The CC-MGR
Combined Cycle - Modular Gas Reactor

by

Ralph S. Hart
402 Carlisle Rd.
Carlisle, ON, L0R 1H1
Tel: (905) 689-3197
Fax: (905)689-5535
e-mail:rshart@cogeco.ca

Abstract

The Combined Cycle-Modular Gas Reactor (CC-MGR) takes advantage of established combined cycle gas turbine generation (CCGT) technology, utilizing a Modular High Temperature Gas Reactor (MHTGR) rather than natural gas to provide the heat source.

Development of Helium cooled, graphite moderated High Temperature Gas Reactors (HTGRs) began with the Dragon project in the 1950s, and resulted in demonstration and commercial reactors being built in Germany (AVR-15 and THTR-300) and in the US (Peach Bottom 1 and Fort Saint Vrain). By the late 1980s all operating HTGRs were shut down and interest in the technology was fading. However, interest in HTGRs was revitalized over the past 15 years and HTGR research reactors now operating in Japan and in China and a commercial HTGR under construction in China. Two major MHTGR programmes currently in the design and development stage, the Pebble Bed Modular Reactor (PBMR) in South Africa, and the Gas Turbine-Modular Helium Reactor (GT-MHR) by an international consortium headed by General Atomics, are focused on direct closed cycle technology in which the helium from the reactor is passed directly through a helium/gas turbine which subsequently drives a generator. In both of these designs, heat in the helium exhaust from the power turbine is transferred to the helium flow entering the reactor via a recuperator located downstream of the compressors. The amount of heat transferred in the recuperator is slightly greater than the reactor thermal power.

In the CC-MGR power plant, the helium exhaust from the power turbine is directed to a steam generator which generates steam that subsequently drives a steam turbine-generator. The helium leaving the steam generator passes through a recuperator, where heat is transferred to the helium flow entering the reactor downstream of the compressors. This arrangement reduces the amount of heat transferred in the recuperator by approximately half, and results in a reduced reactor helium inlet temperature, which in turn facilitates an increase of approximately 50% in reactor power without reducing the inherent residual heat removal safety characteristics of the MHTGR through the increase of the active reactor core length. This paper focuses on the power conversion system. The reference reactor design is the GT-MHR.

1. Introduction

Recovery of heat from the exhaust of gas turbines is essential to achieving high thermodynamic efficiency in all gas turbine power plants, regardless of the operating media. In the early days of conventional gas turbine development, efforts were made to utilize recuperators, located between the compressor and combustion chamber to recover turbine exhaust heat. Several small power plants were produced, including a unit installed in the Chrysler gas-turbine prototype car. However it was soon realized that large scale recuperator costs were prohibitive, and attention was redirected to heat recovery utilizing a steam cycle. Today, the majority of large gas turbine power plants utilized steam heat recovery (CCGTs).

It is essential to minimize the helium temperature prior to compression in direct cycle Modular High Temperature Gas Reactor (MHTGR) power plants in order to limit the energy required for compression. MHTGRs currently under development, the PBMR and the GT-MHR, utilize recuperators to transfer heat from the power turbine exhaust to the helium flow downstream of the compressors before the helium enters the reactor. In both designs, more heat is added to the helium flow by the recuperator than by the reactor. The recuperators in both designs are very large, and correspondingly expensive. In addition, although the helium compressors are relatively efficient, continuous recirculation of a large quantity of heat detracts from overall efficiency. In the design study presented in this paper, as in the case of CCGT power plants, a substantial portion of the power turbine exhaust heat is transferred to water to generate steam, which subsequently drives a steam turbine.

The reference reactor design for this design study is the General Atomics GT-MHR which has an output of 400 MW thermal. In the CC-MGT power conversion system configuration presented here, the helium temperature entering the reactor is substantially reduced. This facilitates a 50% increase in the active core length, and a power increase to 600 MW thermal, while maintaining the inherent shutdown and decay heat rejection capability of the GT-MHR. The helium temperature at the exit of the additional core length is the same as the GT-MHR core inlet temperature, and the core outlet temperature is the same as in the GT-MHR. Hence, an increase in net electrical output of approximately 50% is realized without an increase in circuit helium flow. There is a significant power gradient over the core length, with the highest power density near the top where helium and graphite temperatures are lowest. Core optimization may lead to a reduction on active core length.

2. The GT-MHR Power Systems

The GT-MHR reactor configuration is presented in Figure 2-1. A simplified GT-MHR power systems flow sheet is presented in Figure 2-2. Conditions around the GT-MHR power conversion circuit are presented in Table 2-1. The GT-MHR power conversion system is housed within a single pressure vessel, and it employs a single shaft configuration, with both compressors, power turbine and generator rotating at 3000 rpm. Advantages of this configuration are the minimization of helium piping and the avoidance of seals for shafts that penetrate the pressure boundary. The generator, housed within the power conversion module pressure boundary is helium cooled and insulated.

Table 2.1: GT-MHR Design Parameters		
	Parameter	**Value**
Reactor	Thermal Power	600 MW
	Helium Temp at core inlet/outlet	490/850 ^oC
	Helium flowrate through the core	316 kg/s
	Helium Pressure at core inlet	7.07 MPa
Turbomachine	Rotor speed	3000 rpm
	Helium Temp at turbine inlet/outlet	850/510 ^oC
Recuperator	Thermal Power	325 MW
	Hot side Helium inlet/outlet temp.	510/125 ^oC
	Cold side Helium inlet/outlet temp.	105/495 ^oC
Precoooler	Thermal power	173 MW
	Inlet/Outlet Helium temp.	125/26 ^oC
	Helium flowrate	318 kg/s
Intercooler	Thermal Power	133 MW
	Inlet/outlet helium temp.	107/26 ^oC
NPP Power Unit	Gross electrical output	285 MW
	Net Electrical Output	278 MW
	Efficiency	47%

3. The CC-MGR Power Systems

The helium flow through the core of the CC-MGR and the core helium outlet temperature are the same as for the GT-MHR. However, since the helium discharged by the power turbine passes through a steam generator where heat is transferred to water to generate steam before passing through the recuperator, the helium temperature entering the reactor is reduced. Due to the lower core inlet temperature of the CC-MGR, this requires a 50% increase in reactor power, from 600 MW_{th} to 900 MW_{th} in order to maintain the same core helium outlet temperature. This is facilitated by a 50% increase in the active core length.

The CC- MGR employs a two loop configuration, similar to that utilized by MOTHER. Each loop includes a compressor module and a power module. A major advantage of this configuration is the intercooler and/or precooler of one train can be used for decay heat removal while maintenance is completed on components of the other train, thereby avoiding the requirement for a separate decay heat removal system. Each loop, as illustrated in Figure 3-2, incorporates a two shaft configuration with the compressors and compressor drive turbine located on one shaft, which rotates at 16,000 rpm at full power, and the power turbine and generator located on a separate shaft that rotates at 3600 rpm. The use of high speed rotating machinery in the compressor module greatly reduces component sizes and cost. Analysis indicates that the coupling of the compressor module and power module of each loop provided by the helium flow is stable under all operating and transient conditions. A single 3600 rpm steam turbine and generator assembly, similar in design to that utilized in CCGT plants, receives the steam generated by the steam generators in both loops. The five shaft configuration described above is appropriate for a demonstration plant, offering the maximum flexibility of operation. However, investigations suggest that commercial CC-MGR plants can be simplified, with a single power module serving both loops. It may also be feasible to connect the steam turbine to the power module generator via a SSS clutch unit, which allows the steam turbine to drive the generator, but precludes the generator from driving the steam turbine. These clutch assemblies are used on all single shaft CCGT plants. However, this requires the development of helium seals for the shaft penetrating the power module: such seals are a feature of the PBMR design. The configuration is thereby simplified, resulting in a three shaft configuration.

Table 3.1: CC-MGT System Design Parameters

	Parameter	**Value**
Reactor	Thermal Power	900 MW
	Helium Temp at core inlet/outlet	310/850 ^{o}C
	Helium flowrate through the core	316 kg/s
	Helium Pressure at core inlet	7.07 MPa
Turbomachine	Rotor speed	3000 rpm
	Helium Temp at turbine inlet/outlet	850/510 ^{o}C
Steam Generator	Thermal Power	292 MW
	Helium inlet/outlet temp.	510/320 ^{o}C
	Feedwater inlet Temp	205 ^{o}C
	Steam outlet Temp/pressure	310 ^{o}C/
Recuperator	Thermal Power	172 MW
	Hot side Helium inlet/outlet temp.	320/125 ^{o}C
	Cold side Helium inlet/outlet temp.	105/310 ^{o}C
Precoooler	Thermal power	173 MW
	Inlet/Outlet Helium temp.	125/26 ^{o}C
	Helium flowrate	318 kg/s
Intercooler	Thermal Power	133 MW
	Inlet/outlet helium temp.	107/26 ^{o}C
Helium Turbine Units	Gross electrical output	285 MWe
Steam turbine Unit	Gross electrical output	111 MWe
Total Net output		396 MWe
	Efficiency	44%

The compressor module (Figure 3.2) houses the low and high pressure compressors, the compressor drive turbine and a standby electric motor within a single pressure boundary. Helium from the compressor drive turbine is discharged to the inlet of the power turbine. The standby motor connects to the turbines shaft via a one way clutch, which prevents the turbines assembly from driving the standby motor, but automatically connects the standby motor to the turbines shaft when the standby motor speed exceeds that of the turbines shaft. This allows the LP and HP compressors to be powered, thereby providing helium circulation through the reactor core, when one of the compressor modules is undergoing maintenance. The standby motor speed is 3600 rpm. There are no shafts that penetrate the compressor module pressure boundary.

The power modules house the power turbines and the generators. The generators are helium cooled and insulated. There are no shafts that penetrate the power module pressure boundary.

4. Summary

The Combined Cycle - Modular Gas Reactor takes advantage of the steam cycle heat recovery technologies that have been developed and implemented for CCGT facilities to facilitate an increase in MHTGR reactor thermal output, and a corresponding increase in net electrical output. The efficiency gains resulting from the increase in thermal power without an increase in helium flow through the reactor largely offsets the relative inefficiency of the Rankin steam cycle relative to the Brayton cycle. Within the accuracy of the calculations, the overall efficiency of the GT-MHR and the CC-MGR are the same.

A significant reductions in specific capital cost (installed dollars per MWe) and in specific Operations and Maintenance cost are achieved, largely through economy of scale. However, the net output of approximately 400 MW electrical remains within the small reactor output range required by many markets.

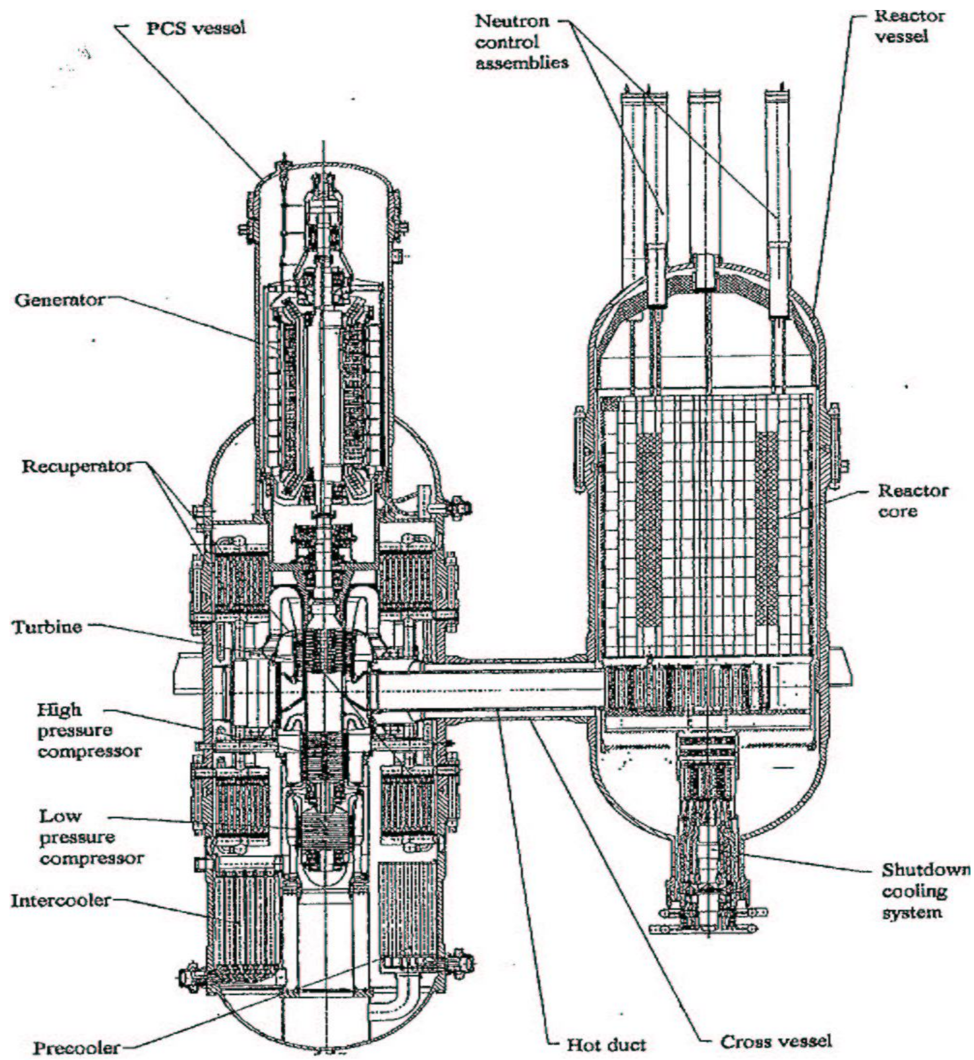


Figure 2.1: GT-MHR Arrangement

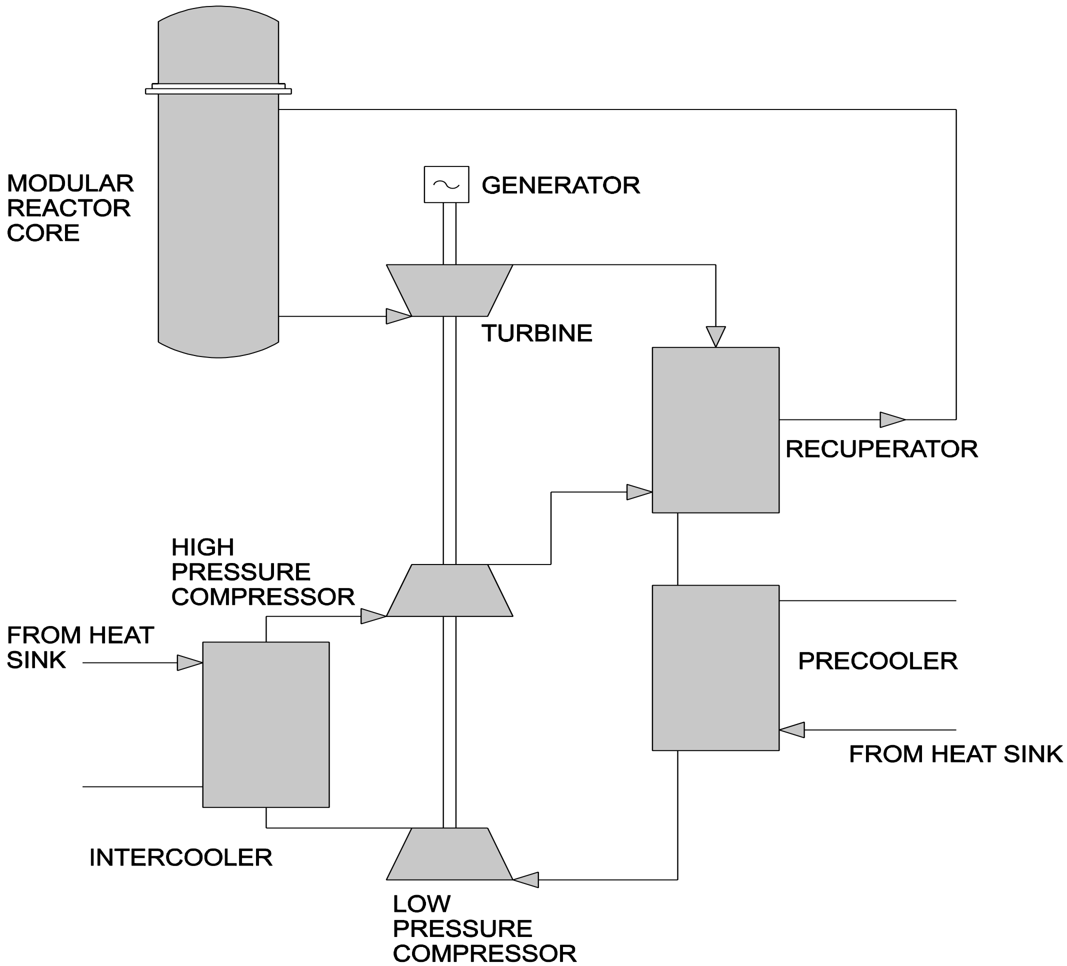


Figure 2.2: GT-MHR Simplified Flow Diagram

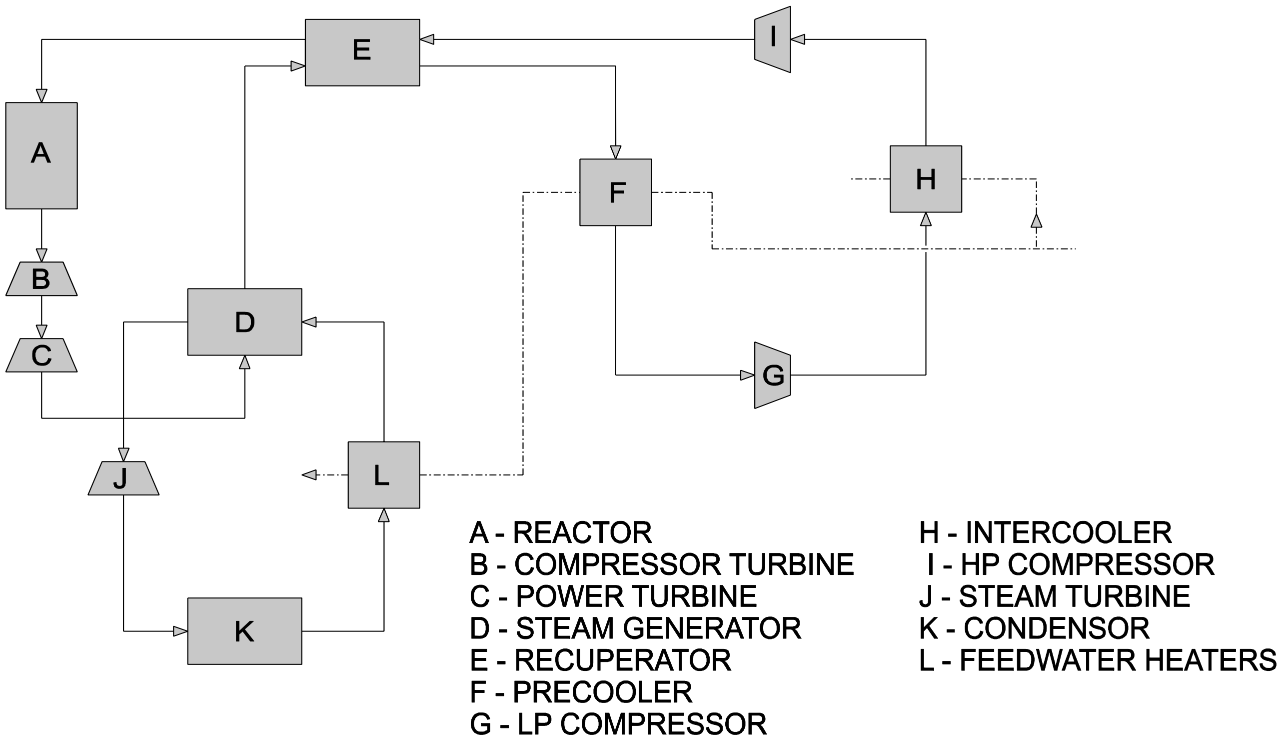
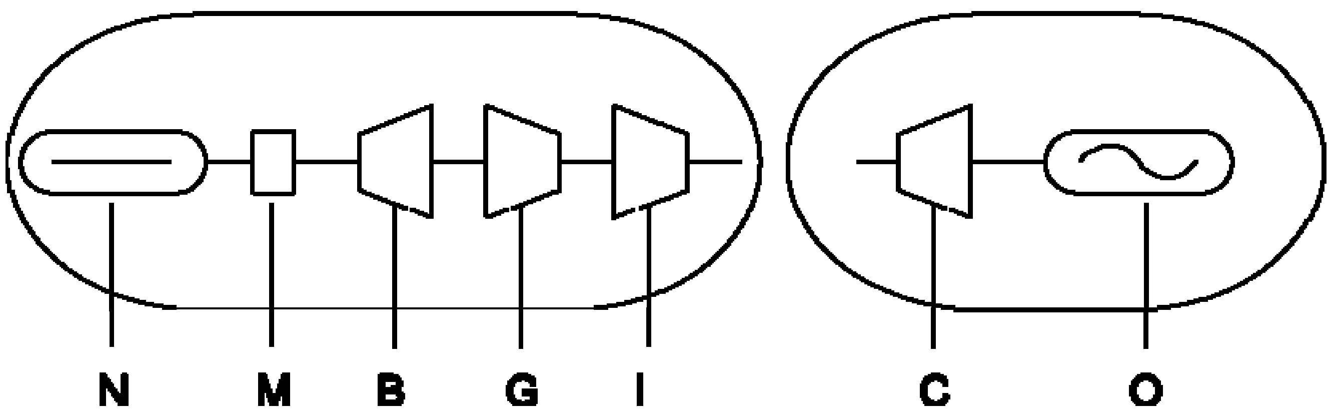


Figure 3.1: CC-MGR Simplified Flow Diagram



B - Compressor Turbine
C - Power Turbine
G - Low Pressure Compressor
I - High Pressure Compressor
M - Clutch
N - Electric Motor
O - Generator

Figure 3.2: Compressor Module and Power Module Configurations