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The Gas Turbine – Modular Helium Reactor: A Promising Option for Near Term Deployment

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Abstract – *The Gas Turbine – Modular Helium Reactor (GT-MHR) is an advanced nuclear power system that offers unparalleled safety, high thermal efficiency, environmental advantages, and competitive electricity generation costs. The GT-MHR module couples a gas-cooled modular helium reactor (MHR) with a high efficiency modular Brayton cycle gas turbine (GT) energy conversion system. The reactor and power conversion systems are located in a below grade concrete silo that provides protection against sabotage. The GT-MHR safety is achieved through a combination of inherent safety characteristics and design selections that take maximum advantage of the gas-cooled reactor coated particle fuel, helium coolant and graphite moderator. The GT-MHR is projected to be economically competitive with alternative electricity generation technologies due to the high operating temperature of the gas-cooled reactor, high thermal efficiency of the Brayton cycle power conversion system, high fuel burnup (>100,000 MWd/MT), and low operation and maintenance requirements.*

I. INTRODUCTION

The Gas Turbine – Modular Helium Reactor (GT-MHR) is an advanced gas-cooled reactor currently under development in a joint United States – Russian Federation program to provide capacity for disposition of surplus weapons plutonium. The GT-MHR is designed to provide very high safety, high thermal efficiency and environmental advantages. Fueled with uranium, the GT-MHR produces electricity at competitive generation costs. Because of these characteristics, the GT-MHR is a promising candidate for near term commercial deployment in the United States. In this paper, the GT-MHR design, performance, safety environmental, and economic characteristics are identified and the plans for commercial deployment are described.

II. DESIGN DESCRIPTION

The GT-MHR module, Figure 1, couples a gas-cooled modular helium reactor (MHR), contained in one vessel, with a high efficiency Brayton cycle gas turbine (GT) energy conversion system contained in an adjacent vessel. The reactor and power conversion vessels are interconnected with a short cross-vessel and are located in a below grade concrete silo.

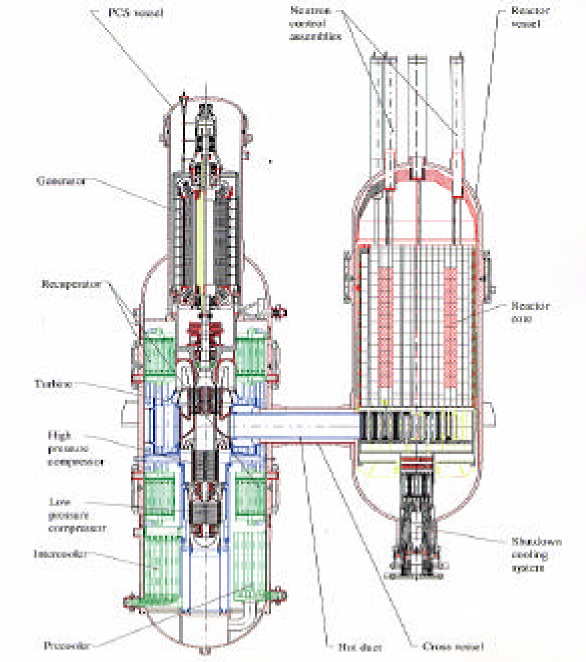

Figure 1. GT-MHR Module

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Key design characteristics of the gas-cooled MHR are the use of helium coolant, graphite moderator, and refractory coated particle fuel. The helium coolant is inert and remains single phase under all conditions; the graphite moderator has high strength and stability to high temperatures; and the refractory coated particle fuel retains fission products to high temperatures

The helium coolant is heated in the reactor core by flowing downward through coolant channels in graphite fuel elements and then through the cross-vessel to the power conversion system. The power conversion system contains a gas turbine, an electric generator, and gas compressors on a common, vertically orientated shaft supported by magnetic bearings. The power conversion system also includes recuperator, precooler and intercooler heat exchangers.

Figure 2 is a schematic of the coolant flow through the power conversion system. Heated helium from the reactor is expanded through the gas turbine to drive the generator and gas compressors. From the turbine exhaust, the helium flows through the hot side of the recuperator. From the recuperator, the helium flows through the precooler and then passes through low and high-pressure compressors with intercooling. From the high-pressure compressor outlet, the helium flows through the cold, high-pressure side of the recuperator where it is heated for return to the reactor.

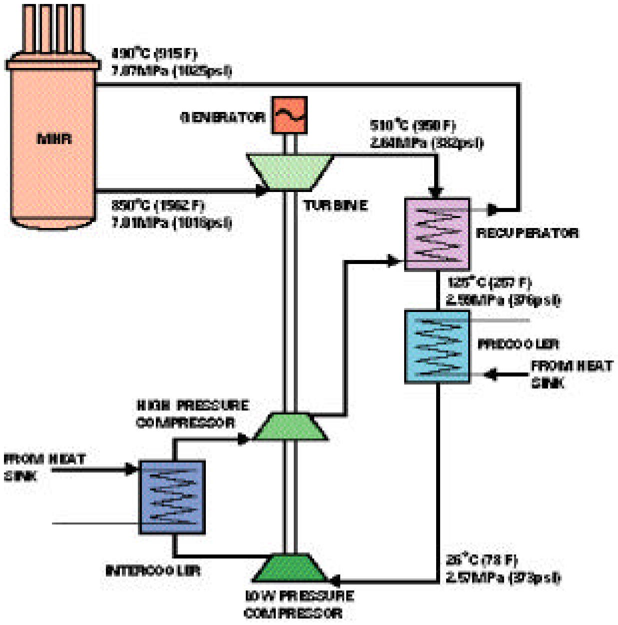


Figure 2. GT-MHR Coolant Flow Schematic

As indicated in Figure 3, the use of the direct Brayton cycle to produce electricity results in a net plant efficiency of approximately 48%. This efficiency is 50% higher than that in current nuclear power plants. Nominal full power operating parameters are given in Table 1.

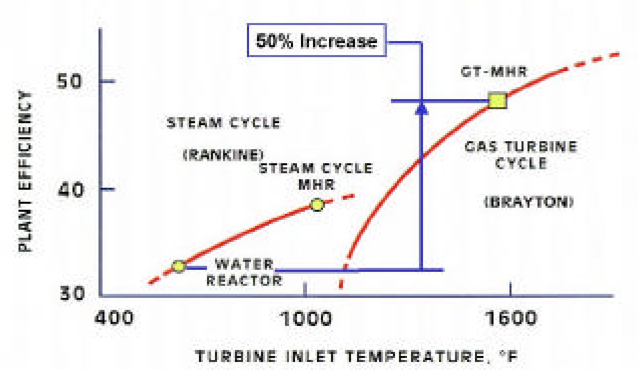


Figure 3. Comparison of Thermal Efficiencies

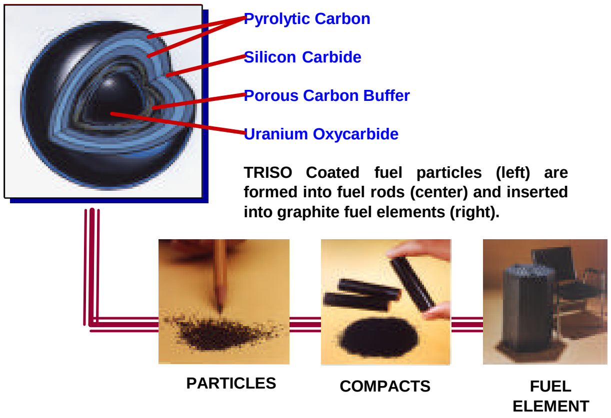
Table 1.
GT-MHR Nominal Full Power Operating Parameters

Reactor Power, MWt	600
Core Inlet/Outlet Temperatures, °C	491/850
Core Inlet/Outlet Pressures, MPa	7.07/7.02
Helium Mass Flow Rate, Kg/s	320
Turbine Inlet/Outlet Temperatures, °C	848/511
Turbine Inlet/Outlet Pressures, MPa	7.01/2.64
Recuperator Hot Side Inlet/Outlet, °C	511/125
Recuperator Cold Side Inlet/Outlet, °C	105/491
Net Electrical Output, MWe	286
Net Plant Efficiency, %	48

The GT-MHR gas turbine power conversion system has been made possible by key technology developments during the last several years in large aircraft and industrial gas turbines; large active magnetic bearings; compact, highly effective gas-to-gas heat exchangers; and high strength, high temperature steel alloy vessels.

The MHR refractory coated particle fuel, Figure 4, identified as TRISO coated particle fuel, consists of a spherical kernel of fissile or fertile material, as appropriate for the application, encapsulated in multiple coating layers. The multiple coating layers form a miniature, highly corrosion resistant pressure vessel and an essentially impermeable barrier to the release of gaseous and metallic fission products. The overall diameter of standard TRISO-coated particles varies from about 650 microns to about 850 microns.

As shown in Figure 5, the TRISO coatings do not start to thermally degrade until temperatures approaching 2000°C are reached. Normal operating temperatures do not exceed about 1250°C and worst case accident temperatures are maintained below 1600°C. Extensive tests in the United States, Europe, and Japan have proven the excellent performance characteristics of this fuel.



TRISO Coated fuel particles (left) are formed into fuel rods (center) and inserted into graphite fuel elements (right).

Figure 4. GT-MHR Coated Particle Fuel

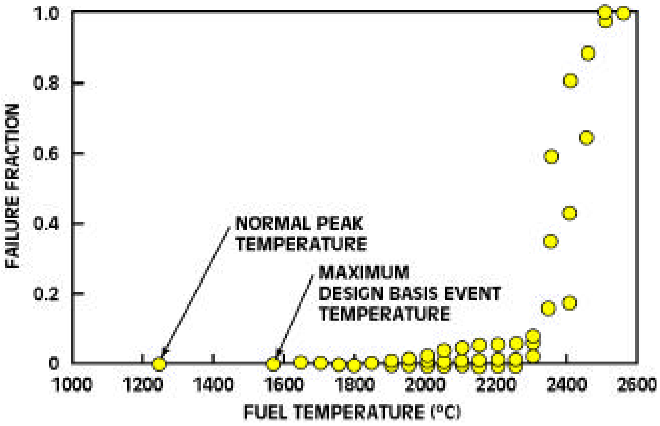


Figure 5. Coated Particle Fuel Temperature Capability

For the GT-MHR, TRISO coated particles are mixed with a carbonaceous matrix and formed into cylindrical fuel compacts, approximately 13 mm in diameter and 51 mm long. The fuel compacts are loaded into fuel channels in hexagonal graphite fuel elements, 793 mm long by 360 mm across flats. One hundred and two columns of the hexagonal fuel elements are stacked 10 elements high to form an annular core, Figure 6. Reflector graphite blocks are provided inside and outside of the active core.

The TRISO fuel particle coating system, which provides containment of fission products under reactor operating conditions, also provides an excellent barrier for containment of the radionuclides for storage and geologic disposal of spent fuel. Experimental studies have shown the corrosion rates of the TRISO coatings are very low under both dry and wet conditions. The coatings are ideal for a multiple-barrier, waste management system. The measured corrosion rates indicate the TRISO coating system should maintain its integrity for a million years or more in a geologic repository environment.

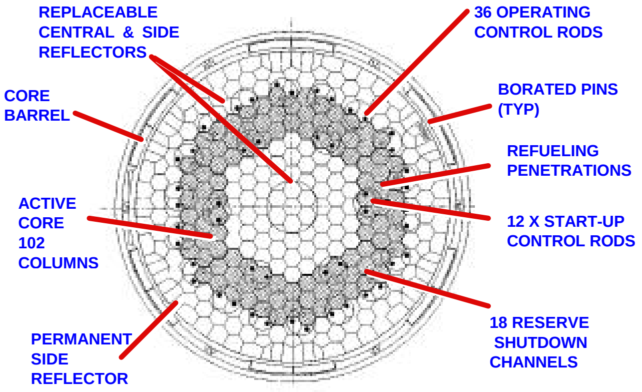


Figure 6. GT-MHR Annular Core

III. GT-MHR SAFETY CHARACTERISTICS

The GT-MHR safety is achieved through a combination of inherent safety characteristics and design selections that take maximum advantage of the inherent characteristics. These characteristics and design selections include:

1. Helium coolant, which is single phase, inert, and has no reactivity effects;
2. Graphite core, which provides high heat capacity, slow thermal response, and structural stability at very high temperatures;
3. Refractory coated particle fuel, which retains fission products at temperatures much higher than normal operation and postulated accident conditions;
4. Negative temperature coefficient of reactivity, which inherently shuts down the core above normal operating temperatures; and
5. An annular, low power density core in an uninsulated steel reactor vessel surrounded by a natural circulation reactor cavity cooling system (RCCS).

The GT-MHR has two active, diverse heat removal systems, the power conversion system and a shutdown cooling system that can be used for the removal of decay heat. In the event that neither of these active systems is available, an independent passive means is provided for the removal of core decay heat. This is the reactor cavity cooling system (RCCS) surrounding the reactor vessel. For passive removal of decay heat, the core power density and the annular core configuration have been designed such that the decay heat can be removed by heat conduction, thermal radiation and natural convection without exceeding the fuel particle temperature limit. Core decay heat is conducted to the pressure vessel and transferred by radiation from the vessel to the natural circulation RCCS as shown in Figure 7.

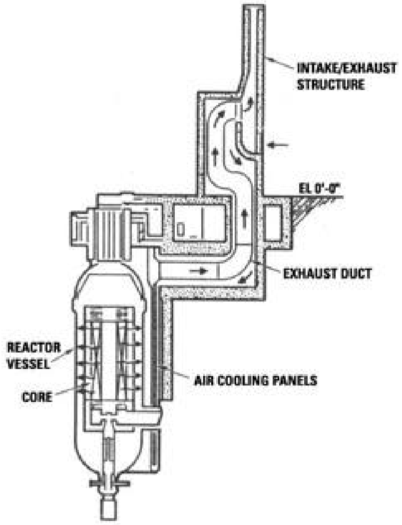


Figure 7. Passive Reactor Cavity Cooling System

Even if the RCCS is assumed to fail, passive heat conduction from the core, thermal radiation from the vessel, and conduction into the silo walls and surrounding earth, as shown in Figure 8, is sufficient to maintain peak core temperatures to below the design limit, Figure 9. As a result, radionuclides are retained within the refractory coated fuel particles without the need for AC powered systems or operator action. These safety characteristics and design features result in a reactor that can withstand loss of coolant circulation or even loss of coolant inventory and maintain fuel temperatures below damage limits (i.e., the system is meltdown proof).

The large heat capacity of graphite core structure is an important inherent characteristic that significantly contributes to maintaining fuel temperatures below damage limits during loss of cooling, or coolant, events. The core graphite heat capacity is sufficiently large to cause any heatup, or cooldown, to take place slowly. A substantial time (on the order of days vs minutes for other reactors) is available to take corrective actions to mitigate abnormal events and to restore the reactor to normal operations.

III. GT-MHR ENVIRONMENTAL ADVANTAGES

The thermal discharge (waste heat) from the GT-MHR is one-half that for light water reactors per unit of electricity because of the 50% greater thermal efficiency. If this waste heat were to be discharged using conventional power plant water heat rejection systems, the GT-MHR would require one-half as much water coolant per unit of electricity produced. Alternatively, because of its significantly lesser waste heat, the GT-MHR waste heat can be rejected directly to the atmosphere using air cooled heat rejection systems

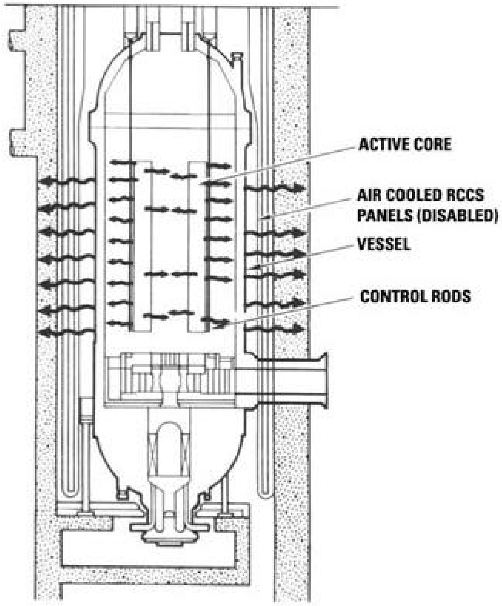


Figure 8. Passive Radiation and Conduction of Afterheat to Silo Containment

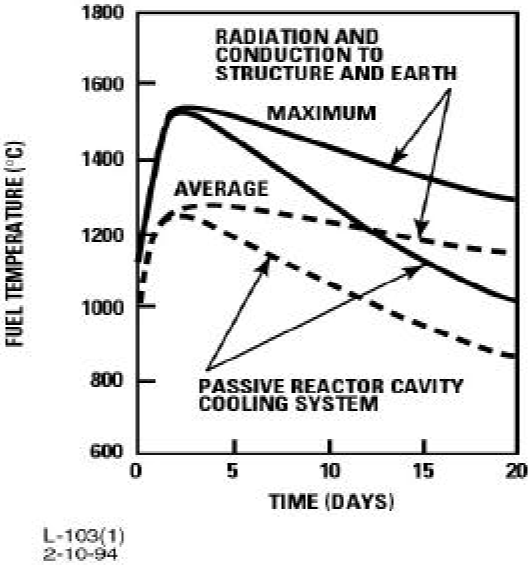


Figure 9. Core Heat-up Temperatures with Passive Heat Rejection

such that no water coolant resources are needed. Because of this capability, the use of the GT-MHR in arid regions is practical.

The GT-MHR produces less heavy metal radioactive waste than other reactor options because of the plant's high thermal efficiency and high fuel burnup. Light water reactors produce 150% more heavy metal radionuclides (actinides) than the GT-MHR per unit electricity production.

IV. GT-MHR PROLIFERATION RESISTANCE

The GT-MHR has very high proliferation resistance due to low fissile fuel volume fractions and due to the refractory characteristics of the TRISO coated particle fuel form that forms a containment from which it is difficult to retrieve fissile materials.

Both GT-MHR fresh fuel and spent fuel have higher resistance to diversion and proliferation than the fuel for any other reactor option. The GT-MHR fresh fuel has high proliferation resistance because the fuel is very diluted by the fuel element graphite (low fuel volume fraction) and because of the technical difficulty to retrieve materials from within the refractory fuel coatings. GT-MHR spent fuel has the self-protecting, proliferation resistance characteristics of other spent fuel (high radiation fields and spent fuel mass and volume). However, GT-MHR spent fuel has higher proliferation resistance than any other power reactor fuel because:

1. The quantity of fissile material (plutonium and uranium) per GT-MHR spent fuel element is low due to the low fuel volume fraction.
2. The GT-MHR spent fuel plutonium content, the material of most proliferation concern, is exceedingly low in both quantity per spent fuel block and quality because of the high fuel burnup. The discharged plutonium isotopic mixture is degraded well beyond light water reactor spent fuel making it particularly unattractive for use in weapons.
3. There is neither a developed process nor capability anywhere in the world for separating the residual fissionable material from GT-MHR spent fuel.

V. GT-MHR ECONOMIC COMPETITIVENESS

There are several important considerations in the evaluation of economic competitiveness of nuclear power. Nuclear power, in general, has several advantageous economic characteristics, but also suffers from a number of disadvantageous characteristics. The advantageous economic characteristics are:

- Low and predictable fuel and operation and maintenance (O&M) production costs. Nuclear production costs exhibit low volatility over both the short and long term because the primary energy source, uranium ore, represents a very small fraction of the total production cost. On the other hand, the cost of the primary energy source in fossil-fired plants is a large fraction of the production cost.
- High capacity factors. The operating nuclear plants in the U.S. now consistently achieve fleet-average capacity factors in the 90 % range. The projected lifetime averaged capacity factors for competing base load gas-fired combined cycle plants is in the range of 80 – 85% (Reference 1).
- Long Operating Lifetime. Operating lifetime licensing extensions have been obtained for several U.S. nuclear plants and more are expected in the future. New nuclear plants are being designed for a 60-year life. On the other hand, there is little experience in the long-term operation of competing base load gas-fired combined cycle plants. Nominal gas-fired combined cycle plant lifetimes are not expected to exceed 25 years (Reference 1).

The key disadvantageous economic characteristics of nuclear power are:

- Large plant size. Most new nuclear power plants are designed in the size range of 1,000 – 1,350 MWe to gain economy of scale benefits and reduce the capital costs expressed in $/kWe. The drawback of this size range is high potential for exceeding demand growth. Widely used base load gas-fired combined cycle plants are in the range of 500 – 600 MWe.
- Capital intensiveness. Nuclear plants are capital intensive projects. Total overnight capital costs of new nuclear plants are estimated to be in the 1,000 – 1,600 $/kWe cost range. For a 1,350 MWe plant at 1,600 $/kWe, an investment of 2.16 billion dollars would be required, excluding time related costs. The competing base load gas-fired combined cycle plant capital cost is in the 450 – 650 $/kWe range. A 600 MWe combined cycle plant at 650 $/kWe would require an investment of less than 0.4 billion dollars.
- Long construction time. The construction time for new nuclear plants optimized for short construction times are in the range of 3 – 4 years. The construction period for competing gas-fired combined cycle plant is about 2 years.
- Investment financing. The higher capital cost results in a higher total investment at risk and the longer construction time results in higher interest costs during construction as well as longer time-at-risk. These factors

are projected to result in high equity investment fractions and return on investment rates.

The GT-MHR benefits from all of the advantageous economic characteristics of competing nuclear power (water reactor plants) and minimizes the disadvantageous economic characteristics. The GT-MHR is projected to have economic advantages over both new water reactor nuclear plants and gas-fired combined cycle plants. The economic competitiveness of the GT-MHR is a consequence of the use of the direct Brayton cycle power conversion system and the passive safety design. The direct Brayton cycle provides high thermal conversion efficiency and eliminates extensive power conversion equipment required by the Rankine (steam) power conversion cycle. Reduction in the complexity of the power conversion equipment reduces both capital and operation and maintenance (O&M) costs. The passive safety design eliminates the need for extensive safety related equipment which reduces both capital and operation and maintenance (O&M) costs.

A summary of the overnight capital costs for the nth-of-a-kind reference GT-MHR plant containing four standardized reactor modules is given in Table 2. The nth-of-a-kind plant costs are the costs estimated for the 8th plant built assuming the eight plants were built one after another resulting in the cost economies from bulk material orders for multiple plants and construction cost efficiencies resulting from the sequential deployment of plant construction resources (manpower and equipment).

Table 2
GT-MHR Nth-of-a-kind Plant Capital Costs
(2002 Dollars)

Direct Cost, M$	787
Indirect Cost, M$	137
Contingency & Owners Cost, M$	191
Total Overnight Cost, M$	1,115
Plant Capacity, kWe	1,145
Overnight Unit Capital Cost, $/kWe	975

As opposed to competing water reactor plants, not all of the above capital cost, 1,145 MWe at 975$/kWe (1.12 billion dollars) is at risk all at same time. The four modules in the standard plant are designed to be deployed sequentially. The highest value of investment-at-risk prior to generation of revenue is the cost of the first module plus the required balance of plant infrastructure. This investment is estimated to be 0.45 billion dollars. The construction period to complete the first module is projected to be 3 years. As a result of these characteristics, both the investment-at-risk and the time-at-risk is reduced for the GT-MHR relative to competing water reactor plants.

A comparison of the GT-MHR nth-of-a-kind plant levelized busbar generation costs with competing water reactor and gas-fired combined cycle plants is given in Figure 10. This figure shows the GT-MHR busbar generation cost to be significantly less than the competing new generation alternatives.

The plant cost parameters used to develop Figure 10 are summarized in Table 3. With the exception of the gas fuel cost, the parameters for the gas-fired combined cycle and water reactor plants are based on the mid-range of values given in Reference 1. The gas fuel cost is based on the low end of the range for natural gas cost, $3.50/MBTU, and the high end of the range (least favorable) for the heat rate, 7000 BTU/kWe. The GT-MHR costs are all current projected mid range values.

For the combined cycle plant, the capital cost component of the generation cost was based on a 10-year levelization period. For the nuclear plants, a 20-year levelization period was assumed due to their significantly longer design lifetimes. The capital cost components for both the combined cycle and nuclear plants could vary by about ±20% depending on financial parameters used for debt-to-equity ratio, return-on-debt, and return-on-equity.

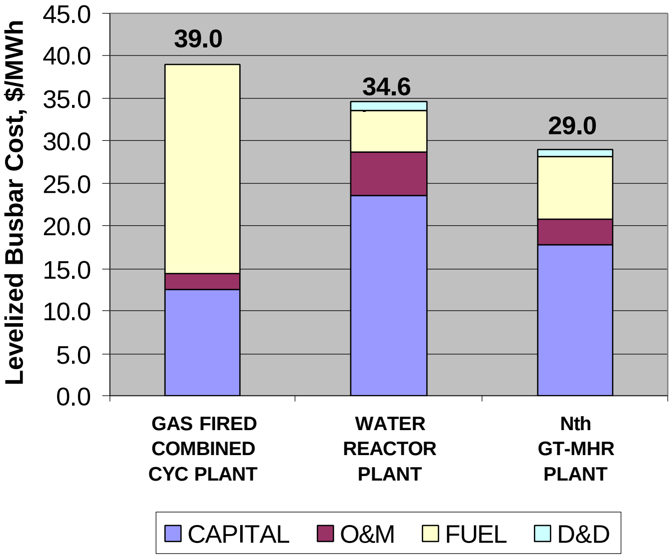


Figure 10. Comparison of Busbar Generation Costs for Alternative Electricity Generation Plants

Table 3
Alternative Electricity Generation Plant Cost Parameters

Parameter	Gas-fired Combined Cycle Plant	Water Reactor Plant	Nth GT-MHR Plant
Capital cost, $/kWe	550	1300	975
Plant capacity, MWe	500	1150	1145
Capacity factor	85%	90%	90%
O&M cost, $/MWh	2	5	3
Fuel cost, $/MWh	24.5	5	7.4

VI. GT-MHR COMMERCIAL DEPLOYMENT PLAN

The GT-MHR is currently being developed in Russia under the "Agreement between the Government of the United States of America and the Government of the Russian Federation on Scientific and Technical Cooperation in the Management of Plutonium that has Been Withdrawn from Nuclear Military Programs" (July 24, 1998 US/RF Agreement). The US (DOE) and the RF (Minatom) are jointly sponsoring the development work; Japan and the European Union are providing support. The plan in Russia is to:

- Design, construct and operate a prototype GT-MHR module by 2009
- Design, construct and license a GT-MHR Pu fuel fabrication facility in Russia
- Operate a first 4-module GT-MHR plant for Pu disposition by 2015

Because the GT-MHR is an effective nuclear power electric generation plant for commercial deployment when fueled with uranium, a program has been implemented for commercial deployment in the US of the technology being developed in Russia. The engineering tasks necessary for adapting the technology developed in Russia for commercial plant deployment in the US consists of:

- Conversion of GT-MHR design, technology and engineering documentation from the Russian program to US standards
- Preparation of incremental design items required for commercial deployment of the technology (e.g., uranium core design)
- Performance of plant safety analyses and NRC licensing
- Design, construction and qualification of uranium fuel fabrication facilities
- Performance of plant design and analysis

No new R&D is needed; all of the necessary development and test work will be performed in Russia.

A summary schedule of the activities for commercial deployment of the GT-MHR technology is given in Figure 11. Construction in the US of a first commercial GT-MHR module meeting US standards and satisfying US regulations can closely follow construction of the prototype in Russia. Construction of the first commercial module will require approximately 3 ½ years from first concrete pour. Additional modules at the same site will require progressively shorter construction times.

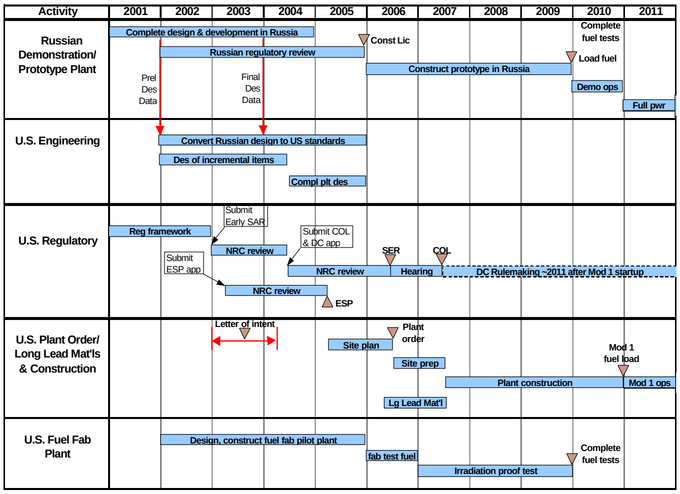


Figure 11. GT-MHR Commercial Deployment Schedule

The commercial effort is strongly supported by nearly every U.S. utility that has an expressed interest in building new nuclear plants in the future, including Entergy, Dominion Resources, Nuclear Management Corp. Constellation, Progress Energy, Omaha Public Power District, and Public Service Gas and Electric. Importantly, the Russian interest in the GT-MHR commercial potential is very high and they are being closely integrated into the U.S. commercialization effort.

VII. CONCLUSIONS

The GT-MHR design offers several advantageous performance characteristics. These include:

- Unique Reactor Safety - The GT-MHR is meltdown-proof and passively safe. The overall level of safety is achieved through a combination of inherent safety characteristics and design selections consisting of: (1)

helium coolant, which is single phase, inert, and has no reactivity effects; (2) graphite core, which provides high heat capacity and slow thermal response, and structural stability at very high temperatures; (3) refractory coated particle fuel, which allows extremely high burnup and retains fission products at temperatures much higher than normal operation; (4) negative temperature coefficient of reactivity, which inherently shuts down the core above normal operating temperatures; and (5) an annular, 600 MWt low power density core in an uninsulated steel reactor vessel surrounded by a reactor cavity cooling system..

- High Plant Efficiency - Use of the Brayton Cycle helium gas turbine in the GT-MHR provides electric generating capacity at a net plant efficiency of about 48%, a level that can be obtained by no other nuclear reactor technology. The high plant efficiency reduces power generation costs, thermal discharge to the environment and high level waste generation per unit electricity produced.

- Superior High Level Waste Form - Coated particle fuel provides a superior spent fuel waste form for both long-term interim storage and permanent geologic disposal. The refractory coatings retain their integrity in a repository environment for hundreds of thousands of years. As such, they provide defense-in-depth to ensure that the spent fuel radionuclides are contained for geologic time frames and do not migrate to the biosphere.

- Low Environmental Impact - Relative to water reactor plants, the GT-MHR thermal discharge is about 50% less and the actinide production is about 60% less per unit electricity produced.

- High Proliferation Resistance – The GT-MHR spent fuel has very high proliferation resistance because the quantity of fissile material (plutonium and uranium) per GT-MHR spent fuel element is low, the plutonium isotopic composition is unattractive and there is neither a developed process nor capability anywhere in the world for separating the residual fissionable material from GT-MHR spent fuel.

- Competitive Electricity Generation Cost – The GT-MHR levelized busbar generation cost is evaluated to be less than competing water reactor and gas-fired combined cycle plants. The GT-MHR retains the low production cost, high capacity factor and long lifetime advantages of nuclear power. But, the GT-MHR can be deployed in relatively small increments (286 MWe) in relatively short construction times to minimize cost-at-risk and time-at-risk prior to generation of revenue.

The GT-MHR technology is currently being developed in Russia as part of the joint US/RF program for disposition of weapons plutonium. A program has been implemented for commercial deployment of the GT-MHR using uranium fuel. Commercial deployment of the first GT-MHR module can be done by about 2010. The commercial effort is strongly supported by nearly every U.S. utility that has an expressed interest in building new nuclear plants in the future.

REFERENCES

1. “ A Roadmap to Deploy New Nuclear Power Plants in the United States by 2010,” Prepared for the United States Department of Energy, Office of Nuclear Energy, Science and Technology and its Nuclear Energy Research Advisory Committee, Subcommittee on Generation IV Technology Planning, October 31, 2001.