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ANNULAR CORE FOR MODULAR HIGH TEMPERATURE GAS-COOLED REACTOR (MHTGR)

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Abstract

The active core of the 350 MW(t) MHTGR is annular in configuration, shaped to provide a large external surface-to-volume ratio for the transport of heat radially to the reactor vessel in case of a loss of coolant flow. For a given fuel temperature limit, the annular core provides approximately 40% greater power output over a typical cylindrical configuration. The reactor core is made up of columns of hexagonal blocks, each 793-mm high and 360-mm wide. The active core is 3.5 m in o.d., 1.65 m in i.d., and 7.93-m tall. Fuel elements contain TRISO-coated microspheres of 19.8% enriched uranium oxycarbide and of fertile thorium oxide. The core is controlled by 30 control rods which enter the inner and outer side reflectors from above.

Keywords

Gas-cooled reactor
High temperature reactor
Core design
Annular core
Coated fuel particles
Modular reactor

Introduction

The utility/user requirements for the MHTGR design call for fundamental changes in the traditional approach toward attaining the economic and safety goals of the plant (Ref. 1). The safety and investment protection goals are to be met at the plant exclusion area boundary without any need for sheltering or evacuation. The safety goals are to be achieved without any reliance upon complex active systems, such as pressurized secondary containment or active heat removal circuits (Ref. 2).

A significant feature of the Standard MHTGR design is its capability for passive decay heat rejection. In the unlikely event that both the normal and shutdown cooling systems are unavailable, decay heat must be rejected by radiation, conduction, and natural convection from the core to the reactor vessel wall and outward to air-cooled panels within the reactor cavity structure. These passive decay heat rejection requirements influence the shape and size of the reactor core. A relatively tall core with a high surface-to-volume ratio provides for acceptable fuel temperatures during a total loss of coolant flow, whether the primary coolant system is pressurized or depressurized. At the rated core thermal power of 350 MW, the peak fuel temperature is approximately 1600°C for the most severe loss-of-forced circulation case. This temperature is well within the limits for high retention of fission products by the all-ceramic coated fuel particles (Ref. 3).

Reactor Core Configuration

The reactor core and the surrounding graphite neutron reflectors are supported within a steel reactor vessel. The configuration is shown in Fig. 1 in both an elevation view and a plan view. The restraining structures within the reactor vessel are a steel and graphite core support structure at the bottom and a metallic core barrel around the periphery of the side reflectors.

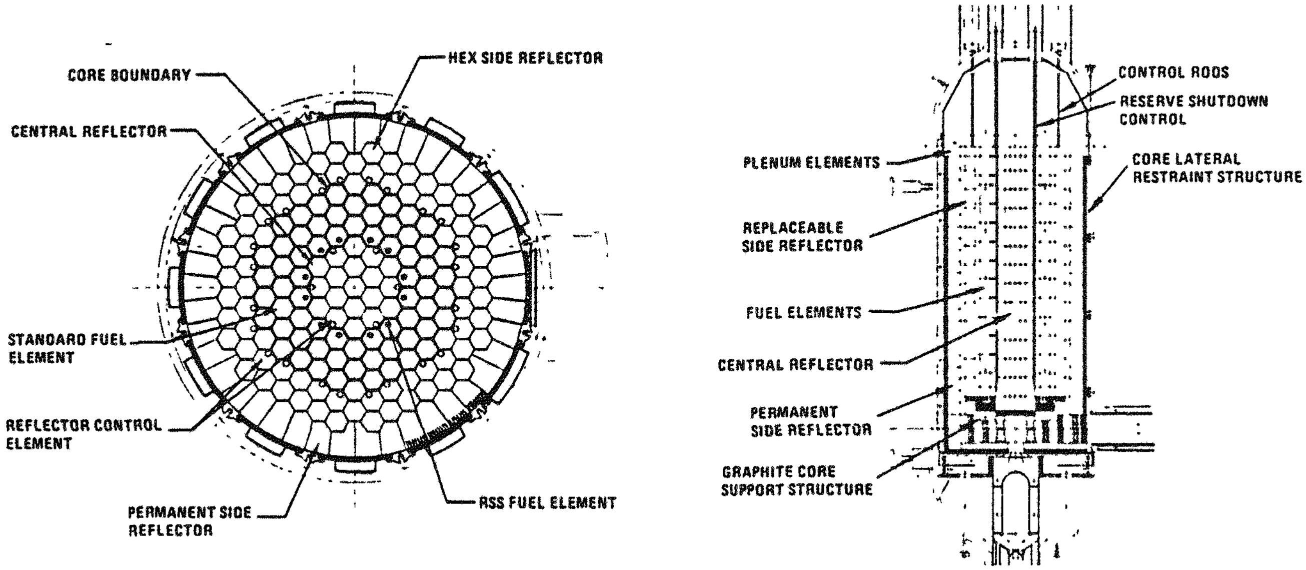

Fig. 1: Reactor Core Configuration

The annular active core is 3.50 m in o.d., 1.65 m in i.d., and 7.93-m (10 fuel elements) tall. The 660 fuel elements, each a hexagonal prism 360-mm wide by 793-mm tall, are arrayed in columns within the active core. Key core design parameters are given in Table 1. The primary coolant is helium which flows downward through the core.

Core power, MW(t)	350
Core power density, MW/m^3	5.9
Core outlet helium temperature, °C	690
Core refueling interval, yr	1.6
Fuel element lifetime, yr	3.2
Fuel burnup (Average), MWd/Tonne	100,000

Table 1: Core Design Parameters

Neutron control is provided by 30 control rods which enter channels in the columns of replaceable elements immediately adjacent to the active core. Six of the control rods are in the central reflector, and the remaining 24 are in the outer reflector. In addition to the control rods, there are 12 reserve shutdown control channels within the active core which can receive boron-graphite pellets as the independent shutdown absorber. The reserve shutdown pellets are contained in hoppers located above the active core and can be released manually.

The fuel element are removed during shutdown by a handling machine which enters the reactor vessel through the control rod penetrations.

Fuel Elements

The fuel elements are right hexagonal prisms of the same size and shape as the Fort St. Vrain HTGR elements. The fuel element components are shown in Fig. 2. The graphite block is machined from Great Lakes Carbon H-451 grade material.

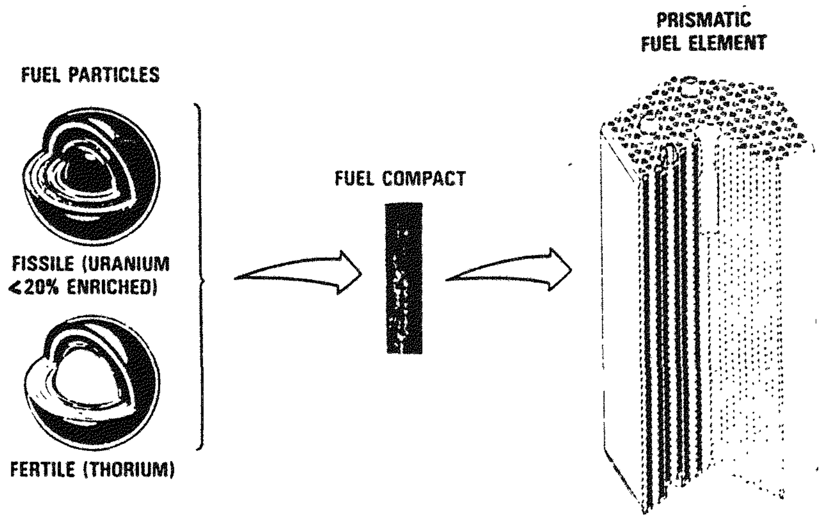

Fig. 2: Fuel Element Components

The fuel element employs low-enriched uranium and thorium (LEU/Th) materials. The fissile fuel is a two-phase mixture of 19.8% enriched UO_2 and UC_2, usually referred to as UCO, having an oxygen-to-uranium ratio of 1.7 in fresh fuel. The fertile fuel is ThO_2. Both fertile and fissile fuels are in the form of dense microspheres coated with TRISO coatings to retain fission products. The coated fissile and fertile particles are intimately blended and bonded together by a carbonaceous binder into fuel compacts. Figure 2 illustrates the TRISO coating concept and how the fuel is packaged within the fuel element. The fissile fuel kernel diameter is 350 microns, and the fertile kernel diameter is 500 microns. The coating thickness is about 200 microns (Ref. 4).

The fuel and coolant holes are located in parallel through the length of the element. The standard fuel element contains a continuous array of fuel and coolant holes in a regular triangular array of two fuel holes per one coolant hole. The six corner holes contain lumped burnable poison compacts.

At each element-to-element interface in a column, there are four dowel/socket connection which provides alignment of coolant channels. A 35-mm diameter fuel handling hole, located at the center of the element, extends down about one-third of the height, with a ledge where the grapple of a fuel handling machine engages.

The fuel compacts, contained in the fuel holes, are 12.5-mm diameter by 50-mm long. Each fuel compact contains fissile, fertile, and graphite shim particles bonded by a carbonaceous matrix. A total of 15 fuel compacts normally make up a stack within a fuel hole. The fuel quality and in-service performance limits are summarized in Table 2 for the fuel compacts. The as-manufactured fuel quality has been demonstrated to this level in both the Federal Republic of Germany (for spheres) and the U.S.A.

AS-MANUFACTURED FUEL QUALITY:	
• Missing buffer fraction	$\leq 5.0 \times 10^{-5}$
• SiC coating defect fraction	$\leq 5.0 \times 10^{-5}$
• Heavy-metal contamination fraction	$\leq 1.0 \times 10^{-5}$
FUEL PERFORMANCE:	
• Average in-service coating failure fraction	$\leq 5.0 \times 10^{-5}$
• Average incremental coating failure fraction during accident (exposed kernel)	$\leq 1.5 \times 10^{-4}$

Table 2: MHTGR Fuel Performance and Fuel Quality Requirements

Reflector Elements

The replaceable reflector elements are graphite blocks of the same shape, size, and material as the fuel elements. The top and bottom reflector elements contain coolant holes to match those in the active core. All reflector elements have dowel connection for alignment.

Core Neutronics

The low-enriched uranium and thorium fuel cycle has been selected to meet the requirements of using nonweapons grade (<20% enriched) uranium. The thorium is included to facilitate zoning of power distributions in both radial and axial directions while using a single uranium enrichment. The thermal performance of fuel elements is essentially the same for fully enriched fuel, as demonstrated in the Fort St. Vrain reactor, or for the lower enriched cycle in the MHTGR.

The core reactivity is controlled by a combination of fixed lumped burnable poison, movable poison and a negative temperature coefficient. The number and location of the 30 top entry control rods and the diverse reserve shutdown control have been specified to assure that the reactor thermal power is controlled both for normal and off-normal conditions. The radial thickness of the active core annulus was specified on the basis of assuring that the control rod worths of the reflector-located rods would meet all shutdown and operating control worth requirements. The choice of reflector control rods was made to assure that the control rod integrity is maintained during passive decay heat removal events.

The evaluation of control rod and reserve shutdown control reactivity worths under both hot and cold conditions show that a large margin exists between the maximum reactivity requirements and the calculated rod worths. The reactivity and rod worth values are shown in Table 3.

A design criterion for the core is that the reactivity feedback characteristics shall limit the core temperatures. The active-core power coefficients are strongly negative. The core isothermal temperature coefficient is about $-7 \times 10^{-5}/°C$ at the beginning-of-cycle conditions and about $-4 \times 10^{-5}/°C$ at the end-of-cycle for the typical moderator operating temperature of 700°C. The power coefficient becomes rapidly more negative at higher temperatures. The high heat capacity of the graphite core and the negative temperature coefficient results in a core which is very stable to changes in reactivity.

	Beginning of Cycle	End of Cycle
Reactivity to Control: (%$\Delta\rho$)		
Core operating excess reactivity	1.0	0.5
Temperature effect (hot to cold)	4.8	1.2
Xenon decay	3.7	3.7
Other fission product decay	0	1.3
Shutdown and uncertainty	2.0	2.0
Total	11.5	8.7
Worths of Control Poisons: (%$\Delta\rho$)		
24 outer control rods	8.1	11.0
24 outer plus 6 inner control rods	16.8	20.2
Reserve shutdown control	10.1	11.3
All control rods and RSC	30.4	35.7

Table 3: Reactivity and Control Rod Worths

Core Performance Characteristics

The performance of the MHTGR core is measured primarily by the degree of retention of fission products within the coated fuel particles. The MHTGR design provides for a significant advancement in the containment concept for power plants

(Ref. 3). The traditional philosophy of metal clad fuel systems for guarding against cladding failures at relatively low temperatures is not applicable to the MHTGR. Even for the most severe events for the MHTGR, the particle coatings contain the fission products at the source, not after some dispersal in a reactor building. The number of individual coated particles in a reactor core is about 10^{10} units. Furthermore, the particle-containment integrity is monitored throughout normal reactor operations by sampling the low level of fission products in the primary coolant.

During normal steady-state power operations, the fuel in the MHTGR operates at temperatures below 1250°C and fluences below 5.5×10^{25} n/m^2 (E>29fJ). The maximum heavy metal burnups are 25% and 3.5% FIMA for the fissile and fertile coated particles, respectively. Fuel performance models have been developed to quantify the integrity of the TRISO coated particles during both normal operation and design basis accidents (Ref. 4). The performance models for the fuel particles have been correlated with tests carried out in the USA, the FRG, and the UK confirming the integrity to fractions less than 5×10^{-5} failure during normal operation and less than 1.5×10^{-4} during heat-up events to a least 1600°C fuel temperatures.

The performance of graphite components in the core has been evaluated by a probabilistic approach which takes account of the volume-related distribution of material properties and the time-dependent accumulation of strains (Ref. 5). Stress criteria have been developed by this approach which allows some local cracking of graphite elements with no effect on the nuclear, thermal, or fission product retention characteristics of the core.

Conclusions

The annular core design for the MHTGR provides for approximately 40% greater output over a cylindrical core, and a capability for maintaining fuel temperatures at levels which limit the failures of coated fuel particles to below 5×10^{-5} fraction during normal operation and below 1.5×10^{-4} during any licensing basis events. The core shape, as a tall annular cylinder, is directly influenced by the requirements to remove heat. Emphasis has been shifted from an external containment building to a coated-particle containment for the ultimate protection against loss-of-forced-circulation events.

The fuel element design is basically that of the Fort St. Vrain reactor, but with low enriched uranium (≤19.8%) used instead of highly enriched uranium. All of the materials in the core are graphite or refractory ceramic.

The core is designed to be highly stable neutronically, with safe (negative) power coefficients at all reactor temperatures.

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