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GT-MHR DESIGN, PERFORMANCE, AND SAFETY

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ABSTRACT

The Gas Turbine-Modular Helium Reactor (GT-MHR) is the result of coupling the evolution of a low power density passively safe modular reactor with key technology developments in the U.S. during the last decade: large industrial gas turbines; large active magnetic bearings; and compact, highly effective plate-fin heat exchangers. This is accomplished through the unique use of the Brayton cycle to produce electricity with the helium as primary coolant from the reactor directly driving the gas turbine electrical generator. This cycle can achieve a high net efficiency in the range of 45% to 48%.

In the design of the GT-MHR the desirable inherent characteristics of the inert helium coolant, graphite core, and the coated fuel particles are supplemented with specific design features such as passive heat removal to achieve the safety objective of not disturbing the normal day-to-day activities of the public even for beyond design basis rare accidents.

Each GT-MHR plant consists of four modules. The GT-MHR module components are contained within steel pressure vessels: a reactor vessel, a power conversion vessel, and a connecting cross vessel. All vessels are sited underground in a concrete silo, which serves as an independent vented low pressure containment structure.

By capitalizing on industrial and aerospace gas turbine development, highly effective heat exchanger designs, and inherent gas cooled reactor temperature characteristics, the passively safe GT-MHR provides a sound technical, monetary, and environmental basis for new nuclear power generating capacity.

This paper provides an update on the status of the design, which has been under development on the US-DOE program since February 1993. An assessment of plant performance and safety is also included.

INTRODUCTION

The challenge for the nuclear industry in the 1990s will be the development of plants that address matters of public acceptance, improved safety, competitive generating costs and reduced radioactive waste. The GT-MHR which has evolved from the steam cycle Modular High Temperature Gas Cooled Reactor (MHTGR) firmly addresses each of these issues. Like the MHTGR, the GT-MHR relies on design selections and passive safety systems to assure retention of radionuclides within the TRISO coated fuel particles. Utilizing a special annular core design which is larger and located nearer to the reactor vessel and Reactor Cavity Cooling System than the MHTGR, peak fuel temperatures during a rare loss of forced cooling and pressure event are within the design goal for the fuel of 1600°C.

The GT-MHR is an environmentally acceptable power plant that has a high degree of inherent safety characteristics. These inherent safety characteristics coupled with a direct cycle gas turbine allow design simplifications that help control costs and schedule. The GT-MHR can uniquely use the Brayton cycle to produce electricity by directly driving a gas turbine electrical generator. The GT-MHR can achieve a net efficiency in the range of 45-48%. This high efficiency leads to competitive economics when compared to the 32% net efficiencies achieved by advanced water cooled reactor power plants. High thermal efficiencies lead to an environmentally compatible design that produces about 50% less high level radioactive waste and about 100% less thermal discharge to the environment than comparably sized LWRs (Ref. 1).

The GT-MHR evolved from a 10 year design effort on the steam cycle MHTGR funded under the U.S. DOE Advanced Reactor Program. Producing ~286 MW(e) per reactor module, the GT-MHR retains many of the key MHTGR design features including refractory coated TRISO fuel, low power density core, factory fabricated steel vessels, below grade siting, and completely passive decay heat removal. Most importantly the GT-MHR retains the capability of meeting all safety goals without relying on active safety systems or operator actions. The GT-MHR couples this impressive safety performance to several key technology developments of the last decade: large industrial gas turbines, large active magnetic bearings, and compact plate-fin heat exchangers. The major difference from the steam cycle design is instead of using steam to drive a steam turbine plant at 38% of efficiency, the GT-MHR produces electricity directly in a closed-cycle helium turbomachine at 45% to 48% net efficiency, thereby eliminating the expense and complication of the steam plant equipment.

The GT-MHR addresses the issues of the 1990s by providing a step increase in economic performance combined with reduced environmental impact and increased reactor safety.

GT-MHR PLANT DESIGN

In the design of the GT-MHR the desirable inherent characteristics of the inert helium coolant, graphite core, and the coated fuel particles are supplemented with specific design features to ensure passive safety. Radionuclides are essentially retained under all licensing basis events within the refractory coated fuel particles. The integrity of the particle coatings as a barrier is maintained by limiting heat generation, assuring means of heat removal, and by limiting the potential effect of air and water ingress under potential accident conditions. The design of the GT-MHR provides redundant and diverse active systems to perform these functions for both normal and transient conditions. However, consistent with the safety and performance objectives, the fuel integrity is maintained because of inherent MHR characteristics and passive design features without the need for active AC powered systems or operator action.

The key features and design selections to ensure the GT-MHR's safety goals include:

- *Helium Coolant* - The inert and single-phase helium coolant has several advantages. No flashing or boiling of coolant is possible, pressure measurements are certain, no coolant level measurements are required, and pump cavitation cannot occur. Further, there are no neutronic reactions with the helium and no chemical or energetic reactions between coolant and fuel.

- *Graphite Core* - The strength and stability of the graphite core and the ceramic fuel at high temperatures result in a wide margin between either operating temperatures or accident temperatures and temperatures that would result in core damage. Further, the low power density of the core and the massive graphite core structure with its large heat capacity ensure that changes in the overall core temperature take place very slowly.

- *Coated Fuel Particle* - The coated fuel particles consist of microspheres of uranium oxycarbide kernels clad with layers of pyrolytic carbon and silicon carbide. This TRISO coating is stable under irradiation and prevents significant release of radionuclides for long times (several hundred hours) even at temperatures reached in severe accidents. The 770 mm diameter coated fuel particles are bonded into rod-shaped fuel particle compacts with a graphitic binder and inserted into cylindrical holes, drilled in the hexagonal graphite fuel elements.

- *Negative Temperature Coefficient of Reactivity* - The nuclear characteristics of the graphite and low enriched uranium materials combine to produce a power coefficient dominated by the temperature coefficient of reactivity, which is strongly negative for all operating and accident conditions. This large negative temperature coefficient will terminate the nuclear reaction if the core heats to beyond normal operating temperatures.

- *Core Power and Power Density* - The maximum thermal output of the reactor core and the core power density have been kept low to limit the amount of decay heat that must be dissipated during an accident - a key factor in enabling passive safety.

- *Core Geometry, Reactor System* - The annular geometry, large height to diameter ratio, and the uninsulated steel reactor vessel and redundant, passive reactor cavity cooling system have been elected to ensure adequate decay heat removal from the core through passive thermal radiation, conduction, and natural convection.

The use of inert helium gas coolant with a graphite core and TRISO coated fuel facilitate operation of the reactor at temperatures compatible with the safe generation of electricity with high thermal efficiency.

The GT-MHR module arrangement is shown in Fig. 1. Each GT-MHR plant is envisioned to consist of four modules. The GT-MHR module components are contained within three steel pressure vessels: a reactor vessel, a power conversion vessel, and a connecting cross vessel. All three vessels, which are made from high strength 9Cr-1Mo-V alloy steel, are sited underground in a concrete silo that serves as an independent vented low pressure containment structure.

The 8.4m diameter by 31.4m high reactor vessel contains the annular reactor core, core supports, control rod drives, refueling access penetrations, and a shutdown cooling system. The reactor core is formed by hexagonal graphite fuel columns, which contain a mixture of 20% enriched fissile and natural uranium fertile fuel encapsulated in ceramic coated microspheres.

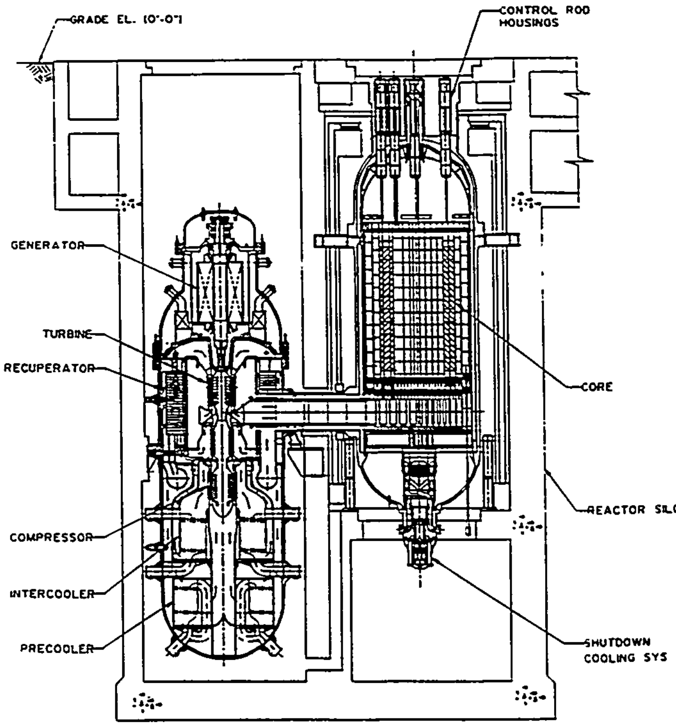

Figure 1. GT-MHR Plant Arrangement

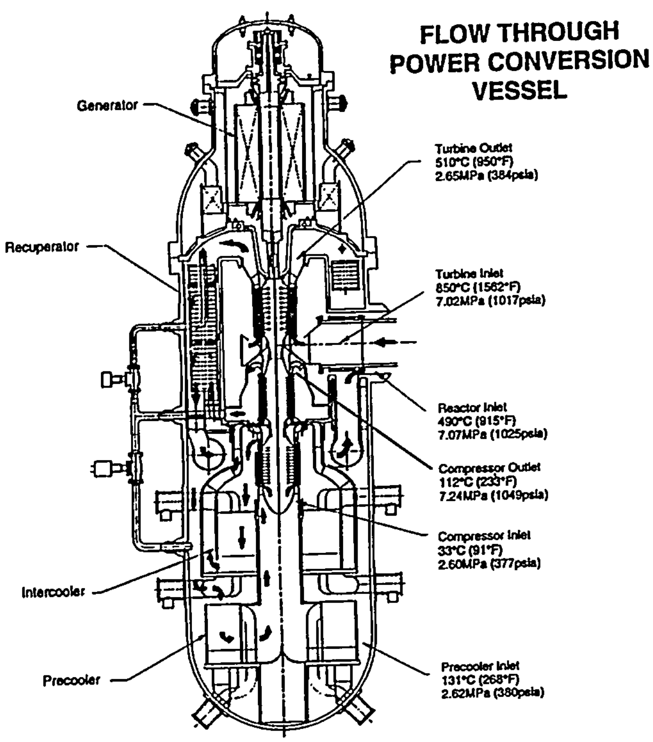

Figure 2. GT-MHR Power Conversion Vessel Assembly

The reactor vessel is surrounded by a reactor cavity cooling system (RCCS), which provides totally passive decay heat removal. The separate shutdown cooling system provides backup decay heat removal for refueling and maintenance activities.

The power conversion vessel contains the entire power conversion system as shown in Fig. 2. The turbomachine consists of a generator, turbine, and two compressor sections submerged in helium, mounted on a single shaft supported by magnetic bearings. The power conversion vessel also contains three compact heat exchangers: the high efficiency plate-fin recuperator and the water cooled intercooler and precooler.

The major component in this vessel is the vertical single-shaft helium gas turbine that drives the synchronous generator. The gas turbine consists of two separated compressor sections which permit intercooling and the turbine. The rotor assembly uses active magnetic thrust and journal bearings. The GT-MHR gas turbine is physically smaller than gas turbines in service due to the high coolant pressurization associated with closed cycle systems.

The three heat exchangers located within the power conversion vessel contribute significantly to the plant's high efficiency. The turbine exhaust is used by the compact plate-fin recuperators to preheat the high pressure compressor discharge helium before it enters the reactor resulting in enhanced efficiency. The low temperature duty helium-to-water heat exchangers provide low inlet temperature helium to the compressors. These helical bundle heat exchangers use finned-tube geometries and operate in a far less demanding temperature environment in the Brayton cycle than in the Rankine cycle. Furthermore, these heat exchangers reduce the potential for water ingress into the helium coolant since the helium is at a higher pressure when the plant is at full power.

DESIGN STATUS

In 1993, the DOE funded gas-cooled reactor program was redirected to design studies focused on the GT-MHR. The GT-MHR reactor core and internals build on technology developed for Fort St. Vrain and development efforts on the steam cycle MHTGR. A power level evaluation in 1994 found that the existing 84-column reactor core could be enlarged to 102 columns by moving the three annular rings of hexagonal fuel elements closer to the vessel and still meet all safety and performance requirements. The study concluded that component requirements for the reactor, power conversion and vessel systems could, with development, be met at power levels up to 600 MWt (Ref. 2). The study recommended that an allowance for design margin be included resulting in a normal power rating of 550 MWt and a stretch capability of 600 MWt. All systems and components are currently being designed for 600 MWt.

In 1991 a fuel irradiation experiment was undertaken designated HRB-21. In the later stages of irradiation limited, but unacceptable, particle coating failures occurred. The causes of the unsatisfactory performance of the fuel in HRB-21 have been identified as inappropriate changes in the particle design and manufacturing process used for the HRB-21 design. A consensus on fixes has been agreed upon which in essence is based on using prior successful technology. Manufacturing process improvements are ongoing, and the next capsule is scheduled for irradiation in 1996.

The helium turbomachine is in an early stage of design but sufficient work has been done to confirm that the performance goals can be realized (Ref. 3) and that the technology for a near-term plant with a turbine inlet temperature of 850°C (1562°F) has a firm basis in the U.S. (Ref. 4). Engineering studies indicate that vertical turbocompressors and submerged generators supported on magnetic bearings are feasible. The recuperator design draws on already proven technology used in the design of similar recuperators for propulsion and industrial gas-turbine plants. In these applications, the number of load cycles and transient conditions are much more severe than in the GT-MHR application (Ref. 5).

Overall the conceptual design of the GT-MHR plant is well advanced. Although significant engineering effort is required, no show stoppers have been identified. Schedule assessments indicate that the first plant could be deployed within 10 years given adequate funding.

PLANT PERFORMANCE

The GT-MHR process flow is shown in Figure 3. The helium coolant exits the reactor core at 850°C (1562°F) and 6.91 MPa (1003 psia), flows through the center hot duct within the cross vessel, and is expanded through the turbine in the Power Conversion System. The turbine directly drives the electrical generator and the high and low pressure compressors. The helium exits the turbine at 510°C (950°F) and 2.56 MPa (371 psia), flows through the high efficiency plate-fin recuperator to return as much energy as possible to the cycle, and then flows through the precooler to reject heat to the ultimate heat sink. Cold helium at 26°C (78°F) enters the intercooled compressor where it is compressed to 7.08 MPa (1027 psia) at 107°C (224°F) and then passes through the recuperator where it is heated. Helium at 488°C (910°F) and 7.00 MPa (1015 psia) flows from the recuperator exit, through the outer annulus within the cross vessel, past the reactor vessel walls for vessel cooling, and finally down through the core to complete the coolant loop.

The GT-MHR with a turbogenerator directly coupled with the reactor produces electricity with up to 45% to 48% net plant efficiency. An efficiency range is given which represents current estimates of how well leakages can be controlled within the Power Conversion System. It also includes an allowance of 0.5% for adverse design evolution. Due to the high efficiency and consequent low thermal discharge, the GT-MHR has the flexibility to operate in dry environments by using dry cooling towers.

A preliminary economic evaluation has been performed for the GT-MHR using U.S. DOE guidelines for advanced reactors. The guidelines define a commercial or "target plant," for representing mature plant costs, as the plant which exceeds 4,500 MWe total installed capacity. All cost estimates are presented in terms of January

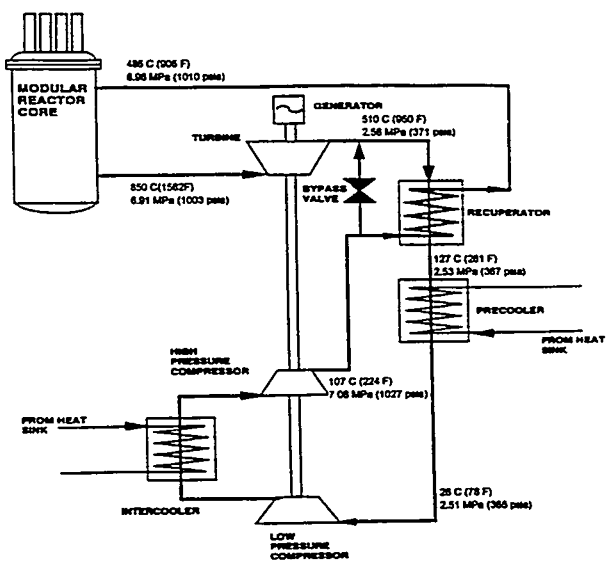

Figure 3. GT-MHR Process Flow Diagram

1992 dollars. Deployment schedules indicate that the target GT-MHR plant could begin power generation in approximately the year 2015.

The GT-MHR target plant performance parameters and economic evaluation results are compared to those of alternative mature plants in Table 1 (Ref. 6). Results are provided for two power levels, 550 MWt and 600 MWt per power unit. The mature GT-MHR is projected to have a lower busbar cost than any other alternative. The primary factors that account for the superior economics of the GT-MHR include: the high thermal efficiency of the closed Brayton cycle; the projection of stable nuclear fuel costs; and the simplicity and reliability of the gas turbine system, which provides for reduced capital cost, low O&M cost, and high operational capacity factors.

TABLE 1
COMPARISON OF GT-MHR GENERATION COSTS
WITH POWER GENERATION ALTERNATIVES

	GT-MHR Target Plant		ALWR 2X600	ALWR 1X1200	Coal IGCC	Gas CCCT
Performance Parameters						
Plant thermal rating, MWt	4x550	4x600	3659	3582	2625	2203
Net thermal efficiency, %	47.7	47.7	32.8	33.5	38.1	45.4
Plant electrical rating, MWe	1049.4	1144.8	1200	1200	4x250	4x250
Plant capacity factor, %	84.0	84.0	80.0	80.0	84.0	84.0
Plant Economic Evaluation Results, 1992 Dollars						
Total capital cost, M$	1740	1740	2034	1860	1611	531
Unit capital cost, $/kWe	1658	1520	1695	1550	1611	531
Total capital cost, $/kWe	33.9	31.2	54.5	45.5	48.4	11.2
Fuel cost, $/MBTU	1.31	1.27	0.77	0.77	1.45	2.33
Fuel real escalation, %/yr	0.0	0.0	0.0	0.0	1.0	2.2
Levelized busbar generation costs, mills/kWh						
- Capital	21.4	19.6	23.2	21.2	21.5	7.1
- O&M	4.6	4.2	7.8	6.5	6.6	1.5
- Fuel	9.4	9.1	8.0	7.9	18.5	38.4
- Decommissioning	0.7	0.6	0.9	0.9	0.1	0.0
Total busbar costs	36.1	33.6	39.9	36.4	46.6	47.0

Unlike fossil fired electric generating plants of similar size, the GT-MHR does not annually discharge to the environment thousands of tons of sulfur dioxide, carbon dioxide, and oxides of nitrogen. In addition, coal plants during combustion release significant amounts of the uranium and thorium contained within the coal. Assuming coal contains 1.3 ppm of uranium and 3.2 ppm of thorium, a 1000 MWe plant releases 5 tons of uranium (containing 70 lb of U-235) and 13 tons of thorium each year to the environment (Ref. 7).

The high efficiency of the GT-MHR has a number of environmental advantages. As shown in Fig. 4, for each electrical kWh, conventional LWR's produce 50% more high level radioactive wastes, 150% more actinide, and 100% more thermal discharge to the environment than the GT-MHR.

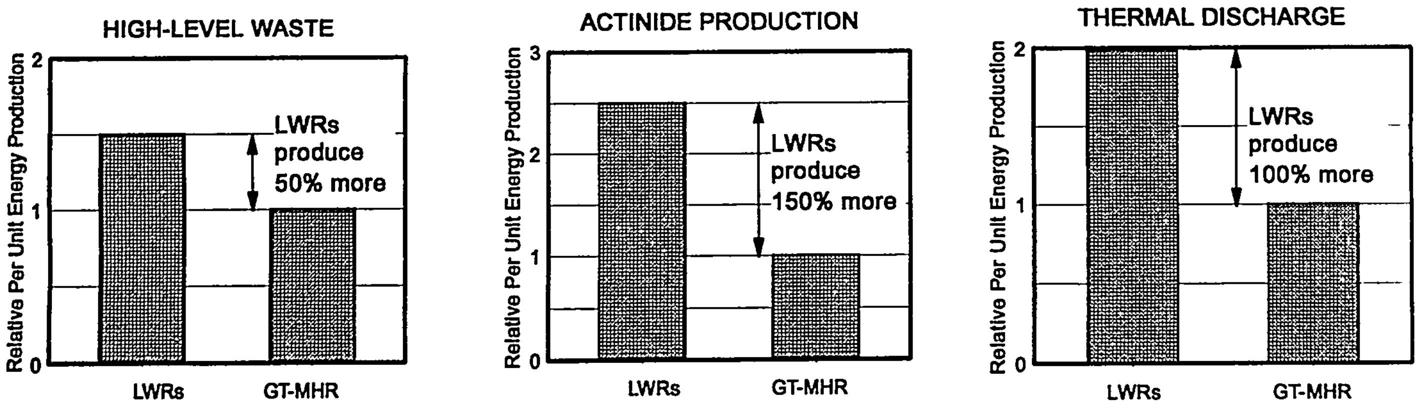

Figure 4. GT-MHR Minimizes Environmental Impact

SAFETY PERFORMANCE

The key to achieving large safety margins in the GT-MHR is in ensuring that the integrity of the fuel coatings, the initial barriers to radionuclide release, is not breached. Additional barriers such as the core graphite, vessel, and vented low pressure containment provide defense-in-depth to mitigate any releases and further increase the safety margins.

The fuel coating integrity is assured by controlling temperatures with ultimate reliance only on inherent characteristics and passive design features:

1. Control of Heat Generation

   Two independent active systems control reactor power levels. These are (1) the inner and outer control rod banks - a total of 54 control rods and (2) a diverse gravity-drop reserve shutdown system of 12 units. Similar systems were successfully demonstrated at Fort St. Vrain. The control rod system is fail-safe and inserts automatically on loss of power. Either system can maintain the core in a safe shutdown condition.

   In addition, a passive feature for heat generation control is provided by the inherent core negative temperature coefficient of reactivity. Following any interruption in forced cooling or a power excursion that increases core temperatures, this system mitigates the core temperature rise. Furthermore, even if forced cooling is completely lost and the active reactivity control system are unavailable, this feature alone will ensure reactor shutdown for more than one day. The German AVR reactor successfully demonstrated this inherent feature during a planned safety demonstration. Thus during an accident the reactor is shutdown, and only the core decay heat need to be removed to maintain acceptable core temperatures.

2. Decay Heat Removal

   Two active systems remove decay heat: the power conversion and the shutdown cooling systems. If neither active system is available, the independent passive reactor cooling system removes the heat. The core materials, power rating, power density, and configuration were chosen to ensure that sufficient heat could be removed to maintain acceptable core temperatures. Heat removal is accomplished by passive means through conduction, convection and radiation from the uninsulated reactor vessel to the passive reactor cavity cooling system. Thus, if neither active heat removal system is available, the continuously operating reactor cavity cooling system can reject heat to the environment by the natural circulation of air in an open loop system.

In the event that all active cooling systems fail and the vessel is breached such that the coolant pressure decreases to near atmospheric, peak nominal core temperatures of about 1521°C (2770°F) are reached after about three days in 5% of the core (Fig. 5). The reactor cavity cooling system will cooldown the core without operator intervention or electrical power. At these temperatures fuel coating remains an effective first barrier to radionuclide release.

An event in the GT-MHR that challenges core cooling is loss of a turbine blade (Ref. 8). The turbine deblading event results in a turbine and reactor trip and subsequent rapid internal helium pressure equalization in the primary coolant circuit. The event has the potential for disruption of the core geometry due to large pressure differentials or flow reversals across the core. Figure 6 shows the variation of coolant pressures at the core inlet and outlet plenums. Core inlet pressure remains greater than core outlet pressure, assuring that flow reversal is precluded. Analysis shows that primary system pressure decreases following the event from 7.00 MPa (1015 psi) to 4.1 MPa (60.0 psi) in 120s. During this

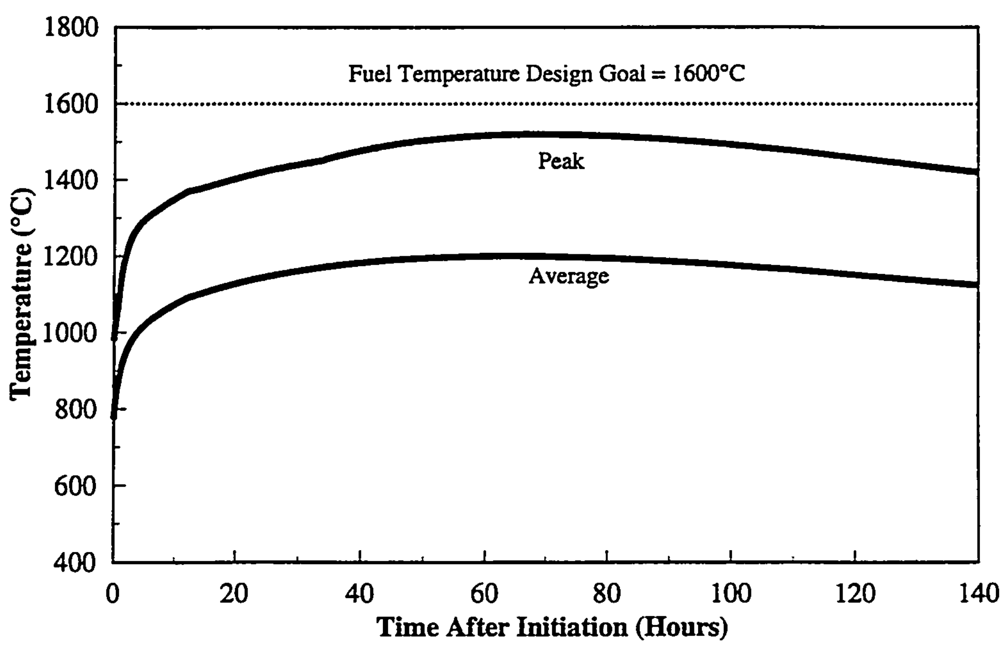

Figure 5. Average and peak fuel nominal temperatures during a 600 Mwt GT-MHR accident resulting in loss of all active cooling systems and loss of coolant pressure. Core cooling only on passive reactor cavity cooling system

time the pressure differential across the core increases to a peak of 0.13 MPa (19 psi) and then decreases as the flow decreases. The maximum pressure differential across the core is well below 0.96 MPa (140 psi) the maximum allowable compressive load. Therefore, core geometry is maintained, assuring a coolable core configuration.

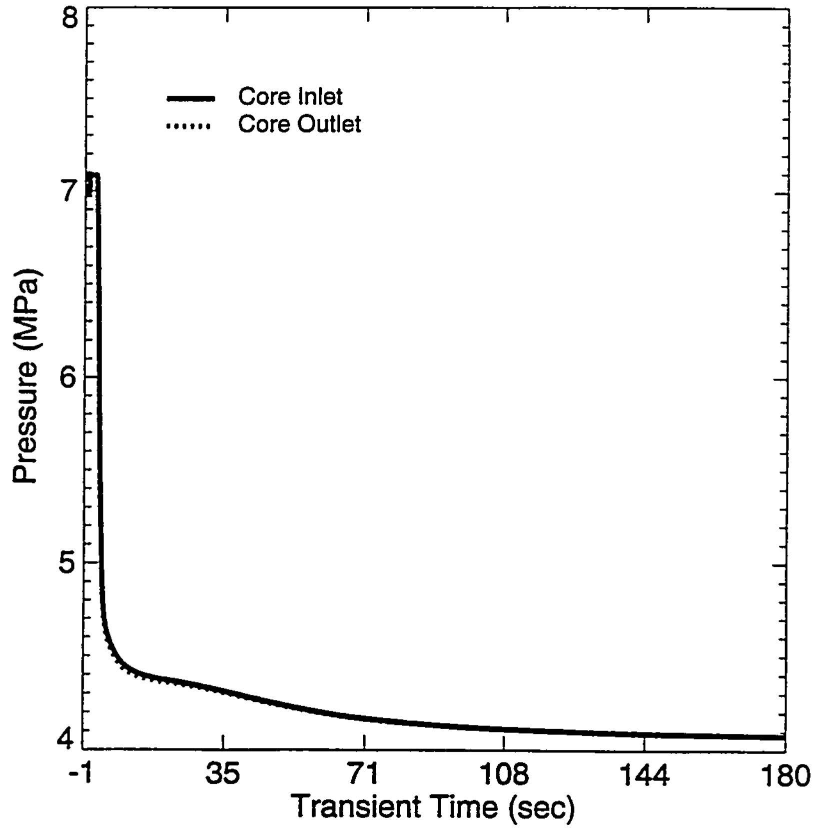

Figure 6. Transient pressure across the GT-MHR core during loss of turbine blade event

3. Effect of Air and Water Ingress is Limited

Passive design features and inherent properties provide the basic defenses against chemical effects on the coated fuel particles. These include the choice of chemically inert helium gas as the primary coolant to preclude any coolant reactions with the reactor or core and the use of multiple physical barriers between the particles and either air or water, the two chemical oxidants in close proximity to the core. Small air or water leaks into the primary system are quickly cleaned up by means of a continuously operating helium purification system. The effect on particles from even large amounts of air or water in the primary coolant is inherently limited by the massive graphite core and the coated particle, which itself is highly resistant to chemical effects from either.

Design features are incorporated in the GT-MHR to limit water ingress and its effect on the graphite core structure or the coated particles. These include limiting the number, pressure, and volume of water sources, locating the sources below the core elevation where possible, and providing a reliable water detection, isolation, and dump system. Of particular note is that the GT-MHR has eliminated the high pressure sources of water in the steam cycle steam generators, which significantly reduces the likelihood of water ingress during operation.

Even if the water enters the primary system, no significant oxidation of the graphite structure would occur unless temperatures were in excess of normal operating conditions.

Further, the water graphite reaction is endothermic (absorbs heat) and is therefore inherently self limiting. If either of the two active cooling systems (primary and shutdown) are available, the core temperature can be maintained at or below normal temperatures. Even if the barriers are breached, releases of radionuclides will be limited to the inventory within the very small fraction of fuel particles which have failed silicon carbide coatings (from manufacturing defects or in-service failure).

The design features that limit air ingress are the use of nuclear grade vessels and the location of the vessels below-grade within the vented low pressure containment. With the arrangement of the primary system, multiple failures in the ASME Section III Class 1 vessels are required for air to displace the lighter helium. Even should vessel openings be available, rapid oxidation of the dense, high-purity nuclear-grade graphite by air requires temperatures well above normal operating temperatures. The temperature of the graphite can be controlled by either of the two active cooling systems. Should they not be available, the rate of any reaction is still limited because the air supply available to support the reaction is constrained by the high flow resistance of the coolant holes in the tall core structure. As a result, the amount of heat generated from the reaction of air with graphite would be small compared to the core afterheat, and radionuclide releases are within acceptable limits. Even if the air reacts sufficiently with the graphite fuel element structure and fuel matrix materials to reach the coated particles, the oxidation would be mitigated by the silicon carbide barrier layer on the particles. Under no circumstances could graphite "burning" be sustained.

CONCLUSION

The GT-MHR is the result of coupling a small, passively safe modular helium cooled reactor with large industrial gas turbines; active magnetic bearings; and highly effective plate-fin heat exchangers. The passively safe GT-MHR provides a sound technical, economic, and environmental basis to address the challenges the nuclear industry faces in the 1990s. The GT-MHR is unique in that it is the only reactor concept which can provide a step increase in economic performance combined with inherent safety features. This is accomplished through its utilization of the Brayton cycle to produce electricity directly with the high temperature primary helium coolant from the reactor directly driving the gas turbogenerator. Although significant effort is required to complete design and much detailed work remains, the design is largely based on existing technology. Design progress is constrained by funding but no show stoppers have been found. The busbar power costs of the GT-MHR are competitive with all other nuclear and fossil energy options in the U.S. The plant is able to achieve these favorable economics while maintaining high levels of passive safety that eliminate the possibility of core melt. Thermal discharge to the environment is low, and releases of harmful greenhouse gases are eliminated.

In conclusion, the GT-MHR offers one of the best opportunities of addressing the key nuclear industry issues of the 1990s of public acceptance, competitive costs, and reduced environmental impacts with an innovative, cost competitive, and passively safe nuclear option.

ACKNOWLEDGEMENT

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