MHR Design, Technology and Applications

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Introduction

Speaking as one who has spent most of his career in the fusion arena, it hard to imagine that, almost inevitably, fusion will not one day become the world's primary means of base-load power generation. However, despite the great progress that has been made in recent years in learning to control the plasma states required for both the magnetic and inertial approaches to fusion, and the fact that both approaches should soon achieve significant levels of fusion power generation, there remains a great deal to be done in materials development and maturation of both reactor concepts before fusion could be considered a serious economic power candidate or, particularly, achieve significant penetration into the power market(s). Therefore, fusion cannot be look upon as an answer to today's power needs. We need a bridge to fusion, and only fission nuclear power can credibly fill that gap while meeting the strict reductions in associated carbon emissions required by concerns of global climate change.

Even though today's Generation III+ reactors represent significant advances in safety, availability, and economics over their predecessors, the next generation of nuclear will be required to satisfy even more demanding requirements. The international Generation IV activity sets high goals for inherent safety and security, proliferation resistance, fuel sustainability and low Operation and Maintenance (O&M) costs. To these can certainly be added additional requirements that may vary with site and/or market: competitive Cost of Electricity (COE), unit-size flexibility, low water consumption, manageable spent-fuel form, etc.

As discussed below, the Modular Helium Reactor (MHR) meets these requirements to a high degree. Its combination of graphite moderator, inert helium coolant, and TRISO fuel-form provides a high degree of operational robustness and safety; and its high helium-gas temperature improves power conversion efficiency. In fact, the MHR was first designed for safety and then made economic, rather than the other way around. The MHR adopts a modular approach that introduces great flexibility, either in module size, ranging from 350 MW(t) to 600 MW(t), and in number for larger plant electrical output. In terms of readiness today, the MHR draws on a number of past and currently operating facilities of varying sizes, so that MHR core design and its safety performance is well established. Even though some development remains for the most advanced power conversion technologies, the MHR core could be used today to provide heat to drive conventional steam turbines at efficiency of 38% owing to the high outlet temperature, 800-850°C.

MHR Design & Technology

The key to the inherent safety of the MHR lies in its TRISO particle fuel form. This engineered fuel comprises a heavy metal central kernel roughly 0.2 mm in diameter, encased in a carbon buffer and three polycarbonate layers that are designed to contain all radionuclides for temperatures up to 2000°C and pressures up to 1000 atm. The fuel kernels can be made up of uranium (up to just below 20% enriched), weapons-grade plutonium, thorium (with a suitable fissile driver), Light Water Reactor (LWR) (and even MHR) spent fuel. In the "block design"

MHR, the TRISO particles, whose total outer diameter is < 1 mm., are packed into graphite compacts which are then inserted into graphite fuel blocks in columns alternately with the helium cooling channels. The "pebble bed" design reactor uses the same TRISO fuel particles but packs them into tennis-ball sized graphite balls that are fed through the reactor.

In effect, the TRISO particle coating acts as a reactor containment vessel, and there can be billions of them in a reactor core. It is, therefore, critical that the particles meet demanding standards for fabrication and endurance under radiation. Early U.S. particle fuels were fabricated to more relaxed standards as those of today. For relative small batches, today's more demanding standards have been met in Germany, the U.S., Japan and China. Remaining to be developed are the automated processes that can allow large batches of particles to be fabricated at low cost while meeting the more demanding standards. Of course, all fuel fabrication processes must also be demonstrated to produce particles that retain the required properties, done by high fluence testing in a reactor.

Given that one has TRISO fuel particles satisfying the above requirements, the design of an inherently safe reactor becomes relatively straightforward. For the "block design" MHR, the blocks containing the fuel are placed in the reactor in an annular array (as shown in Fig. 1). As another step in assisting passive heat removal, the power density is reduced, so that the distance to the reactor vessel wall is such that the core can cool by conduction and radiation to its boundary and the ground heat sink (the reactor is placed below grade, see later). Although some flexibility can be had by varying the core height, one practical limit on the module size is the largest reactor vessel that can be procured. With this design, modeling of various loss-of-coolant-accident (LOCA) scenarios show maximum fuel temperatures are limited to 1600°C, where the safe containment regime of the particle fuel is not exceeded. An important note is that because of the thermal capacity of the graphite, the time to reach the maximum fuel temperature in the 600 MW(t) core is between 2 and 3 days – plenty of time for an operator to take orderly remedial action.

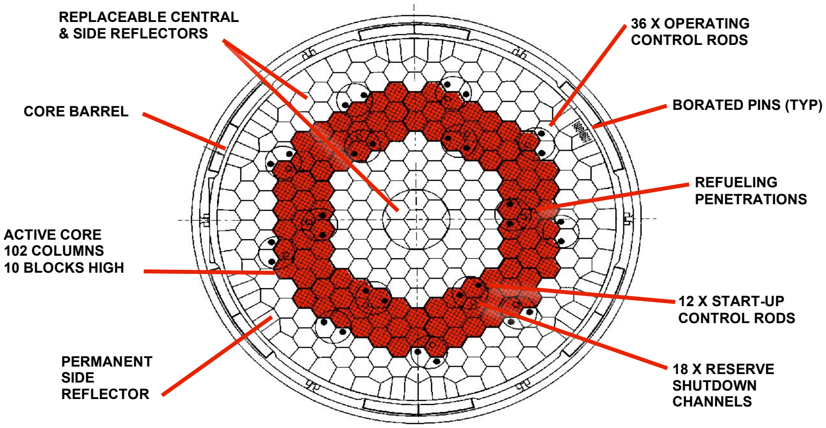

Fig. 1: 600 MW(t) "block design" MHR Layout

Although there are no full-scale MHR reactors in operation today, there are two small experimental reactors in operation: the block HTTR in Japan and the closely related pebble-bed HT-10 in China. The 30 MW(t) HTTR has successfully operated to 950°C coolant outlet temperature. The 10 MW(t) HT-10 operates at a somewhat lower temperature but routinely demonstrates a loss-of-coolant recovery for visitors. The fact that both facilities operate essentially as designed, combined with the successful core performance of the Peach Bottom and Ft. St. Vrain test reactors in the U.S., gives confidence that MHR core design is a well established technology.

MHR Applications

Given that the core capability is well established, we turn to applications of this new heat source. The high temperature output heat is available for multiple applications: high-efficiency electricity generation; hydrogen production; desalination and other process-heat applications. For electricity generation, the technology most readily available today would couple the MHR heat source to a conventional Rankine cycle steam system, similar to those used today in fossil plants or LWRs. The generation efficiency would be higher with an MHR, approximately 38%, owing to the steam heated by the high temperature helium. A module design of 350 MW(t) is the most mature in the sense of having completed Preliminary Design and had an NRC Safety Evaluation. However, even at the higher steam temperatures, the Rankine cycle is limited in efficiency, as shown in Fig. 2. Also shown in Fig. 2, the prospect of driving a turbine directly with the high temperature helium in a Brayton cycle looks very attractive. For example, with a reactor gas outlet temperature of 850°C (1562°F) for the Gas Turbine Modular Helium Reactor (GT-MHR), the efficiency rises to 48%, meaning a 50% increase in electrical power over a Rankine cycle operating at 350°C (662°F).

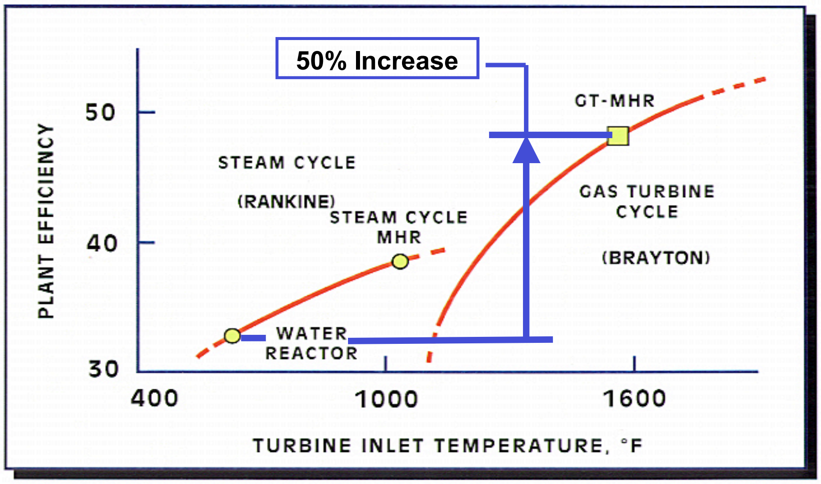

Fig. 2: Plant Efficiency versus Turbine Inlet Temperature

The turbine of a Brayton cycle power conversion unit (PCU) is not predetermined by efficiency considerations, e.g., its layout may be on a horizontal or vertical axis. For several reasons, the GT-MHR developed by General Atomics (GA) adopts an integrated, vertical, single–shaft turbine-generator design: minimum issues of helium blow-by, minimum cross ducting of hot helium, symmetric electromagnetic bearing suspension, etc. Although this vertical PCU layout is still under development, the concept has been given significant engineering analysis through GA working with OKBM in Russia as part of the U.S.-Russia joint program to burn weapons grade plutonium beyond the currently agreed 34 MT MOX program. With the introduction of a vertical PCU, the GT-MHR assumes its final form.

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Originally for economic and LOCA heat removal reasons, the GT-MHR was placed below grade, a concept that assumed new importance after 9/11. All that remains above grade are cranes and other non-nuclear equipment. Fig. 3 shows one complete module that would produce 285 MW(e); a larger power plant would be made up of an appropriate number of such modules, typically four. It is important to emphasize that, owing the passive safety of this reactor, what is shown here is all there is in the sense of there not being required a large, complex, active emergency cooling system. By avoiding the need for such systems, which require attention and maintenance and, therefore, add greatly to O&M costs in conventional LWR reactors, the GT-MHR is able to offset the higher costs incurred by its reduced power density and particle fuel.

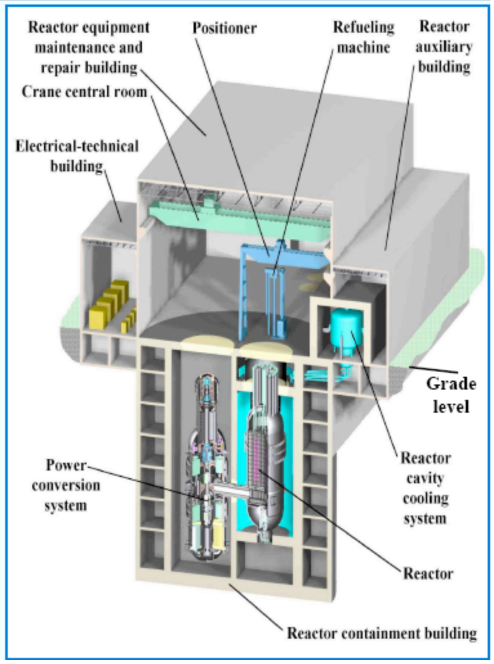

Fig. 3: GT-MHR Module General Arrangement

The projected costs of MHR electricity depend on module size and power conversion technology, whether one is looking at the near or more distant term. For four-module plant installations, the 350 MW(t) + steam-cycle system is projected to have a COE comparable to Generation III systems today. Adopting a combined-cycle power conversion at better efficiency would lower those costs, depending on the system used. The GT-MHR at 48% efficiency, when fully developed, is projected to give quite a significant reduction in COE. Although these are only projected values, they suggest very attractive conclusions. Ultimately, with blade cooling, special materials and other improvements to accommodate even higher coolant outlet temperatures, there are prospects for even further economic improvements in the future.

The operating temperature of the GT-MHR also makes it attractive for hydrogen production. How this is to be done involves the most efficient use of the combination of heat and electricity it produces. Straightforward electrolysis of water is, of course, one option. A better, but related option, is to use some of the heat to raise the temperature of the water, so-called high-temperature electrolysis. A third approach avoids the use of electricity completely and uses the heat directly in a thermo-chemical process, for which several are potentially available. The most attractive of such process in terms of efficiency appears to be the Sulfur-Iodine (S-I) process, requiring temperatures in excess of 800-850°C. As illustrated in Fig. 4, the S-I process comprises three coupled chemical processes. Taken as a whole, the inputs are water and heat,; the outputs are hydrogen, oxygen and waste heat; and all intermediate chemicals are recycled internally. However, these chemicals are corrosive and at high temperature, so development is needed. Nonetheless, the S-I process has been selected independently by the U.S., France and Japan as the most promising for high-temperature hydrogen production.

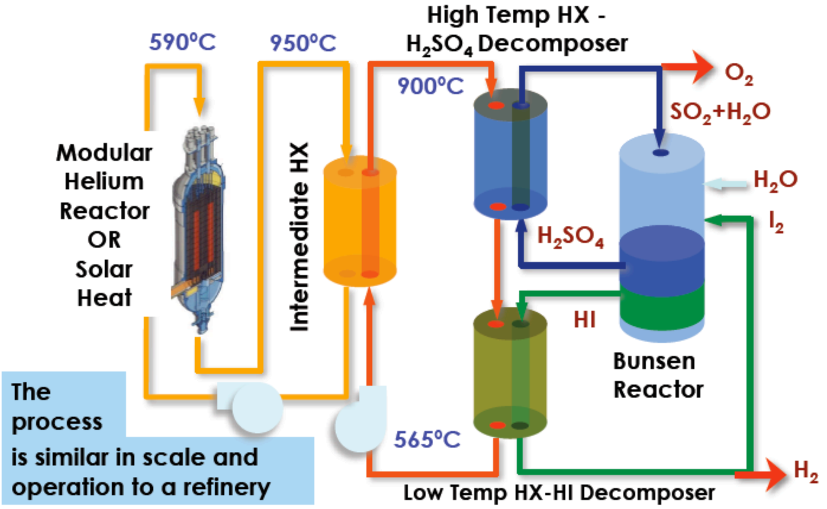

Fig. 4: MHR Application for a S-I Process

Another characteristic of the MHR-class of reactors is the potential for relying solely on air-cooling of the core, leading to a much reduced water demand for waste heat removal. The combination of higher efficiency and higher temperatures relative to the operating environment makes this option feasible without incurring severe increases in the COE. A closely related consideration would be the combination of applying whatever water-based waste heat removal is adapted to desalination of the water thus used. These ideas are today only in early conceptual design stage, but their potential has attracted considerable interest in arid portions of the globe, like the Western U.S. and the Persian Gulf States.

As a final topic, we look at the potential of the MHR for addressing the issue of sustainability of the fuel cycle, which has both resource and spent-fuel aspects. As to the former, the MHR is not a breeder. However, its higher efficiency alone can extend by 50% the total energy that can be extracted from a given amount of uranium. Further, the demonstrated capability of gas reactors to operate well with mixtures of thorium and a fissile driver (both Peach Bottom and Ft. St. Vrain did so) implies a 3x or so expansion in the available fertile resources. In the very long term, either the breeder or fusion will be required, but with this extension their need can be put off a century or more.

The second aspect of the fuel cycle has to do with spent fuel and the need to move away from the policy of once-through and repository disposal. The politics and delays of Yucca Mountain, coupled with the increased capacity required by an increased use on nuclear power, only dramatized this point. Fortunately, the flexibility of the MHR with regard to fuel form introduces an attractive resolution to this issue. It can burn a large fraction of a fuel load comprised of spent fuel from either an LWR or another MHR, even though its neutron spectrum is thermal. Three gas reactor characteristics contribute to this rather surprising conclusion. First, the combination of graphite moderator and helium coolant preclude void reactivity transients and permit 100% transuranic loading. Second, there is good neutron utilization, or high probability of TRU destruction. Finally, the TRISO fuel form is robust under high fluence, permitting the fuel to "cook" to high burn-up. The result is that with one recycle through an MHR core, some 90-95% of the spent-fuel TRU will be destroyed, depending on the actinide. At this point the "dregs" can either be placed in a repository (with ~10x decrease in required repository capacity) or destroyed in an advanced burner reactor (of which many fewer will be required compared to the direct destruction of the original spent fuel). Whichever choice is made, the MHR can play an important role in this issue that is so critical to a resurgence in nuclear power.

Conclusion

In conclusion, we return to the set of requirements set for the next generation of reactors and ask how the MHR stands up. The results are excellent, except possibly for the area of sustainability; but even there the MHR can play a substantial role. For costs, the outlook is very promising, although these remain to be demonstrated in the future.