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AN ASSESSMENT OF THE FUTURE OF CLOSED-CYCLE GAS TURBINES

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ABSTRACT

The closed-cycle gas turbine (CCGT) has not reached the worldwide level of success that was expected inspite of the strongly desirable features of this concept and the success of several large closed-cycle power plants operating in Western Europe today. However, an assessment of the CCGT's future has recently been made at the Institute of Gas Technology (IGT), and IGT has shown that due to innovative developments in technologies relevant to the development of CCGT's, coupled with worldwide changes in some economic factors, the CCGT could become a successful competitor of other externally fired power plants and also of internal combustion engines, especially in sizes ranging from 200 to 5000 kW. Documentation of data recently published in the technical literature and some recent relevant developments at IGT in the area of combustion, show a promising future for the CCGT.

INTRODUCTION

The first CCGT's using low-turbine inlet temperatures were built more than 35 years ago in Europe (1). Some of these are shown in Table 1.

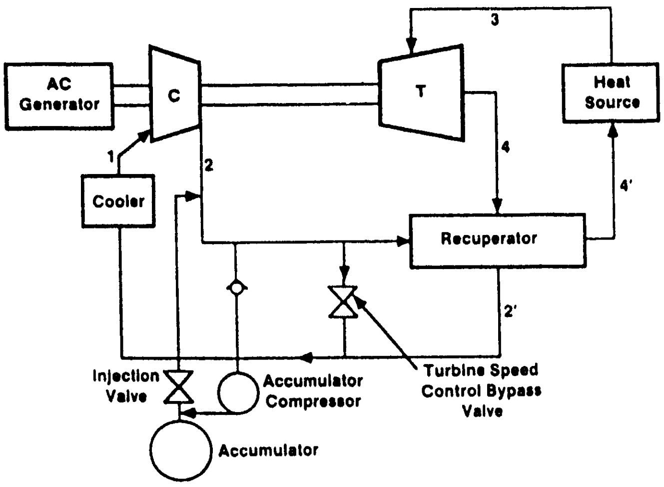
Table 1. EUROPEAN-BUILT CCGT'S

Manufacturer	Power, kW	Location
John Brown	2,000	Atlnabreac
John Brown	700	Foles Hill
John Brown	12,500	Dundee
Escher-Wyss	2,000	Ravensburg
Gutehoffnungs-huette	17,500	Coburg
Escher-Wyss	30,000	Spittlelau

In the U.S., some CCGT's were built in considerably smaller sizes (a few years later) to explore its suitability for special purposes, such as, space power generation with solar and nuclear energy. As a result of these projects, the merits of the closed-cycle concept (shown schematically in Figures 1a and 1b), in which externally generated heat is transferred into a working fluid that circulates in a closed loop, have been fully appreciated for some time. The following is a brief review.

(A) Flow consideration: The physical size of the turbomachinery, the heat exchanger passages, and the magnitude of the friction losses associated with its operation can be greatly influenced by the working fluid. Because of the decisive effects of the molecular weight and transport properties on the Reynolds and Mach number levels in the flow passages, the most common working fluid is helium because it is inert and has a high thermal conductivity. On the other hand, its speed of sound is quite low, requiring a relatively large number of stages in the rotating components for a given cycle pressure ratio. Dilution of the helium with Xenon results in a great improvement.

(B) High turbine inlet temperature potential: When an inert working fluid is used, the resulting absence of corrosion problems simplifies the selection of materials for the highly stressed engine components. Therefore, any number of well-proven superalloys become useable for systems operating with turbine inlet temperatures of up to 1250°K; and several refractory materials, such as, molybendum



	1	2	2'	3	4	4'
P kN/m^2	972	1834	975	1765	979	1800
Temp, K	303	415	469	1256	1018	969

Temperature Ratio	T_3/T_1 = 4.1		Gas Flow Rate	m_e = 2.58 Kg/s	
Pressure Ratio	P_2/P_1 = 1.9		Shaft Weed	n_3 = 52,000 rpm	
Compr. Efficiency	μc = 78%		Cycle Efficiency	μ = 42%	
Turb. Efficiency	μt = 88%				

Figure 1a. SCHEMATIC DIAGRAM OF A CCGT (8)

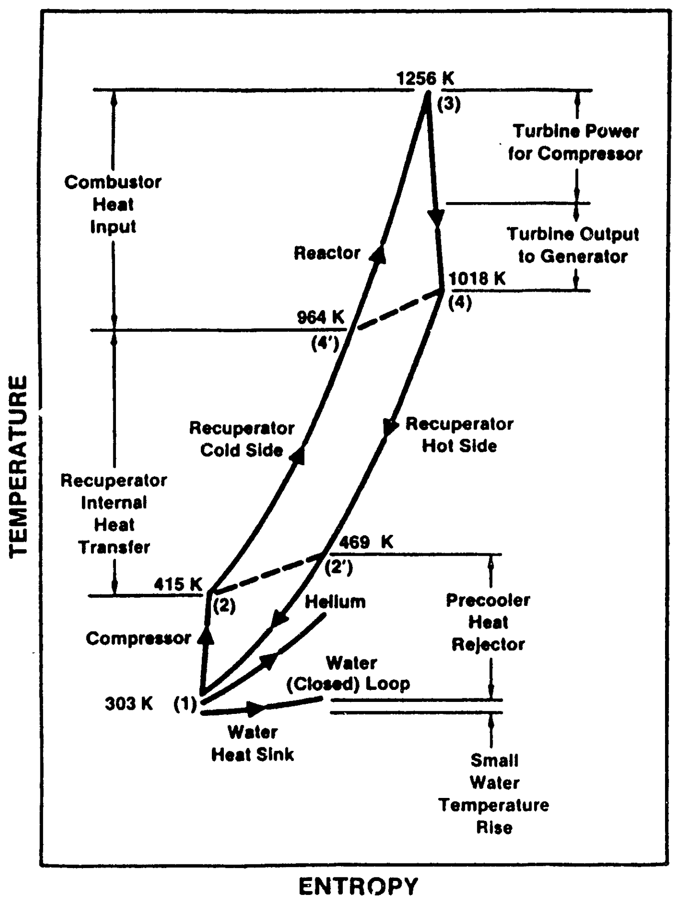


Figure 1b. TEMPERATURE-ENTROPY DIAGRAM OF A CCGT (8)

compounds, can be used at temperatures as high as 1500°K. This way, simple cycle efficiencies can be boosted to values as high as 55% without the need of protective surface coatings or blade cooling. In this context, creep rupture problems are generally being considered minor.

(C) Physical size, part, load, operation, and controllability: Due to the physical separation of the combustion space from the working fluid circuit, the CCGT has the unique feature that an engine or a given physical size can be operated over a wide output range with little or no effect on cycle efficiency by changing the average pressure; i.e., inventory of the working fluid with the aid of a storage vessel. The same scheme allows efficient operation of a given power plant at part load. When, for system control purposes, the maximum rate of change of the power level is too slow, an arrangement can be added to the system that reduces the turbine flow by returning a fraction of the compressed fluid from the discharge of the compressor to its entrance, thereby, by-passing the turbine.

(D) Pollution considerations: In contrast to IC engines, because spatial constraints on the combustion process can usually be avoided in the CCGT, it is relatively easy to keep air pollution under control. It should be noted that pollution by NO_x, CO, and unburnt hydrocarbons can be virtually eliminated by means of a special radiant-convective natural gas burning heater which is being developed at IGT. The features and performance of this device are presented in this paper.

ROTATING SECTION TECHNOLOGY BASE

In the not too distant past, numerous investigations have been made in the U.S. and elsewhere that considered the CCGT from various view points; e.g., for the use of non-petroleum-based fuels (1), exploiting the features of combustion in fluidized beds (2 and 3), the burning of coal (4), and others.

To substantiate the results of this assessment, some pertinent information has been used from a series of publications describing some comprehensive investigations of the CCGT compared to other externally fired power plants. These investigations started with the support of the Office of Naval Research, U.S. Navy, and by some U.S. industrial concerns in 1970 (5), and has been progressing (6, 7, and 8). The study was triggered by the need for compact, light-weight power plants for the propulsion of surface and under-water vehicles, which led to the construction and performance tests of a prototype engine, shown schematically in

Figure 2. It was equipped with a centrifugal compressor and turbine, a ceramic combustor, and a metallic recuperator and cooler. It developed 30 kW with an efficiency of 31% (LHV), when operating at a compressor discharge pressure of 4.9 kN/m^2 and a turbine inlet temperature of 1100°K. This unit demonstrated that the power output could be increased five-fold by raising the turbine inlet temperature to 1250°K and the compressor discharge pressure to 19.4 kN/m^2. At the same time, the thermal efficiency of the engine increased from 31% to 36%. The working fluid in the engine was helium. When this was replaced by a mixture of helium and Xenon a further improvement in efficiency to 41.8% resulted. Figure 3 shows the ramifications of raising the turbine inlet temperature with the aid of high-temperature metals or ceramics achieving significant improvements in efficiency.

In addition to the technological base described in the reports listed in the references, a considerable amount of relevant data are also available from the literature on open-cycle gas turbines that have been obtained in connection with the development of lightweight, efficient prime movers for commercial and military marine applications (9). These are derivatives of the F404 fighter jet engine whose mission objective emphasizes reliability and ease of maintenance in an austere environment. Also, the AGT101 Advanced Gas Turbine Program of NASA that is directed at advancing the development of ceramic technology applicable to high-temperature gas turbine cycles, represents an equally significant data base.

HEAT EXCHANGER TECHNOLOGY BASE

Current technology for commercially acceptable heater designs for a CCGT (such as the one mentioned above for a turbine inlet temperature of 1100°K) usually employs metallic tube bundles. When the temperature is elevated to 1250°K ceramic tube material must be used with a surface temperature that will be around 100°C higher. And in this case, current ceramic heater-tube technology will require some development. In connection with the development of high-temperature heaters, attention should be called to a novel combustion-heater concept which was formulated at IGT. It is described in references 11, 12, and 13 shown schematically in Figure 4. As indicated, this is a surface combustor heater with tubular heat exchanger surfaces that are embedded in a stationary bed of refractory material in which natural gas is burned. The heat liberated by the combustion is occurring simultaneously with the combustion reduces the combustion temperature and suppresses the formation of nitrogen oxides. This natural gas-fired, combustor-heater has a high combustion efficiency and firing density, high-heat transfer rate, and low heat loss. The combustion and high-heat transfer processes in this device are not yet fully understood. However, it seems to be a promising heat source for CCGT's operating with temperatures

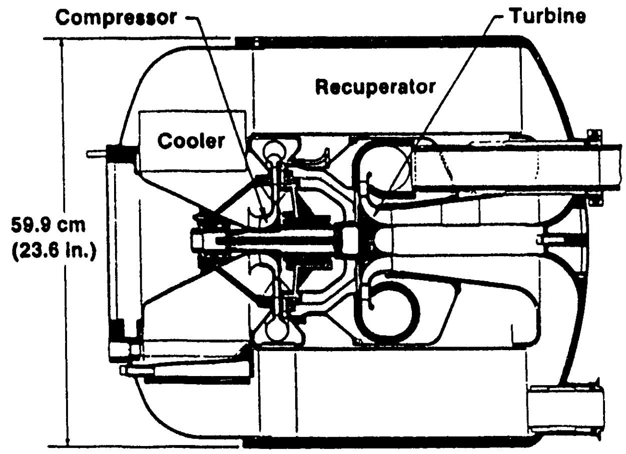


Figure 2. SCHEMATIC OF THE CCPS40 ENGINE (7)

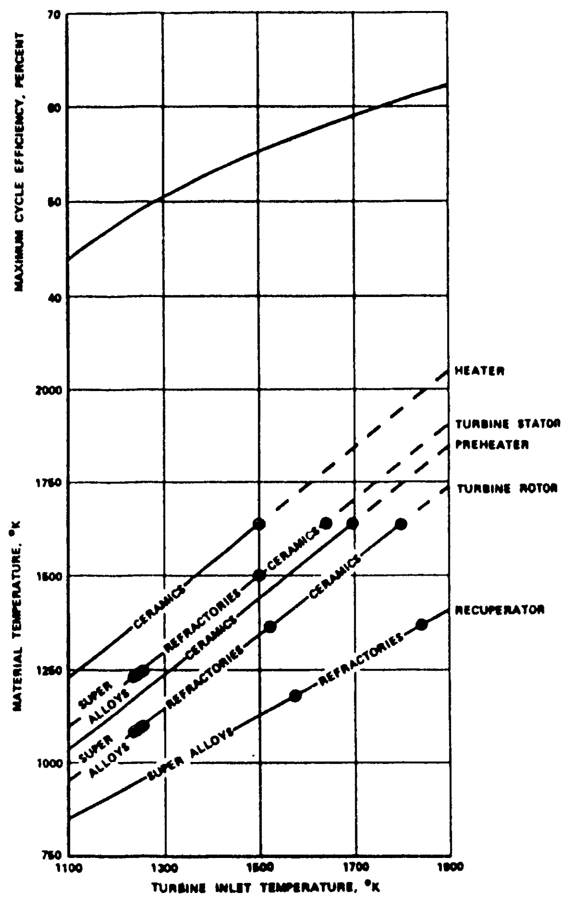


Figure 3. RAMIFICATIONS OF INCREASED TURBINE INLET TEMPERATURE (7)

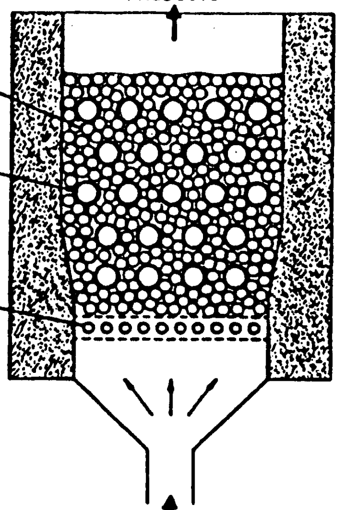


Figure 4. SCHEMATIC OF THE IGT SURFACE COMBUSTOR-HEATER CONCEPT (12)

at the turbine inlet in the vicinity of 1250°K.

CONCLUSION

A compact CCGT with the recuperator operating at a turbine inlet temperature around 1100°K, using standard centrifugal rotor technology, a metallic tube bundle-type heat source, and a helium-Xenon working fluid, can be developed today with the promise of an efficiency of around 35% (LHV). In the size range from 200-3000 kW it could become (fired externally with natural gas), an economically viable power plant for many uses. A future version operating at turbine inlet temperatures around 1800°F, featuring super-alloy rotating machinery and a ceramic IGT-type combustor-heater, could be designed to operate over a very wide power range with an efficiency likely to exceed that of advanced power generating systems of other types.

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