

LOWERING PEAK TEMPERATURES FOR NUCLEAR THERMOCHEMICAL PRODUCTION OF HYDROGEN

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Annotation

The efficient thermochemical production of hydrogen using nuclear heat requires matching the nuclear reactor and the thermochemical processes to convert heat plus water into hydrogen and oxygen. The major challenges are the high temperatures required to produce hydrogen efficiently. Consequently, Oak Ridge National Laboratory, in collaboration with Sandia National Laboratories and the University of California at Berkeley, is investigating nuclear reactor options and thermochemical cycles to minimize those temperatures while efficiently producing hydrogen. We are developing the concept of a molten-salt-cooled Advanced High-Temperature Reactor to produce the heat. The use of a low-pressure liquid coolant minimizes the temperature drops between the hottest fuel elements in the reactor and the thermochemical cycle, thus minimizing peak reactor temperatures. Simultaneously, we are examining the use of inorganic membranes to minimize the temperatures required for the efficient production of hydrogen using the (1) sulfur-iodine, (2) Westinghouse, and (3) Ispra Mark 13 thermochemical hydrogen processes.

INTRODUCTION

The worldwide demand for hydrogen (H₂) is ~50 million tons per year and growing rapidly. Hydrogen is used primarily for production of ammonia for fertilizer and conversion of heavy crude oils into cleaner liquid fuels. An international effort is under way to deliver H₂ as a replacement fuel for transport vehicles. Ultimately, the energy required to produce H₂ could exceed that for electricity. Consequently, strong incentives exist to develop economic methods to produce H₂ using nuclear energy.

Among the leading candidates for low-cost, large-scale H₂ production are thermochemical processes. A thermochemical process consists of a set of chemical reactions in which the net result is high-temperature heat plus water yields H₂ and O₂. Two factors make thermochemical H₂ production costs (with nuclear reactors providing the heat) potentially lower than those for electrolysis.

- *Efficiency.* Thermochemical processes have potentially greater efficiency because conversion of heat to H₂ requires fewer steps than conversion of heat to electricity and electricity to H₂.
- *Capital costs.* The economics of scale for chemical processes (function of volume) is significantly better than the economics of scale for electrolytic processes (function of area).

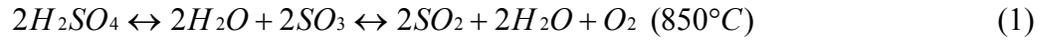
If H₂ is to be produced economically [1], the nuclear reactor must be matched with the thermochemical process. In a recent evaluation [2] of thermochemical cycles, three of the four highest-ranked cycles (Westinghouse, Ispra Mark 13, and sulfur-iodine) were sulfur cycles that have the same high-temperature chemical reactions but different low-temperature chemical reactions. Given these results, we have concentrated our efforts on matching the energy output of the nuclear reactor to the required energy input of these three thermochemical processes.

The three processes require heat input at peak temperatures of ~850°C. This condition presents a major challenge. If the chemical process requires 850°C heat, the nuclear reactor must operate at significantly higher temperatures to allow transfer of the heat from the reactor core to the chemical process. Such temperatures are near the limits of practical current materials. To reduce the material challenges, we have initiated a two-part program to better match the nuclear reactor to the thermochemical cycle: (1) develop a nuclear reactor that delivers heat at 850°C but that is designed to minimize the peak temperatures within the reactor and (2) modify the high-temperature steps within the thermochemical cycles to lower peak temperatures. This paper discusses the status and results of this research.

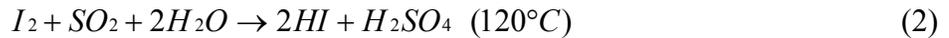
THERMOCHEMICAL PRODUCTION OF HYDROGEN

To understand the challenges of H₂ production, some understanding of the thermochemical cycles is required. As noted earlier, three [2] of the four highest-rated processes (Fig. 1) have the

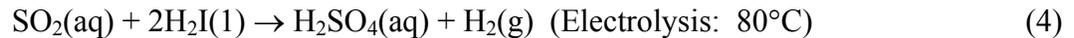
same high-temperature chemical step that requires heat input at $>850^{\circ}\text{C}$. The highly endothermic (heat-absorbing) gas-phase reaction in each of these processes is as follows:



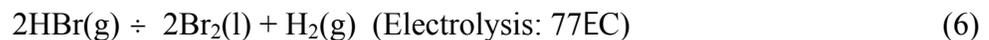
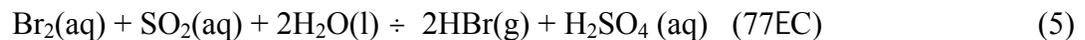
The three thermochemical processes have different lower-temperature chemical reactions. The sulfur-iodine process [2] has two other chemical reactions that when combined, (1) yield H_2 and O_2 from water and heat and (2) recycle all other chemical reagents.



The Westinghouse process (also known as hybrid sulfur, GA-22, and Ispra Mark 11) has a single electrochemical step that completes the cycle [3].



The Ispra Mark 13 process has one chemical reaction and one electrochemical reaction that completes the cycle.



In each of these cycles, the high-temperature sulfur trioxide (SO_3) dissociation reaction is an equilibrium chemical reaction that requires a catalyst. High temperatures and low pressures drive the reaction towards completion. Figure 2 shows this equilibrium as a function of temperature.

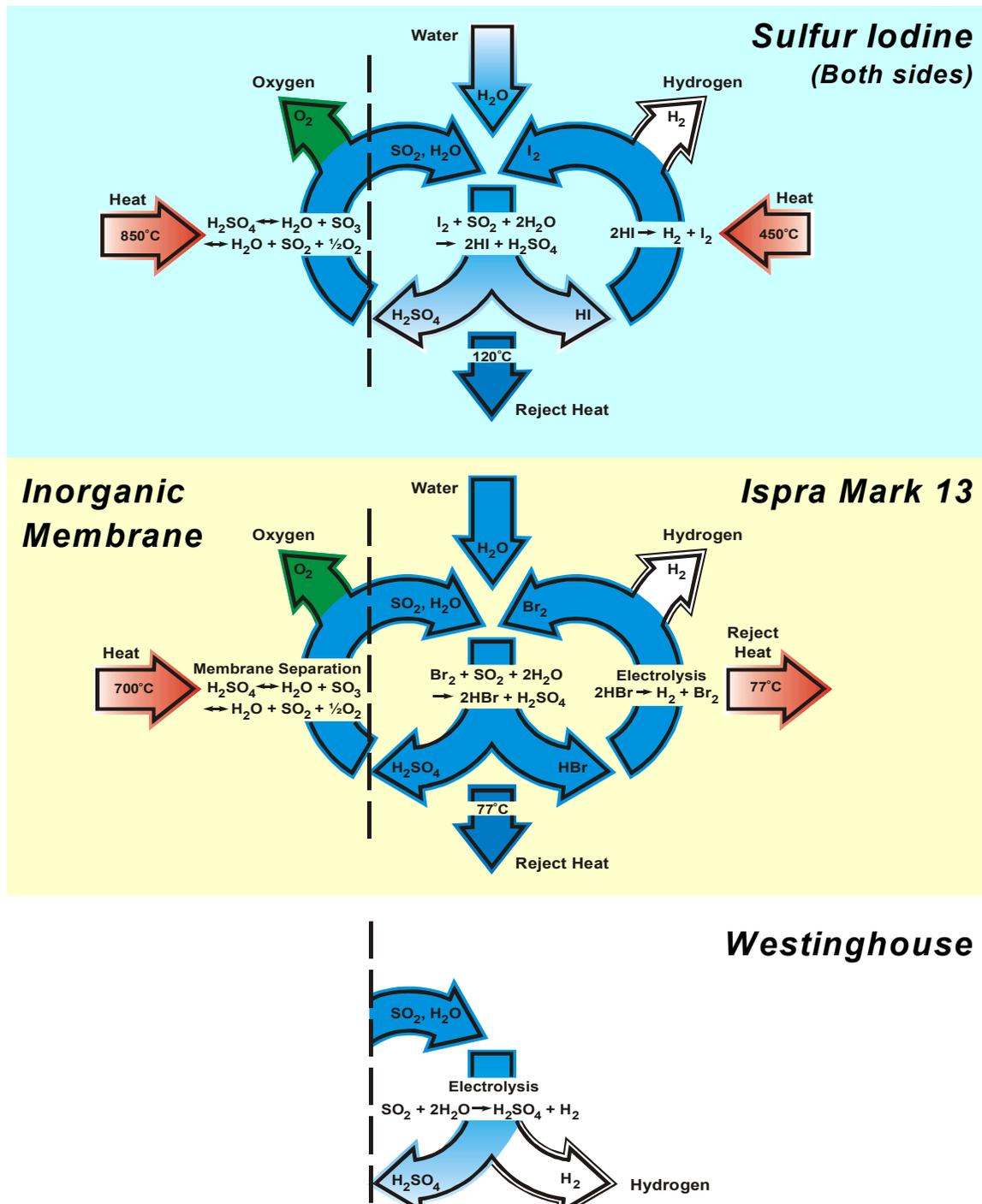


Fig. 1. Sulfur family of thermochemical cycles.

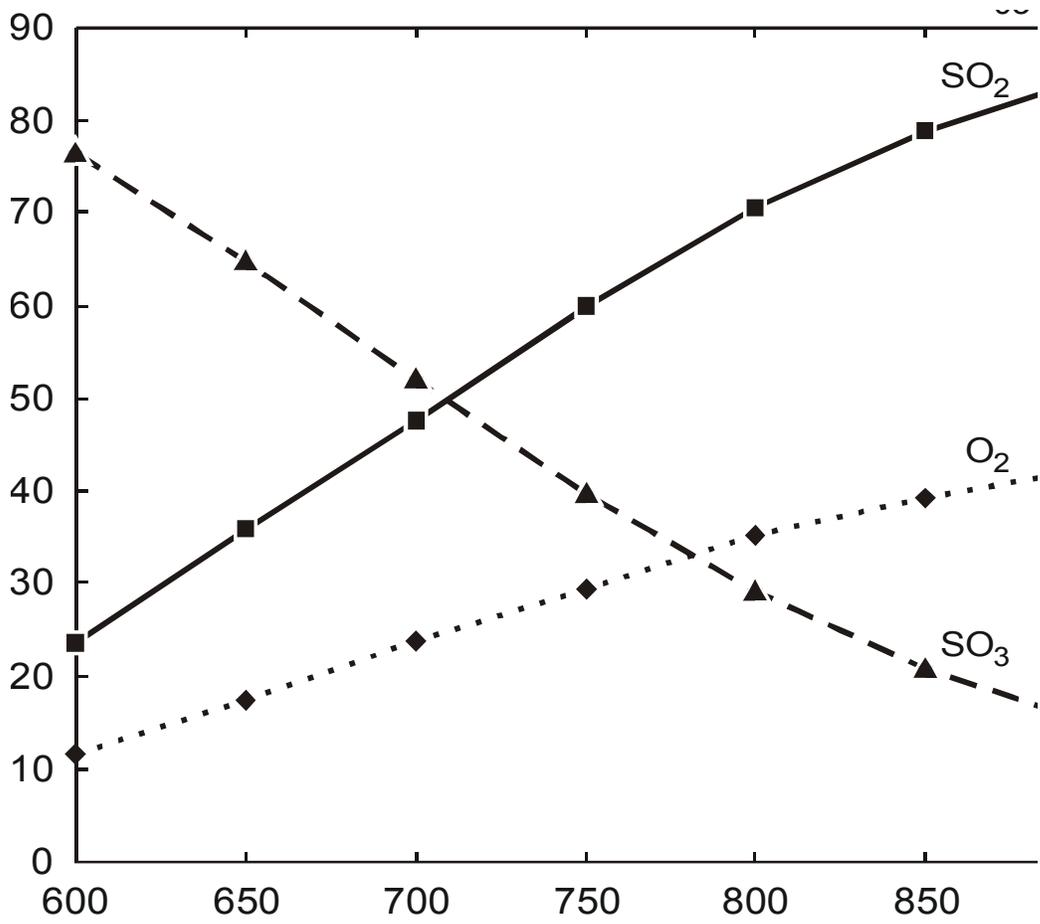


Fig. 2. Equilibrium concentrations of SO_3 , SO_2 , and O_2 vs temperature starting with 100 miles of SO_3 .

Detailed studies have concluded that the required process temperatures need to be very high: ~850°C. After the high-temperature dissociation reaction, all the chemicals must be cooled to near room temperature, the SO_2 separated out and sent to the next chemical reaction, and the unreacted sulfuric acid (formed by recombination of SO_3 and H_2O at lower temperatures) reheated back to high temperatures. Unless the chemical reactions go almost to completion, the energy losses in

separations and the heat exchangers to heat and cool all the unreacted reagents (H_2SO_4) result in a very inefficient and uneconomical process. This phenomenon is illustrated in Fig. 3, in which the overall efficiency of one variant of the sulfur-iodine process [2] is shown as a function of temperature. Efficiency is defined as the higher heating value of H_2 divided by the thermal energy into the process. In this flowsheet, the process inefficiencies increase so rapidly with decreasing temperature (incomplete reactions) that the process cannot produce H_2 at temperatures below 700°C . The process thus defines the nuclear reactor requirements.

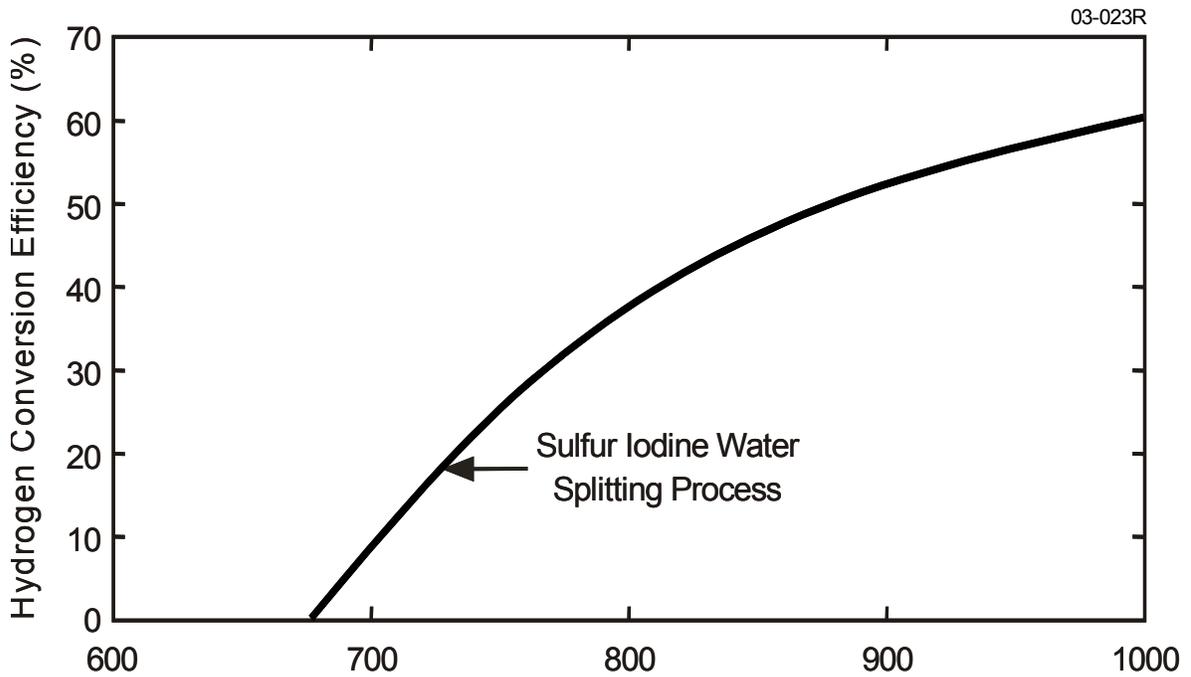


Fig. 3. Efficiency of the sulfur-iodine process versus temperature.

THE ADVANCED HIGH-TEMPERATURE REACTOR

There are two approaches to developing a nuclear reactor for H₂ production. An existing reactor system can be modified to meet the H₂ production requirements, or a new reactor system can be developed. At the current time, only one nuclear reactor system, the gas-cooled (helium) reactor, has the potential high-temperature capabilities to provide the heat at sufficient temperatures to drive a H₂ production system. This reactor has historically [4] been considered the reactor that would be used to provide high-temperature heat for H₂ production. The gas-cooled (helium) reactor was developed for electricity production and uses a coated-particle fuel (see below) and high-pressure helium as a coolant. Several prototype reactors have been built. Last year, Japan began operation of its 30 MW(t)-High-Temperature Test Reactor to develop nuclear heat applications, including H₂ production. This specific reactor has a peak exit temperature of 950°C.

Alternatively, a reactor can be designed specifically for H₂ production. Given the demanding requirements for H₂ production, we are developing a new reactor [5] concept, the Advanced High-Temperature Reactor (AHTR), to match H₂ production requirements. This is a joint effort between three organizations in the United States: Oak Ridge National Laboratory (ORNL), Sandia National Laboratories, and the University of California at Berkeley. The AHTR is based on several earlier technological developments:

- High-temperature, low-pressure molten-salt reactor coolants from the aircraft nuclear propulsion program of the 1950s and the molten-salt breeder reactor program of the 1960s
- Coated-particle graphite-matrix fuel developed in the 1970s for gas-cooled reactors
- Passive safety systems for gas-cooled and liquid-metal reactors developed in the 1980s

Concept Description

The AHTR reactor core consists of coated-particle graphite-matrix fuel cooled with a molten fluoride salt. The molten salt (Fig. 4) flows through the reactor core to an external heat exchanger (to provide the interface for the H₂ production system), dumps the heat load, and returns to the reactor core.

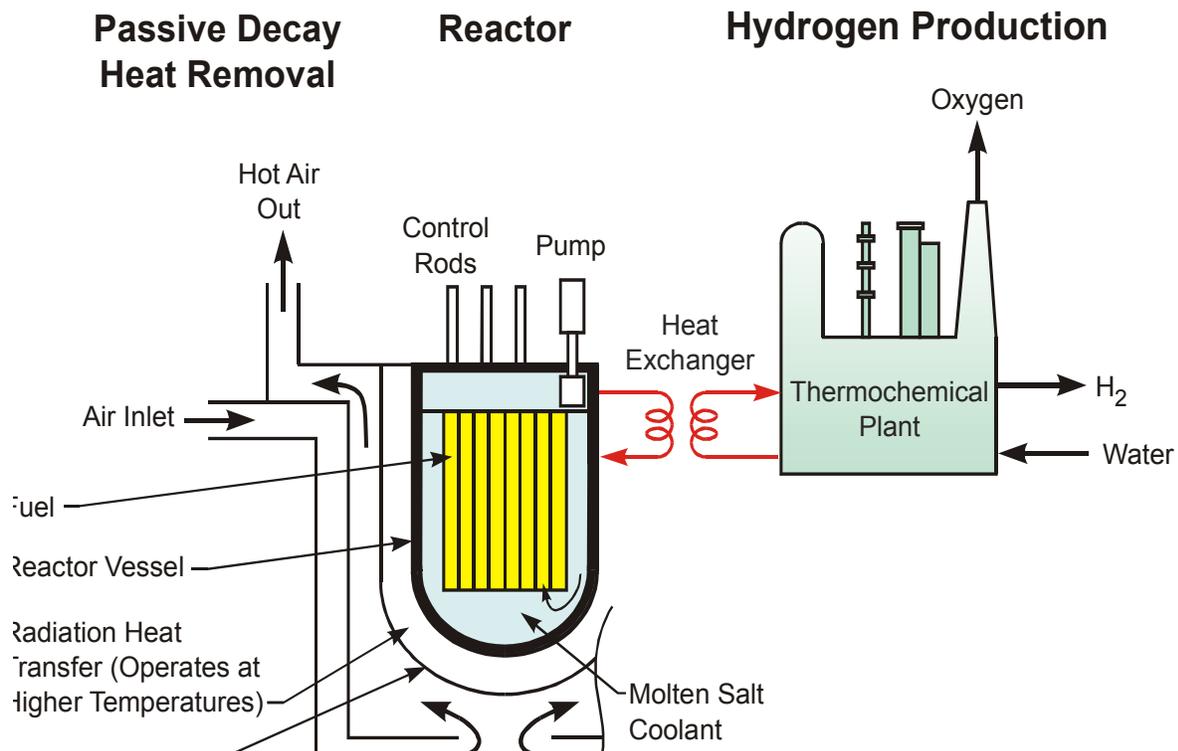


Fig. 4. Advanced High-Temperature Reactor for hydrogen production.

The fuel is essentially the same as that used for the gas-cooled (helium) reactor. The important characteristic of these fuels is that they can operate at very high temperatures with peak fuel operating temperatures of $\sim 1200^{\circ}\text{C}$. Under accident conditions, temperatures can go to 1600°C for several hundred hours without significant failure. These coated-particle fuels are the only commercially demonstrated nuclear fuels capable of producing heat at temperatures sufficient for H_2 production. The fuel consists of small particulates of uranium dioxide coated with layers of carbon and silicon carbide. The multiple layers isolate the fuel and fission products (produced by the

nuclear reactions) from the coolant. The microspheres are embedded in a compact made of graphite. The fuel compact is embedded in graphite blocks and the hexagonal blocks are then assembled into a reactor core.

Molten fluoride salts are the only high-temperature liquids that have been fully demonstrated to be chemically compatible with graphite fuels. Several different fluoride salts are being considered. The current leading candidate is a mixture of sodium and zirconium fluorides. The atmospheric boiling points for molten fluoride salts are near 1400°C. As a consequence, the reactor operates at low pressures.

Matching Reactor Characteristics to Those of the Hydrogen Plant

The use of a low-pressure liquid coolant for production of H₂ using nuclear energy has three potential advantages over other systems: minimized peak reactor temperatures, operation at low pressures, and economics.

Minimizing peak reactor temperatures

The challenge for H₂ production is to minimize reactor temperatures while delivering high-temperature heat to the process. This can best be accomplished by using a liquid reactor coolant. Liquid coolants have good heat transfer capabilities and low pumping power costs in comparison with gas coolants, as shown in Table 1. The temperature rise across gas-cooled reactors is typically several hundred degrees, whereas that across liquid-cooled reactors is typically under 100°C. The AHTR, as a liquid-cooled reactor, can deliver its heat with small temperature drops (20 to 100°C) with low pumping power.

An example serves to illustrate the benefits of a liquid coolant. If heat is needed at 850°C, the maximum temperature of the coolant in a gas-cooled reactor may exceed 1100°C whereas that of the coolant in a liquid-cooled reactor will not exceed 950°C. While the temperature rise in a gas reactor can be reduced, this requires much higher gas flow rates with significant additional pumping costs. Liquid coolants minimize materials requirements by lowering the peak reactor and heat-exchanger temperatures.

Table 1. Temperature drops for different reactor coolants*

System (reactor name)	ΔT inlet to outlet (°C)	Inlet T (°C)	Outlet T (°C)	Coolant
GT-MHR	359	491	850	Gas (helium)
AGR (Hinkely)	355	310	665	Gas (CO ₂)
PWR (Point Beach)	20	299	319	Liquid (water)
LMR (Super Phenix)	150	395	545	Liquid (sodium)

*Abbreviations: GT-MHR: gas-turbine modular helium reactor; AGR: advanced gas reactor; PWR: pressurized-water reactor; LMR: liquid-metal reactor.

Pressure

For H₂, a lower-pressure reactor is preferred. The H₂ production facility will contain significant inventories of hazardous chemicals. A low-pressure, non-chemically reactive coolant minimizes safety risks by minimizing the consequence of heat-exchanger failures between the chemical and nuclear facilities. High-pressure reactor coolants create the potential for pressurization of the chemical plant and releases of toxic gases. At high temperatures, high-pressure coolants also place much greater stresses on the materials of construction. Low-pressure molten-fluoride coolants can match the low pressures of the hydrogen production systems. Molten fluoride salts have boiling points near 1400°C (and thus avoid the potential for chemical plant pressurization), do not react with air, and react only slowly with water.

Economics

Economics ultimately determines whether a particular approach to H₂ production will be viable. Nuclear power production of H₂ faces two main competitors: fossil production of H₂ by steam reforming of natural gas (or coal) and nuclear production of electricity for electrolysis of water. Hydrogen from fossil fuels is a potential long-term option if environmentally-acceptable methods for sequestration of carbon dioxide can be developed to avoid the potential consequences of greenhouse

gases. The newest world-class H₂ production plant (that is under construction and will be fueled with natural gas) will have a H₂ production capacity of 8.5 million cubic meters per day (300 million cubic feet per day). An equivalent nuclear H₂ plant would require an energy output of 2400 MW(t), assuming 50% efficiency, to produce an equivalent quantity of H₂. Current nuclear power plants for electricity production are of similar size.

To match the economics of these H₂ plants, the AHTR is a large [2400-MW(t)] reactor with passive safety systems. Passive safety systems do not require operators for functioning and have no moving parts (motors, pumps, etc.). Such systems offer major advantages in terms of safety and also have the potential to reduce costs. Although, historically, these systems could be used only on smaller reactors, the use of a high-temperature, low-pressure coolant may allow their use in large reactors. If this can be demonstrated, it has major economic advantages.

If a reactor shuts down, heat continues to be generated from the decay of short-lived radionuclides in the fuel. The decay heat decreases with time. If a method to remove decay heat is not provided, the reactor core will overheat with damage to the reactor core. Several types of passive decay heat removal systems have been developed for modular reactors, all of which are similar. Decay heat from the reactor core is conducted through the reactor vessel to some type of passive cooling system outside the reactor vessel. The decay heat option shown in Fig. 4 is similar to that proposed for the General Electric S-PRISM liquid-metal-cooled modular reactor. In this pool-type reactor, decay heat is conducted through the reactor vessel wall, transferred across an argon gap by radiation to a guard vessel, conducted through the guard vessel, and then removed from the second wall by natural circulation of air. The radiation heat transfer from the reactor vessel to the guard vessel increases by T^4 ; thus, a small rise in the reactor vessel temperature greatly increases heat transfer out of the system. The argon gap acts as a thermal switch to limit heat losses during normal operation but allows radiation heat transfer to increase heat losses if the reactor vessel heats up.

The reactor size is limited by the ability to transfer decay heat from the nuclear fuel to the outside of the reactor vessel (Fig. 5) in an emergency. The use of a molten salt coolant and a high-temperature fuel allows much higher reactor power ratings than those found in other reactors with similar passive safety systems *in the same size reactor vessel*. Reducing plant size per unit output reduces plant costs. There has been an evolution in the design of passive safety systems that allows reactors of larger size to use passive safety systems.

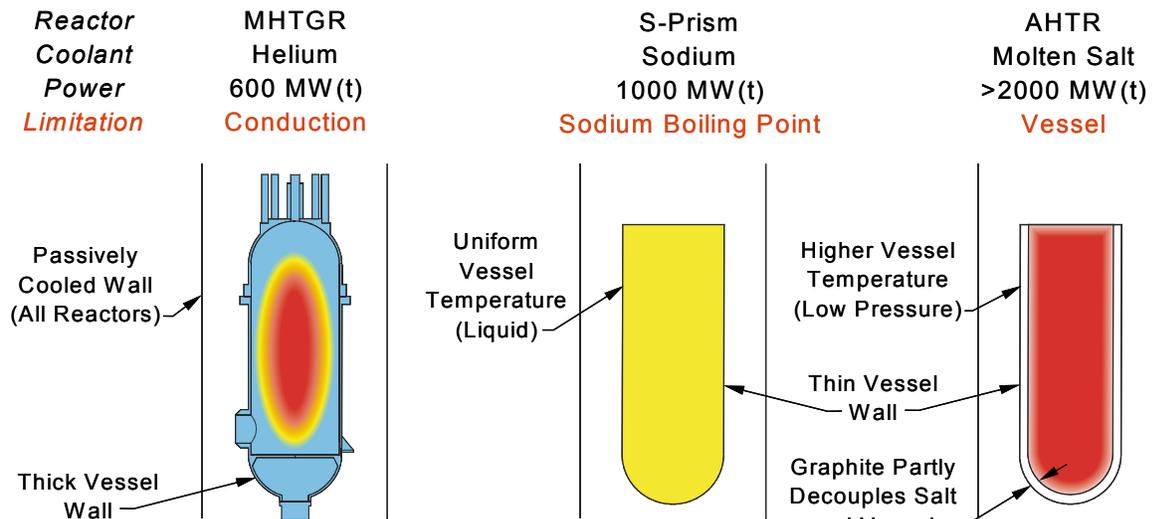


Fig. 5. Evolution of passive decay heat removal systems in similar size reactor vessels to allow larger reactor power outputs

- *Gas-cooled reactors.* In an emergency in which the other cooling systems have failed, decay heat must be moved from the center of the reactor to the vessel boundary by conduction and radiation. This process requires a large temperature drop to transfer heat through the graphite fuel, the graphite reflector, and a thick-wall pressure vessel. To ensure that the fuel in the center of the reactor does not fail, the power production of the reactor is limited to 600 MW(t). Conduction from the center of the reactor to the outside of the pressure vessel limits the ultimate size of the reactor.
- *Sodium-cooled reactors.* In an emergency in which the other cooling systems have failed, decay heat is transferred from the center of the reactor to the vessel wall by natural circulation of sodium. (Natural circulation of a liquid is an efficient way to transfer heat.) If the fuel in the center of the reactor is not to fail in an accident, the power production must be limited to ~1000 MW(t). The limitation in this reactor is that the peak temperature must be significantly below the boiling point of sodium.

- *AHTR*. Decay heat removal in the AHTR is similar to that in a sodium-cooled reactor. However, for the AHTR, the coolant boiling point is 1400°C and the fuel failure temperature is above this level. Thus the only limitation is the reactor vessel. With current vessel materials, the vessel temperature can be as high as 750°C. This may allow a reactor power level of ~2400 MW(t). Because the coolant and fuel can go to such extreme temperatures, the vessel has an internal insulation layer (core graphite reflector that also reduces neutron damage to the reactor vessel) to reduce heat losses during normal operation. This allows the molten salt to operate at higher temperatures than the reactor vessel.

Status of AHTR Development

The AHTR is a new reactor concept (~2 years old). The basis for a preconceptual design has been developed. These preliminary results have been highly favorable; however, significant work is required before a major commitment can be made to the large-scale development of the technology.

LOWER-TEMPERATURE SULFUR THERMOCHEMICAL CYCLES

The high temperatures of the efficient thermochemical cycles present a major engineering challenge. Therefore, ORNL has initiated a parallel [6] effort to reduce the peak temperatures required for these thermochemical cycles. This is a new effort based on the use of inorganic membranes. For over 50 years, ORNL has been developing various inorganic membranes for other applications—such as the separation of uranium isotopes by gaseous diffusion.

Membrane Reactor Concept

An inorganic membrane process is proposed to reduce the peak temperature of the SO₃ dissociation step by several hundred degrees to 700°C. This is accomplished by the separation of SO₂, H₂O, and O₂ from the SO₃. If these reaction product gases are removed, the remaining SO₃ (with a catalyst and heat) will disassociate into its equilibrium concentrations as shown in Fig. 2. If the reaction gases can be selectively removed, the process can be driven to completion. The membrane operates with high pressure on one side and a lower pressure on the other side. This pressure difference drives the separation process.

The operating temperature of the membrane is limited by two considerations. First, significantly lower temperatures are not allowed because the membrane processes separate gases, not liquids. As the temperature decreases, condensation of various sulfur compounds will occur. Membrane

operating temperatures need to be a reasonable margin above the temperatures at which condensation of any species under any condition might occur. From a thermodynamic perspective, lower temperatures would be expected to reduce the process efficiency; thus, there is an incentive to operate at higher temperatures. It requires mechanical work to provide the pressure difference across the inorganic membrane. However, the irreversible (non-thermodynamic) losses in heat exchangers to heat and cool reagents are the primary source of inefficiencies between an ideal process and the real process. Inorganic membranes reduce these inefficiencies. As a consequence, lowering temperatures is not expected to result in major losses in efficiency. The thermodynamic efficiency is less but the irreversible losses are also reduced. Studies are being initiated to define the optimum membrane temperature.

Figure 6 shows a schematic of two ideal high-temperature reactors with inorganic separation membranes. Each alternative option consists of two zones:

- *Oxygen separation.* The top membrane reactor shows the operation of a perfect membrane that allows H₂O and O₂ through the membrane but blocks all other chemical species. At the high temperatures, the H₂SO₄ dissociates into H₂O and SO₃. When these reagents contact the catalyst, the SO₃ partly disassociates into SO₂ and O₂ (Equation 2). This is a highly endothermic reaction; thus, heat must be added to enable this reaction. The dissociation is limited by its equilibrium. As the gas mixture flows to the right past the membrane, O₂ and H₂O go through the membrane. The reaction is driven to the right with the resultant greater concentrations of SO₂. A mixture of SO₂, SO₃, and small quantities of oxygen exits the reactor. Removal of oxygen alone can not drive the reaction to completion (see next section).
- *Oxygen and SO₂ separation.* The membrane reactor is similar to the first case, except that the membrane selectively allows H₂O, O₂, and SO₂ to pass through the membrane. In this case, a perfect membrane would drive the reaction to completion (see next section).

Thermodynamics

A thermodynamic analysis of the separation process was undertaken to understand the ideal theoretical performance of this system. The classical thermodynamic equation for this equilibrium reaction is:

$$K(T, P) = [\text{SO}_2] [\text{O}_2] / [\text{SO}_3] \quad (7)$$

where

- $K(T, P)$ = equilibrium constant (a constant at any temperature but increases with temperature)
 $[SO_2]$ = gas-phase concentration of SO_2 , typically in moles per liter
 $[O_2]$ = gas-phase concentration of O_2
 $[SO_3]$ = gas-phase concentration of SO_3

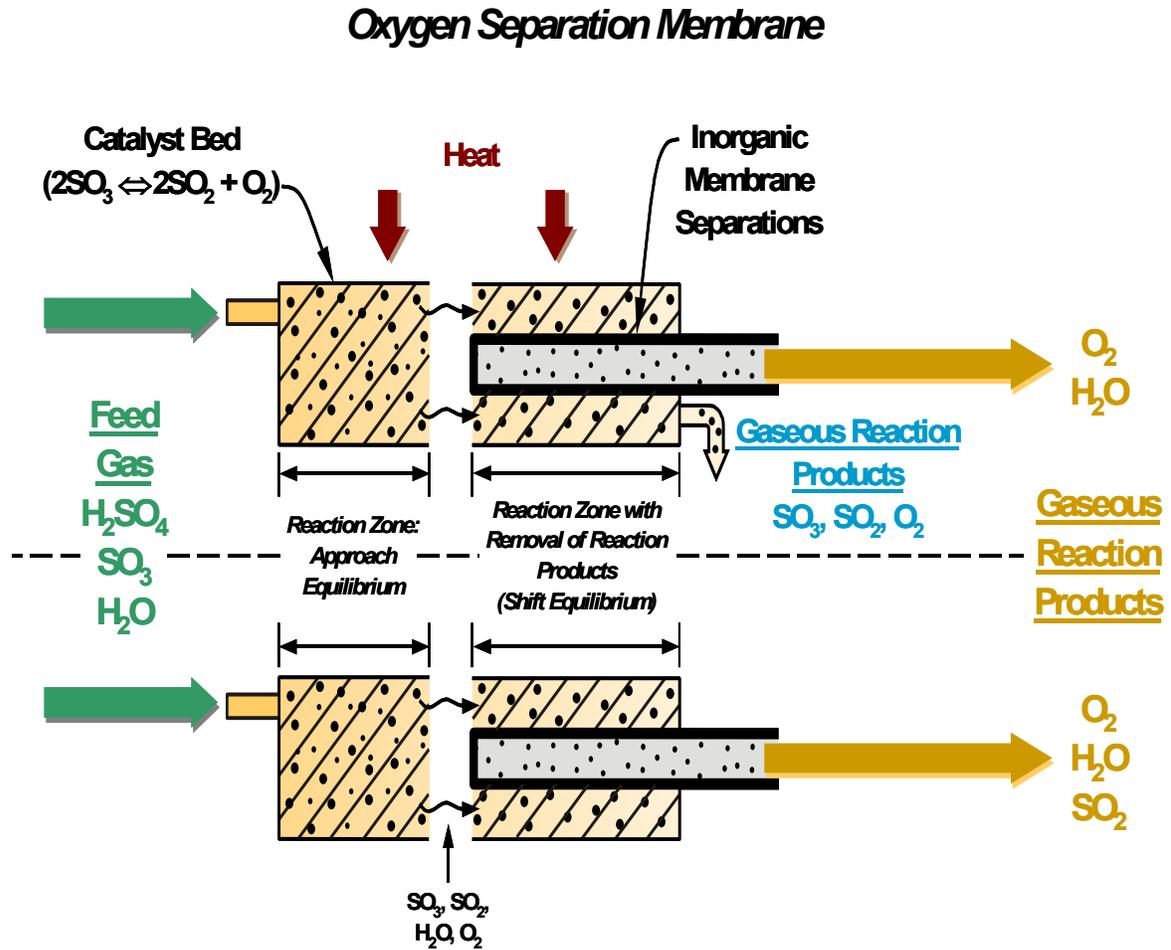


Fig. 6. membrane reactor systems.

As can be seen from the equation, as SO_2 and O_2 are removed from the catalyst bed, more of the SO_3 must dissociate to maintain the required equilibrium until all of the SO_3 is disassociated. However, if only the O_2 is removed, the concentration of SO_2 increases as the SO_3 decreases. With the removal of only one reaction product, the reaction can go far toward, but not all the way, to completion.

A parametric study was conducted to determine the potential benefit that the removal of O_2 and SO_2 could have on the conversion of SO_3 to SO_2 . Using the FactSage computer program, the equilibrium conversion as a function of temperature was calculated (Fig. 2).

Next, the effect of the removal of O_2 was studied. Calculations were made by first assuming that the reaction reached equilibrium in the first (theoretical) stage. At that stage, all of the O_2 was assumed to be removed and the remaining SO_3 and SO_2 were allowed to come to equilibrium again (stage 2). The O_2 was again removed and this process was repeated through six stages. As shown in Table 2, the residual SO_3 at 700°C (21.6%) using inorganic membranes is approximately equal to the residual SO_3 at equilibrium at 850°C (21.13%) with no membrane separation. For the chemical reactor configuration shown in Fig. 4, lengthening the tubes increases the number of theoretical stages. (The stages do not represent physical stages of this equipment.)

Lastly, the effect of the removal of both O_2 and SO_2 was studied. Calculations were made by first assuming that the reaction reached equilibrium in the first stage. At that stage, all of the O_2 and SO_2 were assumed to be removed and the remaining SO_3 was allowed to dissociate and come to equilibrium again (stage 2). The O_2 and SO_2 were again removed and this process was repeated through six stages. After six stages, only 2.08% of the SO_3 remained.

Although the analysis indicates that an ideal membrane that separates only O_2 can effectively lower the peak dissociation temperature 150°C and reduce the unreacted SO_3 to 21.6% at 700°C , there are strong incentives to remove both SO_2 and O_2 . An idealized membrane can reduce the unreacted SO_2 to 2.06% with six ideal states of separations.

Table 2. Effect of removal of oxygen and sulfur dioxide from sulfuric acid decomposition reactor using an ideal inorganic membrane*

Stage no. #	Removal of O ₂ Temperature = 850°C			Removal of O ₂ Temperature = 700°C			Removal of O ₂ and SO ₂ Temperature = 700°C		
	O ₂	SO ₂	SO ₃	O ₂	SO ₂	SO ₃	O ₂	SO ₂	SO ₃
0	0	0	100	0	0	100	0	0	100
1	39.42	78.87	21.13	23.78	47.55	52.45	23.78	47.55	52.45
2	5.43	89.74	10.26	6.8	61.16	38.85	12.47	24.94	27.51
3	1.91	93.55	6.45	3.54	68.24	31.76	6.54	13.08	14.43
4	0.92	95.4	4.6	2.26	72.76	27.24	3.38	6.86	7.57
5	0.53	96.49	3.54	1.6	75.97	24.03	1.8	3.6	3.97
6	0.34	97.14	2.86	1.21	78.4	21.6	0.94	1.89	2.08

*Initial value for SO₃ = 100 moles. Table shows moles of various components remaining in the reaction chamber after each stage.

Characteristics of Inorganic Membranes

The relative rates of transport of different molecules through the membrane determine the capability of the membrane to separate different gases, and multiple gas-transport mechanisms are involved [7]. The precise transport mechanism that is dominant for each gas depends upon a variety of physical factors including temperature (T), pressure (P), molecular mass (m), pore diameter (d_p), molecular size and shape, pore surface composition, pore morphology, and mutual interactions between molecules traversing the membrane.

The performance of a membrane is measured by two parameters: permeance and selectivity. The permeance, defined as flow of the pure gas in question per unit membrane area per unit time per unit pressure, is expressed in moles per square meter per second per pascal [$\text{mol}/(\text{m}^2/\text{s Pa})$]. The selectivity is defined as the ratio of the permeances of two pure gases. The separation factor for a mixture of two gases is defined as $[y/(1-y)] [(1-x)/x]$. Here, y is the concentration of the fastest-permeating component on the permeate side of the membrane and x is the concentration of the

fastest-permeating component on the feed side. The product of the separation factor and permeance is often taken as the figure-of-merit by which to judge a particular membraneBgas mixture combination.

For high-temperature separations, the mechanisms of nanopore diffusion provide the best performance. The term *nanopore diffusion* encompasses several distinct mechanisms that take place in nanometer-diameter pores. For larger molecules, the membrane may function effectively as a molecular sieve, eliminating the transport of such molecules through the membrane and giving high separation factors. For smaller molecules, the transport exhibits thermally activated behavior: as the temperature is increased, the permeance increases exponentially, rather than decreasing as in Knudsen diffusion. This characteristic of improved performance with increases in temperature is a requirement for an efficient high-temperature membrane. Typically, the membrane pore size is no more than three times the diameter of the molecule. One thermally activated mechanism that has been described in the literature is termed *gas translational diffusion (also referred to as thermally activated Knudsen diffusion)*, in which molecules jump between pore walls but with an activation barrier that must be overcome in order to make a diffusion jump. This thermally activated characteristic is similar to the diffusion of defects or atoms in the solid state in the presence of traps, with an activation energy (E_d). Physically, this is plausible, since the lower limit on the size of a pore must correspond to interatomic spacing in the solid state. In the $d_p, \sim 1$ nm regime, separation factors >100 are possible. For example, Uhlhorn et al. [8] report that a separation factor >200 has been measured for a mixture of H_2 and C_3H_6 gases using a supported amorphous silica membrane with a pore diameter of ~ 1 nm.

Status of Inorganic Membrane Development

ORNL has developed and fabricated a wide variety of inorganic membranes and has several test loops. The development of an inorganic membrane for this particular separation has just begun and one of the existing test loops is being modified for these gas mixtures. The operation of inorganic membranes is not fully understood. Consequently, several membranes from our inventories will be chosen and tested using O_2 , SO_2 , and SO_3 as a function of temperature. Based on the experimental results and theory, custom membranes for this specific application will be fabricated and tested. This is an iterative procedure. In parallel, studies have been initiated to understand the performance requirements for such membranes.

CONCLUSIONS

Thermochemical hydrogen production using nuclear energy has the potential to be an economic, efficient, and environmentally friendly source of H₂ for the world. However, major engineering challenges remain, particularly the high temperatures required. To address these barriers, two different technologies are being investigated: an improved nuclear reactor to produce the high-temperature heat and an improved chemical reactor using inorganic membranes to reduce peak thermochemical process temperatures. Although the research is still in an early stage of development, both approaches appear to be potentially attractive.

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