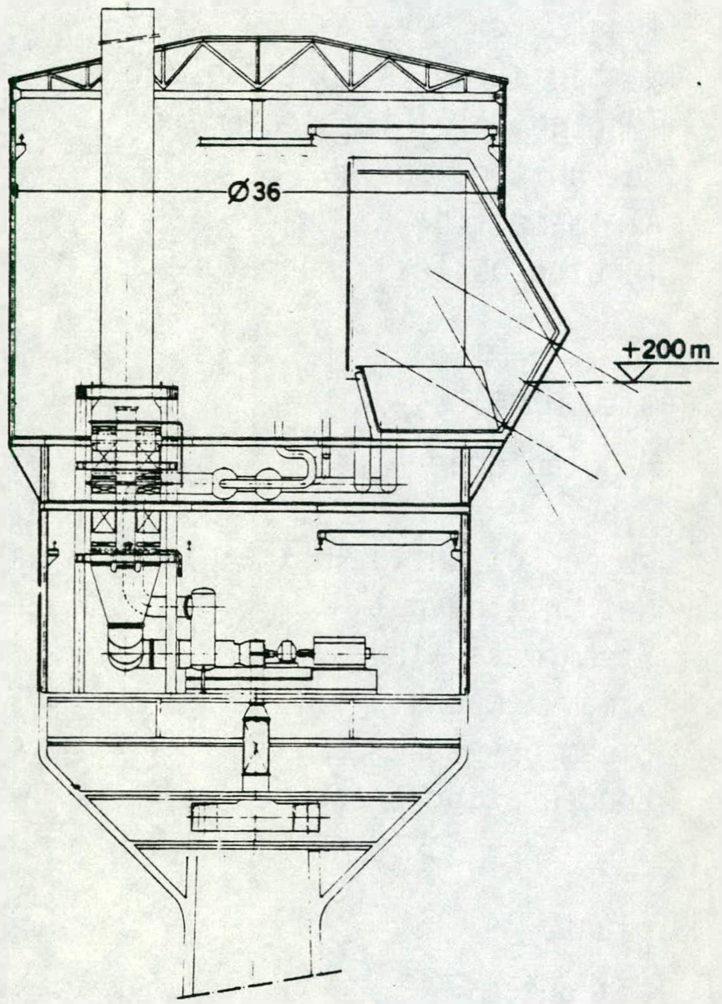
Manufacturer	Siemens
Type	EHNK
Number of units in the plant	1
Net unit output	9,1 MW
Steam mass flow	11,4 kg/s
Steam temperature	4o9°C
Steam pressure	15,5 bar
Condensation pressure	o,12 bar

GUD plant:

Net output	21,6 MW
Net efficiency	36 %

Tower turret
with GUD-plant equipment

FIG. 4



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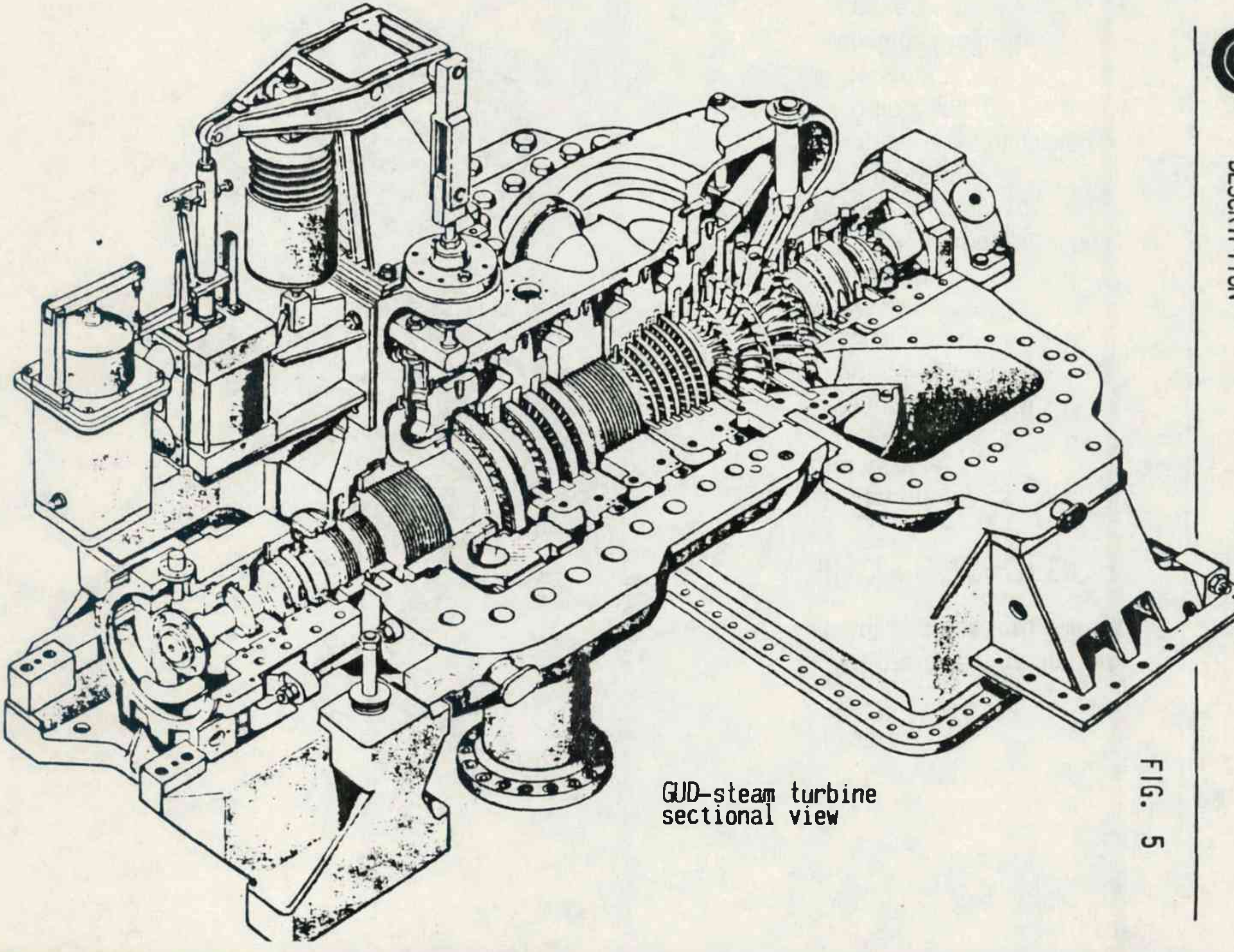

GUD-steam turbine
sectional view

FIG. 5

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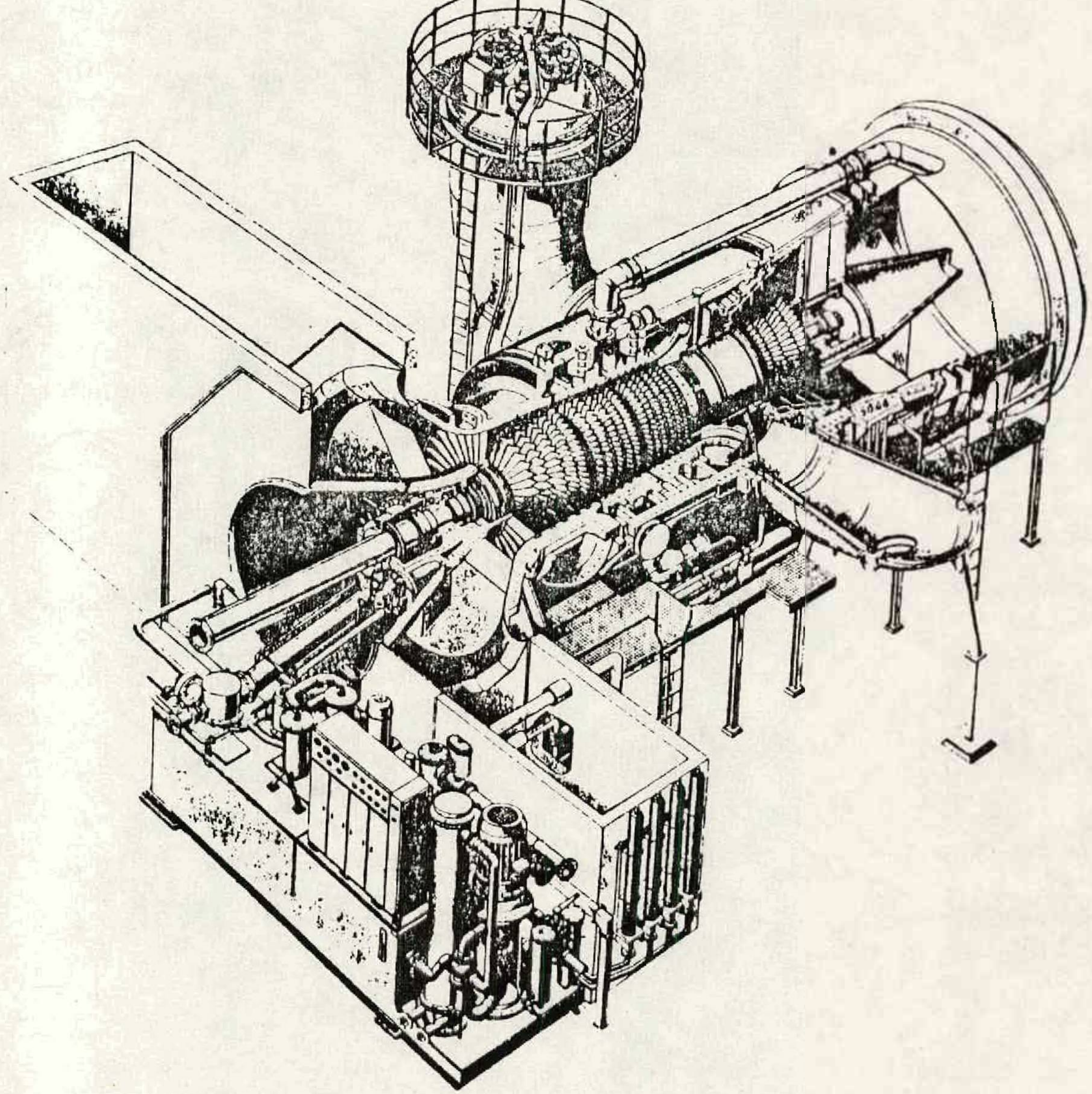
GAST
DESCRIPTION



KWU basic requirement for steam and gas turbines:

HEAVY DUTY DESIGN

Design principles for gas turbines

- Single shaft with only two bearings
- Front end drive
- Easy and quick inspections (large combustors)
- Long life time for all hot gas path components including combustors
- Horizontal split casings facilitate major overhauls

FIG. 6

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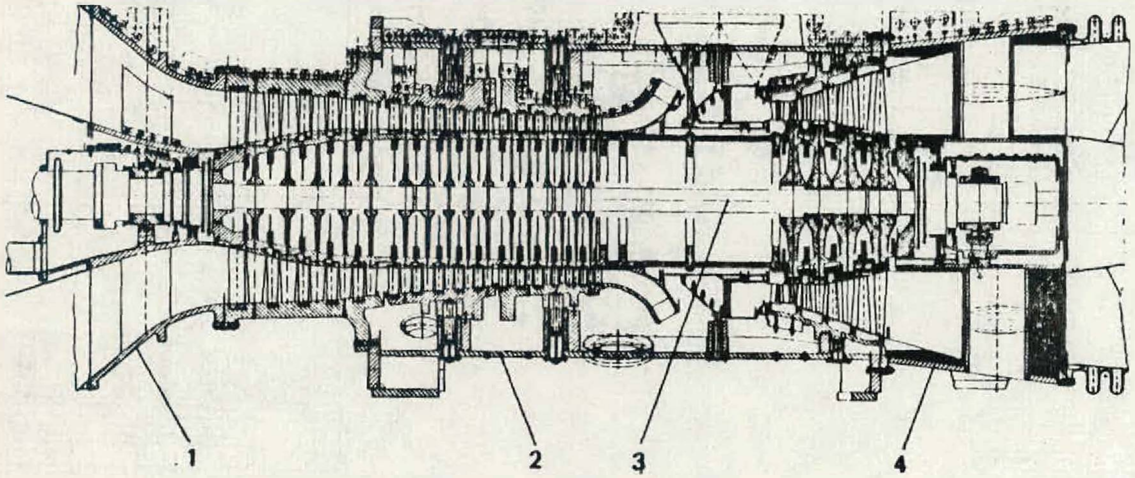
GAST
DESCRIPTION

Gas Turbine
Longitudinal Section



1 Compressor Bearing Housing
2 Centre Section with Stator Blade Carner
3 Compressor and Turbine Rotor With Central Rod Tie
4 Exhaust Casing with Rear Bearing

FIG. 7

Gas Turbine
Arrangement of Combustion Chambers

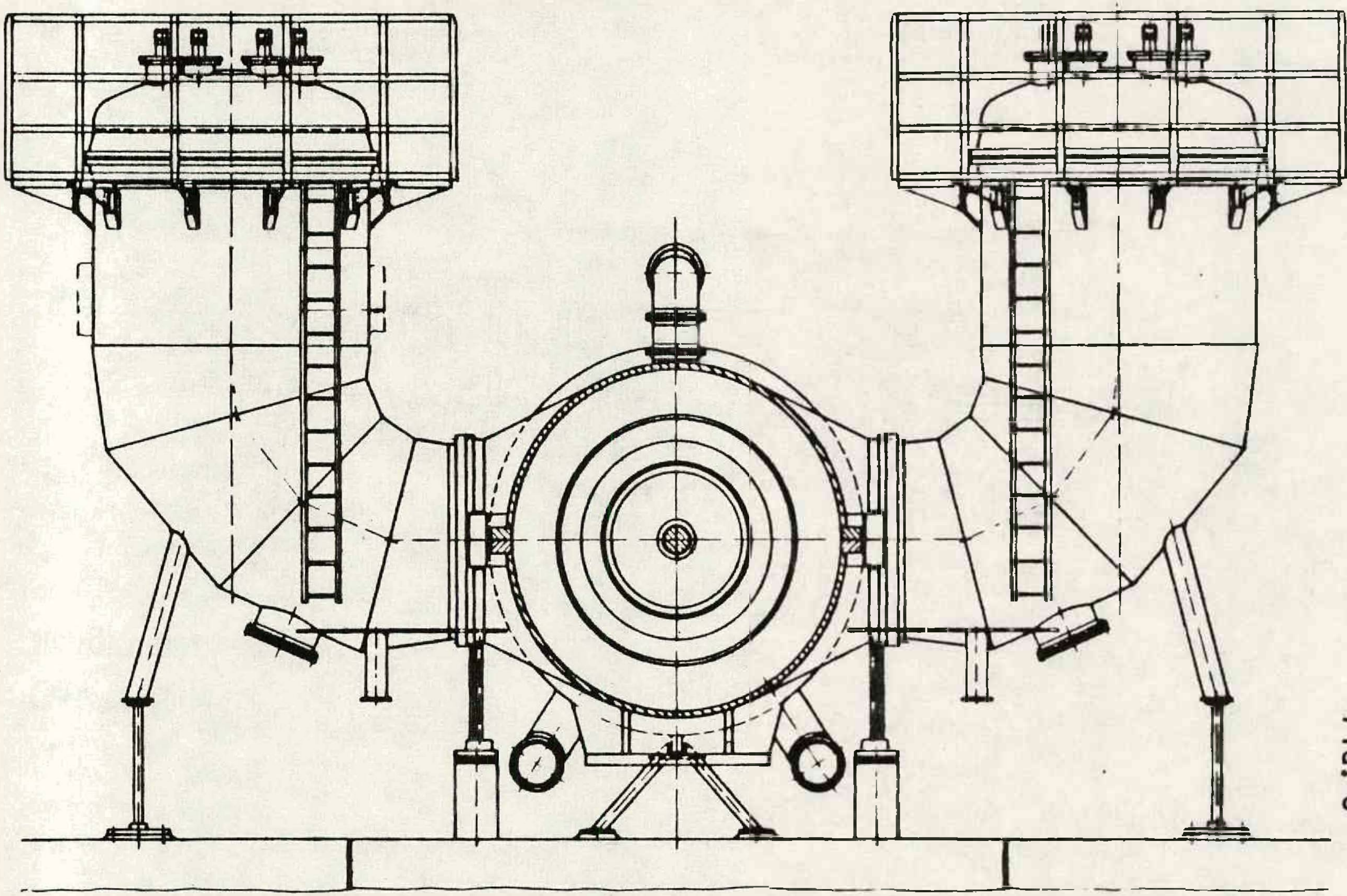
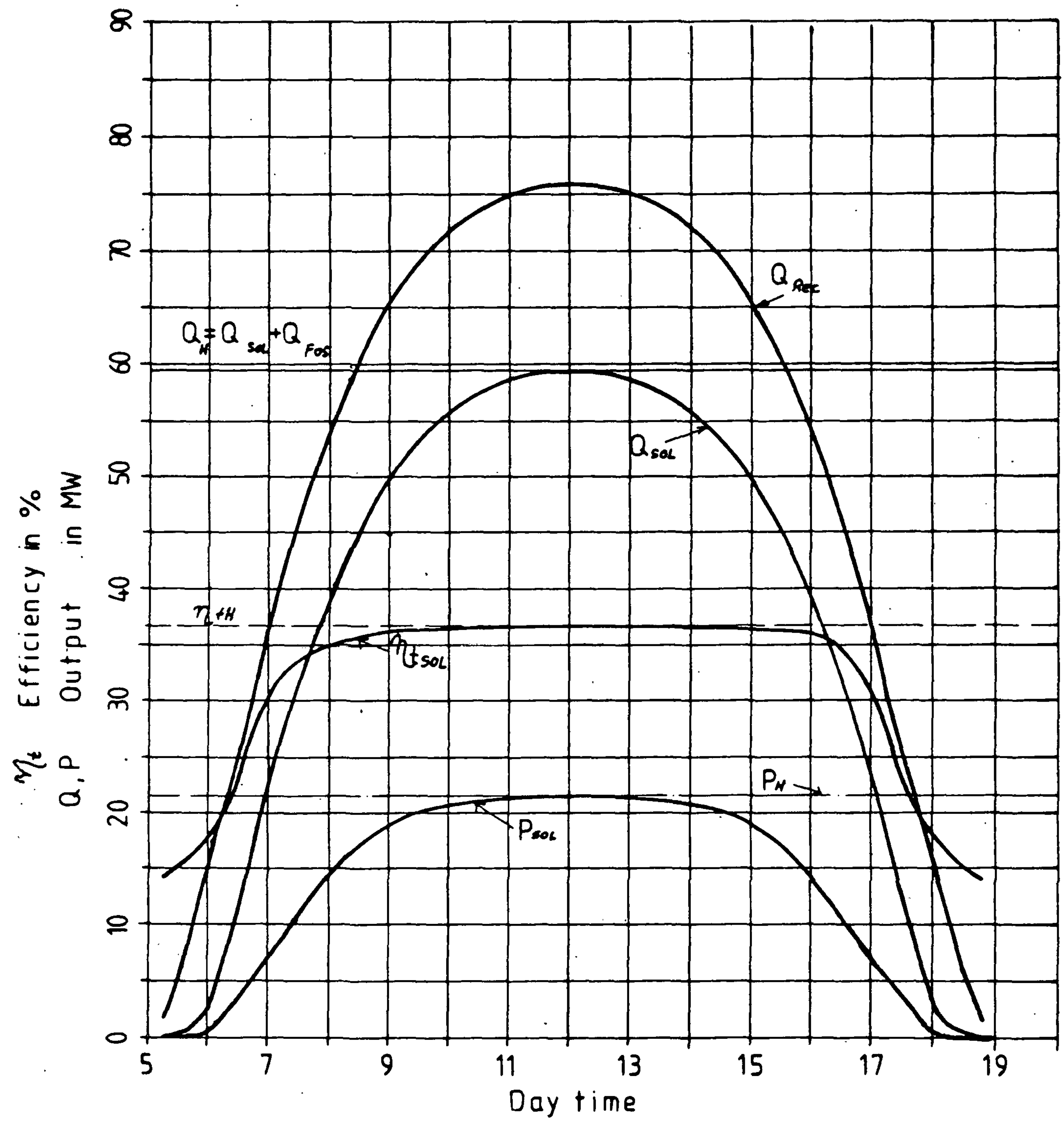


FIG. 8

GAST
OPERATION

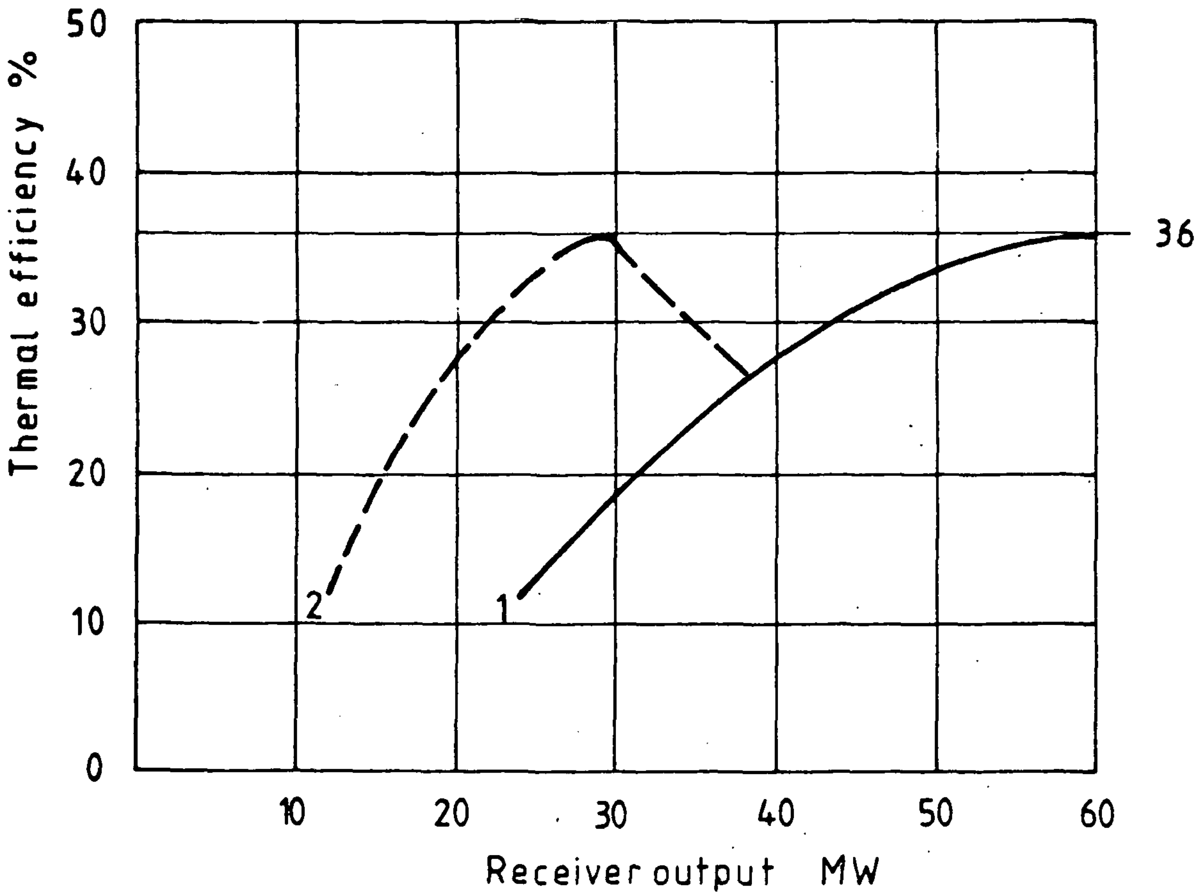
Reference design - fig. 2 | Index | FIG. 9

50° C	0,0 m NN, 21. June	Rec	Receiver
Q	Thermal energy input	Sol	Solar
P	Unit output	Fos	Fossil
η_t	Thermal efficiency	H	Hybrid



Cycle thermal efficiency versus receiver heat output

FIG. 1o



1. GuD - Single - Pressure system - One gasturbine
2. GuD - Single - Pressure system - Two gasturbines

Start-up diagram (hot start) FIG. 11