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GENERATION-IV REACTORS AND NUCLEAR HYDROGEN PRODUCTION WITH EMPHASIS ON MOLTEN SALT REACTORS

Prof. Dr. Sümer Şahin
Gazi Üniversitesi, Teknik Eğitim Fakültesi
Teknikokullar, ANKARA
Türkiye

Prof. Dr. Şenay Yalçin
Bahçeşehir Üniversitesi, Mühendislik Fakültesi
Beşiktaş, İSTANBUL
Türkiye

ABSTRACT
Large scale hydrogen production will only be possible with a massive introduction of high temperature generation-IV reactors. The paper gives an overview first on generation-IV reactors. Their potential for nuclear hydrogen production is discussed. Basic principles of the Iodine-Sulphur Process for hydrogen production are outlined. The high temperature heat energy is supplied by a high temperature reactor. Operation temperature ranges for different process heat applications are addressed. Particular emphasis is focused on molten salt reactor. Major superiority of a molten salt reactor can be summarized as low operation pressure (~ .7 MPa), low coolant volume for the required heat transfer capacity, but very high coolant temperatures (>1100 ^oC if carbon composites are successfully employed).
Keywords: Nuclear hydrogen production, molten salt reactor, generation-IV reactors

1. INTRODUCTION
Combustion of fossil fuels provides 86% of the world’s energy [1,2]. Drawbacks to fossil fuel utilization include limited supply, pollution and carbon dioxide emissions, thought to be responsible for global warming [3,4]. Hydrogen is an environmentally attractive fuel that has the potential to displace fossil fuels However, contemporary hydrogen production is primarily based on fossil fuels. A hydrogen economy will need significant new sources of hydrogen. When hydrogen is produced using energy derived from fossil fuels, there is little or no environmental advantage. Unless large-scale carbon sequestration can be economically implemented, use of hydrogen reduces greenhouse gases only if the hydrogen is produced with non-fossil energy sources. Nuclear energy is one of the limited options available. It is the only realistic path for large scale hydrogen production. One of the promising approaches to produce large quantities of hydrogen from nuclear energy efficiently is the Sulfur-Iodine (S-I) thermo chemical water-splitting cycle, driven by high temperature heat.

2. HYDROGEN REQUIREMENTS
Hydrogen is an energy carrier, not an energy source. While hydrogen is the most abundant element, most is chemically bound as hydrocarbons, carbohydrates or water. Hence external energy is needed to extract the hydrogen. Most hydrogen today is made from fossil fuels. Steam reformation of methane is the primary hydrogen source.

$$CH_4 + 2H_2O + E \rightarrow 4H_2 + CO_2 \quad \ldots(1)$$

If heat energy is supplied from CH_4, more CO_2 will be released, namely ~3 H_2 per CO_2.

US use now 11 million tons H_2/year (48 GW_{th}). Almost all commercial (95 %) H_2 is produced from natural gas (~6 % of total use) through Steam Methane Reformation (SMR), which releases 74M tons CO_2/yr. Most H_2 is used in NH_3 and oil industries. By an average growth of ~10 %/year, X2 by 2010 and X4 by 2020 of this amount of H_2/year will be needed. A functional hydrogen economy will need much more, namely X18 = 200 M tons/year for transportation and X40 for all non-electric energy, total in the range of ~900 GW_{th}.

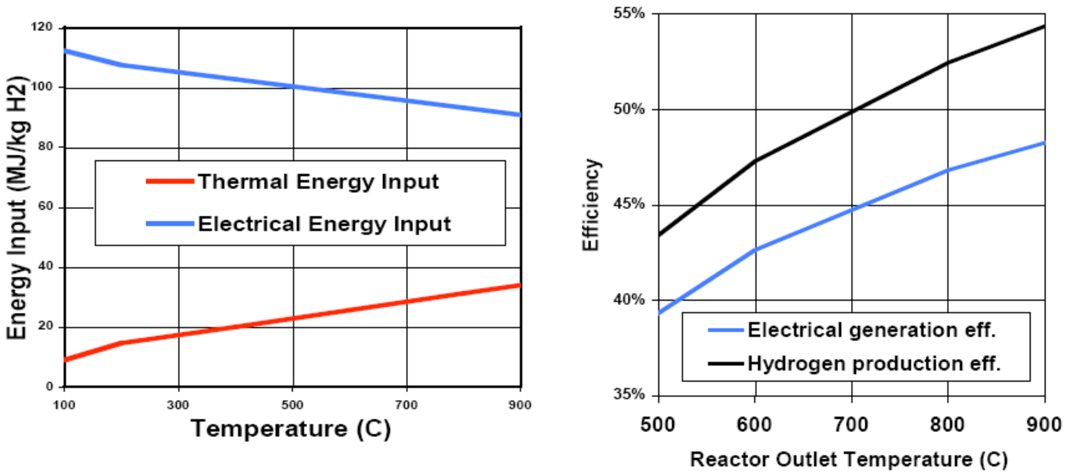
A hydrogen economy only makes sense if hydrogen is produced with non-fossil, non-greenhouse gas energy. Our options for clean energy are limited which are nuclear fission, solar, renewables and eventually nuclear fusion.

3. NUCLEAR PRODUCTION OF HYDROGEN

Nuclear energy can help provide the hydrogen by several routes

• Electric power generation and electrolysis. It is a proven technology. The overall efficiency, defined as efficiency of electric power generation x efficiency of electrolysis will be in the range of ~24% for light water reactors (LWR) and ~36% for high temperature reactors (HTR).

• Electricity + Heat and high temperature electrolysis (HTE) or hybrid thermo chemical cycles [5]. These require developing technologies; needs both electricity generation and high temperature process heat. Efficiencies can increase up to ~ 50%. HTE offers potential high efficiency at high temperature Electrolysis at high temperature substitute's heat for electricity. Figure 1 shows the energy requirements and efficiencies of HTE as a function of reactor outlet temperature.



Overall energy requirements for high temperature electrolysis.

Efficiencies of electricity and hydrogen production.

Figure 1. Energy requirements and temperature dependant efficiencies of HTE.

• High temperature heat and thermo chemical water-splitting [6]. This requires also developing technologies. A set of chemical reactions that use heat to decompose water can be considered. Net plant efficiencies can increase of up to ~50%, avoids cost of electricity generation.

There is currently no large scale, cost-effective, environmentally attractive hydrogen production available for commercialization. The objective of this work is to address an economically attractive process for the production of hydrogen using an advanced high-temperature nuclear reactor as the primary energy source. Hydrogen production by thermo chemical water-splitting, a chemical process that accomplishes the decomposition of water into hydrogen and oxygen, could meet these goals. The goal is to evaluate thermo chemical processes which offer the potential for efficient, cost-effective, large-scale production of hydrogen from water in which the primary energy input is high temperature heat from an advanced nuclear reactor and to select one or two for further detailed consideration.

4. THERMO CHEMICAL WATER-SPLITTING PROCESS SELECTION

Thermo chemical water-splitting is the conversion of water into hydrogen and oxygen by a series of thermally driven chemical reactions. The direct thermolysis of water requires temperatures in excess of 2500 °C for significant hydrogen generation.

$$H_2O \rightarrow H_2 + {}^1/_2O_2 \qquad (2500\ °C\ min) \qquad \ldots(2)$$

At this temperature, only 10% of the water is decomposed. In addition, a means of preventing the hydrogen and oxygen from recombining upon cooling must be provided or no net production would result. With a suitable catalyst, the high-temperature reaction (2) reaches 10 % conversion at only 510 °C, and 83% conversion at 850°C. Moreover, there is no need to perform a high temperature separation as the reaction ceases when the stream leaves the catalyst.

A thermo chemical water-splitting cycle accomplishes the same overall result using much lower temperatures. The sulfur-iodine cycle is a prime example of a thermo chemical cycle. It consists of three chemical reactions, which sum to the dissociation of water.

$$H_2SO_4 \rightarrow SO_2 + H_2O + {}^1/_2O_2 \qquad (850\ °C\ ) \qquad \ldots(3)$$
$$I_2 + SO_2 + 2H_2O \rightarrow 2HI + H_2SO_4 \qquad (120\ °C\ ) \qquad \ldots(4)$$
$$2HI \rightarrow I_2 + H_2 \qquad (450\ °C\ ) \qquad \ldots(5)$$

$$H_2O \rightarrow H_2 + {}^1/_2O_2 \qquad \ldots(2)$$

Figure 1 shows the Sulfur-Iodine (S-I) thermo chemical water-splitting cycle for hydrogen production.

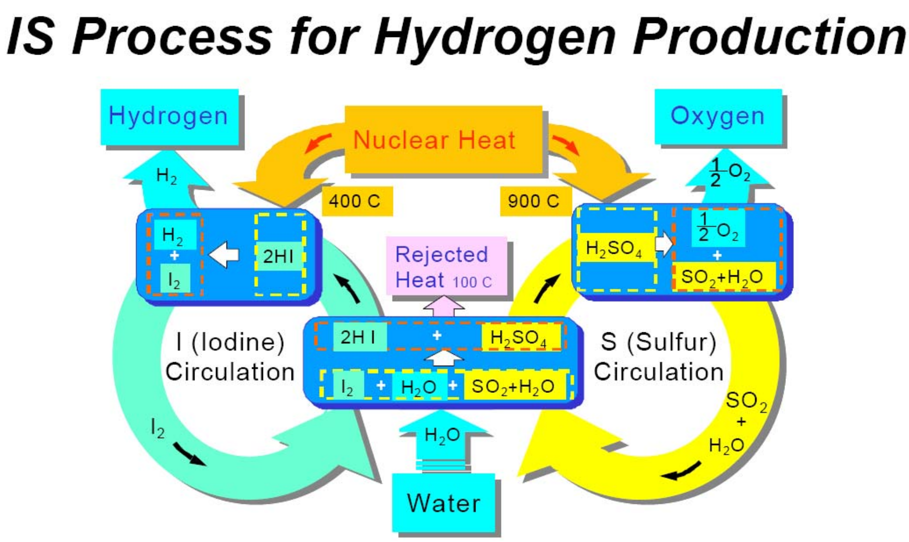


Figure 2. Sulfur-Iodine (S-I) thermo chemical water-splitting cycle for hydrogen production.

Detailed evaluation studies have shown that the following categories of generation-IV high temperature reactors would be suitable (S-I) thermo chemical water-splitting cycle for hydrogen production. Alkali metal, heavy metal, helium gas-cooled, molten salt, liquid-core and gas-core reactors are the most promising projects. Current commercial reactors have too low outlet temperature for thermo chemical water-splitting process, whereas they would work perfectly for electrolysis and to some degree for high temperature electrolysis.

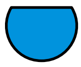
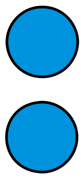
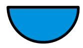
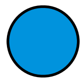
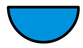
5. MOLTEN SALT REACTORS

There are two demonstrated high-temperature nuclear reactor coolants:

- Helium (High Pressure/Transparent)
- Liquid Fluoride Salts (Low Pressure/Transparent)

Coolant properties determine pipe, valve, and heat exchanger sizes. Small equipment is needed with liquid coolants Table 1 shows coolant properties and number of 1-m-diam. pipes needed to transport 1000 MW_{th} with 100ºC rise in coolant temperature. One can see that liquid salt (at low to moderate pressure) would allow designing the most compact cooling system, followed by water (at high pressure) and sodium (at low to moderate pressure). Whereas, helium cooling requires huge cooling components and high pumping power which can consume up to 30% of total reactor electricity generation.

Table 1. Coolant properties and number of 1-m-diam. pipes

	Water (PWR)	*Sodium (LMR)*	*Helium*	*Liquid Salt*
Pressure (MPa)	*15.5*	*0.69*	*7.07*	*0.69*
Outlet Temp (ºC)	*320*	*540*	*1000*	*1000*
Coolant Velocity (m/s)	*6*	*6*	*75*	*6*
Number of 1-m-diam. Pipes Needed to Transport 1000 MW(t)with 100ºC Rise in Coolant Temperature			 *and 12 X full 1-m-diam Pipes* 	

6. DISCUSSIONS

Hydrogen economy will consume a great amount of hydrogen which can be supplied only by means of advanced nuclear technology in an environmentally clean manner. Most promising candidates are helium based high temperature reactors or molten salt reactors. MSRs are primary candidates for a most compact reactor design and operate at low pressures.

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