H2-MHR CONCEPTUAL DESIGNS BASED ON THE SI PROCESS AND HTE

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Abstract

For electricity and hydrogen production, the advanced reactor technology receiving the most international interest is a modular, passively-safe version of the high-temperature, helium-cooled reactor referred to in the United States as the modular helium reactor (MHR). Because of its ability to produce high-temperature helium, the MHR is well suited for a number of process-heat applications, including hydrogen production. Two hydrogen-production technologies have emerged as leading candidates for coupling to the MHR: (1) thermochemical water splitting using the sulfur-iodine (SI) process and (2) high-temperature electrolysis (HTE). In this paper, we provide an update on conceptual designs being developed for coupling the MHR to the SI process and HTE. These concepts are referred to as the SI-based H2-MHR and the HTE-based H2-MHR, respectively.

INTRODUCTION

Hydrogen and electricity are expected to dominate the world energy system in the long term. The world currently consumes about 50 million metric tons of hydrogen per year, with the bulk of it being consumed by the chemical and refining industries. The demand for hydrogen is expected to increase, especially if the U.S. and other countries shift their energy usage towards a hydrogen economy, with hydrogen consumed as an energy commodity by the transportation, residential, and commercial sectors. Currently, steam reforming of methane is used to produce the vast majority of hydrogen consumed in the world. Eventually, an alternative source of hydrogen will be needed because the demand for natural gas is outpacing its production. In addition, there is strong motivation to not use fossil fuels in the future as a feedstock for hydrogen production, since the greenhouse gas carbon dioxide is a byproduct.

For the reasons given above, there is increased interest in using nuclear energy to produce hydrogen. In principle, nuclear electricity can be used to split water using conventional low-temperature electrolysers. For a conventional light-water reactor that produces electricity with approximately 33% thermal efficiency and current generation electrolyzers operating with an efficiency of about 75% to convert electricity to high-pressure hydrogen, the overall efficiency for hydrogen production is approximately 25%. If a gas-turbine modular helium reactor (GT-MHR) is used to produce the electricity with 48% thermal efficiency, the overall efficiency for hydrogen production improves to 36%. However, even with high-efficiency electricity production, economic evaluations of coupling nuclear energy to low-temperature electrolysis have generally not been favorable when compared to steam reforming of methane [1].

Recent evaluations have shown hydrogen can be produced with high efficiency, safely, economically, and without the emission of greenhouse gases using the modular helium reactor (MHR) coupled to the SI thermochemical water splitting process and HTE [2]. These concepts are referred to as the SI-based H2-MHR and the HTE-based H2-MHR, respectively, and are described in this paper.

THE MODULAR HELIUM REACTOR

The high-temperature process heat required to drive both the SI process and HTE will be provided by the hot helium exiting the MHR reactor core. The reactor system design is based on that developed for the GT-MHR. As shown in Figure 1, the GT-MHR couples the MHR directly to a Brayton-cycle power conversion system (PCS). A GT-MHR module operates with a power level of 600 MW(t) and can produce electricity with thermal efficiencies ranging from 48% to 52% for core outlet temperatures ranging from 850°C to 950°C. For the HTE-based H2-MHR, approximately 68 MW of heat is transferred through an intermediate heat exchanger (IHX) to generate superheated steam and the remaining heat is used to generate electricity. For the SI-based H2-MHR, nearly all of the heat is transferred through an IHX to a secondary helium loop that supplies heat to the SI process. High temperature operation of the MHR with passive safety is enabled through the use of graphite fuel elements containing ceramic, TRISO-coated fuel (see Figure 2). Reference 3 provides additional information on the MHR design and its technology background.

Figure 1. The Gas Turbine Modular Helium Reactor

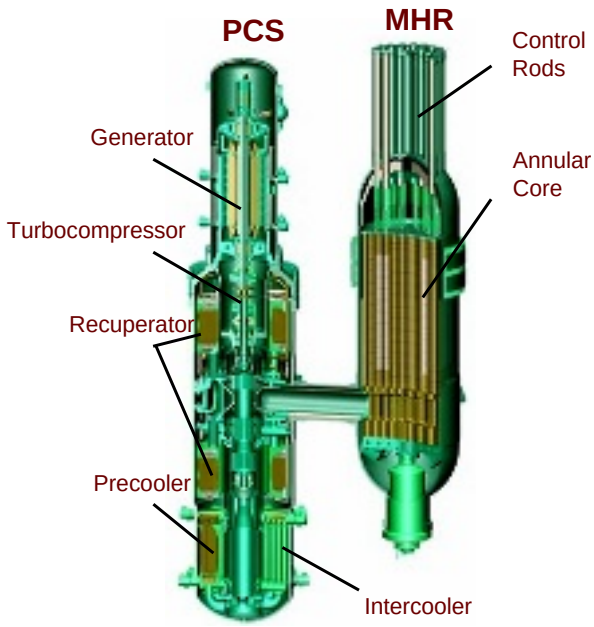
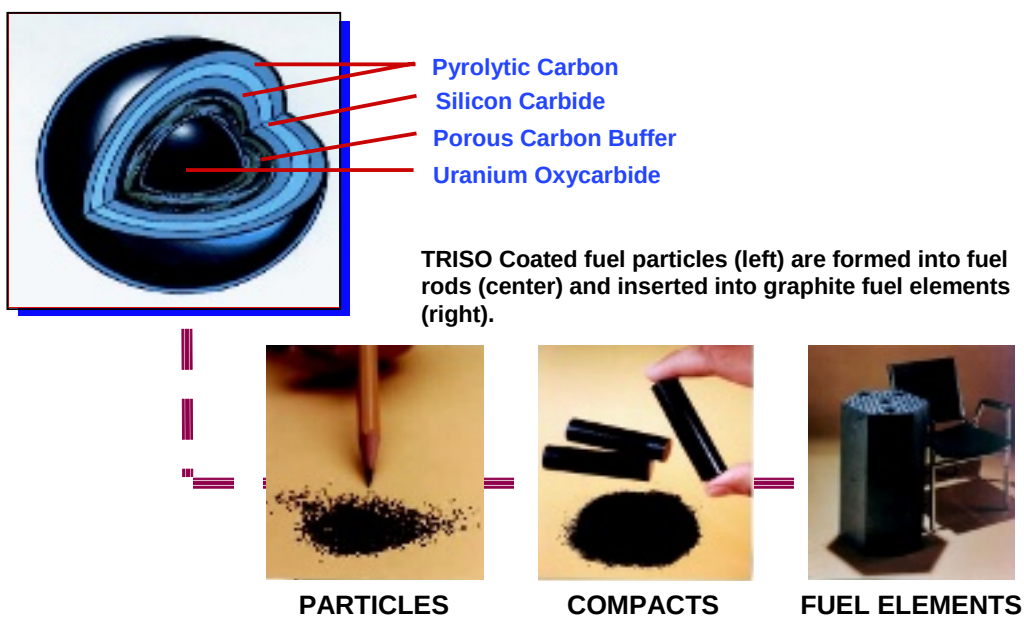


Figure 2. MHR Fuel Element Components



The GT-MHR was designed to operate with coolant inlet and outlet temperatures of 490°C and 850°C, respectively. As indicated in Table 1, the coolant inlet and outlet temperatures are increased to 590°C and 950°C respectively, for the H2-MHR core. The outlet temperature was increased in order to improve the efficiency and economics of hydrogen production, but was limited to 950°C to avoid any potential adverse impacts on fuel performance during normal operation. Also, a higher coolant outlet temperature could require significant advances in technology to develop a viable IHX design. The coolant inlet temperature was also increased in order to maintain the same coolant flow and convective heat-transfer rates within the core as that for the GT-MHR. As discussed in References. 2 and 4, peak fuel temperatures during normal operation are maintained below 1 250°C as the result of design

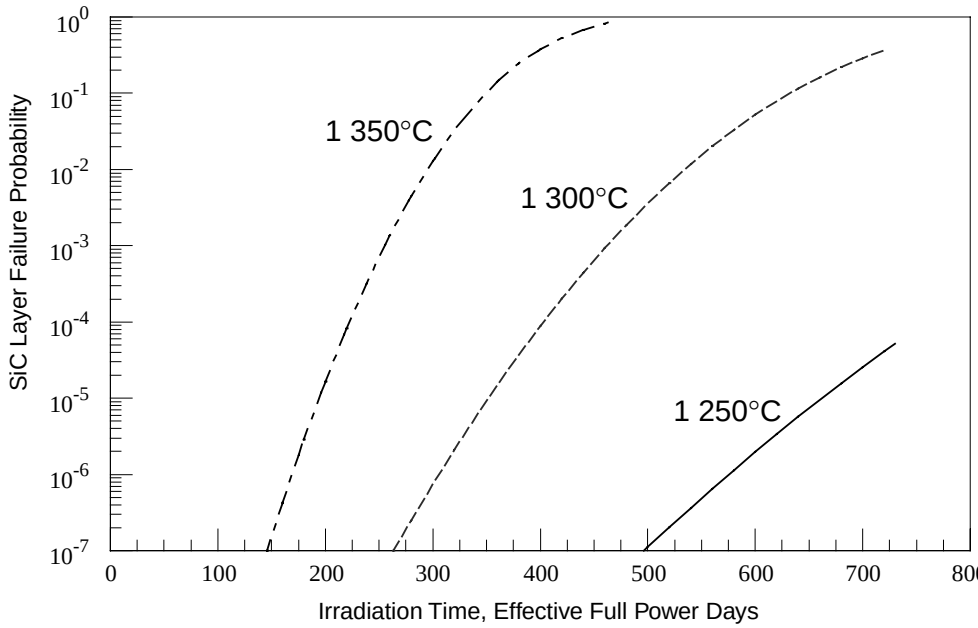
modifications to optimize the core thermal hydraulic and physics designs. These modifications include using lateral restraint mechanisms and sealing keys to reduce the fraction of flow that bypasses the coolant holes (e.g. through gaps between the graphite blocks), improved zoning of fissile/fertile fuel and fixed burnable poison, and improved refueling schemes. As shown in Figure 3, failure of the silicon carbide coating layer by fission-product attack is predicted to be very low for fuel temperatures below 1 250°C.

A potential issue associated with operating at a higher coolant inlet temperature is the impact on the vessel temperature during normal operation and accident conditions. For the GT-MHR, the inlet flow is routed through channel boxes located between the core barrel and the reactor vessel. With this configuration, the vessel temperature during normal operation is approximately 50∞C below the core inlet temperature. For the H2-MHR, the inlet flow is routed through holes in the permanent side reflector, which is similar to the configuration used by the Japan Atomic Energy Research Institute (JAERI) for their GTHTR300 design [5]. As discussed in Reference 2, this configuration should provide enough additional thermal resistance between the inlet flow and reactor vessel to maintain vessel temperatures at acceptable levels. Additional design modifications are being investigated to further lower the vessel temperatures, such that proven light water reactor vessel materials (e.g., SA533 steel) could be used for the MHR vessel.

Table 1. H2-MHR Core Design Parameter

Core thermal power (MW)	600
Number of fuel columns	102
Number of fuel blocks per column	10
Thermal power density (MW/m^3)	6.6
Effective inner diameter of active core (m)	2.96
Effective outer diameter of active core (m)	4.83
Active core height (m)	7.93
Fissile fuel (19.8% enriched in U-235)	$UC_{0.5}O_{1.5}$
Fertile Fuel (natural U)	$UC_{0.5}O_{1.5}$
Equilibrium fuel cycle length (full-power days)	425
Number of columns per refueling segment	51
Mass of heavy metal per refueling segment (kg)	1748 (fissile fuel)
	514 (fertile fuel)
Core inlet temperature (°C)	590
Core outlet temperature (°C)	950
Core upper plenum inlet pressure (MPa)	7.1
Core pressure drop (MPa)	0.058
Coolant flow rate (kg/s)	320

Figure 3. Predicted Failure of the SiC Layer by Fission Product Attack



SI-BASED H2-MHR

As shown in Figure 4, 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. Figure 5 shows a simplified process flow diagram of the SI cycle.

Figure 4. The Sulfur-Iodine Thermochemical Process

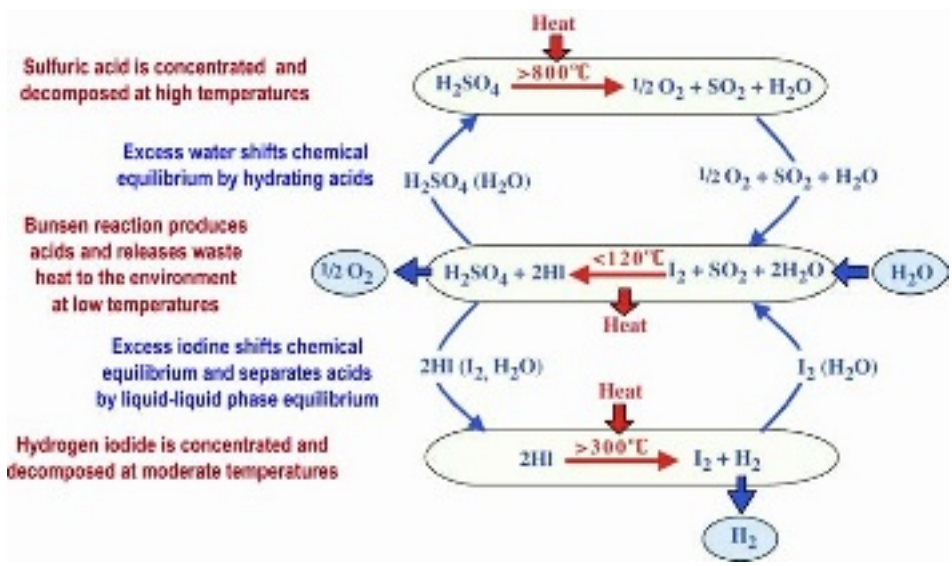
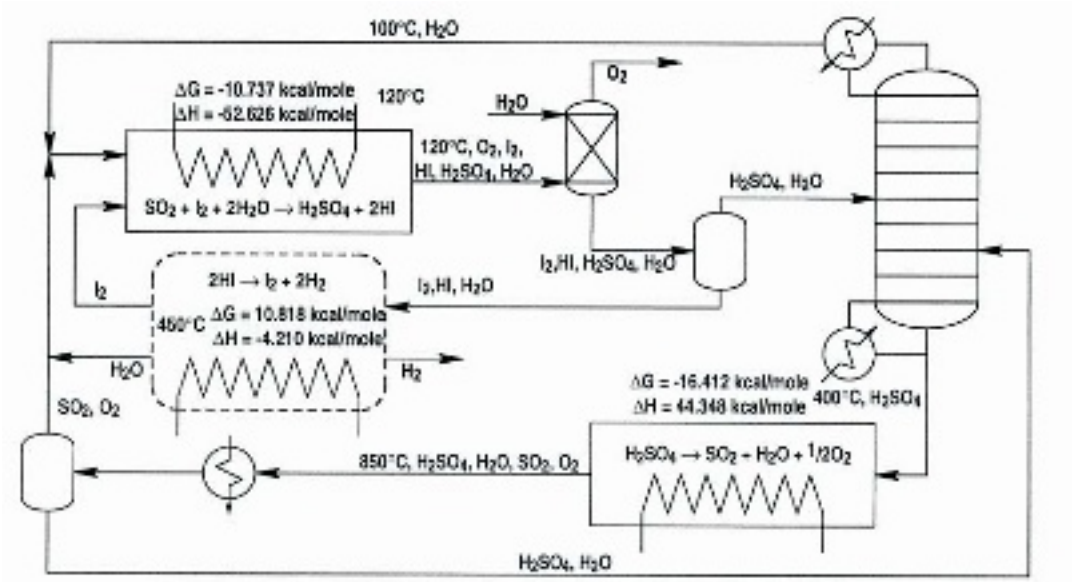
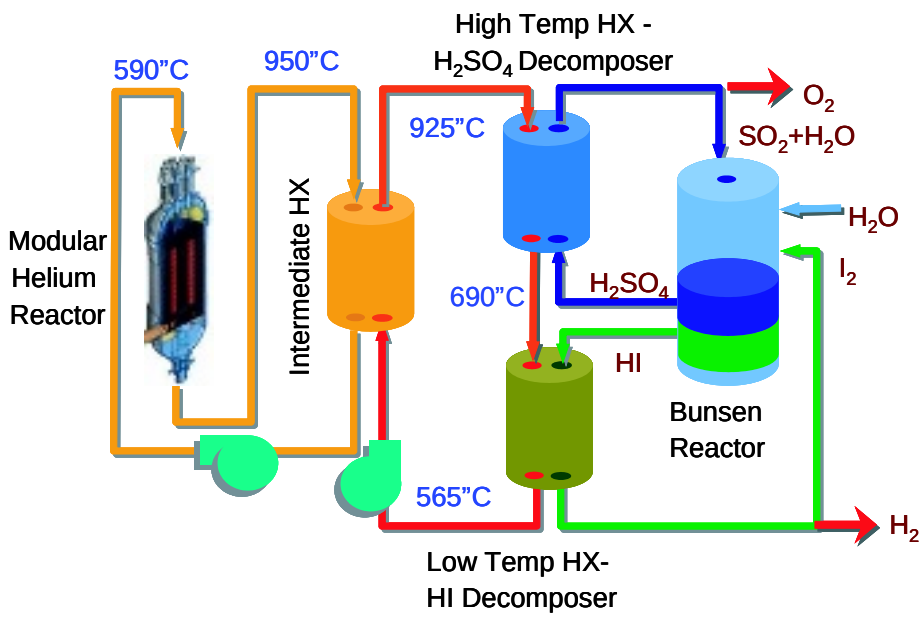


Figure 5. Simplified Schematic of SI Process Flow Diagram



Several different concepts for coupling the MHR to the SI process have been evaluated, including running the H_2SO_4 and HI decomposition reactions in series (see Figure 6) and running them in parallel with a power topping cycle. The series configuration was selected because the design conditions are more optimised with respect to heat utilisation and heat exchanger pinch points, and because the power topping cycle used with the parallel configuration added complexity without a significant improvement in overall efficiency.

Figure 6. MHR Coupled to SI Process with Series Configuration

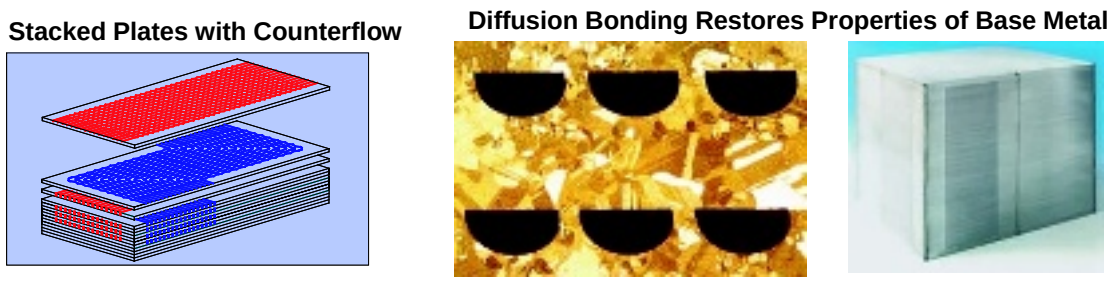


As discussed in Reference 2, the intermediate heat exchanger (IHX) would consist of printed circuit heat exchanger (PCHE) modules. As shown in Figure 7, the PCHE modules are manufactured by stacking individual plates and diffusion bonding the plates to restore the properties of the base metal, which allows for high-temperature, high-pressure operation with high heat transfer surface are per unit

volume. The IHX design has been revised to incorporate an improved PCHE module design developed by Heatric. The IHX would consist of 40 modules and associated manifolds within an insulated steel vessel, with each module transferring about 15 MW of heat. The modules would be manufactured from Inconel 617. Each module weighs approximately 5 tonnes and has dimensions of 0.6 m x 0.65 m x 1.5 m. In order to minimize the size and weight of the IHX vessel, it is desirable to use a compact arrangement to house the PCHE modules within the vessel. However, sufficient room must be provided to accommodate differential thermal expansion. Preliminary results indicate that it should be possible to design a 600-MW(t) IHX with a vessel that is of similar size as the MHR vessel.

Two different processes are being investigated for HI decomposition [6]. One process, referred to as extractive distillation, uses phosphoric acid to strip HI from the HI-water-iodine mixture and to break the HI-water azeotrope. The other process is referred to as reactive distillation and involves reacting the HI-water-iodine mixture in a reactive bed to effect the separation process and produce hydrogen. Extractive distillation is a proven process, but requires significant amounts of energy and many components to perform the extraction, distillation, concentration, reaction, and separation steps of the process. The kinetics for reactive distillation are still relatively unknown, but the process can be performed in a single component without requiring concentration of the acid. For the n^{th}-of-a-kind SI-Based H2-MHR conceptual design, it is assumed that HI decomposition will be performed using reactive distillation. Assuming the electricity needed for the shaft work required by the SI process is supplied by GT-MHRs operating with 48% to 52% thermal efficiency, the overall efficiency for hydrogen production is about 45%, based on the higher heating value (HHV) for hydrogen.

Figure 7. HEATRIC PCHE Design



HTE-BASED H2-MHR

The HTE-based H2-MHR couples the GT-MHR to high-temperature, solid-oxide electrolyzer (SOE) modules. Approximately 68 MW(t) of heat from the MHR is used to generate superheated steam for the electrolysis process, and the remaining heat is supplied to the PCS to generate the electricity required by the SOE modules. The SOE modules are based on the planar cell technology (see Figure 8) that has recently been successfully tested as part of a collaborative project between Idaho National Laboratory (INL) and Ceramatec, Inc [7]. Design parameters for a 12.5 kW(e), 500-cell stack are given in Table 2. For the HTE-based H2-MHR, it is anticipated that a module would contain 40 stacks and consume 500 kW(e). A module would occupy approximately 4.2 m^2 of floor space, which includes space allocated for internal manifolding, piping, etc. Eight modules could be installed within a structure that is similar in size to the trailer portion of a typical tractor-trailer. Approximately 300 of these 8-module units would be required for a full-scale plant with four 600-MW(t) MHR modules. Figure 9 illustrates this SOE module concept.

Figure 8. Interconnect Plate and Single SOE Cell

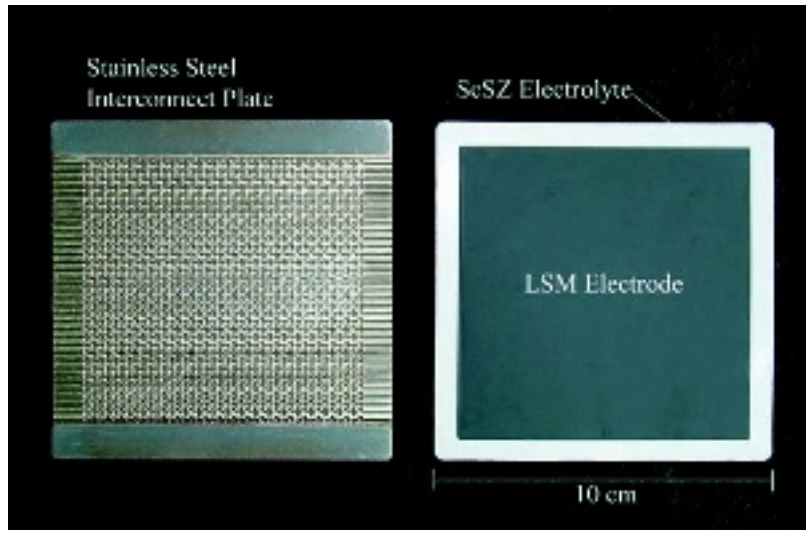


Table 2. Design Parameters for a 500-Cell Stack

Cell Area	
Individual Cell Width	10 cm
Individual Cell Active Area	100 cm^2
Total Number of Cells	12 x 10^6
Total Active Cell Area	120,000 m^2
Cell Thickness	
Electrolyte	10 m (ScSZ - Scandia Stabilized Zirconia)
Anode	1500 m (LSM - Strontium Doped Lathanum Manganite)
Cathode	50 m (Nickel Zirconia Cermet)
Bipolar Plate	2.5 mm (Stainless Steel)
Total Cell Thickness	4.06 mm
Stack Dimensions	
Cells per Stack	500
Stack Height	2.03 m
Stack Volume	0.0203 m^3
Stack Volume with Manifold	0.0812 m^3

Figure 9. SOE Module Concept

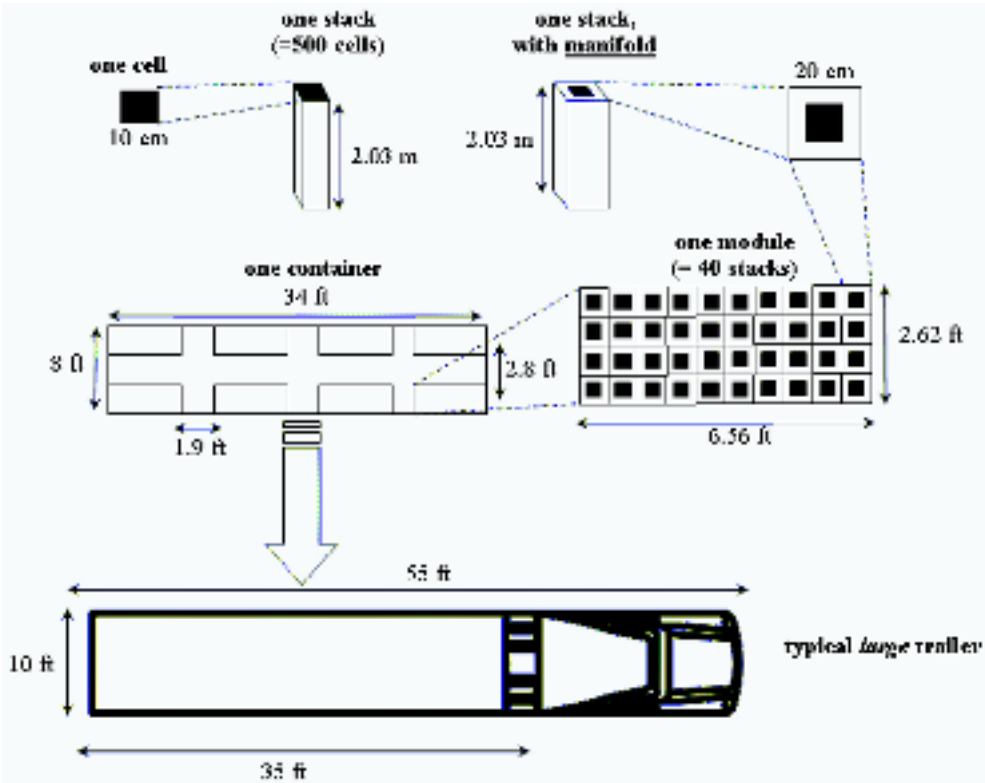
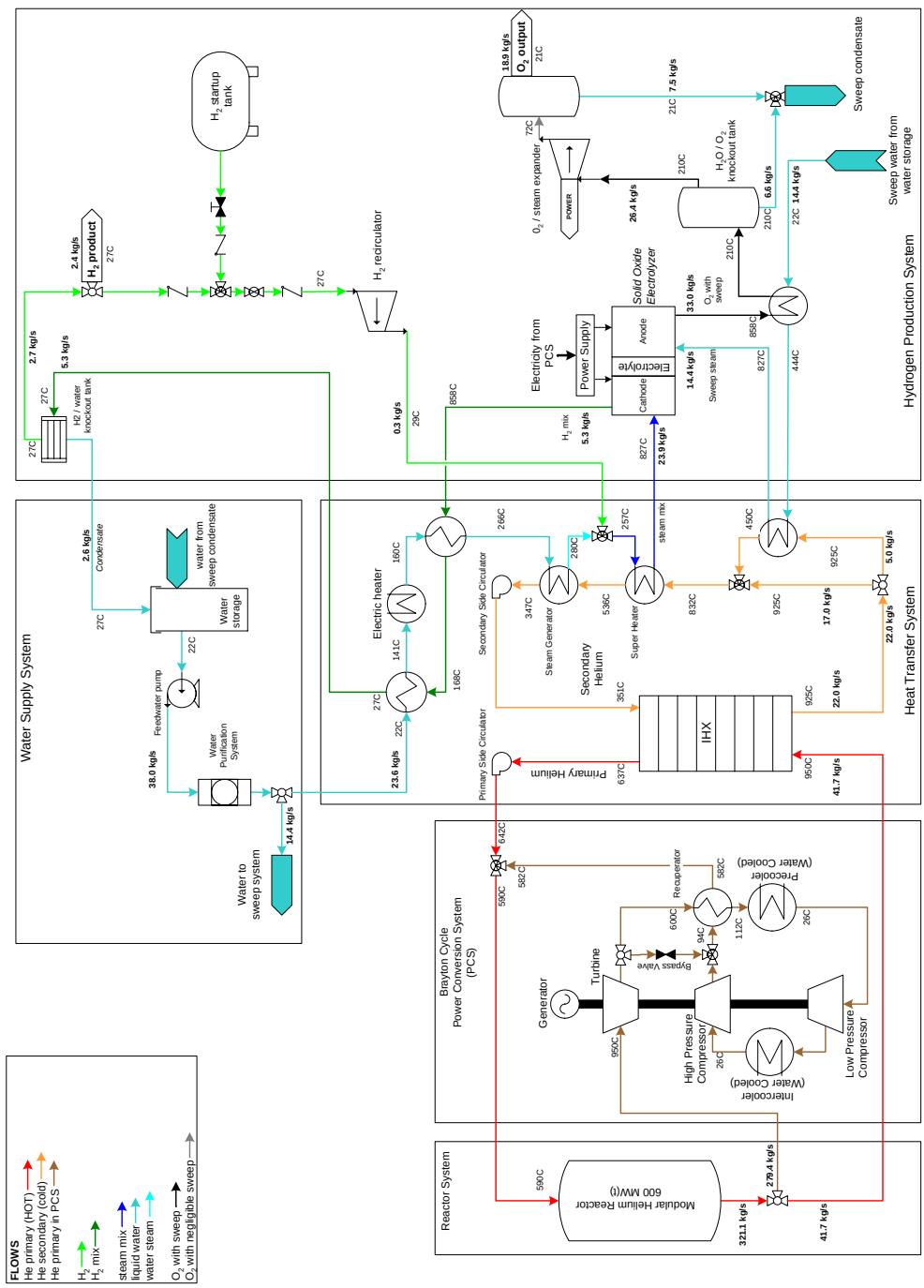


Figure 10 shows a preliminary flow sheet for the HTE-based H2-MHR (this flowsheet is based on a single 600 MW(t) MHR module). The secondary helium loop is included to preclude the potential for tritium migration from the reactor system to the product hydrogen gas. Steam is supplied to the SOE modules for both electrolysis and sweeping of the oxygen from the anode sides of the SOE modules. Steam (at 827°C) supplied to the cathode sides of the modules is first mixed with a portion of the hydrogen product stream in order to maintain reducing conditions and prevent oxidation of the nickel-zirconia-cermet electrode. To maintain high efficiency, heat is recuperated from the product streams and auxiliary power for pumps, compressors, etc., is generated by expanding the oxygen/steam sweep mixture exiting the electrolyser modules through a turbine.

Figure 10. HTE-Based H2-MHR Process Flow Schematic



The HTE-based H2-MHR flow sheet was modeled by INL using the HYSYS process modeling software package. For this particular application, INL developed an SOE electrochemical process model that was incorporated into HYSYS. Table 3 provides a summary of results obtained using the HYSYS model.

Table 3. HTE-based H2-MHR Process Parameters

MHR Module Thermal Power	600 MW(t)
MHR Coolant Outlet Temperature	950°C
PCS Power Generation	312 MW(e)
PCS Thermal Efficiency	52%
Thermal Power Supplied for Hydrogen Production	68 MW(t)
SOE Process Temperature	827°C
Power Supplied to SOE Modules	292 MW(e)
Hydrogen Production Rate	2.36 kg/s
Hydrogen Production Efficiency (based on HHV of H_2)	55.5%
Auxiliary Power Generation	9.3 MW(e)
Overall Process Efficiency	59.9%

SAFETY AND LICENSING CONSIDERATIONS

Passive safety features for the MHR include ceramic, coated-particle fuel and an annular graphite core with high heat capacity and low power density. Recently, INL has used the ATHENA thermal hydraulic code to model the response of the MHR during loss-of-flow and loss-of-coolant accidents and has confirmed these passivity safety features work to maintain fuel temperatures well below failure thresholds [8].

Another key consideration for safety and licensing is co-location of the MHR modules with a hydrogen production plant. The n^{th}-of-a-kind plants consist of 4 MHR modules coupled to hydrogen production plants. As illustrated in Figure 11, it is proposed to locate the two facilities as close as possible (e.g., within about 100 m) in order to minimise the distance over which high-temperature heat is transferred. INL has recently performed an engineering evaluation for these separation requirements and has concluded separation distances in the range of 60 m to 120 m should be adequate in terms of safety [9]. Other recommendations from the INL study include a 100 kg on-site limit for hydrogen storage, use of double-walled pipes for hydrogen transport, and location of the nuclear plant control room outside of the dispersion zone for chemical release. The below-grade installation of the MHR modules, combined with an earthen berm between the MHR modules and the hydrogen production plant for defense in depth, provide additional safety margin for co-location of the two facilities.

ECONOMIC EVALUATIONS

As shown in Figure 12, economic evaluations for an n^{th}-of-a-kind SI-Based H2-MHR show the hydrogen-production costs are competitive with those for steam-methane reforming [10]. Economic evaluations for the HTE-based H2-MHR are currently being evaluated and will depend significantly on the unit costs for the SOE modules. Preliminary evaluations show the hydrogen-production costs for both plants to be comparable if the SOE module unit costs are approximately $500 per kW(e).

Figure 11. Concept for Interfacing the MHR with a Hydrogen Production Plant

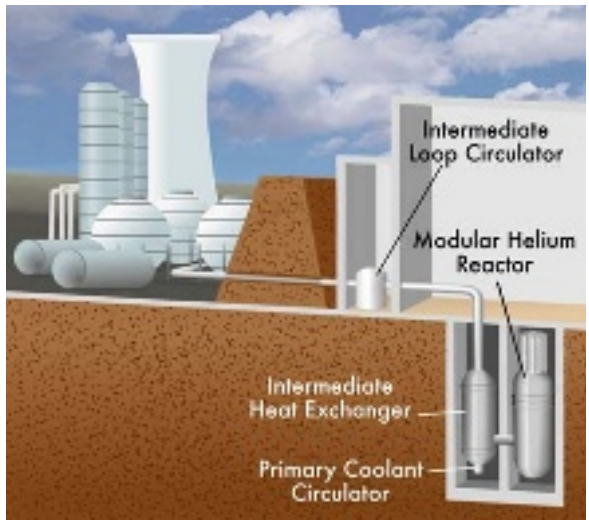
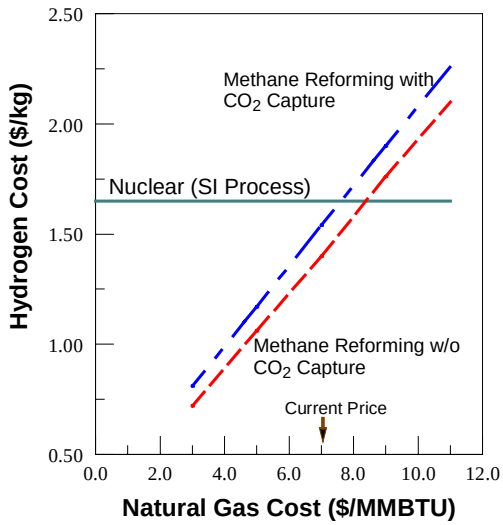


Figure 12. Comparison of Hydrogen Production Costs



CONCLUSIONS

The MHR is well suited for coupling to hydrogen production processes based on thermochemical water splitting and HTE. Both the SI-based and HTE-based H2-MHR concepts have the potential to produce hydrogen safely, efficiently, and economically. Work on both concepts should continue beyond the conceptual design phase, which will provide a sound basis for a focused technology-development program that could eventually lead to commercial deployment of one or both concepts.

ACKNOWLEDGMENTS

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