INL/CON-06-11320
PREPRINT

The Modular Helium Reactor for Hydrogen Production

15th Pacific Basin Nuclear Conference (15PBNC)

M. Richards
A. Shenoy
K. Schultz
L. Brown
M. Fukuie
E. Harvego

October 2006

THE MODULAR HELIUM REACTOR FOR HYDROGEN PRODUCTION

Richards M.[1], Shenoy A.[1], Schultz, K.[1], Brown, L.[1], Fukuie M.[2], and Harvego E.[3]
[1] General Atomics, San Diego, CA, USA
[2] Toshiba Corporation, Yokohama, Japan
[3] Idaho National Laboratory, Idaho Falls, ID

1. Introduction

For electricity and hydrogen production, an advanced reactor technology receiving considerable international interest is a modular, passively-safe version of the high-temperature, gas-cooled reactor (HTGR), known in the U.S. as the Modular Helium Reactor (MHR), which operates at a power level of 600 MW(t). For hydrogen production, the concept is referred to as the H2-MHR. Two concepts that make direct use of the MHR high-temperature process heat are being investigated in order to improve the efficiency and economics of hydrogen production. The first concept involves coupling the MHR to the Sulfur-Iodine (SI) thermochemical water splitting process and is referred to as the SI-Based H2-MHR [1]. The second concept involves coupling the MHR to high-temperature electrolysis (HTE) and is referred to as the HTE-Based H2-MHR [2].

2. MHR Design Description

The MHR concept and its fuel-element design are shown in Figure 1.

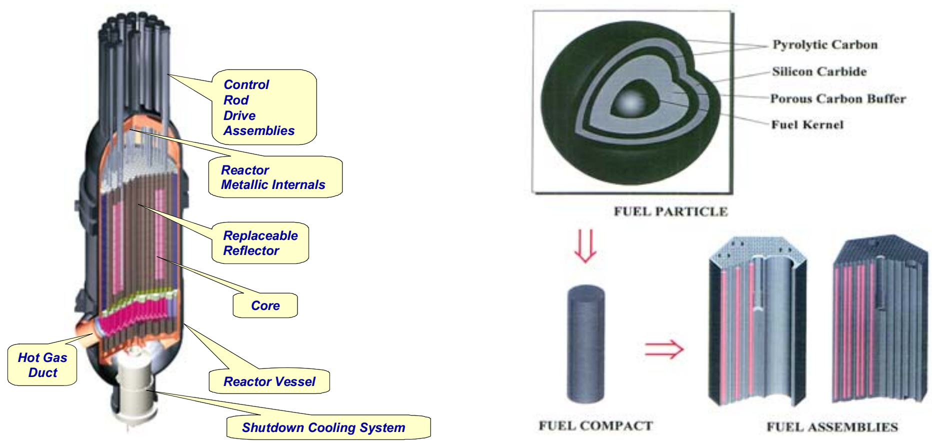

Figure 1. MHR Concept and Fuel-Element Design

The growing international interest in the MHR concept is the direct result of MHR design features, which include:

(1) Passive Safety, Competitive Economics, and Siting Flexibility. The MHR does not require active safety systems to ensure public and worker safety. The high-energy conversion efficiency of the MHR, combined with the elimination of active safety systems, result in a design that is passively safe and economically competitive with other non-passively safe reactor concepts. Because of its high efficiency, the MHR rejects less waste heat than other reactor concepts. This design feature, combined with passive safety, allows for more flexible siting options for the MHR.

(2) High Temperature Capability and Flexible Energy Outputs. The MHR is capable of producing process-heat temperatures of 950°C and higher. This high-temperature capability translates into a high-energy conversion efficiency for a variety of energy outputs, including electricity, hydrogen production, and synthetic fuel production.

(3) Flexible Fuel Cycles. The MHR can operate efficiently and economically with several different fuel cycles. MHR designs have been developed utilizing low-enriched (LEU) uranium fuels, high-enriched uranium (HEU) fuels, mixed uranium/thorium and plutonium/thorium fuels, and surplus weapons-grade plutonium fuels. The thermal neutron spectrum of the MHR, combined with robust, ceramic-coated particle fuel, allow for very high burnup in a single pass through the reactor. More recently, an MHR design has been developed to deeply burn plutonium and other transuranic (TRU) actinides recovered from light-water reactor (LWR) spent fuel [3]. The flexible fuel cycle capability of the MHR, combined with its flexible energy output capability, result in a design concept that is very well suited for a wide variety of energy-growth scenarios.

3. Hydrogen Production Using the Sulfur-Iodine Process

The SI process involves decomposition of sulfuric acid and hydrogen iodide, and regeneration of these reagents using the Bunsen reaction. Process heat is supplied at temperatures greater than 800°C to concentrate and decompose sulfuric acid. The exothermic Bunsen reaction is performed at temperatures below 120°C and releases waste heat to the environment. Hydrogen is generated during the decomposition of hydrogen iodide, using process heat at temperatures greater than 300°C. As shown in Figure 2, the heat required to drive the SI process is supplied by MHRs. The plant consists of four 600 MW(t) MHR modules, with each module coupled to an Intermediate Heat Exchanger (IHX) to transfer the heat to a secondary helium loop. The heat is then transferred to the SI-based hydrogen production system. In addition to the heat required to drive the SI process, the plant requires approximately 800 MW(e). Most of this electricity is needed to power pumps and compressors that are part of the hydrogen production system. Nominal plant design parameters are given in Table 1.

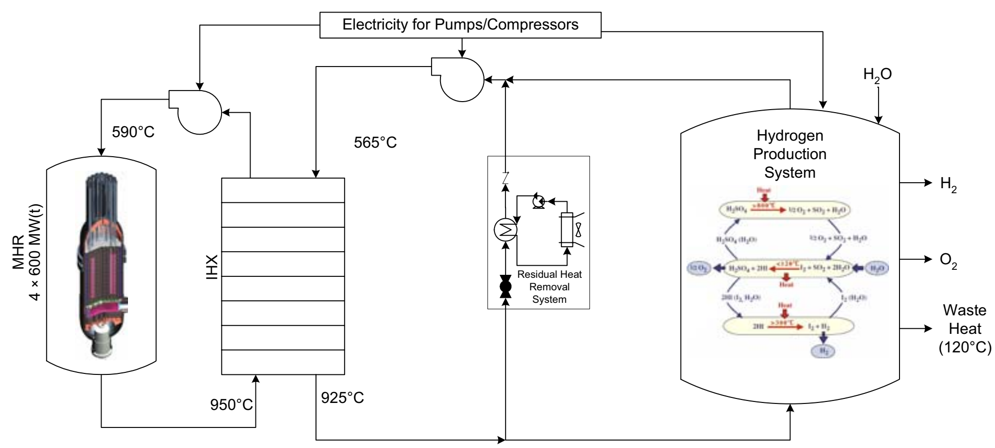

Figure 2. SI-Based H2-MHR Process Schematic

A key component for the SI-Based H2-MHR is the IHX. The IHX design is based on the Printed Circuit Heat Exchanger (PCHE) concept developed by Heatric corporation, which consists of metal plates that are diffusion bonded to restore the properties of the base metal. Fluid-flow channels are chemically milled into the plates using a technique that is similar to that used for etching printed electrical circuits. The IHX design consists of 40 Heatric-type modules manufactured from a high-temperature alloy (Inconel 617 and Hastelloy-XR are candidate materials). Figure 3 shows the PCHE technology and a preliminary IHX design concept. The IHX vessel is manufactured using SA533 steel, and insulated with kaowool to maintain operating temperatures below 350°C and prevent creep damage.

3. Hydrogen Production Using the High-Temperature Electrolysis

Because the electrical energy required to split the water molecule decreases with increasing temperature, the efficiency of electrolysis can be improved if it is performed at higher temperatures, especially if process heat is used directly to convert water into steam. High-temperature electrolysis can be performed using solid oxide electrolyzers (SOEs). For the HTE-Based H2-MHR, the SOE modules are based on the planar cell technology that has recently been successfully tested as part of a collaborative project between Idaho National Laboratory (INL) and Ceramatec [4]. It is anticipated that a single SOE module would contain 40, 500-cell stacks and consume 500 kW(e). As shown in Figure 4, eight modules could be installed within a structure that is similar in size to the trailer portion of a typical tractor-trailer. Approximately 292 of these 8-module units would be required for a full-scale plant with four 600-MW(t) MHR modules.

Table 1. SI-Based H2-MHR Nominal Plant Design Parameters

MHR System	
Number of modules	4
Module power rating	600 MW(t)
Core inlet/outlet temperatures	590°C / 950°C
Peak fuel temperature – normal operation	1250°C - 1350°C
Peak fuel temperature – accident conditions	< 1600°C
Hydrogen Production System	
Peak process temperature	900°C
Peak process pressure	7.0 MPa
Product hydrogen pressure	4.0 MPa
Annual hydrogen production	3.68×10^5 metric tons
Plant hydrogen production efficiency	45.0%

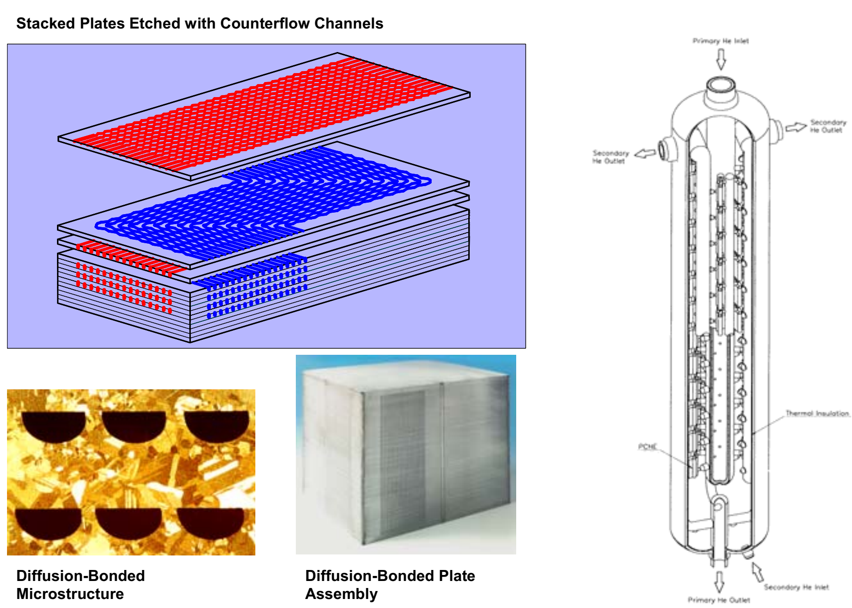

Figure 3. PCHE Technology and Preliminary IHX Design Concept

As shown in Figure 5, MHRs supply both the heat to generate steam and the electricity to split the steam into hydrogen and oxygen. Approximately 90% of the heat is used to produce electricity. The remainder of the heat is transferred though an intermediate heat exchanger (IHX) to produce steam, which is supplied to both the anode and cathodes sides of the electrolyzers. The steam supplied to the cathode side is split into hydrogen and oxygen. The oxygen is transferred through the electrolyte to the anode side. The steam supplied to the anode side is used to sweep the oxygen from electrolyzer modules. The steam supplied to the cathode side is first mixed with a small portion of the hydrogen stream in order to ensure reducing conditions and prevent oxidation of the electrodes. Heat is recuperated from both the hydrogen/steam and oxygen/steam streams exiting the electrolyzer. The full-scale plant includes four, 600-MW(t) MHR modules. Nominal plant design parameters are given in Table 2.

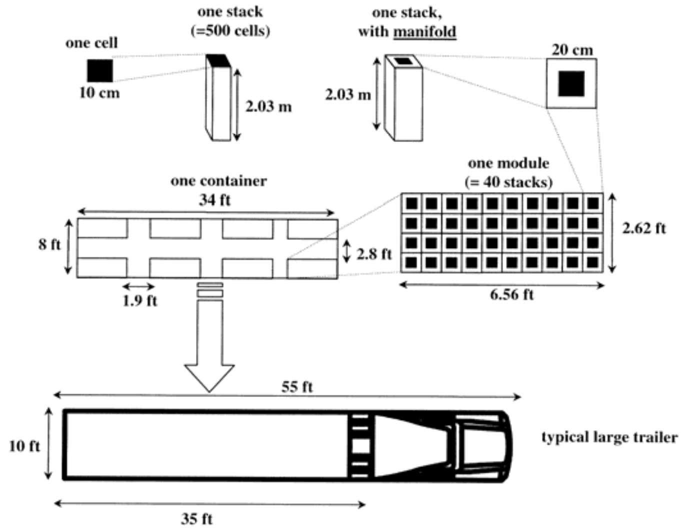

Figure 4. SOE Module Concept

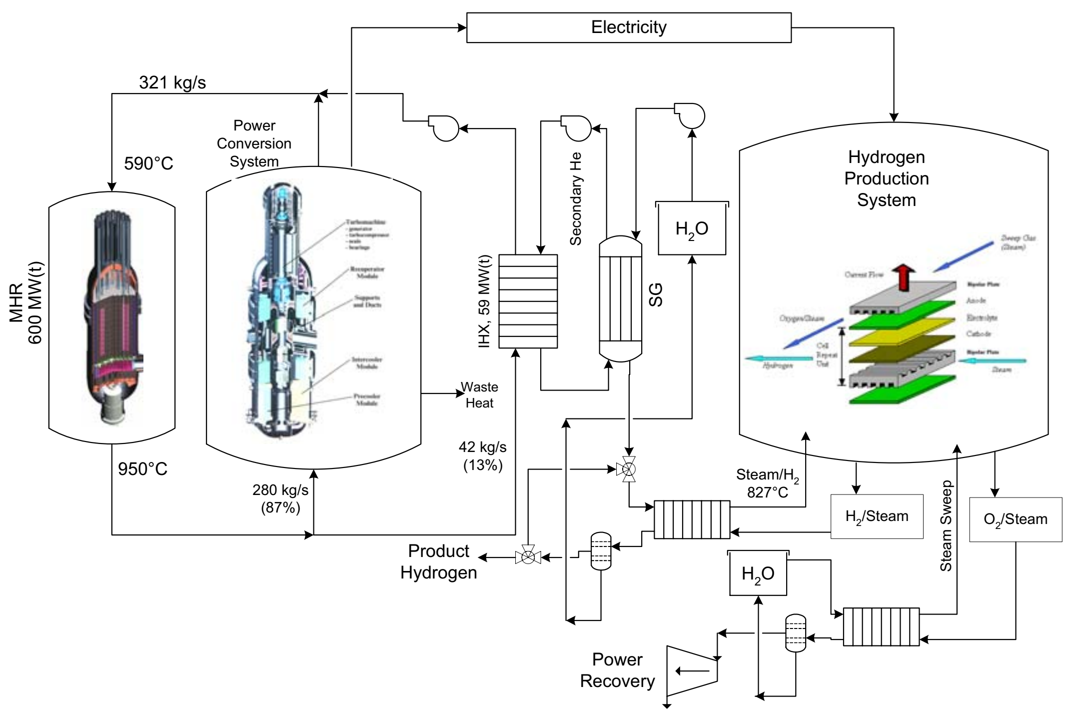

Figure 5. HTE-Based H2-MHR Process Schematic

4. Economic Evaluation

Economic evaluations were performed assuming n[th]-of-a-kind H2-MHR plants could be constructed in 36 months with an annual interest rate of 7% and a fixed charge rate of 12.6% (corresponding to a regulated utility). Hydrogen production costs are summarized in Table 3. The total hydrogen production costs for the SI-Based and HTE-Based plants are estimated to be approximately the same ($1.97/kg and $1.92/kg, respectively). For the SI-Based plant, electricity costs contribute to about 30% of the hydrogen production costs. If the pumping power required by the SI process could be reduced by 50%, the hydrogen production costs could be reduced to about \$1.62/kg and the overall efficiency of the process would increase from 45% to 55%. For the HTE-Based plant, the SOE module cost has significant uncertainty and was assumed to be \$500/kW(e) for this study. If the SOE module cost is increased to \$1,000/kW(e), the hydrogen production cost increases to \$2.55/kg.

Table 2. HTE-Based H2-MHR Nominal Plant Design Parameters

MHR System	
Number of modules	4
Module power rating	600 MW(t)
Core inlet/outlet temperatures	590°C / 950°C
Peak fuel temperature – normal operation	1250°C - 1350°C
Peak fuel temperature – accident conditions	< 1600°C
Power Conversion System	
Mass flow rate	280 kg/s
Electricity generated	292 MW(e)
Electricity generation efficiency	53.9%
Hydrogen Production System	
Peak SOE temperature	862°C
Peak SOE pressure	5.0 MPa
Product hydrogen pressure	4.95 MPa
Annual hydrogen production	2.68×10^5 metric tons
Plant hydrogen production efficiency	55.8%

Table 3. Summary of Hydrogen Production Costs

	SI-Based H2-MHR		HTE-Based H2-MHR	
Account	**Cost (\$M/yr)**	**Percent of Total**	**Cost (\$M/yr)**	**Percent of Total**
MHR Plant Capital Charges	181.2	24.9	178.8	34.8
H2 Plant Capital Charges	135.3	18.6	145.8	28.3
MHR Plant O&M Costs	37.4	5.2	37.8	7.3
H2 Plant O&M Costs	76.6	10.6	81.1	15.8
Nuclear Fuel Costs	71.2	9.8	71.2	13.8
Electricity Costs	224.1	30.9	0	0
Total Annual Costs	725.8		514.7	
	kg/yr		**kg/yr**	
Hydrogen Produced	3.68×10^8		2.68×10^8	
	\$/kg		**\$/kg**	
Hydrogen Production Cost	1.97		1.92	

Figure 6 shows a comparison of nuclear hydrogen production costs with the costs for producing hydrogen using steam-methane reforming (SMR). In December 2005 the wellhead price for natural gas was $10.02 per 1000 cubic feet, which corresponds to $9.72/MMBtu. At this price, nuclear hydrogen production is economically competitive with SMR. Nuclear hydrogen production is economically competitive with SMR for natural gas prices in the range $6 to $8/MMBtu, if a CO_2 sequestration/disposal cost for SMR and an O_2 credit for nuclear hydrogen production are assumed.

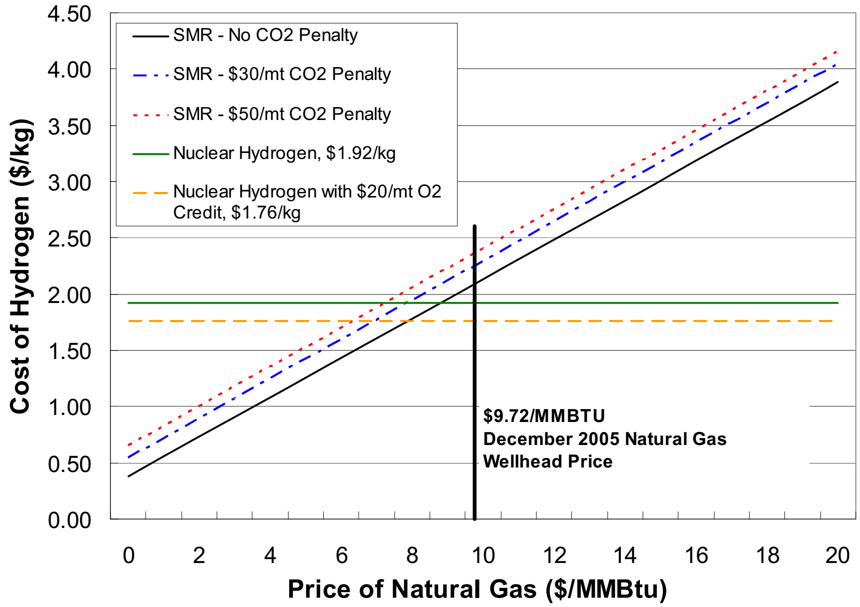

Figure 6. Comparison of Nuclear and SMR Hydrogen Production Costs

5. Conclusions

Because of its passive-safety features, high-temperature capability, and flexibility with regard to fuel cycles and energy outputs, the MHR is well suited for supplying a wide range of future energy needs, including hydrogen production. Based on pre-conceptual design studies, the H2-MHR is capable of producing hydrogen efficiently, economically, safely, and with minimal environmental impact using either thermochemical water splitting or HTE. It is recommended that H2-MHR design development be continued through the conceptual, preliminary, and final design phases.

6. References

[1] Richards, M., Shenoy, S., Brown, L., Buckingham, R., Harvego, E., Peddicord, K., Reza, S., Coupey, J., "H2-MHR Pre-Conceptual Design Report: SI-Based Plant," GA-A25401, General Atomics, San Diego, CA, April 2006.

[2] Richards, M., Shenoy, S., Harvego, E., McKellar, M., Peddicord, K., Reza, S., Coupey, J., "H2-MHR Pre-Conceptual Design Report: HTE-Based Plant," GA-A25402, General Atomics, San Diego, CA, April 2006.

[3] Baxter, A., Venneri, F., Rodriguez, C., Fikani, M., "MHR Fuel Cycle Options for the Future Sustainability of Nuclear Power," Proceedings of Global 2005, October 9-13, 2005, Tsukuba, Japan, Paper 314.

[4] Herring, J., O'Brien, J., Stoots, C., Hawkes, G., Hartvigsen, J., Shahnam, M, "Progress in High-Temperature Electrolysis for Hydrogen Production Using Planar SOFC Technology," Proceedings of the 2005 AIChE Spring National Meeting, Atlanta, GA, April 10-14, 2005, Paper 74f.