GA–A25381

EVOLUTION OF THE POWER CONVERSION UNIT DESIGN OF THE GT-MHR

by

C.B. BAXI, E. PEREZ, A. SHENOY, V.I. KOSTIN, N.G. KODOCHIGOV,
A.V. VASYAEV, S.E. BELOV, and V.F. GOLOVKO

APRIL 2006

GENERAL ATOMICS

DISCLAIMER

GA–A25381

EVOLUTION OF THE POWER CONVERSION UNIT DESIGN OF THE GT-MHR

by
C.B. BAXI, E. PEREZ, A. SHENOY, V.I. KOSTIN,*
N.G. KODOCHIGOV,* A.V. VASYAEV,* S.E. BELOV,*
and V.F. GOLOVKO

This is a preprint of a paper to be presented at the 2006 International Congress on Advances in Nuclear Power Plants, at Reno, Nevada, June 4-8, 2006 and to be published in *Nuclear Science and Engineering.*

*Experimental Design Bureau of Machine Building, Novgorad, RF

Work supported by
the U.S. Department of Energy under
DE-AC03-00SF21868

GENERAL ATOMICS PROJECT 30058
APRIL 2006

GENERAL ATOMICS

ABSTRACT

General Atomics in the USA and Experimental Design Bureau of Machine Building (OKBM) in the Russian Federation are jointly developing a gas turbine modular helium reactor (GT-MHR). The 600 MW(t) reactor is cooled by helium at a pressure of 7 MPa. The power conversion unit (PCU) uses the reactor outlet temperature of 850ºC in a direct Brayton cycle to achieve an efficiency of about 48%. The PCU consists of a gas turbine, a recuperator, a precooler, a low-pressure compressor, an intercooler, and a high-pressure compressor. The turbo machine (TM), including the generator, is mounted on a single vertical shaft. The TM rotates at a speed of 4400 rpm. The asynchronous generator is connected to the turbine by a flexible coupling. The required grid frequency is achieved by a converter. All PCU compon-ents 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. These design features were determined after a comprehensive study carried out over the last 10 years. This paper describes the evolution of the current PCU design and justification for the choices.

I. INTRODUCTION

Interest in the coupling of gas cooled nuclear reactors to gas turbine power conversion systems dates back to the early 1960s. The Army's Mobile Low Power Reactor (ML-1) is one of the first examples of such design.[1] The ML-1 was a nitrogen-cooled, direct Brayton cycle, 3.3 MW(t)/330 kW(e) prototype system. Around the same time, Los Alamos started operating the Ultra High Temperature Reactor Experiment (UHTREX); a 3 MW(t) helium-cooled, graphite-moderated reactor with an outlet temperature of 1320°C.[2]

More recent helium-cooled designs included developments in the UK, France, USA and Germany. The Dragon design was built in the UK and operated form 1965 to 1975.[3] It was a test reactor, with no electrical power being generated. It ran at 20 MW(t) in a steel vessel, making use of TRISO (fuel coated with four ceramic layers) fuel particles for the first time. They were placed in fuel compacts arranged in cylindrical geometry. A few years later in 1967, the Peach Bottom reactor was built in the U.S.[4] It made use of cylindrical fuel elements, in much the same way as Dragon. This was a power reactor, producing 115 MW(t) and 40 MW(e) in a steel vessel, but unlike the Dragon, the fuel elements were composed of BISO (fuel coated with two ceramic layers) particles. The Peach Bottom reactor operated until 1974, providing a successful demonstration of the technology. In 1979, the Fort St. Vrain reactor was built by GA.[5,6] It was similar to earlier concepts in its use of fuel composed of TRISO particles, but the fuel assemblies were arranged in a hexagonal fashion. The power level in this reactor was 842 MW(t)/330 MW(e). The Fort St. Vrain reactor was GA's first iteration of the gas cooled reactor concept. It used a Prestressed Concrete Reactor Vessel (PCRV) for containment of the primary coolant in a pressurized environment and as a biological and thermal shield.

The successes of Fort St. Vrain and Peach Bottom, among others, led to the sale of a number of steam cycle high temperature gas cooled reactors in the U.S. in the late 70s. These were very large HTGRs, with power levels of 2000-3000 MW(t). Most of the orders were received by GA and were scaled-up versions of the Fort St. Vrain reactor using a PCRV. Unfortunately, these orders were soon canceled or withdrawn as a consequence of an adverse political climate towards nuclear power.

Germany built another gas-cooled reactor using a PCRV after the construction of Fort St. Vrain; the Thorium High Temperature Reactor (THTR)[7] started operation in 1985 after a 15 year construction period. The added complexity and cost of the PCRV, along with strong public opposition, was partly responsible for its extended construction period. Following the THTR, Japan and China built the HTTR[8] and the HTR-10,[9] respectively. These reactors were both brought online in 1998, nine years after the HTTR shutdown in 1989. Both these reactors use a (ASTM A336 F22 or F91 for example) steel reactor vessel, and this has since been considered as the favored reactor vessel material. The U.S. development of modular HTGRs began in the 1980s when congress encouraged the industry to develop a "simpler, safer" design. Until that time, reactors had been designed with a height-to-diameter ratio of ~1/1 for neutron economy reasons. Further studies showed that elongating the core to a H/D ratio of 2-3, combined with a lower power level, could lead to passive cooling through conduction, convection, and radiation to the surrounding structures during shutdown in case of a loss of coolant scenario.[10] This ensured the fuel particles maintained their integrity and retained fission products within the TRISO coatings.

To ensure fission product retention and fuel integrity under accident conditions, the physical size and thermal power of the core had to be reduced. Initially, this resulted in a thermal power of 200 MW. However, this would not have been economically feasible at the time compared to competing energy sources. To increase the power level in the core, the annular fuel design was devised. Placing the reflector at the center of the core allowed for an increased power level by flattening the thermal flux profile in the core and therefore reducing power peaking. In addition, surrounding the fuel ring by graphite ensured rapid conduction of heat in an accident scenario (and provided the desirable thermal inertia). Thus, the first modular plant to be designed consisted of an annular core with a thermal power of 350 MW. This plant was coupled with a steam cycle through an intermediate heat exchanger and had a thermal efficiency of 38%. At the time of its design (late 1980s) this was barely economically competitive, so further design optimizations were performed that allowed a core power increase to 450 MW(t), and subsequently to 600 MW(t) making use of economy of scale. Subsequent design modifications for economic improvements included replacing the Rankine cycle with a high-efficiency direct Brayton cycle to increase gross cycle thermal efficiency to ~50%. Using the gas turbine in conjunction with the MHR forms the GT-MHR.

The GT-MHR system retains all the safety features of the MHR nuclear design, but is more economically attractive.

.

II. EVOLUTIONARY GT-MHR PCU DEVELOPMENT

The development of the GT-MHR was spearheaded with a General Atomics design in the 1990s (Fig. 1). This design consisted of a 450 MW annular core MHR. Several options were considered regarding the power conversion unit, namely steam cycle, and direct cycles and indirect GT cycle. In the indirect cycle, options studied were a Rankine and Brayton cycles. The Rankine cycle was considered because of the ample experience and tract record of steam turbines in the industry, but their efficiency was limited to 42.7% (at He temperature of 700ºC and steam temperature of 540ºC). The Brayton cycles had much higher efficiencies of 50.3% in the direct cycle and 47.6% in the indirect cycle (at He temperatures of 850ºC).

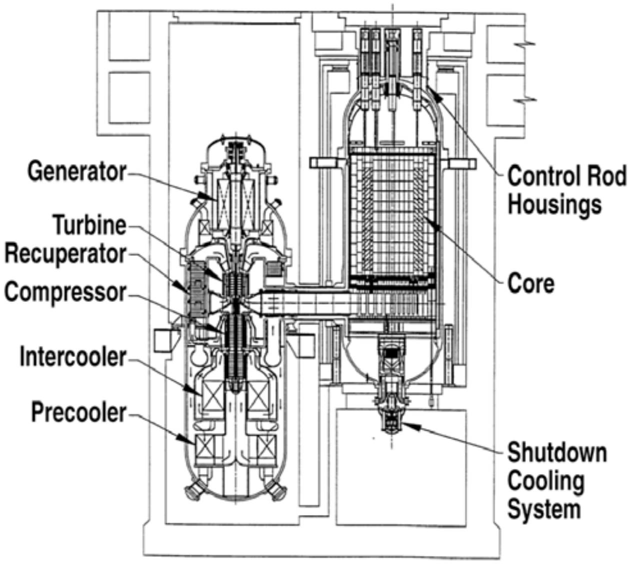


Fig. 1. Previous GT-MHR Design (1990).

The design core was the standard annular MHR design. It consisted of a three-ring active core region containing 84 fuel columns, a 4-ring inner reflector, two rings of outer reflector and the permanent reflector. This core was meant to generate 450 MW of thermal power.

The power conversion unit in the 1990 design for the direct Brayton cycle consisted of a synchronous 3000 rpm generator joined to the turbocompressor with stiff coupling. It had a reference helium mass flow rate of 239 kg/s. Because of its low rotational speed, the turbine and compressor blades were larger and required more stages than the current design, and the diameter of the shaft in the generator was 1.025 m; larger than the 0.9 m in the current design. As a result, the length of the shaft was also shorter.

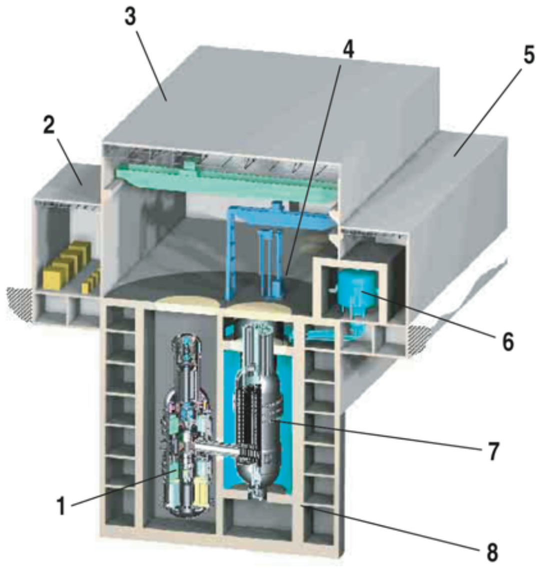
The entire turbomachine rotor, including the generator, was supported by active magnetic bearings, two radial bearings, and one double acting thrust bearing. Catcher bearings were employed for use during turbomachine shutdown and loss of active EMB and were made of a combination of plain surfaces and rolling elements. Rotor construction selection was lightweight and rigid. This was selected for reasons of lower required bearing stiffness and remote disassembly. Further turbodynamic optimization of the design led to a preference of operating speeds higher than 60 Hz. The turbomachine consisted of a turbine, a high-pressure compressor, and a low-pressure compressor. Selection was made for use of a single intercooler between the two compressors in favor of multiple intercoolers because additional intercoolers would significantly offset the gains from lowering the compressor adiabatic head. In addition, packaging multiple intercoolers in the single vessels would further complicate mechanical design.[11]

This design used magnetic bearings in place of oil bearings. 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 rotating turbomachine. 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, CT in U.S.).

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 GT-MHR reactor module is located in an underground containment building as shown in Fig. 2. The components of the primary cooling loop are housed within two metallic pressure vessels that are connected by a cross-vessel (Fig. 3). 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. 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.



1 – Power Conversion Unit
2 – Electric Equipment Compartment
3 – Reactor Building
4 – Refuelling Machine
5 – Auxiliary Reactor Building
6 – Reactor Cavity Cooling System
7 – Reactor
8 – Containment

Fig. 2. GT-MHR Reactor Module Layout.

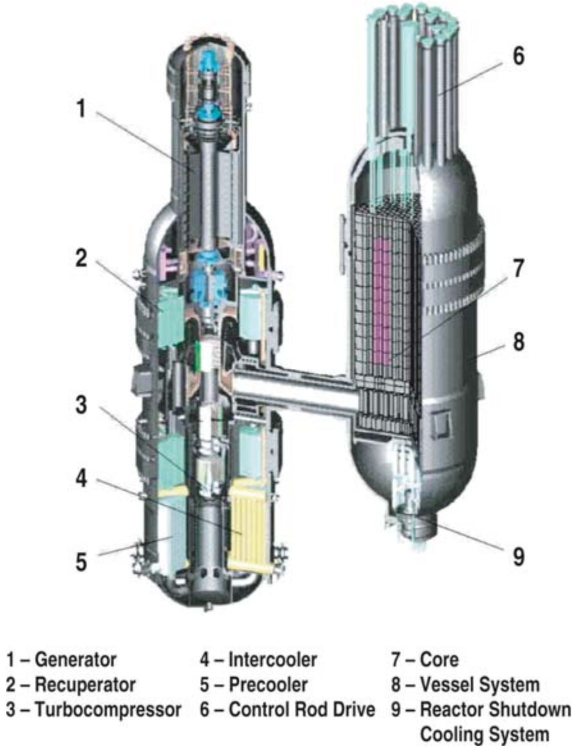


Fig. 3. Key components in the GT-MHR Reactor unit.

The reactor core in the new design has been modified to accommodate a larger power generation. This was done by increasing the size of the inner reflector to five rings, allowing the fuel to remain three rings thick, but increasing their radii. In this manner, the amount of fuel columns in the active core region was increased to 102 columns, thus allowing the core to generate 600 MW of thermal power while still maintaining passive safety. We maintained the prismatic block design with low-pressure drop and thus a higher power conversion efficiency compared to a pebble bed design.

The PCU was modified in the current design for a direct cycle Brayton cycle. With a higher power level, the mass flow rate through the power conversion system in this cycle was increased to 320 kg/s. This, together with the use of a flexible coupling between the turbocompressor and the generator, allowed for asynchronous operation at higher RPM. As a result, the size of the turbine blades decreased and the length of the shaft increased, resulting in an overall decrease in component weight. There are substantial differences between the current and previous turbomachine design (Table 1).

TABLE I: Key Differences Between Current and Previous Design

	Current Design (KOBM-2003)	1994 Design
Reactor power, MW(t)	600	450
Rotation speed, rpm	4400	3000
He mass flow rate, kg/s	320	239
Turbocompressor mass, kg	3.26×10^4	3.70×10^4
Generator mass, kg	3.50×10^4	6.80×10^4
Generator stator od, cm	331	281.9
Generator stator id, cm	104	78.2
Turbomachine shaft mass, kg	6.76×10^4	1.05×10^5
Turbomachine shaft length, cm	2429	1696
Turbine inlet pressure, MPa	7.01	7.01
Max. load TC radial EMB, kN	28	60
Max. load generator radial EMB, kN	34	120
Max. load TC axial EMB, kN	333	3.78×10^4
Max. load generator axial EMB, kN	357	6.94×10^4
Turbine stages	9	12
High pressure compressor stages	13	24
Low pressure compressor stages	10	16

Some of the key differences in the new design arise from the increase in rotation speed from 3000 rpm to 4400 rpm. This change necessitates a higher mass flow rate, which 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 smaller diameter rotor, which results in a weight reduction of 48.5%. 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 increased due to vertical jolting of the shaft.

It is important to note that even though the current design produces more power, it does so at a reduced turbomachine weight. The new shaft is longer and thinner. In addition, the substantially fewer stages in the compressors and turbine contribute to make it lighter overall. The lighter generator is a result of the higher rotation speed brought about by a higher mass flow rate, requiring a much smaller volume in the stator. 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.

The direct Brayton cycle (Fig. 4) 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.

Using an intermediary heat exchanger (IHX), whose flow diagram is shown in Fig. 5, 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 in addition the added benefit of an increase in thermal efficiency of ~2%-3%, as well as lower development costs and simpler construction.

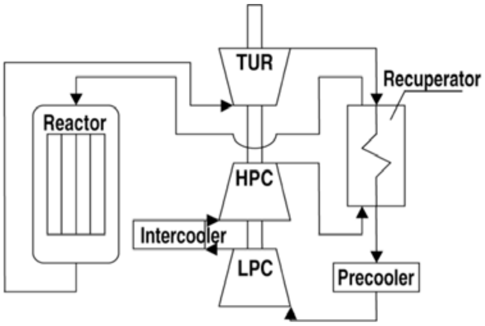


Fig. 4. Direct cycle GT-MHR flow diagram.

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 in the indirect cycle, reducing the conversion efficiency by ~2% to 3% (Fig. 6).

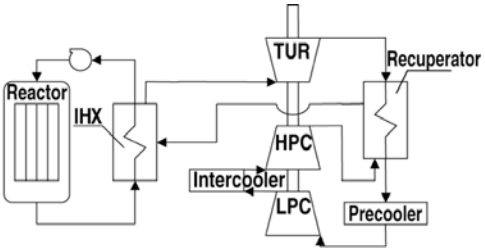


Fig. 5. Indirect cycle GT-MHR flow diagram.

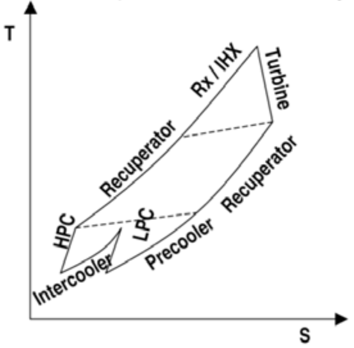


Fig. 6. Temperature entropy diagram for the direct and indirect Brayton cycle.

The use of a vertical PCU has been proven to be compatible with the current reactor design. The flow in the core is downwards, exiting at the bottom. 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 potential disadvantage of integrated design, which needs further study is assurance of missile containment following a deblading accident, and prevention damage to other components in a single PCU vessel.

Turbine thrust can present a problem in horizontal systems, but a vertical system makes use of gravitational force to offset thrust, further simplifying the system. 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 asynchronous design, however, the shaft rotates much faster, at 4400 rpm. This causes the blades for the turbocompressor to be much smaller, leaving a clearance between them and the vessel walls in the order of millimeters. Bowing in the shaft of even a few millimeters could therefore cause the blades to come in contact with the walls and result in failure of the turbomachine. In a vertical configuration, the shaft is not bent by gravitational forces, solving this problem.

The reasoning for selection of an integrated PCU stems mainly from superior economics and the elimination of piping. By using an integrated system there are minimum pressure losses and reduced bypass flows (~4%-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. In addition, by making the system more compact, its transportation as a prefabricated module can be facilitated.

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.

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 1/2 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 bearing in the field. This is due in part of 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, but this can be counteracted by using a higher number of smaller PCUs should the shaft mass exceed that allowed by the 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.

Intercooling the power conversion system brings about additional efficiency gains of ~2%, but has the disadvantage of introducing increased complexity and cost. Studies have shown a single stage of intercooling is ideal. After that, the costs outweigh the benefits.

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 a higher rotational speed by isolating 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 bearings. The axial load is in this manner split into two independently supported paths.

Due to 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, 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. In addition, they provide turbomachine braking during abnormal events, such as loss of electromagnetic bearing support.[3]

The frequency converter allows for the higher rotational speed, which in turn allows for a reduced weight of the TC as outlined in Sec. II. In addition, the higher rotational speed and mass flow rate allow for a higher efficiency of the turbocompressor.

III. 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 steam turbines. Coupled with the MHR, efficiencies of ~47%-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 in LWRs. Gas turbine MHR's modular nature facilitates preconstruction and remote assembly at the site, significantly reducing construction costs and time.

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

REFERENCES

[1.] "Army Reactor Systems Program," Power React. Technol. **6**, 57 (1963).

[2.] B. HOGLAND, "UHTREX: Operation Near," Power React. Technol. **9**, 51 (1965).

[3.] E. N. SHAW, *Europe's Nuclear Power Experiment: History of the OECD Dragon Project*, Pergamon Press, New York, (1983).

[4.] J. L. EVERETT and E. KOHLER, "Peach Bottom Unit #1: A High Performance Helium Cooled Nuclear Power Plant," Ann. Nucl. Energy **5**, 321 (1978).

[5.] G. MELESE and R. KATZ, "Thermal and Flow Design of Helium Cooled Reactors," ANS Publication (1984).

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

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

[8.] K. OHASHI, F. OKAMOTO, H. HAYAKAWA, "Modular High Temperature Reactor Contributing the Global Environmental Protection," Progress in Nuclear Energy **37**, 307-312 (2000).

[9.] L. SHI, et al., "Preliminary Design of the of the Power Conversion Unit of the HTR-10," Nucl. Eng. Des. **218**, 249-257 (2002).

[10.] *Evaluation of the Gas Turbine Modular Helium Reactor,* Gas-Cooled Reactor Associates, San Diego, California (1994).

[11.] M.P. LABAR, A.S. SHENOY, W.A. SIMON, E.M. CAMPBELL, *The Gas-Turbine Modular Helium Reactor*, Nuclear News **46**, 28 (2003).

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

[13.] *Research Work Report: Design Development of the Turbomachine With Increased Rotor Speed*, Experimental Design Bureau of Machine Building (OKBM) Product 02.03-002.09B (2004).

ACKNOWLEDGEMENTS

This work was supported by the U.S. Department of Energy under DE-AC03-00SF21868