HIGH TEMPERATURE WATER ELECTROLYSIS FOR HYDROGEN PRODUCTION

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INTRODUCTION

About 4 percent of the hydrogen produced in the world is through water electrolysis.

Ragheb and Salimi [1] considered the use of High Temperature Electrolysis (HTE) from fusion or fission nuclear systems intended for process heat production.

If fusion energy is used, a ceramic, molten metal or a refractory blanket could use the penetrating properties of fusion neutrons as a volumetric heat source. With suitable heat insulation, the first wall and blanket structural components can be kept at a lower temperature than the bulk blanket. Heat can then be extracted from the blanket, achieving high temperatures in the range of 2,000 ^oC using inert gas coolants. It is thought possible to develop materials and techniques for use in thermo chemical processes around 1,500 K.

In comparison, high temperature gas cooled reactors, steam cycle heat exchangers, and fast breeder reactor material limits are in the range of 1,000 ^oC.

The interest is substantiated by the fact that there appears to be no shortage of technologies that can meet future electrical needs, but very limited options for supplying portable fuels in the form of hydrogen H_2 or methanol CH_3OH.

Coal conversion is costly and in the long term may be restricted by environmental and supply factors. Conversion to a hydrogen and hydrogen fuel based economy derived from inexhaustible sources has been advocated.

As a transition step, hydrogen produced in fission reactors can be used in conjunction with coal gasification and liquefaction processes. The amount of coal feed can then be reduced by a factor of 2 for liquid, and 3 for gas production, with a 2- to 3- fold reduction in the environmental pollution factors: mining hazards, release of toxic agents, and buildup of CO_2 leading to a possible global greenhouse effect.

HIGH TEMPERATURE ELECTROLYSIS, HTE

Hydrogen can be produced from water by conventional low temperature electrolysis methods, which in fact are the inverse to the fuel cell reactions.

$$\begin{aligned} &2H_2O \rightarrow 2H_2 + O_2 \\ &E_0 = +1.229V \end{aligned} \tag{1}$$

A kg of hydrogen is about equivalent to a gallon of gasoline. It could be produced by electricity from wind power at a cost of \$2.27-5.55.

The energy required for the reaction is given by:

$$\Delta H = \Delta F + T\Delta S \tag{2}$$

where:
ΔH = energy required for water decomposition,
ΔS = entropy change,
$T\Delta S$ = necessary thermal energy,
ΔF = required electrical energy, which is equivalent to the free energy change.

This equation is plotted in Fig. 1. Note that as the temperature increases, the electrical input needed for the decomposition process decreases. This leads to an increase in the overall efficiency of the process.

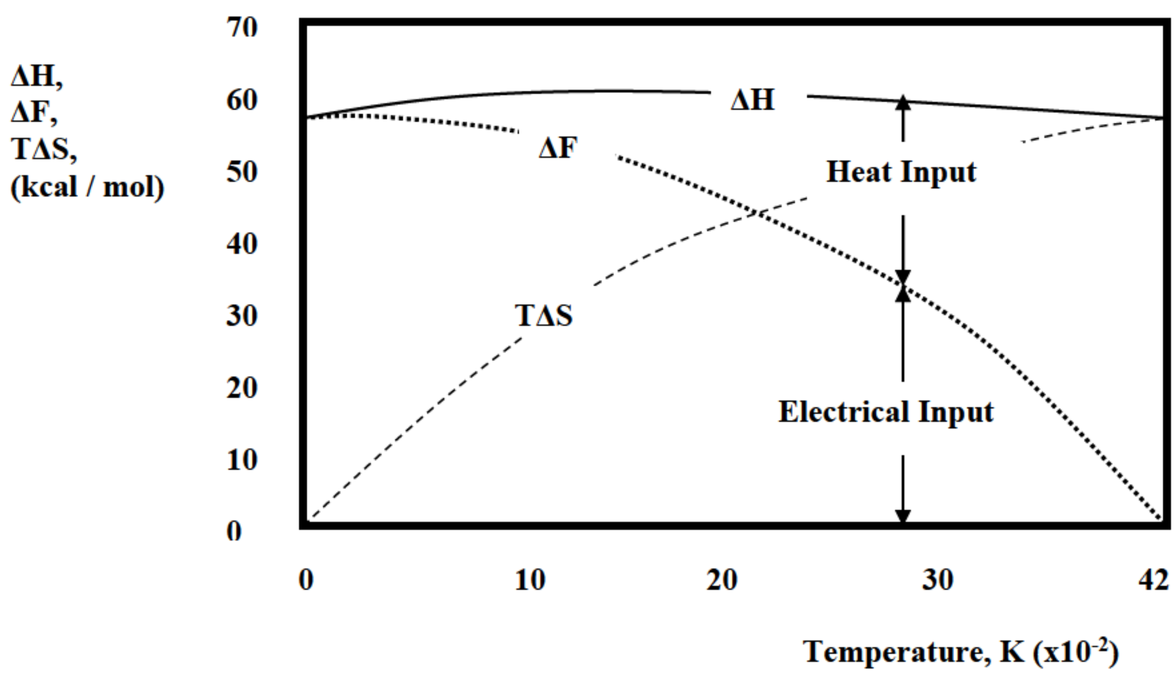

Figure 1. Energy splits for water decomposition as a function of temperature in the High Temperature Electrolysis (HTE) process [1].

PROCESS EFFICIENCY

The efficiency is of the process is measured as the fraction of electrical energy used that is actually contained within the produced hydrogen. In this process, some of the electrical energy is converted into waste heat. Efficiencies of 50-70 percent are attainable. Those efficiencies are based on the Lower Heating Value of Hydrogen which is the total thermal energy released when hydrogen is combusted minus the latent heat of vaporization of the water.

This definition of efficiency does not represent the total amount of energy contained in the hydrogen, thus it is lower than a more strict definition. The theoretical maximum efficiency of the electrolysis process is 80-94 percent. The theoretical maximum value accounts for the total amount of energy absorbed by both the hydrogen and oxygen.

These values consider the efficiency of converting electrical energy into the hydrogen's chemical energy.

Thus, High Temperature Electrolysis (HTE) is a more efficient process for hydrogen production. The electrolysis step itself offers very high efficiencies:

$$\eta_{electrolysis} > 0.90.$$

Even if a conventional electrical generating process having 40 percent efficiency is used with no voltage losses in the electrolyzer, the overall efficiency for hydrogen production at 1,400 ^{o}C can be on the order of:

$$\begin{aligned}\eta_{hydrogen} &= \eta_{electrolysis} . \eta_{electrical} \\ &= 0.90 \times 0.40 \\ &= 0.36 \\ &= 36 \ \textit{percent}\end{aligned}$$

For a high efficiency electrical generating efficiency around 60 percent, the hydrogen production efficiency would be:

$$\begin{aligned}\eta_{hydrogen} &= 0.90 \times 0.60 \\ &= 0.54 \\ &= 54 \ \textit{percent}\end{aligned}$$

In HTE, a large energy fraction in the range of 30-50 percent is supplied as high temperature heat, and the rest as electricity, which can be produced through a conventional thermal cycle.

THE HYDROGEN NUCLEAR ECONOMY

Currently nuclear fission energy is used in an inefficient way as an expensive way of boiling water to produce steam and then electricity. Nuclear power plants are operated half the day to satisfy demand at the peak hours. Instead, nuclear power plants can be operated economically ats base load to primarily produce hydrogen for both transportation and as a portable fuel. Neither the power plants nor the produced fuel would generate pollutants. Wind turbines and solar technologies can satisfy part of the demand by billions of people, but the majority of the demand will have to be satisfied by the nuclear approach to hydrogen.

High temperature electrolysis of water can be used to efficiently produce hydrogen for distribution possibly through the existing natural gas distribution pipeline system. Electricity can also be used locally to dissociate water, whenever available, through low temperature electrolysis. For a location that is short on water supplies in arid regions of the world, or with polluted water supplies from agricultural wastes, the burning of hydrogen will provide both a source of energy and pure unpolluted water.

The ultimate course toward a hydrogen economy would be the development of fusion reactors which themselves burn hydrogen in the form of its isotopes deuterium, produced from heavy water or D_2O electrolysis, and tritium, tritium would be produced from the isotope of lithium: ${}_3Li^6$, and in the process produce hydrogen from water. They would offer three advantages compared with fission plants:

1. No fission products are produced, requiring geological isolation like in the case of fission reactors, even though some activation products will be produced, and there will be a need to handle tritium which a radioactive isotope of hydrogen.
2. Fusion reactors are not subject to criticality accidents like fission reactors, even though some plasma disruption accidents can occur.
3. The fuel supply in the form of heavy water and lithium are practically unlimited.

FISSION REACTORS FOR HYDROGEN PRODUCTION

The thermo chemical production of hydrogen if fission reactors are used requires operation at high temperatures ranging from 750 to 1,000 degrees Celsius. It also requires the transfer of the process heat from the reactor to the chemical plant at high temperature. The reactor plant and the chemical plant are thus to be isolated from each other. Considering that each has its particular inventory of hazardous materials, the safety design and analysis of the combined configuration has to be addressed. Three fission reactors designs that could operate at the required high temperature can been identified:

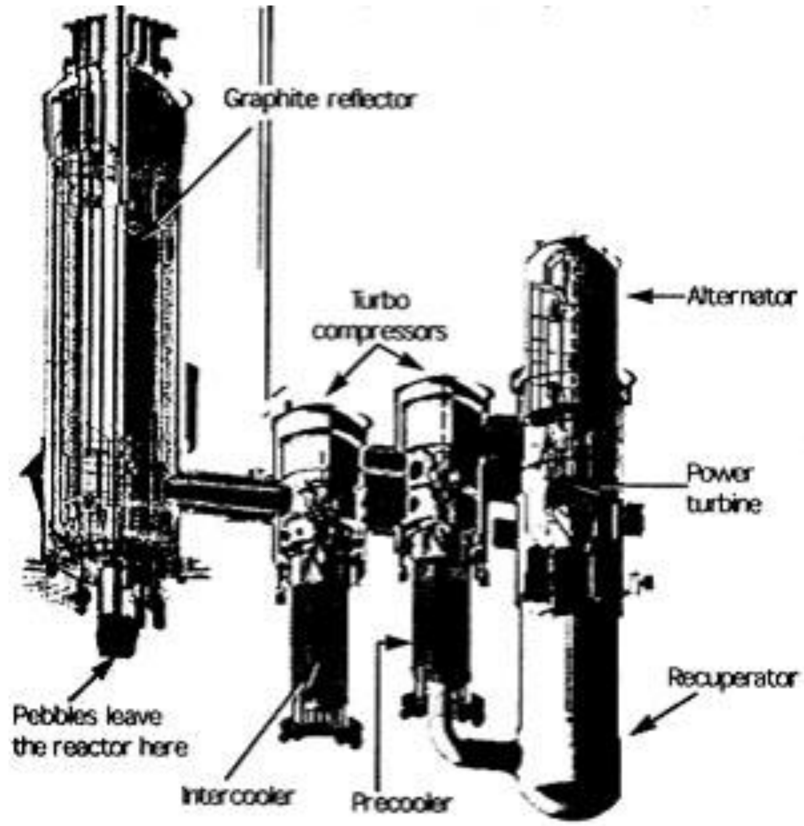

Figure 2. Diagram of the Pebble Bed Modular Reactor (PBMR).

1. The High Temperature Gas Cooled Reactor (HTGR):

Many variant of this reactor exist including the modular HTGR, a hexagonal block core design and a more recent pebble bed configuration using the Brayton gas turbine cycle rather than the Rankine steam turbine cycle. A diagram of the pebble bed reactor under consideration is shown in Fig. 2. Figure 3 shows its process flow diagram.

2. Molten Salt Advanced High Temperature Reactor (AHTR):

This is a molten salt cooled reactor, which uses a coated particle graphite matrix. The low-pressure molten salt replaces the high-pressure helium coolant, which eliminates the possibility of the gas coolant depressurization accident. The operation at atmospheric pressure and the higher exit temperature of the coolant are perceived as advantages of this approach. Molten salt cooling has been considered in the past for both fission and fission-fusion hybrid reactors [7].

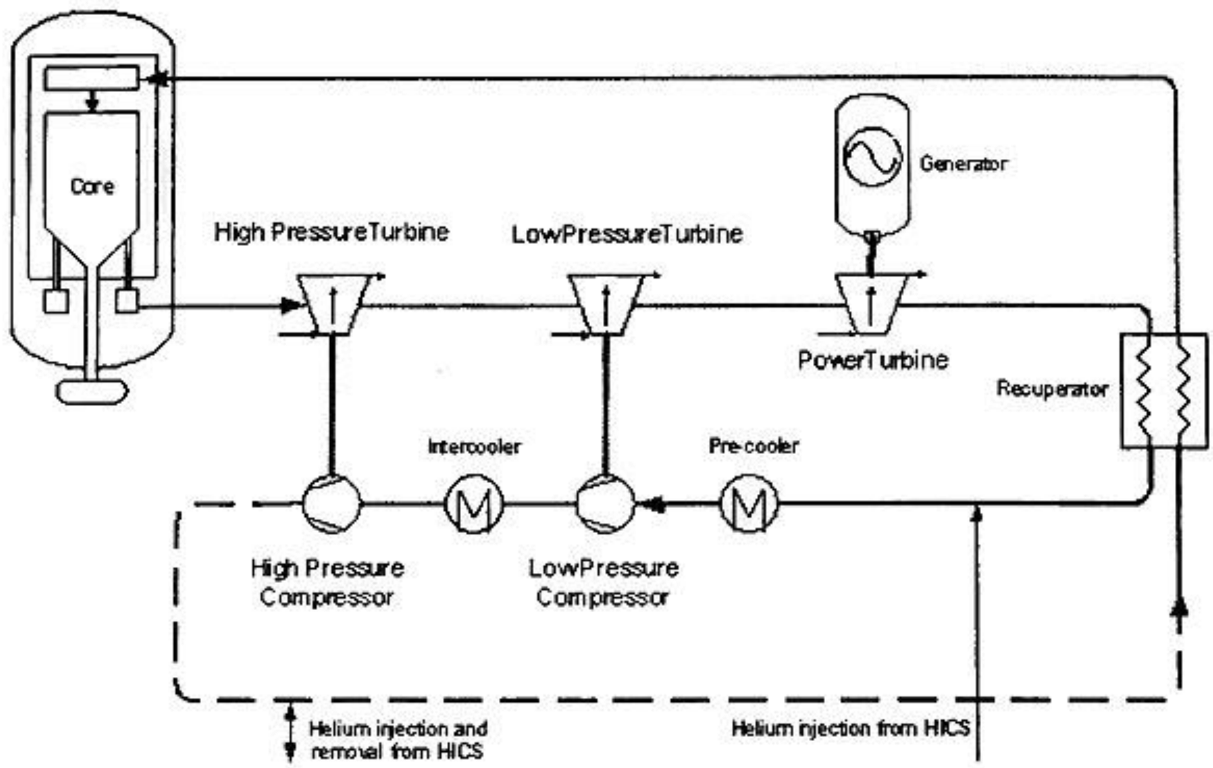

Figure 3. Flow Diagram of the Pebble Bed Modular Reactor (PBMR).

3. Lead Cooled Fast Reactor (LCFR)

Such a reactor would operate with a fast neutron spectrum since lead is not a good neutron moderator. Sodium is precluded as a coolant since it would reach its boiling point at 883 degrees Celsius close to the temperature needed for thermo chemical hydrogen production. With lead as a coolant the operational temperature is lower than that for the gas cooled systems.

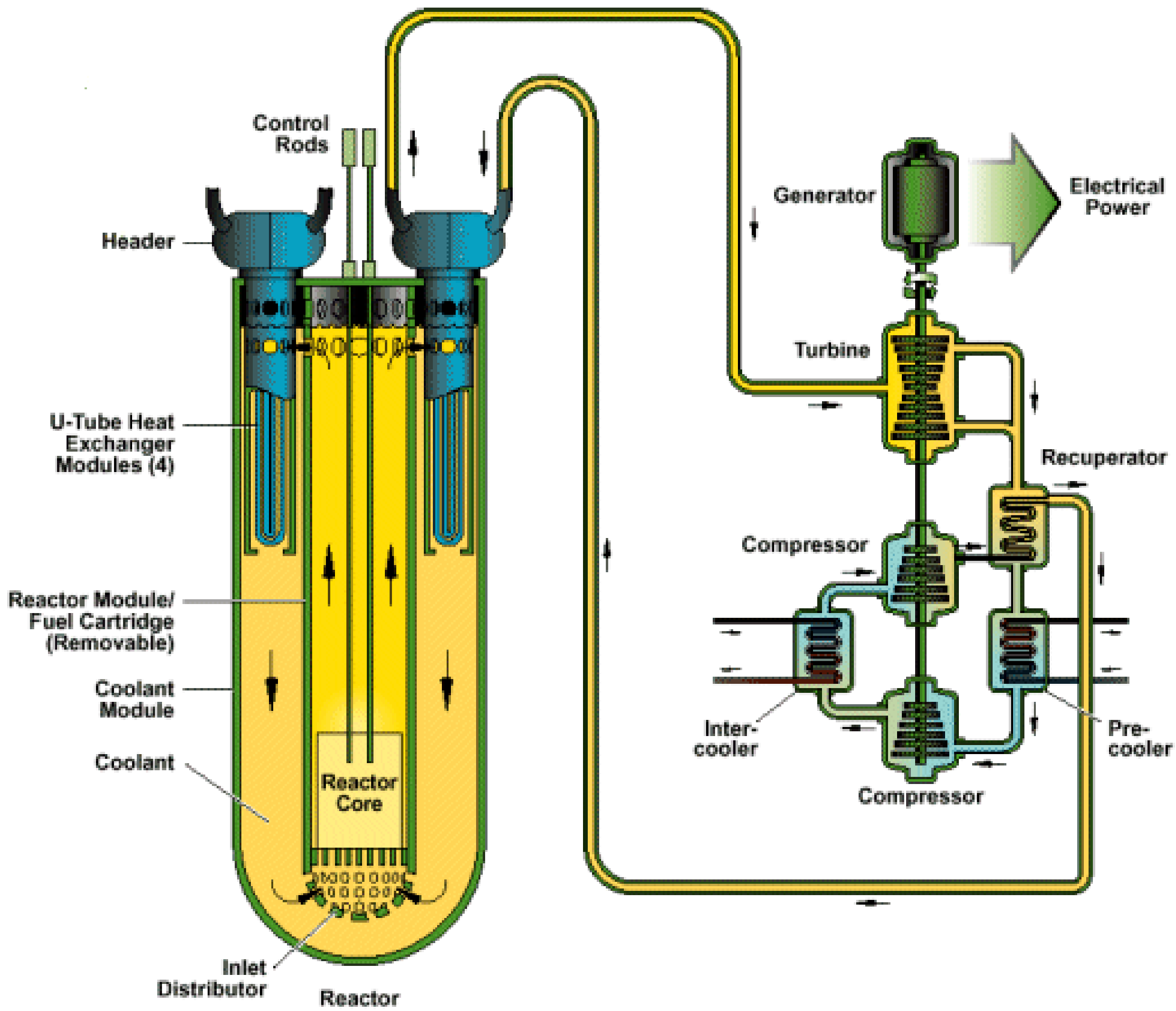

Figure 4. Lead Cooled Fast Reactor. Source: INL.

IMPROVING ENERGY USE EFFICIENCY

In parallel to the movement toward hydrogenation, there is a need to improve the overall efficiency of energy use. The overall efficiency of the energy system advanced from the low value of 1 percent in the year 1,000 to no more than 2 percent in the year 2,000. Current fossil fuel and nuclear electrical power plants using the steam cycle have a thermodynamic efficiency ranging from 30-40 percent. The use of the higher temperature gas turbine cycle can lead to efficiencies in the range of 50 percent. And even better, using fusion fuel cycles producing charged particles would allow the direct conversion of their kinetic energy into electricity, without the intermediate step of the heat cycle at efficiencies that can reach 70 percent.

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