THE MHTGR GAS TURBINE: A POWER PLANT IDEALLY SUITED TO MEETING THE ENERGY NEEDS OF THE NEWLY INDUSTRIALIZING NATIONS

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ABSTRACT

It has been estimated, that shortly after the year 2050, the energy use in the developing nations will exceed energy use in the industrialized countries. Utilization of the human resources in the newly industrializing nations will be a key factor to ensure global economic stability, and an important element towards an increase in their standard of living will be assurance of a secure and economic source of power. Lessons learned from the industrialized nations will include avoidance of fragility of their economy based on the dependence of fossil fuels, and the negative environmental consequences; simply stated the economic future of the newly industrializing nations is very dependent on the deployment of nuclear power.

The Modular High-Temperature Gas-Cooled Reactor (MHTGR), with its unquestionable safety, must be viewed as a leading candidate to meet the aforementioned energy needs. Utilizing a helium turbine power conversion system, the basic module rating is around 200 MW(e). The modular approach permits incremental expansion as the electrical grid infrastructure expands. The nuclear gas turbine plant has many attributes, including the following: (1) complete factory fabrication and assembly; (2) minimum site construction work; (3) siting flexibility (cooling water not required since economic dry cooling can be realized with the Brayton cycle); (4) operation in a cogeneration mode without loss of electrical output (i.e., steam production, desalination); and (5) increasing local participation in module fabrication as the system matures.

This paper highlights the advantages of the modular nuclear gas turbine plant, and emphasizes the fact that the major components are based on proven technology. With introduction of this inherently safe, high efficiency, nuclear power plant shortly after the turn of the century, the ever-increasing demand for power throughout the 21st century by the newly industrializing nations will be assured.

1. INTRODUCTION

Many of the newly industrializing nations have no indigenous fuel source, and in others there are constraints on oil, gas, and coal supplies. An abundant, secure, and economical energy source for the potentially large labor force is paramount, not only to meet world product demand, but to improve quality of life. This can be met by deployment of safe nuclear plants, which initially will be based on simple, standardized, small capacity systems. The MHTGR with a gas turbine power conversion system is ideally suited to meeting the aforementioned energy needs.

The MHTGR-GT has the following attributes: (1) unquestionable safety, (2) system simplicity, (3) complete factory fabrication and assembly, (4) minimum site work, (5) short construction schedule, and (6) high power-to-heat ratio when operated in a cogeneration mode. The Brayton cycle is ideally suited to operation in arid regions and would utilize a dry cooling tower, which would also be of modular construction. Waste heat rejection from the Brayton cycle is after the prime-mover, with no loss of electrical power output when a supply of process steam is needed. If sited near oceans, or sources of brackish water, this reject heat could be used for desalination.

This paper discusses the MHTGR-GT concept with emphasis on how it can meet the energy needs of the newly industrializing nations. With nonexistent, or limited electrical grid infrastructure, initial deployment will likely only involve a single module, but have the potential for incremental growth as demand increases. Local and emerging industries would have the MHTGR-GT plant as their focal point, in a manner analogous to today's industrialized nations that started modestly over two centuries ago with centralized steam engines as their energy sources. The nuclear gas turbine is an evolution of proven gas-cooled reactor plant experience. This paper includes a discussion on the extensive existing technology base to make this plant concept a reality early in the first decade of the 21st century.

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2. NUCLEAR POWER FOR THE NEWLY INDUSTRIALIZING NATIONS

2.1 Energy Needs

The newly industrializing nations are defined in this paper as those countries which missed the Industrial Revolution of the 19th century and, with a rapidly growing work force, need energy to advance industrial production capabilities and improve living standards. As the developing nations advance toward their goal of increased industrialization, they will base their economies on an energy mix of resources that are available (i.e., oil, gas, coal, hydro-power, biomass, etc.). The goal of increasing electrification in industry and in rural areas can be readily met initially by steam and gas turbine plants, but of course, these require oil or gas. It would not be prudent for developing nations to entirely base their industrialization plans on a resource such as oil whose nonavailability and rapidly changing price could destroy their economic growth. In the case of uranium, the situation is different since large fluctuations in price only marginally affect power generation economics. An increase in ore price of 100% would increase electricity by only about 10% because nuclear power is so capital intensive.

The major role of nuclear power will be in providing electricity for industrial, rural, and urban development. As will be discussed in a later section, the high-efficiency MHTGR-GT can provide the total energy needs for the newly industrializing nations. In addition to electricity, the plant can provide process steam (for industry), hot water (for district heating), and low-grade heat for desalination.

The MHTGR-GT concept offers many advantages in meeting the needs of the newly industrializing nations. In a stable electricity grid and transmission system, no single generating unit should represent more than 10% to 15% of the employed capacity. The gas turbine plant is based on stand-alone and dedicated module with an output of about 200 MWe, and accordingly incremental capacity of this value can be added as demand grows.

Attaining attractive economics for small nuclear power plants is closely related to systems simplicity, standardization in design and licensing, and maximization of factory fabrication. Accordingly, for the first few plants built, the major components would be fabricated by the nuclear vendor, and to the degree possible, local organizations would be utilized, particularly in materials supply and some site construction work. The modular concept is particularly amenable to providing a well defined indigenous learning curve, leading to increased local participation in each successive plant (i.e., module). Some of the perceived needs and major factors of newly industrializing nations in the deployment of nuclear power plants are given in Table 1.

2.2 Nuclear Vendor's Capabilities

In the past, importance was placed on offering to the newly industrializing nations the minimum size of reactor commercially available in the industrial world. This approach has clearly not worked, as evidenced by the paucity of reactor sales to the developing nations. Recognizing that the introduction of nuclear power, and the time for its deployment to impact industrial growth, will occur over a period of decades in the first half of the 21st century, a different approach is suggested, and indeed was discussed a decade ago (McDonald, 1983) at the onset of MHTGR studies.

Since the MHTGR-GT is in a preconceptual design stage, participation from the onset by technologists from the developing nations has merit. Scientists, engineers, and management would be involved in the design, development, and licensing and would contribute to the construction and commissioning of the first plant. As a result, the newly industrializing nations would not have a predetermined plant design imposed upon them, but would have a nuclear plant that they really understand and that truly meets their needs. Initial deployment and proof of concept in the industrial world (e.g., Japan or U.S.) would also allow training of operators and maintenance staff from the overseas countries prior to construction of the plant in their homeland.

The matching of the developing nation's energy needs in terms of plant features (Table 1) with the capabilities of the industrialized nuclear vendors (Table 2) must be done on a mutual basis involving close joint participation and industrial ties. The MHTGR-GT plant concept outlined in the following section could be the vehicle for a cooperative program with the newly industrializing nations, structured so that their needs are recognized, and indeed are an inherent part of the reactor criteria preparation, design, development, construction, operation, and maintenance.

3. MHTGR GAS TURBINE PLANT CONCEPT

3.1 Power Conversion System Selection

With the hiatus in the nuclear industry in the U.S., the emergence of a new utility prime mover in the
will have an efficiency of 60%. This will be the combination of modern industrial gas turbines that are operating with molten salt plants burning natural gas, will surely extend into the late 1980s, namely large advanced open cycle gas turbines burning natural gas, will surely extend into the next century. These large gas turbines in a simple cycle form are rated at 150 to 200 MW(e) and exhibit thermal efficiencies in the high thirties. When operated in a combined cycle mode, efficiencies up to 54% have been demonstrated. With more advanced cycles (i.e., intercooling, steam injection, humid air turbines, chemical recuperation, etc.) it is projected that by the year 2000, utility size combustion turbines will have an efficiency of 60%. This will be the competition facing nuclear vendors as they attempt to penetrate the newly industrializing nations energy market in the 21st century.

At the onset of studies of the MHTGR it was recognized that establishing acceptable economics for a small gas-cooled reactor would be a challenge (McDonald and Sonn, 1983), the key factors in offsetting the economy of scale effect being plant simplicity, serial factory fabrication, and minimization of site construction schedule. In the last decade very significant advancements have been made in MHTGR steam cycle technology in terms of design advancement (Bramblett and Ople, 1991), safety and competitive performance (Eichenberg, et al., 1992), and work is on-going.

To compete with the aforementioned advanced open cycle gas turbines, however, it is felt that an MHTGR variant with substantially improved power generation economics will be necessary, to not only initially penetrate the market for the newly industrializing nations, but to be capable of economically viable operation through the 21st century. Recent work done on the MHTGR plant with a direct cycle helium gas turbine (Burger, et al., 1992) has shown, based on the results of initial economic assessments, that the gas turbine variant has a cost advantage relative to the steam cycle of 21%. Another important finding from this study was that the nuclear gas turbine showed a power generation estimated cost value almost identical to combined cycle combustion gas turbines. Clearly, power generation economics was the dominant factor in selection of the helium gas turbine power conversion system in this paper, but other considerations such as factory fabrication/assembly, and economic dry-cooling are important, and these will be discussed in the following sections.

3.2 Gas Turbine Plant Configuration

A flow schematic of the direct cycle gas turbine illustrating the major components in the circuit is given in Fig. 1. Three of the parameters which have a strong impact on the plant efficiency are turbine inlet temperature, compressor pressure ratio, and recuperator effectiveness. For the initial plant a reactor outlet temperature of 850°C (1562°F) was selected, this representing only a small extrapolation from that experienced in the Fort St. Vrain plant. The helium turbine

![Fig. 1. Direct cycle gas turbine flow schematic](https://example.com/gas_turbine_flow_schematic.png)

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steel vessels coupled with a horizontal coaxial cross vessel. The nuclear heat source, consisting of a graphite moderated prismatic core reactor, is contained in the right hand vessel. The complete power conversion system is installed in the left hand vessel. The complete power plant assembly is located in a below-grade concrete confinement silo.

More details of the power conversion vessel assembly are shown in Fig. 3. The focal point is the vertical rotating group consisting of an axial flow helium compressor and turbine directly coupled to a submerged generator. An important element of the integrated generator is that it obviates the need for a shaft penetration through the vessel, that was the nemesis of earlier nuclear gas turbine designs (McDonald and Peinado, 1982). With all of the power conversion system installed in the steel vessel a premium is placed on component compactness, particularly for the helium-to-helium recuperator, a key component for high efficiency realization. Rejct heat from the cycle is removed in the helical geometry precooler. In this heat exchanger the helium pressure is much higher than the water (which is only pressurized to suppress boiling), and hence water ingress, for long a concern with gas-cooled reactors, is obviated. The two key technologies that make this configuration practical are: (1) the utilization of active magnetic bearings and (2) compact plate-fin heat exchangers and these will be addressed in a later section.

Much design work remains to be done to establish an optimum plant configuration, particularly when considering the following: (1) pressure loss minimization, (2) practical seal(s), (3) ability to remove and replace the helium turbomachine, (4) heat exchanger inspection and in situ repair, and (5) maintenance and handling of large contaminated components. The arrangement shown in Fig. 3 represents an excellent starting point for detailed design studies. Salient features of the plant are given in Table 3.

### 3.3 Plant Fabrication/Assembly

A major advantage of the fully integrated direct cycle gas turbine plant is that complete factory fabrication and assembly can be realized. For the first few plants all of the major components will be assembled in

#### Table 3
SALIENT FEATURES OF MHTGR GAS TURBINE PLANT

<table>
<thead>
<tr>
<th>PLANT TYPE</th>
<th>NUCLEAR GAS TURBINE</th>
</tr>
</thead>
<tbody>
<tr>
<td>CONSTRUCTION TYPE</td>
<td>MODULAR</td>
</tr>
<tr>
<td>REACTOR TYPE</td>
<td>HIGH</td>
</tr>
<tr>
<td>CORE GEOMETRY</td>
<td>ANGULAR CORE</td>
</tr>
<tr>
<td>FUEL ELEMENT TYPE</td>
<td>PRISMATIC BLOCK</td>
</tr>
<tr>
<td>POWER CONVERSION SYSTEM</td>
<td>DIRECT CYCLE</td>
</tr>
<tr>
<td>CORE THERMAL RATING</td>
<td>455 MWe</td>
</tr>
<tr>
<td>MODULAR POWER OUTPUT, MWe</td>
<td>266</td>
</tr>
<tr>
<td>NET EFFICIENCY, %</td>
<td>44</td>
</tr>
</tbody>
</table>

| THERMODYNAMIC CYCLE | RECUPERATION EXCHANGER-INTERCOOLED |
| TURBINE INLET TEMPERATURE, °C | 665-642 |
| TURBINE INLET PRESSURE, MPa (psi) | 7.07 (1025) |
| COMPRESSOR EFFICIENCY | 90.3 |
| TURBINE EFFICIENCY | 91.8 |
| RECOMBINATION EFFECTIVENESS | 0.96 |
| SYSTEM PRESSURE LOSS (PPM) | 4.3 |

| HEAT REJECTION | DRY COOLING TOWER |
| TURBOMACHINE | SINGLE-SHAFT ROTOR |
| COMPRESSOR TYPE | MULTISTAGE AXIAL FLOW |
| TURBINE TYPE | MULTISTAGE AXIAL FLOW |
| COMPONENT DESIGN | SUBMERGED |
| BEARING TYPE | ACTIVE MAGNETIC BEARINGS |
| FLOW | INVENTORY CONTROL |
| COMHATURE | COMPACT PLATE-FIN MODULES |
| PRESSURE DROP | FINNED-TUBE HELICAL BUNDLE |
| PRESSURE DROP | VERTICAL JUXTAPOSITIONED STEEL VESSELS |

| PLANT STATUS | PRECONCEPTUAL |
| TECHNOLOGY STATUS | STATE-OF-THE-ART |
| DEPLOYMENT | 2005-2010 |

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Fig. 2. MHTGR-GT arrangement

Fig. 3. Power conversion vessel assembly
the two vessels in the factory based on a computer controlled system. Because of transportation weight limitations all of the graphite components will be removed from the reactor vessel and transported separately. Similarly, the rotating machinery will be removed from the other vessel before shipping. The advantage of factory assembly is to resolve any "fitting or mismatch" problems, which would be time-consuming to resolve at the site. Another advantage is that the vertical rotating assembly could be spun up to high speed (in air) by using the generator as a motor, and this would assure balance in the correct orientation, and again avoid time wasted at the site.

Transportation of the large components to the plant site would be based on well established procedures. From the factory to the nearest local port would involve transportation by ship/barge, and an example is shown in Fig. 4. It is unlikely that many of the newly industrializing nations would have a rail network, and transportation from the nearest port to the site would be likely based on the use of overland vehicles (Fig. 5).

![Fig. 4. Barge transportation of large components (courtesy ABB-Combustion Engineering)](image4)

In the case of the gas turbine plant, the site construction work is simple and conducive to a short schedule. Prior to arrival of the two major vessels the below-grade silo and above grade structures would have been completed. The two juxtapositioned vessels would be installed and the cross vessel welded in position. Advantage would be taken of the computer-controlled component installation procedure (verified in the factory) to expedite plant erection. The component(s) installation should be straightforward and be realized with minimum site crew. There is one more facility that must be constructed, and this is addressed below.

### 3.4 Waste Heat Utilization

With a module rating of 450 MW(t) and an electrical output of 200 MW(e), there is about 250 MW(t) of heat to be rejected from the power plant, and this must be done in an environmentally acceptable manner. The primary motivation for introduction of the MHTGR-GT in the newly industrializing nations is electrification, including the needs of several sectors, including industrial, urban, and rural. While the high grade reject heat from the precooler has economic worth, it is unlikely to be utilized in the first plants introduced.

In many of the newly industrializing nations there is uncertainty over the availability of cooling water for power plants, and this potential lack of water, together with ever increasing environmental demands, may no longer permit plant siting near existing bodies of water (i.e., lakes, rivers, oceans). The heat rejection characteristic of the closed-cycle gas turbine is conducive to economic dry cooling, and the use of natural-draft dry cooling towers can provide good performance over a wide range of temperatures in virtually any region desired. Plant siting flexibility is one of the motivating factors for deployment of the nuclear gas turbine.

In dry-cooling, the MHTGR-GT rejects its heat over a wide band of temperatures, since the heat is derived from the sensible, rather than latent heat of the single-phase working fluid. This temperature range is about an order of magnitude higher than permissible condensate temperature rise, meaning that the dry towers for a Brayton cycle plant could be designed for about a tenth of the airflow needed for the Rankine cycle steam plant. The towers are therefore smaller, and the higher exit air temperature induces greater buoyancy, causing an almost threefold increase in air velocity to aid heat transfer and further reduce the tower size.

Consistent with a major theme of this paper, namely that of maximizing factory fabrication and assembly this can be extended to the dry cooling tower by utilizing fabric structures (Barts, 1991). Natural draft cooling tower shells constructed of fabric (Fig. 6) have received considerable attention in several countries. The merits of this type of construction include: (1) complete factory fabrication, (2) low initial cost, (3) short erection time, (4) reduced seismic concerns, and (5) greater design flexibility.

As mentioned above, the high grade reject heat from the precooler has economic worth, and will be utilized as the industry infrastructure grows following initial electrification. Possibilities include process steam production (for industry), hot water supply (for district heating) and desalination of brackish or salt water. An important factor to remember in comparing Brayton and Rankine cycle systems, is that in the case of the Brayton cycle the heat is rejected after the
The evolution of helium cooled reactors is shown in Fig. 7, and this is complemented by more than 50 carbon dioxide cooled reactors built and operated in the U.K. In the 1960s four experimental facilities were constructed and operated, namely Dragon (U.K.), AVR (Germany), and Peach Bottom I and UHTREX (USA). Data from these plants were used to facilitate the deployment of two commercial plants in the 1970s, namely Fort St. Vrain (Brey, 1991) and THTR (Baumer, 1991).

Of the above, the most germane in terms of the gas turbine is the AVR plant in Germany which operated for over 21 years, and between 1974 and 1988, a helium outlet temperature of 950°C (1742°F) had been maintained on a long-term basis with low contamination of the circuit. This achievement, obtained with a pebble bed reactor is important, since for maintenance of the direct cycle gas turbine components, it is vital to maintain a clean circuit.

The next gas-cooled reactor to be constructed will be the 30 MW(t) high temperature test reactor (HTTR) in Japan, and this could be operational in the mid-1990s (Saito, et al., 1991). With initial operation planned at 850°C (1562°F), the reactor has been designed to have the capability to advance to 950°C (Sudo, 1989). Successful operation of this reactor is a major stepping stone for the nuclear gas turbine since it will confirm the viability of the prismatic core to operate at elevated temperature.

4.2 Power Conversion System

For helium components (e.g., turbomachinery, heat exchangers, etc.) the thermal, aerodynamic, and mechanical design procedures are essentially identical to conventional air-breathing gas turbine practice, for which there is a formidable technology base. It is of interest to note that the first helium closed-cycle gas...
turbine was built and operated in the U.S. over three decades ago (LaFleur, 1963). Today, the design of helium turbomachinery is well understood (McDonald and Smith, 1981).

The largest of the European closed cycle gas turbines was the 50 MW Oberhausen II helium turbine plant that operated in Germany (Zenker, 1988). The fossil-fired plant (Fig. 8) operated for over 30,000 hr with a turbine inlet temperature of 750°C (1382°F). The selection of a relatively low system pressure for this plant (compared with future nuclear systems) yields a larger volumetric flow of the helium working fluid, and accordingly the actual equipment is comparable in size to a plant rated at over 200 MW(e). The size of the rotor (compressor and turbine) as shown in Fig. 9 would, in fact, be similar to that needed for the MHTGR-GT turbomachine (Fig. 3).

There are two key technologies that make possible the compact submerged rotating machine assembly. The utilization of active magnetic bearings precludes the possibility of lubricant ingress in closed cycle systems (McDonald, 1988). Over 500 machines are operational with magnetic bearings, over 100 of which are heavy duty turbomachines that have accumulated over a million hours of trouble-free operation. Today's magnetic bearing technology is directly applicable to the levels of loading to be encountered in the thrust and journal bearings of the vertical 200 MW(e) helium turbomachine. The utilization of submerged electrical rotating machinery in a helium environment is state-of-the-art as evidenced by many years of trouble-free operation with the electric motor driven circulators in the AVR and THTR plants. Perhaps the major advantage of this system is that it obviates a shaft penetration through the reactor primary pressure boundary. The generator can also be used as a motor for starting the plant, and for slow-speed operation to remove the core decay heat.

Heat exchangers play a key role in nuclear gas turbine plant concepts to realize high efficiency. Recent advances in compact recuperator technology (McDonald, 1990) make possible a very compact plate-fin helium-to-helium recuperator with the capability for an effectiveness of 95%, with an acceptable pressure loss in the confines of the steel vessel. It is of interest to note that a plate-fin recuperator was utilized in the only nuclear gas turbine to have operated (i.e., the U.S. Army ML-1 plant, Loftness, 1964).

The water-to-helium precooler is a low temperature heat exchanger, that can readily be integrated into the system. A finned-tube helical bundle geometry perhaps represents the best solution, and experience from HTGR steam generator work is directly applicable (McDonald and Defur, 1986). Heat exchanger technology for the MHTGR-GT is currently available, and the challenge to designers will be to establish means for inspecting and repairing the units should leaks develop in service.

5. CONCLUDING REMARKS

In the near-term the newly industrializing nations will likely be dependent on combustion turbines to meet their energy needs. Modern gas turbines operate with efficiencies up to 56% (increasing to 60% by the year 2000) and can be installed at competitive capital costs. These plants will see service into the early decades of the next century.

There are essentially three factors that will necessitate a transition to nuclear power in the developing nations: (1) lessons learned from the industrial nations to avoid having their economies based on the availability, and low cost of fossil fuels; (2) increasing environmental concerns about burning fossil fuels; and (3) the sheer magnitude of the power required, recalling that after the year 2050 their energy use will exceed that used in the industrialized nations.

By the year 2000 there is expected to be a renaissance in the nuclear power industry, and there could be as many as 12 different reactor types vying for the market place (Nuclear News, 1992). At the forefront of this emergence of second generation reactors will be the MHTGR, with its major attributes being unquestionable safety and versatility to meet a wide range of energy needs (McDonald, 1992).

The MHTGR gas turbine variant has been highlighted in this paper because the following attributes are well
suited to introduction of this power plant to the newly industrializing nations, namely: (1) competitive power generation economics; (2) each module [rated at about 200 MW(e)] is a stand-alone plant and permits incremental expansion on a modest basis to match industrial growth; (3) the plant can be completely factory fabricated and assembled and this will avoid the all to well known site erection problems; (4) with initial priority on electrification (industrial, urban, and rural) considerable site flexibility is afforded by the use of economic dry-cooling, it being important to note that the efficiency of the dry-cooled gas turbine is 44% compared to 35% for a Rankine cycle MHTGR, and 30% for a dry-cooled light water reactor; and (5) as industrial growth is realized, the high grade reject heat from the gas turbine can be used for process steam production, hot water supply (for district heating) and for desalination.

The technology for the gas turbine plant has a sound basis, and no breakthroughs are necessary in terms of component design/performance or materials advancements, however, a thorough program of development and testing for design verification must be adhered to. There are essentially two major technical steps towards deployment of the MHTGR-GT, namely: (1) operation of the Japanese HTTR plant verifying that the prismatic core has very high temperature capability and (2) an orderly transfer of technology from industrial gas turbines (e.g., magnetic bearings, compact heat exchangers).

The deployment of the MHTGR-GT is only a matter of resolve, and it is hoped that with a cooperative international program, the nuclear gas turbine could be realized early in the first decade of the 21st century, and meet the needs of the newly industrializing nations through the next century.

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7. REFERENCES


