Chapter 4

HIGH TEMPERATURE GAS COOLED REACTOR

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4.1 INTRODUCTION

The High Temperature Gas-cooled Reactor (HTGR) technology is receiving increasing interest in many countries around the world as a promising future energy option. HTGR research reactors are operational in Japan and China, and two power plant designs are being pursued as international development projects. The renewed interest is based primarily on modular design concepts that utilize the unique properties of the technology to assure retention of radioactive fission products by inherently safe and passive means. They can use the Th fuel cycle with the possibility of breeding and a larger fuel resource base than the uranium fuel cycle. They also operate at high temperatures using the Brayton gas turbine cycle implying a high overall thermal efficiency. They can be used for water electrolysis or thermo-chemical processes to produce hydrogen from water as an energy carrier. With the use of dry cooling towers, they can be deployed in arid locations without the need for cooling water supplies. These characteristic offers the promise of an economically competitive electricity generation option at a modest unit size, suitable for construction and operation in both industrialized and developing nations.

Table 1. Comparison of the High Temperature Gas Cooled Reactor (HTGR) and Light Water Reactor (LWR) technologies.

	High Temperature Gas Cooled Reactor (HTGR)	Light Water Reactor (LWR)
Thermodynamic cycle	Gas turbine, Brayton cycle	Steam turbine, Joule cycle
Attainable thermal efficiency	70 %	35 %
Coolant temperature	He gas: 1,000 ^oC	Steam: 300 ^oC
Operational temperature ranges		
Process heat	30-250 ^oC	-
Power generation	250-600 ^oC	30-300 ^oC
Hydrogen production	600-950 ^oC	-

4.2 HISTORICAL DEVELOPMENT

Pilot plants were as the Peach Bottom reactor in the USA and the Dragon reactor in the UK.

The smaller, modular designs of HTGRs have been under development beginning with the AVR and THTR designs originating in Germany, and the Fort Saint-Vrain reactor in the USA. The supporting HTGR technology has been under development with major programs in the UK, the USA and Germany from the 1950's through the early 1990's. Important milestones have been achieved in the design and successful operation of three steel vessel HTGRs during the 1960's and 1970's, and in the production and demonstration of robust, high quality fuel and other key elements of the technology.

Table 2. Comparison of the technical characteristics of different HTGR designs.

	Peach Bottom USA	Dragon UK	AVR Germany	THTR Germany	Fort Saint-Vrain USA
Power generation	1967-1974	1966-1975	1968	1985	1976
Power MWth/MWe	115/40	20/-	46/15	750/300	837/330
Fuel type	cylinders	cylinders	Pebble bed, spheres	Pebble bed, spheres	Hexagonal blocks
He outlet temperature ^oC	750	750	950	750	785
He coolant pressure bar	25	20	11	40	48
Fuel composition	Th, uranium carbide	Th, uranium carbide	Th, uranium oxides	Th, uranium oxides	Th, uranium carbides
Reactor vessel	Steel	Steel	Steel	PCRV	PCRV

PCRV = Prestressed Concrete Pressure Vessel

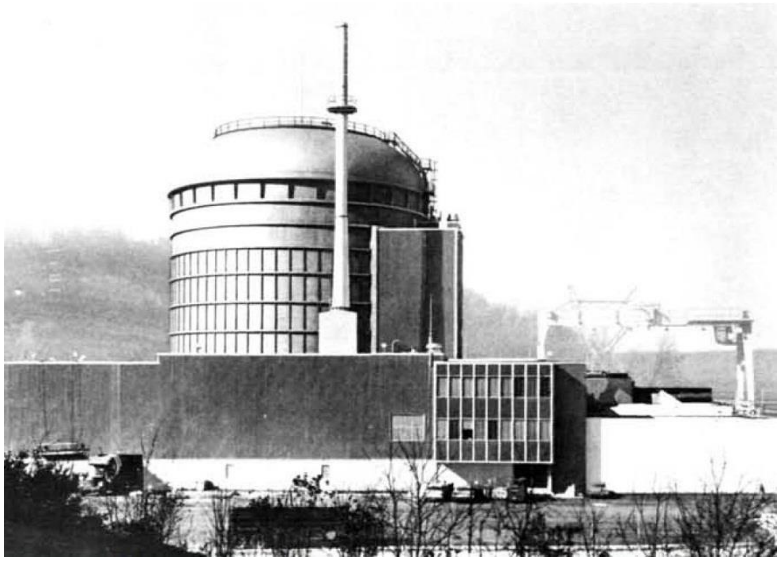

Figure 1. Peach Bottom 40 MWe HTGR. Photo: General Dynamics.

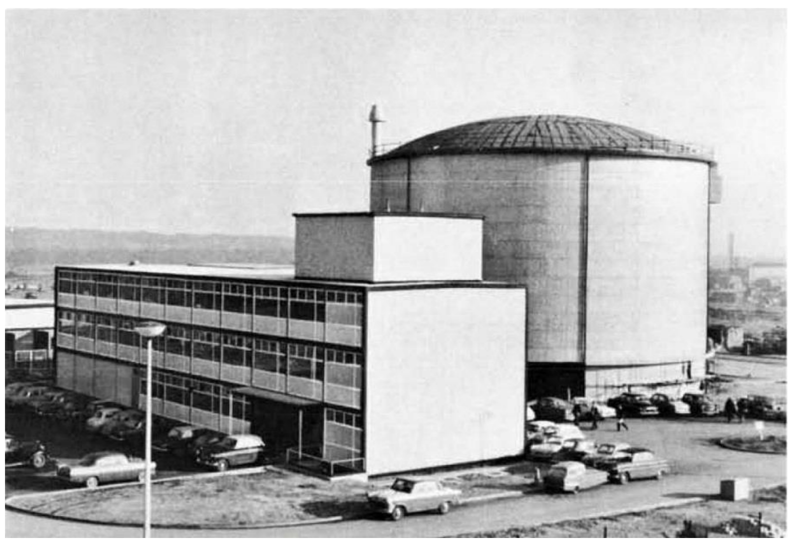

Figure 2. Dragon reactor at Winfrith Heath, UK.

Figure 3. Fort Saint-Vrain reactor, Colorado, USA. Photo: General Atomics (GA).

Figure 4. One of 1482 prismatic graphite blocks lowered into the core of the Fort Saint-Vrain HTGR. Photo: General Atomics (GA).

The technology has developed along two distinct paths: pebble bed fuel consisting of ceramic spheres 6 cm in diameter with continuous refueling, and prismatic fuel consisting of hexagonal blocks approximately 35 cm across the flats and 75 cm in height with periodic batch refueling. Both fuel systems utilize ceramic coated micro-particles of less than 1 millimeter diameter.

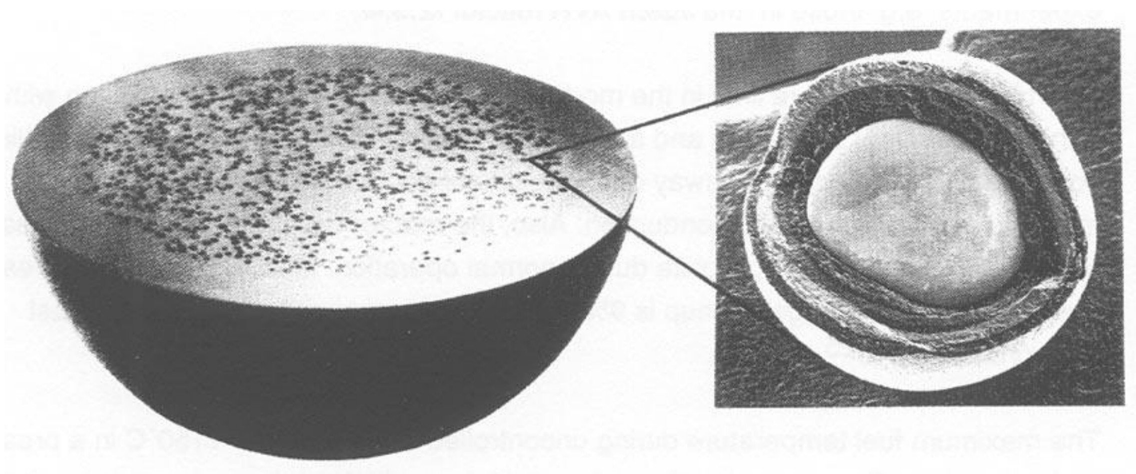

Figure 5. Fuel particles used in the pebble bed and the prismatic fuel designs.

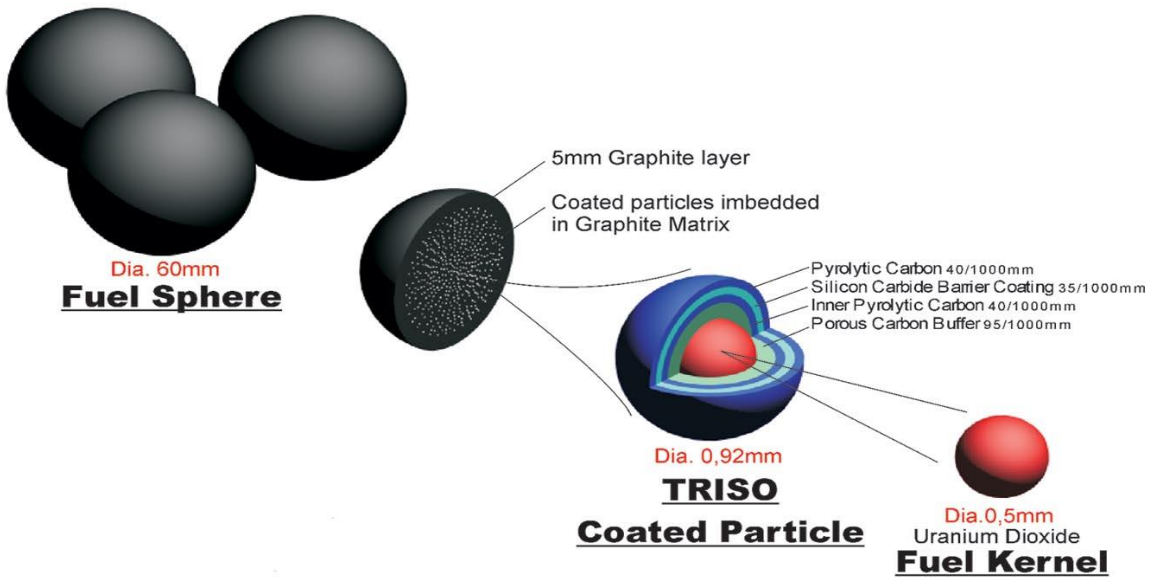

Figure 6. Fuel kernel, coated triso fuel particle and pebble fuel sphere design.

Figure 7. Graphite fuel pebbles used in the PBMR.

Figure 8. THTR pebbles inside core.

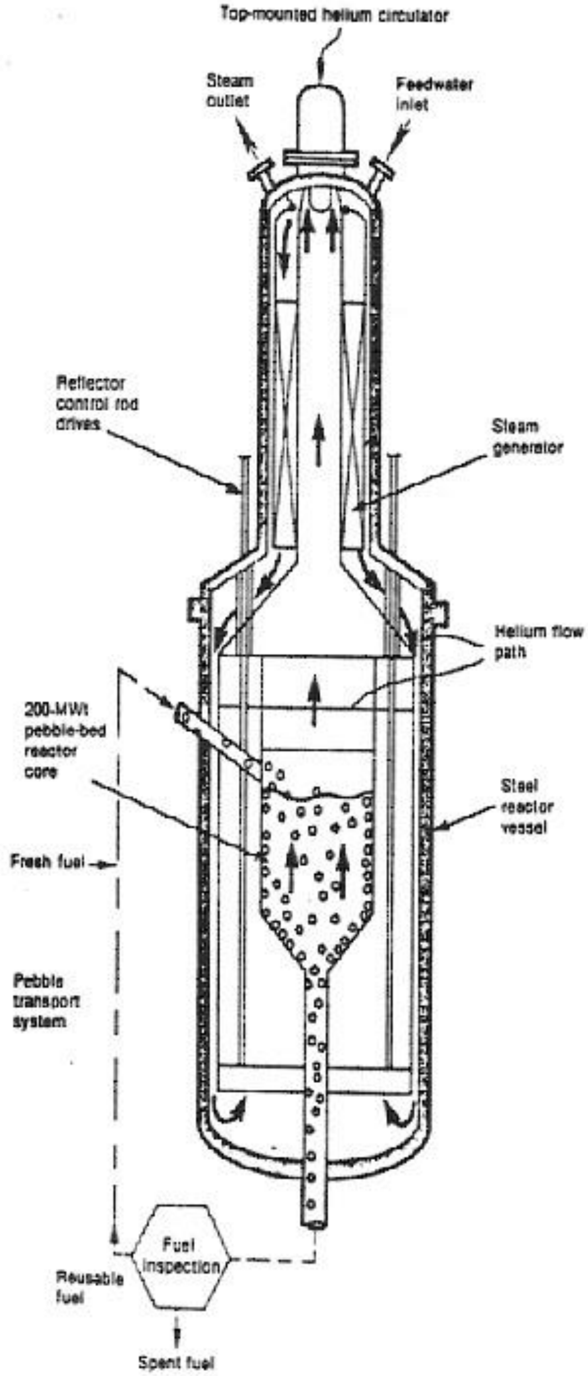

Figure 9. Pebble bed AVR reactor.

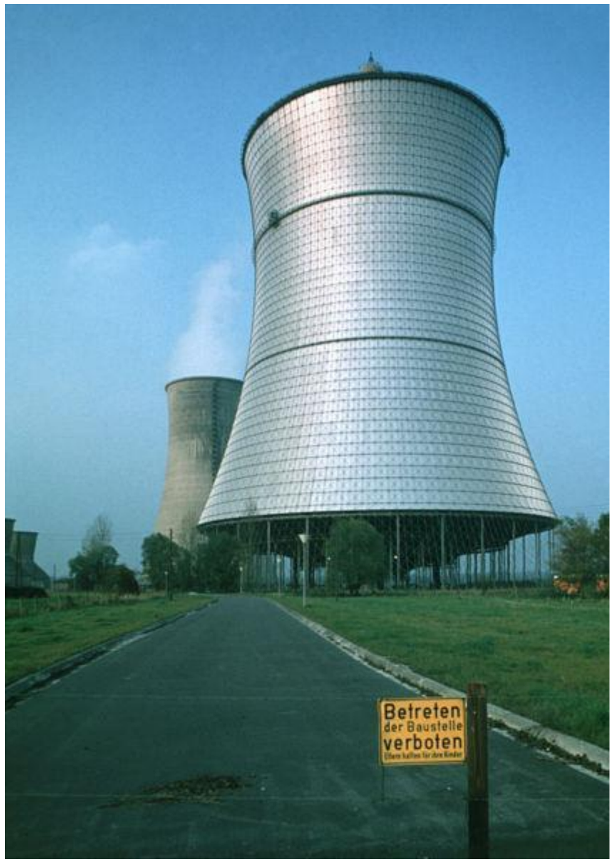

Figure 10. THTR dry cooling tower in the front and water cooling tower in back.

4.3 PEBBLE BED MODULAR REACTOR PBMR

INTRODUCTION

The Pebble Bed Modular Reactor, PBMR has been advanced by an international design team led by the South African electric utility Eskom. The design comprises a pebble bed core and closed cycle gas turbine with a thermal power of approximately 260 MWth and net electrical output of approximately 110 MWe. An initial single unit prototype will be followed by commercial offerings for plants of up to 10 modules, which can be incrementally constructed in accordance with generation needs and financial constraints.

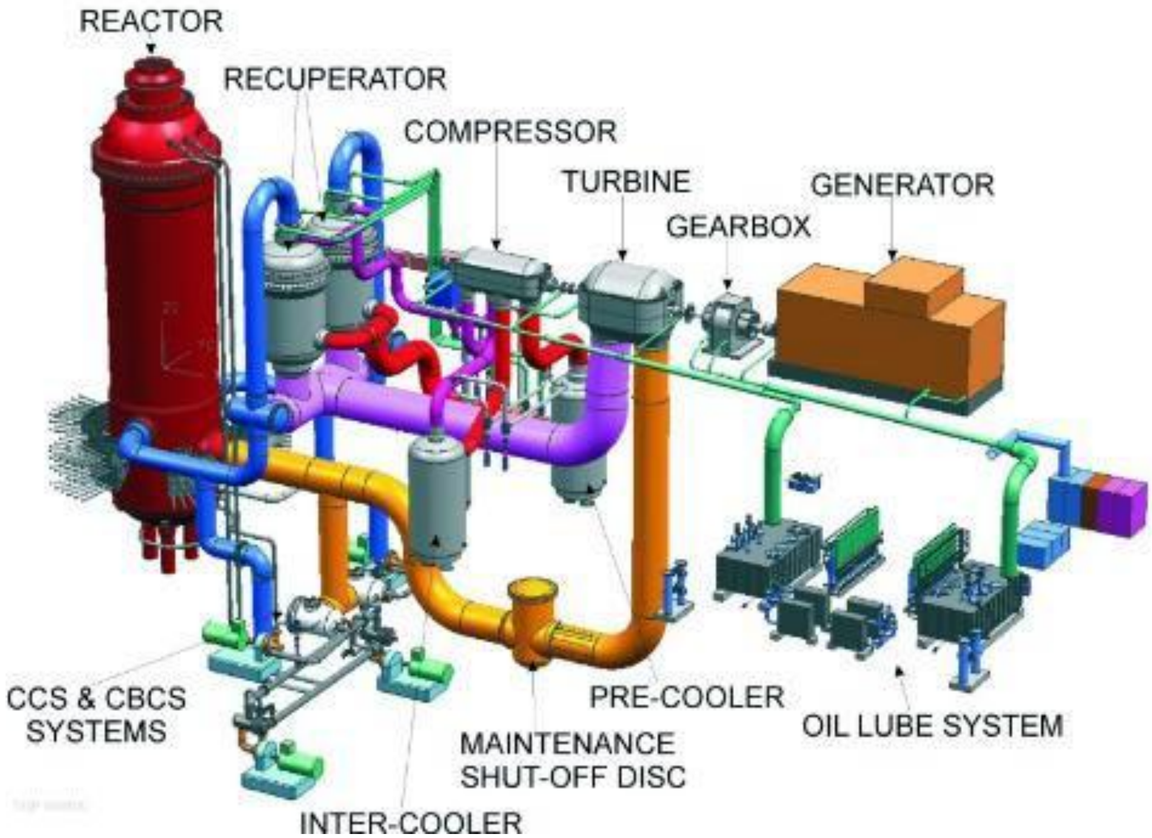

Figure 11. Single reactor unit arrangement of the Pebble Bed Modular Design PBMR design using the gas turbine or Brayton thermodynamic cycle.

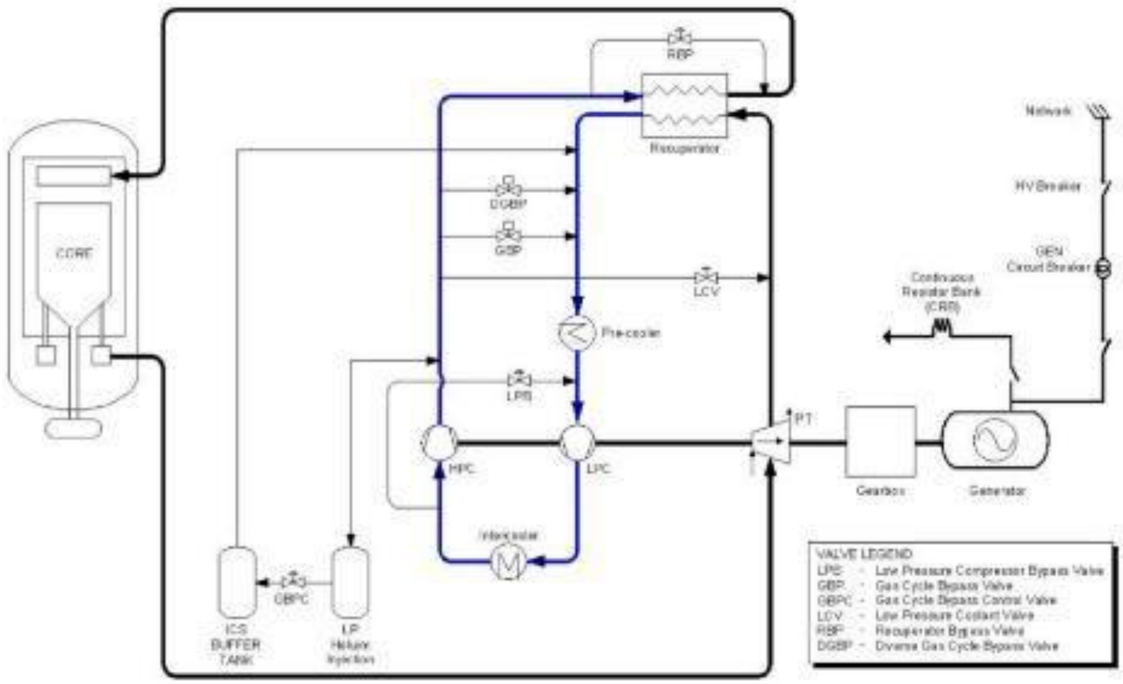

Figure 12. Flow diagram of the Pebble Bed Modular Design PBMR desig**n.**

DESIGN FEATURES

The South African Pebble Bed Modular Reactor Company, PBMR (Pty) Ltd., was established in 1999 with the intention of developing and marketing small scale, high temperature reactors both locally and internationally. The PBMR project is based in Centurion near Pretoria, South Africa.

The PBMR is a High Temperature Gas cooled Reactor (HTGR), with a closed-cycle, gas turbine or Brayton power conversion system. High efficiency and attractive economics are possible without compromising the high levels of passive safety expected of advanced nuclear designs.

The PBMR comprises a steel pressure vessel which holds about 450,000 fuel spheres. The fuel consists of low enriched uranium triple coated (triso) isotropic particles contained in a molded graphite sphere. A coated particle consists of a kernel of uranium dioxide surrounded by four coating layers.

The PBMR system is cooled with helium. The heat transferred by the helium to the power conversion system is converted into electricity through a gas turbine. The plant comprises a module building with the Reactor Pressure Vessel (RPV) and the Power Conversion Unit (PCU).

The vertical steel pressure vessel is 6.2 m in diameter and about 27 m high. It is lined with a 1 meter (39 inch) thick layer of graphite bricks, which serves as an outer reflector and a passive heat transfer medium. The graphite brick lining is drilled with vertical holes to house the control elements.

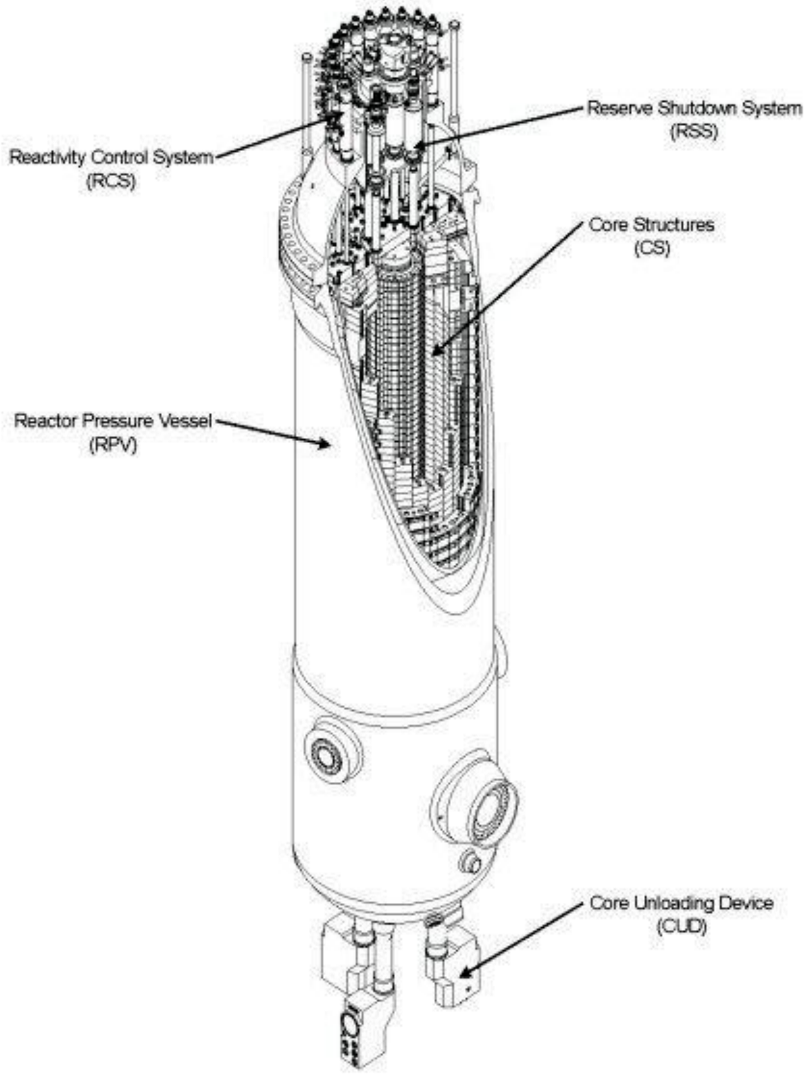

Figure 13. Reactor Pressure Vessel and core of the PBMR.

The PBMR uses particles of enriched uranium dioxide coated with silicon carbide and pyrolitic carbon. The design is capable of thermal breeding using the thorium and U^{233} fuel cycle. The particles are encased in graphite to form a fuel sphere or pebble 6 cms in diameter, about the size of a tennis ball.

Helium is used as the coolant and energy transfer medium, to drive a closed cycle gas turbine and generator system. When fully loaded, the core would contain 456,000 fuel spheres. The geometry of the fuel region is annular and located around a central graphite column. The latter serves as an additional nuclear reflector.

To remove the heat generated by the nuclear reaction, the He coolant enters the reactor vessel at a temperature of about 500 ºC (932 ºF) and at a pressure of 9 MPa or 1,323 pounds per square inch (psi). The gas moves down between the hot fuel spheres, after which it leaves the bottom of the vessel having been heated to a temperature of about 900 ºC (1,652 ºF). The hot gas then enters the turbine which is mechanically connected to the generator through a speed-reduction gearbox on one side and the gas compressors on the other side.

The coolant leaves the turbine at about 500 ºC (932 ºF) and 2.6 MPa (377 psi), after which it is cooled, recompressed, reheated and returned to the reactor vessel.

4.4 SAFETY ASPECTS OF THE PBMR

The PBMR is considered as inherently safe because of the choices of materials used as its fuel with confinement in multiple layers, its graphite moderator thermal inertia and the physics involved. Should a worst case scenario occur, no human intervention is required in the short or medium terms.

Nuclear accidents may driven by the need to extract the residual or decay heat that is caused by radioactive decay of the fission products. In existing reactors, heat is removed by active cooling systems using pumps, which rely on the presence of coolant such as water and the local as well as the external supplies of electricity. For increased reliability, they are duplicated in conventional reactors.

In the PBMR the possibility of overheating is independent of the state of the reactor coolant. The PBMR combines very low power density of the core at about 33.3 $MWth/m^3$ or 1/30th of the power density of a Pressurized Water Reactor (PWR), and the resistance to the occurrence of a high temperature of fuel in billions of independent fuel particles.

The helium coolant which is used to transfer heat from the core to the power-generating gas turbines, is chemically inert. Since air cannot ingress into the primary circuit, oxygen cannot get into the high temperature core to oxidize the graphite used in the reactor. Thus chemical reactions and oxidation are sidelined in the construction of the PBMR.

Should a loss of power occur, the decay heat generation is absorbed by the high thermal inertia of the graphite and is radiated through the steel pressure vessel without fuel element failure or radioactive release.

4.5 GAS TURBINE MODULAR HELIUM REACTOR, GT MHR

The GT MHR is under development as a combined private and public sector project. The project is advanced by an international consortium led by General Atomics (GA) in the USA and OKBM in the Russian Federation. The design comprises a prismatic core and closed cycle gas turbine with a thermal power of approximately 600 MWth and net electrical output of approximately 280 MWe. The initial application is intended to be the burning of plutonium from dismantled weapons in conjunction with the generation of electricity using the Mixed Oxide (MOX) UO_2-PuO_2 fuel approach. Future commercial deployment for electricity production using low enriched uranium fuel is anticipated.

The GT MHR combines a meltdown proof reactor and advanced gas turbine technology in a power plant with a significant improvement in thermal efficiency approaching 50 percent. This efficiency makes possible much lower power costs, without the environmental degradation and resource depletion of burning fossil fuels. Conventional, low temperature nuclear plants operate at about 33 percent thermal efficiency.

Existing reactors produce 50 percent more high-level waste than will the GT MHR. The higher thermal efficiency results in less thermal discharge to the environment.

Such plants can use air cooling instead of unsightly cooling towers, which allows for more flexible siting options. The reactor uses an annular core with a high thermal inertia offering an improved safety characteristic.

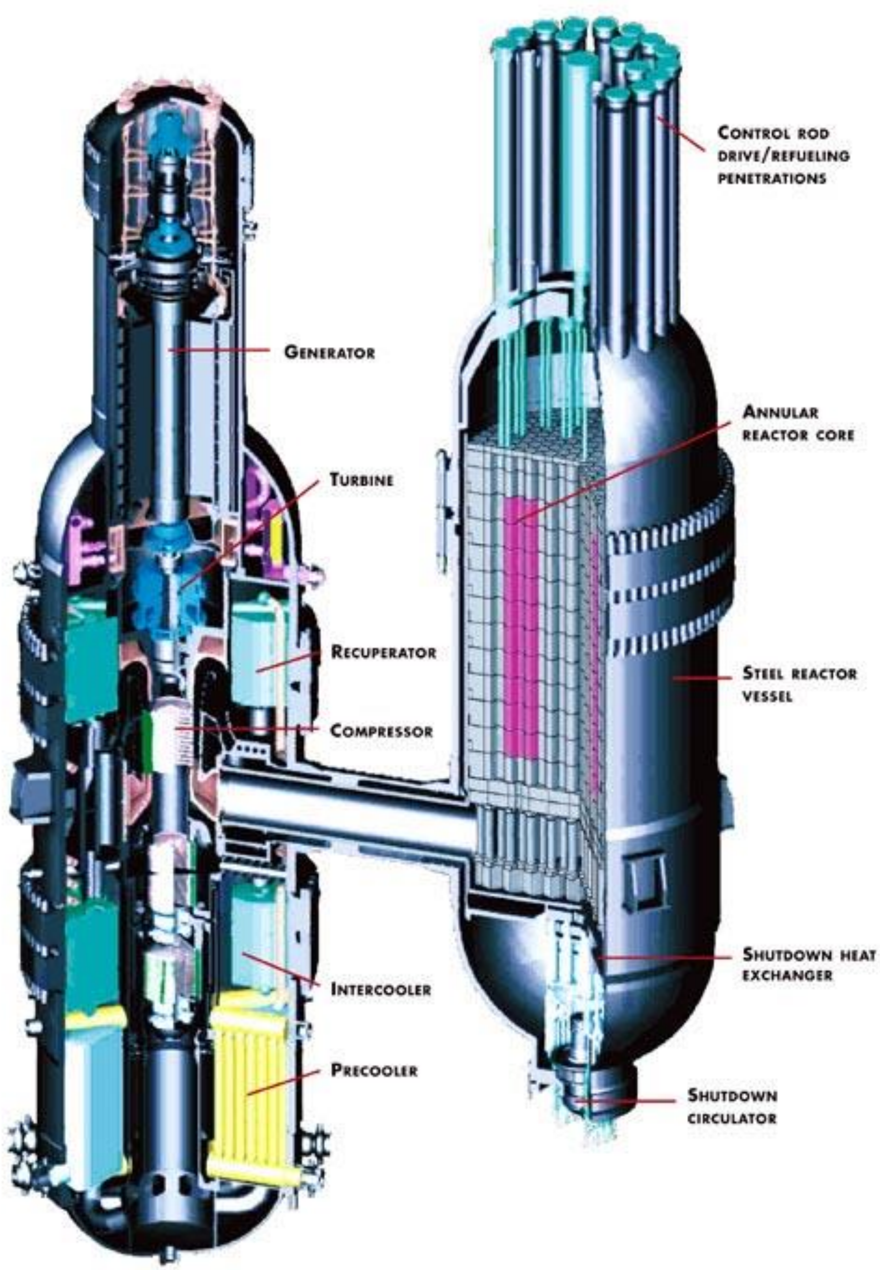

Figure 14. Gas Turbine Modular Helium Reactor design, GT MHR.

4.6 GAS COOLED RESEARCH REACTORS

Two designs for the modular HTGR power plants are currently under active research and development.

HIGH TEMPERATURE ENGINEERING TEST REACTOR, HTTR

The High Temperature Engineering Test Reactor (HTTR) is a 30 MWth prismatic core HTGR designed, constructed and operated by the Japan Atomic Energy Research Institute (JAERI). The reactor achieved initial criticality in 1998 with full power operation started in 2000.

It supports the development of high temperature process heat and closed cycle gas turbine technology. It uses prismatic fuel in the form of hexagonal blocks 35 cm in width and 75 cm in height.

JAERI has been constructing the High Temperature Engineering Test Reactor with a nominal outlet coolant temperature of 850 ^{o}C, and a maximum of 950 ^{o}C, as the facility for the development of a hydrogen production system using high temperature gas from the HTTR. It is also meant as a source for process heat for chemical manufacture.

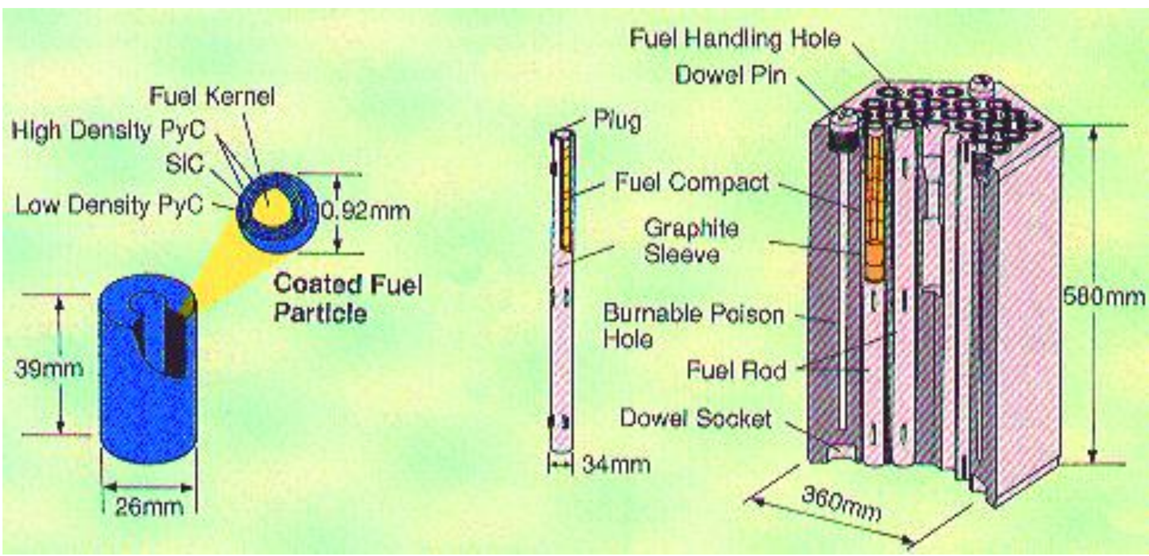

Figure 15. Prismatic hexagonal graphite fuel block.

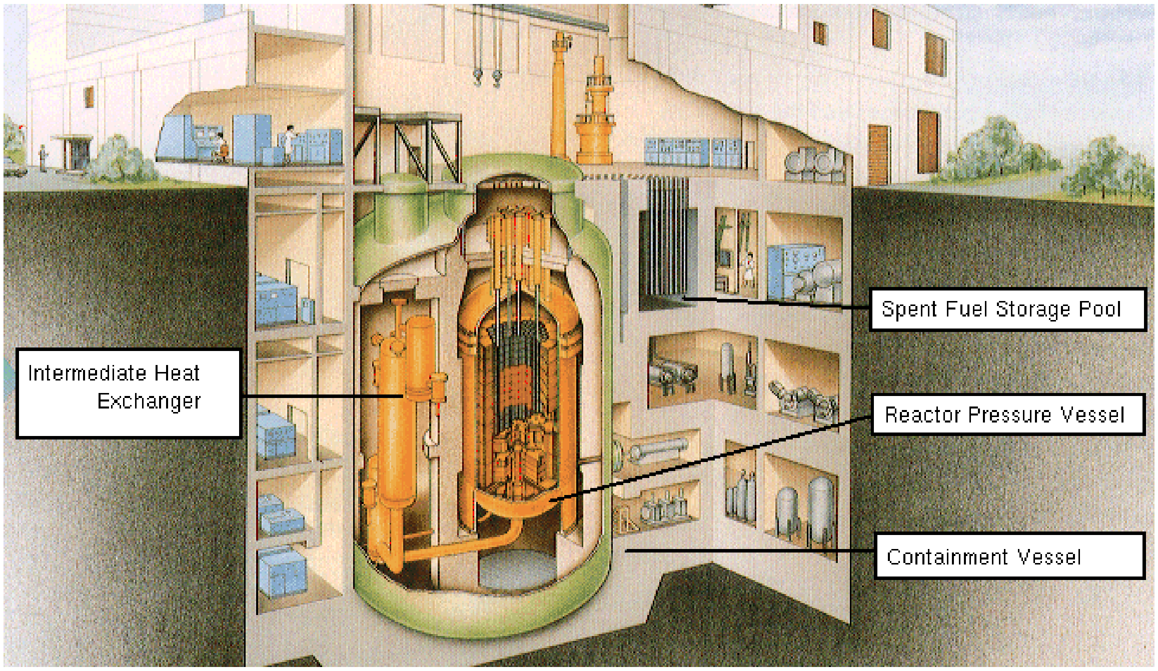

Figure 16. High Temperature Engineering Test Reactor, HTTR is sited underground.

HIGH TEMPERATURE REACTOR HTR-10

The HTR-10 is a 10 MWth pebble bed core HTGR designed, constructed and operated by the Institute for Nuclear Energy Technology (INET) at Tsinghua University in China. The reactor achieved initial criticality in 2000. The design employs pebble fuel composed of 6 cm diameter spheres. It operates with a core outlet temperature of 950 ºC to support the development of high temperature process heat and electricity generation.

Figure 17. The HTR-10 at Tsinghua University, China.

DISCUSSION

The high temperature capability and smaller unit size also offers the prospect of non electrical applications for high temperature process heat, as well as low temperature energy supply through cogeneration.

The HTGR, with its inherent safety and high temperature heat supply at about 1,000 ^{o}C from the reactor, can provide effective use of nuclear heat in various fields. For instance, the HTGR makes it possible to produce hydrogen as an energy carrier for use as a transportation fuel consumed in fuel cells driving electrical motors.

EXERCISE

1. For heat rejection at 20 degrees Celsius, compare the Carnot cycle efficiencies for an HTGR operating in the following modes:

a) Process heat,
b) Power generation,
c) Hydrogen production.