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PRODUCING THERMOCHEMICAL HYDROGEN WITH THE TANDEM-MIRROR REACTOR

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PRODUCING THERMOCHEMICAL HYDROGEN WITH THE TANDEM MIRROR REACTOR*

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Abstract

Fusion power holds the promise to supply not only electricity but also fuels to meet the balance of our energy needs. A new integrated power and breeding blanket design is described for tandem mirror reactors. The blanket incorporates features that make it suitable for synthetic fuel production. In particular, it is matched to the thermal and electrical power requirements of the General Atomic water-splitting process for production of hydrogen. Some improvements to the high temperature chemical process steps are described. These improvements are expected to allow production of hydrogen at about $13/GJ wholesale, including financing costs, capital amortization, and profit.

INTRODUCTION

Our study on synfuels is intended to focus primarily on the engineering aspects of coupling a tandem mirror fusion reactor (TMR) to a thermochemical cycle for the express purpose of producing hydrogen from water. The hydrogen is then to be used:

- As a portable fuel
- As a feedstock to synthesize other fuels such as gasoline or methanol
- To produce other useful chemicals such as NH_3.

This report presents substantial details of how to produce hydrogen using a fusion reactor as the energy source and a thermochemical cycle as the water decomposition process.

The fusion reactor is the tandem mirror (TMR) of the Lawrence Livermore National Laboratory. This machine, with its linear topology and output of both thermal energy and high voltage dc electrical energy, has advantages for this application. This energy source uses the D-T reaction producing an energetic neutron and an alpha particle.

$$D + T \rightarrow n\ (14.1\ \text{MeV}) + \alpha\ (3.5\ \text{MeV})$$

An artist's view of a TMR is shown in Fig. 1.

The thermochemical process uses General Atomic's sulfur-iodine cycle. The net result of this cycle, as Fig. 2 illustrates, is the thermochemical decomposition of water to make hydrogen

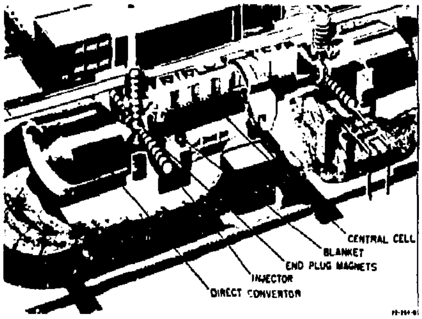

Fig. 1 The Tandem Mirror Reactor

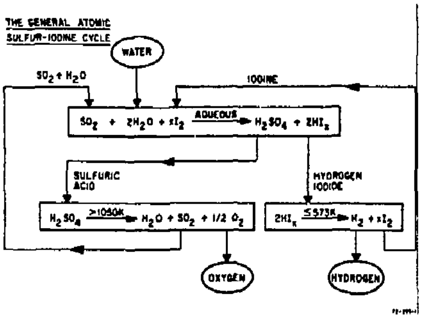

Fig. 2 The General Atomic Sulfur-Iodine Cycle

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and oxygen using only water as the feedstock. This cycle is one of three throughout the world that have been demonstrated at the laboratory level.

MOTIVATION FOR THE STUDY

A reminder of the extreme importance to the U.S. economy of synthesizing portable fuels is suggested by Fig. 3, the familiar spaghetti chart showing our U.S. energy flow for 1979 and how it is distributed in the consumption process; roughly 73% used as fuels and chemicals, and 27% used for electricity generation. As these nonrenewable energy supplies of oil and gas predictably diminish in the early decades of the 21st century and are replaced by the renewables--fusion being one of these--it seems clear that not only must the renewable energy sources produce electricity but they also must produce fuels and chemical feedstock in even greater quantity. Coal could be a temporary but not a permanent solution, particularly if increased CO_2 production is found to induce climate changes.

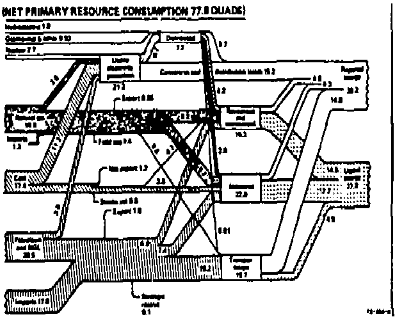

Fig. 3 U.S. Energy Flow - 1979

Beyond postulating a method for producing fuel there is a logical case for studying synthetic fuel production in conjunction with the fusion reactor. At least three objectives important to fusion are served by these fusion/synfuel studies:

(1) The base for fusion's applicability to our future national overall energy needs is broadened.

(2) Fusion reactor studies for the production of electricity gain measurably by the reactor designs carried out for synfuels. Different scientific disciplines become involved. Different industrial partners become aware of fusion.

(3) The timing of fusion's availability and the need for synfuels coincide. About the time when fusion energy sources are on the threshold of commercial reality, synthetic fuels will be needed to bolster the waning supplies of the exhaustables. Somewhere around 2010 or perhaps a decade thereafter there is a high probability of an energy shortfall and it is then that fusion must begin to be commercialized.

MAJOR CONCLUSIONS AND OBSERVATIONS

Our studies on synfuels, carried out over the last two years, have been very productive. We now have a plot plan of a representative fusion/synfuel plant. We have a new process flow sheet tailored to the fusion driver and the plant process energy demands. The need for very high temperature blankets in the reactor has been avoided by our introduction of a new concept for H_2SO_4 decomposition (see Fig. 2). We call this concept Joule Boosting. We have a good materials base. The linear topology of the tandem mirror reactor, its steady-state operation, and its production of energy in both thermal and electrical form have been fully utilized. We believe fusion/synfuels to be a sound concept.

Costs of Producing the Hydrogen and Plant Efficiency

Our preliminary cost estimate indicates a potential price as low as $\sim$ \$10-12/GJ for H_2. In comparison, a barrel of oil priced at \$50 at the wellhead and valued at \$75/bbl after refining has a cost of \$12.30 GJ. A few decades in the future, these will probably be bargain prices, in constant dollars.

Our synfuel plant thermal efficiency percentages range in the mid forties based on two study approaches. One was a 800-900 K fusion reactor with a heat pipe blanket using the Joule-Boosted SO_3 decomposer. The other was a two-temperature zone, helium-cooled blanket (850 K and 1160 K) used with a fluidized bed decomposer. The heat pipe blanket has now been superseded by a helium-cooled blanket using a Li_2O moderator.

Meeting the High Temperature Requirements of the Process

Roughly 25% of the energy demand of the thermochemical plant is at high temperature (> 1050 K) and is required to decompose SO_3 to SO_2, which is the final step in the H_2SO_4 decomposition. The remaining 75% of the energy requirement is at much lower temperature (see Fig. 2.).

Our introduction of the Joule-Boosted decomposer concept is an important system improvement in fusion/synfuels compatibility allowing very high SO_3 decomposition temperatures ($\sim$ 1250 K) to be provided electrically but significantly relaxing temperature demands on the reactor blanket to approximately 875 K to 950 K. This Joule Boosting works by using the unique high voltage direct current output from the TMR plus some additional electricity that is thermally derived from the blanket. The electric power produces high temperatures using electrical heating elements right in the decomposer itself rather than delivering high temperature process heat.

A fluidized bed decomposer which we also introduced last year requires the use of higher temperature (> 1200 K) blankets. The fluidized bed nevertheless is also a significant system improvement in reducing blanket temperatures compared to its pebble bed predecessor that started our study. Figure 4 illustrates very vividly how we have been able to reduce blanket temperatures using fluidized beds or Joule Boosting while concurrently increasing the SO_3 decomposition temperature. The result is that the blanket design is thermally much less difficult and the decomposer is more efficient. Blanket design is very complex and involves heat transfer requirements as well as materials choices in addition to other considerations.

The choice between Joule Boosting and the use of a fluidized bed for the SO_3 decomposition process is very sensitive to the equilibrium decomposition of SO_3 to SO_2 as a function of temperature and pressure. This is illustrated in Fig. 5. The choice is also sensitive to the practical consideration of how hot the reactor blanket temperature can be and sensitive to what fraction of the electrical energy needed for the Joule Boosting can come from the tandem mirror reactor's direct converter. A figure of merit, M, provides a basis for making a choice.

Let η_J = conversion efficiency in converting SO_3 to SO_2 via Joule Boosting

η_{FB} = conversion efficiency via fluidized bed

η_{TH} = efficiency of converting thermal energy to electricity for Joule Boosting

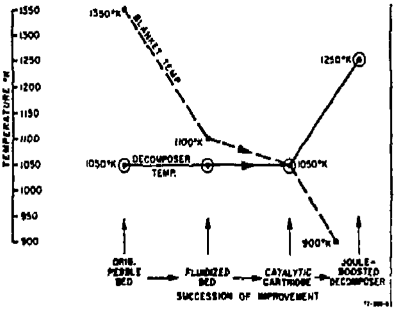

Fig. 4 Progress in Lowering Blanket Temperature and Raising Decomposer Temperature

f = fraction of electricity obtained directly from the fusion reactor direct converter

$T_{BL(FB)}$, $T_{BL(J)}$ = blanket temperatures for fluidized bed and Joule Boosted

For Joule Boosting to be preferred, M must be greater than 1.0 and is defined by:

$$M = \frac{\left(1 - \eta_{FB}\right)}{\left(1 - \eta_J\right)} \quad \frac{\eta_{TH}}{(1-f)} \quad \left[\frac{T_{BL(FB)}}{T_{BL(J)}}\right]^m$$

* Quantum steps in materials choices may be required.

As a current example:

η_{FB} = 0.68, η_J = 0.84, η_{TH} = 0.4, f = 0.2

$T_{BL(FB)} \simeq 1300$ K, $T_{LB(J)} \simeq 1000$ K, m = 1.0

with the result that M = 1.46. Other sets of numbers can be chosen but predominantly the Joule Boosting will be the better choice.

Reactor Blanket Design

The source of thermal energy that drives the thermochemical processes is a Li_2O-containing blanket. This blanket, one of two being studied in parallel, may be described as follows, using Figs. 6a-c.

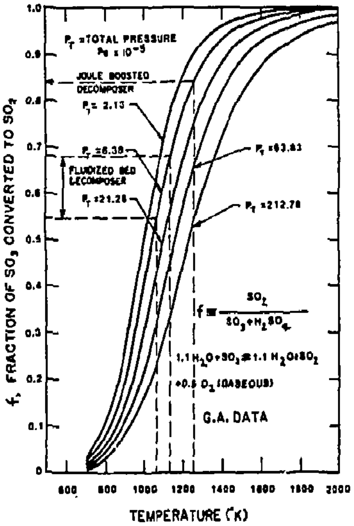

Fig. 5 Equilibrium Decomposition Curves for SO_3

To define some terms, the Li_2O blanket <u>ring module</u> is an assembly of canisters within a <u>ring (actually the cold shield)</u>. The ring is a *pressure vessel and support structure and the* canisters are the <u>blanket modules</u>. Each blanket module is filled <u>with an assembly</u> of Li_2O pieces or cartridges that provide the neutron moderating, tritium producing media. The cartridges are contained within tubes that nearly fill the canister module. The closely spaced tubes, as an assembly, become part of a multiple pass cross flow heat exchanger. Helium is the coolant.

Tube lengths are 2 meters, which is the full axial length of the blanket module. There are two ring modules between successive central cell coils and a total of 75 ring modules. The tube diameter must be determined and may vary as a function of moderator radius. However, it is likely that this diameter must be in the 1-4 cm range.

The tube material must have low permeation for tritium since one of the reasons the tube is used is to control the tritium release from the *Li_2O to the helium coolant stream. The other* reason for placing the Li_2O in a tube container is to protect the Li_2O from possible disintegration due to the high velocity helium flow.

The practical metals for use as canister material or high temperature heat exchangers are too permeable to tritium to act as significant barriers. A thin coating (100 μm) of SiC on the outside of each canister would greatly reduce the

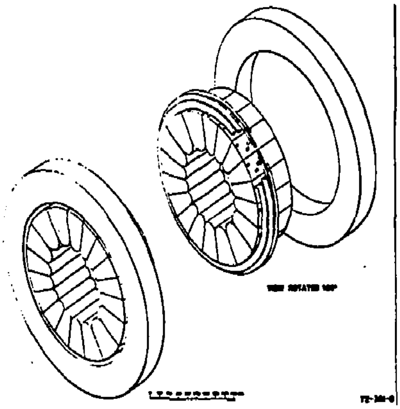

Fig. 6.a Thermal Blanket Ring Modules

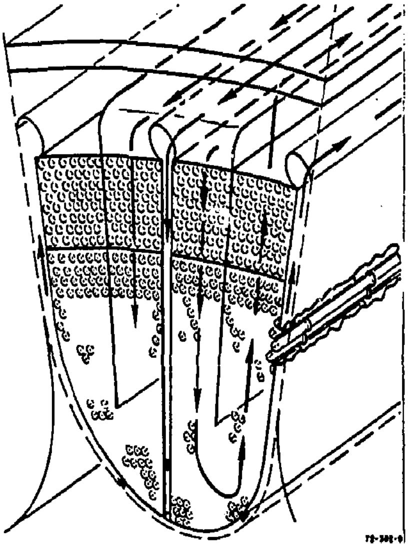

Fig. 6.b Thermal Blanket Canisters

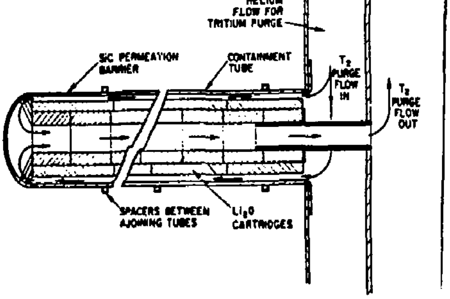

Fig. 6.c Li_2O Tube Cartridges

permeation of tritium into the main helium coolant. It is calculated that only 900 std cc per day would permeate at 950 K into the main coolant. By processing 10^{-4} of the main helium coolant for tritium removal, the amount permeating into an intermediate process steam cycle, for example, would be only 1 std cc/day. This assumes another permeation barrier such as alumina is used on the tubes in the intermediate heat exchanger.

We propose to fill the tubes with half washers or split rings of Li_2O. The advantage of this shape is that the cartridges are "pre-cracked" axially and radially so that thermal stress problems can be minimized. The subassembly is thus a long tube filled with half washers or split rings. These filled tubes are assembled in the canister normal to the helium coolant flow. The tubes are mounted in a tube sheet at one end of the blanket.

Purge flow helium is introduced around the outside and into the tube center for tritium removal. The purge flow quantity may be less than 1% of the total flow. This circuit is completely separate from the main stream helium. The small gap, δ in Fig. 6c, is provided between the tube wall and the Li_2O to enhance tritium removal and, equally important, to introduce a temperature gradient so that the Li_2O can run hotter or cooler than the structure as we choose by adjusting this gap size. The purge helium pressure is adjusted to be slightly less than the main flow helium pressure. It flows into the annular gap and out the hole in the washer. The assembly of tubes are mutually supporting, separated by helically wound wires or by staggered rings.

The Li_2O must be chemically protected from the tube material and vice versa. Nickel plating on the substrate is our tentative method, although we wish to minimize nickel for minimum activation.

A PLOT PLAN FOR THE HYDROGEN PLANT

To create a total fusion/synfuel plant there are four major plant components that must be designed, interfaced and iterated. As shown in Fig. 7 these are:

(1) The Tandem Mirror Reactor (TMR) with its associated physics.

(2) The reactor blanket and direct convertor, sources of the process energy.

(3) The energy transport and conversion system.

(4) The synfuel plant, producer of the hydrogen.

This plot plan is shown in Fig. 8. In this land area we produce (for one particular study) ~ 4900 gmol/s of H_2. The equivalent output in electricity would be ~ 1400 MW. We found that the land area was roughly comparable to the land area used by the Pacific Gas & Electric Company's Diablo Canyon Fission Reactor Power Station. Some statistics on this fusion synfuel plant will place the plot plan in proper perspective. These data are given in Table 1 in terms of reactor and synfuel plant energetics.

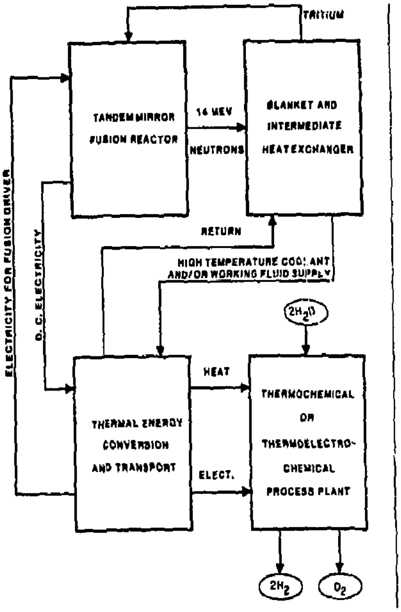

Fig. 7 Four Major Plant Components for a Fusion-Based Hydrogen Production System

Table 1 Reactor and Synfuel Plant Energetics

Reactor	
Blanket thermal energy	2580
Direct converter thermal energy	287
Energy to direct converter	2867
Less provision for reactor pumps, etc	(52)
Net thermal to synfuels	2815 MW_t
Direct converter elec. energy	430 MWe
Less provision for neutral beam injectors, etc.	(315)
Net electrical to synfuels	115 MWe
Synfuel Plant	
H_2 produced	4900 gmol/s
Hydrogen heating value	286 kJ gmol
Equivalent output	1445 MW

THE THERMOCHEMICAL PLANT PROCESS

The sulfur-iodine cycle, which is the focus of our study, is being developed by the General

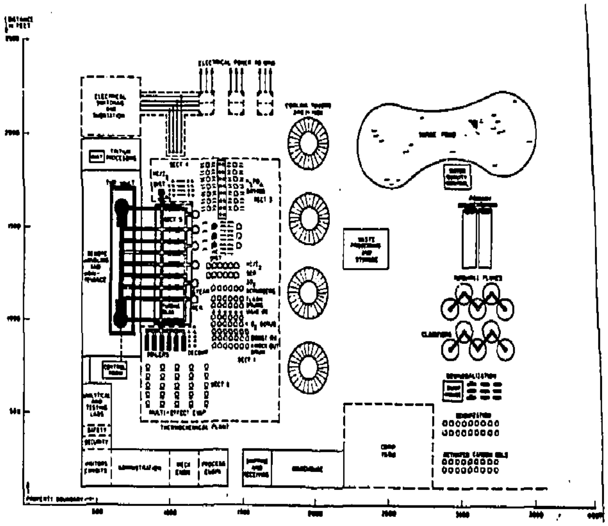

Fig. 8 Plot Plan for the Hydrogen Plant

Atomic Company. It is a pure (without electrolysis) thermochemical cycle and is described by the following major reaction steps:

$$2H_2O + SO_2 + I_2 \rightarrow H_2SO_4 + 2HI \ (270\text{-}290\ K) \quad (1)$$

$$2HI \rightarrow H_2 + I_2 \ (393\ K) \quad (2)$$

$$H_2SO_4 \rightarrow H_2O + SO_2 + 1/2\ O_2 \ (\sim 1144\ K) \quad (3)$$

Major parts of the process are associated with separation and purification of the reaction products. For example, a critical aspect for the successful operation of the process is in the separation of the aqueous reaction products in reaction (1). Workers at the General Atomic Company have solved this problem by using an excess of I_2, which leads to separation of the products into a lower density phase, containing H_2SO_4 and H_2O, and a higher density phase containing HI, I_2 and H_2O.

Reaction (2) shows the catalytic decomposition of HI, which is in the purified liquid form (50 atm). Pure H_2 is obtained by scrubbing out I_2 with H_2O.

The equilibrium for reaction (3) lies to the right at temperatures above 1000 K, but catalysts or higher temperatures are needed to attain sufficiently rapid decomposition rates below 1250 K. Catalysts are available for this process, but careful consideration needs to be given to their costs versus effectiveness.

MAJOR COMPONENTS OF THE PROCESS

The plot plan for the physical plunt and the cost of producing our hydrogen product could not have been accomplished had we not first developed process flow sheets and diagrams detailing the process units. The chemical plant strongly influence the design of the reactor in terms of temperatures, temperature ranges, and quantities of energies. We will illustrate this by discussing just two of the process units. These are units that we felt needed our first design attention or were high cost items. There are many units yet to be improved or further developed.

JOULE-BOOSTED SO_3 DECOMPOSER

The Joule-Boosted decomposer uses electrical energy to heat SiC heating elements. Such a decomposer design is depicted in Fig. 9. Large SiC heating elements, $\sim$ 5 cm in diameter and 3-m long, are arranged vertically with the process gases fed in crossflow, very similar to commercial crossflow shell and tube heat exchangers. The high effectiveness of this decomposer is evident from Fig. 5 where the conversion fraction is $\sim$ 84%, compared to 64% for the fluidized bed decomposer, our parallel design. The former runs 200 K hotter.

THE FLUIDIZED BED DECOMPOSER

Figure 10 illustrates a decomposer which

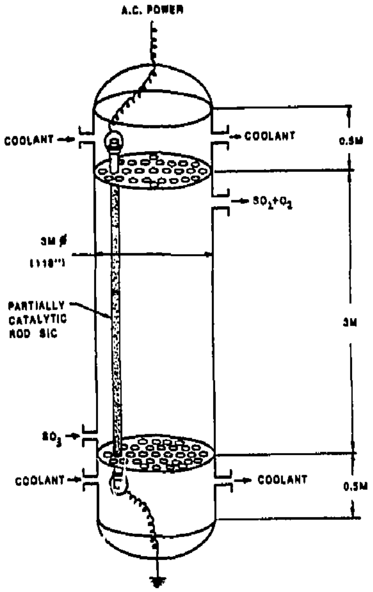

Fig. 9 Joule-Boosted Decomposer

provides the necessary production of SO_2 by efficiently using the high temperature heat from the two-zone blanket, our alternate blanket design to the heat pipe blanket. The decomposer is a catalytic fluidized bed reactor operating at 1100 K. The unit contains internal heat exchanger tubes to provide the heat for the highly endothermic SO_3 decomposition. A 65% conversion can be obtained using a CuO catalyst, if sulfation of the substrate does not become a problem around 1050 K, or a more expensive platinum catalyst on a titania support can be used if sulfation is a serious problem.

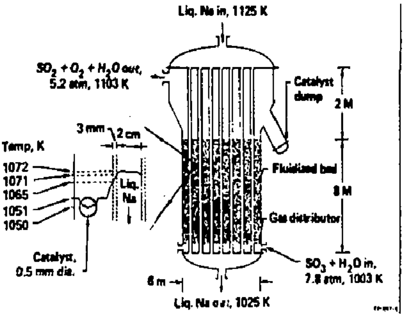

Fig. 10 Fluidized Bed Decomposer

CONCLUSIONS

It is generally agreed that fusion is a desirable energy source in the long term. It is also generally agreed that some parts of our energy consumption menu are better served by fuels than by electricity. While investigating the likelihood of producing fuels from fusion, we have developed some new blanket concepts that should be of interest to other reactor designers too. The advisability of producing the fuels in this manner has not yet been either conclusively proved or disproved, but work in that direction is continuing.