Printed in U.S.A.

69-GT-43

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Nuclear Power Plants with High Temperature Reactor and Helium Turbine

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The present stage of development of nuclear power plants with helium turbine and high temperature reactor is reported and a description given of the first plant of this type, the Geesthacht KSH plant (Kernkraftwerk Schleswig-Holstein) in Germany. Particular stress is laid on the control of closed-cycle gas turbines. The special cases of reactor scram, shutdown of the turbine and load release as well as starting up and turning off of the plants are taken into consideration. The design of the turboset and the arrangement of the components of helium turbines of high output are described. Furthermore results of calculations for optimum layout of helium turbine plants with regard to simultaneous power and process heat generation are given.

Contributed by the Gas Turbine Division for presentation at the Gas Turbine Conference and Products Show, Cleveland, Ohio, March 9-13, 1969, of The American Society of Mechanical Engineers. Manuscript received at ASME Headquarters, December 20, 1968.

Copies will be available until January 1, 1970.

THE AMERICAN SOCIETY OF MECHANICAL ENGINEERS, UNITED ENGINEERING CENTER, 345 EAST 47th STREET, NEW YORK, N.Y. 10017

Nuclear Power Plants with High Temperature Reactor and Helium Turbine

K. BAMMERT **E. BOHM**

Since more than 12 years closed-cycle gas turbines with air as working medium are operating successfully. Meantime they have reached a high stage of development and dispose of matured design features. Data of the operating closed-cycle air turbines are given in Table 1, cols. 1 to 8. The most important steps of development, which can be read from the table, are the increase of power output from 2.3 mwe of the Ravensburg plant (col. 1) up to 17.25 mwe of the Gelsenkirchen plant (col. 8), as well as the raise of the turbine inlet temperature of more than 50 C from 660 C (col. 1) up to 711 C (col. 8), causing an increase of the efficiency of nearly six percentage points. Furthermore, the table shows that the closed-cycle air turbine has also been applied as heating power station (cols. 1, 3, 4, 6, 7, 8), as its wasted heat is received at a favorable temperature level (1-3).[1] According to the numbers of working hours of the first plants (cols. 1 to 4), a long life of the closed-cycle gas turbine can be expected.

The advanced development of the high temperature reactor (HTR) opens to the closed-cycle gas turbine a further field of application. The direct coupling with the HTR (single-cycle system) using helium as working medium is of considerable advantage. Owing to the absence of the heat transmitter, which is necessary in two-cycle systems with separate coolant and working medium circuit, high efficiencies, because of the complete utilization of the coolant temperatures and simple designs of the plant, will be obtained (4, 5). In addition, a major part of development work and

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

Table 1 Data of Closed-Cycle Gas Turbines

		1	2	3	4	5	6	7	8	9	10	11
plant		Ravensburg Germany	Toyotomi Japan	Oberhausen Germany	Coburg Germany	Nippon Kokan Japan	Novokaschirsk USSR	Haus Aden Germany	Gelsenkirchen Germany	Geesthacht Germany	Oberhausen Germany	Germany
working medium		air	air	air	air	air	air	air	air	helium	helium	helium
type		HPS	PS	HPS	HPS	PS	HPS	HPS	HPS	PS	HPS	PS
fuel		pit coal	natural gas	pit coal	pit coal	blast-furnace gas	brown coal	marsh gas pit coal	blast-furnace gas, fuel oil	nuclear fuel	coal	nuclear fuel
working data												
maximum lasting power	MWe	2,3	2,0	13,75	6,0	12,0	12,0	6,37	17,25	25	50	600
compressor inlet temperature	°C	20	20	30	20	25	20	20	20	15	25	15
compressor inlet pressure	bar	7,2	7,2	8	7,3	6,7	7	9,3	10,2	9,5	15,6	21,6
turbine inlet temperature	°C	660	660	710	680	680	680	680	711	750	750	800
turbine inlet pressure	bar	27	27	32	27,5	29	29	31	38,5	25	40	60
efficiency at terminals	%	25	26	29,5	28	29	28	29,5	30,8	39	33	48
speed of the turbo set	rpm	12 750	13 000	6640	8240	6600	6600	8220	6654	8000	6500	3000
alternator speed	rpm	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000
heating water												
quantity	m^3/h	70	–	325	110	–	280	130	340	133	1110	–
inflow temperature	°C	75	–	90	100	–	75	90	90	90	90	–
outflow temperature	°C	45	–	40	40	–	45	40	40	60	40	–
quantity of heat	Gcal/h	2,1-3,5	–	16-24	7-14	–	8-10	6,7	16,9-25,0	4	55,5	–
design features												
compressor												
type		radial	radial	axial	axial, radial	axial	axial	axial	axial	axial	axial	axial
stages		3	3	9+10	6+7+1	5+5+10	9+10	9+6	7+8	9+9+9	15+15+14	9+8+8
turbine												
type		axial	axial	axial	axial	axial	axial	axial	axial	axial	axial	axial
stages		5	5	6	5	6	6	5	6	12	14	2×14
beginning of operation		1956	1957	1960	1961	1961	1962	1963	1967	1972	1972	1976
working hours till 31.10.1968		70 150	71 100	52 200	51 200	38 000	31 000	42 800	3 380			

HPS heating power station PS power station

manufacturer: column 1,3,4,7,8,9,10 Gutehoffnungshutte Sterkrade AG column 1,2,6 Escher Wyss AG column 2,5 Fuji Denki costs will be saved, as the design features of the single-cycle helium turbine plant are similar to those of the conventional closed-cycle air turbine; e.g., the principle of control can be largely adopted from the closed-cycle air turbine. The first nuclear power plant with HTR and directly coupled helium turbine is to be built at Geesthacht near Hamburg, Germany, within the Third German Nuclear Energy Programme (Table 1, col. 9) (6). It is laid out for an output of 25 mwe with a maximum turbine inlet temperature of 750 C and will be in operation in 1972. With this plant the favorable performance of HTR and helium turbine will be demonstrated.

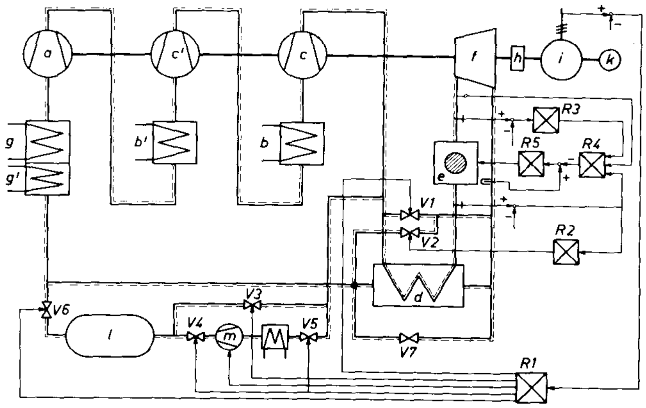
In parallel with the Geesthacht plant, a conventional heated 50-mwe helium turbine will be built at Oberhausen, Germany, within a German development programme (Table 1, col. 10). This plant will also operate with a maximum turbine inlet temperature of 750 C. By selecting a relatively low pressure level, the volume flows of the circuit and thus the dimensions and the material stresses of the 50-mwe Oberhausen turbine will range in an order comparable to that of turbines with high output. The purpose of the construction and operation of this plant is to investigate the individual components of the helium turbine in a real power plant circuit under almost the same conditions prevailing for nuclear helium turbines of high output. In detail, long-time experiences concerning material stresses, blade cooling, shaft seal, helium tightness, and so forth, will be acquired so that the direct transition to helium turbines of high output will be forced.

The aim of the present development in the construction of a 600-mwe nuclear power plant with HTR and helium turbine (Table 1, col. 11). The efficiency of this plant, which will be built in Germany, amounts to 48 percent at a turbine inlet temperature of 800 C (7). At present, a detailed layout of the 600-mwe nuclear power plant is worked out within the German development programme.

The closed-cycle gas turbine is suitable not only for exclusive power generation or as heating power station, but also for simultaneously generating power and process heat, the forms of energy which are generally demanded by the industry. Usually, steam is needed as heat carrier. When applying the nuclear helium turbine to satisfy the demand of industrial energy, the question arises how

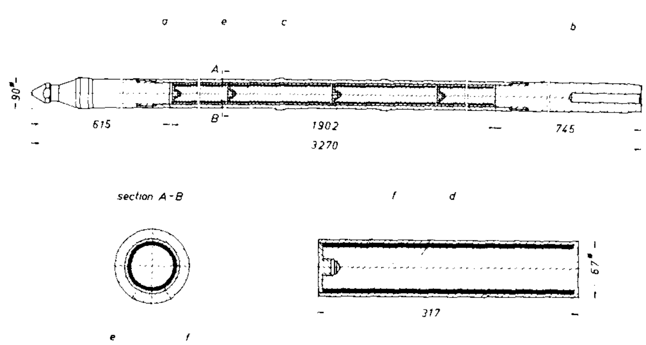
Table 2 Data of the 25-mwe Geesthacht plant

Thermal power		65.7	MW
Electrical power	at terminals	25.5	MW
	net	24.5	MW
Efficiency	at terminals	39	%
	net	37	%
Power density		6.4	MW/m^3
Coolant pressure		25	bar
Reactor inlet temperature		425	°C
Reactor outlet temperature		735	°C
Helium mass flow		40.6	kg/sec
Number of axial and radial fuel zones		2	each
Number of fuel elements		657	
Fuel element length		3270	mm
Fuel element diameter		89	mm
Heavy metal loading		100	kg U 235
		11	kg U 238
		1000	kg Th 232
Core lifetime		900	days
Burn-up	mean	0.057	fima
	max.	0.085	fima
Maximum fuel temperature		1300 ± 50	°C
Maximum sleeve temperature		1000	°C
Expected main loop cooland activity approx.		100	Curie
Number of control rods		28	
Reactivity worth of all rods		25	%
Turbine inlet temperature	normal	730	°C
	max.	750	°C
Compressor inlet temperature		15	°C
Heat exchanger temperature difference		30	°C
Cooling water temperature		10	°C
Pressure ratio turbine		2.55	
Number of stages (Turbine, LP/MP/HP Compressor)		12/9/9/9	
Turbine rotating speed		8000	rpm



a = LP compressor
b' = 1st intercooler
c' = MP compressor
b = 2nd intercooler
c = HP compressor
d = heat exchanger
e = reactor
f = turbine
g', g = hot and cold parts of precooler
h = gear
i = alternator
k = starting motor
ℓ = control vessel
m = charging compressor
V1 - V7 = valves
R1 - R5 = controllers

Fig.1 Scheme of circuit and control



a = upper graphite reflector
b = lower graphite reflector
c = active zone
d = graphite container
e = graphite sleeve
f = annular groove

Fig.2 Fuel element

the plant is to be laid out to obtain the best possible combination of power and steam generation.

2 THE GEESTHACHT KSH PLANT

The scheme of the Geesthacht KSH plant (Kernkraftwerk Schleswig-Holstein) is shown in Fig.1. This diagram is valid for plants of high output, too. The helium is sucked in by the low-pressure compressor a. There it is compressed, then it is cooled in the first intercooler (b'), further compressed in the medium-pressure compressor (c'), cooled again in the second intercooler (b), and compressed to the maximum cycle pressure in the high-pressure compressor (c). In the heat exchanger (d) it is preheated, and then it enters the reactor (e) in which it is heated to the maximum cycle temperature. In the turbine (f) it is expanded and then enters the low-pressure part of the heat exchanger in which part of its remained heat is given off to the gas coming from the high-pressure compressor. Afterward, in the hot and cold parts of the precooler, g' and g, the helium is cooled down to the lowest cycle temperature. Thus, the cycle is closed. Fig.1 also shows the gear (h), which,however, in larger plants is not required, the alternator (i) and the starting motor (k). The most important data of the Geesthacht plant are summarized in Table 2.

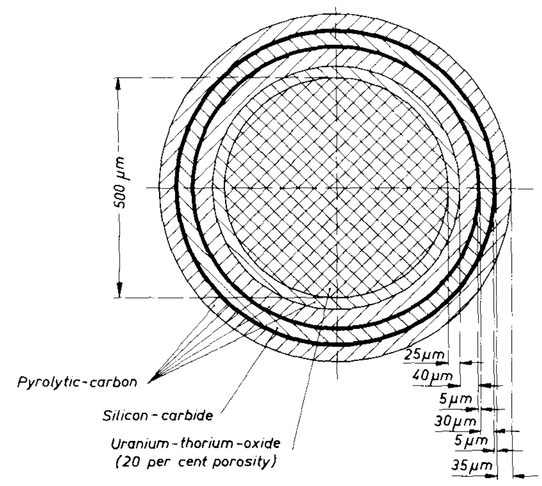
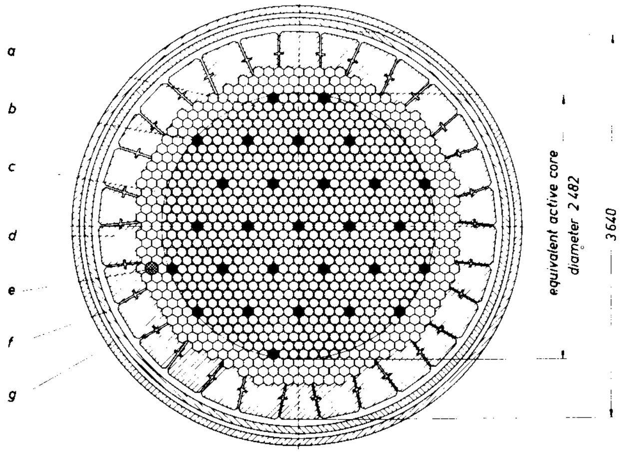


Fig.3 Coated particle

The reactor contains 657 cylindrical fuel elements, the structure of which is shown in Fig. 2. The fuel element is a graphite cylinder. It is axially divided into three zones, an upper and lower reflector (a, b), and an active zone (c). In the active zone, six fuel containers (d) are standing loosely one upon the other, which are enclosed by the graphite sleeve (e). The fuel containers have an annular groove (f) which is filled with the fuel particles. For the first loading mixed uranium/thorium oxide kernels (Fig.3) are foreseen. They are surrounded by an inner relatively porous layer of pyrolytic carbon and outer layers of pyrolytic carbon and silicon carbide which constitute the main barriers to the release of fission products. An additional diffusion barrier for the solid fission products released from the particles is provided between the fuel and the coolant by the structural graphite of the fuel element.

The fuel rods are arranged vertically in the



a = fuel element
b = control rod
c = reflector element
d = reflector block
e = charge position
f = thermal shield
g = pressure vessel

Fig.4 Cross section of the reactor core of the Geesthacht plant

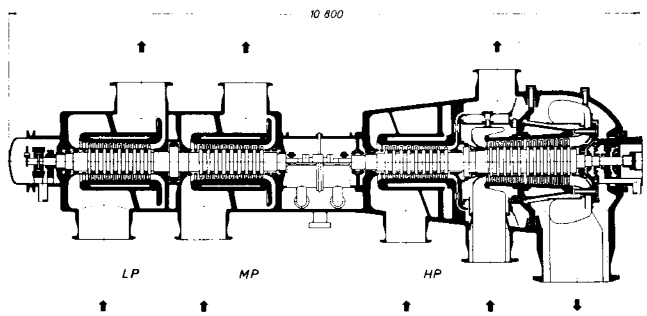
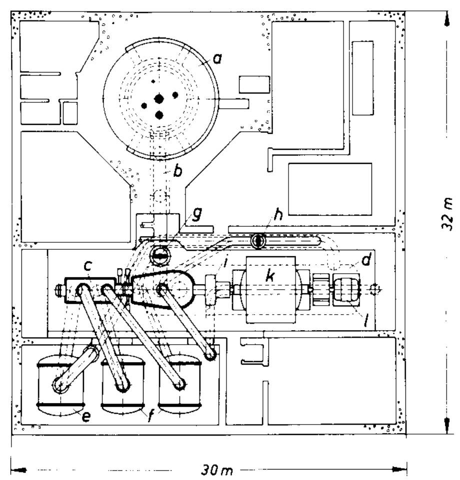


Fig.5 Turboset of the Geesthacht plant



a = reactor
b = concentric pipe
c = turboset
d = heat exchanger
e = precooler
f = intercoolers
g = hot gas valve
h = cold gas valve
i = gear
k = alternator
l = starting motor

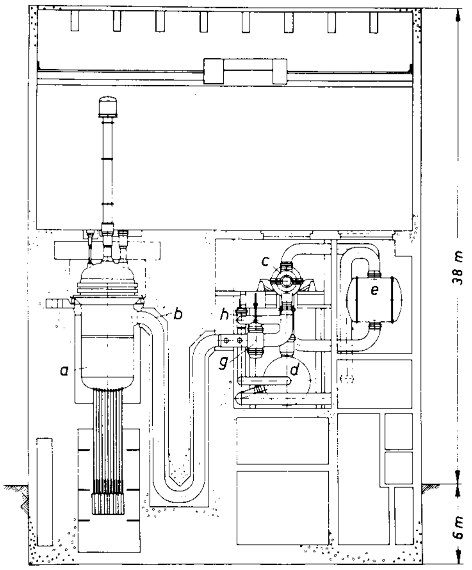
Fig.6 Ground plan of the Geesthacht plant

reactor pressure vessel in such a way that, except in the peripheral zone and beside the absorber rods, each element has six direct neighbors (Fig. 4). The coolant flow in the core is directed upward. At the core periphery there are 251 hexagonal graphite reflector elements arranged in three rows and standing like the fuel elements on the core grid plate. The outer radial boundary is formed by 30 large graphite blocks. The core is not clamped mechanically but by utilizing the coolant flow. The pressure difference between the cold and hot gas, due to the pressure loss in the reactor core, causes the tilting reflector blocks to exert an inward clamping force on the spacer rings of the fuel elements. The absorber rods are arranged at the corners of equilateral triangles. Within the core the absorber rods move in graphite guide tubes.

The core loading for 900 full-power days with full xenon override consists of 100 kg of U 235 (90 percent enriched) as fissile material and 1000 kg of Th 232 as fertile material. This loading gives the lowest fuel cycle costs (3.0 - 3.25 mills/kwhr) for a given maximum reactivity of the cold new core. The mean burn-up is 0.057 fima (53,000 mwd/ton h.m.) with a maximum burnup of 0.085 fima at an average conversion rate of 0.43. In a small core with graphite reflectors, the peak power is generated in the core boundary region. Therefore, zoning of the fuel loading was introduced to achieve a flat power distribution and to limit the maximum fuel temperature to 1300 ± 50 C. Due to the high thorium content, the reactor has, in the whole temperature range, a negative temperature coefficient of reactivity. Fast reactor excursions are limited by the strong negative Doppler coefficient of the fuel. During slow excursions, a scram system limits the temperature rise.

The reactor core is enclosed by a steel pressure vessel with a height of 9.9 m, an inner diameter of 4 m, and a weight of 155 tons. The reactor is connected with the helium turbine by a concentric pipe with adequate U-bends for neutron shielding and piping flexibility, which penetrates the biological concrete shield around the reactor pressure vessel. Two identical emergency cooling systems are provided. They are designed to operate with both helium and nitrogen depending on the hazard occurred.

The turboset (Fig.5) is of the axial flow type with a shaft speed of 8000 rpm. It is sup-



a = reactor
b = concentric pipe
c = turboset
d = heat exchanger
e = precooler
f = intercoolers
g = hot gas valve
h = cold gas valve
i = gear
k = alternator
ℓ = starting motor

Fig.7 Elevation of the Geesthacht plant

ported in four bearings. The length of the turboset is about 11 m, with 12 stages in the turbine and 9 stages in each of the compressors. With regard to helium tightness, the turbine casing is welded.

Reactor and turbine are in a non-integrated arrangement and together with all cycle components and the electricity generating equipment within the reactor building, Figs.6 and 7. The heat exchanger is arranged underneath the turbo set; whereas the precooler and the two intercoolers are located in neighboring rooms. The dimensions of the reactor building are, in the vertical direction, greatly influenced by the reactor pressure vessel with bottom entering control rods and the equipment for off-load fuel handling from the top of the pressure vessel and horizontally, by the length of the turboset. The building itself is a concrete building vented by a stack. The building is pressurized to 1.29 bar in the case of a complete rupture of the concentric pipe. A service building houses the electrical supply systems, switch gears, emergency Diesel sets, and several auxiliary systems.

3 OPERATIONAL BEHAVIOR OF HELIUM TURBINES

A characteristic feature of the closed-cycle gas turbine is the pressure level control by which the power output is reduced on taking part of the working medium out of the circuit (8, 9). Therewith, the output change is effected by the change in density of the working medium. As the volume rates and the temperatures in the circuit remain almost constant, the machine efficiencies and, thus, also the plant efficiency practically do not drop. Thus, the advantage of pressure level control is its economical operation. When the output is to be decreased by reducing the pressure level, the valve V3 (Fig.1) is opened so that helium flows from the high-pressure side of the circuit into the control vessel ℓ in which, at full load, there is a pressure only slightly exceeding the pressure at the precooler inlet. After the pressure balance has been reached, a further quantity of helium is fed into the vessel by means of the compressor m. For this purpose, the valves V4 and V5 are opened and valve V3 is closed. The helium stored in the vessel will be fed back into the circuit by opening the valve V6 when the power output is to be raised.

The pressure level control is combined with a by-pass control system for quick load decreases. In case of bypass control, part of the gas coming from the high-pressure compressor is conducted by the valve V1 to the low-pressure side. As a result, the turbine mass flow and (according to the pressure ratio and efficiency) the head of the turbine drop, so that the turbine output decreases. As the sum of the compressor powers remains almost constant, the electric output, being the difference between the turbine and compressor power, is reduced as quickly as the turbine output. A bypass mass flow of about 33 percent, related to the turbine mass flow for closed bypass valve, is already sufficient for idling operation. To prevent an unduly high changing of the reactor inlet temperature which is undesired in regard to the strength of reactor material, the bypass mass flow must be divided into two partials. The major partial has to be added to the turbine mass flow upstream of the heat exchanger; as otherwise, owing to the falling pressure ratio and the resultant increase in the turbine outlet temperature, the reactor inlet temperature would rise. The rest partial is conducted by the valve V2 to the precooler inlet. The bypass valves may be of a small size as the bypass volume flows are small, and at the main valve V1, there is predominantly an overcritical pressure ratio. As a result, the valve lifts are rather low, so that short lift periods may be obtained. Hence, the bypass control is characterized by a very high control rate. Arranging valve V2 downstream, the main valve is of advantage as only one valve; that is V1, must

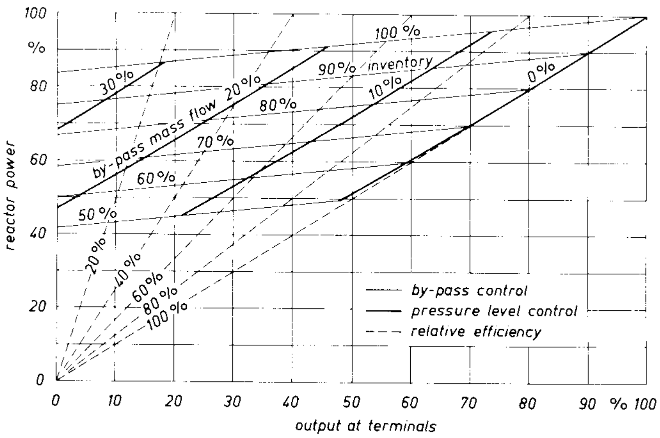
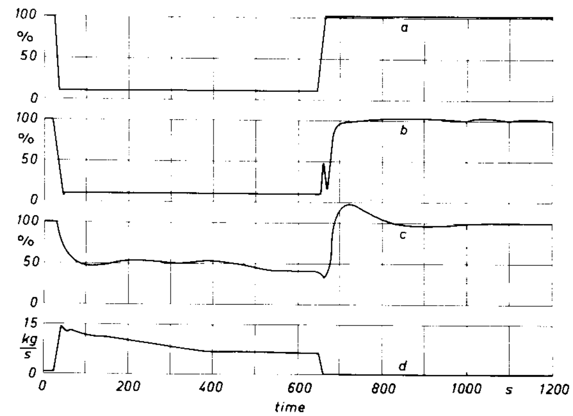


Fig.8 Part-load behavior



a = power requirement
b = actual output
c = reactor power
d = bypass mass flow

Fig.9 Control action

close absolutely tight, so that for valve V2 a relatively simple design may be chosen. Naturally, there is at valve V2 only the pressure ratio resulting from the pressure losses of the heat exchanger and the adjoining pipes. But on the other side, the by-pass mass flow, which has to be conducted to the precooler inlet, is very low, too (20 percent of the whole bypass mass flow in maximum), so that the dimensions of valve V2 remain small. Another advantage consists in the fact that the bypass valves are admitted by helium which is relatively cold.

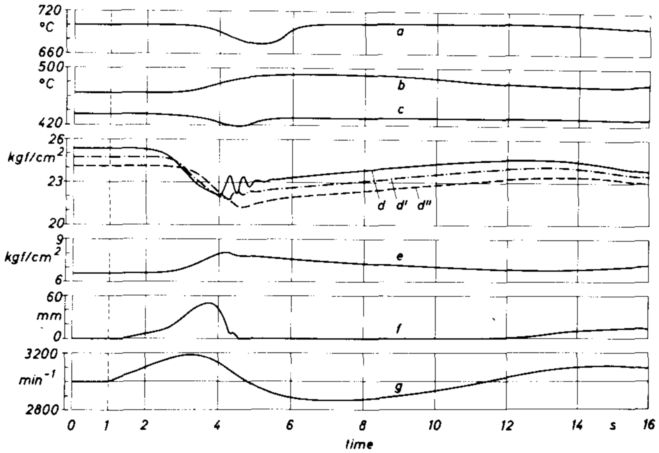
The automatic pressure level control of the Geesthacht plant will be limited for a part-load of 50 percent. When choosing this value, even the full load will be reached in a sufficient short time. If a rather small part-load shall be maintained during a longer time, the pressure level can be dropped further by manual operation.

The part-load behavior of the plant is illustrated in Fig.8 in which the reactor power is plotted against the output at terminals. Parameters are the inventory of the circuit, the bypass mass flow, which is related to the design value of turbine mass flow, and the relative efficiency at terminals. The full lines apply to pressure level control with constant bypass mass flow, the thin lines to by-pass control with constant inventory. In normal operation pressure level control will be used, so that the point of state in Fig.8 moves along the curve for bypass flow zero, the efficiency having its optimum. Only in case of quick load changing bypass control will be employed temporarily. Already a short time later, however, it will be replaced by pressure level control. If the automatic pressure level control is rated for an output reduction of 50 percent, and if the pressure level shall not be lowered further by manual operation, the range of regulation in Fig.8 is limited by the bypass line at about 50 percent of inventory. For idling operation the reactor power then amounts to 41 percent.

The bypass valve V1 (Fig.1) and the regulating apparatus of the pressure level control are actuated by the output controller R1, the input signal of which being the difference between the nominal and the actual power output. As the controller must have appropriate transient behavior for both bypass and pressure level control, and also has to make a number of logical decisions and switching operations, it consists of a multiloop control system. The bypass valve V2 is controlled by the temperature controller R2 in such a way, that in case of bypass control, the reactor inlet temperature remains almost constant.

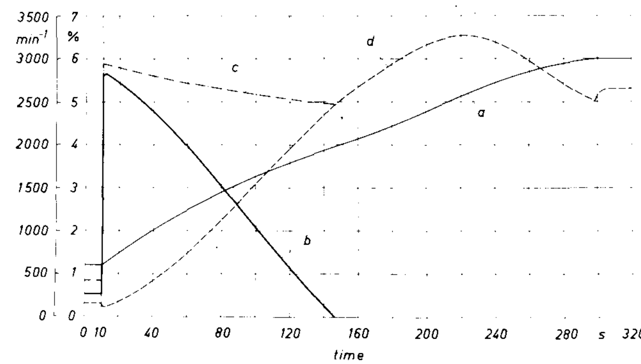
As to be seen in Fig.8, the reactor power primarily depends on the inventory respectively on the pressure of the circuit. Therefore, the reactor power is controlled proportionally to the turbine inlet pressure. The reactor outlet temperature is controlled by the temperature controller R3 (Fig.1), the output signal of which is conducted to the power controller R4. Other input signals of the controller R4 are the circuit pressure and the reactor inlet temperature as disturbance variable. These values determine the required reactor power, which value is compared with the actual. The difference of both values controls the position of the control rods of the reactor by means of the rod controller R5. The reactor power is measured by neutron monitoring with the aid of ionization chambers. Thus, the reactor control is not connected directly to the circuit control but receives its signals from the gas turbine cycle. This principle has proved successful for the control of the heaters of closed-cycle air turbines.

For examining the control action, the



a = turbine inlet temperature
b = turbine outlet temperature
c = heater inlet temperature
d = pressure at high-pressure compressor outlet
d' = pressure at heater inlet
d" = pressure at turbine inlet
e = pressure at turbine outlet
f = lift of the bypass valve
g = alternator speed

Fig.10 Isolated operation



a = alternator speed
b = torque of the starting motor
c = torque for accelerating the machine set and for overcoming bearing friction and gear losses
d = aerodynamic torque

Fig.11 Startup of a helium turbine

Geesthacht KSH plant was simulated on an analog computer. For the investigations calculation models of the individual cycle components had to be developed, which were connected to simulate the entire cycle. A typical transient behavior is shown in Fig.9, where the power requirement (a), the actual output (b), the reactor power (c), and the bypass mass flow (d) are plotted. The load was changed between 100 and 10 percent; the chosen speed of load changing was 5 percent/sec. The calculation has shown that rates of load changing of more than 10 percent/sec can be mastered. Thus, if necessary, the plant is able to take part in controlling the frequency after a disturbance in the network only by means of the economical pressure level control, the bypass valves being closed.

To determine the control action of a closed-cycle gas turbine, we have made several tests on the closed-cycle air turbine in Oberhausen, Germany (Table 1, col. 3). In principle, circuit and control scheme of this plant correspond to those in Fig.1.

Fig.10 contains some results of a test in which the machine was disconnected from network at an output of 7.4 mw, while a consumer of a capacity of 3.1 mw remained connected. The plant ran on in isolated operation. For the first decisive seconds, following curves are plotted against the time: the inlet and outlet temperatures of the turbine (a, b) and the temperature at the heater inlet (c), the pressures at the high-pressure compressor outlet (d), the heater inlet (d'), the turbine inlet (d"), and the turbine outlet (e), the lift of the by-pass valve (f), and the alternator speed (g). The effectiveness of the control operation can be seen from the slope of the speed curve. The speed increases to 106 percent of the nominal speed in maximum and will balance out after some small oscillations to its nominal value. About 30 sec later the speed oscillations have ceased. The tripping speed amount to 110 percent. A reason for the small overspeed is the fact that the compressor power increases at the third power of rotor speed and that, therefore, the compressors dissipate part of the excess of output during rotor acceleration. Fig.10 illustrates that the control of the closed-cycle gas turbine does not present difficulties even in case of rapid load changing.

For protecting the nuclear gas turbine plant with HTR in case of extraordinary occurrences, several automatic safety operations have been provided. In the following, the operations necessary in case of shut-down of the plant are treated. Shut-down is either caused by a signal from the plant safety system or by manual operation. It is necessary to differentiate between the reactor scram and the shut-down of the turbine. When scramming the reactor, all control and safety rods, which are outside the core or in an intermediate position, will be put into the reactor with maximum speed. Under normal circumstances, the turbine set will remove the afterheat. During this time, the machine set may be rotated by the starting motor. A shut-down of the turbine automatically causes a reactor scram. For reducing the turbine output, the bypass valve is fully opened, causing the machine to come to standstill immediately. The afterheat will be removed by the emergency cooling system. The load release represents a special case, as it causes neither a shutdown of the turbine nor a reactor scram. The machine can be caught with the aid of the normal bypass control. The stationary behavior of the plant running idle has already been shown in Fig.8. Only a few seconds after the load release, the machine can be reconnected to network.

On principle a helium turbine with HTR is started up and turned off in the same way as a closed-cycle air turbine, except that, in addition to the reactor outlet temperature, the inlet temperature also has to be controlled. To render possible a gradual rise of the reactor inlet temperature, there is made use of a heat exchanger bypass on the low pressure side (Fig.1). In the beginning of start up, the valve V7 of the heat exchanger bypass is opened. It is gradually closed during the heating-up period in order to raise the reactor inlet temperature. The ratio of the temperature gradients of the reactor inlet and outlet temperature is to be approximately 2:3. Having reached a turbine inlet temperature of approximately 450 C, the machine set is accelerated by the starting motor and passes through the critical rotor speeds, the inventory still being low. The starting motor must be designed for such an output that the machine set is accelerated to full speed within a sufficiently short period, so that unduly high-vibration deflections in the range of the critical speeds are avoided. For dimensioning the starting motor, a method of calculating the torque required from the starting motor as a function of time has been developed. For this calculation, to be carried out by means of a digital computer, a cycle model was established. The results of a calculation are shown in Fig.11 The torques plotted against the time are related to the torque which results from the design output at terminals and the rotor speed of the alternator. At the time t = 10 sec, the operation of accelerating the machine which then has a rotor speed of 20 percent of its design value begins, burding the starting motor up to the limit of its capacity. The speed curve (a) corresponds to the normal starting speed of a conventional closed-cycle gas turbine. The torque of the starting motor (b) results from the difference between the torque required for accelerating the machine set and for overcoming bearing friction and gear losses (c) and the aerodynamic torque of the turboset (d). At the time t = 10 sec, the curves (b) and (c) are discontinuous resulting from the sudden burding of the starting motor.

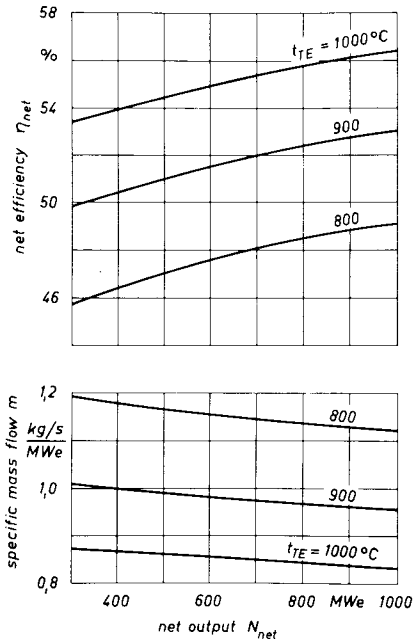


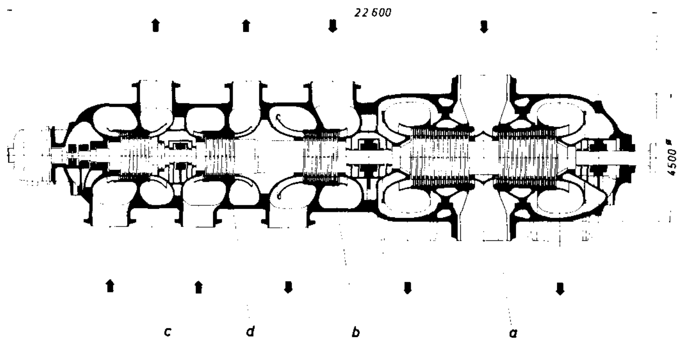
Fig.12 Net efficiency and specific mass flow of helium turbine plants

It can be seen that with rising speed the aerodynamic torque increases owing to the growing pressure ratio, thus contributing to the accelration of the machine. Accordingly, the required torque of the starting motor decreases. After approximately 135 sec the turbine itself is able to accelerate the machine set without being supported by the starting motor. The torque curve (b) is taken as the basis for dimensioning the starting motor.

Turning off is effected nearly in reverse order to start up. The reactor outlet temperature is lowered continuously by reducing the reactor power, which results in a drop of the electric output. Simultaneously, the inventory of the circuit is lessened. When the electric output nearly becomes zero, the machine is disconnected from network. In order to pass the range of the critical rotor speeds within a sufficient short time, a separate low-pressure compressor bypass is opened. A simultaneous increase of the reactor inlet temperature is avoided by adequately opening the heat exchanger bypass V7 (Fig.1) Till the plant is completely cooled down, the machine set is turned by the starting motor. The particular operations are again virtually identical to those of a closed-cycle air turbine.

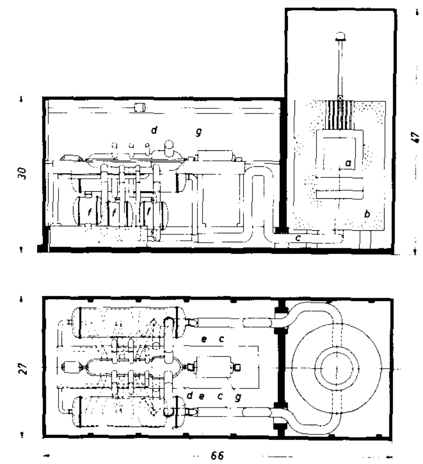
4 NUCLEAR HELIUM TURBINES OF HIGH POWER OUTPUT

The design of helium turbines of high power output does not differ basically from that of air



a = turbine
b = LP compressor
c = MP compressor
d = HP compressor

Fig.13 Longitudinal section of a 600-mwe turboset



a = reactor core
b = pressure vessel
c = concentric pipes
e = heat exchangers
f = coolers
g = alternator
dimensions in m

Fig.14 300-mwe nuclear helium turbine plant of conventional arrangement

turbines used in the closed cycle. It has been proved by extensive investigation that technologically and from the aspect of design there are no fundamental difficulties in manufacturing single-shaft helium turbosets for capacities of up to 1000 mwe. The possibilities existing with helium turbines are illustrated in Fig.12. It can be seen that, for instance, the efficiency of a 600-mwe plant increases by 8.5 percent when the turbine inlet temperature is raised from 800 to 900 C. The specific mass flow of the plant decreases in that case by 15 percent. Temperatures of 800 to 900 C can be applied already today when using suitable heat-resistant alloys and adopting special design measures such as the provision for appropriate cooling.

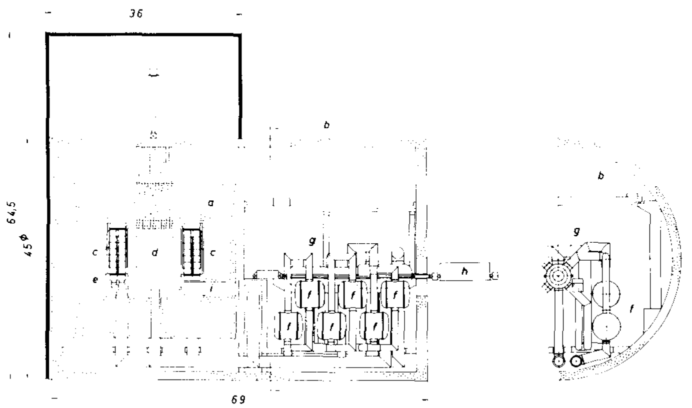
With regard to size and aerodynamic layout, the helium turbine is particularly suitable for high output. In the range from 300 to 1000 mwe, conventional steam turbosets exceed helium turbine sets consisting of turbine and three compressors by about 50 percent in length, i.e. when two-stage intermediate cooling is provided (4). The maximum blade length of helium turbines are less than 500 mm even for 1000 mwe units. With a primary pressure of 60 bar, the shaft and casing diameters are about the same as those of open-cycle gas turbines supplying 1/10 of the power output. Therefore, in building a 300-mwe helium turbine plant, one can generally rely on the knowledge acquired in many years of operation of open-cycle gas turbines of about the same dimensions. While for the 300-mwe turboset a uni-flow turbine is adopted, the turbine of the 600-mwe set is of the double-flow design. The dimensions differ but little. Fig. 13 shows such a helium turboset with double-flow turbine (a) and the single-flow compressors (b), (c), and (d).

The excellent heat-transfer characteristics of helium lead to economical layouts of the heat exchangers and coolers even at small temperature differences and low pressure losses. The heat exchanging surfaces amount to only 1/3 of the surfaces required for closed-cycle air turbines. However, starting at 300 mwe, it is necessary to adopt several units in parallel arrangements, as the increased helium mass flow with limited pressure losses leads to cross sections of admittance which, for reasons of manufacture and transport, have to be divided.

Apart from optimizing and layout, the arrangement of the components within the plant is economically of decisive importance. As the helium turbine in connection with the reactor forms the primary circuit of the power plant, the arrangement is virtually determined by safety aspects. The surroundings must not be endangered even in case of the maximum credible accident. This principle may impose restraints on the selection of components in view of optimum individual layouts.

4.1 Conventional Arrangement

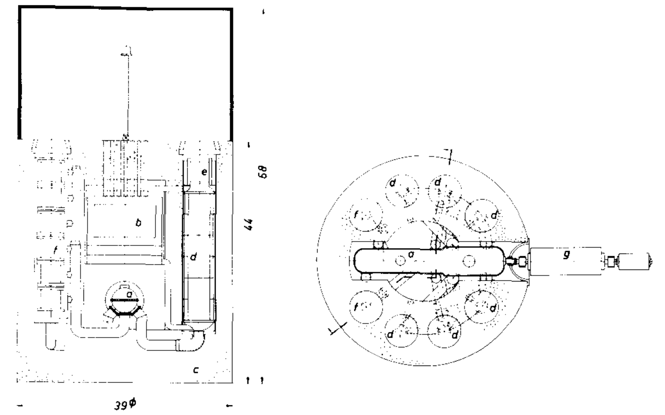
The machine set is arranged in a turbine hall as in a conventional thermal power plant with the reactor standing apart. Fig.14 shows the conventional arrangement of a 300-mwe plant. This concept is based on a well-known technology. The machine set is easily accessible and its design corresponds to that of operating closed-cycle gas turbine plants. The reactor core (a) is encased



a = pressure vessel
b = cylindrical containment
c = heat exchangers
d = reactor core
e = liner
f = coolers
g = turboset
h = alternator

dimensions in m

Fig.15 600-mwe nuclear helium turbine plant of partly integrated arrangement



a = turboset
b = reactor core
c = prestressed-concrete pressure vessel
d = heat exchanger
e = precoolers
f = intercoolers
g = alternator

dimensions in m

Fig.16 1000-mwe nuclear helium turbine plant of fully integrated arrangement

in a prestressed-concrete pressure vessel (b) of the usual simple design. The reactor building and the turbine hall are connected with concentric pipes (c). The turboset (d) is of single-shaft design; the heat exchanger (e) and the cooler (f) are divided each into two parallel units and arranged in the turbine hall together with the turboset and the alternator (g). The design considerations of the individual components are not solely limited by arrangement but virtually determined by aerodynamic, thermodynamic, and economic considerations, so that the possibilities inherent in the cycle can be utilized to the greatest extent.

In order to guarantee the cooling of the reactor for after heat removal in case of a rupture of the main circuit, two independent emergency cooling systems are provided to cover secondary failures.

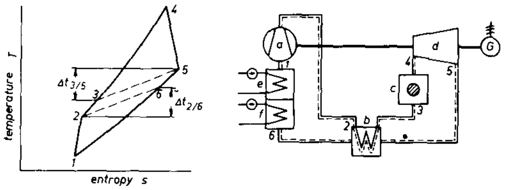
With the separate arrangement of reactor and turbine, there are special problems with regard to uncontrolled helium leakage. If the hot-gas pipe (c) breaks, the high-pressure gas enters the turbine hall, causing an increase of the pressure in the hall. The smaller the building volume, the higher the pressure. As the admissible superpressure is limited by the maximum safety stress in the walls, the building volumes of plants with high outputs would rise to a rather large extent. Thus, for high power units partly or fully integrated arrangements have to be chosen.

4.2 Partly Integrated Arrangement

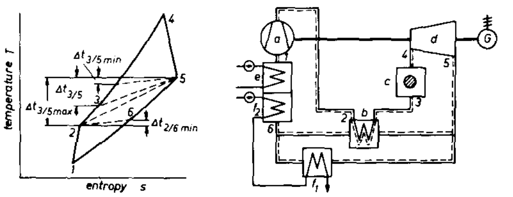
For a 600-mwe plant, Fig.15 shows an arrangement which permits adoption of reactor pressure vessels built so far and generally maintains the conventional arrangement of the turboset shown in Fig.13. The helium turbine set is located together with the reactor pressure vessel (a) in a horizontal cylindrical containment (b). While the reactor pressure vessel is subjected to a pressure of 60 bar, the containment (b) in the turbine hall has to be rated only for the equalizing pressure, which is about 4 bar at 600 mwe. The heat exchanger (c) is located in the reactor pressure vessel concentrically about the core (d), so that the liner (e) of the reactor vessel is cooled by the relatively cold gas of the high-pressure compressor. The coolers (f) are arranged in six units on both sides of the single-shaft turboset (g). The alternator (h) is arranged outside the containment. This arrangement incorporates prestressed-concrete pressure vessels of simple design with only a few openings and thus a distinct stress distribution. Partly integrated arrangements of this kind would require a short time of development compared to a conventional arrangement. The principal difficulties in case of an accident are easily controllable, so that economic aspects alone are decisive for adopting this arrangement for large helium turbine plants. Two independent emergency cooling systems (i) are provided.

4.3 Fully Integrated Arrangement

The building volume of the entire plant can be reduced even further by adopting the fully integrated arrangement. In that case the helium turbine components and the reactor are accommo-

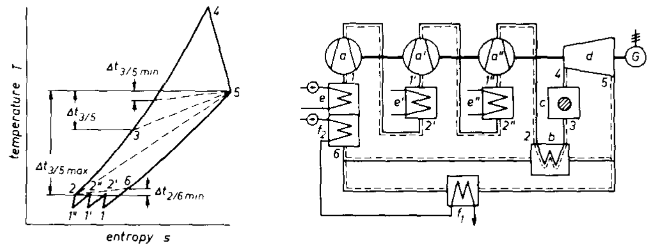


arrangement I: heat exchanger and steam generator series-connected



arrangement II: heat exchanger and steam generator parallel-connected

Fig.17 T,s-diagrams and cycle schemes of helium turbine plants for power and steam generation



a = LP compressor
a' = MP compressor
a'' = HP compressor
b = heat exchanger
c = reactor
d = turbine
e = precooler
e', e'' = intercoolers
f = steam generator

Fig.18 T,s-diagram and cycle scheme of a 300-mwe helium turbine plant for power and steam generation (arrangement II)

dated in a common prestressed concrete pressure vessel. A proposed fully integrated arrangement for a 1000-mwe plant is shown in Fig.16. The single-shaft turboset (a) is horizontally arranged below the core (b). The heat exchangers are accommodated in vertical openings of the prestressed-concrete pressure vessel (c). There are six parallel units each of the heat exchanger (d), the precooler (e), and the intercoolers (f). While the precoolers are arranged above the heat exchangers in accordance with the flow pattern of the gas, six parallel intercoolers each are arranged in two additional vertical openings. All these openings (total of 8) are so arranged in the vessel wall to leave sufficient space for horizontal openings for the turboset and the two emergency cooling systems in the foregoing. The alternator (g) is arranged outside the concrete pressure vessel. The heat exchanger and cooler units in parallel are all of the same size, which permits easy replacement when one unit each is kept as a stand-by. All heat exchanging units are rated for small temperature differences (20 C for the heat exchanger and 5 C on the cold side of the coolers) and very low pressure losses. Therefore, together with the single-shaft turboset and a fully integrated arrangement, a virtually optimum utilization of the inherent potentialities offered by the thermal cycle is achieved. Specific problems relating to the gas ducts, erection, and maintenance, still require detailed examination with this type of arrangement. Thorough examinations and further developments are still required with regard to design of the prestressed-concrete pressure vessels taking into account the proposed openings. The low specific volume and high nuclear safety favor such a solution.

5 THE NUCLEAR GAS TURBINE FOR COMBINED POWER AND PROCESS HEAT GENERATION

The forms of industrial energy demand are generally power and heat, usually with steam as heat carrier. Therefore, an industrial nuclear power plant is required to produce power and steam at the same time. Investigations have shown that the reactor-heated helium turbine is suitable, not only for exclusively generating electric power, but also for combined power and steam generation (10). For the generation of steam and regenerative heat exchange in a closed gas turbine cycle, the heat of the working medium arising between the turbine outlet and the compressor inlet is available. With the turbine inlet temperature generally realized today, and with optimum expansion ratios, the gas temperature at the turbine outlet ranges between 400 and 500 C. It is thus high enough for the generation of steam for industrial purposes. Fig.17 shows the possible arrangements in the form of two-cycle schemes. The heat contained in the working medium on the low-pressure side of the cycle, between the points 5 and 1, is utilized as far as possible for regenerative preheating of the cold high-pressure gas and for steam generation; the nonuseful part is transferred to the cooling water.

The two arrangements shown in the following differ inasmuch as in one case (I) the heat exchanger (b) and the steam generator (f) are arranged one after the other so that the full helium volume flows to both of them, while in the other case (II), the heat exchanger (b) and the steam generator part (f_1) are arranged in parallel lines.

Hence, with the arrangement I there is the following temperature development on the low-pressure side of the cycle: In the heat exchanger (b) the helium is cooled from t_5 to 56 and, subsequently, in the steam generator f to $t_{6/1}$; at this temperature it enters the cooler (e). With the arrangement II, the division of the helium flow has the result that on the hot side of the heat exchanger (b), the gas mass flow per unit of time is smaller than on the cold side; i.e., there is more cooling of the hot gas than heating of the cold gas. In the steam generator part (f_1) the other partial is cooled from t_5 to t_6, and then the total helium volume is cooled in the steam generator part (f_2) from t_6 to $t_{6/1}$, and finally in the cooler (e) from $t_{6/1}$ to t_1. These are the principles characterizing the arrangements of plants for the combined generation of power and steam (without intercooling). The question arises how reactor-heated helium power plants are to be rated to ensure the best possible combination of power and steam generation, and what efficiencies and power/heat ratios can be achieved.

The basis for answering this question is the cycle scheme of a 300-mwe plant shown in Fig.18. This plant has two intercoolers with the steam generator part (f_1) added to the heat exchanger (b) in a parallel stream and with the precooler divided into the steam generator part (f_2) and the cooler (e). This arrangement (Fig.18) differs from the arrangement II (Fig.17) only in that it has two intercoolers.

When fixing certain layout parameters and the electric output for these arrangements, and when further setting certain data for the steam to be generated, it is possible to determine the optimum electric net efficiency of the plant as a function of the steam quantity produced. The results are shown in Fig.19. From the steam data (state and quantity), one can determine the heat quantity in addition to the electric output; hence, for every value of steam quantity on the abscissa, there is plotted a particular power/heat ratio.

The calculations were first made for steam conditions of about 5 bar and 170 C (graph on left, Fig.19) with an electric net power of 300 mw; the internal consumption of the plant itself is very low with such plants; according to previous investigations it was fixed at 2.5 percent of the power put out at the coupling of the turboset (7). For a temperature of 800 C at the turbine inlet (thick unbroken line) the efficiency - only net efficiencies are considered here - falls considerably with increasing steam generation, starting from a maximum value of 46.7 percent; this maximum cannot yet be achieved in practical operation as, with very low steam volumes - with the

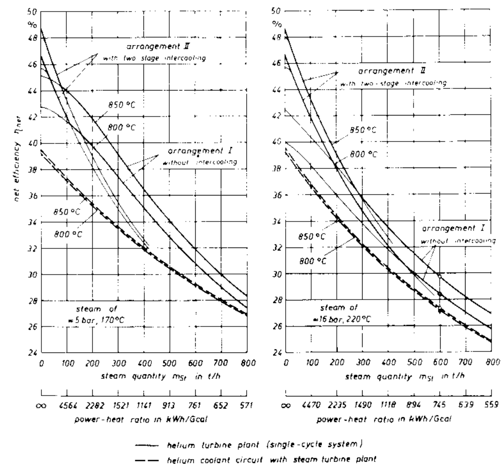
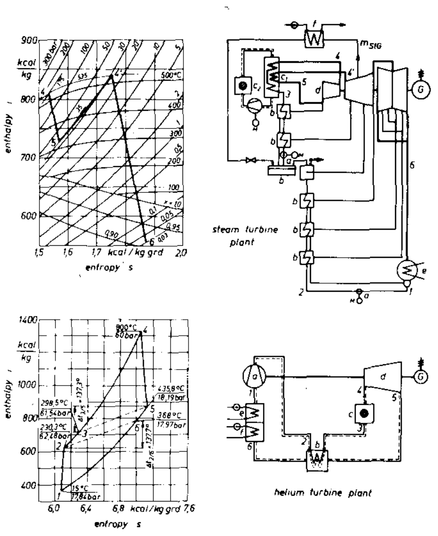


Fig.19 Net efficiency of 300-mwe plants for power and steam generation

plant generating almost exclusively electric power - it is not possible to choose layout data which are an optimum with regard to efficiency. To establish this optimum the reactor inlet temperature would have to exceed a limit set by the heat resistance of the reactor core support. The maximum that can be achieved is thus 45.7 percent, a value which had resulted already from the layout of a 300-mwe plant for 100 percent power generation (7) (thin unbroken line with very small steam volumes).

A comparison with the efficiency curve for the higher steam data (about 16 bar, 220 C; graph on right of Fig.19) shows that with the arrangement II with two-stage intercooling the steam data have little influence; the reason for this is that the steam temperature compared with the turbine outlet temperature of the helium is relatively low so that its variation is of hardly any consequence, and that enthalpy increases of the heat carrier differ relatively little with the two steam qualities considered.

The investigations have shown further that, independent from the steam quantity, the efficiency with the arrangement II is better with two-stage intercooling than it is with single stage or not intercooling at all; however, in case of arrangement I, it was found that, with the two steam qualities under consideration and with greater steam quantities, there is the opposite tendency; i.e., the achievable efficiency rise with decreasing numbers of intercooling stages. From a certain steam quantity limit upward, these efficiencies are even higher than those that can be achieved with the arrangement II with two-stage intercooling. In the connection it should be noted that the efficiencies in case of arrangement



Steam turbine plant:

a = pumps
b = feedwater heater
c_1 = steam generator
c_2 = reactor
d = turbine
e = condenser
f = steam transformer

Helium turbine plant:

a = compressor
b = heat exchanger
c = reactor
d = turbine
e = cooler
f = steam generator

Fig.20 Single- and two-cycle systems for power and steam generation. Output at terminals 300 mwe, steam quantity 600 tons/hr at 16 bar and 220 C

I (without intercooling) are greatly dependent on the steam data. The steam quantity limit at the transition from arrangement II with two-stage intercooling to arrangement without intercooling is shifted from 112 tons/hr at 5 bar/170 C (graph on left, Fig.19) to 460 tons/hr at 16 bar/220 C (graph on right, Fig.19).

The plants considered in the foregoing - reactor-heated helium turbine plants - are also called single-cycle systems, especially when they are to be compared with two-cycle systems in which the reactor is also cooled with helium but the helium cooling circuit is followed by a conventional steam turbine set. The two-cycle system adopted for this comparison is one with a pass-out condensing turbine working with a live-steam pressure of 175 bar at a live-steam temperature of 535 C, intermediate superheating to 535 C, and six feed-water preheating stages (top illustrations of Fig.20); it is assumed that the internal consumption of the plant itself is 8.9 percent of the net output, which is 300 mwe also in this case. With these data a net efficiency of 39.3 percent is achieved with 100 percent power generation, when the helium temperature at the steam generator inlet is 800 C. The steam extracted from the turbine heats the heat carrier in a steam/steam heat exchanger to the required temperature and is then led to the feedwater tank in the form of condensate. However, the condensate of the heat carrier is not returned. Starting from the aforementioned maximum value, the efficiency curve drops the more steeply, with increasing steam generation, as the required steam quality goes higher (broken lines in Fig.19).

A comparison of the two systems shows that the efficiencies of the single-cycle system in the range under consideration are higher than those of the two-cycle system. However, this difference in efficiency decreases with increasing steam generation as, generally speaking, the efficiencies of the single-cycle system decrease more than those of the two-cycle system. However, the advance of efficiency of the single-cycle system over the two-cycle system, in case of exclusively generating electric power, is so great that it has a decisive effect up to the range of large steam quantities.

The advance of efficiency with 100 percent power generation and thus also with additional steam output, is the greater as the helium temperature at the turbine inlet (in the case of the single-cycle system) or at the steam generator inlet (in the case of the two-cycle system) goes higher. When increasing this temperature from 800 to 850 C, both diagrams show a considerable thermodynamic improvement of the single-cycle system, while the efficiencies of the two-cycle system remain virtually unchanged. The slight improvement in efficiency is only due to the decrease of the power consumption of the compressors (and thus of the internal consumption of the plant) with reduced heating surfaces of the steam generators.

The points marked in the graph on the right of Fig.19 - the double circles are for 800 C and the single circles for 850 C - show the net efficiencies of the two systems specially for 600 tons/hr of steam at about 16 bar and 220 C; these are, for the single-cycle system, 28.4 percent at 800 C and 29.8 percent at 850 C and, for the two-cycle system, 27.2 percent at 800 C and 27.4 percent at 850 C. These considerable differences between the single-cycle and the two-cycle systems increase with both increasing reactor outlet temperatures and decreasing steam quantity.

Fig.20 shows the relevant arrangements of the two systems. The schemes are based on a helium temperature of 800 C, an electric output of 300 mw, and a steam output of 600 tons/hr at about 16 bar and 220 C. The illustration shows how simple the single-cycle system is, which has also the higher efficiencies.

As the foregoing considerations are based on the generation of steam of only one quality, the question arises as to the possibilities of generating different steam qualities in a single-cycle system. With the basic arrangements shown in Fig.17, the possibility offers itself of adopting several steam generators instead of only one, and of arranging these either in one line with the heat exchanger or parallel thereto or partly in one line with and partly parallel to the heat exchanger. The arrangement of these units between turbine outlet and compressor inlet can be chosen in dependence on the steam qualities and quantities and in such a way that the regenerative heat volume and thus the efficiency of the plant are a maximum.

SUMMARY

Nuclear power plants with high-temperature reactor and directly coupled helium turbine are characterized by a high efficiency and a simple design. In addition, the reactor-heated helium turbine covers a large range of power, beginning at 25 mwe of the Geesthacht KSH plant up to output units of 600 and 1000 mwe. Hence, it can be operated not only in conjunction with thermal gas-cooled reactors, but also with gas-cooled fast breeding reactors, which will be designed for very high outputs. It has been proved that single-shaft turbosets, which are relatively small in length, can be applied almost to all power outputs. Thus, compact partly or fully integrated arrangements of the components, particularly in case of greater output units, are achieved, which meet the requirements of safety. Independent of the power the helium turbine can be applied not only for exclusive power generation but also for simultaneously generating power and steam.

The design of helium turbines is based on the experiences which have been gained at the closed-cycle gas turbines during more than 12 years. Many structural elements can be adopted from the closed-cycle air turbine without greater modifications. This concerns e.g. the complete power and speed control system. Further experiences, particularly with the working medium helium, will be acquired at the helium turbine plants at Geesthacht and Oberhausen, which will go in operation in 1972; so that in a few years, all conditions for the construction of a 600-mwe nuclear helium turbine plant will exist.

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