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# Status of the GT-MHR for Electricity Production

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## Introduction

The Gas Turbine–Modular Helium Reactor (GT-MHR) is an advanced nuclear power system that offers unparalleled safety, high thermal efficiency, high proliferation resistance, low environmental impact, waste management benefits and competitive electricity generation costs.

The conceptual design of the GT-MHR was previously presented at the 22nd Symposium of the Uranium Institute [1], [2], and [3]. Since the 22nd Symposium, a preliminary design of the GT-MHR has been completed and a series of reviews of the preliminary design have been conducted. The reviews concluded the least proven areas of the design to be (1) the TRISO-coated particle fuel and (2) the highly integrated power conversion system. While there are very encouraging data to support both of these items, uncertainties remain because there is no directly applicable prior experience with either.

In this paper, a summary of the preliminary design of the GT-MHR is provided, the advantages of the GT-MHR are identified, the results of the preliminary design reviews are summarized, and the technology demonstration programme that has been initiated to demonstrate key unproven technologies is described.

## GT-MHR design summary

The GT-MHR 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 (*Figure 1*). The reactor and power conversion vessels are interconnected with a short cross-vessel and are located in a below grade concrete silo (*Figure 2*).

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 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 3* 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, 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 recovers heat from the turbine exhaust prior to returning to the reactor.

As indicated in *Figure 4*, the use of the direct Brayton cycle to produce electricity results in a net plant efficiency of approximately 48%. This efficiency is about 50% higher than that in current light water reactor nuclear power plants. Nominal full power operating parameters are given in *Table 1*.

*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 MHR refractory coated particle fuel, *Figure 5*, 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.

Tests in the United States, Europe, and Japan have demonstrated TRISO-coated particle fuel to have high potential for retention of fission products to high burnups and high temperatures [4]. As shown by example test results in *Figure 6*, the TRISO coatings do not start to thermally degrade until temperatures approaching 2000°C are reached. The MHR has been designed such that normal operating temperatures do not exceed about 1250°C and worst case accident temperatures are maintained below 1600°C.

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 (*Figure 5*). One hundred and two columns of the hexagonal fuel elements are stacked 10 elements high to form an annular core, *Figure 7*. Reflector graphite blocks are provided inside and outside of the active core.

**Summary of GT-MHR advantages**

The GT-MHR is a nuclear power system evaluated to have significant benefits in the areas of:

- Safety
- Proliferation/terrorist resistance
- Spent fuel management
- Environmental impact
- Economic competitiveness

***Safety***

The GT-MHR is meltdown-proof and passively safe. 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:

- helium coolant, which is single phase, inert, and has no reactivity effects;
- graphite core, which provides high heat capacity and slow thermal response, and structural stability at very high temperatures;
- refractory (TRISO) coated particle fuel, which retains fission products at temperatures much higher than normal operation and postulated accident conditions;
- negative temperature coefficient of reactivity, which inherently shuts down the core above normal operating temperatures without the need for operator action; and
- an annular, low power density core in an uninsulated steel reactor vessel surrounded by a natural circulation reactor cavity cooling system (RCCS).

***Proliferation/terrorist resistance***

The GT-MHR has very high proliferation/terrorist resistance. Both GT-MHR fresh fuel and spent fuel have higher resistance to diversion, proliferation and potential terrorist opportunities than other nuclear reactor options. GT-MHR fresh fuel has high proliferation/terrorist 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 these same characteristics plus self-protecting high radiation fields. Furthermore, the low volume fraction and low quality (high degradation due to high burnup) of plutonium in GT-MHR spent fuel make it particularly unsuitable for use in weapons.

***Spent fuel management***

GT-MHR spent fuel is ideally suited for both long term storage and permanent disposal in a repository. 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 fuel particle TRISO coatings are very low under both dry and wet conditions [5]. Measured corrosion rates indicate the TRISO coating system should maintain its integrity for a million years or more in a geologic repository environment.

### *Low environmental impact*

The high thermal efficiency and high burnup capability of the GT-MHR results in reduced environmental impacts relative to other reactor options. The thermal discharge (waste heat) from the GT-MHR is one-half that for light water reactors per unit of electricity produced because the GT-MHR's thermal efficiency is 50% greater than that of light water reactors. Also, because of its high efficiency and high fuel burnup, the GT-MHR produces significantly less heavy metal radioactive waste than conventional nuclear power plants per unit of electricity produced.

### *Economic competitiveness*

The GT-MHR is projected to have economic advantages over other electric generation plants for new base load generation capacity [6]. 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 that also reduces both capital and O&M costs.

The overnight capital cost for the *n*th-of-a-kind reference GT-MHR plant containing four standardized reactor modules is projected to be ~US$975/kWe and the 20 year levelized busbar generation cost is projected to be 2.9 cents/kWh including capital, O&M, fuel, waste disposition and decommissioning.

## Commercialization potential and application flexibility

Currently, the GT-MHR design and development is being carried out in Russia under a joint US-Russia agreement to cooperate on development of systems for the disposition of surplus weapons plutonium. The GT-MHR is of interest for disposition of plutonium because of the potential to achieve high burnup for near complete plutonium destruction and energy recovery.

The GT-MHR, initially developed for plutonium disposition, has high commercialization potential because of its high safety, high thermal efficiency, economic competitiveness, high proliferation resistance, low environmental impact and waste management benefits. The GT-MHR designed for plutonium disposition will require a minimum of design changes for commercial deployment. The main design change will be the use of uranium fuel rather than plutonium fuel. No new R&D is required except for the basic design changes related to the use of uranium fuel.

The GT-MHR has high application flexibility because the high outlet temperature of the MHR reactor can be utilized to provide high temperature process heat energy for applications other than to produce electricity. A current application having high potential for a demonstration project in the US is coupling of the MHR with a Sulphur-Iodine (S-I) thermochemical water-splitting process to produce hydrogen [7]. The S-I cycle (*Figure 8*) consists of three chemical reactions, which sum to dissociation of water. Only water and high temperature process heat are input to the cycle and only hydrogen, oxygen and low temperature heat are output. All the chemical reagents are regenerated and recycled; there are no effluents. An intermediate helium heat transfer loop would be used between the MHR coolant loop and the hydrogen production system. At the standard MHR outlet temperature of 850°C, a maximum temperature of 825°C is estimated for the heat to the process, which yields 43% efficiency. At a reactor outlet temperature of 950°C and a 50ºC temperature drop across an intermediate heat exchanger, an efficiency of 52% is estimated.

An alternative hydrogen production process using high temperature process heat from the MHR is high temperature electrolysis. In this process, some of the energy would be used as electricity and some used directly as heat. Hydrogen production efficiencies of about 50% at 900°C are theoretically achievable with this process.

**Design development status**

The conceptual design of the GT-MHR for disposition of surplus weapons Pu was completed and fully documented by the end of 1997. In June 1999, an international panel of gas reactor experts conducted a detailed review of the GT-MHR conceptual design and concluded that while significant research and development work was necessary, there did not appear to be any “technological show stoppers” for completing the GT-MHR as proposed [8]. Key technical challenges were identified to be:

- performance/maintainability of the power conversion system;
- quality manufacturing/integrity of the Pu fuel;
- timely supply of the reactor and power conversion system vessels.

Work on the GT-MHR preliminary design phase was begun January 2000 in Russia and was completed on the reactor plant (i.e. the reactor system, power conversion system plus key auxiliary support systems) by December 2001. During the preliminary design, design issues identified by the conceptual design review panel were addressed and ways devised to mitigate the associated investment, technical or safety risks.

A review of the maintainability of the power conversion system was carried out by Electric Power Research Institute (EPRI) in 2001 to support development of the preliminary design [9]. This review was done to ensure adequate provisions were made for maintenance early in the design development process of the highly integrated power conversion system design. Key areas were identified deserving particular attention during the design process to provide adequate maintainability margins. These areas included access considerations, development of remote tooling, alignment and balance, hot gas duct insulation and catcher bearings.

During 2002, two independent design reviews were conducted of the GT-MHR reactor plant preliminary design. One of these was performed in Russia under the guidance of Minatom and the other was performed by US organizations under the guidance of the National Nuclear Security Agency of the US Department of Energy.

The preliminary design reviews identified areas where R&D should be given high priority. Most of these areas were associated with the Pu TRISO fuel fabrication and irradiation performance and the power conversion system development and integration. Long lead development activities for the reactor vessel material, reactor system graphite, and validation of reactor system analysis methodologies were also identified as high priority R&D areas. The results on the Pu TRISO fuel and power conversion system from review of the preliminary design are consistent with the conclusions reached in the international review of the conceptual design.

These preliminary design review results have led to the definition of a GT-MHR Technology Demonstration Programme to be carried out in Russia to perform high priority R&D activities.

## GT-MHR Technology Demonstration Programme

### *Pu TRISO fuel*

Technology demonstrations are required that show the Pu TRISO fuel can be fabricated to GT-MHR requirements and fuel fabricated to these requirements satisfy the performance requirements. Irradiation testing is required to demonstrate the integrity of the coatings and retention of fission products under normal operating conditions and during design basis accident conditions. Additional tests of the transport of fission products in the fuel under operating conditions are also needed for core and reactor design and licensing.

Test fuels for the demonstration tests will be fabricated in a Bench-Scale Facility (BSF) now under construction at the All-Russian Scientific Research Institute for Inorganic Materials (VNIINM). Both a reference Pu TRISO fuel kernel and a backup kernel will be tested. The primary and backup TRISO fuels will be fabricated at the BSF and tested at the All-Russian Institute of Atomic Reactors (NIIAR) irradiation facilities. Prior to making the Pu fuels, TRISO fuel using uranium oxide, or oxycarbide kernels will be fabricated and tested to verify the BSF coating and compacting manufacturing processes.

### *Power Conversion System*

The PCU consists of a turbomachine, a recuperator, a precooler, and an intercooler.

Of these four major components, only the turbomachine (TM) is considered a technology risk item. The recuperator, precooler and intercooler designs for the GT-MHR are fairly well proven technologies, so no technology demonstrations are planned for these items.

The TM consists of two major subassemblies, a Turbocompressor Assembly (TCA) and a generator. A flexible coupling between the TCA and the generator rotors decouples the dynamic response of the two rotors. Generators similar to the GT-MHR design are available commercially, so technology demonstration of the generator is not required. Performance of the TCA is, therefore, the primary item requiring high priority technology demonstration.

The TCA consists of four main components:

- Turbocompressor
- Electromagnetic Bearings (EMBs) and Control System
- Catcher Bearings (CBs)
- Turbocompressor Stator Seals.

The complete technology demonstration of the TCA consists of a series of tests at the subcomponent level followed by design vertification tests at the component level and then integrated system level tests on a full-scale prototype TCA.

To demonstrate that the turbine and compressor materials can withstand the design service life, a qualification programme will be conducted on selected materials to verify their mechanical characteristics under GT-MHR operating conditions. The high temperature turbine materials will be qualified for a maximum temperature of 850°C and for a service lifetime not less than 60 000 hours (equivalent to 7 years).

To demonstrate the performance of the CBs at the component level, full-scale prototypes of the radial and axial CBs will be manufactured and tested in a special test facility under the GT-MHR loading conditions. Non-destructive design verification tests will be conducted to verify bearing performance for run-up and run-down test conditions, and survivability under loss of EMB power events. Tests will be conducted at design temperatures, design loading conditions in helium.

To demonstrate the performance of the EMBs at the component level, full scale axial and radial EMB prototypes will be manufactured and tested. The tests will demonstrate control system stability during startup, steady state, and shutdown using a simulated mass model of the TCA rotor shaft, turbine and compressor. The tests will be run at temperature and in helium. The key demonstration parameters include the ability of the EMBs to maintain the required clearances between the rotor disks and magnetic couplers.

To demonstrate the performance of the large diameter segmented seals located between the TCA stator and the support structures, component level tests of full-scale prototype seals will be performed in a special test rig under design operating conditions. The tests will be done first in air and then in helium. The most demanding GT-MHR operating conditions will be used in the tests combined with worst case seal misalignments and out-of-round mating surface conditions.

The flexible coupling between the TCA and generator rotors will be demonstrated using a scale model since all of the coupling performance characteristics are readily scaleable. Loads simulating the most severe plant design transients will be used for this test. The test will verify the capability of the flexible coupling to handle rotor axial and radial misalignments, the decoupling and the dynamic responses of the two rotors, and will satisfy service life requirements.

A prototype TCA will be manufactured, assembled and integrated with the prototype EMBs, CBs, and stator seals for performance of TCA integrated tests. A special test facility will be constructed for these integrated tests. The other parts of the power conversion system will be simulated in the facility. The facility will be equipped to house and support the TCA in a pressure vessel with helium as the working fluid. External electric heaters will be used to simulate reactor core thermal energy.

Design of the TCA prototype and special test facility is nearing completion. Fabrication and construction activities are expected to begin next year.

### *Vessel System*

The GT-MHR requires large pressure vessels, for both the power conversion unit and the reactor system, and the reactor and cross vessels operate at high temperatures. During Conceptual Design, 9Cr-1MoV steel was selected for the reactor vessel in the US programme. During Preliminary Design, the conclusion was reached that the cost and schedule for the work required to qualify this steel for nuclear service and to develop the manufacturing processes required to fabricate the reactor vessel would be very extensive and expensive.

An alternative to 9Cr-1Mo steel is 2¼-1Mo steel which currently approved for pressure vessels in ASME Code Sections I and VIII for temperatures up to 1200ºF -1Mo is also the material used for Japan's HTTR reactor pressure vessel.

High priority Vessel System R&D activities identified for the technology demonstration programme are as follows:

- qualification of the 2¼-1Mo material for nuclear service for the GT-MHR operating design life (60 years) at operating temperature (440ºC); and

- qualification of fabrication processes (forging, welding, heat treating) in section sizes required for fabricating the GT-MHR vessels from 2¼-1Mo material: there are, for example, no currently qualified fabrication facilities for manufacturing forgings from 2¼-1Mo in the sizes required for the GT-MHR vessels.

R&D activities that address each of these high priority vessel system areas are in the process of being prepared.

### *Reactor System*

The areas in the Reactor System identified for high priority technology demonstration are qualification of the core graphite and validation of the core nuclear design analysis computer programs.

The GT-MHR core design employs graphite fuel elements, graphite reflector elements and graphite core support structural elements. The graphite used for these components must meet certain property requirements and the effects of irradiation on the graphite properties must stay within design limits. Nuclear grade graphite has not been in production in the US, or elsewhere, for a number of years. Graphite irradiation testing is required to qualify the material produced by either a domestic supplier or by a foreign supplier. The long lead time required for performing the irradiation tests places graphite qualification at high priority.

To assure safety requirements are satisfied, GT-MHR safety - related physics parameters must be calculated for the final design using validated computer codes and models. The code validation process is performed by comparing computer calculations with data from analytical benchmark models and/or with data from experiments. The time required to perform the experimental work places validation of the reactor physics codes and models at high priority.

Technology Demonstration Programme plans are currently being prepared which address each of these high priority Reactor System areas.

## Conclusions

The key conclusions from the foregoing sections are as follows:

1. The GT-MHR is an advanced nuclear power system that offers unparalleled safety, high thermal efficiency, high proliferation resistance, low environmental impact, waste management benefits and competitive electricity generation costs.

2. The GT-MHR design and development is being carried out in Russia under a joint US-Russia agreement to cooperate on development of systems for the disposition of surplus weapons plutonium.

3. The GT-MHR designed for plutonium disposition has high commercialization potential. A minimum of design changes will be required for commercial deployment. The main design change will be the use of uranium fuel rather than plutonium fuel.

4. The GT-MHR has high application flexibility because the high outlet temperature of the MHR reactor can be utilized to provide high temperature process heat energy. A current application having high potential, for a demonstration project in the US, is coupling of the GT-MHR (for high temperature process heat and electricity), or the MHR alone (for high temperature process heat only), with a hydrogen production process.

5. A preliminary design of the GT-MHR has been completed and a series of reviews of the preliminary design have been conducted. The reviews concluded the least proven areas of the design to be (1) the Pu TRISO-coated particle fuel and (2) the highly integrated power conversion system. While there is very encouraging data to support both of these design items, uncertainties remain because there is no directly applicable prior experience with either.

6. A Technology Demonstration Programme Plan has been prepared to address Pu TRISO fuel, power conversion system, vessel system and reactor system areas that require long lead times to carry out required R&D activities.

   The GT-MHR is well suited for the Next Generation Nuclear Power (NGNP) demonstration project currently being planned in the USA for operation by 2015. The current design meets the “Generation IV” nuclear programme goals, including passive safety, competitive economics, enhanced proliferation resistance, and improved waste disposal characteristics. The GT-MHR can be a major element in the revival of nuclear power.

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*Figure 1*. GT-MHR reactor module

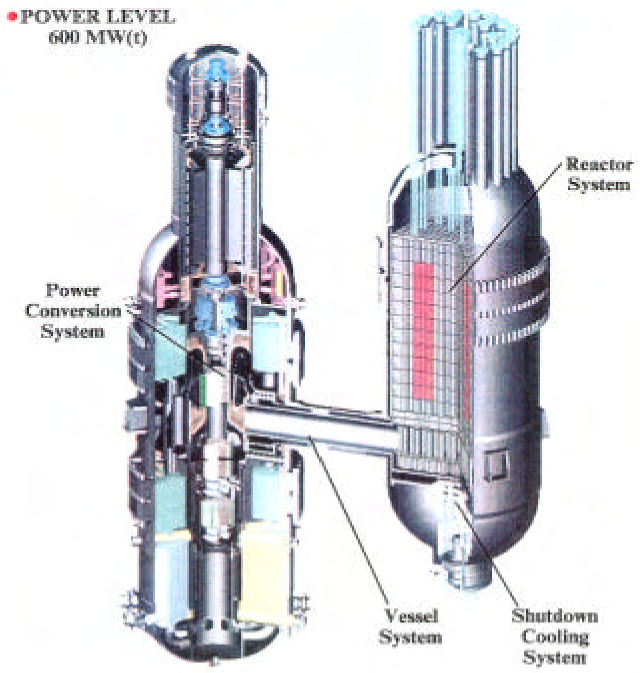


*Figure 2*. GT-MHR below grade installation

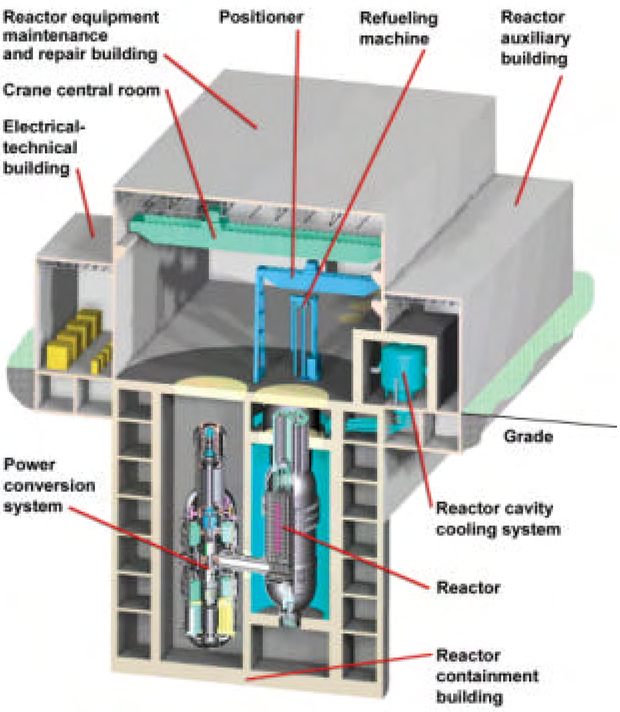

*Figure 3*. GT-MHR coolant flow schematic

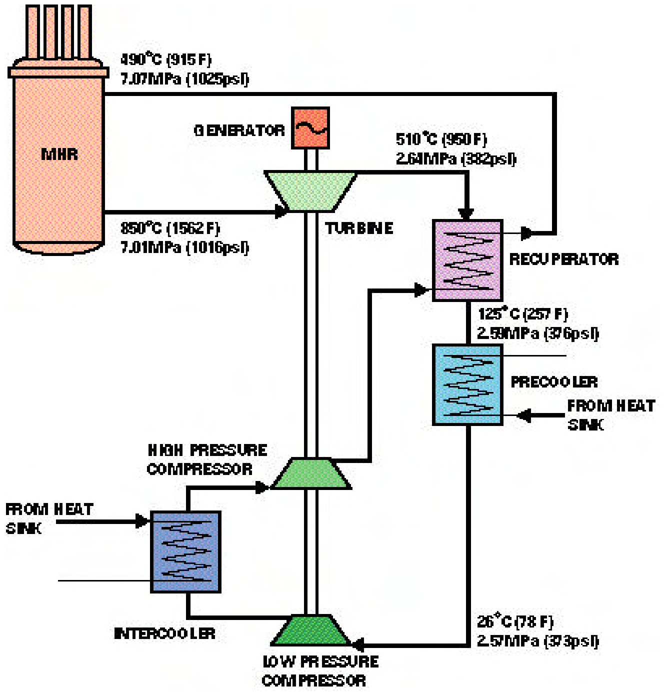


*Figure 4*. Comparison of thermal efficiencies

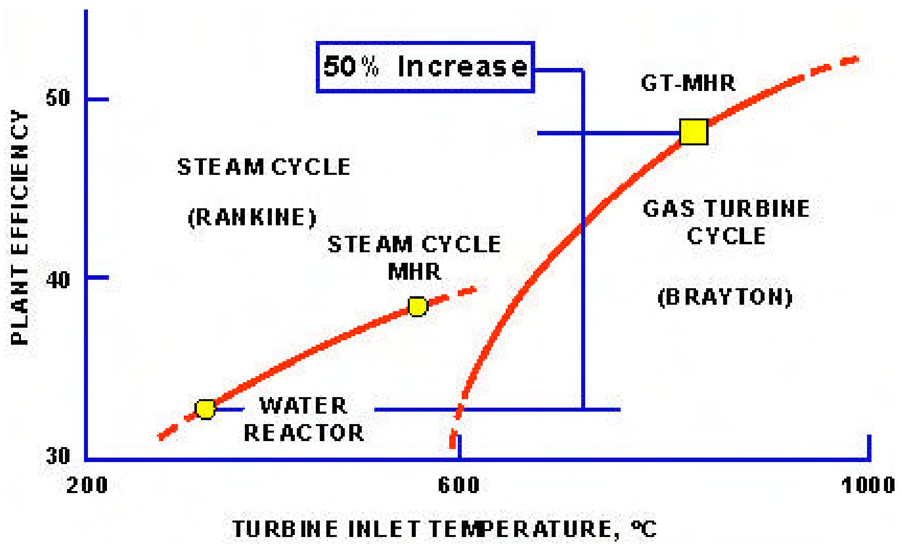

*Figure 5*. GT-MHR TRISO-coated particle fuel

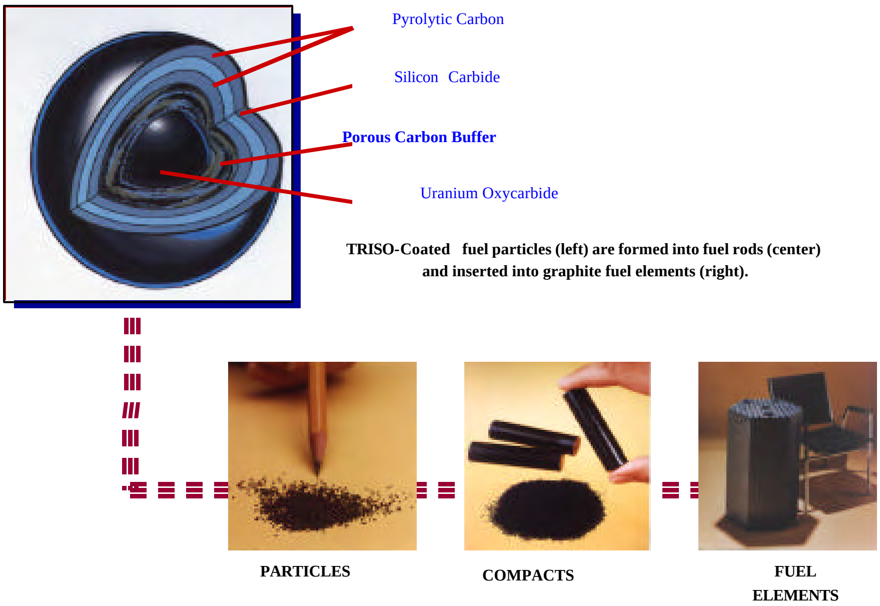


*Figure 6*. TRISO-coated particle fuel temperature capability

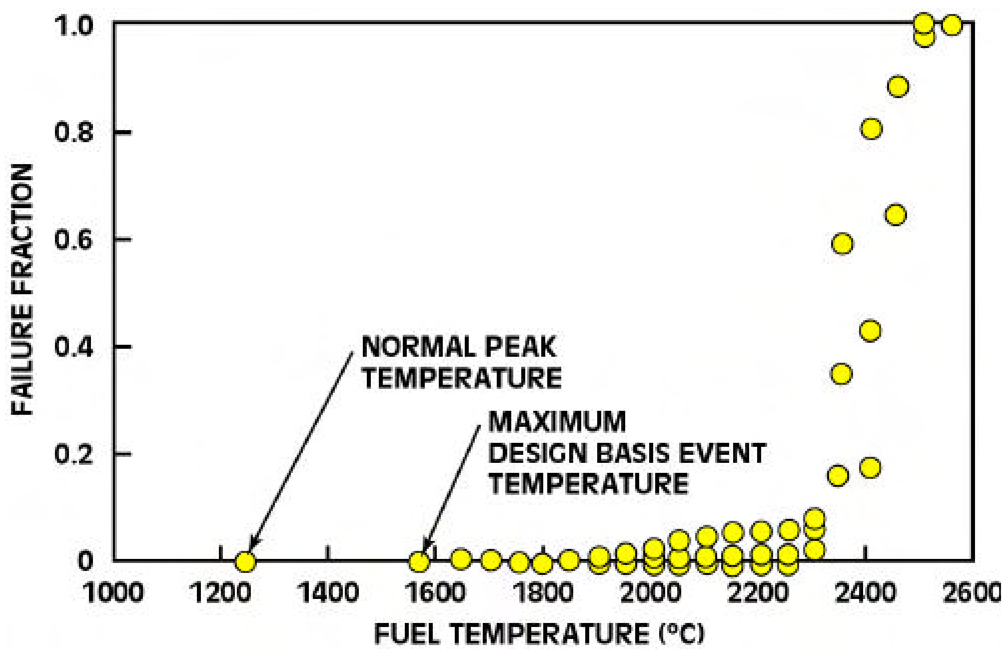

*Figure 7.* GT-MHR annular core arrangement

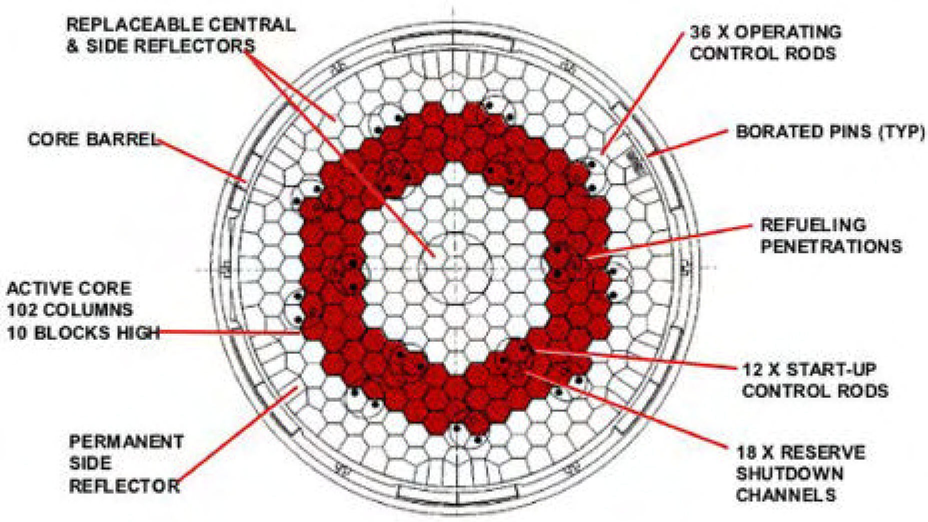


*Figure 8*. Sulphur-Iodine (S-I) thermochemical water splitting process