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SOURCE FOR HYDROGEN PRODUCTION

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PERFORMANCE REQUIREMENTS OF AN INERTIAL-FUSION-ENERGY SOURCE
FOR HYDROGEN PRODUCTION*

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ABSTRACT

Performance of an inertial-fusion system for the production of hydrogen is compared to a tandem-mirror-system hydrogen producer. Both systems use the General Atomic sulfur-iodine hydrogen-production cycle and produce no net electric power to the grid. An ICF-driven hydrogen producer will have higher system gains and lower electrical-consumption ratios than the design point for the tandem-mirror system if the inertial-fusion-energy gain $nQ > 8.8$. For the ICF system to have a higher hydrogen production rate per unit fusion power than the tandem-mirror system requires that $nQ > 17$. These can be achieved utilizing realistic laser and pellet performances.

INTRODUCTION

Currently, the United States consumes about 70% of its energy for non-electrical applications.¹ The production of hydrogen as a relatively nonpolluting fuel will be necessary for the long-term development of cost-effective commercial fusion power. A hydrogen economy based on fusion energy may ensure a self-sufficient energy future for the United States.

Of the various processes for producing hydrogen, the best developed is electrolysis; work is also proceeding on thermochemical and hybrid thermochemical-electrochemical cycles. Since neither advanced

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electrolysis nor thermochemical processes have been demonstrated on a power-plant scale, the costs and efficiencies of both systems are uncertain.

The U.S. Department of Energy is currently sponsoring two studies of magnetically-confined fusion-energy sources for hydrogen production.² Exploring thermochemical cycles is the joint project of LLNL and the University of Washington (UW). The high-temperature electrolysis project is being performed at Brookhaven National Laboratory (BNL). The BNL study employs a tokamak fusion-energy source and emphasizes the design of high-temperature fusion blankets.^{3,4} The LLNL/UW study of hydrogen production using fusion energy utilizes the General Atomic (GA) sulfur-iodine cycle⁵ with a tandem-mirror fusion reactor.⁶⁻⁹

SYSTEMATICS OF A FUSION-ENERGY SOURCE FOR THE PRODUCTION OF HYDROGEN

Figure 1 shows a power-flow diagram for a fusion-energy-driven hydrogen-production source. The fusion energy is furnished to the hydrogen-production plant as heat and electricity. The high temperatures required in the hydrogen-production process can be generated by Joule heating. The performance of a fusion plant that produces a ratio, ζ , of hydrogen to net electricity can be estimated from

$$\zeta \equiv \frac{P_{\text{net-H}_2}}{P_{\text{net-e}}} = \frac{rQM\eta_D[f + \alpha\eta_t(1-f)]}{\eta_D\eta_t(1-\alpha)(1-f)QM}$$

where α is the fraction of the electric power produced that is circulated to the hydrogen-production plant, and f is the fraction of the fusion power that is utilized as heat by the hydrogen-production plant. An additional constraint on this analysis is that the hydrogen-production plant will require a given ratio, ξ , of the thermal power to the electric power for the process,

$$\xi = \frac{f}{\alpha\eta_t(1-f)}.$$

Q = Capsule gain	Γ = Fuel plant efficiency
N = pulse repetition frequency	M = Blanket energy multiplication factor
E = Driver energy	η_D = Driver efficiency
$\dot{m}$ = Mass flow rate of H_2	η_t = Heat to electricity conversion efficiency
ϵ = Heat of combustion of H_2	f = Fraction of fusion heat for fuel plant
	α = Fraction of electricity for fuel plant

$$P_{net_e} = \frac{NE}{\eta_D} [\eta_D(1-\alpha)\eta_t(1-f)QM - 1]; P_{net_{H_2}} = \Gamma NEQM[f + \alpha\eta_t(1-f)]$$

Fig. 1 Power-flow diagram for hydrogen-production plant using fusion energy in a low-temperature cycle.

Combining these equations yields

$$f = \frac{\xi \xi [\eta_D \eta_T - 1]}{\eta_D \eta_T [\xi (\xi \eta_T + 1) + 1 (\xi + 1)]}$$

There are three important figures of merit for a fusion-driven hydrogen producer: the system gain, G , the production fraction, x , and the electric consumption ratio, y . For a system producing no net electric power ($\xi = \infty$), the system gain, G , is defined as the ratio of the hydrogen production rate to the fusion-reactor circulating electric power requirements; G is thus a rough ratio of the revenues from the hydrogen produced to the operating cost of the fusion-energy source. The production fraction, x , is the ratio of the hydrogen production rate to the fusion power. The ratio is roughly proportional to the ratio of the revenues from the hydrogen produced to the capital cost of the plant. The electricity-consumption ratio, y , is the ratio of the reactor circulating power to the gross electric power produced by the system. This ratio is a relative comparison of the cost of electricity for running the fusion plant with the cost of electricity to run the total system.

We compared an ICF-driven system for producing hydrogen to the LLNL tandem-mirror hydrogen producer⁸ in order that we can use their designs for the H_2 production portion of the plant with inertial fusion replacing mirror fusion. Both systems use the GA sulfur-iodine hydrogen production cycle, consisting of the following three reactions:

Neither system produced net electric power to the grid. The performance of the tandem-mirror and ICF hydrogen-production systems are compared in

Table I. The blanket neutron-energy multiplication factor listed in the table is applied to 80% of the fusion energy for the tandem-mirror reactor system, and to 68% of the fusion energy in the inertial fusion reactor. The auxiliary heating fraction is applied to the total plasma power for the tandem-mirror system and to the fusion power for the ICF reactor system. The plasma gain for the tandem-mirror reactor system is 11.6, which does not include the heating power to the plasma.

Table I. Performance comparison for tandem-mirror-driven and inertial-fusion-driven, hydrogen-production systems.

<u>Component</u>	<u>System</u>	
	<u>Tandem Mirror</u>	<u>Inertial Fusion</u>
Thermoelectric conversion efficiency, η_t (%)	40	40
Heat-to-electricity ratio for hydrogen plant, ξ	4.0	4.0
Auxiliary heat fraction	0.03	0.03
Blanket neutron-energy multiplier, M	1.12	1.12
Driver efficiency, η_D (%)	55	4-8
Direct converter efficiency, η_{DC} (%)	55	NA
Plasma gain, Q	11.6	100-300
Net electric power	0.0	0.0
System gain, G	1.89	1-5
Hydrogen production fraction, x	0.33	0.2-0.35
Electric consumption ratio, y	0.57	0.3-0.8

The system gain for the ICF-driven hydrogen production plant are shown in Fig. 2 as a function of fusion energy gain $\eta_D Q$ where η_D is the driver efficiency and Q is the pellet gain. For very large fusion gains, the maximum system gain becomes 12.0, the maximum production fraction becomes 0.39, and the minimum electric consumption ratio becomes 0.075.

An ICF-driven hydrogen producer will have higher system gains and lower electrical consumption ratios than the design point for the tandem-mirror system if the inertial-fusion energy gain $\eta_D Q > 8.8$.

*LLNL-TMR syn fuel plant courtesy T. Galloway and R. Werner

System gain, $G \equiv$ heat value of H_2 produced/reactor circulating electric power

Production fraction, $x \equiv$ heat value of H_2 produced/fusion power

Electric consumption ratio, $y \equiv$ reactor circulating power/system electric power

Fig. 2 Performance characteristics of an ICF-driven hydrogen-production plant.

However, for the ICF system to have a higher production fraction than the tandem-mirror system requires that $\eta_D Q > 17$. The advantage of the tandem-mirror system, in terms of the hydrogen-production fraction for $9 < \eta_D Q < 17$, is due to the direct converter (see Table I) which supplies all the tandem mirror injection power requirements.

A design curve for ICF using the same hydrogen-production plant as the tandem-mirror system is shown in Fig. 3; the figure shows pellet gain, Q for various driver energies, E_D .¹⁰ For a given $\eta_D Q = 8.8$, and a given laser efficiency of 7%, the required pellet gain is 126. The lowest driver energy that falls in the "best-estimate" gain area on the figure for a gain of 126 is 4 MJ. For a production rate of 5.8 kg-moles/s of H_2 , the required pulseretpetition frequency is 11 Hz. This case is given as Example 2 in Table II.

Table II. Performance comparison for the inertial fusion-driven, tandem-mirror, hydrogen-production plant for several pellet gains and driver energies.

<u>Performance parameter</u>	<u>Example 1</u>	<u>Example 2</u>	<u>Example 3</u>
Fusion-energy gain, $\eta_D Q$	8.8	8.8	17
Driver efficiency, η_D (%)	4.4	7.0	7.0
Fusion gain, Q	220	126	240
Driver energy (MJ)	10	4	10
Fusion yield (MJ)	2200	500	2400
Pulse repetition rate (H_2)	3	11	< 3
System gain, G	1.89	1.89	3.6
Hydrogen-production fraction, x	0.28	0.28	0.33
Electric-consumption ratio, y	0.57	0.57	0.41

The inertial-fusion reactor system in Fig. 3 will have the same system gain and hydrogen production rate as the tandem-mirror system, but a lower hydrogen-production fraction. Reducing the driver efficiency to 4.4% will require a pellet gain of 220 (Example 1 in Table II). The

Fig. 3 Pellet-driver parameter space for the hydrogen-production plant in Fig. 1, producing 5.8 kg-mole/s of H_2 .

lowest driver energy for this gain in the "best-estimate" gain curve is 10 MJ. For a fusion-energy gain of 17 and a driver efficiency of 7%, the required pellet gain is 240 (Example 3 in Table II). Using a 10-MJ driver will require that the pellet performance slightly exceed the "best-estimate" gain.

FUSION-REACTOR DESIGN CONSIDERATIONS

For a given $\eta_D Q$, a low-efficiency driver will need to deliver more energy to the pellet to achieve the required larger pellet gain. This will result in high-yield fusion microexplosions that reduce the variety of first-wall protection schemes available for the reactor compared to those available for lower-yield microexplosions. According to Table II, for example, a system with $\eta_D Q \approx 8.8$ will have a required yield of 2200 MJ for a 4.4%-efficient driver. This high required yield may limit effective reaction-chamber options to thick liquid-metal-wall chambers.¹¹ If the driver efficiency is 7%, the required 500-MJ fusion yield may allow, in addition to thick liquid-metal-wall chambers, both dry-wall and wetted-wall chambers.

The most efficient method of producing hydrogen requires temperatures in the range of 1200 to 1500 K. These temperatures restrict the material options available, and require cooled structures that are well insulated from the high-temperature blanket. The use of high temperature alloys will increase the cost of the fusion-reactor system. The higher capital cost of the high-temperature systems may be overcome, however, by the increased revenues from the hydrogen (or electricity) produced by the more efficient system.

ICF reactors can tolerate flowing conducting fluids, high vapor pressures in the fusion cavity, and large reactor geometries more readily than can magnetic-confinement fusion reactors. These freedoms associated with ICF should be exploited. For example, the gas heated by the short-range fusion product in a gas-protected first-wall concept such as SOLASE¹¹ is unable to radiate its energy to the reactor structure in reasonable times. This hot gas could be circulated through an intermediate heat exchanger, and the extracted energy used in a hydrogen-

production plant. Blanket options could include high-temperature circulating lithium or lead-lithium mixtures in a Nb-1% Zr structure, since the Nb-1% Zr corrosion rate by lithium is acceptable up to temperatures as high as about 1300 K. Other acceptable high-temperature blankets can be made up of a solid-lithium compound such as Li_2O , with graphite moderators and boron carbide absorbers.

In addition to the fusion-system performance requirements for economically producing hydrogen, there are additional practical constraints. These constraints on the fusion-driven hydrogen-production plant system are as follows:

- The system must be self-sufficient as a tritium producer.
- The thermal energy produced must be in a form that matches the requirement of the hydrogen plant processes.
- The primary coolant systems of the fusion reactor must be physically decoupled from the energy-transport media into the hydrogen plant.
- The energy-transport media entering the hydrogen plant must be inert with respect to the ingredients of the hydrogen-plant process materials at the process temperature.

These constraints have several effects, including

- Requiring a heat exchanger in the primary reactor coolant loop.
- Requiring either the use of an inert gas energy transport media or the use of Joule heating for the high-temperature leg of a thermochemical hydrogen-production process.
- Effectively eliminating neutron radiolysis from consideration as a hydrogen-production process.

CONCLUSIONS

The selection of a given hydrogen-production method is premature at this time. However, an inertial-fusion energy source utilizing realistic pellet and laser performances can compete in terms of system performance with the proposed LLNL tandem-mirror energy source for the GA sulfur-iodine hydrogen-production system. The freedom of materials selection and cavity environment will ensure that ICF can contribute to the production of hydrogen in the long-term future.

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