THE GAS-TURBINE MODULAR HELIUM REACTOR

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Summary

The Gas Turbine – Modular Helium Reactor (GT-MHR) couples a High Temperature Gas-cooled Reactor (HTGR) with a Brayton power conversion cycle to produce electricity at high efficiency. It is based on HTGR technology developed over the past 40 years that includes the design, construction and operation of seven HTGR plants. The GT-MHR satisfies the Gen-IV goals of passive safety, good economics, high proliferation resistance, and improved environmental characteristics including reduced waste and better fuel utilization than the current generation of nuclear power plants. Because of its capability to produce high coolant outlet temperatures (at least 850°C with potential for still higher temperature), the modular helium reactor system can also efficiently produce hydrogen by high temperature electrolysis or thermochemical water splitting. The technology embodied in the GT-MHR concept has high potential, with modest further development work, to meet the requirements for the Next Generation Nuclear Plant (NGNP) demonstration project planned to be built at the Idaho National Engineering and Environmental Laboratory (INEEL). The NGNP objectives are to demonstrate passive safety, licensing of new nuclear plants, use of the Brayton cycle for

high efficiency electricity generation and use of high temperature nuclear heat for production of hydrogen.

1. Introduction

The HTGR concept evolved from early air-cooled and CO_2-cooled reactors. The use of helium in lieu of air or CO_2 as the coolant in combination with a graphite moderator offered enhanced neutronic and thermal efficiencies. The combination helium cooling and graphite moderator makes possible production of high temperature nuclear heat, and hence the name, High Temperature Gas-cooled Reactor (HTGR).

Feature	**Dragon**	**Peach Bottom**	**AVR**	**Fort St. Vrain**	**THTR**	**HTTR**	**HTR-10**
Location	UK	USA	Germany	USA	Germany	Japan	China
Power (MWt/MWe)	20/ -	115/40	46/15	842/330	750/300	30/ -	10/ -
Fuel Elements	Cylindrical	Cylindrical	Spherical	Hexagonal	Spherical	Hexagonal	Spherical
He Temp (In/Out°C)	350/750	377/750	270/950	400/775	270/750	395/950	300/900
He Press (Bar)	20	22.5	11	48	40	40	20
Pwr Density (MW/m^3)	14	8.3	2.3	6.3	6	2.5	2
Fuel Coating	TRISO[(a)]	BISO[(b)]	BISO[(b)]	TRISO[(a)]	BISO[(b)]	TRISO[(a)]	TRISO[(a)]
Fuel Kernel	Carbide	Carbide	Oxide	Carbide	Oxide	Oxide	Oxide
Fuel Enrichment	LEU[(c)]/ HEU[(d)]	HEU[(d)]	HEU[(d)]	HEU[(d)]	HEU[(d)]	LEU[(c)]	LEU[(c)]
Reactor Vessel	Steel	Steel	Steel	PCRV[(e)]	PCRV[(e)]	Steel	Steel
Operation Years	1965-1975	1967-1974	1968-1988	1979-1989	1985-1989	1998 -	1998 -

(a) TRISO refers to a fuel coating system that uses three types of coatings, low density pyrolytic carbon, high density pyrolytic carbon and silicon carbide
(b) BISO refers to a fuel coating system that uses two types of coatings, low density pyrolytic carbon and high density pyrolytic carbon
(c) LEU means low enriched uranium (<20% U^{235})
(d) HEU means high enriched uranium (>20% U^{235})
(e) PCRV means Prestressed Concrete Reactor Vessel

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Table 1: HTGR plants constructed and operated

To-date, seven HTGR plants have been built and operated (Table 1). The first was the 20 MWt Dragon test reactor in the UK. Dragon was followed by construction of two relatively low power plants, the 115 MWt Peach Bottom I (PB-1) in the USA and the 49 MWt AVR in Germany. PB-1 and AVR demonstrated electricity generation from HTGR nuclear heat using the Rankine (steam) cycle. These two plants were followed by the construction of two mid-size steam cycle plants, the 842 MWt Fort St. Vrain (FSV) plant in the USA and the 750 MWt THTR plant in Germany. In addition to demonstrating the use of helium coolant (with outlet temperatures as high as 950°C) and graphite moderator, these early plants also demonstrated coated particle fuel, a fuel form that employs ceramic coatings for containment of fission products at high temperature which is a key feature of HTGRs.

In the USA, General Atomics used the HTGR technology from these early plants to design several large, 2000 – 3000 MWt, HTGR plants and orders were received for 10 of these large HTGR plants. The large HTGR plant orders were canceled, along with the cancellation of orders for a large number of other nuclear power plants, following the oil embargo in the early 1970s and the ensuing energy conservative measures that dramatically reduced energy demand and the need for new electricity generation capacity.

Most recently, two additional HTGR test reactors have been constructed and are successfully operating, the 30 MWt High Temperature Test Reactor (HTTR) in Japan and the 10 MWt High Temperature Reactor (HTR-10) in China (Table 1), with design outlet temperatures of 950ºC and 900ºC respectively.

The US modular HTGR concept began in 1984 when the US Congress challenged the HTGR industry to investigate the potential for using HTGR technology to develop a "simpler, safer" nuclear power plant design. The goal was to develop a passively safe HTGR plant that was also economically competitive. Like most nuclear power plants up to that time, HTGR plants had been designed with reactor core length-to-diameter (L/D) ratios of about 1 for neutron economy. Detailed evaluations showed that low power density HTGR cores with L/Ds of 2 or 3, or more, were effective for rejecting decay heat passively. In the long slender, low power density HTGR cores, it was found that decay heat could be transferred passively by natural means (conduction, convection and thermal radiation) to a steel reactor vessel wall and then thermally radiated (passively) from the vessel wall to surrounding reactor cavity walls for conduction to a naturally circulating cooling system or to ground itself.

To maintain the coated particle fuel temperatures below damage limits during passive decay heat removal, the core physical size had to be limited, and the maximum reactor power capacity was found to be about 200 MWt for solid cylindrical core geometry. However, a 200 MWt power plant was not projected to be economically competitive. This led to the development of an annular core concept to enable larger cores and therefore, higher reactor powers. The first Modular High Temperature Gas-cooled Reactor (MHTGR) designed with an annular core had a power of 350 MWt. When coupled with a steam cycle power conversion system, the plant had a net thermal efficiency of 38% and was economically competitive (marginally) at that time (late '80s). To improve economics while maintaining passive safety, the core power was subsequently raised to 450 MWt and then to the current reference core power of 600 MWt. The resultant modular HTGR design, now known as the Modular Helium Reactor (MHR), represents a fundamental change in reactor design and safety philosophy (Figure 1).

The latest evolution made for the purpose of economics has been replacement of the Rankine steam cycle power conversion system with a high efficiency Brayton (gas turbine) cycle power conversion system to boost the thermal conversion efficiency to

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~48%. The coupling of the MHR with the gas turbine cycle forms the GT-MHR. The GT-MHR retains all of the MHR passive safety characteristics but is projected to have more attractive economics than any other generation alternative.

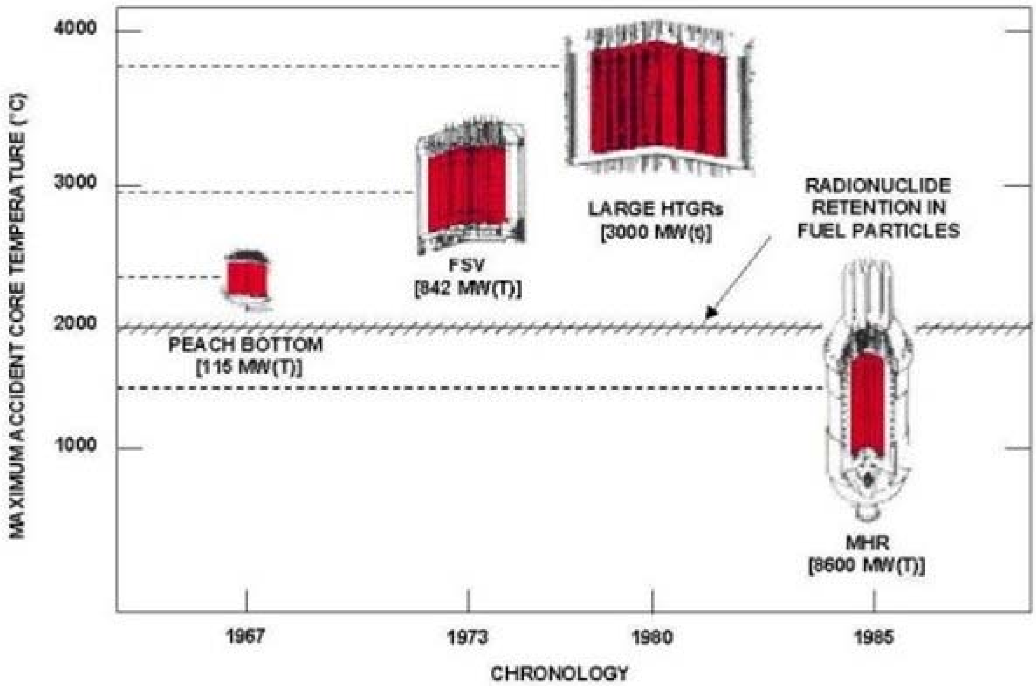

Figure 1: Modular helium reactor represents a fundamental change in reactor design and safety philosophy

2. GT-MHR Design Objectives

The GT-MHR design characteristics are well suited for satisfying Gen-IV goals relating to safety, economics, environmental impact and proliferation resistance. The original basis for the MHR concept was to provide passive safety, and then was evolved to provide high thermal efficiency for competitive economics. The high efficiency provides for reduced environmental impacts and the reactor design intrinsically has good proliferation resistance, primarily because of the low fissile material inventory used for low core power density.

The GT-MHR design objectives can be summarized as follows:

- Safety: The GT-MHR safety design objective is to provide the capability to reject core decay heat relying only on passive (natural) means of heat transfer (conduction, convection, and radiation) without the use of any active safety systems.
- Economics: The GT-MHR economics design objective is a busbar generation cost (20 year levelized) less than the least cost generation alternative. Subcomponents of this objective include:
  - An overnight capital installation cost of < $1000/kWe,
  - A construction period of ≤ 3 years for the first module of a reference 4-

module GT-MHR plant with successively shorter periods for sequentially constructed follow-on modules.

- Environmental Impacts: The GT-MHR environmental impact design objectives, relative to the impacts of LWRs, are:
  - Reduced thermal discharge,
  - Reduced heavy metal wastes,
  - Reduced risk of repository spent fuel radionuclide migration to the biosphere.
- Proliferation Resistance: The GT-MHR proliferation resistance design objective is a plant and fuel system that has high resistance to sabotage and to diversion of either weapons usable special nuclear materials or radioactive materials.

3. GT-MHR Design Description

The GT-MHR (Figure 2) couples a gas-cooled modular helium reactor (MHR), contained in one pressure vessel, with a high efficiency Brayton cycle gas turbine (GT) power conversion system (PCS) contained in an adjacent pressure vessel. The reactor and power conversion vessels are interconnected with a short cross-vessel and are located in a below-grade concrete silo. The below-grade silo arrangement provides high resistance to sabotage – a requirement in a post 9/11 world.

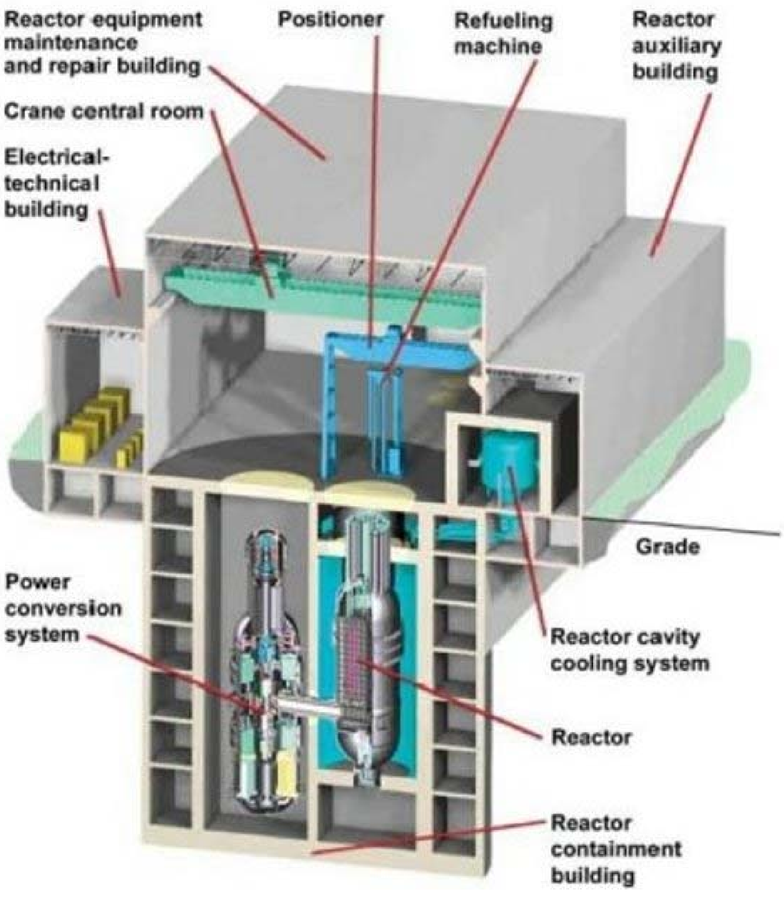

Figure 2: GT-MHR module

The key HTGR technology design characteristics of the 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.

3.1. Fuel

The MHR refractory coated particle fuel (Figure 3), identified as TRISO coated particle fuel, consists of a spherical kernel of either fissile (LEU) fuel or fertile material (natural U), as appropriate for the application, encapsulated in multiple layers of refractory coatings. 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. For the MHR design, the TRISO coated fuel particles are mixed with a carbonaceous matrix and bonded into cylindrical fuel compacts nominally 12.5 mm OD x 50 mm long and loaded into hexagonal fuel blocks 360 mm across flats x 800 mm long (Figure 3).

Figure 3: GT-MHR TRISO coated particle fuel

The TRISO coatings provide a high temperature, high integrity structure for retention of fission products to very high burnups. The coatings do not start to thermally degrade until temperatures approaching 2000°C are reached (Figure 4). Normal operating temperatures do not exceed about 1250°C and worst case accident temperatures are maintained below 1600°C for a core with an outlet coolant design temperature of 850ºC. Extensive tests in the United States, Europe, and Japan have demonstrated the performance potential of this fuel, but tests still need to be done to demonstrate it satisfies GT-MHR performance requirements for normal operating and accident conditions.

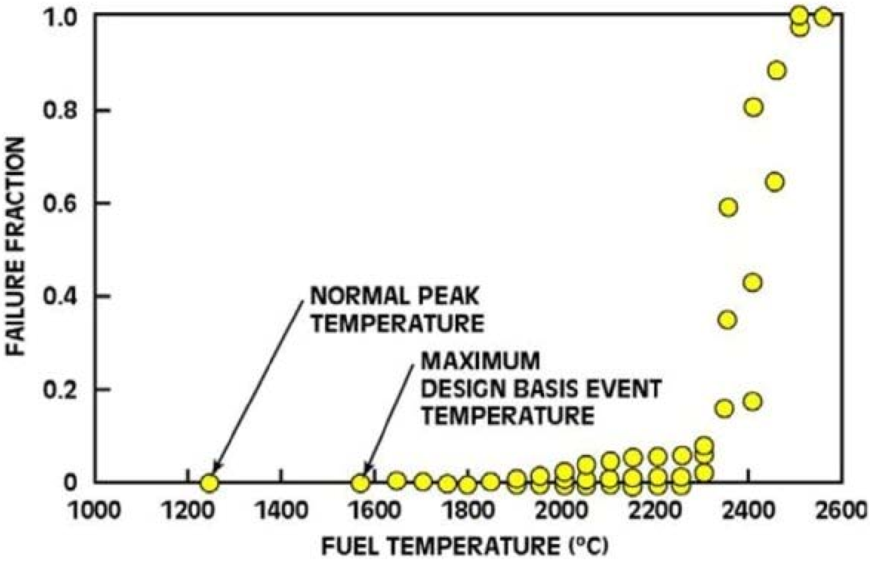

Figure 4: TRISO coated particle fuel temperature capability

3.2. Reactor

The MHR core design consists of an array of hexagonal fuel elements surrounded by identically sized solid graphite reflector elements vertically supported at the bottom by a core support grid plate structure and laterally supported by a core barrel. The fuel elements are stacked 10 high in an annular arrangement of 102 columns (Figure 5) to form the active core. The core is enclosed in a steel reactor pressure vessel. Control rod mechanisms are located in the reactor vessel top head, and a shutdown cooling system provided for maintenance purposes only is contained in the bottom head.

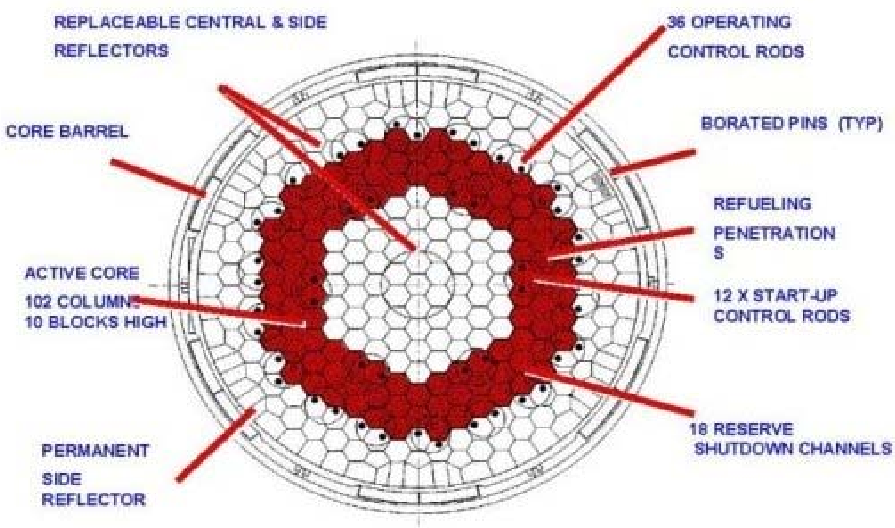

Figure 5: GT-MHR annular core arrangement

In the reference MHR design, mixed mean helium outlet temperature is 850°C. The hot outlet helium flows from the reactor core to the PCS through a hot duct located in the center of the cross-vessel; helium is cooled to 490°C in the PCS and returns to the reactor through the annulus formed between the cross-vessel outer shell and the central hot duct. The cooled helium flows up to an inlet plenum at the top of the core through the annulus between the reactor vessel and the core barrel. From the top inlet plenum, the helium is heated by flowing downward through coolant channels in the fuel elements, collected in a bottom outlet plenum and guided into the cross-vessel hot duct. All the core components exposed to the heated helium are either graphite or thermally insulated from exposure to the high temperature helium. Graphite has high strength, does not readily combust and has dimensional stability to very high temperatures (~2300°C).

A goal for the NGNP is a core outlet temperature of 1000°C to provide higher efficiencies for either electricity generation or hydrogen production. The primary challenges the 1000°C NGNP outlet temperature poses are related to the reactor fuel and metallic materials. Core designs having lower peaking factors may be required so peak fuel temperature limits are not exceeded, or a revised fuel particle coating system (e.g., ZrC instead of SiC coating) may be required having higher temperature limits.

The key NGNP metallic material challenges are the reactor vessel and the thermal barrier structural materials. An alternate, higher temperature reactor vessel material may be required because the core inlet temperature, that governs the reactor vessel temperature, will most likely be higher for the higher core outlet temperature. Higher temperature vessel materials are available but have not been fabricated in the vessel sizes required by the NGNP. The largest comparable vessel for which there is significant fabrication experience is the ABWR vessel fabricated from a lower service temperature material. The indicated size requirement for the NGNP is a reactor vessel ~1.5 times the weight of the ABWR vessel and fabricated from a material with a higher service temperature. In the GT-MHR, thermal barriers containing insulation are used to protect metallic structural components from the hot outlet temperature coolant gas but, the thermal barriers make use of metallic materials for holding the thermal insulation. For the NGNP 1000°C outlet temperature, alternative materials (e.g., carbon-carbon composites) may be required in place of these thermal barrier metallic materials.

Because of the accident at Chernobyl in 1986, the role of graphite in reactor safety has received increased attention. However, the consequences of the Chernobyl accident were caused by massive fuel failure and not by graphite oxidation that occurred during the accident. Decay heat from the nuclear fuel was sufficient to maintain relatively high graphite temperatures for an extended period of time, causing the graphite to radiate the “red glow” that was observed during the accident. High-purity, nuclear-grade graphite reacts very slowly with oxygen and would be classified as noncombustible by conventional standards.

In fact, graphite powder is a class D fire extinguishing material for combustible metals, including zirconium. For the GT-MHR, the oxidation resistance and heat capacity of graphite serves to mitigate, not exacerbate the radiological consequences of a hypothetical severe accident that allows air into the reactor vessel.

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