GA Technologies

GA-A--18633

DE87 000915

THE MODULAR HIGH-TEMPERATURE GAS-COOLED REACTOR (MHTGR)

by
A. J. NEYLAN

This is a preprint of a paper to be presented at the Technical Committee Meeting on Gas-Cooled Reactors and Their Applications, Jülich, Federal Republic of Germany, October 20-23, 1986.

Work Supported By
Department of Energy

Contract DE-AC03-84SF11963

GA PROJECT 7800
OCTOBER 1986

THE MODULAR HIGH-TEMPERATURE GAS-COOLED REACTOR (MHTGR)

A. J. Neylan
GA Technologies Inc.

ABSTRACT

The MHTGR is an advanced reactor concept being developed in the USA under a cooperative program involving the US Government, the nuclear industry and the utilities. The design utilizes basic HTGR features of ceramic fuel, helium coolant and a graphite moderator. However the specific size and configuration is selected to utilize the inherently safe characteristics associated with these standard features coupled with passive safety systems to provide a significantly higher margin of safety and investment protection than current generation reactors. Evacuation or sheltering of the public is not required. The major components of the nuclear steam supply, with special emphasis on the core, are described. Safety assessments of the concept are discussed.

ACKNOWLEDGEMENTS

The author would like to thank Mr. A. C. Millunzi, Acting Director, Division of HTGR, U.S. Department of Energy, for approval to publish this paper. Thanks are also expressed to the management of GA Technologies Inc. for permission to write and present this work, which was supported by the Department of Energy, San Francisco Operations Office Contract DE-AC03-84SF11963.

THE MODULAR HIGH-TEMPERATURE GAS-COOLED REACTOR (MHTGR)

A. J. NEYLAN
DIVISION DIRECTOR - GA TECHNOLOGIES

The Modular High-Temperature Gas-Cooled Reactor (MHTGR) is being developed in the United States under a cooperative program involving the U.S. Government's Department of Energy (DOE); the nuclear reactor industry led by GA Technologies Inc. (GA), the industrial pioneer of the HTGR concept; and the utility/user industry represented by Gas-Cooled Reactor Associates (GCRA). The design is an advanced version of the basic High Temperature Gas-Cooled Reactor (HTGR) concept. The overall goal is to provide safe economical power with a standardized, pre-licensed factory fabricated reactor.

This modular design uses the following standard HTGR features:

- refractory coated particle fuel capable of retaining fission products at very high temperatures,
- graphite moderator which remains stable to very high temperatures and has a high heat capacity, and
- helium coolant which is inert, non-corrosive, and remains as a gas under all operating conditions.

As in previous concepts these standard HTGR features provide the capability to operate at temperature for high efficiency electricity generation and offer the potential to access the cogeneration and high temperature process heat markets. The basic characteristics also provide inherent advantages associated with safety, investment protection, and environmental compatibility which are greatly enhanced by the special design features of the MHTGR reactors.

DESIGN DESCRIPTION:

In the MHTGR, the low thermal output, the annular geometry of the core, the use of a totally passive ultimate heat removal system and the installation of the reactor system in a below grade silo are design features incorporated in the design to provide safety which is not dependent on active safety systems, on operator actions or on the evacuation or sheltering of the public.

The reference MHTGR plant design consists of four reactor modules, each rated at 350 MW(t), coupled to two steam turbine generators yielding a net power output of about 550 MW(e). An added advantage of the modular concept is the flexibility of providing sequential deployment of individual reactor modules to match the end user's load growth requirements or financing constraints.

The four-module plant is divided into two major areas, the Nuclear Island comprising the reactor enclosures, reactor modules, and the safety related systems, and the balance of the plant housing the electric power generating systems. Each reactor module is housed in a vertical cylindrical concrete enclosure which is fully embedded in the earth. Each reactor enclosure serves as an independent confinement structure having a vented and filtered exhaust system. The Nuclear Island portion of the plant also includes auxiliary structures which house common systems for fuel handling, helium processing, and other essential services.

The modular reactor components are contained within three steel vessels: a reactor vessel, a steam generator/circulator vessel, and a connecting concentric crossduct vessel. The vessels use existing LWR technology and have weight and dimensions within previously demonstrated fabrication and transportation limits.

The reactor vessel, 6.9m (22.5 ft.) in diameter and 22m (72 ft.) in length, contains the core, reflector, and associated supports. A shutdown heat exchanger and a shutdown cooling circulator are located at the bottom of the reactor vessel. Eighteen top-mounted standpipes contain the control rod drive mechanisms and hoppers containing boron carbide pellets for reserve shutdown. Six of these standpipes are also the access ports for refueling and in-reactor inspection.

A helical coil steam generator and the electric motor-driven main helium circulator are contained in the steam generator vessel which is 4.3m (14 ft.) in diameter and 26m (85 ft.) in length. Feedwater enters the steam generator through a bottom-mounted header and superheated steam exits through a side-mounted nozzle. The steam generator is similar to, but simpler than, the Fort St. Vrain (FSV) design. The main helium circulator is located above the steam generator.

The reference design circulator utilizes magnetic bearings and a submerged motor to eliminate the water ingress problems that have plagued Fort St. Vrain (FSV). Although this is an important and preferred design selection to meet availability goals, it would also be possible to meet the design requirements with a greatly simplified third generation water bearing system that has already been full scale tested at GA. The single stage axial circulator, driven by a variable speed 3.6 MW electric motor, delivers 158.0 Kg/s (1,254,000 lb/hr) of helium at 6.378 MPa (925 psia.)

In the primary flow circuit, the helium coolant, at approximately 260^{o}C (500^{o}F), flows downward through the core, where it is heated by the nuclear reactions. The hot helium, at approximately 688^{o}C (1270^{o}F), then flows through the inner cross-duct and downward over the steam generator bundle where its heat is transferred to the water to make steam. The cooled gas then flows upward in an annulus between the steam generator bundle and the vessel, is recompressed by the circulator and driven into the annulus between the inner and outer crossduct. The cool gas entering the reactor vessel flows up through channels in the lateral core restraint structure to the top of the core to complete the circuit. All surfaces of the steel pressure vessels are in contact with helium at the lower temperature.

In the secondary flow circuit, feedwater is transformed to superheated steam in the once-through, uphill boiling steam generator. The steam generator delivers 137.3 Kg/s (1,089,700 lbs/hr.) of superheated steam at 17.340 MPa (2515 psia) and 540^{o}C (1005^{o}F) to a two-turbine generator unit. Exhaust steam from the turbine is condensed and returned to the steam generator through a standard condensate/feedwater system. Control of operations for the complete plant is performed from a single control room in the control building located adjacent to one end of the reactor services building.

A completely independent shutdown cooling loop, comprising a heat exchanger and circulator, is provided at the bottom of the reactor vessel for maintenance purposes. Provision of this capability is directly in response to user requirements to minimize downtime and meet availability goals. In the shutdown cooling mode hot helium enters the shutdown helium to water heat exchanger through a flow-activated shut-off valve. After transferring its heat, the cool helium is compressed by the shutdown circulator. The compressed helium is then discharged into a plenum at the bottom of the reactor vessel and returns to the top of the core through the annular flow passage between the core and the reactor vessel.

The key to the MHTGR performance and capability is the refractory coated fuel. As in the FSV fuel, fissile and fertile fuel particles are blended into 1.27cms (1/2") dia x 5.08cms (2") long fuel rods which are in turn loaded into prismatic fuel elements approximately 78cms (31") in height by 35.6cms (14") across flats. Vertical coolant holes are provided in the fuel element blocks. Major differences from the FSV fuel are the adoption of Low Enriched Uranium (≤19.9%) to meet National policy guidance on proliferation resistance and improvements in the fuel manufacturing process to produce a fifty fold improvement in fuel quality --- a remarkable objective considering the excellent operating experience and performance of fuel in FSV.

The fuel elements are stacked in columns to make up an annular-shaped core having a radial thickness of about 0.9m (3 ft.), an average outer diameter of 3.5m (11.5 ft.) and a height of 7.6m (25 ft.) Unfueled graphite blocks surround the active core to form replaceable inner and outer radial and upper and lower axial reflectors. Permanent reflector blocks are located at the outer periphery of the replaceable graphite blocks.

The total assembly is restrained in a steel core barrel within the reactor pressure vessel. Lessons learned at FSV on preventing core fluctuations have been factored into the design. Although the core is taller both ends of each column are pinned (the design fix at FSV) and the core pressure drop (the driving force) is considerably lower due to the elimination of orifice valves and the six year core region fuel loading used on FSV.

Refueling of a module is accomplished with the reactor shutdown and depressurized. After removal of the required control rods and drive mechanisms by an auxiliary service machine, the refueling machine is located over the desired refueling port by the crane in the reactor services building and fuel elements are removed from the core and transported in shielded casks to the fuel storage area in the fuel building. One half of the fuel is replaced each 20 months resulting in a 3.3 year fuel cycle.

Two independent and diverse reactivity control systems are provided. Reactor power is controlled by 6 inner and 12 outer articulated control rods that travel in vertical channels located in the inner and outer graphite reflector regions. Twelve reserve shutdown channels are provided which, when activated, permits small boron carbide spheres to enter channels located in the innermost row of fuel columns.

The annular core geometry and power density of 5.91 w/cc were selected to limit peak temperatures and hence fuel failure during loss of forced circulation events such that the user requirement of not exceeding US Environmental Protection Agency's Protective Action Guidelines (PAG) dose limits at the site boundary would be achieved.

Decay heat removal during shutdown, inspection or maintenance periods can be accomplished using the main heat transport loop with the steam generated in the secondary circuit bypassing the turbine and condensing in the condenser. The decay heat can also be removed by the shutdown cooling system located at the bottom of the reactor vessel.

In addition to the two independent active systems used to remove heat from the core i.e. the main loop (steam generator/circulator) and the shutdown cooling loop (heat exchanger/circulator) a third totally passive system is located in the reactor cavity adjacent to the reactor vessel. This system, designated the Reactor Cavity Cooling System (RCCS), removes radiant heat from the reactor vessel under normal and accident conditions using naturally circulating ambient air in specially designed cooling panels. The system is totally passive; no valves, fans or mechanisms are utilized. It is the only system needed to remove heat from the core to meet regulatory safety requirements.

SAFETY ASSESSMENT:

The safety characteristics of the MHTGR are a result of the ability to effectively utilize the inert coolant; the capability of the refractory coated fuel to withstand high temperatures; and the high thermal inertia and high temperature stability inherent in the graphite core and support structures. These unique features have been exploited in the MHTGR to yield a reactor that does not depend on active engineered safety features or human actions for safety of the public or the investment.

Helium gas, the reactor coolant, is inert so there are no chemical reactions between the coolant and the fuel, graphite core structure, or reactor vessel which could lead to fires or explosions. Further, helium has no effect on the nuclear reaction.

The graphite fuel elements and reactor internals which make up the reactor core have a high heat capacity and maintain strength to temperatures beyond 2760^{o}C (5000^{o}F). As a result, temperature changes of the core occur slowly and without damage to the core structure even in the event of accidents where the capability to remove heat is impaired.

As stated previously the annular core geometry, core power density, and the total module power of the MHTGR have been chosen such that the decay heat generated within the core can be passively removed by means of conduction, radiation, and natural convection without the fuel reaching a temperature at which the refractory coating would fail during an accident.

Primary cooling systems and shutdown cooling systems are available to remove heat and the core temperatures do not exceed normal levels. Even if both active cooling systems are unavailable, decay heat is dissipated by conduction and radiation to the reactor cavity cooling system (RCCS) in the reactor enclosure. The heat transfer is sufficient to avoid damage to the fuel or reactor components. The maximum fuel temperature is limited to about 1600°C, well below the failure temperature.

The high temperature stability and slow heatup characteristics of the graphite reactor core and fuel not only retains fission products within the coated particles but provide a user friendly and forgiving reactor design that allows many many hours for operator corrective action.

The inherent characteristics of the MHTGR also assure the safety of the system against other types of accidents.

- Anticipated Transients Without Scram (ATWS) are mitigated by the strong negative temperature coefficient and zero coolant void coefficient of the reactor core. These inherent characteristics cause the reactor to automatically shutdown in the event reactor temperature rises above normal as a result of equipment failure or operator error.

- The reactivity control systems provide considerable margin over the most adverse reactivity insertion accident including unlimited water ingress.

- Chemical reactions between steam and graphite can only occur as a result of accidents or equipment failures allowing the steam or water to come into contact with the graphite. At normal operating temperatures the reaction rate is insignificant. The reaction rate increases with temperature but, in any event, is highly endothermic (heat absorbing) and therefore self terminating.

- Air/oxygen reactions with graphite are exothermic (heat releasing) but can only be sustained if multiple breaches of the reactor vessel occur and if the graphite is heated to temperatures much higher than normal. The silo installation limits the air available to support combustion in the extent of any reaction would be minor. Even were the graphite to be burned away the fission product activity is retained by the refractory particle coatings.

No public evacuation or sheltering is required even for severe low probability accidents because the consequences are mitigated by the inherent passive features of the MHTGR.

CONCLUSION:

The Modular High Temperature Gas-Cooled Reactor (MHTGR) is a second generation nuclear power system which can satisfy the concerns of the public, the government, the utilities and the investor community about nuclear safety and investment protection. Based on technology developed and demonstrated in the U.S. and Germany, the unique system makes use of refractory coated nuclear fuel, helium gas as an inert coolant and graphite as a stable core structural material. The safety and protection of the plant investment is provided by inherent and passive features and is not dependent upon operator actions or the activation of engineered systems. The high performance MHTGR provides flexibility in power output and siting, competitive energy costs, and can serve diverse energy needs both domestically and internationally.

The work described in this paper reflects the combined efforts of all the US program participants under contract to the Department of Energy. I wish to express my appreciation to DOE for permission to publish this paper.