PROSPECTS FOR THE USE OF HYDROGEN AS AN ENERGY CARRIER

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ABSTRACT

As the United States, and the rest of the world, begin to deplete their resources of fossil fuels, attention must be paid to the best way to use the more abundant energy resources such as nuclear and solar energy. At the present time, technology is directed to converting these energy sources primarily to electricity. Electricity presently supplies only about 10% of our energy needs, is relatively inflexible in use because it cannot be stored, and is expensive to transmit underground. It is hard to see how electric power can find universal use for such things as air transportation, automobiles, and many other applications.

Nuclear or solar energy can be used to split water into hydrogen and oxygen. Hydrogen is a fuel gas that is easily transported in underground pipelines, can be stored by relatively inexpensive techniques, and can be used to meet most of the applications at present met by oil and natural gas. By drawing an analogy with the natural gas system, no insurmountable obstacles have been found to prevent the universal use of hydrogen. As an aircraft fuel, it is unexcelled on an energy-to-weight basis, and as an automobile fuel it is almost entirely nonpolluting. The use of hydrogen is not without problems, however, both real and imagined. The real problems include reducing its cost of manufacture and finding a way of storage on board vehicles, among others. The imagined problems have mainly to do with the safety. When the various alternatives for future energy scenarios are considered, "hydrogen energy" emerges as a very favorable choice for the time period when the production rate of carbonaceous fuels cannot keep up with demand. "Hydrogen energy" is of direct interest to the

rare earth community in two areas: Rare earth hydrides have been considered as a convenient means of storing hydrogen in both stationary and mobile applications, but no hydride system has yet emerged that solves all the problems of weight, volume, cost, and efficiency. Secondly, some of the so-called "thermochemical cycles" used for splitting water with heat from nuclear or solar sources utilize compounds of the rare earths. Again, no cycle has yet emerged that promises to solve economic and efficiency problems. The need for research and the potential of payoff from research in these areas are enormous.

BACKGROUND

"Hydrogen energy" is a possible candidate for one of the energy delivery and storage systems of tomorrow. Although no insurmountable obstacles to the use of hydrogen as a fuel gas have yet been encountered, some of the most challenging research areas lie in production and storage of this material. Rare earths have been considered to play a role in both of these fields, so that the future development of a "hydrogen energy" technology might depend partly upon rare-earth technology, and if successful, might stimulate development in the rare-earth industry.

Perhaps I should begin by outlining the basic objectives and advantages of a hydrogen-energy delivery system. Repeating this once again, in the light of the wide coverage already given hydrogen energy by the technical and popular press, may be superfluous to many people, but I believe it is important to ensure that the basic importance of the concept is understood and that my later remarks are not misinterpreted.

When we look at the alarming decline in the availability of the conventional fossil fuels, particularly oil and gas, we can clearly see that a major shift must be made toward other energy sources — nuclear and solar being the most abundant and important. The use of conventional technology will stress the conversion of these energy forms into electricity for delivery to the customer. Because electricity is not readily storable, is expensive to transmit, and is not immediately useful in the vast majority of industrial and domestic energy-consuming equipment, the alternative course of converting these non-fossil energy sources to a chemical fuel that is more compatible with today's energy distribution and utilization equipment has merit. In some applications, electricity will serve our needs best; in others, hydrogen will be superior. A mixed hydrogen-electricity energy delivery system may well become the best long-term compromise.

The attractiveness of using hydrogen as an energy delivery medium depends upon the following assumptions:

- Hydrogen may be produced from water by the input of energy, using electrolysis or thermochemistry, or by chemical reactions energized by direct solar or nuclear radiation.
- Hydrogen may be transported as a fuel gas by long-distance pipelines in much the same way as we transport natural gas today.
- Hydrogen can be stored by the same techniques used for natural gas storage — either in underground rock formations or by liquefaction.
- Hydrogen may be delivered to existing gas customers in existing gas distribution pipes and burned in existing gas-combustion equipment that has undergone only minor modifications.

If these assumptions are valid, then hydrogen made from tomorrow's nuclear or solar energy can, in principle, replace today's natural gas with only a minor disruption of the consumer's equipment. The use of hydrogen is the only way that the 30% of national energy needs now being supplied with natural gas can be provided with nuclear-based energy without the complete replacement of the already existing distribution and consuming equipment.

Research work already carried out has shown a) that electrochemical, thermochemical, and radiochemical processes for the production of hydrogen are all technically feasible, but require increasing technological advances in the order shown; b) that pipeline transmission and distribution of hydrogen is technically feasible at costs that are significantly below those of moving electricity; c) that the storability of hydrogen either underground or as a liquid is feasible; and d) that this feature could lead to considerable savings resulting from improvements in the load factors of the generation and transmission facilities. On the negative side, however, the overall efficiency of a hydrogen-energy delivery system, using conventional technology available today, will be somewhat less than that of an all-electric system. It is thus assumed to be economically unattractive. Although it may be possible to trade this loss in efficiency for the economic advantages of transmission and storage, much of today's hydrogen-energy research is directed toward improving the efficiency of hydrogen-energy systems and is mainly aimed at the hydrogen production stage.

Sparked by the promise of a hydrogen-energy analog of the natural gas system, some enthusiasts have broadened the scope of the concept to allow other attractive features of hydrogen energy to be exploited. Because hydrogen is the lightest of all fuels (51,500 Btu/lb compared with 18,500 Btu/lb for jet fuel), it is a superior aircraft fuel, and much has already been done to tackle the problems confronting its use in this application. Because it is almost nonpolluting, its use as an automobile fuel would eliminate many environmental problems, which has stimulated research into this application. In these applications where specialized advantages can be claimed, the objective of using hydrogen is not dependent upon producing it from nonfossil fuels. For this reason, the production of clean hydrogen from coal could be considered for use in these applications. Finally, the ready "interchangeability" of electricity and hydrogen, via the electrolyzer and the fuel cell, has stimulated research into the possible use of hydrogen storage as a peakshaving or load-leveling device for electric utilities.

Even though early work concentrated on the concept of the overall "hydrogen economy," a concept in which hydrogen produced from nonfossil fuel is used as a universal fuel for almost every energy application, many of the efforts today are aimed at one or more of the rather smaller segments of the overall concept — the production and use of hydrogen as an energy form for some specialized applications.

PRESENT RESEARCH ACTIVITIES

Most of today's hydrogen-energy research is concerned with the production of hydrogen from water. The production of hydrogen by electrolysis, using electric power, is a way of using known technology and existing generating equipment. Electrolysis technology is available today; indeed, several large electrolyzer plants are in operation (although none in the United States), producing electricity from hydrogen at an efficiency of about 70%. Several research programs are aimed at making improvements in electrolyzer efficiency without significantly increasing capital costs. Most researchers in the field believe that electricity-to-hydrogen efficiencies in the 90% to 95% range can be achieved, so that overall heat-to-hydrogen efficiencies of 35% to 38% can be predicted, using advanced nuclear-electricity generation technology. To achieve these higher electrolyzer efficiencies, there is a need for the development and testing of new materials capable of withstanding higher temperature operation than at present, and there are benefits to be gained from the operation of electrolyzers at high pressure, which would allow hydrogen to be delivered directly to the pipelines. However, because the electrolyzer-manufacturing industry is a small one, it cannot afford to fund the research necessary to make dramatic improvements in its product. Such research must be supported by the potential users of the hydrogen that these improved electrolyzers would produce.

A second hydrogen-production method, and the one that is receiving the most research support today, is the thermochemical splitting of water, using a nuclear or solar heat source, without an electrical intermediate. Heat is used to drive a number of chemical steps in a cyclic sequence, all the components of the cycles, except water, hydrogen, and oxygen, being recycled. Although no commercial technology is available for this process today, several research groups are conducting experimental trials of chemical reactions, and an even greater number have carried out detailed thermodynamic analyses of the theoretical efficiencies of various cycles. Much of this work is held proprietary by the researchers. The Institute of Gas Technology (IGT) has identified some 170 theoretically possible cycles, several of which possess calculated heat-to-hydrogen efficiencies greater than 50%. In contrast, nuclear heat-to-electricity efficiencies are at present only about 35% and are only expected to rise to about 45% in the future. To date, four cycles have been completely demonstrated in the laboratory at IGT. By a process of elimination, cycles with low efficiencies, high cost, or poor experimental "workability" have been rejected. As we shall see later, all cycles that contain rare earths have been rejected at this time. We recognize that the lead times required to develop a substantial business to produce thermochemical hydrogen are very long — about 20 years or more.

A small amount of work is going on in the area of hydrogen transmission, mainly to calculate the cost of moving hydrogen in pipelines over long distances. IGT's studies have shown that, using natural gas pipeline technology, transmission costs over distances of several hundred miles are about 3.5¢ to 5.5¢/million Btu-100 miles, in contrast to overhead electrical transmission costs of 40¢ to $1.05/million Btu-100 miles. Our studies have also shown that the energy needed to pump hydrogen through a pipeline is less than 1% of the total energy throughput per 100 miles, compared with an energy loss of about 10% in moving electricity over the same distance.

Investigation of the effect of hydrogen on the embrittlement of conventional pipeline steels has just begun in several laboratories; no research results have yet been published.

Conceptual, system, and techno-economic assessments of the prospects for moving energy from offshore wind- and solar-power stations using hydrogen pipelines or seagoing tankers have also been completed.

Hydrogen can be stored by liquefaction or in underground rock formations or depleted gas and oil wells. Some studies to improve the efficiency of hydrogen-liquefaction processes have been begun, and ERDA plans to commence work shortly, to demonstrate the feasibility of bulk underground hydrogen storage. The storage of hydrogen as a chemical hydride is receiving significant research attention, and I will return to this topic in a moment.

The utilization of hydrogen as an automobile fuel has received much well-publicized attention, but, in fact, remarkably little funding has been applied to this application. Some "over-the-road" demonstrations, carried out by student teams on "shoe-string budgets," have done little more than to show that it is relatively easy to convert conventional automobile engines to operate well and extremely cleanly on hydrogen. The major and unsolved problems are in the handling of the fuel itself, both in the vehicles and in the distribution and storage network needed to supply the refueling stations. At this time, surprisingly, very little reliable and systematic data are available on the actual test-bed performance, efficiency, and emissions of hydrogen engines; on the design of engines specifically engineered to take advantage of the properties of hydrogen; or on such fundamental information as the octane number of hydrogen, which appears to be well over 100.

The use of hydrogen as an aircraft fuel has been discussed a great deal. Design studies that have recently been completed for hydrogen-fueled wide-bodied passenger jet aircraft show very considerable potential improvements in efficiency, performance, and noise over the conventional jet-fueled version. Even though NACA (the predecessor of NASA) actually flew a hydrogen-fueled experimental jet aircraft in 1956 and an aircraft gas turbine specially designed to operate on hydrogen was developed and tested in industry at about the same, since then no actual tests of a hydrogen-fueled airplane have been conducted, nor are there any plans to do so known at this time.

It is believed that the regulators, valves, meters, and pipework now used in conventional gas systems will be compatible with hydrogen, and a program is in progress at IGT to prove this point. Similarly, the use of hydrogen in conventional natural-gas-fired burners appears to require only minor burner modifications, but, to date, detailed design and testing of modified burners has not been a significant feature of any hydrogen-energy research program.

Although no major conversion problems are envisaged, I am surprised that this particular end-use aspect of hydrogen energy has received so little attention, in contrast to the use of hydrogen in automobiles and aircraft. Fifty-two per cent of the total U.S. energy consumption is used for combined space heating, industrial process heating, and industrial process steam applications. About half of this amount is now being supplied by natural gas. The natural-gas-fueled equipment used in these applications could seemingly be converted to hydrogen far more easily and far more cheaply than to electricity. Not many people realize that the amount of energy used in the United States to produce industrial process steam alone is 17% of the total energy budget, about the same as that used to drive all the automobiles in the country. It seems to me that the conversion of this sector of the energy market to nonfossil fuels, via hydrogen, should receive as much emphasis as the efforts now being made to develop hydrogen-fueled or battery-operated automobiles.

Some significant work is under way on the development of catalytic burners for use with hydrogen. Since hydrogen "oxidizes" (rather than "burns") at low temperatures without a flame on a catalyst bed, this technique has merit for many domestic and industrial heat applications. A nonflame catalytic hydrogen burner can be made to produce no nitrogen oxides, and because its only combustion product is water, can be operated without a vent or flue. At IGT, hydrogen-fueled water heaters with efficiencies of about 85% have been demonstrated, and without a flue, 100% of the heating value of hydrogen can be used in a space heating plant. The importance of these developments is apparent when we consider the efficiencies of hydrogen versus electricity systems.

I would now like to return to the topic of storage of hydrogen as a hydride, because this is the most important and fertile field open to the rare-earth chemist. Hydrides of magnesium, iron-titanium alloys, and the rare earths can all be formed spontaneously by reacting the finely divided metal with hydrogen gas; the hydrogen can then be recovered by heating the hydride. Because waste heat is released in the hydride-formation step, the storage process is not 100% efficient. In general, known hydrides are either to inefficient, too heavy, or too costly to be completely satisfactory for mobile storage applications (e.g., for hydrogen automobiles). Small programs of basic research on the understanding of alloy hydride chemistry are under way in the hope that improved formulations can be developed. Meanwhile, engineering studies on relatively large-scale stationary storage systems using an iron-titanium alloy hydride are aimed at the electrical peakshaving application.

What basic characteristics are we looking for in hydride storage? For portable or vehicle applications, major considerations are low weight, low cost, and low reaction enthalpy. The first two are obvious needs; the third consideration results from the fact that on "filling the fuel tank" with hydrogen, heat is released and is wasted, and a similar amount of heat must be supplied to decompose the hydride when the hydrogen is required for use. Heats of formation of as much as 20% to 30% of the heating value of the stored hydrogen result in a severe heat dissipation problem on rapid refueling of a vehicle, equivalent to the burning of 3 gallons of gasoline for every 10 gallons of fuel added to the tank!

The temperature of dissociation is important also, because it is highly desirable to use either engine exhaust heat or the radiator coolant to supply the enthalpy of decomposition, although the hydride must remain stable on the hottest tropical day. The equilibrium pressure of hydrogen over the hydride must not create hazardous problems by overpressuring the storage tank on the hottest days, or pulling a vacuum and encouraging inward leakage of air on the coldest days. Both the fully hydrided and fully dehydrided metal must be safe when exposed to air in case of an accident that ruptures the fuel tank — several hydrides and finely divided metals are pyrophoric when exposed to air. Finally, if a large portion of the world's vehicle fleets are to operate on hydride storage, there must be an ample supply of the material to service this huge market.

For stationary storage applications, considerations of low reaction enthalpy, cost, and availability are of paramount importance, whereas tailored pressure-temperature relationships are desirable to aid rapid charging and discharging procedures at appropriate production and transmission pressures. Figure 1 shows some critical properties that must be considered when selecting hydrides for storage.

Where does present technology stand? And where do the rare earths fit in? Figure 2 shows typical reaction isotherms for hydride systems. We need long flat plateaus of pressure (A-B). We would like a relatively small temperature coefficient of pressure, and we would like hydrogen equilibrium pressures in the 1- to 10-atmosphere range at normal temperatures. Table 1 shows some properties of various candidates for hydride storage, and Figure 3 shows the temperature/pressure relationship for the attractive series of rare earth alloy hydrides of the "AB_5" family. In general, materials with low weights, like magnesium, have too-high heats of formation, whereas metals with low heats of formation, like the rare earths and iron-titanium, are heavy. Iron-titanium combines low cost with low heat of formation and is a prime candidate for hydrogen storage where weight is unimportant. Most experimental work to date has been on this system.

It is possible to radically alter the dissociation behavior of many hydrides, including those of the rare earths, by modifying the composition. For example, Sandrock (1) recently showed that the plateau pressure can be drastically changed when calcium is substituted for the rare earth in the "AB_5" family of hydrides, as shown in Figure 4. This gives hope that hydriding systems might be "tailored" to fit particular applications. However, at the present time both weight and reaction enthalpy are severe handicaps to any known hydride system, including the rare earth family.

- WEIGHT
- VOLUME
- ENTHALPY OR HEAT OF FORMATION
- EQUILIBRIUM PRESSURE
- USEFUL TEMPERATURE SPAN
- COST
- ABUNDANCE
- PHYSICAL FORM
- RATE OF FORMATION AND DISSOCIATION
- PHYSICAL STABILITY
- TOLERANCE TO IMPURITIES
- SAFETY
- THERMAL CONDUCTIVITY

Figure 1. CRITICAL PROPERTIES OF HYDRIDES

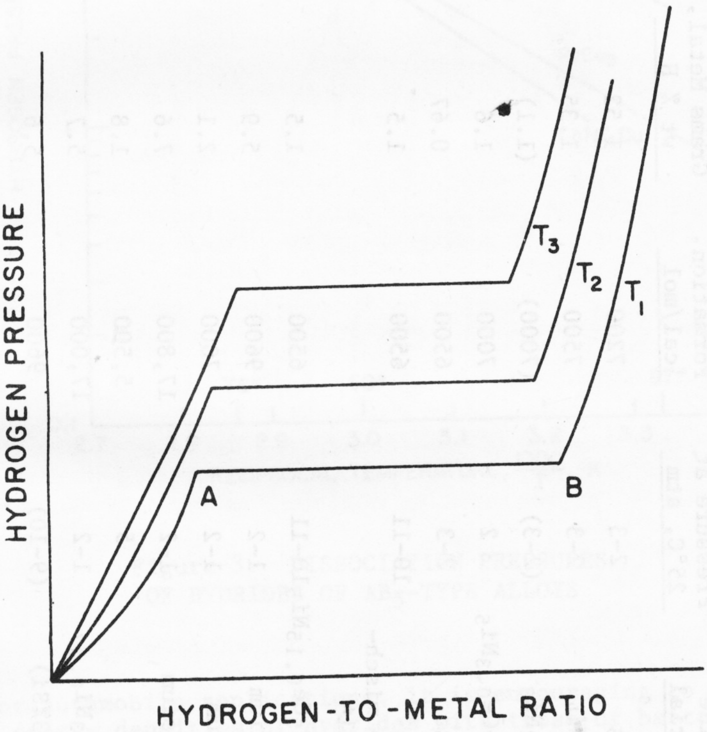

Figure 2. PRESSURE-COMPOSITION ISOTHERM IN A TYPICAL HYDROGEN-METAL SYSTEM

Table 1. CANDIDATES FOR METAL HYDRIDE STORAGE

Hydride Material	Plateau Equilibrium Pressure at 25°C, atm	Heat of Formation, cal/mol	Grams H / Grams Metal, wt % H	Effect of Other Gases (H_2O, O_2)	Relative Rates of Absorption
$LaNi_5$	2-3	7200	1.52	Small	Fast
$LaCuNi_4$	2-3	7500	1.35	Small	Fast
$LaCu_2Ni_3$	(2-3)	(7000)	(1.1)	Small	Fast
$La_{0.7}Ce_{0.3}Ni_5$	2	7000	1.6	Small	Fast
$SmCO_5$	2-3	6500	0.67	Small	Fast
$MmNi_5$ (Mm)= misch-metal*	10-11	6500	1.5	Small	Fast
$Mm_{0.85}Ce_{0.15}Ni_5$	10-11	6500	1.5	Small	Fast
Vanadium	1-2	9600	5.9	Large	Fast
Niobium	1-2	7000	2.1	Large	
Magnesium	1-2	17,800	7.6	Large	Slow
FeTi	5	5,500	1.8	Large	Fast
$Mg_{0.93}Ni_{0.07}$	1-2	17,000	5.7	Large	Fast
V(o.93%Si)	(9-10)	9600	5.6	Large	Fast

* A "mischmetal" is a mixture of rare-earth metals in their naturally occurring composition.

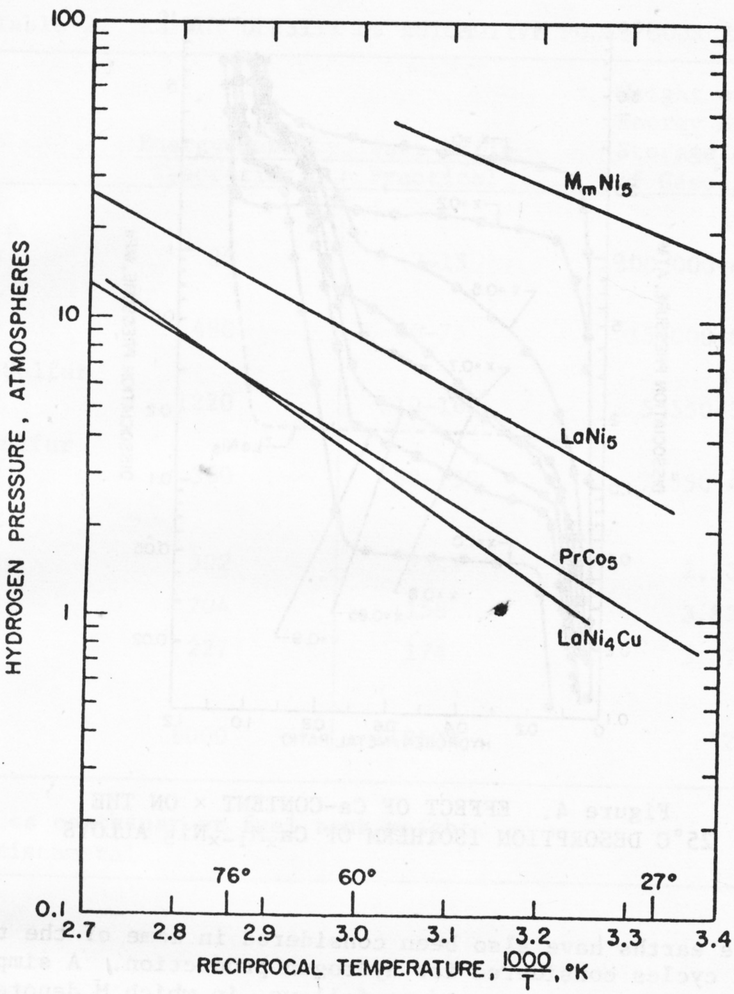

Figure 3. DISSOCIATION PRESSURES OF HYDRIDES OF AB_5-TYPE ALLOYS

For automobile applications, it is encouraging to compare the stored energy densities of hydrides with those of battery systems. Table 2 is an interesting comparison of vehicle storage weights showing that the hydride systems, though uncompetitive with gasoline, are considerably better than batteries.

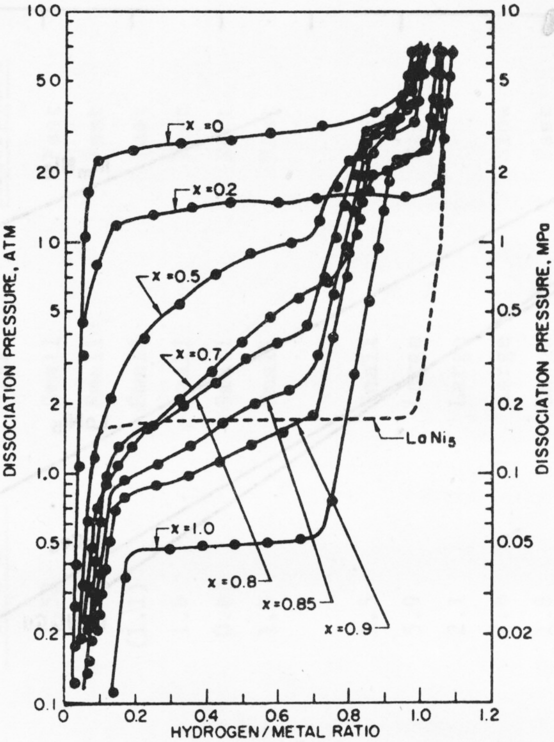

Figure 4. EFFECT OF Ca-CONTENT × ON THE 25°C DESORPTION ISOTHERM OF $Ca_xM_{1-x}Ni_5$ ALLOYS

Rare earths have also been considered in some of the thermochemical cycles considered for hydrogen production. A simple two-step cycle is represented as follows, in which M denotes a metal:

$$M + H_2O \rightarrow H_2 + MO$$

$$\underline{MO \rightarrow M + 1/2O_2}$$

Sum $H_2O \rightarrow H_2 + 1/2O_2$

Unfortunately, two-step cycles of this type, which operate at a temperature compatible with available nuclear or solar heat sources, do not exist; and cycles with three or more steps must usually be considered. IGT has considered and analyzed over 170 cycles, of which three have involved rare earths. Of these, the first two require excessive temperatures for operation.

Table 2. ENERGY DENSITY OF AUTOMOTIVE POWER SOURCES

Power Source	Energy-Density, watt-hr/lb Theoretical	Practical	Weight of Stored Energy Equal to Storage of 20 gal of Gasoline, lb
Lead-Acid Battery	80	2-15	300,000-40,000
Zinc-Air Battery	480	40-75	15,000-8,000
Lithium-Sulfur Battery	1220	110-160	5,550-3,770
Sodium-Sulfur Battery	360	80-150	7,550-4,000
$FeTiH_{1.95}$	302	234*	2,580
$LaCuNi_4$	204	158	3,826
$MmNi_5$ **	227	174	3,470
Gasoline	6000	4850*	125

* Includes container or fuel tank weight.
** Mm = Mischmetal

IGT Cycle K1

No.	Reaction Step	Temp, °C	ΔH kcal	ΔG kcal
1	$2SmCl_2(s)+2HCl(g)\rightarrow 2SmCl_3(s)+H_2(g)$	125	-10.60	+5.40
2	$2SmCl_3(\ell)\rightarrow 2SmCl_2(\ell)+Cl_2(g)$	1225	+41.20	+6.00
3	$Cl_2(g)+H_2O(g)\rightarrow 2HCl(g)+1/2O_2(g)$	925	+14.22	-5.41
	$H_2O\rightarrow H_2+1/2O_2$			

IGT Cycle K2

No.	Reaction Step	Temp, °C	ΔH (kcal)	ΔG (kcal)
1	$2SmCl_2(\ell)+3H_2O(g)\rightarrow Sm_2O_3(s)+4HCl(g)+H_2(g)$	925	+45.55	-9.75
2	$Sm_2O_3(s)+6HCl(g)\rightarrow 2SmCl_3(s)+3H_2O(g)$	325	-50.79	-4.24
3	$2SmCl_3(\ell)\rightarrow 2SmCl_2(\ell)+Cl_2(g)$	1225	+41.20	+6.00
4	$Cl_2(g)+H_2O(g)\rightarrow 2HCl(g)+1/2O_2(g)$	925	+14.22	-5.41
	$H_2O\rightarrow H_2+1/2O_2$			

IGT Cycle M-2

No.	Reaction Step	Temp, °C	ΔH (kcal)	ΔG (kcal)
1	$2CeCl_3(\ell)+4H_2O(g)\rightarrow 2CeO_2(s)+6HCl(g)+H_2(g)$	925	+76.84	+1.70
2	$2CeO_2(s)+8HCl(g)\rightarrow 2CeCl_3(s)+4H_2O(g)+Cl_2(g)$	125	-39.84	-7.96
3	$Cl_2(g)+H_2O(g)\rightarrow 2HCl(g)+1/2O_2(g)$	925	+14.22	-5.41
	$H_2O\rightarrow H_2+1/2O_2$			

These cycles are not being pursued at IGT at this time because of the high inventories of rare-earth compounds required and the substantial cost of the separated rare earths needed. (Mischmetal cannot be used in this application.) Los Alamos Scientific Laboratory is considering a similar cesium cycle.

Workers at Iowa State University have reported studies on another rare-earth cycle as follows:

$$12H_2O+2EuCl_2+2HCl\rightarrow 2EuCl_3\cdot 6H_2O+H_2$$

$$2EuCl_3\rightarrow 2EuCl_2+Cl_2$$

$$Cl_2+H_2O\rightarrow 2HCl+1/2O_2$$

Again, one should be concerned about the cost and availability of Europium if large-tonnage hydrogen production plants are contemplated.

In general, there is a scarcity of thermodynamic data on the rare-earth compounds, which makes analysis of rare-earth cycles difficult.

Work to date on both hydrides and thermochemical cycles using rare-earths has not produced any clear solutions to the hydrogen storage or production problems. However, there is a real chance that, with a better understanding of hydride behavior and a better knowledge of thermodynamic data, a more appropriate system might evolve for either of these two technologies. This remains a challenge for the rare-earth community — a challenge that should be answered only in the context of economics, availability, and performance effectiveness with competing systems already under development.

REFERENCE

1. G. D. Sandrock, "A New Family of Hydrogen Storage Alloys Based on the System Nickel-Mischmetal-Calciums," Proceedings of the 12th Intersociety Energy Conversion Engineering Conference, 951-58, Paper 779146, American Nuclear Society, LaGrange, Park, IL, 1977.

PERFORMANCE CHARACTERISTICS OF THE HYCSOS CHEMICAL HEAT PUMP SYSTEM BASED ON RARE EARTH TRANSITION METAL AB_5 HYDRIDES*

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ABSTRACT

The Argonne HYCSOS system is a chemical heat pump based on rare earth-transition metal AB_5 hydrides that functions in heating, cooling and energy conversion modes. Hydrogen gas is transferred from one hydride bed by thermal energy input at a characteristic temperature to a second bed where hydrogen is absorbed and thermal energy is released at another characteristic temperature. The two materials used in the present system are $LaNi_5$ and $CaNi_5$.

The demonstration unit has four hydride containing steel tanks of three liter capacity each with internal heat transfer tubing. Three fluid heat transfer loops which can be remotely valved and fluid pumped into the appropriate tank are available. The thermal energy input, solar or other suitable low temperature heat, is simulated by an 18 KW electric heater. A 25 KW water cooled heat exchanger is used for heat rejection. Hydrogen and heat transfer fluid flows and temperature and heater and pump power are measured and recorded on a data logger. Important data are visually displayed on analog readout meters on a graphic panel. For safety considerations, the hydrogen containing subassembly is contained in an enclosed hood provided with continuous hydrogen concentration monitoring. The unit is of sufficient size that thermal losses are small compared to measured heat transfer rates in a heat storage mode, refrigeration mode and power generation mode. Experimental data will be compared with predicted performance.