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GENERAL ATOMICS

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ABSTRACT

General Atomics in the USA and Experimental Design Bureau of Machine Building (OKBM) in the Russian Federation have jointly developed a nuclear power plant design, the gas turbine modular helium reactor (GT-MHR). There have been some considerable improvements during the last 10 years, which resulted in a more effective, efficient and safe design. The existing design is based on a 600 MW(t) reactor cooled by helium at a pressure of about 7 MPa. The power conversion unit (PCU) uses reactor outlet helium with a temperature of 850°C in a direct Brayton cycle to achieve the cycle efficiency of about 48%. The PCU consists of a gas turbine, a recuperator, a precooler, low-pressure and high-pressure compressors, an intercooler, and a generator. The turbomachine (TM) includes the turbine, compressors and generator mounted on a single vertical shaft. TM shaft rotation speed is 4400 rpm. The shaft of generator is connected to the turbine shaft by a flexible coupling. The required grid frequency of generated electricity is achieved by a converter. All PCU components are enclosed in a single vessel. TM uses radial and axial electromagnetic bearings (EMB) for support. Catcher bearings (CB) are provided as redundant support for the TM rotor in case of EMBs failure. Several alternative PCU designs were analyzed on the basis of current progress in technologies, new world experience, and experience accumulated in the process of GT-MHR design development. Results of these analyses will be taken into account when a final PCU design is selected.

1. INTRODUCTION

HTGR is the only demonstrated nuclear technology that can achieve reactor outlet coolant temperatures to 1000°C. HTGR is also characterized by high safety and efficient electricity generation with low impact on the environment.

Pilot commercial plants with HTGR designed and built for electricity generation used the proven steam turbine cycle, which ensured reliable operation and reduced technical risks associated with creation of power plants with new reactor designs. Prototype power reactors Fort St. Vrain (USA) and THTR-300 (Germany) with the power of 340 and 300 MW(e) respectively were started in the late 1970s and operated until the second half of 1980s [1,2].

The steam turbine cycle, however, could not provide any substantial improvement of efficiency, which amounted to 40% to 43% with the gas temperature at reactor outlet reaching 800°C.

In the world practice, modern steam-turbine power units with supercritical steam parameters (to 30 MPa, 600°C) achieve net efficiency of 45% and more [3], whereas the efficiency of plants combining open gas turbine and steam turbine cycles can be as high as 58% [4]. However, application of these technologies in nuclear power plants can in the first case increase technical risks associated with development and use of special steels in steam generators and turbines, and in the second case – overcomplicate the design and impair manageability and flexibility.

For various reasons, including economic ones, HTGR development programs in countries most advanced in this field were canceled and active reactors were shutdown.

The potential of HTGR for electricity generation can be fully achieved when it is coupled with a conversion system based on the direct (in the primary circuit) closed gas turbine cycle. With gas temperatures of 850-950°C, efficiency of HTGR plants can reach 50% and more (Fig. 1), which is higher than steam cycle efficiency [5]. Use of direct closed gas-turbine cycle, as compared with the steam cycle, simplifies the design and reduces the required amount of equipment and systems.

One of the most important design simplifications is elimination of turbine hall with steam generator, steam pipelines, condenser, deaerator, etc. This, together with the minimum required number of support systems, makes the power conversion system more compact and reduces its fabrication, operation and maintenance costs.

In view of these advantages, in 1980s OKBM (USSR) considered a PCU with gas-turbine cycle (instead of steam cycle) for their design of nuclear power plant (NPP) with the integrated 1000 MW VG-400 reactor for electricity generation. PCU components were arranged in horizontal and vertical shafts of the reinforced-concrete vessel [6].

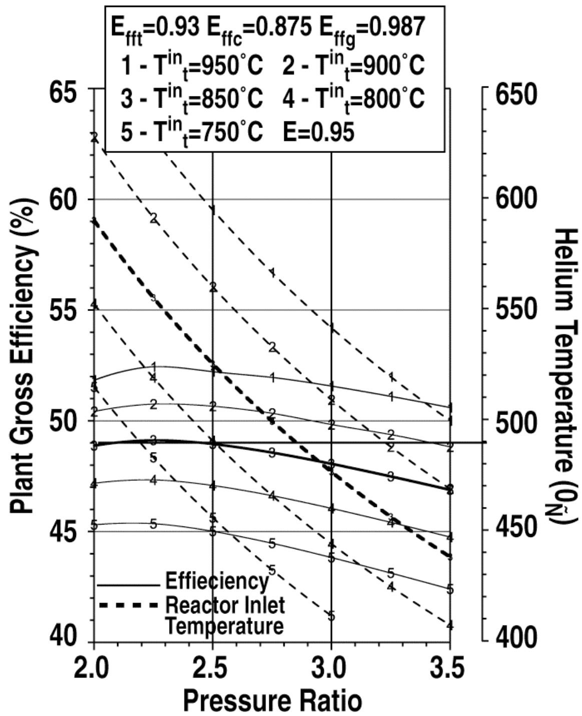

Fig. 1. Impact of reactor outlet helium temperature (at the turbine inlet) on plant efficiency, reactor inlet helium temperature.

By the beginning of 1990s, achievements in the technologies of gas turbines, high-performance recuperators and magnetic bearings opened the way for development of reactor plant coupling a safe modular gas-cooled reactor to an efficient PCU with the Brayton gas turbine cycle.

The leader in coupling of gas turbine PCU (GT) to a safe modular gas-cooled reactor (MHR) is General Atomics [7] who developed the first design of GT-MHR for electricity generation in 1990. By 1994, as a result of several optimizations, reactor power was increased to 600 MW. The GT-MHR PCU was integrated, with a vertical TM [8].

In 1994, after numerous discussions on the future of HTGR, General Atomics and Minatom of Russia founded a jointly financed program for GT-MHR development. Later they were joined by such organizations as Framatome (France) and Fuji Electric (Japan) [9].

GT-MHR is one of the most advanced international projects developed jointly by Russian and American institutes under the auspices of the Russian and U.S. Departments of Energy.

The GT-MHR power plant consists of two interconnected units: modular high-temperature reactor and direct gas turbine cycle PCU. The plant is intended for efficient generation of electricity in the direct gas turbine cycle. Thermal efficiency of the GT-MHR gas turbine PCU amounts to as high as 50%, which is an advantage in the electricity market over any other thermal or nuclear power plant. Preliminary estimations showed that cost price of produced electricity will be the level of 1.3-1.5 ¢/kW•h.

In the end of 1990s, ESKOM Company (SAR) started development of PBMR plant based on pebble-bed HTGR and gas-turbine PCU. Start of the demonstration plant with a 400 MW reactor is planned for 2011 in Koeberg [10]. The PCU design of this plant passed through a number of modifications. Currently, it is a distributed PCU with a horizontal TM and generator outside the primary circuit.

Starting from 2000, JAERI, Toshiba, and Mitsubishi (Japan) are working on a state-funded program to develop a commercial 300 MW(e) GTHTR300 plant with HTGR and gas turbine cycle [11]. This design has a distributed PCU layout and a horizontal TM.

INET (China) have designed and are now manufacturing a gas-turbine PCU for the experimental 10 MW HTR-10 reactor that was brought to power in January 2003 [12]. The PCU design is consolidated and the TM is arranged vertically.

The variety of gas turbine PCU configurations in modern HTGR power plant designs is indicative of the need to continue the search for optimal technical solutions. Absence of actual operating experience complicates this task and may require detailed research and comparison of technical and economic indicators, as well as technical risks.

2. GT-MHR PCU DEVELOPMENT

2.1. GT-MHR PCU

The power conversion unit of GT-MHR (Fig. 2) in the 1994 design (GA) for the direct Brayton cycle consisted of a synchronous generator stiff joined to the turbocompressor with rotational speed 3600 rpm equal to electrical grid frequency (in USA). It had a reference helium mass flow rate of 320 kg/s.

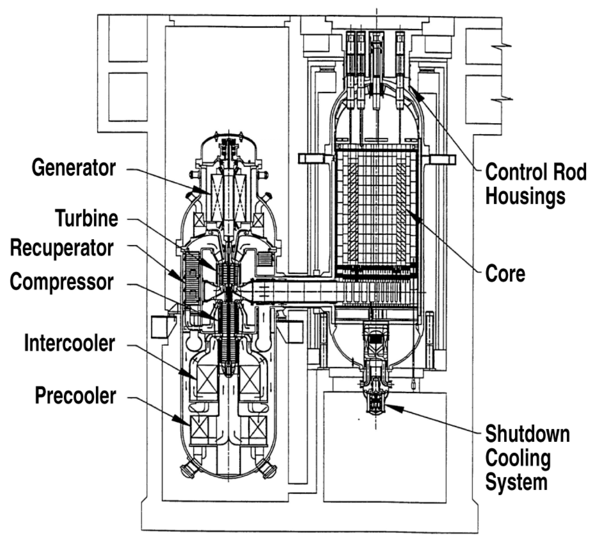

Fig. 2. GA GT-MHR design (1994).

The reactor core in the design has been modified to accommodate a larger power generation up to 600 MW of thermal power while still maintaining passive safety.

The entire turbomachine rotor, including the generator, was supported by active magnetic bearings – 5 radial bearings (2 in generator and 3 in turbocompressor) and one double acting thrust bearing (between generator and turbocompressor). Catcher bearings were employed for use during turbomachine shutdown and loss of active EMB and were made of a combination of plain surfaces and rolling elements. Rotor construction selection was lightweight and rigid. This was selected for reasons of lower required bearing stiffness and remote disassembly. The use of magnetic bearings eliminated the use of complicated shaft seals and expensive helium/oil separation systems, as well as lowering the requirements of the helium purification system. By doing so, negative environmental effects and costs associated with disposing of contaminated oils, filters, and oil system components were reduced. In addition, magnetic bearings have significant advantages for the rotor dynamic of turbomachine shaft. Since they are electronically controlled, they provide active dampening of the system, helping to avoid shaft deflections as the shaft passes through critical speeds by changing the dampening as a function of rotational speed. By doing so, they can also provide real-time monitoring of the system (such magnetic bearings are manufactured by Waukesha Magnetic Bearings, Franklin, Wisconsin, USA).

The further development of project PCU was carried out in OKBM (Russia) for which rotation speed of 3000 rpm was accepted equal to frequency 50 Hz in the electrical grid (in RF). The reactor prismatic block design with low-pressure drop was maintained and thus a higher power conversion efficiency was achieved compared to a pebble bed design.

The following new constructional decisions were realized in the project:

- Flexible coupling between the turbocompressor rotor and the generator rotor;
- The rotor of the generator and turbine is supported by two radial and one axial active magnetic bearings;
- Heat transfer equipment is modified (recuperator, coolers);
- The unloading device in turbine helium entrance area excluding a bend of turbomachine stator is inserted;
- Heat transfer modules of a recuperator are located on two levels, providing axial helium flow with uniform distribution and the minimal pressure losses;
- Coolers are located at one level, and the horizontal massive plate dividing them inside PCU is excluded;
- Buffer repair seal providing isolation of a generator cavity from the first circuit is inserted.

The GT-MHR reactor module is located in an underground containment building as shown in Fig. 3.

The components of the primary cooling loop are housed within two metallic pressure vessels that are connected by a cross-vessel (Fig. 4). One of the vessels contains the modular high-temperature reactor nuclear heat source and the other the PCU.

The PCU design is based upon a recuperated direct gas-turbine cycle that is optimized for minimum cost and high efficiency. During normal operation, the heated, high-pressure helium leaving the core is routed via the hot duct inside the cross-vessel to the turbine where it is expanded to produce mechanical energy. The mechanical energy produced in the turbine is used to drive the generator, as well as two compressor stages located on the same shaft. In the recuperator, residual thermal energy is recovered from the reduced pressure, but still hot gas stream exiting the turbine.

The helium then enters the precooler which is the main heat sink for the cycle. The cool low-pressure helium is compressed in two stages with intermediate cooling in the intercooler. It is then directed to the high-pressure side of the recuperator, where it is preheated, using thermal energy recovered from the turbine exhaust. It is then routed to the core via the annular passage between the outer shell of the cross-vessel and its internal hot duct.

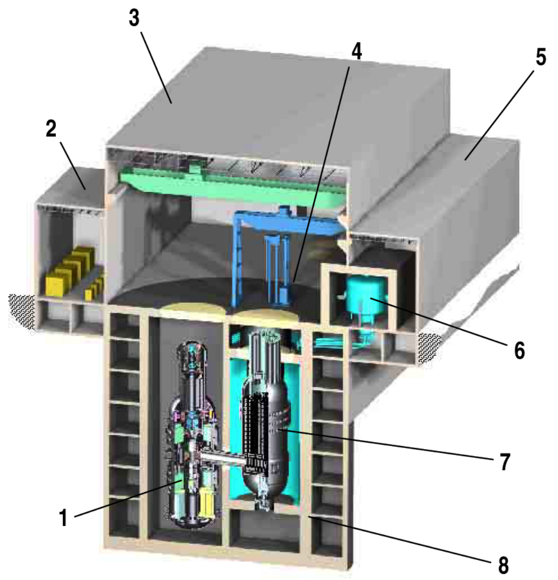

Fig. 3. GT-MHR reactor module layout.

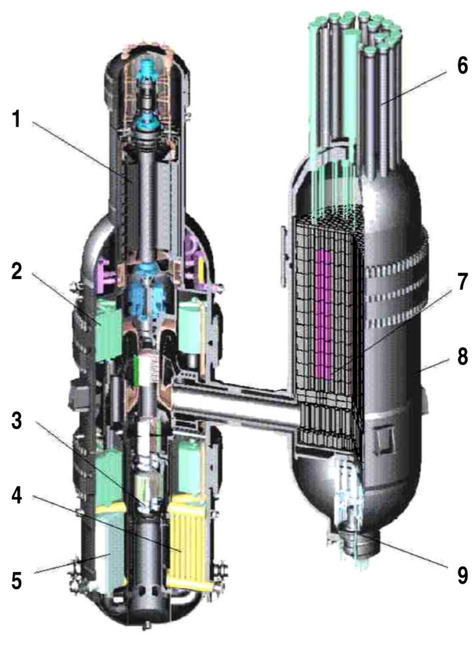

Fig. 4. Key components in the GT-MHR reactor unit.

Although the gas cooled rector can be designed to produce helium at temperatures up to 1000ºC, a helium temperature of 850ºC was chosen for the current design as a compromise between efficiency and material limitations.

The current design is a further iteration of the past GT-MHR. It has been modified for an increased power density and improved economics. In addition, advances in turbomachine technology, such as magnetic bearings, have enabled advancements in the PCU design.

The PCU was modified in the current design for a direct Brayton cycle. For the turbomachine, a higher speed of rotation was accepted. As a result, the size of the turbine decreased, resulting in an overall decrease in turbomachine component weight. There are substantial differences between the current and previous turbomachine design (Table 1).

Table 1
PCU GT-MHR

	Project (GA) 1994	**Project (OKBM) 1997**	**Project (OKBM) 2003**
Reactor power, MW(t)	600	600	600
Rotation speed, rpm	3600	3000	4400
He mass flow rate, kg/s	320	320	320
Turbocompressor shaft mass, kg	1.27×10^4	4.20×10^4	3.26×10^4
Generator shaft mass, kg	4.0×10^4	6.93×10^4	3.50×10^4
Generator stator OD, cm	281.9	392	331
Generator stator ID, cm	78.2	125.5	104
Turbomachine shaft mass, kg		11.1×10^5	6.76×10^4
Turbomachine shaft length, cm	1696	3070	2429
Turbine inlet pressure, MPa	7.0	7.03	7.01
Max. load TC radial EMB, kN	60	60	28
Max. load generator radial EMB, kN	120	120	34
Max. load TC axial EMB, kN		378	333
Max. load generator axial EMB, kN		694	357
Turbine stages	11	12	9
High pressure compressor stages	19	24	13
Low pressure compressor stages	14	16	10

Some of the key differences in the new design arise from the increase in rotation speed from 3000 to 4400 rpm. This change results in the reduction of stages in the compressors and turbine. This in turn leads to a reduction of costs of manufacture and an overall reduction of mass. In addition, the faster generator has a thinner shaft, which results in a weight reduction of 48.5%. The lighter generator is requiring a smaller volume in the stator. As a result of the reduction in weight, the radial and axial loads on the electromagnetic bearings are reduced as well. The figures noted on the table for EMB loads are based on the weight of the shaft alone. During conditions such as seismic events, the load would be significantly increased on radial EMB.

It is important to note that even though the current design produces more power, it does so at a reduced turbomachine weight. In addition, the substantially fewer stages in the compressors and turbine contribute to make it lighter overall. Aside from these similarities, most of the other parameters have been left essentially unchanged, such as the turbine inlet pressure, flow loop and thermodynamic cycle. The end result is a lighter machine, which current EMB technology can support, that produces a higher power output.

The current design has many advantages from previous iterations. These optimizations have been performed to ensure safety and economics.

2.2. DIRECT VERSUS INDIRECT CYCLE

The direct Brayton cycle (Fig. 5) had an impact on economics. By using a direct energy conversion cycle, the system achieves a higher efficiency than the indirect cycle. In addition, because there are fewer components, there is a reduced capital cost.

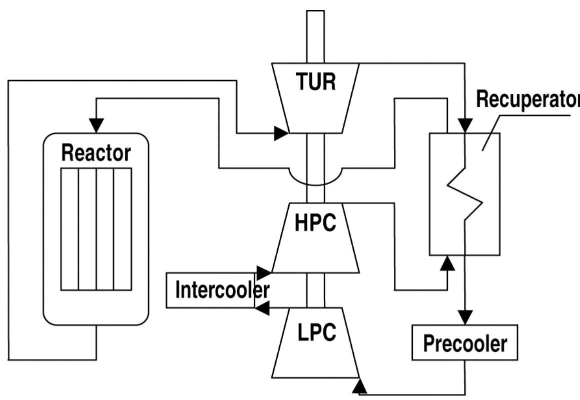

Fig. 5. Direct cycle GT-MHR flow diagram.

Using an intermediary heat exchanger (IHX), whose flow diagram is shown in Fig. 6, had some technical problems and substantially increased cost, as well as potential licensing difficulties. An IHX represents additional piping and potential for leaks, as well as increased pressure losses in the system. These problems are eliminated by using a direct cycle. In addition, there is no secondary loop, which had increased cost due to the increased material costs. Eliminating the IHX had the added benefit because of lower development costs and simpler construction.

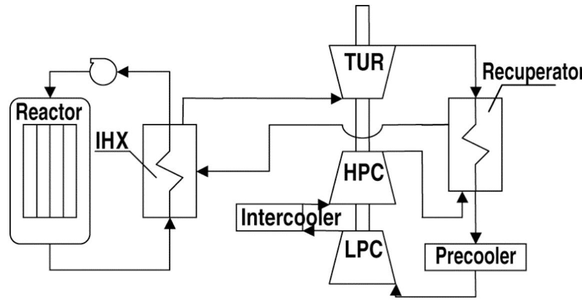

Fig. 6. Indirect cycle GT-MHR flow diagram.

The direct cycle is nonetheless very similar to the indirect cycle. On the secondary side, the reactor is essentially replaced by the IHX. This allows for some flexibility and additional future upgrade possibilities, but ultimately succumbs to the previously mentioned issues. From a thermodynamic standpoint, however, both systems are identical, with either the reactor or IHX serving as the power source (Fig. 5). However, due to temperature drop across the IHX, the inlet temperature to the turbine will be lower (15-50°C), in the indirect cycle, reducing the conversion efficiency by ~2% to 3% (Fig. 1).

2.3. VERTICAL VERSUS HORIZONTAL TM

The use of a vertical PCU has been proven to be compatible with the current reactor design. The PCU can also be placed in a below-ground embedded architecture, reducing capital costs and enhancing public safety and invulnerability to terrorist attacks. In addition, the vertical design allows for circular closures, which are much simpler to couple and uncouple, and making maintenance more straightforward. One disadvantage of integrated design, which needs further study, is the effect of deblading accident, and resulting missile problem on all the components in a single PCU vessel. As well as in GT-MHR, advantages of vertical orientation turbomachine were determining at development of the project experimental PCU for reactor HTR-10GT (Fig. 7).

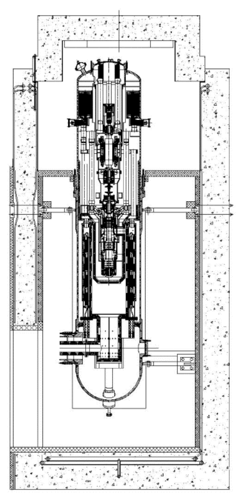

Fig. 7. Layout of the HTR-10GT PCU.

Turbine thrust can present a problem in horizontal systems (Fig. 8), but a vertical system makes use of gravitational force to offset thrust, further simplifying the system.

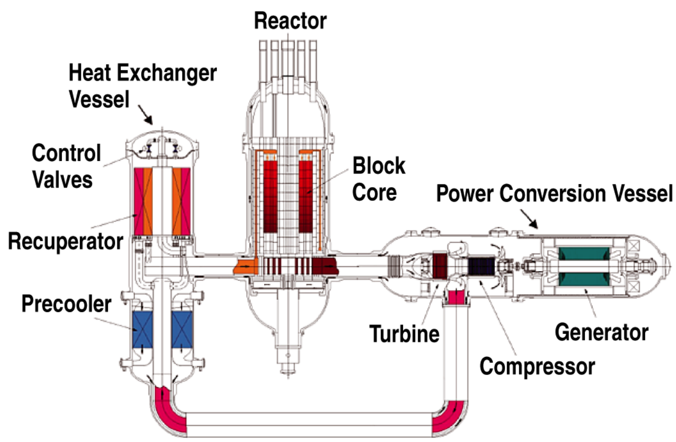

Fig. 8. GTHTR300 plant system arrangement.

The key disadvantages of the vertical system are the axial bearing loads and a more difficult lateral support path. Bowing of the shaft in a horizontal configuration is a serious hurdle in gas turbines. Because of gravitational forces, horizontally-laid shafts tend to bow a few millimeters. In addition, the blades for a helium system are significantly smaller than for earlier CO_2-cooled and steam cycle turbines. In the older, synchronous 3000 rpm design, this may have been mitigated. In the newer design, however, the shaft rotates much faster, at 4400 rpm. This causes the turbocompressor size to be smaller, leaving a clearance between the blades and the vessel stators in the order of millimeters.

Bowing in the shaft of horizontal turbomachine a few millimeters could cause decreasing the efficiency of its components. In a vertical configuration, the shaft is not bent by gravitational forces, solving this problem.

Integrated versus distributed PCU. The reasoning for selection of an integrated PCU stems mainly from economics and the elimination of piping (Fig. 9).

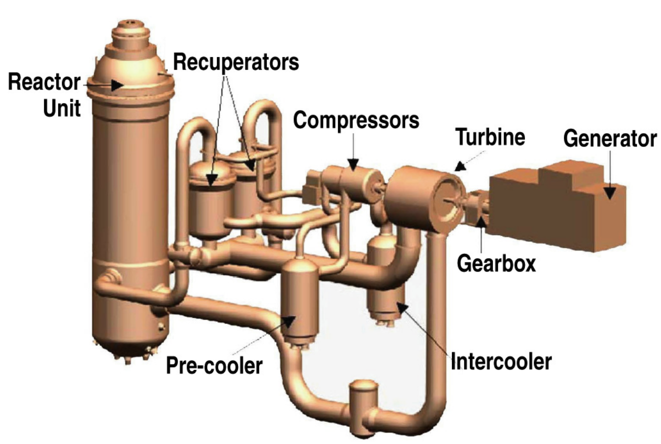

Fig. 9. PBMR main power system.

By using an integrated system there are minimum pressure losses and reduced bypass flows (~4% to 5%). In addition, using fewer materials directly translated into lowered capital costs, despite slightly higher manufacturing costs.

Having an integrated setup also had substantial advantages from a material standpoint. By containing the turbine and recuperator in the same region, the volume and surface area in the high-temperature region is reduced. This translates into lower creep and fatigue of the material elements in the shaft and a longer component life, which helps with maintenance schedule, availability of the plant and economics.

The primary pressure boundary is minimized in an integrated design. By doing this, the system is made more robust and resistant to leakage. There are some key disadvantages to using an integrated design, but they are substantially less than those present in a distributed design. The main disadvantages present in this design consist of a more difficult initial integration and development. In addition, by keeping all components in a highly integrated fashion, maintenance access to them is inevitably made more difficult.

2.4. SUBMERGED VERSUS EXTERNAL GENERATOR WITH OIL BEARINGS

By submerging the electromagnetic bearings and the generator, we can avoid having to use a rotating seal in the primary pressure boundary. This would inevitably bring about additional complexity in attempting to prevent leakage of the primary coolant. In addition, the system pressure would be limited to safe limits dictated by the gas seal.

Using electromagnetic bearings has been shown to reduce energy losses compared with conventional oil bearings. In fact, the losses due to EMBs are less than one-half of those caused by conventional oil bearings. In addition, oil bearings pose additional complexity problems and the risk of leakage of oil into the primary coolant and ultimately into the core. This would create further problems for neutronics, core materials degradation, and decontamination. Electromagnetic bearings have also been proven to be more reliable than conventional oil bearings in the field. This is due in part to the fact that there are no contacting parts that could wear with the primary pressure boundary or rotating shaft. In addition, the complexity of high-pressure oil lubrication auxiliary systems is done away with. The electronic nature of the EMBs also allows for an inherent real-time on-line diagnostic system.

There are some key disadvantages in this design, however. The main disadvantage is that EMBs have a lower unit load capacity than oil bearings. In addition, there is a need to use auxiliary catcher bearings to allow for emergency malfunction in the EMBs and during transport of the components.

Although not part of the reference design, we are seriously considering this option.

2.5. INTERCOOLING VERSUS NONINTERCOOLING

One single stage of intercooling the power conversion system brings about additional efficiency gains of ~4%. In addition, packaging multiple intercoolers in the single vessels would further complicate mechanical design. Studies have shown (Fig. 10) that additional intercoolers lead to insignificant increase of efficiency. One single stage of intercooling is the ideal, and after that, the costs and increased complexity outweigh the benefits [5].

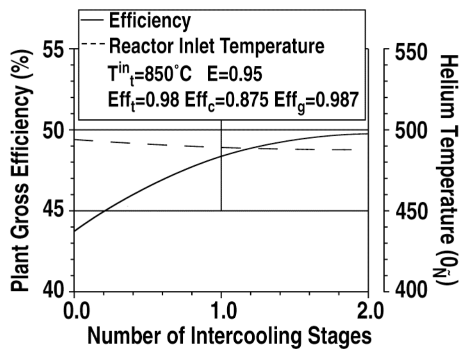

Fig. 10. Impact of intercoolers number on plant efficiency, reactor inlet helium temperature.

2.6. FLEXIBLE VERSUS STIFF COUPLING

A flexible (diaphragm) coupling was used in the current design in favor of the stiff coupling previously considered in the turbomachine. This coupling is designed to transfer torque between the two shafts during normal operation and accident conditions and allows some displacement in the axial, radial, and angular directions. This enabled to isolate vibrations and eigenshapes in the turbocompressor from traveling into the generator and vice-versa. It also reduces the number of critical speeds that are seen by the electromagnetic bearings and reduces control complexity by functionally separating the turbomachine into two separate machines, each supported by two radial bearings and one axial bearing. The axial load is in this manner split into two independently supported paths.

Because of the asynchronous speed of 4400 rpm (73 Hz), a frequency converter had to be employed. Technology for this converter is based on high voltage direct current designs (HVDC), a well-established technology. At this size, converter efficiency is estimated to be no less than 98.5%. The frequency converter is also used in conjunction with the generator to provide monitoring of the turbocompressor for PCU startup. The frequency converter allows for the higher rotational speed of TC, which in turn allows for a reduced weight. In addition, the higher rotational speed allows for a higher efficiency of the turbocompressor.

2.7. MULTIPLE PCU LOOPS

The weight of the PCU vessel and loads on the bearings can be reduced by use two parallel loops with two PCU vessels and two sets of turbo-machines (TMs).

2.7.1. Rotor Size

The turbine and compressors for two PCU design (TPD) will be smaller due to 50% power produced by each unit. Smaller machines have a maximum performance at a higher speed. A preliminary study has estimated that a 150 MW TC will have an optimum speed of 5000 rpm, compared to 4400 rpm for a TC of 300 MW.

- Torque = Power/N
- $\sigma = Tr/J$

where T = torque, N = speed, σ = stress, r = radius, J = modulus of rigidity.

Since power to be transmitted is smaller and rpm is higher for TPD, the mass of the rotor is reduced by ~ 40% to 21 T from 35 T.

2.7.2. Vessel Size

The reduction of the TC size will reduce the PCU vessel diameter and height to about 70%. Since the thickness of the vessel is determined by:

$\delta = PD/2\sigma$

where, P = pressure, D = diameter, δ = thickness

The thickness required for smaller PCU vessel will reduce to 60%. Thus the estimated weight for smaller PCU vessel will be ~300 mT. This will greatly facilitate handling, transportation and fabrication of the vessel.

The calculated parameters for 2 PCU design are compared to the reference design in Table 2.

2.7.3. Loads on EMBs

Reduced size of the TC and generator reduces loads on the electromagnetic bearings (Table 3). The axial load on the bearings (due to rotor weight) will be reduced to 60% and dynamic loads on the radial bearings will be reduced to 75%. Also, the energy to be absorbed by catcher bearings will be reduced due to smaller rotor weights.

2.7.4. TC Designs

No helium TCs of the size required for GT-MHR have been built to date. Thus a 150 MW TC will be a smaller extrapolation than to built a 300 MW TC.

2.7.5. Frequency Converter or Gear Box Size

The current design needs a frequency converter of 300 MW capacity. An alternate design of the GT-MHR under consideration will use a rotating gas seal with external generator. In this design, a gear box capable of transmitting 300 MW of power will be required to change the 4400 rpm of the turbine to 3000 rpm required for the synchronous generator. Neither the frequency converter nor the gear box of 300 MW capacity exist in the world. Use of two PCUs will need smaller extrapolation from the existing technology.

Table 2
Data for Single and Two PCU Designs for GT-MHR

Parameter	1 PCU	2 PCU
Thermal power, MWt	600	600
Net plant efficiency, %	48.5	47.5
Helium inlet/outlet temp, °C	581/1000	581/1000
Rotational speed, rpm	4400	5000
Turbine mass flow rate, kg/s	301	150.8
Turbine stages number	9	10
Adiabatic turbine efficiency, %	93.0	93.0
LPC volumetric flow rate, m^3/s	75	48.4
Number stage LPC / HPC	9/14	10/16
HPC outlet helium pressure, Mpa	7.24	5
Overall pressure ratio in compressor	2.86	2.68
Adiabatic LPC /HPC efficiency	88/87	88/87

Table 3
Loads on EMBs

	Reference Design	Two PCU Design
Load on Axial EMB of Generator (rotor weight), t	35	21
Load on Axial EMB of TC (rotor weight), kN	30	21
Load on Radial EMB of Generator (dynamic load), kN	3.4	2.8
Load on Radial EMB of TC (dynamic load) , kN	2.5	2.5

2.7.6. Flow Distribution in Lower Plenum

Another advantage of two PCU design, overlooked till now, is flow distribution in lower plenum of the reactor (Fig. 11). In the reference design of the GT-MHR reactor, all down flow from the core travels to one side of the lower plenum to-wards the hot duct. For TPD, flow to the hot duct and from the cold duct will be more uniform.

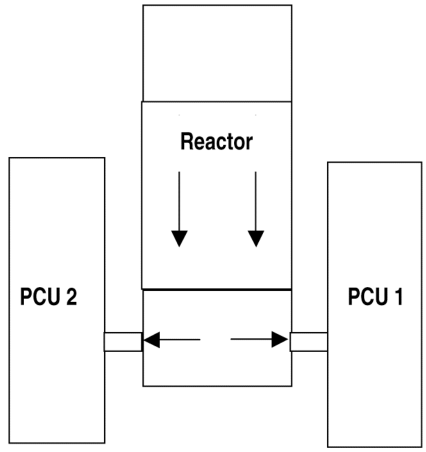

Fig. 11. Flow distribution in lower plenum will be better with 2 PCU design.

2.7.7. Availability

With two sets TMs, the probability of both failing at the same time will be reduced. Thus, the availability of power, admitted at lower value, will be higher.

2.7.8. Negatives

The advantages of multiple PCUs have to be evaluated against lower efficiency (1% less due to size and clearances), bigger building size, difficult control and more cost.

Although not part of the reference design, we are seriously considering this option.

3. CONCLUSIONS

The GT-MHR is the culmination of 40 years of work in the area of Brayton-cycle-coupled nuclear reactor systems. It has many advantages in the areas of economics and safety that are unparalleled by current light water systems. With the modular helium reactor design, the GT-MHR provides additional flexibility to be used in unison with hydrogen generating stations or other such industrial processes requiring high process heat.

The unique design of the Brayton-cycle PCU offers additional advantages over conventional LWR turbines. Coupled with the MHR, efficiencies of ~47% to 51% are attainable; much higher than the ~32% of conventional LWRs. In addition, the PCU and MHR require a smaller housing structure, and no containment building like that present in LWRs. Gas turbine MHR's modular nature facilitates preconstruction and remote assembly at the site, thus significantly reducing construction costs and length of time required.

After several iterations, we have concluded that the current design has many advantages, which currently make it the most desirable option. The vertical design eliminates bowing caused by gravity, allowing a smaller clearance between the blades and stationary components and, thus, higher efficiency, ensuring that the turbocompressor blades don't fail by coming in contact with the walls and allowing higher rotational speed. In addition, a smaller footprint is required to house the equipment, lowering construction costs. By using an integrated design we can also minimize the extent of the primary pressure boundary and the volume in the high temperature region of the PCU. This option also represents the minimum pressure losses and bypass flows, improving the efficiency by ~4% to 5%. In addition, this design has the lowest capital cost.

REFERENCES

[1] Walker, R., and Johnson, T., "Fort St. Vrain Nuclear Power Station," Nucl. Eng. Int. **14**, 163, 1069 (1969).

[2] Mattic, W., "Technical Status and Potential for the HTR Line in the FRG," Proc. 4th Intl. Conf. on Peaceful Uses of Atomic Energy, Geneva, Switzerland (1971).

[3] Oeyhansen, H., Bergmann, D., Termuehlen, H., "Large Steam Turbines for Advanced Power Plants," American Power Conf. 1993.

[4] Siemens AG Corporate Communications Media Relations, 80312 Munich, Germany. Reference Number: PG 200509.071_e, September 26, 2005.

[5] Golovko, V.F., Dmitrieva, I.V., Kodochigov, N.G., Kuzavkov, N.G., Shenoy, A.S., "Features of Adapting Gas Turbine Cycle and Heat Exchangers for HTGRs," Proc. Tech. Committee Mtg., Palo Alto, November 14-16, 2000. IAEA–TECDOC–1238, 2001, p. 63-74.

[6] Golovko, V.F., Kiryushin, A.I., Kodochigov, N.G., Kuzavkov, N.G., "State of HTGR Development in Russia. Design and Development of Gas Cooled Reactors with Closed Cycle Gas Turbines," Proc. Tech. Committee Mtg., Beijing, China, Oct. 30 – Nov. 2, 1995.

[7] Labar, M.P., Shenoy, A.S., Simon, W.A., Campbell, E.M., "The Gas-Turbine Modular Helium Reactor," Nuclear News, **46**(11), 28 (2003).

[8] "Power Conversion Unit Development Plan," General Atomics Report, San Diego, California (2004).

[9] Kiryushin, A.I., et al. "Project of the GN-MHR High-Temperature Helium Reactor with Gas Turbine," Nucl. Engin. Design **173**, 119 (1997).

[10] Johan Slabber, "The PBMR Power Conversion Unit Design," presented at the IAEA Workshop on Safety Demonstration and Market Potential for High Temperature Gas Cooled Reactors, Sep. 27-30, 2004.

[11] Xing Yan, Takakazu Takizuka, Shoji Takada, Kazuhiko Kunitomi, Isao Minatsuki, Yorikata Mizokami "Cost and Performance Design Approach for GTHTR300 Power Conversion System", Nucl. Engin. Design **226**, 351 (2003).

[12] Wang Jie., Huang Zhiyong, Zhu Shutang, Yu Suyuan, "Design Features of Gas Turbine Power Conversion System for HTR-10GT," Proc. HTR–2004 Conf. on High-Temperature Gas-Cooled Reactors, Beijing, China, Sep. 22-24, 2004.

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