The status of high-temperature gas-cooled reactor development and design

In the United States and other countries important benefits are foreseen from smaller, modular systems

by L.D. Mears and A.J. Goodjohn

Gas-cooled reactors have had a long and varied history dating back to the very early days of nuclear energy development. Most of the early development centered on low-temperature systems using graphite moderator, metal-clad fuel and carbon-dioxide coolant. Commercial deployment of such systems started in the mid-1950s primarily in the United Kingdom and France with the natural uranium-fuelled Magnox stations, followed by the higher temperature, low-enriched-uranium fuelled advanced gas-cooled reactor (AGR) stations, solely deployed in the United Kingdom, starting in the mid-1970s. These two pioneering programmes have now concluded with some of the early Magnox stations being decommissioned and the final AGR stations at Heysham-2 and Torness completed and recently put into service. Experience from over 1000 reactor-years of operation comprises a very valuable database for the ongoing development and design programmes on higher temperature reactors.

From the very beginning, it was recognized that greater benefits of gas-cooling (in particular, at that time, the ability to attain modern fossil-fired steam conditions, thereby permitting more highly efficient electricity production) would accrue if higher gas temperatures could be achieved. It was this goal, coupled with the vision that such higher gas temperatures might also lead to even broader applications of nuclear energy such as providing industrial process heat, that motivated the development of the high-temperature gas-cooled reactor (HTGR) with its characteristic reactor core of graphite moderator and ceramic fuel, and its use of the inert helium gas as coolant.

Development work on HTGRs started in the mid-1950s both in the United States and in the Federal Republic of Germany. As a result of effective co-operative agreements between the governments and industrial entities in both countries, the respective programmes have evolved down similar development paths. The only basic difference is the fuel element form. All present HTGR concepts utilize fuel in form of small spherical kernels coated with multiple successive layers of the refractory materials pyrocarbon and silicon carbide. In the Federal Republic of Germany, the fuel element designs incorporate this coated particle fuel in spherical fuel element balls (six centimetres diameter) and a continuous fuelling system is employed. In the US designs, similar coated fuel particles are incorporated into fuel rods using a graphitic binder, which are inserted into blind holes drilled in hexagonal graphite fuel element blocks, 36 centimetres across the flats and about 79 centimetres long. Off-line refuelling is employed in the US designs.

As will be described in this article, it is the unique capability of this coated particle fuel that had led to the development of the present modular versions of the HTGR, the HTR-module in the Federal Republic of Germany, and the modular HTGR or MHTGR in the USA.

HTGR design development

The first HTGR plants to be built and operated included: Dragon, a 20-MWth research reactor in the UK; Peach Bottom-1 Unit, a 40-MWe developmental plant in the USA; and the AVR 15-MWe developmental plant in the Federal Republic of Germany. All three began operation in the mid-1960s, and all three had very good operating histories. Both Dragon and Peach Bottom were decommissioned after achieving their planned objectives. AVR was shut down for power generation at the end of 1988 after serving over 20 years as a valuable test bed for fuel plus safety experiments relevant to the MHTGR concept.

The 330-MWe Fort St. Vrain plant in the USA, which was commissioned in 1979, and the 300 MWe THTR-300 plant in the Federal Republic of Germany, commissioned in 1987, followed. Fort St. Vrain experience has been mixed, with excellent fuel performance and almost insignificant personnel radiation exposure, in contrast to disappointing availability,

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primarily due to the unique design of the helium circulators and their water-lubricated bearing system. This realiability problem and the high-operating and fuel costs associated with a one-of-a-kind plant have resulted in plans to shut down the plant by June 1990. The THTR-300 plant experience has been overall good. However, technical problems with the fuel handling systems, the hot duct cover plates, and the graphite floor dowels have been experienced. Again, the poor power cost economics plus the lack of assured fuel supply and Government financial support have resulted in plans to shut down the plant, probably by 1991.

Following Fort St. Vrain deployment, 10 large commercial HTGRs (five twin plant contracts) were ordered in the United States. However, these were terminated in the mid-1970s due to the economic recession following the Arab oil embargo. In the Federal Republic of Germany, design development of the HTR-500, a 550 MWe plant, has proceeded but no commercial orders have been received.

As the hiatus in new nuclear plant orders in the USA extended into the early 1980s and in the wake of the Three Mile Island (TMI) accident, a consensus emerged that a new approach was required to overcome the underlying technical and institutional problems associated with nuclear power. This consensus led to heightened interest in reactors with improved safety characteristics that would provide the basis for enhanced public confidence and reduced licensing risks. In response to these interests, a framework for the development of advanced nuclear plants gradually evolved. The framework involved several factors but clearly the most important in terms of setting the direction for future design development were those associated with size and safety.

Concerning power plant size, lower electrical load growth rates had been among the major effects of the mid-1970s developments related to the oil embargo, business downturn, and conservation ethic. Also, the risks associated with the massive capital investment, the long schedules, and the increasingly complex regulatory environment characterizing large systems had become extremely complex. Thus, large, single-reactor plants were no longer the prudent choice for most utility planners. Plants enabling smaller capacity increments and which could be constructed in shorter times with lesser capital commitments were being increasingly viewed as essential for coping with the future era of uncertainty. Moreover, smaller and simpler nuclear plants were obviously more suited to the needs of developing countries.

In the matter of safety, public concern had increased following TMI. Additional safety requirements were being imposed on existing and future reactors and planning for emergency sheltering and evacuation of the proximate public had become a major issue. Moreover, the TMI accident led to a significant loss of the utility's investment even though the actual impact on public health and safety has been insignificant. Based upon these concerns, improved safety/investment protection with a greater emphasis on passive safety features was seen as desirable for improved public/investor acceptance and reduced licensing risks. Similarly, the possibility that such a plant could be less sensitive to operator error or equipment malfunction was also seen as highly desirable.

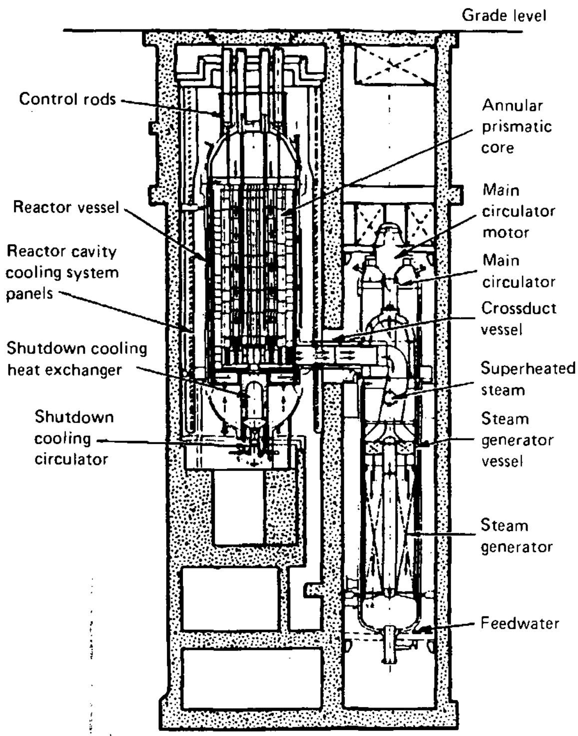

Diagram of the 350-MWth modular high-temperature gas-cooled reactor in the USA.

Within the US programme, a rigorous evaluation led to the selection of the MHTGR, as the reference concept for the ongoing Department of Energy (DOE)/Industry design development programme. Similar factors were involved in the movement of the German programme towards consideration of smaller HTGRs and the evolution of the HTR-module. *(See accompanying figures.)* This article will concentrate on the US MHTGR concept as representative of the basic characteristics of these smaller modular gas-cooled reactors.

The MHTGR design concept

The heart of the MHTGR concept is the coated particle fuel. Spherical kernels or uranium oxycarbide fuel, about 0.5 millimetre in diameter, which are coated with multiple layers of the refractory materials, pyrolytic carbon and silicon carbide, enclose each fuel particle and the fission products generated during power operation; hence they act as a tiny thick-walled containment vessel. The safety characteristics of the MHTGR

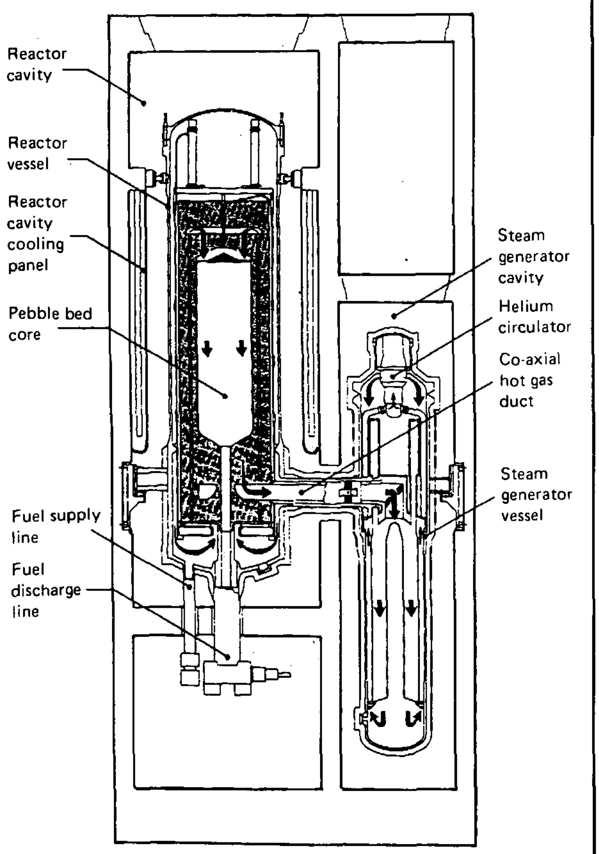

Diagram of the 200-MWth high-temperature reactor module in the Federal Republic of Germany.

are due to the inherent properties of the coated particle fuel to withstand elevated temperatures without significant failure and the capability of the design concept to passively limit the temperature rise in the fuel during transients associated with postulated severe accidents.

In the MHTGR core design, the graphite fuel elements are configured in an annular geometry with both inner and outer graphite reflectors. The annular core geometry was selected to enhance the surface-to-volume ratio of the core, allowing a power output of 350 MWth while retaining the capability to dissipate decay heat by passive means.

Each reactor module consists of the annular reactor core contained within a steel vessel, connected via a concentric crossduct vessel to a single, helically-coiled, once-through steam generator within a third vessel located to the side and below the elevation of the reactor vessel. A variable-speed, electric-motor-driven main circulator is located on top of the steam generator vessel. For removal of decay heat during maintenance when the main heat transport system is unavailable, the concept incorporates a small shutdown helium-to-water heat exchanger and electric motor-driven circulator located at the bottom of the reactor vessel. Control rod drives and their associated control rods and reserve shutdown material hoppers are installed through penetrations on top of the reactor vessel. Off-line refuelling of the reactor is also accomplished through these same penetrations.

In normal operation, the helium coolant flows down through the coolant channels in the graphite fuel elements, is collected and mixed in an annular chamber below the core, then transports the reactor heat through the centre duct of the concentric crossduct vessel to the steam generator. After flowing down through the helical bundle of the steam generator, the helium flows up in the annulus between the steam generator shroud and the vessel to the circulator. The compressed helium is then routed back to the reactor vessel via the outer annulus of the concentric crossduct and to the top of the core via the annulus between the core barrel and the reactor vessel. Thus, coolant helium continuously bathes the walls of all three steel vessels. Feedwater enters at the bottom of the steam generator vessel and superheated steam at 1000 degrees Fahrenheit/2500 pounds per square inch exits through a side-mounted nozzle on the vessel.

An overall plant concept would comprise multiple modules located side-by-side in below-grade level enclosures in a slide-along configuration. The number of modules and the schedule for their deployment would be selected to match load growth and/or financing constraints. Each module transmits energy in the form of steam to the adjacent energy conversion area. With an energy conversion efficiency of approximately 38%, each module can provide a net electrical output of 135 MWe. The reference MHTGR plant configuration consists of four modules with a net output of 540 MWe.

The MHTGR passive safety concept

Three alternatives are available for the removal of decay heat. The first of these is the non-safety related main heat transport system, which would transfer the decay heat via the steam generator and a turbine bypass to the condenser. In the event that the main heat transport system is not available due to planned maintenance or component failure, decay heat would be rejected through the shutdown cooling system. The shutdown cooling system is also a non-safety related system which rejects decay heat via a closed cooling water loop and individual air blast heat exchangers.

In the event that neither of the above two active cooling systems is available, decay heat would be rejected through the third alternative, the reactor cavity cooling system (RCCS). The RCCS is a continuously operating, safety-related, passive heat removal system. In the RCCS, ambient air is directed via an intake/exhaust structure and concentric ducts to air cooling panels located within the reactor enclosure. The air is heated within the panels by decay heat conducted and radiated from the reactor, and is returned to the environment via the inner portion of the concentric ducts and the intake/exhaust structure. The passive decay heat removal will occur without exceeding fuel design limits or incurring plant damage, even loss of forced helium flow and/or depressurization of the primary system.

This capability, coupled with the always-negative temperature coefficient of reactivity of the reactor which automatically assures a power shutdown to decay levels as the reactor temperature increases, is the unique passive safety concept for the MHTGR. Even further, while the probability of coincidently losing all three heat transport systems is diminishingly small, an evaluation of even that "beyond design basis event" was made. The results indicate that while some investment-related plant damage may occur, decay heat would be passively rejected to the ground, and resulting fuel temperatures would not be appreciably above those if the RCCS were available. Moreover, at the request of the US licensing authorities, several other accidents well beyond the licensing basis were also evaluated, including total control rod withdrawal with delayed scram, unrestricted air ingress, unrestricted water ingress, and simultaneous failure of all heat removal systems coincident with massive vessel failure at the crossduct. For all such events, radiological dose levels requiring protective action would not be exceeded even at the exclusion area boundary, using a 425-metre radius site. Thus, a technical basis is provided for the elimination of early notification (sirens, etc.) and emergency evacuation and sheltering drills as required elements of an offsite emergency plan. In addition, the above results are achieved with no reliance on AC-powered systems or operator actions and with the fission product containment function provided solely by the coatings on the fuel particles. An unprecedented level of safety has been made available by the full implementation of the passive safety concept in the MHTGR.

Economic feasibility

Any consideration of returning to the deployment of smaller nuclear plants faces the issue of competitive economics. During the 1960s and early 1970s, and in fact, continuing in many industrialized countries today, competitive pressures have led to the commercial offering of ever larger nuclear plants in recognition of the perceived economies of scale associated with such capital-intensive ventures. Experience has shown, however, that the commitment to such a massive capital investment over a long-time frame entails inordinate risks; risks that, in many countries and particularly in the USA, have been realized with disastrous economic consequences, and even if not realized, remain as factors to be considered in any evaluation.

The approach to achieving competitive economics with the MHTGR is keyed to three principal factors: the simplicity provided by the passive safety concept, the ability to readily achieve standardization through the use of modularity and factory fabrication, and risk belief.

The passive safety concept eliminates the need for many high-cost safety systems and enables the necessary safety and investment protection features of the reactor modules to be both physically separated and functionally decoupled from the turbine plant. As a result, only the nuclear island, consisting of the reactor modules and all the necessary nuclear service systems need be constructed to nuclear standards, whereas the turbine plant can be constructed to conventional standards. The nuclear island can also be separately fenced and secured.

Modularity, not only in the context of multiple, smaller-power-output reactor modules, but also with respect to modular design of components, systems, piping, instrumentation, controls, etc., throughout the plant permits a large fraction of the plant to be factory-fabricated and pre-assembled. Factory-fabrication facilitates quality control and, from experience, is much less expensive than field fabrication and construction. The benefits of reduced cost due to learning are more readily achievable in a factory environment.

Deployment of smaller capacity generating plants with the flexibility of reaching that capacity in modular increments results in reduced financial exposure. This is probably the most significant tangible factor related to risk relief, although other more intangible factors such as reduced licensing risk and increased public acceptance are also important.

Economic analyses of the MHTGR have taken into account the above factors to the extent that they were believed to result in tangible cost difference. These analyses indicate that the reference four-module 540-MWe plant will be competitive with the most modern coal-fired alternative for the majority of the projected coal regions within the USA. It is important to note that the several factors involved in such comparisons are very much dependent on local factors within any country or locale interested in the nuclear alternative and, hence, must be carefully evaluated.

Future perspectives

The world is clearly demanding smaller, more passively safe nuclear power plants. The MHTGR appears ideally suited, primarily due to its apparent simplicity and benign behaviour, to contribute to meeting this worldwide demand. A demonstration (or lead) plant project is required to provide evident proof of the overall performance (safety, reliability, operability, etc.) claimed. Such first projects are presently being evaluated in the USA (a MHTGR plant with industrial participation of the Federal Republic of Germany) and in the USSR (a variant of the HTR-module with both Government and industry participation of the Federal Republic of Germany). Subsequent deployment in the competitive marketplace is contemplated after the turn of the century.