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## Paper Session II-C - Aerospace Hydrogen Technology and Its Potential Impact on a 21st Century Global Hydrogen Economy

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**AEROSPACE HYDROGEN TECHNOLOGY AND ITS POTENTIAL  
IMPACT ON A 21st CENTURY GLOBAL HYDROGEN ECONOMY**

by

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**ABSTRACT**

Extensive use of liquid hydrogen (LH<sub>2</sub>) in the Space Shuttle Program, helps make the NASA Kennedy Space Center (KSC) one of the world's largest consumers of liquid hydrogen. Hydrogen also has the exciting potential of becoming a universal fuel and energy carrier in the global energy infrastructure of the 21st Century. Because contemporary spaceport operations and aerospace system technologies involve the safe and efficient handling, storage and consumption of large quantities of hydrogen, it is logical and timely to explore the potential technology transfer role a spaceport, such as the NASA Kennedy Space Center, might play in supporting the establishment of an effective terrestrial hydrogen fuel infrastructure in the next century. Early emphasis is placed on innovative programs involving hydrogen-powered surface vehicles, manned and robotic, and the establishment of an academic-industrial center of excellence in close cooperation with government agencies. Because of the inherent demand for large quantities of LH<sub>2</sub> at a major spaceport, the efficacy of co-located hydrogen generation demonstration projects is also suggested.

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**DISCLAIMER:** The views expressed in this paper reflect the personal opinions of the authors and do not necessarily reflect the official views of NASA, EG&G, Inc. or the Florida Institute of Technology (FIT).

## INTRODUCTION

"Plentiful, clean, high in energy content, adaptable to power generation and to industrial, residential and transportation users" -- this statement could be the description of the perfect fuel. In fact, it is a description of the element hydrogen [H], the lightest and most abundant element in the universe [1, 2]. Pure hydrogen is a clean fuel, its only combustion product when burned with oxygen is water. Even when burned in air, hydrogen yields essentially no pollutants. When cooled to a liquid, hydrogen becomes an extremely valuable propellant for rocket vehicles and is the fuel used by the Space Shuttle's Main Engines. Counterbalancing hydrogen's desirable properties is one major drawback: it is rare in elemental form (on Earth). Though terrestrially abundant, hydrogen is almost invariably bonded into chemical compounds. Two common examples are water (H<sub>2</sub>O) which covers some 70 percent of the Earth's surface and all organic matter. Releasing the elemental hydrogen stored in these materials requires expending significant amounts of energy. Since energy must be invested in hydrogen before elemental hydrogen becomes useful as a clean nonpolluting fuel, hydrogen (like electricity) must really be treated as an energy carrier and not a primary energy source in its own right [1-4].

Currently, several million tons of hydrogen are produced annually in the United States, primarily for use in petroleum refining and in making ammonia and methyl alcohol, two major industrial chemicals. Most hydrogen is produced by reacting natural gas or light oil with steam at a high temperature. Small amounts of very pure hydrogen are produced by electrolysis. This more expensive hydrogen is used in special applications (like food processing) that require a higher purity gas than can be inexpensively produced from natural gas or light oil.

Projecting into the next century, strategic energy planners and visionaries anticipate a much larger role for hydrogen as a universal energy storage medium and fuel. Advanced energy storage technologies have become recognized as vital to the more effective use of both solar and nuclear energy resources, not only in space but also on Earth [3-6]. In addition, terrestrial energy applications involving extensive use of traditional fossil fuel resources are now being tempered by the specter of provoking a runaway greenhouse effect.

The use of electricity (another energy carrier) is widespread and growing throughout the world. But electricity is difficult to store economically, requiring the electric power industry to scale its overall generating capacity to accommodate peak demand rather than average demand. With appropriate aerospace technology transfer and mutually beneficial demonstration projects (e.g. hydrogen handling, hydrogen applications, and hydrogen generation projects), future terrestrial electric power systems might produce hydrogen with excess electricity during off-peak hours, store it, and then reconvert the hydrogen to electricity (perhaps using space age

fuel cell technologies) to meet peak demands. The largescale use of solar energy on Earth and on the surface of the Moon (i.e. at the lunar base) also requires a way of storing energy for operations when there is no sunlight available. Hydrogen, produced with electricity, has the potential of serving as this efficient storage medium, with the added feature that its future application could either be in satisfying the need for electric power or the need for a transportation system fuel (surface, air or space).

#### HYDROGEN ACTIVITIES AT THE NASA KENNEDY SPACE CENTER

Liquid hydrogen (LH<sub>2</sub>) is odorless, transparent and noncorrosive. Because of its low boiling point [20.4 K (-423<sup>o</sup>)], LH<sub>2</sub> must be stored in well-insulated cryogenic dewars to preclude excessive boil-off. When exposed to the atmosphere, liquid hydrogen boils vigorously, creating a voluminous white cloud of condensed water vapor. The liberated gaseous hydrogen (GH<sub>2</sub>) is highly combustible over a wide range of mixtures with air or oxygen and burns in air with a pale blue, almost invisible flame. Liquid hydrogen, itself, as well as the cold hydrogen gas evolving from the vigorously boiling liquid can produce severe burns similar to thermal burns upon contact with the skin or other body tissues [7].

At the NASA Kennedy Space Center, LH<sub>2</sub> is principally required as the Space Shuttle Main Engine (SSME) propellant. Other KSC requirements for liquid hydrogen include fuel cell powerplant (FCP) servicing, payload servicing, launch equipment and test facility (LETF) testing, and gaseous hydrogen (GH<sub>2</sub>) production. Gaseous hydrogen is required for fuel cell purging at the launch pad and in the Orbiter Processing Facility (OPF). Table 1 describes the liquid and gaseous hydrogen usage at KSC in support of the first twenty-five Space Shuttle flights [7, 8].

The Space Shuttle Orbiter's main propulsion system (MPS) is supplied with liquid hydrogen and liquid oxygen from the external tank (ET) at prescribed pressures, temperatures, and flow rates. The huge external tank is covered with a multilayered, thermal protective coating approximately 1-inch (2.54 cm) thick which provides a heat shield for the onboard cryogenic propellants (LH<sub>2</sub>/LO<sub>2</sub>). The liquid hydrogen tank is the largest component of the external tank. Its primary functions are to hold 1,449,905 liters (383,066 gallons) of liquid hydrogen at a temperature of 20 K (-253<sup>o</sup>C or -423<sup>o</sup>F) and to provide a mounting platform for the Orbiter and the solid rocket boosters (SRBs). The LH<sub>2</sub> tank is equipped with a vent and relief valve to permit loading, pressurization, and relief functions. The external tank is also instrumented for sensing ullage pressure, ullage temperature, and vent position. Tank level sensors provide propellant loading and shutdown signals. The LH<sub>2</sub> tank comprises the lower three quarters of the Shuttle's external tank (see Figure 1) and is a semi-monocoque structure composed of fusion-welded barrel sections, five-beam ring frames, and forward and aft 0.75-

ellipsoidal domes. The  $LH_2$  tank has a volume of 1497 cubic meters (52,900  $ft^3$ ) and is designed to operate at a nominal pressure of 32 to 34 psia (220.6 to 234.4 kilopascals) with a maximum relief pressure of 42 psia (289.6 kilopascals). This tank contains an antivortex baffle and a siphon outlet to transmit the liquid hydrogen propellant to the ET/Orbiter disconnect through a 17-inch (43.2 cm) line. In a typical Space Shuttle mission, main engine cutoff (MECO) occurs some eight minutes after lift-off. The ET separates immediately after MECO and impacts in a broad ocean area. Other portions of the Shuttle System involving the use of  $LH_2/GH_2$  are: the power reactant storage and distribution system (PRDS), the fuel cell powerplant (FCP), and various payload systems [7].

Electrical power for the Orbiter is generated by three fuel cells that use cryogenically stored hydrogen and oxygen. The power reactant storage and distribution (PRSD) system contains the cryogenic oxygen and hydrogen reactants that are supplied to the fuel cells and the oxygen that is supplied to the environmental control and life support system (ECLSS). The oxygen and hydrogen are stored in double-walled vacuum-jacketed (VJ) Dewar-type spherical tanks in a supercritical condition, that is, 97 K (-176°C or -285°F) for oxygen and 22 K (-251°C or -420°F) for hydrogen. In this supercritical condition, the hydrogen or oxygen takes the form of a cold, dense, high-pressure gas that can be expelled, gaged, and controlled under microgravity conditions. The PRSD supplies hydrogen at 250 psia (1723.4 kilopascals) and oxygen at 900 psia (6205.5 kilopascals) nominal pressure in a single-phase gaseous state to the fuel cell powerplant (FCP) which regulates pressures to a nominal range of 55 to 65 psia (379 to 448 kilopascals). Automatic controls, activated by pressure, energize tank heaters and therefore provide thermal energy to the reactants to maintain pressure during tank depletion. Each tank has relief valves to prevent overpressurization from abnormal operating conditions. About 41.7 kg (92 lbm) of  $LH_2$  are stored in each of the  $LH_2$  storage dewars; or approximately 170 kg (370 lbm) per set of four  $LH_2$  tanks [7]. Each oxygen tank can store 354 kg (781 lbm) of oxygen, or approximately 1400 kg (3100 lbm) per set of four  $LO_2$  tanks. The hydrogen tank is 115.6 cm (45.5 in) in diameter and the oxygen tank is 93.5 cm (36.8 in) in diameter.

Low-temperature fuel cell powerplants (FCPs) that generate power through the electrochemical reaction of hydrogen and oxygen, supply the primary inflight electric power used by the Orbiter. Each FCP is capable of providing DC power at 27.5 to 32.5 volts over a range of 2 to 12 kilowatts. A byproduct of the fuel cell hydrogen-oxygen reaction is potable water, which is provided to the crew [7].

Liquid hydrogen for the launch equipment test facility (LETF) testing of the  $LH_2$  tail service mast (TSM) and  $GH_2$  external tank vent umbilical is supplied from an  $LH_2$  mobile tanker positioned adjacent to the TSM [7]. The LETF hydrogen

system is portrayed in Figure 2. Gaseous hydrogen is used at the Orbiter Processing Facility (OPF) for power reactants storage and distribution (PRSD) system and fuel cell powerplant (FCP) purging, functional checkout of the integrated PRSD/ECLSS, LH<sub>2</sub> detanking from the PRSD system, and FCP startup, as required.

At the launch pads, liquid hydrogen for PRSD system servicing is supplied by an LH<sub>2</sub> mobile tanker through a 1.5 in (3.81 cm) VJ line to the 2,000 gallon (7571 liter) dewar located on the 47.2 m (155 ft) level of the fixed service structure (FSS). This 2,000-gal (7571 liter) dewar is equipped with the following: (1) gas pressurizing system for pressure transfer to the Orbiter PRSD; (2) main transfer/fill valve complex complete with filters; and (3) a vent, emergency dump, and pressure relief system [7].

The 1,450,000 liter (384,000 gal) LH<sub>2</sub> tank of the Shuttle's external tank system is filled from the 3,220,000 liter (850,000 gal) pad LH<sub>2</sub> storage sphere through a 25.4 cm (10-in), 457 m (1,500 ft) long VJ transfer line.

#### Hydrogen Production and Procurement

The liquid hydrogen used at KSC is produced industrially. The most common industrial process for producing hydrogen is the steam reforming process, using natural gas from another major hydrocarbon process, naphtha, or coal gas as the feedstock. Hydrogen is produced by catalyzing the hydrocarbon feedstock with steam and natural gas, propane, or fuel oil for process heat. Currently, the steam reforming process is being used in producing liquid hydrogen for NASA needs. Air Products and Chemicals, Inc. (APCI) of New Orleans now operates two 33-ton/day plants at New Orleans, Louisiana. Since the commercial and government (i.e. Space Shuttle Program) usage projections for liquid hydrogen appear to exceed current production capacity, it appears most appropriate as part of the development of a strategic plan for a hydrogen technology center of excellence based on "spaceport hydrogen experience" to consider once again the possibility of generating hydrogen on site at KSC, perhaps using advanced solar or biotechnology demonstration projects that would satisfy multiple needs (i.e. hydrogen availability, research, prototype engineering demonstrations, technology transfer and commercialization activities, and even effective public education and communication efforts) [3, 7, 9-11].

#### Hydrogen Transportation, Handling & Storage

Currently, under a 12-year contract (awarded by the NASA Marshall Space Flight Center in 1975) APCI of New Orleans provides liquid hydrogen to all government users located east of the Mississippi River. In 1985 management of this contract was transferred to the NASA Kennedy Space Center and in 1987 the contract was extended through November, 1990. The EG&G Fluids Management Office at KSC orders and schedules all liquid hydrogen deliveries for both the Kennedy Space Center and Cape Canaveral

Air Force Station (CCAFA).

Liquid hydrogen is transported from the APCI plant at New Orleans to KSC by government-owned 13,000-gal (49,210 liter) over-the-road mobile tankers. These hydrogen tankers are supplemented when needed with APCI-owned 13,000 gal (49,210 liter) mobile tankers. In addition to these over-the-road LH<sub>2</sub> tanker trucks, four government-owned 34,400 gal (130,220 liter) railcars are also available for transporting LH<sub>2</sub> from New Orleans to KSC [7]. (See Figure 3)

In general, a maximum of five mobile tankers or two railcars can be offloaded simultaneously at the existing LH<sub>2</sub> storage sphere fill manifolds. Liquid hydrogen mobile tankers are received at the KSC Launch Complex-39 Propellant Operations Area where tankers are inspected and then sampled, if necessary. Personal safety equipment is also issued to the drivers, if required. Upon acceptance, the LH<sub>2</sub> tankers are dispatched to the Launch Complex-39 LH<sub>2</sub> Storage Sphere fill manifold. Liquid hydrogen railcars are received and inspected at the East Yard (formerly Beach) siding, which is located between Launch Complex 39A and Launch Complex 39B. Upon acceptance, the railcars are moved to the appropriate Launch Complex 39 LH<sub>2</sub> Sphere for off-loading.

The liquid hydrogen is then transferred from the mobile tankers or railcars through special vacuum-jacketed (VJ) transfer hoses to the facility storage sphere fill manifolds. Tanker and facility LH<sub>2</sub> transfer equipment is purged of possible air contamination, using gaseous helium. When the oxygen content is less than one percent, the equipment is considered ready for liquid hydrogen transfer. Five mobile tankers can connect, off-load, and disconnect in less than one hour; while two railcars can connect, off-load, and disconnect in less than four hours. Generally, a liquid hydrogen transfer loss of about ten percent is experienced during these operations. Personnel safety during liquid hydrogen transfer operations is of prime importance and two major personnel precautions are needed. First, personnel involved in liquid hydrogen handling operations must avoid contact with the liquid or gaseous fluid or with cold components and equipment; second, sparks or initiation of a fire in the vicinity of the hydrogen operation must be avoided [7].

The primary storage of liquid hydrogen at the NASA Kennedy Space Center is accomplished in the two large 3,220,000 liter (850,000 gal) LH<sub>2</sub> Storage Spheres, that are located near the perimeter of each of the two pads at Launch Complex 39. (See Figure 3) Each LH<sub>2</sub> storage sphere inner shell is made of stainless steel and has a diameter of 18.8 m (61.8 ft). The outer shell of each sphere is made of carbon steel and has a diameter of 21.34 m (70 ft). The annular space is filled with perlite insulation and evacuated. The LH<sub>2</sub> Storage Sphere at Complex-39A (since reactivation of the Shuttle Program) has experienced a boiloff rate of about 0.08 percent of the sphere volume or approximately 1890 liters/day (500 gal/day). The

sphere's maximum allowable internal working pressure is 90 psig (621 kilopascals). The remainder of the hydrogen storage system consists of a vaporizer, heat exchanger, vent system, fill manifold, liquid level sensors, and manual and remote-controlled valving. Adjacent to the launch pad LH<sub>2</sub> storage facility is the high-pressure GH<sub>2</sub> facility which has a 34 cubic meter (1,200 ft<sup>3</sup>) capacity at a working pressure of 4,000 psig (27,580 kilopascals).

Finally, a 25.4 cm (10 in) diameter, 460 m (1,500 ft) long, VJ pipeline is used to transfer LH<sub>2</sub> from the 3,220,000 liter (850,000 gal) LH<sub>2</sub> Storage Sphere to the Space Shuttle's ET. This pipeline is adequate to accommodate a nominal 45,425 liter/min (12,000 gal/min) fast-fill rate for the Space Shuttle vehicle [7].

#### A SPACEPORT HYDROGEN TECHNOLOGY CENTER OF EXCELLENCE

Hydrogen holds great promise for becoming a universal, "pollution-free" fuel and versatile energy carrier in a 21st Century global energy infrastructure. The NASA Kennedy Space Center, with its unique hydrogen operations, represents an exciting nucleation site at which to create a world-class hydrogen technology center. We are now developing a strategic plan to explore the creation of a "Spaceport Hydrogen Technology Center of Excellence" through which the unique hydrogen handling experience, safety procedures, applications, and even projected consumption patterns associated with a growing national space program are effectively transferred into projects and demonstration programs supporting the use of hydrogen in a global energy economy.

This proposed Center of Excellence could be achieved through a variety of implementation pathways, including (but not limited to): (1) a mutually beneficial transfer of NASA KSC hydrogen operations experience to academic-industrial projects exploring hydrogen energy applications; (2) the creation of a NASA Center for the Commercial Development of Space that focuses on hydrogen applications in both space and terrestrial energy systems; (3) the establishment of a NASA Space Engineering Center of Excellence with primary emphasis on space energy storage, propulsion and power systems that use hydrogen; or possibly (4) the formation of an innovative industrial-university consortium on Florida's Space Coast to champion the utilization of aerospace hydrogen technology experience in the pursuit of advanced hydrogen energy projects for both lunar base and terrestrial applications. The initial funding for our proposed Hydrogen Technology Center of Excellence would come from a mixture of federal and state sources as well as private industry. Participating universities would provide key human resources, the professional experience of world-reknown faculty members, and research facilities.



What areas of development would this proposed Center of Excellence pursue? As currently envisioned in our strategic plan, this proposed center would focus on several or all of these areas (taking advantage to the greatest extent possible of the rich and fertile spaceport hydrogen heritage): (1) LH<sub>2</sub> safety, handling, transport and storage; (2) remote operations involving the fueling and servicing of LH<sub>2</sub> powered surface vehicles; (3) the test and demonstration of advanced hydrogen-powered surface vehicles, both manned and robotic; hydrogen-combustors and fuel cell driven; (4) biotechnology and advanced solar techniques for the generation of hydrogen for use both on Earth and in selected space applications such as a mature lunar base; and (5) public communication and education concerning a global hydrogen economy, using key demonstrations integrated into Florida's tourism industry.

One area of potential development, hydrogen-powered surface vehicles, will now be used to suggest technology transfer and growth pathways. Hydrogen will probably not be used as a surface vehicle (e.g. automobile, bus or truck) fuel under today's "oil rich" environment, but any of the following circumstances could quickly rekindle an interest in this promising area: (1) the development of large, stationary energy sources such as solar or nuclear fusion, that produce hydrogen as a principal product or as a byproduct; (2) a global environmental requirement for significantly reducing pollution or for the control of carbon dioxide emissions; (3) another political crisis which curtails or endangers existing oil supplies; or (4) the actual depletion of global petroleum reserves.

An interesting program involving manned and/or robotic surface vehicles would be undertaken to explore the efficacy of hydrogen combustion engines and fuel cell-driven vehicles for a variety of terrestrial (and even lunar base) applications. Vehicle performance, engine characteristics, and extensive test operations could be performed in the vicinity of the NASA Kennedy Space Center, taking advantage of both hydrogen operations experience and the large LH<sub>2</sub> storage capacity that already exists there. One particularly interesting research pathway is the design, development and prototype demonstration of "automated" LH<sub>2</sub> refueling stations. In a reverse aerospace technology transfer process experiences with an automated terrestrial vehicle LH<sub>2</sub> refueling station might have direct transfer potential to the teleoperated/automated refueling of space and surface vehicles at a lunar base spaceport. The testing of a fleet of hydrogen-powered vehicles would provide valuable insight into the utility of hydrogen as a universal fuel in the next century.

#### Hydrogen Car Fleet

Hydrogen vehicle technology has been intensively developed in the United States, Western Europe, Canada, Japan, and Australia. For example, Daimler Benz in the Federal Republic of Germany has recently concluded a \$ 32 million test program

involving an  $LH_2$  fueled internal combustion (IC) automobile [12]. Ten hydrogen-powered station wagons and vans operated around the clock in West Berlin. BMW is working with the German aerospace research agency, DFVLR. Two large sedans, running on liquid hydrogen, are being tested in Munich at BMW headquarters. BMW is also converting one of its new production models for hydrogen tests, and it plans to have a fleet of hydrogen-fueled cars powered by an advanced hydrogen combustion engine in production in the 1995-2000 time frame.

In these recent hydrogen-fueled vehicle developments, pressurized liquid hydrogen was injected by a pump into modified IC engines. The most promising development for powerful hydrogen-fueled IC engines will be the internal mixture formation with late injection, in contrast to the external fuel-air mixture formation in contemporary gasoline engines [13]. Other significant modifications were needed in the  $LH_2$  fuel tank and a fuel preheater. Exhaust emissions are expected to be below the existing regulated limits. One advantage of using  $LH_2$  in contrast to pressurized  $GH_2$  or metal hydrides, is that it enables the vehicle to achieve approximately the same range per fuel filling at about the same mass of gasoline [14]. The main obstacles remaining are safety (real issues and perceived) and the development of a hydrogen fuel infrastructure (i.e. convenient refueling stations, hydrogen availability in bulk, the development of safe refueling procedures, etc..) However, a hydrogen operations and handling infrastructure already exists at the NASA Kennedy Space Center, making it a potentially ideal location for the testing of a fleet of surface vehicles. Human operated test vehicles could be run extensively as part of normal base operations activities, providing a wealth of valuable engineering data in a technically controlled and monitored environment. Large test vehicles, such as specially designed "hydrogen-powered" trams, buses, and "people movers" could readily be integrated into the spaceport tourism infrastructure, providing a multiple return in the form of controlled engineering test data, public education, and tourism stimulation. A fleet of hydrogen-powered robot vehicles might prove to be an exciting future industrial-academic project, conducted perhaps under the aegis of the Florida Solar Energy Center (FSEC) [15, 16]. (See Figure 4)

An alternative to internal hydrogen combustion is to convert hydrogen to electricity (using advanced fuel cell technology) to then power an electric motor driven surface vehicle. Substantially higher efficiency in energy conversion is possible with this technology choice compare to combustion engines, that is 50 percent versus 15 to 25 percent, respectively [17]. Aerospace fuel cell technology dates back well into the Gemini Program, and the aerospace community has a wealth of experience with space-qualified hydrogen-oxygen fuel cells. An advanced fuel cell powered automobile or robot vehicle would use hydrogen, stored as a liquid or in a metal hydride, to generate electricity for an electric motor drive. New developments in fuel cell technology are occurring, such as the alkaline-electrolyte cell

that uses air instead of oxygen [18]. Electric cars have been developed extensively, especially in the case of Paul MacCready (AeroVironment, Inc. and General Motors). The solar-electric vehicle, Sunraycer, which recently won a race across the interior of Australia, featured outstanding developments in power transmission and new materials [19]. Although photovoltaic power is not commercially feasible at this time, the technology advances demonstrated in Sunraycer have brought the electric automobile much closer to widespread utilization. Up until now, electric vehicles have traditionally been powered by heavy storage batteries. However, an advanced hydrogen-powered fuel cell vehicle offers significant advantages, especially in terms of weight and cargo volume.

One important technology now under active development is the use of metal hydrides for storing hydrogen. Although Daimler-Benz and BMW are presently testing  $\text{LH}_2$  fueled vehicles, some test vehicles have been operated with metal hydride storage systems [13]. Certain metal alloys in powdered form can store large volumes of gaseous hydrogen, input at ambient temperature and at pressures below 50 psia (345 kilopascals), in a dense form with about 25 percent smaller volume than liquid hydrogen. Metal alloys such as iron-titanium, lanthanum nickel, and magnesium-nickel, react reversibly with hydrogen to form the solid hydride along with a release of thermal energy. Hydrogen can be removed from the solid simply by reheating. Metal hydrides used as heat pumps and hydrogen compressors operate with thermal energy input but without a mechanical compressor. Their advantages are low-pressure storage, typically 50 to 500 psia (345 to 3450 kilopascals) at room temperature, low volume, economical hydrogen preparation (no liquefaction and little compression cost), and greater relative safety. Their disadvantages are their initial cost (although not completely prohibitive) and their "empty weight", ranging from  $\text{FeTiH}_2$  which stores about 1 wt% hydrogen to  $\text{MgH}_2$  which stores some 7 wt% hydrogen. Metal hydride devices have been successfully used in vehicle road tests as both thermal-powered air conditioners and as hydrogen fuel tanks [13]. There was brief experimentation in the past at NASA/KSC concerning the use of a metal hydride compressor for capturing liquid hydrogen boiloff [20]. This application appears technically and economically feasible and represents another intriguing research pathway for our proposed Hydrogen Technology Center of Excellence. A metal hydride compressor would be used to boost boiloff hydrogen to the required input pressure for a reliquefaction plant, resulting in large savings in  $\text{LH}_2$  cost. One recent study in Japan has suggested the possibility that a metal hydride process can directly liquefy hydrogen without mechanical compression [21]. Studies sponsored by the Marshall Space Flight Center and the Kennedy Space Center have predicted that metal hydrides have potential aerospace uses, including spacecraft thermal storage [22], heat pumping or refrigeration, and longterm hydrogen storage [23].

Photovoltaics (PV) and water electrolysis techniques have progressed to commercial availability on a small scale. For

example, the Florida Solar Energy Center (as well as other centers around the country) has accumulated many person-years of hands-on experience with advanced solar-electric systems. Good quality electrolyzers are also available. An integrated hydrogen-photovoltaic system could be developed using contemporary PV cells, commercial electrolyzers, and advanced metal hydride storage devices. Solar-powered PV cells provide direct power to daytime loads, while part of the power is stored as hydrogen, which is made in the electrolyzer from sea water. Oxygen and concentrated brine are two byproducts. Hydrogen from the electrolyzer, as well as recovered hydrogen boiloff, would then be stored in metal hydride tanks. When needed, hydrogen would be driven off the hydride in a range of pressures (depending on the driving temperature) to various end uses and to a reliquefaction plant. The byproduct oxygen could be used in fuel cells or in various other aerospace industry applications. Thus, stimulated by advances in PV cell technology, metal hydride storage technology, and electrolyzer technology, and building on previous work [9-11], our proposed Center of Excellence in Hydrogen Technology might explore and validate the efficacy of advanced hydrogen generation demonstration projects in conjunction with expanded space activities at both KSC and CCAFS in the 1990s and beyond.

#### SUMMARY

Hydrogen has the potential of becoming the universal fuel and major energy carrier of the global energy system of the next millennium. Capitalizing on the unique and highly successful spaceport hydrogen experience now resident at the NASA Kennedy Space Center, an innovative industrial-academic Center of Excellence (working in close cooperation with government agencies) could be developed. This Hydrogen Technology Center of Excellence, thriving on aerospace technology transfer, could easily grow into a world-class facility that establishes a truly advanced energy system technology pathway not only for terrestrial applications but even for future space applications on the lunar and Martian surfaces. The authors are now actively developing a strategic plan for the creation of this Center of Excellence and encourage inputs and suggestions.

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