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Large Helium Turbines for Nuclear Power Plants

W. ENDRES

Manager of Engineering,
Gas Turbine Division,
Brown Boveri-Sulzer
Turbomachinery Ltd.

A short review of the state-of-the-art of the closed cycle gas turbine technology is given and the future requirements for large helium turbines are described. The necessary development of components and turbine sizes is outlined. In a second part of the paper the configuration and layout of power plants with gas turbines are discussed.

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INTRODUCTION

There have been many proposals (1,2)[1] for the use of closed-cycle helium turbines with high-temperature reactors (HTR) and even gas-cooled fast breeders. Many of these proposals imply some far-reaching extrapolations from present technology. Therefore, it is worth while to examine the state of art today, to assess what size of turbine is needed, and to take the necessary steps to arrive at sound engineering solutions for large atomic power stations. Furthermore, the configuration of such a plant will be discussed.

STATE OF TECHNOLOGY TODAY

The closed-cycle gas turbine has reached the 25-MW range now. It has found rather specialized applications in plants, where power production and heat recovery, particularly in connection with district heating, are combined. The high-temperature level, at which heat is rejected from the gas turbine process, makes it particularly suited for this purpose. This specialized application, more than any principal problems, has limited the power capacity of the closed-cycle gas turbine so far.

A cross section through a 25-MW gas turbine, which is under construction now, is given in Fig.1. The flow of the working gas, which is air in this case, enters at the left side and passes subsequently the low-pressure (LP) compressor, the first intercooler, the medium pressure (MP) compressor, the second intercooler, the high-pressure (HP) compressor, and leaves to the recuperator in which the compressed air is heated by the exhaust from the gas turbine to 345 C (max. 370). Then the gas is further heated in a fossil-fired air heater. At 720 C and 43 bar, the air enters the high pressure (HP) gas turbine and then, via a cross-over duct, the low-pressure (LP) turbine. The air then gives up its residual heat in the regenerator and precooler and returns to the LP compressor. The LP turbine runs at alternator speed (3000 rpm), while the rest of the group turns at

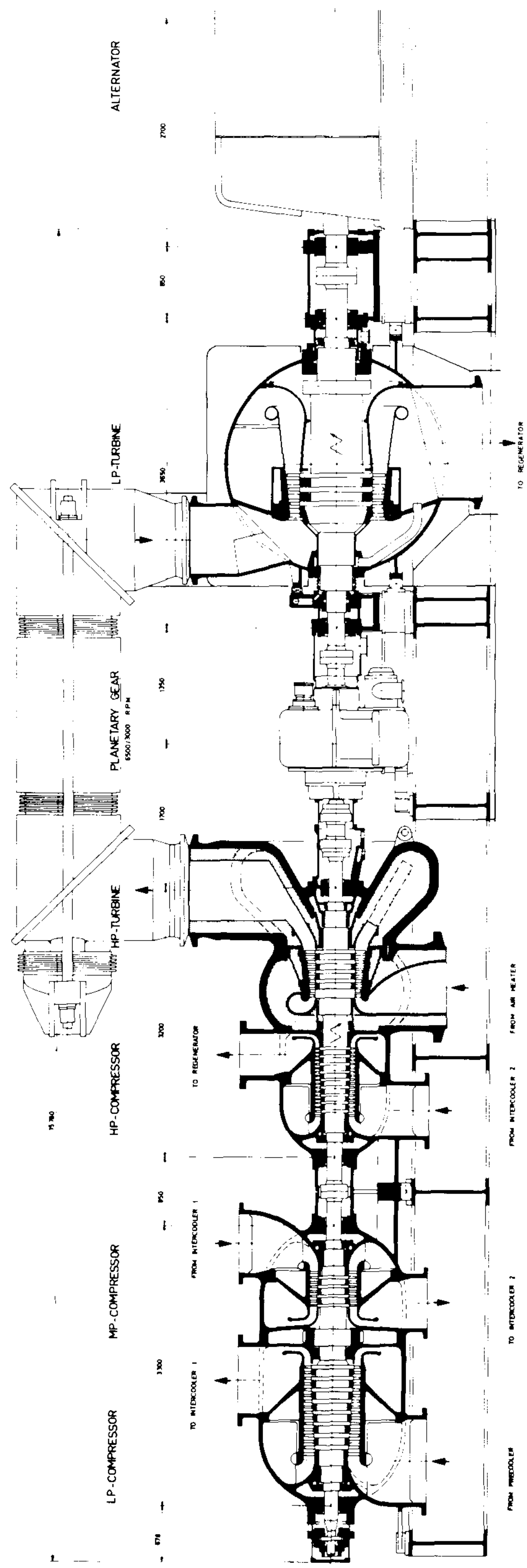


Fig.1 Closed-cycle 25-MW gas turbine for a conventional power plant. Working gas is air

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

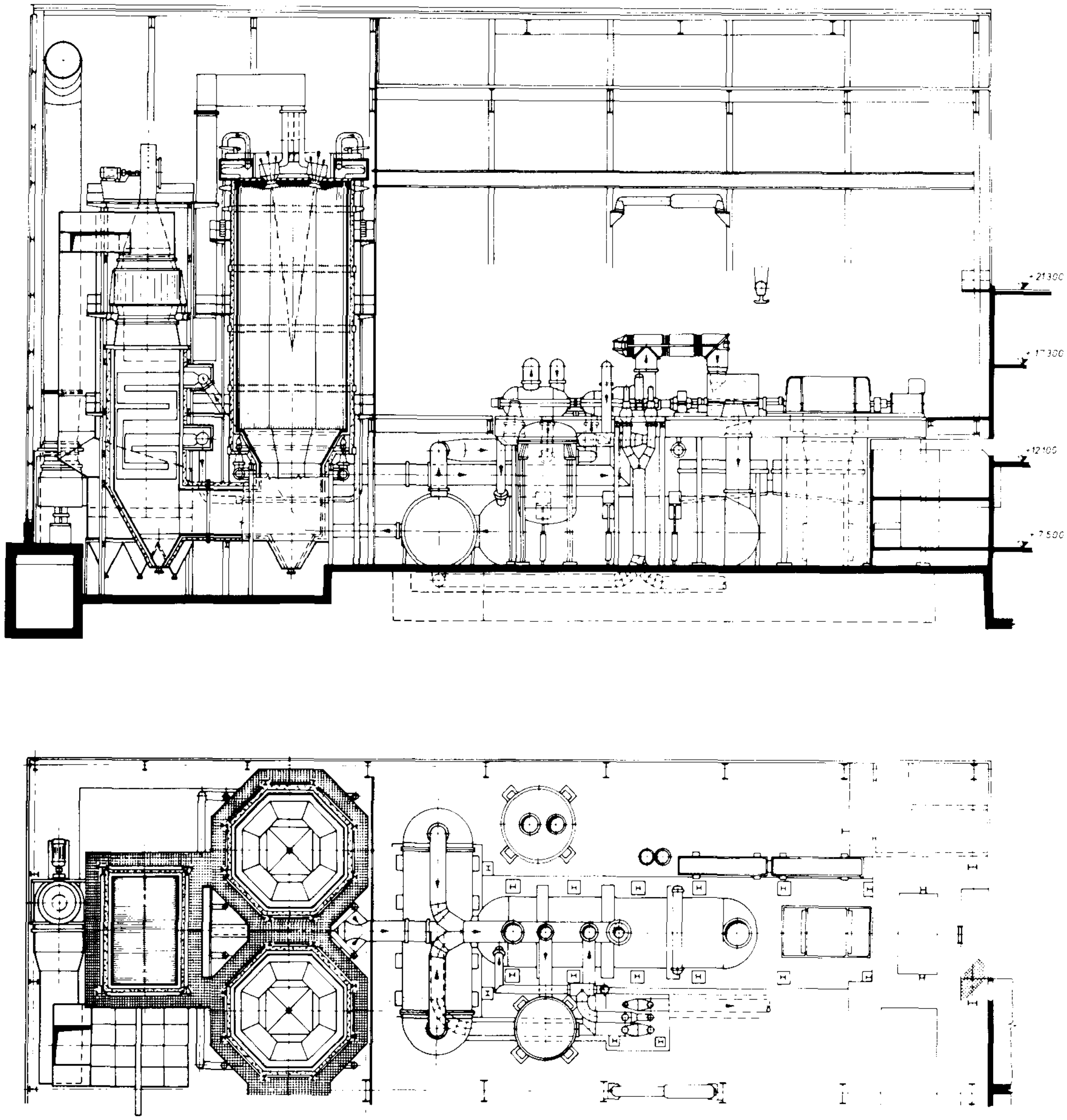


Fig.2 Layout of fossil-fired 25-MW turbine, shown in Fig.1

6500 rpm, which is the optimum for the small volume flows involved. A gear transfers surplus power from the high-speed shaft to the low-speed shaft. A layout of the station is shown in Fig.2. The first impression of this layout is the small size of the gas turbine proper as compared to the heat exchanging equipment. This is a consequence of the relatively poor heat-transfer properties of air. Except for the two air heaters, which in the case of a nuclear plant will be replaced by the reactor, this layout contains all the essential elements of a gas turbine in a nuclear power plant.

As the working gas passes through such a plant, its main and most costly function is to pick up heat and reject it. Therefore, from the very beginning, Ackeret and Keller considered gases with better heat-transfer properties than air. Helium is the best gas in this respect. Also for compressors and turbines, particularly large ones, helium is ideally suited.

This statement is quite opposed to common opinion, but the high velocity of sound in helium allows very high blade tip speeds, which means low bending stresses, and additionally the low pressure and volume ratios lead to relatively small changes in blade length and, consequently, reasonable blade lengths in the first stage of the compressor and the last stage of the gas turbine. The inertness of the gas avoids oxidation and corrosion problems, thus opening the way to high temperatures.

For the preceding reasons, conventional closed-

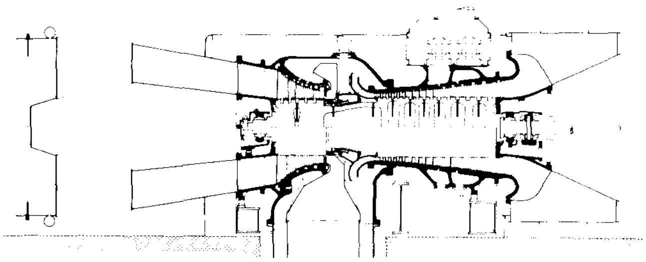


Fig.3 Open-cycle gas turbine of compact design

cycle gas turbines of larger size than 50 MW will use helium instead of air. Comparative studies have shown a considerable reduction in overall plant size, the heat transferring parts for a helium system being about half the size and cost of those for an air system. Even if a complete loss of the helium content every three years is assumed, the economics are still in favor of helium. Plants of 50 to 100 MW are now being considered with helium.

The open-cycle gas turbine has reached the 50-MW range, and very compact designs like that shown in Fig.3 are being built. A main feature of this design is a common shaft for compressor and turbine. The shaft is welded from single disks, which are free of any stress-raising holes, thus forming a monolithic rotor without any mechanical joints. On the turbine side, a cooling system passing through the blade roots protects the rotor material from the high gas temperature.

This design has almost no limitation in size as rotors of 2.7 m dia weighing 200 tons are in production for steam turbines. Starting from this state of the art, let us now look at what is likely to be required in the future.

LARGE HELIUM TURBINES

One of the first questions, which arose in connection with gas-cooled nuclear power plants, was the possible size of helium turbines. Such power stations are expected to be in the 600-1200 MW range, smaller stations probably not being competitive. It is still open to discussion, whether one reactor should be combined with three or more parallel turbines for safety reasons or whether one single turbine can be used. Economic arguments favor one large single set, as with steam turbines where the largest possible units are being developed. A 1200-MW, 3000-rpm single-shaft arrangement has, therefore, been studied; Fig.4 shows a cross section of the turbine. All the essential elements of the conventional gas turbine of Fig.1 can be seen, but due to the higher volume flow, no high speed shaft is necessary and a much

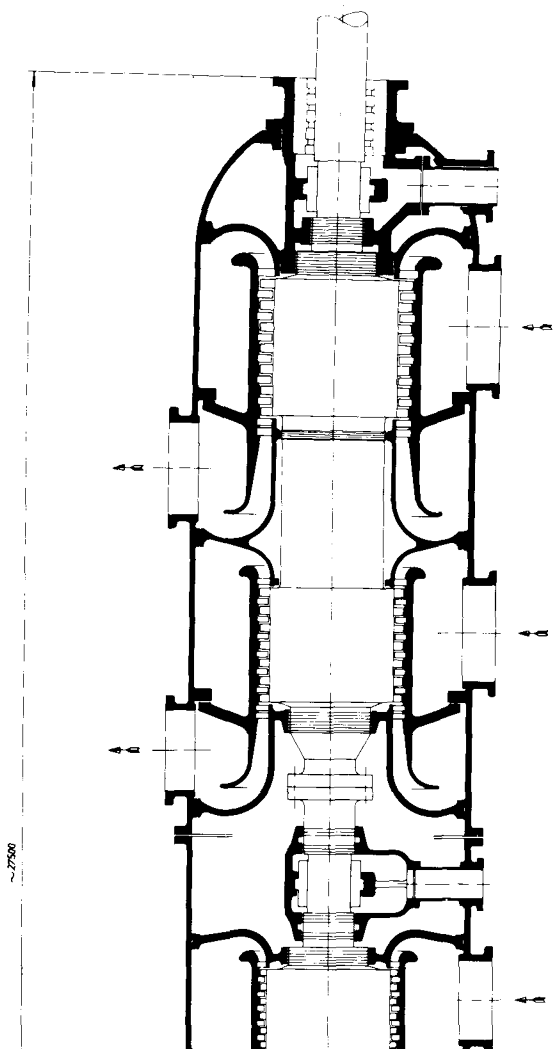


Fig.4 1200-MW helium turbine for nuclear power plant

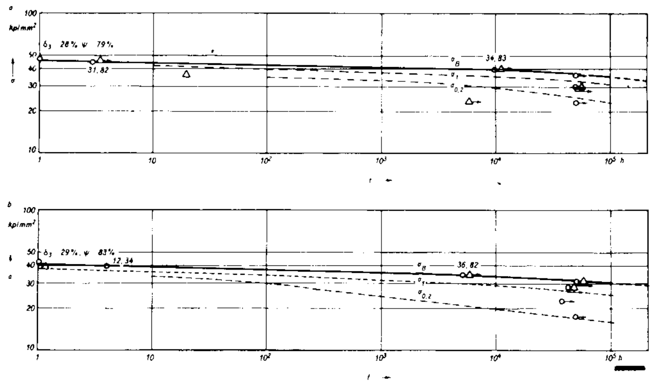
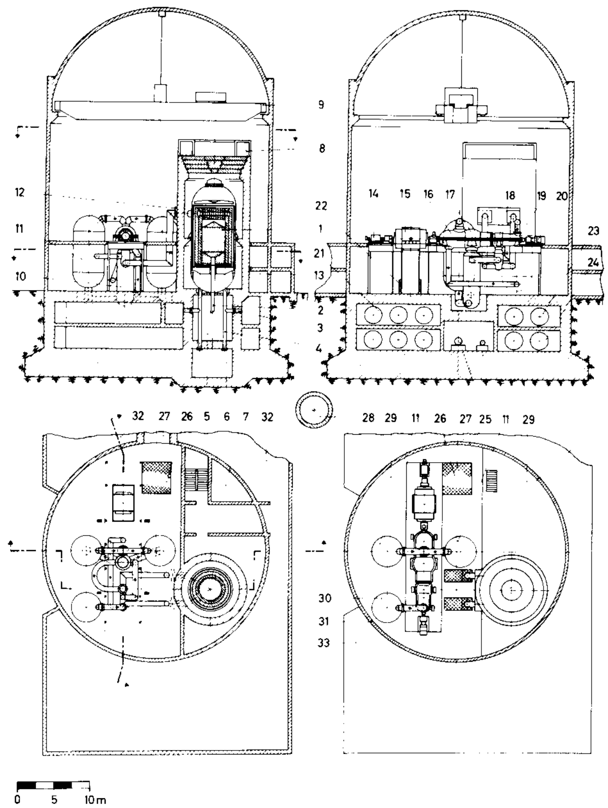


Fig.5 Time-rupture behavior of T_ZM Molybdenum alloy. Tests in helium atmosphere

simpler arrangement results. The LP and MP compressors are on the first rotor, which is coupled to the second rotor on which are the HP compressor and the turbine. Each rotor weighs approximately 100 tons. The second rotor has the same configuration and design as the rotor of the open-cycle gas turbine in Fig.3. Again, the rotor, which is made from ferritic steels using a well proven technology, is cooled in the turbine area with cool helium bled from the HP compressor outlet.

A gas inlet temperature of 950 C was chosen; this is possible with blades made of molybdenum or niobium alloys or by the use of conventional alloys together with conventional blade cooling techniques. Fig.5 shows the result of long-time rupture tests on molybdenum alloys conducted in a helium atmosphere.

Another feature of helium turbines is the requirement for minimum helium leakage, particularly in non-integrated plants. The outer casing is, therefore, of welded design, very similar in concept to the spherical casing of the LP turbine in Fig.1 For the shaft seal, two alternatives are considered: In the first, the alternator would be filled with helium, entering directly from the purification plant. Between the alternator and the turbine, a conventional shaft seal would be placed from which helium would be bled at a lower pressure than that in the alternator and the turbine. This helium would be pumped back into the main cycle. With this method, all helium-air shaft seals could be avoided. A second method would use seals on the main shaft. Such seals would resemble the hydrogen seals of alternators and use oil as a barrier between helium and air. Long operating experience of such seals with comparable diameters and speeds is available. Also in synthetic gas compressors similar seals exist for pressures of 200 bar and higher. For both of these proposals, there is still some development



1 Reactor, pebble-bed type
2 Ball discharge pipe
3 Control rod drive
4 Control rod
5 Fuel loading room
6 Maintenance room
7 Helium purification
8 Water
9 Crane
10 Regenerator
11 Precooler
12 Shut-off valve
13 Operating room
14 Exciter
15 Alternator
16 LP compressor
17 LP turbine
18 HP turbine
19 HP compressor
20 Starting motor
21 LP accumulator
22 Alternator cooler
23 HP accumulator
24 Spare accumulator
25 Transfer compressor
26 Erection opening
27 Air lock
28 Stack
29 Working area
30 Intercooler
31 Prestressed concrete containment building

Fig.6 50-MW nuclear power station with helium gas turbine. Hot gas at 750 C and 40 bar

necessary.

The turbine and the high-temperature pipe ducts are internally insulated in the same way as in conventional closed-cycle gas turbines. Instead of fibrous ceramic insulation, however, a sheet metal insulation is preferred, similar to that used in many gas-cooled reactors.

Thus, the design of such a 1200-MW turbine can be based on well proven elements in many respects

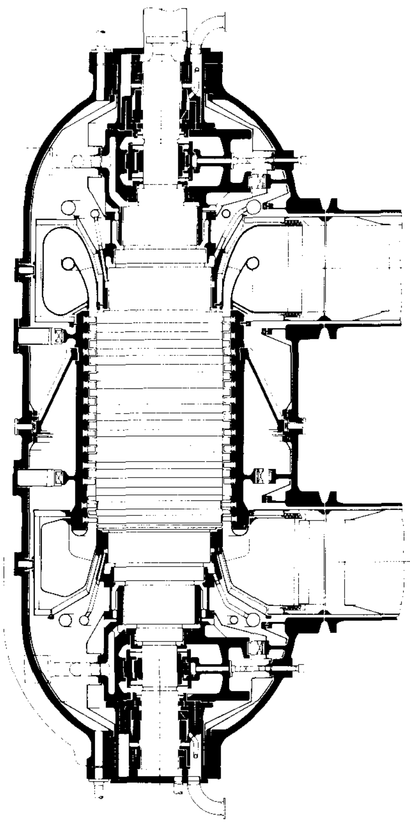


Fig.7 Helium turbomachine for component testing

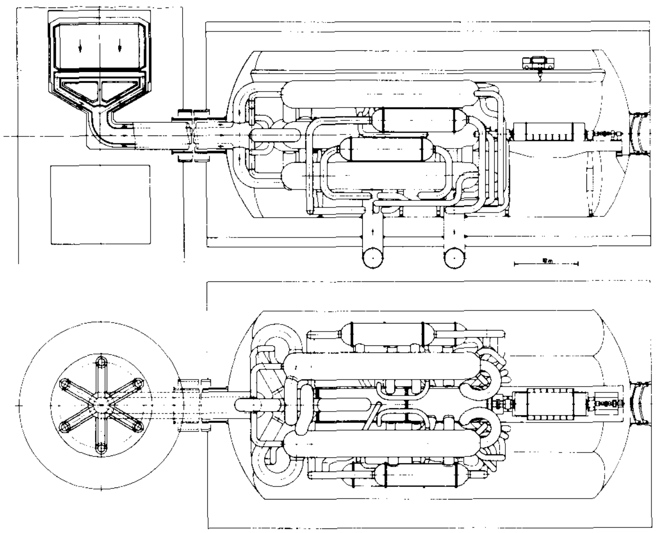


Fig.8 Layout of a 1200-MW nuclear power plant with helium turbine

and leads to a very compact arrangement. The desired goal of a large helium gas turbine can, therefore, be reached with reasonable confidence, based on present technology. Some of the intermediate steps necessary to go from the 25- to 1200-MW size are described in the next section.

FUTURE DEVELOPMENT

It is expected that closed-cycle gas turbines of 50- and 100-MW will be built in the next few years. These would be fossil-fired plants, but studies for nuclear plants are also under way. Fig.6 shows a 50-MW nuclear plant in a non-integrated arrangement. This seems to be the best solution for smaller plants.

Another step is the construction of a turbomachine (Fig.7) of a size comparable to a 300-MW gas turbine. The idea is to demonstrate the feasibility of building a machine containing most of the critical parts of a 300-MW helium turbine, i.e. the high-pressure high-temperature side of the turbine, including inlet casing with its insulation, the first two stages of the turbine, a rotor comparable in size to a 300-MW gas turbine rotor, the bearings and the lubrication system, shaft seals, and all the different cooling systems required. This machine is planned to be part of a test-loop, in which vital components such as pipes, valves, etc., can be tested full size under actual service conditions.

The turbomachine has the task of circulating the helium in the loop; therefore, compressor stages are added after the two first turbine stages. In the compressor section, the pressure is raised from 44 bar to 50.6 bar. The gas leaves at 850 C, but temperatures up to 1000 C can be reached. In the test loop, a pressure drop of approximately 1 bar is provided, and the gas enters the turbine at 49.6 bar. The difference between compressor and turbine power amounts to 33.5 MW; this is provided by a 3000-rpm motor, which drives the test machine.

No external heat has to be added to the loop, since the gas will be heated sufficiently by the aerodynamic losses in the process. Heat equivalent to the power input is removed from the process by coolers in the main loop and in auxiliary cooling loops. The complete test loop is planned under the sponsorship of the Ministry of Scientific Research of the German Federal Republic. It is part of a large program aimed at the development of high-temperature reactors (HTR) in conjunction with helium turbines.

The testing of full-size components under actual operating conditions in the aforementioned test loop is one of the vital steps preceding the construction of a complete power station.

CONFIGURATION OF A HELIUM TURBINE WITH A HIGH-TEMPERATURE REACTOR

The main incentive to combine helium gas turbines in a direct cycle with HTR's is the possibility to reduce generating cost. In such a cycle, the helium, which cools the reactor core, would also be used as working fluid in the turbine. In the gas turbine HTR cycle, the steam generators, necessary for the steam cycle, can be avoided. These steam generators have to be absolutely leak tight to prevent steam entering the helium circuit and corroding the hot graphite in the core. The recuperator of the gas turbine cycle, which is comparable in size to the steam generator of the steam cycle, does not require absolute leak tightness and works at moderate temperatures between 100 to 500 C approximately. A comparison of the most important aspects shows that a capital cost reduction can be expected by the use of the gas turbine cycle. The consequent reduction in generating cost will probably be enhanced by the ability to achieve a higher plant thermal efficiency. The first HTR's are planned with secondary steam cycles and well proven steam turbines for obvious reasons. The gas turbine technology will have to prove that it can reach unit sizes and reliability levels which are comparable to large steam turbines. How this can be achieved was indicated by the first part of this paper.

A question, which is still unsolved, is the optimum means of combining the gas turbine and the reactor cycles. There are many suggestions in the literature (3-6), but the sheer number of proposals shows that no single solution has overriding advantages.

To find the answer, a thorough process of selection and elimination is underway. Some of the main factors to be considered are discussed here, but no definite solutions can be given yet.

SINGLE VERSUS SPLIT-SHAFT

This is a question in which the turbine design plays the leading role and nuclear requirements are of secondary importance.

For the blading of the compressors and the turbine, it is desirable to use the highest possible shaft speed with an optimum tip-to-hub ratio. Since the power turbine speed is given by the alternator, it is necessary to split the shaft for small units to be able to run the compressors and the HP turbine at the optimum speed. In case of loss of load, this configuration gives high overspeeds on the alternator shaft, particularly if large gas volumes between HP and LP turbines are enclosed. Therefore, valves have to be provided to bypass the LP turbine. These valves should be duplicated for safety reasons (as all overspeed protection) and are very large. Therefore, it is also preferred to arrange the LP compressor on the LP turbine and alternator shaft to avoid this problem. Larger units have lower optimum speeds for the HP shaft, and from about 250 MW upward (with 40-50 bar inlet pressure), single shaft units are preferred. For these, overspeed is no serious problem.

For the safety of the reactor, a split-shaft turbine has the advantage that in case of shut down of the LP turbine, the HP turbine can be turned by the starting motor to remove the fission product decay heat from the core.

LAYOUT

A conventional arrangement, as shown in Fig. 6, would follow the lines of classical station design and will certainly be preferred by the gas turbine manufacturer and the operators of the plant. Within the air-filled containment, easy access to all turbomachinery and heat exchangers is possible. The safety aspects are comparable to those of a steam turbine with a Boiling Water Reactor (BWR). Shut-off valves are provided at the reactor outlet so that in the event of failure of external pipework or other accidents, the reactor can be isolated to prevent a loss of reactor coolant accident; this is important to reduce the possibility of reactor damage due to rapid depressurization and to prevent air from entering the primary circuit and reacting with the hot graphite core. The size of the auxiliary blowers to remove the decay heat is reduced if pressure is maintained in the reactor vessel; this is an additional reason for incorporating isolating valves in the design. Two shut-off valves in series are provided for safety reasons in each of the two pipes leading from the reactor to the turbine. Two pipes are provided so that the valves in one pipe can be checked during reactor operation. The pipes and the valves are concentric ducts with the hot gas inside and the cold gas, returning to the reactor, outside in an annular channel. The design of such valves for 750 C and 40 bar is a delicate task, but it is confidently expected that they can be made in the sizes required.

The containment would be designed for a limited internal pressure, and a controlled release of helium to the atmosphere is permitted in case of an accident.

The first nuclear plant to be built with a direct cycle helium turbine, the 25-MW Geesthacht station (2), is based on a similar concept.

With increasing size, the safety requirements will be more difficult to meet. The reactor will be placed in a prestressed concrete reactor vessel (PCRV), and for the turbine, too, a higher degree of integration becomes desirable. If the same concept is used for a 1200-MW station with gas turbine (Fig.4), the arrangement shown in Fig. 8 results. The turbine and all heat exchangers are housed in a containment which can withstand a pressure of 5 bar in case of a pipe rupture. No shut-off valves are provided in the concentric duct which connects the turbine to the reactor. The size of the heat exchangers is considerable and the recuperator has to be split into six parallel flows. The connecting pipes are of considerable diameter and complexity.

A further evolution of this design will try to place all the heat exchangers and ducts into the PCRV and integrate the turbine, too (3). Safety, and possibly costs, benefit from such integration, but maintenance will be more difficult.

Other integrated solutions consider several vertical turbines working in parallel (4). This leads to another topic of our discussion.

NUMBER OF LOOPS AND TURBINES

For small stations, only one turboset is usually considered. Emergency cooling is assured by an auxiliary loop. For larger stations, it is obviously an easy solution to use several small turbines in parallel to achieve the desired output. This allows standardization of turbines and components with the consequent advantages. Another important advantage of the multi-loop layout is the safe cooling of the reactor in case one turbine fails; in this case, no auxiliary cooling loops are necessary. At least three turbines and main loops are required for safety reasons. A disadvantage of the multi-loop layout is the complex governing and valving system needed to run the groups separately.

Single units have the advantage of a simpler layout and lower cost. For a 600-MW nuclear station, a comparison of one 600-MW turbine with 3 x 200 MW turbines shows a 4 to 5 percent station cost increase by the use of three turbines. More than three or four units are, therefore, unlikely to be attractive.

Considering that the development of conventional steam and gas turbines continuously tends toward larger single units, a similar trend can be expected with helium turbines.

CONCLUSION

The development of helium gas turbines can lead to large units within the next few years. Studies of different configurations with the reactor are underway, but no definite choice is possible yet. A tendency to very large units can be expected.

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