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Industrial Closed-Cycle Gas Turbines for Conventional and Nuclear Fuel

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Development reports on closed-cycle gas turbines (CCGT) as proposed by Ackeret and Keller (AK system) and promoted mainly by Escher Wyss Ltd., Zurich, Switzerland, and Gutenhoffnungshütte (GHH), Germany, have been presented since 1945 at ASME meetings about every five years (1).[1] This, the sixth paper, reports on the operating experience with some newer fossil-fuel fired plants made by different manufacturers and gives the study results of European designers for nuclear gas turbines which can be built already with today's technology for the 600 to 1000-Mw range. The special physical properties of air and helium and their influence on plant design are discussed. The combination of a CCGT and a high-temperature reactor offers many possibilities for simplifications of nuclear plants and lowering capital costs.

[1]Numbers in parentheses designate References at the end of the paper.

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C. KELLER D. SCHMIDT

THE CLOSED CYCLE AND THE TOTAL-ENERGY CONCEPT

In many modern thermal plants not only the thermodynamic cycle efficiency and the conversion of heat to mechanical work are important but also the total energy delivered in the form of mechanical work plus useful heat. Most closed air cycles are designed as "power and heating station" in the power range of 2000 to 30,000 kw (see Table 1 and Figs.1, 2, 3). Waste heat from a gas cycle is available at a much higher and directly useful temperature level than that from steam cycles. Gas cycles show quite outstanding properties, being able to work from full load to a very low load with good efficiency (at constant full temperature before the turbine) and follow easily the heat and temperature requirements of a hot-water distribution network independent of electric efficiency. The total energy delivered can amount to about 85

Plant		Ravensburg Germany	Toyotomi Japan	Coburg Germany	Kashira Russia	Nippon Kokan Japan	Oberhausen Germany	Haus Aden Germany	Dye Oxygene Phoenix Arizona,USA	Gelsen-kirchen Germany
Manufacturer		EW Ltd.+ GHH Ltd.	Fuji Electric EW Ltd.	GHH Ltd.	EW Ltd.	Fuji Electric	GHH Ltd.	GHH Ltd.	EW Ltd. + LF Corp.	GHH Ltd.
Use		Power + Heat	Power	Power + Heat	Power + Heat	Power	Power + Heat	Power+ Heat +Turbo Compressor drive	Cryogenic Helium Cycle	Power + Heat
Fuel		Bituminous Coal	Natural Gas	Bituminous Coal	Brown Coal	Blast Furnace Gas	Bituminous Coal	Mine Gas and Bituminous Coal	Natural Gas	Blast Furnace Gas+Oil
OPERATING DATA:										
Continuous output	kW	2 300	2 000	6 600	12 000	12 000	14 300	6 370	—	17 250
Temperature at compressor inlet	°C	20	20	20	20	25	30	20	20	20
Pressure at compr.inlet	ata	7,2	7,2	7,3	7	6,7	8	9,3	—	10,2
Temperature at turbine inlet	°C	660	660	680	680	680	720	680	680	720
Pressure at turbine inlet	ata	27	27	27,5	29	29	32	31	—	38,5
Plant efficiency at generator terminals	%	25	26	28	28	29	29,5	29,5	—	30
Compressor+turbine speed	rpm	12 750	13 000	8 220	6 600	6 600	6 600	8 220	18 000	6 640
Generator speed	rpm	3 000	3 000	3 000	3 000	3 000	3 000	1 500	—	3 000
HEATING WATER:										
Quantity	m^3/h	70	—	110	280	—	325	130	—	200
Temperature at cooler outlet	°C	75	—	100	75	—	90	90	—	95
Temperature at cooler inlet	°C	45	—	40	45	—	40	40	—	40
Amount of heat	Gcal/h	2,1-3,5	—	7-14	8-10	—	16-24	6,7	—	16,9
DESIGN CHARACTERISTICS:										
COMPRESSOR:										
Type		radial	radial	axial+ radial	axial	axial	axial	axial	axial	axial
TURBINE:										
Type		axial	axial	axial	axial	axial	axial	axial	axial	axial
In operation since:		1956	1957	1961	1962	End of 1961	1960	1963	starts end 1966	starts 1967
Running hours up to December 1966 abt.		60 000	57 000	39 000	20 000	30 000	42 000	29 000	—	—

EW Ltd.: Escher Wyss Ltd. Zurich (Switzerland)

GHH Ltd.: Gutehoffnungshütte Sterkrade Ltd., Oberhausen-Sterkrade (Germany)

Fuji Electric: Fuji Electric Kawasaki (Japan)

LF: The La Fleur Corporation, Torrance, Calif., USA

Table 1 List of Some Recent Closed-Cycle Gas Turbine Plants

Fig. 1 Model of new "Gelsenkirchen" (Germany) 17, 250-kw heat-power CCGT plant under construction. Cycle data: Inlet pressure = 38 kg/sq cm; inlet temperature = 720 C; Fuel: blast-furnace gas and oil; Heat production = 17 x 10^6 kcal 68. 10^6 Btu/h). In foreground: Precooler and intercoolers for hot-water production. Recuperator below turbine group

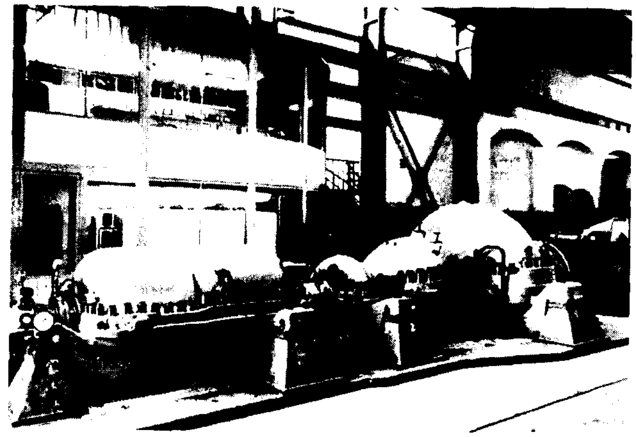


Fig. 2 14, 000 Mw turbine at Oberhausen (Germany) shows simplicity of turbine design without regulating valves at machines. Operation of plant (710 C, 32 kg/sq cm) has reached 42, 000 hr by end of 1966. Automatic plant survey from control room in left background

percent of the total fuel calorific energy content.

Fossil fuels such as brown coal, bituminous coal, oil, natural gas, and furnace gas can be burned as in a steam boiler. Until now a limitation of the upper cycle temperature to about 720 C has been practically determined by the creep resistance of the heater tubes and, in the case of heavy fuel oil, also by the resistance to corrosion. Fig.3 shows the layout of a modern conventional 30 Mw CCGT station. The machine set is the same for an oil, gas, or coal-fired heater. Plant efficiency is 34 to 36 percent, depending on cooling water.

In closed-cycle plants with a nuclear reactor, as discussed later in this paper, the temperature can be pushed to a much higher level, giving a considerable gain not only in efficiency but also in electrical output per unit mass flow of the working medium.

DESIGN OF CLOSED-CYCLE GAS TURBINE WITH REGARD TO CONSTRUCTION MATERIALS OF COMPONENTS

In a smaller part of the cycle the temperature level is high enough to make use of special steels and alloys necessary, i.e., austenitic steels and in some cases alloys on nickel bases.

The tubes of the gas heater, with wall temperatures around 750 C, represent the most costly element; the tubes of the combustion (radiation) section are made of plain austenitic steel or of austenitic steel with higher cobalt or chromium content. The material stress is as low as 2 to 2.5 kg/sq mm, owing to the small tube diameter (1 in.), but a certain margin has to be included for the more or less pronounced agressiveness of the combustion gases. Also heavy fuel oil has been used successfully in continuous industrial service, thanks to the inhibitor effect of dolomite CaMg $(CO_3)_2$ powder injected directly into the combustion chamber. The cost of this additive is practically negligible.

The "hot" pipe between the heater and the turbine is of double-wall design. Hot gas flows through a thin inner tube of austenitic steel separated from the outer pressure pipe by an insulation of mineral wool or a high-pressure cold gas flow.

Owing to the elevated working pressure level, the machines are small. Rotor and blades are forged pieces of austenitic steel and in some cases of Nimonic alloy. No cooled blades have been used until now; the blade serrations of the first turbine stage are slightly cooled by the small sealing gas flow through the HP labyrinth (only about 1 percent of the main flow).

The stress problem in turbine blades is illustrated by Fig.4 which shows the relation between peripheral velocity at the hub, hub ratio, and blade stress. In this diagram the bending stress due to aerodynamic forces has been added to the centrifugal stress. In our closed-cycle gas turbines both stresses are of the same magnitude at full load. In the lower part, at right, stress curves have been plotted, corresponding to 2/3 of the rupture stress. The experience of many years of industrial service has shown that blades are safely designed under this assumption.

SEALING PROBLEMS

Practically no loss of working medium from the cycle into atmosphere occurs, neither in pipe joints nor through the blow-off valve. Even in the glands, losses can be completely avoided, using the oil sealing system according to Fig.5,

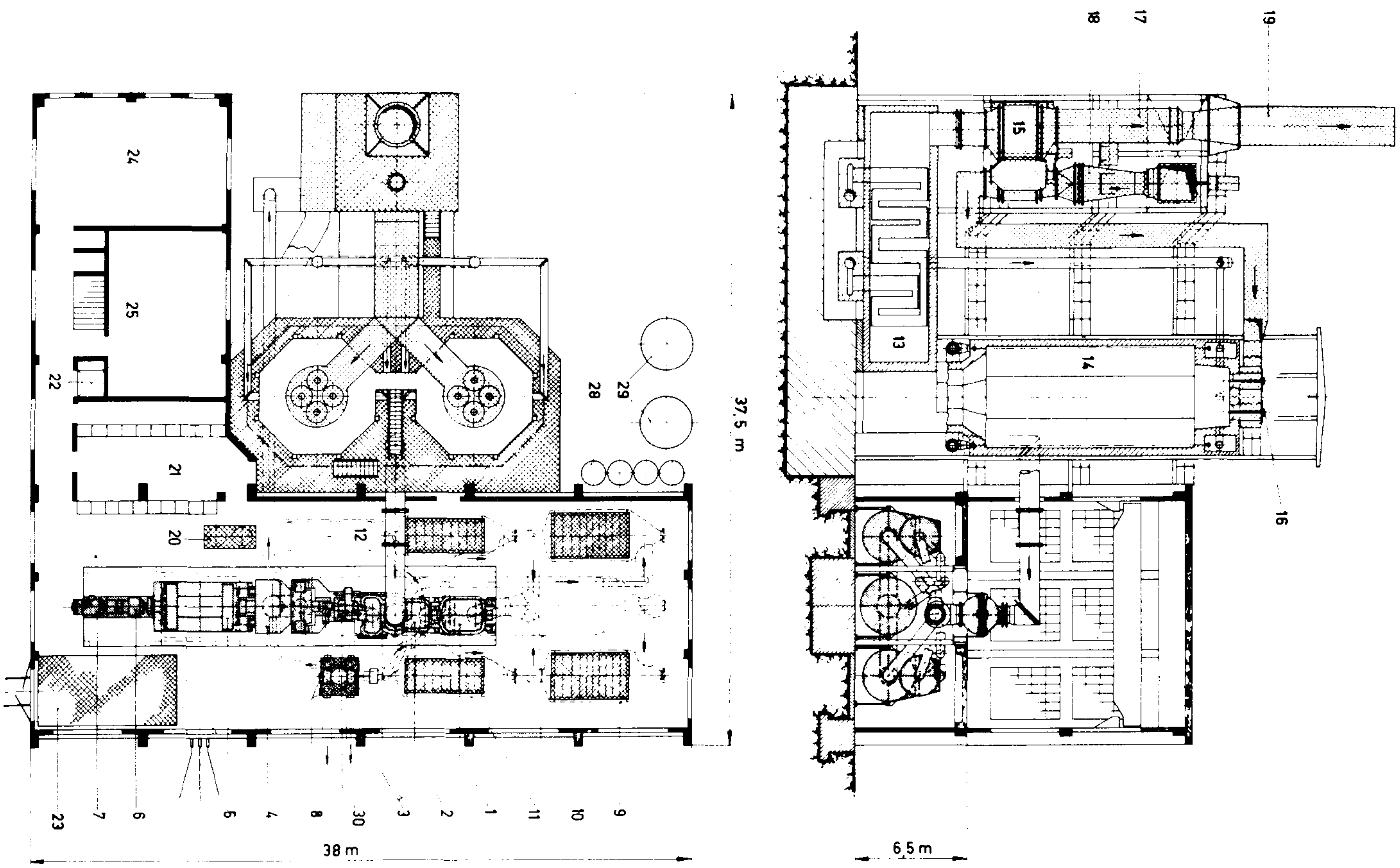


Fig. 3 Layout of modern 30-Mw closed-cycle power station. Oil-fired air heater can be replaced by coal-fired heater without change of layout and with approximately the same volume

1 LP compressor	11 Intercooler	21 Control room
2 HP compressor	12 Lubricating oil tank	22 Elevator
3 HP turbine	13 Air heater (convection)	23 Assembly area
4 LP turbine	14 Air heater (radiation)	24, 25 Machine and assembly shop
5 Generator	15 Combustion air preheater	28 Compressed-air reservoirs
6 Exciter	16 Burner	29 Hot-water reservoirs
7 Starting motor	17 Suction fan	30 Gear
8 Bypass and relief valve	18 Fresh-air fan	
9 Precooler	19 Chimney	
10 Regenerator	20 Oil cooler	

in which we see from left to right the following connections to or from the HP gland:

- A bleed line to the LP compressor suction.
- A pipe for cleaned sealing gas with automatically controlled pressure difference above the LP cycle pressure.
- A gas and oil outlet pipe to a closed tank under the cycle's low pressure.

The rotor bearing is working both as a supporting and sealing element (oil seal).

Oil at atmospheric pressure flowing from the outer side of the bearing is pumped back into the closed tank. In an atomic plant with a helium closed cycle, an additional air separator is provided in this oil line to get rid of the air absorbed by oil.

HELIUM VERSUS AIR AS WORKING MEDIUM FOR LARGER UNITS

In recent years development work for the closed cycle has been concentrated on the two most promising working media, i.e., air and helium. Table 2 shows a comparison of some physical data. With the help of simple relations of thermodynamics, very conclusive practical rules can be drawn from these few figures.

We first assume that the working cycles to be compared for air and for helium must remain simple and show a good efficiency. It follows therefore that the lower and the upper cycle temperatures will be about the same for both cases,

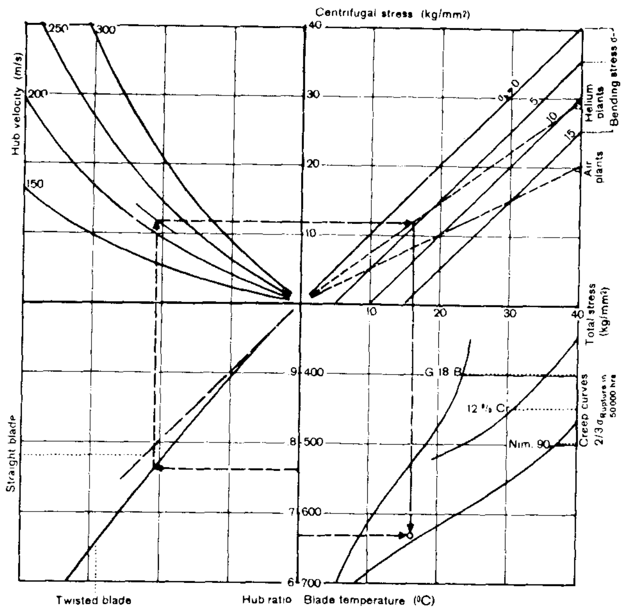


Fig. 4 Diagram for evaluating blade stresses in CCGT

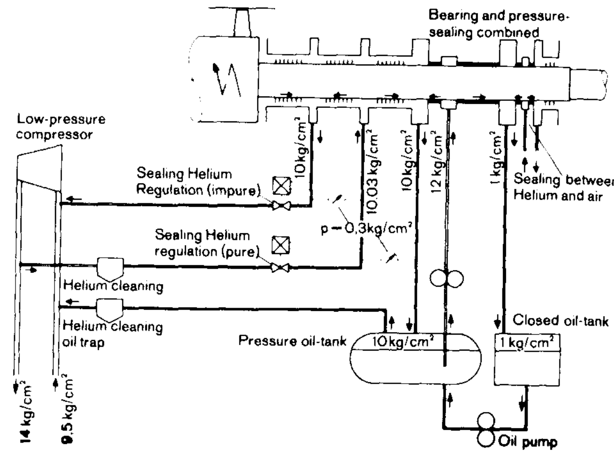


Fig. 5 Schematic of shaft seal for CCGT

as well as the temperature ratio of compressor and expansion.

1 The heat drop being $\Delta i = \Delta T\, c_p$ and the specific heat of helium 5 times that of air, the energy dealt with in the helium machines per pound mass flow will be five times higher.

2 From

$$\pi = \left(\frac{T_1}{T_2}\right)^{\frac{k}{k-1}}$$

where

π = pressure ratio

k = ratio of specific heats

a lower expansion ratio for helium than for air results at a given temperature ratio.

3 According to

$$\frac{V_2}{V_1} = \left(\frac{T_1}{T_2}\right)^{\frac{1}{k-1}}$$

the change of volume is considerably smaller for helium. For example, for an isentropic expansion 720 to 398 C:

With air: The pressure ratio π amounts to 4.4 and the volume ratio amounts to 3.

With helium: The pressure ratio π amounts to 2.66 and the volume ratio amounts to 1.8.

4 The energy losses in pipes, diffusor, and bends leads to a diminution of heat drop in the turbine for a given compression ratio.

If T_2' and p_2' are the outlet figures for the reduced heat drop, we can put

$$\frac{T_2'}{T_2} = \left(\frac{p_2'}{p_2}\right)^{\frac{k-1}{k}}$$

with

$$\frac{p_2'-p_2}{p_2} = \varepsilon = \frac{\Delta p}{p} \quad (\varepsilon = \textbf{relative pressure loss})$$

and assuming the same temperature T_2 and T_2' for air and helium, we get

$$(1+\varepsilon_H)^{\left(\frac{k-1}{k}\right)_H} = (1+\varepsilon_A)^{\left(\frac{k-1}{k}\right)_A}$$

for the same energy loss compared with turbine work.

Because ε is small we can put

$$\left(\frac{k-1}{k}\right)_H \times \varepsilon_H = \left(\frac{k-1}{k}\right)_A \times \varepsilon_A$$

or

$$\frac{\varepsilon_H}{2.5} = \frac{\varepsilon_A}{3.7}$$

Pressure losses are approximately proportional to the dynamic pressure head

$$\varepsilon = a\,\frac{\rho}{2}\,c^2$$

For the same energy loss compared with turbine work we have, therefore, from

$$\frac{\varepsilon_H}{\varepsilon_A} = \frac{2.5}{3.7} = \frac{\rho_H \cdot c_H^2}{\rho_A \cdot c_A^2}$$

$$c_H = \sqrt{7.2/1.48} = 2.2\, c_A$$

Therefore, with the foregoing assumption, a velocity of 25-45 m/s in the pipes of an air closed cycle corresponds to a velocity of 55-100 m/s in a helium closed cycle for equal percentage loss of energy.

If we consider that for the same temperature ratio, helium yields 5 times more work per unit mass flow, we find for plants of the same output the necessary section to be smaller for helium than for air (at the same pressure), with the ratio

$$\frac{2.2 \times 5}{7.2} = 1.53 \qquad \text{(7.2 being the density ratio } \rho_A/\rho_H\text{)}$$

At the LP side of the helium cycle the flow section will be further reduced owing to the higher pressure level in comparison to the air cycle.

Unquestionably, helium is an adequate working medium for closed-cycle plants of large output, as illustrated by the rather small dimensions of machines up to 600 Mw, Figs.12 to 15.

5 The shock-wave velocity (velocity of sound) in helium $(gkRT)^{1/2}$ is 3 times higher than in air and therefore the Mach number does not limit the peripherical speed of the compressor runner blades, as is the case in air. However, owing to stress considerations, the speed cannot be raised more than by a factor of about 1.5 to 2. On the other side, c_p being 5 times bigger, the difference of enthalpy Δi in the compressor is also 5 times larger and therefore the total number of compressor stages for similar load coefficients will be bigger by a factor of about

$$\frac{5}{1.5^2} = 2.2 \text{ to } \frac{5}{2^2} = 1.25$$

6 The surface of heat exchangers is highly influenced by the nature of the working gas. For comparable helium and air cycles, with the same temperatures and the same useful output, the same amount of heat has to be transferred, in the recuperator as well as in the coolers. If the same temperature drop is assumed, the surface will be simply inversely proportional to the heat-exchange coefficient α. According to Krausold, α is given by the relation

$$Nu = \frac{\alpha d}{\lambda} = 0.024 \times Re^{0.8} \, Pr^{b}$$

$$[\text{with } 0.31 < b < 0.37]$$

where

Nu = Nusselt number
Re = Reynolds number

		Air	Helium
Molecular weight		29	4
Specific Heat c_p	1 ata 20°C	0,24	1,242 kcal/kg°C
	30 ata 600°C	0,267	1,242 "
Adiabatic Coeff. k	1 ata 20°C	1,4	1,665
	30 ata 600°C	1,36	1,665
Conductivity α	1 ata 20°C	0,022	0,127 kcal/m°C hr
	30 ata 600°C	0,05	0,27 "
Dynamic Viscosity η	1 ata 20°C	$1{,}85.10^{-6}$	$2{,}0.10^{-6}$ kgsec/m^2
	30 ata 600°C	$4{,}0\ .10^{-6}$	$4{,}24.10^{-6}$ "

Table 2 Physical Properties of Air and Helium

The velocity of helium can be taken as, according to paragraph 4, up to 2.2 times the velocity in the corresponding air heat exchanger.

With this factor and the physical data of Table 2 for

$$Re = \frac{cd\rho}{\eta}$$

where

d = diameter
ρ = density
η = viscosity

we get

$$\frac{Re_{He}}{Re_{Air}} = \frac{2.2}{7.2 \ 1.07} = 0.29$$

and

$$\left(\frac{Re_{He}}{Re_{Air}}\right)^{0.8} = 0.37$$

The influence of Pr, being here smaller than 1 percent, can be neglected, and it remains

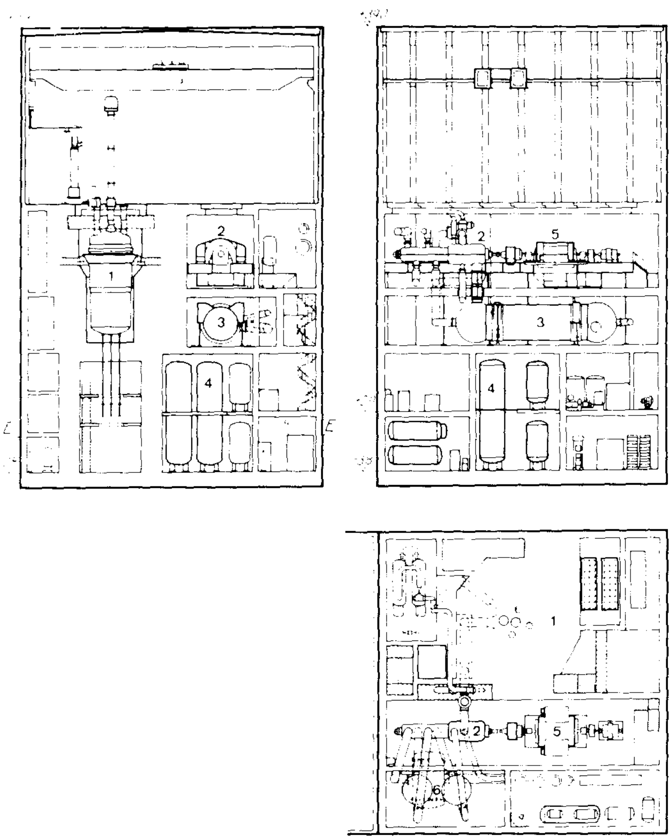
$$\frac{\alpha_{He}}{\alpha_{Air}} = \left(\frac{Re_{He}}{Re_{Air}}\right)^{0.8} \frac{\lambda_{He}}{\lambda_{Air}} = 0.37 \times 5.5 = 2.04$$

That means that the recuperator surface in the helium cycle theoretically will be 2.04 times smaller than in the air cycle.

Practically, the flow path being much shorter, the helium velocity can be increased further without undue energy losses and the surface ratio lowered to about 1/3.

THE NUCLEAR CLOSED-CYCLE GAS TURBINE

Since the successful start and operation of high-temperature gas-cooled (helium) reactors such as "Dragon" (England), "Peach Bottom" (U.S.A.), and BBC/Krupp (Germany) last year, it has become obvious that this new heat source for thermal machines is most promising for gas turbine opera-



1 HT reactor 3 Recuperator 5 Generator
2 Gas turbine 4 Helium container 6 Intercooler

Fig. 6 25-Mwe nuclear prototype plant with high-temperature helium-cooled reactor and CCGT. Designed in 1966 by Gutehoffnungshütte (GHH) and Escher Wyss. Temperature T = 730 C, pressure = 25 kg/sq cm, plant efficiency = 37 percent

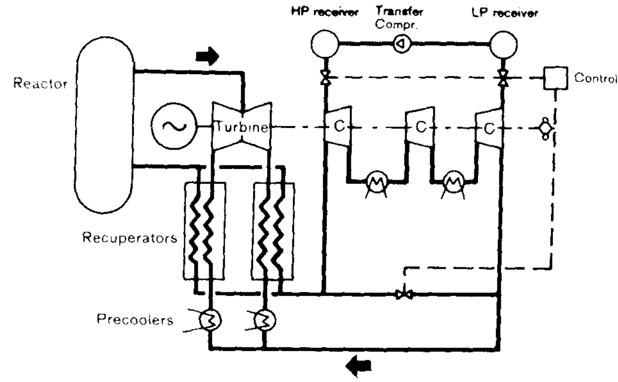


Fig. 7 Schematic for 600-Mw nuclear CCGT plant with HTR

tion. Also, the earlier small 300-kw set of the U.S.Army (ML-1)--really the first operating nuclear power plant with a gas turbine (nitrogen) --pointed in this direction (2). The outlet temperatures of all the reactors' cooling gas is above 750 C and reactor builders do not see any barrier to achieve 850-1000 C without any significant change of design (3). In the U.S.A. a pioneer reactor for even as high as 1300 C outlet (UHTREX, Los Alamos) is already under development.

A strong incentive to use high-temperature reactors as a perfect heat source for gas turbines exists in the form of small pyrolitic-coated particles. These new fuel elements for high-temperature reactors make the danger of gas-stream activity and contamination practically nonexistent. Therefore, the earlier proposed two-loop systems (e.g. gas cycle/steam cycle) can be much simplified to a direct-cycle system using the pressurized cooling gas of the reactor directly as the working medium for a closed-cycle gas turbine. It is our belief that such systems will not only have higher efficiencies than today's water reactor/steam stations but will be simpler in operation and more compact.

The helium gas turbine is much smaller than a steam turbine for the same output. The simpler gas turbine can lower capital costs, which is decisive for unit electric costs.

This system is the base of a recent proposal by Gutehoffnungshütte (GHH) and Escher Wyss for a 25 Mwe industrial prototype plant (7) of which some data are given in Fig.6. Such a solution already had been anticipated by Ackeret and Keller a long time ago (4). The technological and metallurgical development in the last ten years together with the vast experience gained in fossil-fueled closed-cycle gas turbine plants offer now a sound technical basis to build the gas turbine as a prime mover for atomic power stations.

Different gases, such as helium, argon, carbon dioxide, nitrogen, or mixtures of them, are available for the design. Combined studies of reactor physicists and turbine builders have led to the conclusion that helium as a working medium is the preferable choice, both from the nuclear physicists' and the mechanical engineers' point of view. The use of gases such as nitrogen or carbon dioxide results in somewhat simpler machines and less stages, but on the other hand asks for much bigger heat-transfer surface in coolers and recuperators. Thermodynamically, nothing can be gained in plant efficiency with a specific gas, when taking into account all the cycle losses involved. Therefore, all recent studies of different designers have concentrated on the use of helium (7,8).

Most gas turbine builders still do not seem to have realized that helium closed-cycle gas turbines can be built without departure from known techniques from very small outputs of a few hundred kw up to 600 Mw and more in one machine set. There is practically no limit for unit outputs. Such plants may work according to the schematic in Fig.7 and the corresponding entropy chart, Fig.8.

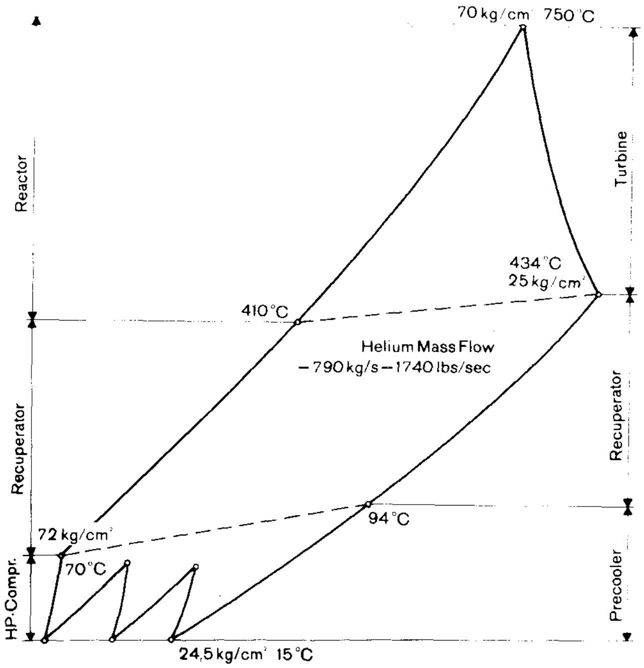


Fig. 8 Approximate entropy diagram for helium cycle in nuclear plant

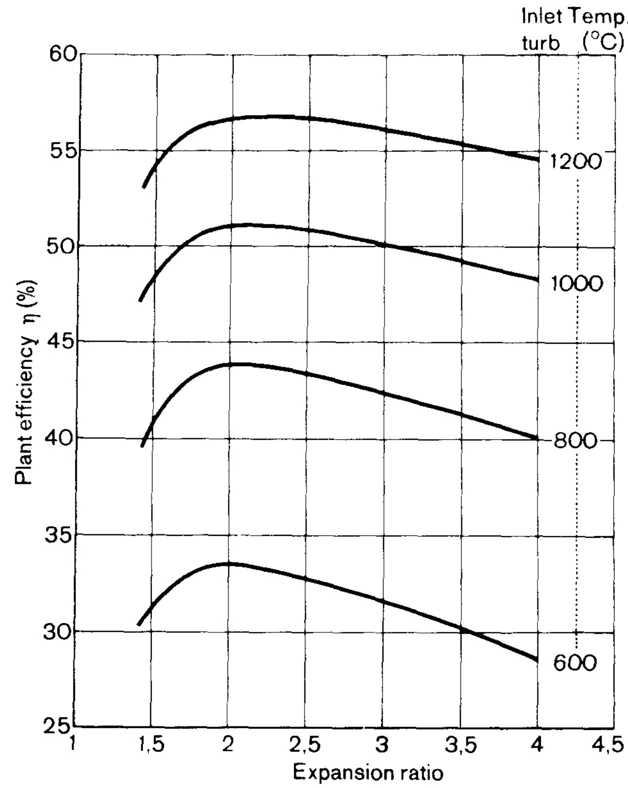


Fig. 9 Overall plant efficiencies of CCGT-HTR nuclear stations as function of turbine expansion ratio (all losses included)

As--contrary to steam cycles--circuit efficiencies are independent of pressure level, most suitable working pressures can be chosen freely to give favorable dimensions. Even in the future very high unit outputs over 600 Mwe, a maximum working pressure of about 70 kg/sq cm (1000 psi) will not be exceeded.

The last Gas Turbine Division Meeting in Zurich, March 1966, has, for the first time, shown a great number of closed-cycle gas turbine proposals from U.S. designers also. Many studies for space applications and in chemical processes are under way; but all the U.S. studies delt with installations below 2000 kw. Contrary to this, today's European studies deal mainly with power stations and ship propulsion plants in the medium and high output ranges comparable with steam plants. Only the earlier 23,000-shp closed-cycle plant by General Atomics is similar to such projects (Maritime Gas-Cooled Reactor Program MGCR 1960) (5).

When it became certain that high-rated gas-cooled reactors would be available in the near future, the feasibility designs for gas turbine application in combination with such reactors were intensified, especially in Switzerland (Escher Wyss, Brown Boveri), in England (Rolls Royce, National Gas Turbine Establishment) and in Germany (GHH = Gutehoffnungshütte).

Today's generally agreed-upon conclusions and the special plant and cycle properties are the following:

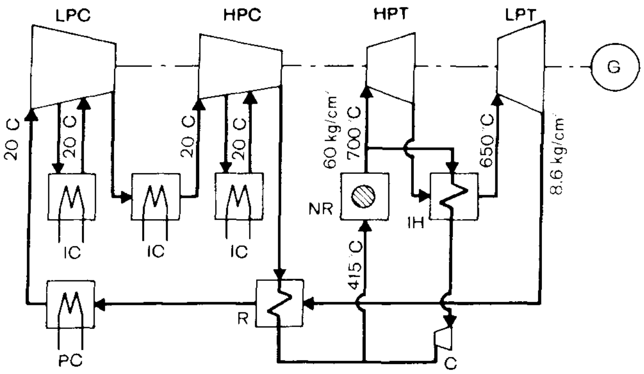
1 Helium is a very suitable gas both from the reactor builders' and the turbine builders' points of view.

2 At present, with 750 C maximum temperature, overall plant efficiencies of 37 to 43 percent according to size can be reached without complex cycles. Intermediate heating would add another 3-4 points. Future temperature rise will have very pronounced effect towards higher efficiencies.

3 Load variation by pressure-level control at constant working temperature leads to a high efficiency for part load also. No regulating valves at machine bodies and in elevated temperature ranges are necessary.

4 The pressure-level regulation also can be applied to reactor output variation at constant temperature. Nuclear plants with gas-cooled reactors and gas turbines can be built as power stations for varying load demands for small, medium, and very large outputs, just as can conventional thermal plants. Restrictions to base-load service such as with today's water reactors are nonexistent.

5 Combined power and heat production as in conventional closed-cycle plants using the waste heat from the cycle coolers can also be applied to nuclear sets. Total-energy installations look especially promising also from the economical point of view.



NR = High Temperature-Reactor

IH = Intermediate reheat

R = Regenerator

PC = Precooler

IC = Intermediate cooler

HPT = HP-Turbine

LPT = LP-Turbine

LPC = LP-Compressor

HPC = HP-Compressor

C = Circulator

G = Generator

Fig. 10 Schematic for reheat CCGT — nuclear plants

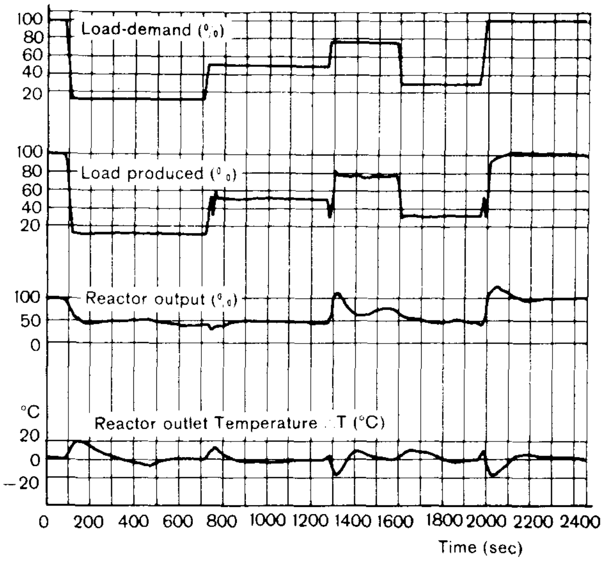
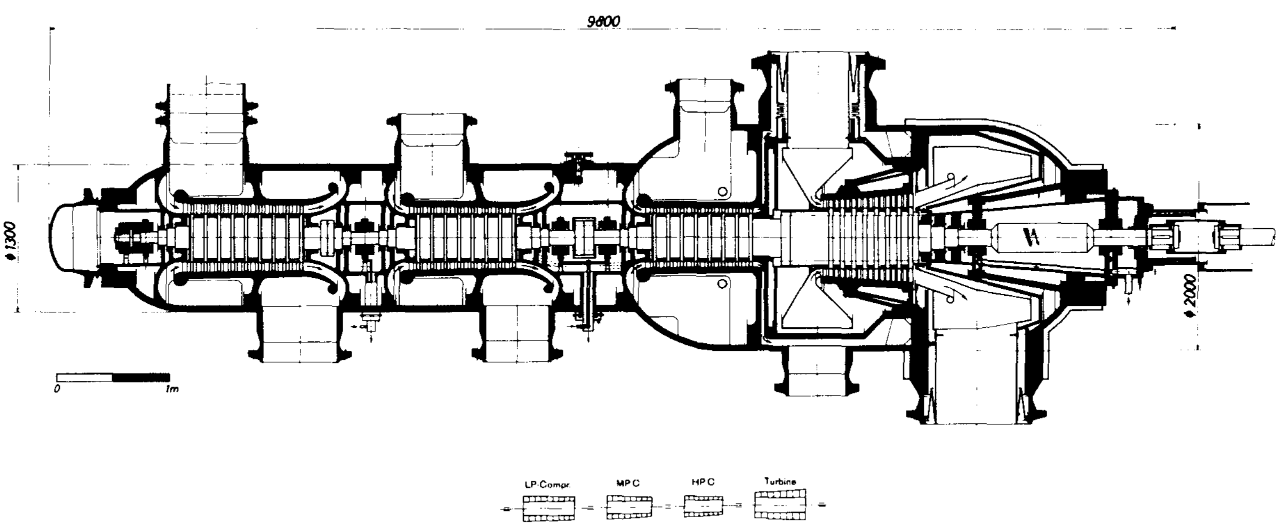


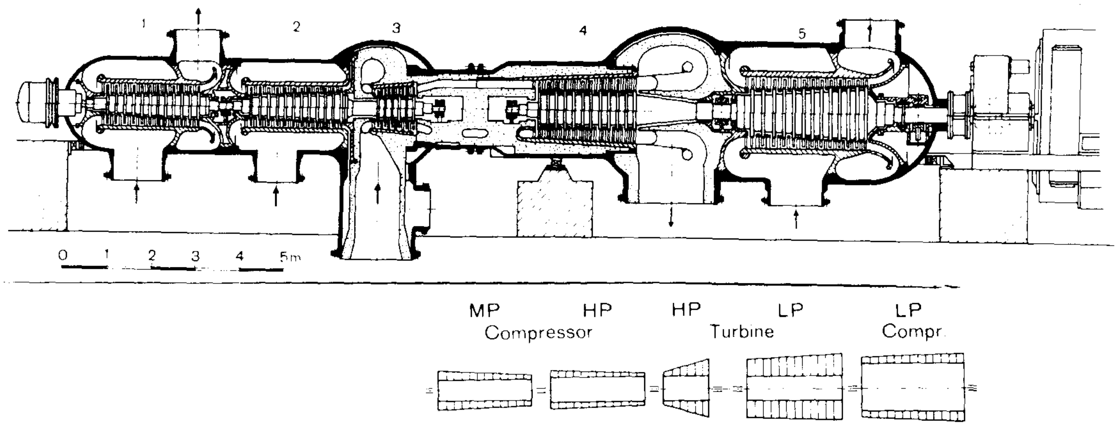
Fig. 11 Variation of reactor outlet temperature with load changes



	LP-Compr	MPC	HPC	Turbine	
Max.Diam.	615	575	545	800	mm
Number of stages	9	8	8	8	
Max. blade length	95	75	60	130	mm
RPM	10'000	10'000	10'000	10'000	

Inlet pressure	25 kg/cm^2 = 360 psi
Inlet temperature	750°C = 1380°F
Outlet pressure	8,5 kg /cm^2 = 120 psi
Outlet temperature	443°C = 830 psi

Fig. 12 Cross section of 25-Mw helium CCGT with main data



	MP Compr.	HP Compr.	HP Turb.	LP Turb.	LP Compr.	
Max. Diam.	900	900	1000	1600	1600	mm
Number of stages	12	12	6	12	13	
Max. blade length	130	90	160	200	125	mm
RPM	6000	6000	6000	3000	3000	

2 Regenerators Diam. 2,5 m

Inlet pressure	50 kg/cm^2
Inlet temperature	700^{o}C
Counter pressure	18 kg/cm^2

LP-Turbine

Inlet temperature	580 ^{o}C
Outlet temperature	406 ^{o}C
Mass flow	160 kg/sec

Fig. 13 Cross section of 100-Mwe helium CCGT with main data

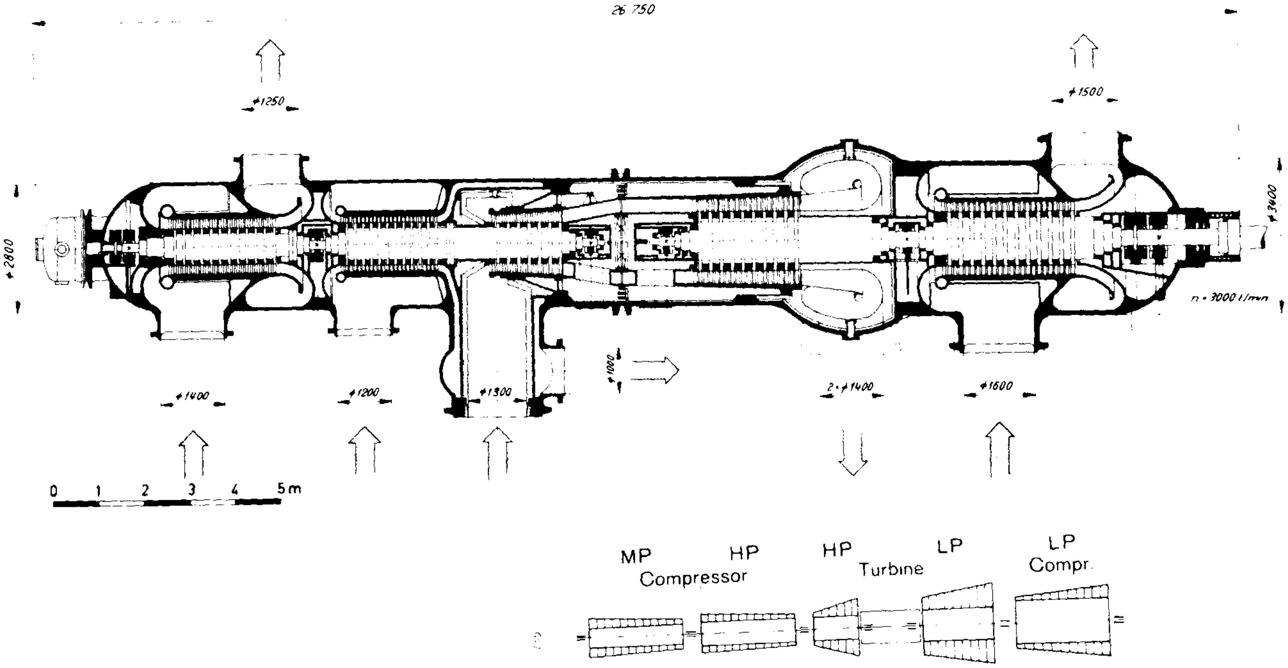
6 Dimensions of helium machinery are much smaller than comparative steam turbines. Working pressures are lower too, 1000-psi maximum even for very large output. Closed-cycle gas turbine application to gas-cooled reactors make reactor circulators superfluous. There is no danger of corrosion or erosion as in steam turbines.

7 As danger of explosion or of steam leaking from the secondary cycle into the primary gas-coolant reactor cycle is not present, safety is improved.

8 The cooling water requirement is small, only 1/3-1/5 of a comparative steam turbine plant.

9 Use of an inert working gas such as helium prevents oxidation. Therefore, materials such as molybdenum alloys with high stress properties at elevated temperatures above 1000 C, which cannot be used in an oxidizing atmosphere, can be applied for turbine design. This opens the way to elevated plant efficiencies of over 50 percent, never attainable with steam cycles.

The special properties of the closed-cycle



	MP Compr.	HP Compr.	HP Turb.	LP Turb.	LP Compr.	
Max. Diam	1220	1220	1400	1940	1620	mm
Number of stages	12	12	7	10	12	
Max. blade length	200	145	260	280	210	mm
RPM	4200	4200	4200	3000	3000	

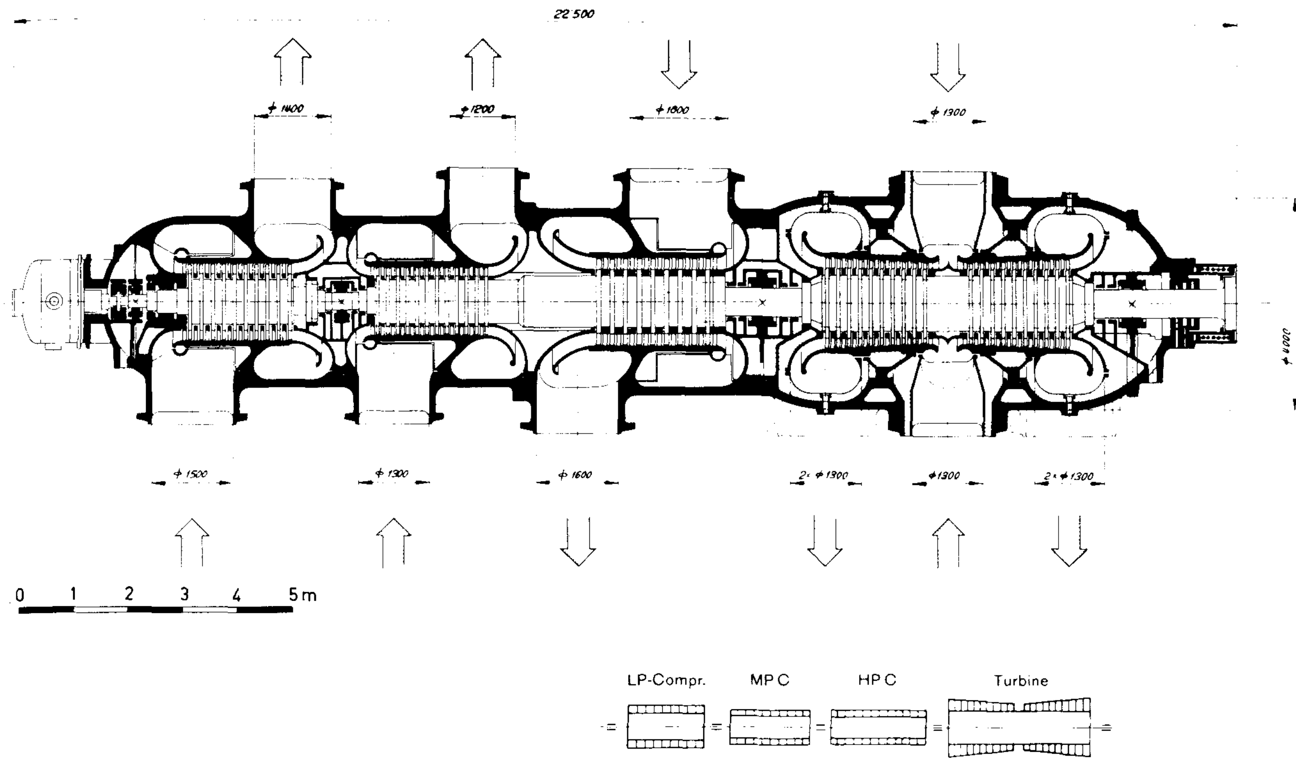
HP-Turbine

Inlet pressure	60 kg/cm^2
Inlet temperature	700 ^oC
Counter pressure	22,3 kg/cm^2

LP-Turbine

Inlet temperature	580 ^oC
Outlet temperature	406 ^oC
Mass flow	400 kg/sec

Fig. 14 Cross section of 250-Mwe helium CCGT with main data



Anordnung:		LP Compr.	MP Compr.	HP Compr.	Turbine
Max. Diam		1664	1463	1308	1744 mm
Number of stages		9	10	12	2 x 10
max. blade lehgth		233	205	183	222
RPM		←---------- 3600 ------------→			
Turbine pressure	- inlet 71 kg/cm^2				
	- outlet 25 kg/cm^2				
Temperature	- inlet 750 °C				
	- outlet 435°C				
Massflow	780 kg/sec				

Fig. 15 Cross section of 600 Mwe helium CCGT with main data

system are illustrated and summarized in the following paragraphs, together with some comments on the different points of the foregoing list.

To Point 1: The decisive characteristics of helium use have been explained in detail in the foregoing paragraphs. The main advantages for the gas turbine builder are the following:

Pure helium does not get activated when passing through the reactor. It has very good heat-transfer properties (many times better than air), leading to small heat-exchanger surfaces. Large output per unit mass flow together with allowable higher permissible stream velocities result in smaller flow sections than with air.

The velocity of sound is about three times higher than in air; therefore, very high circumferential velocities of turbomachines can be chosen without running into Mach troubles. Helium is cheap and easily available today in liquid or gaseous form.

To Point 2: Fig.9 shows overall plant efficiencies including all losses according to the following data: $\eta_{turbine} = 0.89$; $\eta_{compr.} = 0.85$; $\eta_{mech} = 0.98$; $\eta_{generator} = 0.97$; $\Delta t_{regenerator} = 25^{\circ}C$; total pressure losses $\varepsilon_{tot} = 8$ percent; 2 intercoolers; 1 stage expansion.

Intermediate turbine heating could be applied, e.g., according to Fig.10, adding another 3-4 points to efficiency. Gas is reheated by split-stream. The intermediate heater (IH) is small because of good heat transfer. Circulator C needs only a few percent of plant output.

To Points 3 and 4: The constant working temperature at all loads is most favorable to safety of operation, both for the reactor as well as for the mechanical parts, as no deformations occur once the plant is heated up. During load variation with a combined bypass and pressure-level control system, the reactor outlet temperature (750 C) can be kept practically constant. Fig.11 for example, shows that this plant control system creates only very small temporary changes in reactor outlet temperature ($\pm$ 20 deg C) even when load changes are abrupt and heavy. No steam or water reactor can respond to such requirements.

To Point 5: Heat at a high and directly useful level (70-150 C) is available as in conventional closed-cycle plants. For each Mw of electricity about 4 to 8.10^6 Btu/h can be used for heating purposes (total-energy plants) or desalting without influencing thermodynamic cycle efficiency (electrical production).

To Point 6: Figs.12 to 15 show the still mostly unknown fact that closed-cycle helium gas turbines of very different unit outputs can be built now with today's turbine technique. These designs work with an inlet temperature of 750 C as already offered by today's gas-cooled reactors. Assumed operating hours and design is for 100,000 hr.

Up to about 300 Mwe straight-through flow with only one turbine outlet can be achieved at 3000 rpm. For big outputs such as 600 Mwe and above, a double-outlet turbine of 3000 or 3600 rpm is favored owing to larger mass flow and thrust balancing.

Blade stresses for large sets are not exceeding 15-20 kg/sq mm in the top-temperature stages. Low-pressure blades also are not heavily loaded.

Compared with a suitable nuclear steam turbine of the same output (e.g. 250 mw), the maximum tip diameter of the closed-cycle turbine is less than 1/3, the blade length is less than 1/5, and, therefore, centrifugal force of one blade is much smaller, as is also the total length of the whole set. These favorable dimensions of helium turbines are the result of the small expansion ratio (π = 2.5 to 3) and the corresponding small specific volume change compared with π = 1500-6000 for a steam turbine. In order to handle the very big volumes at the outlet of a nuclear steam turbine with saturated steam, a 600-Mwe 1500-rpm set requires in addition at least 4 parallel outlets with an outer diameter of about 5.3 meters, compared with about 1.7 meters for a helium double-outlet turbine of 3600 rpm. Steam turbines with 3000 rpm and high outputs need 6 to 8 outlets (9). It can be stated, contrary to many prejudices, that helium machinery is by no means very different from conventional closed-cycle air turbines. This fact is demonstrated by Fig.16.

To Point 7: The inherent safety of a gas-cooled reactor gas turbine plant is acknowledged today. The pyrolitic-coated fuel particles (0.2-0.5-mm dia) prevent all diffusion of fission products in the primary cycle, as most impressively demonstrated in the "Dragon" experiments. Even after a long exposure time to radiation, the graphite tubes containing the fuel particles could be handled and touched without special protection.

All this experience shows that the working cycle and the machinery can be built outside a special containment. Only the reactor needs a primary concrete shield.

The gas turbine is situated near the reactor in a machine hall built as a thin-walled concrete housing, Fig.6. In case of an MCA (maximum credible accident) the total release of the helium content in the closed reactor turbine system would result in a pressure rise of only 4 psi maximum in the building, and the helium could be released without danger through a chimney as its radioactivity would be below the tolerable limit for the surroundings.

To Point 8: As in conventional closed-cycle plants, the great available temperature difference between cooling water and cycle gas between the compressor stages, compared with the small temperature difference for a steam turbine at the condenser, is the reason for the diminished quantity. Air cooling could be used too.

To Point 9: In Fig.17 long-time high-temperature stress curves for different materials are shown. For the same working temperature, molybdenum and other alloys offer about 3 to 4 times better stress properties at elevated temperatures. Such materials already are applied in space techniques and it is certain that they will appear in the near future also in gas turbines for high-temperature service.

This unique possibility of high-temperature

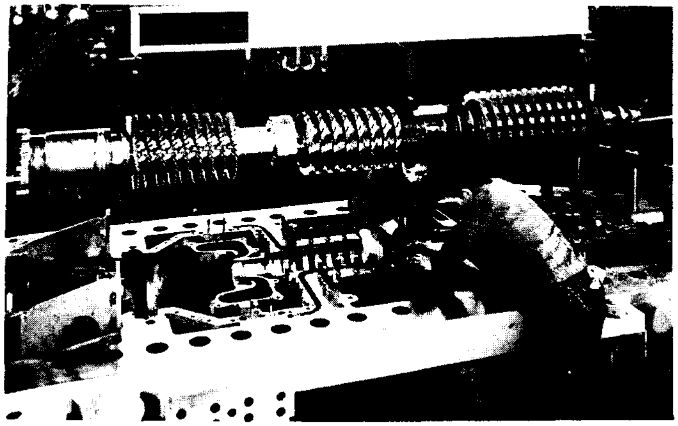


Fig. 16 First helium CCGT (about 6500 kw rotor output) for power unit of cryogenic cycle. Inlet temperature 700 C, pressure 25 kg/sq cm

operation in closed gas cycles is a strong incentive to further development with the aim to achieve soon thermal power-plant efficiencies of over 50 percent without complex installations (6,7).

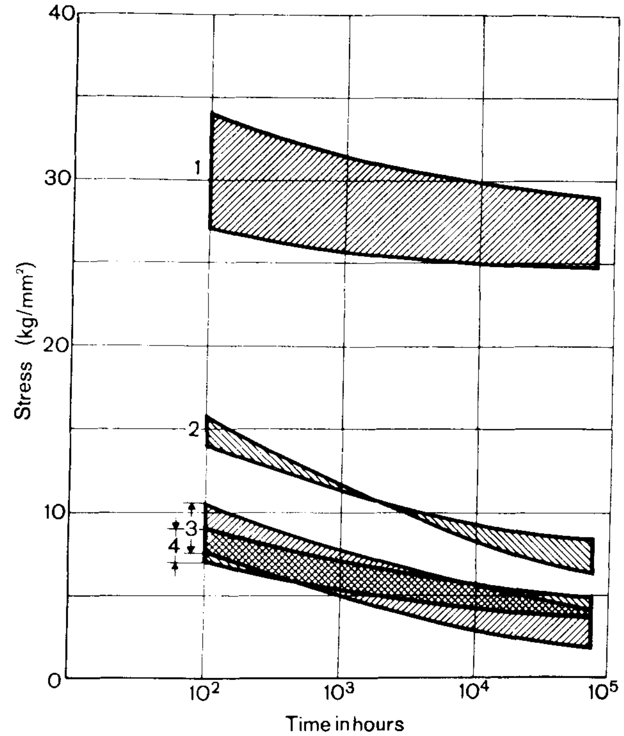


Fig. 17 Allowable long-time rupture stress for high-temperature materials in nonoxydizing gases (values for 1000 C). After Larson and Miller

1 Molybdenum base
2 Nickel base
3 Columbium base
4 Cobalt base

REFERENCES

1 C. Keller, Trans. ASME, New York, November 1946, pp. 791-822; August 1950, pp. 835-850. ASME Paper 56-GTP-15, Washington, April 1956. ASME Paper 61-GTP-2, Washington, March 1961.

W. Spillmann, "The Closed Cycle Gas Turbine for Nonconventional Applications," ASME Paper 66-GT/CLC-8, Zurich, March 1966

K. Bammert and E. Nickel, "Design of Combustion Chambers of Heaters for Transmission of the Primary Heat of CCGT," ASME Paper 66-CLC-1.

2 J. M. Janins and G. T. Seely, "The Development and Operating Experience of the ML-1 Mobile Nuclear Power Plant," ASME Paper 66-GT/CLC-12, ASME Gas Turbine Meeting, Zurich, 1966.

W. M. Crim, Jr., "The Compact AK Process Nuclear System," ASME Paper 66-GT/CCL-6.

3 Symposium on High Temperature Reactors and the Dragon Project, British Nuclear Energy Society, London, May 1966.

European Nuclear Energy Agency of OECD, Colloquium in Paris, May 1965.

4 C. Keller, "Operating Experience and Design Features of Closed Cycle Gas Turbine Power Plants," ASME Paper 56-GTP-15, ASME Gas Turbine Power Conference, Washington, D. C., April 1956. Also in "Applied Atomic Power," Part IV, Chapter III, edited by R. Tom Sawyer, Prentice-Hall, Inc., New York, N. Y., 1946.

5 P. A. Berman, "A Gas Turbine for a Helium-Cooled Reactor," Monograph No.7, Journal of the Franklin Institute, May 1960. Also: Frederic de Hoffmann and W. T. Furgerson, "MGCR as a Small Central-Station Power Plant," GA-1516, General Atomic, July 15, 1960.

6 For details see: Escher Wyss News, vol. 39, No.1/1966, Special issue: "Closed Cycle Gas Turbine for all Fuels: Coal, Oil, Gas, Nuclear." Also: C. Keller, "The Nuclear Gasturbine," Gasturbine Magazine USA, July/August 1965.

7 E. Böhm, "Project for a High Temperature Reactor with a Gas Turbine," Symposium on HTR, London, May 1966.

8 K. Bammert, "Remarks to the Problem of Optimum Design of Nuclear Gas Turbine Power Plants," Atomkernenergie, January/February 1966.

9 W. Trassl, "Dampfturbinen für Kernkraftwerke," Energie und Technik (Germany), September, 1966.