Clean Energy Research Institute

University of Miami □ Coral Gables, Florida 33124

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DoE Research Project

SOLAR HYDROGEN ENERGY SYSTEM

#DE-FG36-95GO10060

ANNUAL REPORT

1995-1996

Principal Investigator: T. Nejat Veziroglu

Prepared for

U.S. Department of Energy
Hydrogen Program
1000 Independence Avenue, S. W.
Washington, DC 20585

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CONTENTS

	Pages
1. TASK A: SYSTEM COMPARISON OF HYDROGEN WITH OTHER ALTERNATIVE FUELS IN TERMS OF EPACT REQUIREMENTS (Task Director: F. Barbir / T. N. Veziroglu)	A1-A10
2. TASK B: PHOTOVOLTAIC HYDROGEN PRODUCTION (Task Director: H. W. Hiser)	B1-B30
3. TASK D: HYDROGEN SAFETY STUDIES (Task Director: M. R. Swain)	D1-D35

TASK A

**SYSTEM COMPARISON OF HYDROGEN WITH OTHER ALTERNATIVE FUELS
IN TERMS OF EPACT REQUIREMENTS**

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Abstract

The feasibility of several alternative fuels, namely natural gas, methanol, ethanol, hydrogen and electricity, to replace 10% of gasoline by the year 2000 has been investigated. The analysis was divided into two parts: (i) analysis of vehicle technologies, and (ii) analysis of fuel production storage and distribution, from the primary energy sources to the refueling station. Only technologies that are developed to at least demonstration level were considered. The amount and type of the primary energy sources have been determined for each of the fuels being analyzed. A need for a common denominator for different types of energy has been identified.

Project Rationale

Section 502 (a) of the Energy Policy Act (EPACT) of 1992, requires a program promoting domestic replacement fuels in light duty motor vehicles which will have the greatest impact in reducing oil imports, improving the health of the Nation's economy and reducing greenhouse gas emissions. It sets the goals of achieving 10% replacement by 2000 and 30% replacement by 2010. Energy Policy act defines alternative fuels as: methanol (or mixtures of >85% of methanol), ethanol (or mixtures of >85% of ethanol), natural gas, liquefied petroleum gas, electricity, **hydrogen**, coal derived liquids and fuels derived from biological materials. Each of these fuels is derived from primary sources and has different efficiencies associated with its processing, delivery, storage and end use. Different processes involved imply different

economic requirements and different emissions. Consequently, the impact each of these fuels may have on the health of our nation's economy and environment would be different as well.

The objectives of this project were:

- determine technical and economic feasibility of each of the replacement fuels to meet the EPACT goals;
- determine the potential effects of such replacement on economy and environment;
- examine and highlight hydrogen's potential as compared with other replacement fuels.

Transportation Fuel Requirements

Gasoline is the primary transportation fuel in the U.S. Current gasoline consumption is 315 million gallons per day (over 100 billion gallons per year) [1]. DOE projects that gasoline consumption will continue to increase in spite of increasing vehicle efficiency (Table 1) [1]. This forecast is based on an assumption of uninterrupted oil supply and relatively steady prices [2].

Table 1 Current and future gasoline consumption

		1995	2000	2010
gasoline consumption	10 ⁶ gallons/day	315	340	353
avg. vehicle efficiency	mpg	19.3	20.3	21.8
new vehicle efficiency	mpg	27.8	28.9	32.8
vehicle-miles	10 ¹² miles/yr	2.22	2.52	2.81
gasoline price*	1993 \$/gallon	0.727	0.815	0.867

* taxes not included

In order to achieve 10% fuel savings by 2000 (34 million gallons of gasoline per day) it would be necessary to introduce vehicles powered by alternative fuels and traveling 2.52×10^{11} miles/yr. This may be achieved by replacing 10% of vehicles with average efficiency (20.3 mpg in 2000) or 6% of the most inefficient (older) vehicles (with 13.5 mpg fuel efficiency on average). The later is a more likely scenario.

Alternative fuels make insignificant contribution today (less than 1% of total vehicle fuels) [3]. However, large amount of methanol and ethanol are added to gasoline as oxygenates (either directly or indirectly), as shown in Table 2. This is still much less than required 10%. In order to determine the amount of each alternative fuel needed to replace 10% of gasoline, it is important to determine the efficiency of the alternative fuel vehicles first, i.e., to determine the amount of fuel needed to travel distance of 1 mile (or 1 km).

Table 2 Consumption of vehicle fuels in U.S. (1995)
(million gallons of gasoline equivalent)

	consumption	percentage
<u>Alternative Fuels</u>		
LPG	260.0	0.23
CNG	43.6	0.04
LNG	3.1	
Methanol (85%)*	2.4	
Methanol (100%)	3.1	
Ethanol (85%)*	0.1	
Ethanol (95%)*	0.1	
Electricity	0.6	
Subtotal	312.9	0.28
<u>Oxygenates</u>		
MTBE	2,973.3	2.57
Ethanol in gasohol	919.3	0.79
Other alcohols & ethers	201.2	0.17
Subtotal	4,093.8	
<u>Diesel</u>	26,739.6	
<u>Gasoline**</u>	115,809.0	

* includes gasoline

** includes oxygenates

Vehicle Efficiency Analysis

Several vehicle propulsion technologies are available and applicable for alternative fuels. Almost each of the alternative fuels (except electricity) may be used in internal combustion engines with minor modifications mainly in fuel supply components. Another technology which is currently being developed is fuel cell/electric vehicle technology. Fuel cells, particularly proton exchange fuel cells, are very promising because of their high conversion efficiency, simplicity, high power density, and zero emissions. Hydrogen is the fuel of choice for fuel cells. However, due to lack of hydrogen infrastructure some car manufacturers are developing on-board reforming systems that enable the use of more conventional fuels such as methanol and natural gas. Direct methanol fuel cells are being developed, but are far from being developed even to a demonstration level. Electricity is also considered to be an alternative fuel. The only way to use it as fuel is to store in on-board in batteries. A variety of battery technologies are being developed with a common goal to reduce the weight and increase vehicle range [4].

**Table 4 Results of vehicle efficiency analysis for fuel cell vehicles
(FUDS cycle)**

	100 miles range		300 miles range	
	kWh*/km	mpg**	kWh*/km	mpg**
GH ₂	0.306	68.6	0.327	64.2
LH ₂	0.301	69.8	0.311	67.5
CNG	0.464	45.3	0.478	43.9
Methanol	0.470	44.7	0.483	43.5

* lower heating value of fuel (1 kWh = 3,412 Btu)

** gasoline equivalent

**Table 5 Results of vehicle efficiency analysis
for battery electric vehicles
(FUDS cycle)**

type of battery	100 km range	
	kWh*/km	mpg**
Na/Sulfur	0.256	82.0
Lead-Acid	0.516	40.7
Li-Ion	0.230	91.3
Li-AIS or Li-FeS	0.276	76.1
Nickel/Iron	0.533	39.4
Nickel/MeH	0.250	84.0
Zn/Bromine	0.281	74.7

*charging included

** gasoline equivalent

Fuel Production Analysis

Table 6 summarizes the results of the above analysis and shows the amount of each fuel needed to achieve 10% of gasoline replacement. However, the analysis has been expanded further to include fuel production, processing, storage and delivery technologies, in order to determine possible obstacles (in terms of quantitative and qualitative primary energy requirements, costs, technology availability, infrastructure issues, etc.) and benefits (in terms of reduced greenhouse gas emissions throughout the analyzed pathways).

**Table 6 Summary of vehicle efficiency analysis:
Amount of fuel needed to replace 10% of gasoline**

	kWh/km	10 ⁹ kWh/yr (10%)	10 ⁹ kWh/yr (10%)	current production
<u>Internal combustion engine</u>				
CNG	0.661	271.0	162.6	5,600
LPG	0.650	266.5	159.9	644
Methanol	0.578	237.0	142.2	28
Ethanol	0.567	232.5	139.5	31
GH ₂	0.707	289.9	173.9	~300
LH ₂	0.624	255.8	153.5	
<u>Fuel cells</u>				
GH ₂	0.327	134.1	80.5	~300
LH ₂	0.311	127.5	76.5	
CNG	0.478	196.0	117.6	5,600
Methanol	0.483	198.0	118.8	28
<u>Battery electric vehicles</u>				
Electricity	0.260	106.6	64.0	3,000

For each of the fuels there are several possible pathways from primary energy sources to the fuel. In this pathway typically one or more energy conversions are included, such as for example, solar energy into electricity (e.g. photovoltaic conversion) and then electricity into hydrogen (e.g. water electrolysis). The efficiencies of these conversions were taken into account when calculating primary energy requirement. In addition, other forms of energy, typically electricity (but in some cases fuels), are needed in process of fuel transportation, storage or delivery. For example, in case of hydrogen, electricity is needed for hydrogen compression to a desired pressure needed for pipeline transport, or for liquefaction. For harvesting biomass, fuels are needed (gasoline, diesel or biomass based fuels). This type of energy (electricity and already processed fuels) represents high quality inputs and have to be accounted separately. Therefore, primary energy and high quality inputs were quantitatively and qualitatively determined. Figure 1 shows a typical pathway analysis (a) and corresponding system analysis (b) that shows energy conversions and high quality inputs. High quality inputs do not necessarily have to be energy; they may be goods and services.

Tables 7 and 8, show the results of these pathway analysis. The amounts and types of both primary energy and high quality inputs are shown.

**Table 7 Primary energy and high quality feedback for fuel production and distribution
(internal combustion engine vehicles)**

	primary energy 10 ⁹ kWh/yr	primary energy type	high quality feedback 10 ⁹ kWh/yr	high quality feedback type
natural gas (CNG)	271.0	natural gas	54.5	electr./nat. gas
LPG	266.5	nat. gas/oil	30.9	LPG/nat gas
methanol from natural gas	381.0	natural gas	34.7	el./fuel
methanol from biomass	11,200.0	solar	56.0	fuel/el.
ethanol from corn	12,900.0	solar	65.0	fuel/el.
gaseous hydrogen from nat. gas	402.6	natural gas	87.4	nat. gas/electr.
GH ₂ from biomass	12,000.0	solar	82.0	fuel/electr.
GH ₂ from electricity mix	828.3	mix	63.2	electr.
GH ₂ from solar electricity	2,636.0	solar	63.2	electr.
GH ₂ from wind electricity	1,530.0	wind	63.2	electr.
liquid hydrogen from nat. gas	355.4	natural gas	104.0	nat. gas/electr.
LH ₂ from biomass	10,600.0	solar	99.2	fuel/electr.
LH ₂ from electricity mix	731.0	mix	82.6	electr.
LH ₂ from solar electricity	2,326.0	solar	82.6	electr.
LH ₂ from wind electricity	1,347.0	wind	82.6	electr.

**Table 8 Primary energy and high quality feedback for fuel production and distribution
(fuel cell vehicles)**

	primary energy 10 ⁹ kWh/yr	primary energy type	high quality feedback 10 ⁹ kWh/yr	high quality feedback type
natural gas (CNG)	196.0	natural gas	39.4	electr./nat. gas
methanol from natural gas	318.0	natural gas	30.0	el./fuel
methanol from biomass	9,360.0	solar	46.8	fuel/el.
gaseous hydrogen from nat. gas	186.2	natural gas	40.4	nat. gas/electr.
GH ₂ from biomass	5,550.0	solar	37.9	fuel/electr.
GH ₂ from electricity mix	383.1	mix	29.2	electr.
GH ₂ from solar electricity	1,220.0	solar	29.2	electr.
GH ₂ from wind electricity	708.0	wind	29.2	electr.
liquid hydrogen from nat. gas	177.1	natural gas	51.8	nat. gas/electr.
LH ₂ from biomass	5,280.0	solar	49.4	fuel/electr.
LH ₂ from electricity mix	364.0	mix	41.2	electr.
LH ₂ from solar electricity	1,160.0	solar	41.2	electr.
LH ₂ from wind electricity	671.0	wind	41.2	electr.

Discussion of Results

It would be impossible to draw any conclusions from Tables 7 and 8 unless a common denominator is applied that would allow combining primary energy sources and high quality inputs. Possible candidate for a common denominator is money, or costs of fuels. However money is only paid for high quality services, actually goods and services. No money goes for the primary energy sources - money only goes for the goods and services needed to extract and utilize those services. It has therefore been proposed to use emergy as a common denominator in such analyses. Term "eMergy" has been introduced by Odum [12-13]. It stands for embodied energy, and it is energy of one type (typically solar) required in transformations to generate flow of energy, materials, goods and services, or money. Emergy is therefore a more complete unit than money, because it does include primary energy sources. The system that maximizes the power with minimum use of the primary energy sources is therefore preferable. Emergy analysis has yet to be performed. A complete analysis should include all the inputs, not only energy, such as goods and services which can also be expressed in terms of embodied energy, i.e., emergy. Emergy therefore combines energy and economic analysis. Environmental effects could be expressed in terms of monetary value of environmental damage [14], and could eventually be added to this analysis.

Another common denominator that may be used for comparisons between different fuels and their production pathways is land requirement. For any energy activity land is required. Table 9 shows the results of land requirement analysis, based on data in [15]. Surprisingly, solar hydrogen (photovoltaics to electricity to hydrogen) results in the least amount of land area being used. It requires 12 times less area than alcohols, and this area does not have to be good quality agricultural land, thus competing with food production. On the contrary, the highest insolation is in dry desert areas in the south which are not being used for agriculture.

Table 9 Land area requirement for various fuels

	fuel required 10 ⁹ kWh	land area required km ²
<u>Internal combustion engine vehicles</u>		
Gasoline	301.0	4,800
Methanol	237.0	87,300
Ethanol	232.5	192,000
GH ₂ from biomass	289.9	52,200
GH ₂ from hydropower	289.9	11,500-500,000
GH ₂ from solar PV el.	289.9	2,516
GH ₂ from wind el.	289.9	3,700-26,900
<u>Fuel cell vehicles</u>		
Methanol	198.0	73,000
GH ₂ from biomass	134.1	24,100
GH ₂ from hydropower	134.1	5,300-240,000
GH ₂ from solar PV el.	134.1	1,200
GH ₂ from wind el.	134.1	1,710-12,400

Conclusions and Plans for Future Work

Several energy pathways were defined for each of the fuels being considered, namely, hydrogen, compressed natural gas, electricity, methanol and ethanol. The analysis was divided in two parts: (i) analysis of vehicle technologies, and (ii) analysis of fuel production storage and distribution, from the primary energy sources to the refueling station. Only technologies that are developed to at least demonstration level were considered. The efficiencies of individual steps as well as the efficiencies of the overall pathways were calculated. The amount of each of the alternative fuels analyzed needed to meet the EPACT goals have been determined.

In the subsequent phases of this project the results of individual step analyses will be synthesized. For each alternative fuel a steady state model will be compiled, that will then be used to assess economic and environmental impacts per unit of services delivered, which in this case is the vehicle-mile. Both energy and money will be used as common denominators and the results of these two analyses will be compared mutually compared.

At the end of the projects the conclusions will be reached regarding the feasibility of each alternative fuels to meet the EPACT goals and recommendations will be given regarding, not only the fuel, but also the specific technologies that would meet the EPACT requirements with optimal benefits to national economy and to the environment.

Various technologies being evaluated are at different stages of development, which makes comparisons very difficult. A carefully and objectively selected set of assumptions is needed in order to compare the technologies on an equal basis. Development of key technologies will have to be monitored and the set of assumptions constantly updated.

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Figure 1 Comparison between pathway analysis and proposed system analysis

TASK B

PHOTOVOLTAIC HYDROGEN PRODUCTION

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Abstract

This is a new project, which started in June 1995, and involves photovoltaic hydrogen production as a fuel production method for the future. In order to increase the hydrogen yield, it was decided to use hybrid solar collectors to generate D.C. electricity, as well as high temperature steam for input to the electrolyzer. In this way, some of the energy needed to dissociate the water is supplied in the form of heat (or low grade energy), to generate steam, which results in a reduction of electrical energy (or high grade energy) needed. As a result, solar to hydrogen conversion efficiency is increased.

In the above stated system, the collector location, the collector tracking sub-system (i.e., orientation/rotation), and the steam temperature have been taken as variables. Five locations selected - in order to consider a variety of latitudes, altitudes, cloud coverage and atmospheric conditions - are Atlanta, Denver, Miami, Phoenix and Salt Lake City. Plain PV and hybrid solar collectors for a stationary south facing system and five different collector rotation systems have been analyzed. Steam temperatures have been varied between 200°C and 1200°C.

During the first year, solar to hydrogen conversion efficiencies have been considered. The results show that higher steam temperatures, 2 dimensional tracking system, higher elevations and dryer climates cause higher conversion efficiencies. Cost effectiveness of the sub-systems and of the overall system will be analyzed during the second year. Also, initial studies will be made of an advanced high efficiency hybrid solar hydrogen production system.

Introduction

There are two important global issues facing mankind: Depletion of fossil fuels and environmental problems caused by the combustion of fossil fuels. Fossil fuels today meet about 80% of our energy requirement. However, they are being depleted fast. According to the best estimates, petroleum production and natural gas production will peak in the early 2000s, and will then start to decline. Coal

deposits will last longer. It is possible to manufacture synthetic gasoline and synthetic natural gas from coal. However, we may not be able to use all the coal resources because of the environmental complications.

Combustion products of fossil fuels produce pollution, acid rains, global warming and ozone layer depletion. According to our studies at the University of Miami's Clean Energy Research Institute, the worldwide environmental damage caused by fossil fuels will be \$ 2,600 billion for this year alone, which is about 14% of the Gross World Product. This is a very large figure. Conversion to clean energy sources and carriers would enable the world to save this enormous sum, and perhaps use it to improve the quality of life throughout the planet Earth - not only for humans, but also for its flora and fauna, as well.

Because of the foregoing, there is a need for new and environmentally compatible primary energy sources and energy carriers. Studies show that this condition is best met by hydrogen, a clean and efficient energy carrier, produced using solar energy, an environmentally compatible and renewable primary energy source. A solar hydrogen energy system could meet the energy requirements of the world, as well as that of the United States, forever or at least as long as the sun exists.

In the solar hydrogen energy system, it is important that hydrogen must be produced as efficiently as possible, and as economically as possible. The first year's study concentrates on obtaining the best efficiency, and the second year's study will concentrate on cost optimization.

APPROACH AND RATIONALE

In the electrolysis of water, it is well known that as the water temperature increases, electrical energy required to electrolyze the water decreases. If high temperature steam is used instead of high temperature water, the electrical energy needed for electrolysis further decreases. Low grade thermal energy is used in order to reduce the amount of high grade electrical energy.

In a PV collector only electricity (d.c. electricity) is produced. However, using a hybrid solar collector, one could produce both electricity and heat, thereby increasing the overall conversion efficiency. Hence, it becomes quite convenient to match a solar hybrid collector with a high temperature steam electrolyser in order to increase the solar to hydrogen conversion efficiencies. It has therefore been decided to investigate a hybrid collector/high temperature electrolyser system for solar hydrogen production, in order to come up with an efficient, clean and sustainable energy system.

SOLAR HYDROGEN PRODUCTION SYSTEM

Fig. 1 is a schematic of the solar hydrogen production system investigated. It consists of a solar hybrid collector, electricity storage sub-system, power regulator, high temperature steam storage sub-system and a high temperature steam electrolyser. As raw material, water is supplied to the system, and the products are hydrogen, oxygen and high temperature steam.

Fig. 2 is a schematic of a possible solar hybrid collector. Relatively high temperature PV cells, such as GaAs, are to be wrapped around the water/steam tubes located along the focal axis of each parabola (Sharan et al 1987). The tubes could be single flow or possibly counter flow to produce a more uniform temperature for the PV cells mounted on them (Sopian et al 1995). A cover over the collector can be used to reduce losses from the water/steam tubes. Also, it may be possible to use a transparent thin film PV membrane on the upper surface of this cover in order to increase the overall electrical production (Seidenfaden 1995).

In a hybrid collector, solar radiation of certain wavelengths can be converted to D.C. electricity with efficiencies of 5 to 30%, depending on the photovoltaic material and temperature. The remainder of the solar radiation (viz., 70 to 95%) can be converted to heat with higher efficiencies (e.g., 50%), and this heat can be used to produce high temperature steam in parabolic through type collectors.

In this system study, five different collector rotation systems have been selected as suitable for use with two dimensional hybrid parabolic collectors. Four systems rotate around a single axis, and the fifth system rotates around two axes, so that the collector is always facing the sun (See Fig. 3).

The electrical storage sub-system, in order to provide for a 24 hour operation, could use batteries, hydro, fly wheel, compressed air, etc. The high temperature storage sub-system should be well insulated.

In order to see the effect of location (latitude, elevation, humidity, wind speed and cloud coverage), five locations have been selected. They are: Atlanta, Georgia; Denver, Colorado; Miami, Florida; Phoenix, Arizona; and Salt Lake City, Utah. The steam temperatures have been varied between 200°C and 1200°C.

ANALYSIS

Solar Insolation:

In order to make comparisons of collector mounting axes and rotation as they affect incident annual solar energy and production

efficiencies of hydrogen, oxygen and excess heat, it is necessary to define collector orientation angles. Fig. 4 presents the collector orientation angle definitions relative to a horizontal surface tangent to the earth at the collector location. Note that for a sun-tracking collector, the collector angle would equal the solar elevation angle. Also, the collector azimuth angle γ would equal the solar azimuth angle γ_s .

Insolation Equations:

In this sub-section, the equations defining the insolation impinging on the collector area are presented. The total annual solar energy impinging on the receiver or collector (E_s) is made up of a direct component (I_{dr}), a diffuse component (I_{df}) and a ground reflected component (I_{re}), i.e.,

$$E_s = A_c \sum_{n=1}^{365} \int_{t_r}^{t_s} m_i (I_{dr} + I_{df} + I_{re}) dt \quad (1)$$

where A_c is the collector area, n is the day, i is the augmentation factor due to i th-type tracking system, I_{dr} and I_{re} are the components of solar radiation, t_s and t_r are the sunset and sunrise hours, and t the time.

Direct component of solar radiation is given by

$$I_{dr} = I_b R_b \quad (2)$$

where R_b is the geometric factor, and I_b is the beam radiation on a horizontal surface.

Diffuse radiation, I_{df} , has three components: isotropic diffuse sky dome radiation, circumsolar diffuse radiation and horizon diffuse radiation (Duffie and Beckman 1991), and can be expressed as

$$I_{df} = I_{df'sd} + I_{df'cr} + I_{df'hd} \quad (3)$$

where radiation from sky dome,

$$I_{df'sd} = I_d (1-F_1) (1+\cos(\beta))/2 \quad (4)$$

circumsolar radiation,

$$I_{df,cr} = I_d F_1 a/b \quad (5)$$

horizon diffuse radiation,

$$I_{df,hd} = I_d F_2 \sin(\beta) \quad (6)$$

Also, I_d is the radiation on a horizontal surface; β is the surface elevation angle depending on tracking system; F_1 and F_2 are the circumsolar and horizon brightness coefficients; and a and b are the angles of incidence parameters for the cone of circumsolar radiation.

Ground reflected component of solar radiation is given by,

$$I_{re} = I_p (1 - \cos(\beta))/2 \quad (7)$$

where p is the ground reflectivity and I is the total insolation on a horizontal surface. Fig. 5 presents a schematic of the solar radiation components given above, which are impinging on a solar collector.

Hybrid Collector Energy Conversion:

In the hybrid collector, solar radiation is converted both to electrical and thermal energies. Annual electricity production is given by,

$$E_{ce} = \eta_{ce} A_c E_s \quad (8)$$

where η_{ce} is the electrical energy conversion efficiency for the collector.

Annual thermal energy production is given by,

$$E_{ct} = \eta_{ct} A_c E_s \quad (9)$$

where η_{ct} is the thermal energy conversion efficiency. Then, the total annual energy conversion rate for the collector becomes,

$$E_c = (\eta_{ct} + \eta_{ce}) A_c E_s \quad (10)$$

Energy Entering Electrolyser:

Electrical and thermal energies produced in the collector follow two paths on the way to the electrolyser. Electricity goes either directly to the power regulator or to the electrical storage to be used during the periods of insufficient (or no) PV electricity generation. From the power regulator electricity is supplied to the high temperature electrolyser.

Annual electrical energy entering the electrolyser is given by,

$$E_{ee} = \eta_{se} \eta_{re} E_{ce} \quad (11)$$

where η_{se} is the electrical energy storage efficiency, and η_{re} is the electrical power regulator efficiency.

High temperature steam produced in the collector enters the thermal storage sub-system, where water is used to regulate the steam temperature. Steam at the desired temperature and quantity then enters the electrolyser. Because of the discrepancies between the electrical and thermal conversion efficiencies of the solar collector, and the electrical and thermal requirements of the electrolyser, there is always more steam produced than the amount which can be electrolysed. Excess steam then becomes available for various residential, commercial and/or industrial applications.

Annual thermal energy (steam energy) entering the electrolyser becomes,

$$E_{et} = \eta_{st} \eta_{rt} (e_{et}/e_{ee}) E_{ce} \quad (12)$$

where η_{st} is the thermal energy storage efficiency, η_{rt} is the thermal energy regulating efficiency, e_{et} is the thermal energy requirement of the electrolyser per unit mass of steam and e_{ee} is the electrical energy requirement of the electrolyser per unit mass of steam.

Total energy supplied to the electrolyser per year becomes,

$$E_e = (\eta_{se} \eta_{re} + \eta_{st} \eta_{rt} (e_{et}/e_{ee})) E_{ce} \quad (13)$$

Then the excess thermal energy available per year is given by,

$$E_h = \eta_{st} (E_{ct} - E_{et}) \quad (14)$$

High Temperature Electrolyser Characteristics:

Fig. 6 presents the electrical energy (high grade energy) and the thermal energy (low grade energy) requirements of a steam electrolyser as a function of steam temperature. It can be seen that as the steam temperature rises thermal energy requirement increases and electrical energy requirement decreases. The pertinent relationships are presented here below.

The electrical energy (high grade energy) requirement per unit mass of steam is defined as,

$$e_{ee} = e_{ee,373} + S_e(T_e - 373) \dots (= \Delta G) \quad (15)$$

The thermal energy (low grade energy) requirement per unit mass of steam is defined as,

$$e_{et} = e_{et,373} + S_t(T_e - 373) \dots (= T\Delta S) \quad (16)$$

The total energy requirement of electrolyser is given as,

$$e_e = e_{ee,373} + e_{et,373} + (S_e + S_t)(T_e - 373) \dots (= \Delta G + T\Delta S) \quad (17)$$

where S_e is the change in electrical energy requirement of the electrolyser per unit mass of steam per unit temperature difference (de_{ee}/dT), ΔG is the free energy change, T is the absolute temperature, S_t is the change in thermal energy requirement of the electrolyser per unit mass of steam per unit temperature difference (de_{et}/dT), ΔS is the entropy change.

Fig. 7 shows the mismatch between the electrical and thermal energies produced at the hybrid collector in one hand, and those required at the electrolyser in the other hand for an electrolyser temperature of 1000 °C. It can be seen that whereas the E_{therm}/E_{elect} ratio at the collector is 1.80, it is 0.45 for the electrolyser. Hence, there is always some excess heat produced, which increases with the energy generation.

Hydrogen, Oxygen and Excess Heat Production Rates:

At the electrolyser, annual hydrogen and oxygen production are given by,

$$\dot{m}_{H_2} = \eta_e E_e / 9e_e \quad (18)$$

and

$$\dot{m}_{O_2} = \eta_e 8E_e / 9e_e \quad (19)$$

where η_e is the electrolyser efficiency, and $\dot{m}$ is the annual amount (mass) produced.

At the thermal storage, the annual amount of excess heat (in terms of energy) available is given by,

$$E_h = \eta_{st} (E_{ct} - E_{et}) \quad (20)$$

where η_{st} is the thermal energy storage efficiency, E_{ct} is the thermal energy production per year in the hybrid collector, and E_{et} is the thermal energy entering the electrolyser per year.

EVALUATION AND DISCUSSION

In calculating the annual hydrogen, oxygen and excess heat production rates, various conversion efficiencies included in the above equations are needed. It should be pointed out that the calculations are to be made for the early 2000s. The conversion efficiencies selected for such a time are presented in Table I. They are considered to be quite reasonable.

The augmentation factors m_i have been calculated using the formula presented in (Duffie and Beckman 1991) for various collector rotations. The atmospheric data needed, i.e., insolation, wind speed and direction, dew point temperature, dry bulb temperature, ambient temperature and snow depth, for the five cities selected have been obtained from the TMY2 files, down loaded from the National Renewable Energy Laboratory's data bank.

Using the above stated data together with the equations (1) through (20), annual insolation, hydrogen, oxygen and excess heat production rates for the five tracking systems and the five cities selected, and for various steam temperature levels, together with the pertinent efficiencies have been calculated. The results are presented in Tables II through VI.

Table II presents the insolation results for the five tracking systems plus the stationary system, for Miami. It can be seen that the annual insolation received per square meter of collector area ranges from a minimum of 2014 kW.hr for the stationary system to a

maximum of 2910 kW.hr for the 2D tracking system. The second best tracking system is the 1D system with the axis of rotation parallel to the Earth's north-south axis, followed by the 1D system with a horizontal axis parallel to the local north-south direction. The last two columns of Table III presents the difference in insolation and the percent improvements with respect to the insolation for the stationary collector. It can be seen that the 2D system is 45% more efficient, followed by the 1D north-south axis system with 36% more efficiency.

The percentage improvements for the other cities (for any location for that matter) would be the same, although actual insolation would differ from location to location.

Table III presents the annual hydrogen, oxygen and excess heat production rates for plain PV and hybrid collectors, and six tracking systems for Miami. The collector area is 1 m^2 and the electrolyser temperature 1000°C . It can be seen that the hydrogen production rates (and for that matter the oxygen production rates) follow the insolation rates, i.e., 2D tracking system gives the highest rates, followed by 1D system with the axis parallel to the north-south axis of Earth. The stationary system gives the lowest rates, as expected.

When plain PV and hybrid collectors are compared regarding hydrogen and oxygen production rates, hybrid collectors are about 57% more efficient.

Excess heat produced by the hybrid collectors follow the same trend as the hydrogen/oxygen production rates, i.e., 2D tracking system giving the best result, followed by the 1D system with axis parallel to the north-south axis of Earth.

Local efficiencies have been calculated for "hydrogen" and for "hydrogen + excess heat" based on the local insolation. For plain PV collectors, they are 17%, as there is no heat generation. For hybrid collectors, hydrogen production efficiency is 27% (58% higher than the plain PV case), and the total energy (hydrogen + excess heat) production efficiency is 50%. The last column in Table III, gives the efficiencies based on the 2D tracking system. In this case the efficiencies follow the insolation rates, the best being those for 2D system.

Table IV presents the annual averages for the meteorological conditions (i.e., temperature, wind, humidity, clearness and insolation) for the five locations considered. Table V presents hydrogen, oxygen and excess heat production rates for the plain PV and hybrid collectors, for the same locations. The tracking system is the 2D system, collector area 1 m^2 and the electrolyser temperature 1000°C . It can be seen that the location with higher insolation, higher clearness index, lower humidity and lower wind

speed (i.e., Phoenix) gives the best production rates. Hence, in the last column of Table V, the locations selected have been compared with Phoenix. It can be seen that the second best location is Salt Lake City, followed by Atlanta and Denver tying for third place. Although Miami is the most southerly location, higher humidity and higher wind speed (i.e., higher collector losses) make it a close fourth.

Table VI presents the production rates as a function of the steam temperature. The location is Miami, collector area 1 m^2 and the tracking system 2D. It can be seen that the hydrogen and oxygen production rates increase with increasing steam (or electrolyser) temperatures. The excess heat production rate decreases with increase in temperatures, as more of the heat produced is outlined in the electrolyser.

CONCLUSIONS

As a result of this investigation the following conclusions are reached:

1. Hydrogen (and oxygen) production rates are greater for hybrid collectors than those for plain PV collectors. In the case studied, hybrid collectors are 59% more efficient.
2. Hybrid collectors also produce excess (useful) heat. In the case studied, excess heat generation ranged from 16% of the insolation for a stationary collector to 23% for a 2D tracking system.
3. When the tracking systems are compared, 2D system is the best, followed by the 1D system with the axis parallel to the north-south axis of Earth. For the system studied, in comparing hydrogen production, only the 2D system was 42% more efficient than the stationary system. The ratio was the same for the excess heat generation.
4. Locations with higher insolation, higher clearness index, lower humidity, lower wind velocity and higher ambient temperature are better suited for increased hydrogen/excess heat production.

WORK PROPOSED FOR NEXT YEAR

The work proposed for the next year is divided into two parts: (A) cost studies for the hybrid collector/high temperature hydrogen production system, and (B) Initial studies for a super efficiency solar hydrogen production system.

- A. Costing of Present System: This will cover the following studies.

1. Types of hybrid collectors - related costs,
2. Types of electricity storage sub-systems - related costs,
3. Types of thermal storage sub-systems - related costs,
4. Types of electrolyzers - related costs,
5. Overall systems and related costs,
6. Comparisons (environmental and economic).

B. Initial Studies for Super Efficient System:

Fig. 8 presents the proposed super efficient solar hydrogen system. In this system, part of the excess heat is used for D.C. electricity generation through a heat engine/generator combination, and the rest is used as the high temperature steam for additional hydrogen production.

The study will cover the following items:

1. Efficiency studies for sub-systems,
2. Efficiency for overall system.

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Table I. EFFICIENCIES USED IN ANALYSIS

1. Collector Electrical Efficiency, $\eta_{ce} = 0.25$
2. Collector Thermal Efficiency, $\eta_{ct} = 0.38$
3. Electrical Storage Efficiency, $\eta_{se} = 0.80$
4. Thermal Storage Efficiency, $\eta_{re} = 0.80$
5. Electrical Regulator Efficiency, $\eta_{st} = 0.95$
6. Thermal Regulator Efficiency, $\eta_{rt} = 0.95$
7. Electrolyser Efficiency, $\eta_e = 0.90$

**Table II. ANNUAL SOLAR ENERGY INCIDENT ON A 1 m²
COLLECTOR AREA VERSUS COLLECTOR MOVEMENT (MIAMI)**

Collector Movement Mode		Annual Solar Energy Incidence E_s (kWhr)	Difference $E_{si} - E_{sf}$ (kWhr)	Percent Improvement
1. Stationary	W — E	2014	0	0
2. 1-D North-South Axis Continuous Adjustment	W — E	2633	619	31
3. 1-D East-West Axis Continuous Adjustment	W — E	2154	140	7
4. 1-D Rotation About Vertical Axis, Fixed-Slope Continuous Adjustment	W — E	2415	401	20
5. 1-D Parallel-to-Earth Axis Continuous Adjustment	W — E	2733	719	36
6. 2-D Axis Continuous Adjustment	W — E	2910	897	45

**Table III. ANNUAL HYBRID SOLAR HYDROGEN, OXYGEN
AND EXCESS HEAT PRODUCTION VERSUS COLLECTOR MOVEMENT**
(Location: Miami; Collector Area: 1 m²; Hybrid System Electrolyser Temp.: 1000C)

Collector Movement Mode	Type	Hydrogen		Oxygen	Excess Heat	Local Efficiency		2-D Efficiency	
		kg	kWhr	kg	kWhr	Hydrogen	Hydrogen + Heat	Hydrogen	Hydrogen + Heat
1. Stationary	Plain	8.6	341	68.8	0	17	17	12	12
	Hybrid	13.6	536	108.8	468	27	50	19	35
2. 1-D North-South Axis Continuous Adjustment	Plain	11.4	447	91.2	0	17	17	15	15
	Hybrid	17.8	700	142.4	612	27	50	24	45
3. 1-D East-West Axis Continuous Adjustment	Plain	9.3	365	74.4	0	17	17	13	13
	Hybrid	14.5	573	116.0	500	27	50	20	37
4. 1-D Rotation About Vertical Axis, Fixed-Slope Continuous Adjustment	Plain	11.3	442	90.4	0	17	17	15	15
	Hybrid	17.6	693	140.8	606	27	50	24	45
5. 1-D Parallel-to-Earth Axis Continuous Adjustment	Plain	11.8	463	94.4	0	17	17	16	16
	Hybrid	18.5	727	148.0	635	27	50	25	47
6. 2-D Axis Continuous Adjustment	Plain	12.5	493	100.0	0	17	17	17	17
	Hybrid	19.6	774	156.8	676	27	50	27	50

**Table IV. ANNUAL MEAN METEOROLOGICAL CONDITIONS
FOR DIFFERENT LOCATIONS**

Location (Latitude, Elevation)	Mean Temp. (C)	Mean Wind Speed (m/s)	Mean Humidity (%)	Mean Clearness Index	Mean Insolation (MJ/m ²)
Atlanta (33.7 deg./315 m)	16.0	4.0	68.3	0.50	0.70
Denver (40.0 deg./1634 m)	10.0	3.6	51.9	0.63	0.69
Miami (25.8 deg./2 m)	24.3	4.3	72.5	0.51	0.74
Phoenix (33.4 deg./339 m)	22.5	3.0	36.3	0.68	0.87
Salt Lake City (40.8 deg./1288 m)	11.3	4.0	53.9	0.63	0.70

**Table V. ANNUAL HYBRID SOLAR HYDROGEN, OXYGEN
AND EXCESS HEAT PRODUCTION FOR DIFFERENT LOCATIONS
(2-D Tracking System; Collector Area: 1 m²; Hybrid System Electrolyser Temp.: 1000 C)**

Location (Latitude, Elevation)	Type	Hydrogen		Oxygen	Excess Heat	local Efficiency		Phoenix Efficiency	
		kg	kWhr	kg	kWhr	Hydrogen	Hydrogen + Heat	Hydrogen	Hydrogen + Heat
Atlanta (33.7 deg./315 m)	Plain	13.1	519	104.8	0	17	17	14	14
	Hybrid	20.8	815	166.4	712	27	50	22	40
Denver (40.0 deg./1634 m)	Plain	13.0	515	104.0	0	17	17	14	14
	Hybrid	20.5	808	164.0	706	27	50	22	40
Miami (25.8 deg./2 m)	Plain	12.5	493	100.0	0	17	17	13	13
	Hybrid	19.6	774	156.8	676	27	50	21	38
Phoenix (33.4 deg./339 m)	Plain	16.3	643	130.4	0	17	17	17	17
	Hybrid	25.6	1010	204.8	882	27	50	27	50
Salt Lake City (40.8 deg./1288 m)	Plain	13.6	538	108.8	0	17	17	14	14
	Hybrid	21.5	845	172.0	738	27	50	23	42

**Table VI. ANNUAL HYBRID SOLAR HYDROGEN, OXYGEN
AND EXCESS HEAT PRODUCTION VERSUS STEAM TEMPERATURE
(Location: Miami; Collector Area: 1 m²; 2-D Tracking System)**

Electrolyser Temperature (C)	Type	Hydrogen		Oxygen	Excess Heat	Local Efficiency	
		Kg	KW hr	Kg	KW hr	Hydrogen	Hydrogen + Heat
Room	Plain	13.1	515	104.8	0	17	17
200	Hybrid	16.4	644	131.2	852	21	50
400	Hybrid	16.5	679	132.0	821	22	50
600	Hybrid	18.3	717	146.4	787	24	50
800	Hybrid	19.3	760	154.4	749	25	50
1000	Hybrid	19.8	774	158.4	676	27	50
1200	Hybrid	21.9	863	175.2	657	28	50

Fig. 1. Schematic of Solar Hydrogen Production System

Tubes Covered With High Temperature PV Cells (e.g., GaAs)

Fig. 2. Schematic Diagram of Hybrid Collector

A. Rotation About East-West Axis

B. Rotation About North-South Axis

C. Rotation About Vertical Axis

D. Rotation About Axis Normal To
Equatorial Plane

E. Movement About Two Axes

Fig. 3. Collector Tracking Systems

Fig. 4. Collector Orientation and Angle Definitions

Fig. 5. Solar Radiation Components

Fig. 6. Energy Relationships for Steam Electrolysis

Fig. 7. Energy Production and Use Mismatch

Fig. 8. Schematic of High Efficiency Solar Hydrogen Generating System

TASK D

HYDROGEN SAFETY ANALYSIS

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Abstract

This report covers two topics: The first is a review of codes, standards, regulations, recommendations, certifications, and pamphlets which address safety of gaseous fuels. The second is an experimental investigation of hydrogen flame impingement. Four areas of concern in the conversion of natural gas safety publications to hydrogen safety publications are delineated. Two suggested design criteria for hydrogen vehicle fuel systems are proposed. It is concluded from the experimental work that light weight, low cost, firewalls to resist hydrogen flame impingement are feasible.

Introduction

The following report covers two subjects: a review of safety publications and an experimental investigation of hydrogen flame impingement. In the context of this report, safety publications include codes, standards, regulations, recommendations, certification, and pamphlets which address safety and are published by the following organizations:

A. G. A.	American Gas Association
A. N. S. I.	American National Standard Institute, Inc.
A. P. I.	American Petroleum Institute

A.S.T.M.	American Society for Testing and Materials
C.F.R.	Code of Federal Regulations
C.G.A.	Compressed Gas Association, Inc.
N.F.P.A.	National Fire Protection Association
S.A.E.	Society of Automotive Engineers
U.L.	Underwriters Laboratories

There are presently no safety publications for the use of hydrogen as a vehicle fuel. There are safety publications dealing with the transportation of hydrogen, and the use of compressed natural gas and liquid petroleum gas as vehicle fuels. These existing safety publications are being reviewed because they formulate guidelines for new safety publications governing the use of hydrogen as a vehicle fuel.

Terminology

When the various codes and standards are considered as a single body of work, terminology conflicts can cause confusion. It is important to recognize, when reviewing the various codes and standards, that the publications have been written by various committees over many years. For this reason the terminology is specific to each publication. A specific term may be defined somewhat differently in different publications. By way of example, the terminology used to describe pressurized storage of fuel gases is reviewed in the following section.

NFPA 52 refers to "containers" for all storage of compressed natural gas. Containers take the form of either "cylinders" or "pressure vessels". Cylinders are containers that meet DOT or TC regulations, ANSI/AGA NGV2, or CSAB51 standards. Pressure vessels are containers which meet ASME codes.

NFPA 50A refers to "containers" for storage of compressed hydrogen gas. Containers take the form of either "containers" or "pressure vessels". Containers meet DOT or ASME requirements. Pressure vessels are containers which meet ASME requirements.

NFPA 55 refers to "containers" or "cylinders" for storage of compressed gases. Containers and cylinders are used interchangeably and must be fabricated to or authorized for use by DOT, TC, or ASME.

NFPA 50B refers to "containers" for all storage of liquified hydrogen. Containers must meet DOT or ASME requirements.

NFPA 51 refers to "containers" or "cylinders" for all storage of compressed gases. Containers and cylinders are used interchangeably.

CGA P1-1991 refers to "containers" for all storage of compressed gases. Containers are either compressed gas cylinders or liquid containers. Containers are described as vessels that meet DOT, TC, or ASME requirements. Cylinders are compressed gas containers of less than 120 gallon capacity.

NGV2-1992 refers to "containers" or "vessels" for storage of compressed natural gas on vehicles. Containers and vessels are used interchangeably.

Differences in terminology have not produced significant problems in implementation, but must be recognized when comparisons are made between various safety publications.

Development of Hydrogen Standards

ISO/TC 197 (International Standards Organization Technical Committee) is presently developing standards, codes, and guidelines to assist in the implementation of hydrogen energy systems. The goal of ISO/TC 197 is to eliminate barriers to international trade, establish safe handling practices, facilitate the standardization of interfaces, and to harmonize testing methods and quality criteria. There are presently three working groups pursuing this goal. They are:

Working Group 1   Liquid Hydrogen Fueling Systems for Land Vehicles

Working Group 2   Liquid Hydrogen Tank Containers

Working Group 3   Product Specification for Hydrogen Used as a Fuel

They have produced the following working documents:

WD-13984   Liquid Hydrogen: Land Vehicle Fueling Interface: storage vessels, piping, valves, transfer hose, interface with vehicle fuel tank, interlocks, and safety.

WD-13985   Liquid Hydrogen: Land Vehicle Fuel Tanks: fuel container, piping, valves, interface, location, safety.

WD-13986   Tank Containers for multimodal transportation of liquid hydrogen: hydrogen container, piping, valves, transportation factors, interface, interlocks, safety.

Fuel Specifications

Fuel specifications are presently under development by ISO/TC 197. The allocated project number for "Hydrogen Fuel-Product Specification" is ISO/NP 14687. The project has participation from Canada, Egypt, Japan, Republic of Korea, Turkey, and the United States. Belgium, France, Germany, and Switzerland supported the addition of the project as a new work item. The convener for the project is Addison Bain.

The fuel specifications for natural gas are an example of the requirements for an existing gaseous fuel. Hydrogen fuel specifications share common needs with natural gas specifications. Three publications describe accepted fuel specifications for natural gas. They are SAE J 1616, NFPA 52, and ANSI/AGA NGV2-1992. Five chemical compounds are restricted in those specifications, referenced in the following gas quality statements: Water concentration, sulfide concentration, methanol concentration, oxygen concentration, and carbon dioxide concentration.

Water concentration restrictions differ slightly in the three publications. SAE J 1616 requires a water concentration below the dew point at -20 °C (-4 °F). NFPA 52 requires a water concentration below 7.0 lb/mmCF. NGV2 requires a concentration below the dew point 5.5 °C (10 °F) less than the 99% winter design temperature. The 99% winter design temperature is listed under Chapter 24, Table 1, Climatic Conditions for the United States, in the American Society of Heating, Refrigerating and Air Conditioning Engineering (ASHRAE) Handbook, 1989 Fundamentals Volume.

Hydrogen sulfide plus soluble sulfide restrictions are practically identical for the three publications. SAE J 1616 requires sulfide concentrations below 1.0 gm/100 CF (8 to 30 ppm mass). Though hydrogen sulfide can be corrosive in the presence of condensed water this restriction is primarily to avoid excessive exhaust catalyst poisoning. Both NFPA 52 and NGV2 limit sulfide concentration to 0.05 psi partial pressure. This would be typically 20 ppm, similar to the SAE J 1616 requirement.

Methanol concentration restrictions are identical for SAE J 1616 and NGV2. They both prohibit the addition of methanol to natural gas. Methanol addition is not needed if water condensation is prevented by remaining below the required maximum concentration of water vapor. NFPA 52 does not include a gas quality statement for methanol.

Oxygen concentration restrictions are identical for SAE J 1616 and NGV2. They both require the oxygen concentration to be below the flammability limit of the mixture. Corrosion is avoided by limiting the water vapor content of the fuel gas, making flammability the principal concern of the restriction. The restrictions of NFPA 52 are more stringent. NFPA 52 limits oxygen concentration to 0.5%, considerably below the flammability limit.

Carbon dioxide concentration restrictions are treated differently by each publication. SAE J 1616 restricts carbon dioxide concentrations to 3.0% (30,000 ppm) this done to maintain a relatively constant relationship between volumetric fuel flow rate and stoichiometry. NFPA 52 restricts carbon dioxide concentration to 7 psi partial pressure (approx. 2800 ppm). NGV2 does not address carbon dioxide as a natural gas constituent.

Gaseous Fuels in Safety Publications

In the following discussion comparisons are made of the hydrogen and natural gas transport and handling guidelines in the Codes of Federal Regulations and pamphlets by the Compressed Gas Association. These highlight the relative treatment of hydrogen and natural gas. Additionally, SAE makes statements concerning the future use of hydrogen.

The Codes of Federal Regulations (49 CFR 172 Hazardous Materials Table, Special Provisions, Hazardous Materials Communications, Emergency Response Information, and Training Requirements) compares compressed hydrogen with compressed methane and liquid hydrogen as hazardous materials for the purpose of transportation of those materials. In particular, the fuels are rated by hazard class, quantity allowed in passenger aircraft or rail car, and quantity allowed in cargo aircraft.

The hazard class is an indicator of how the fuel should be treated during transport. Compressed hydrogen, compressed methane, and liquid hydrogen are all classed as Division 2.1 (flammable gases). These are defined in 49 CFR 173.115. All three fuels have the same hazard class (Division 2.1) and are treated the same during transport.

49 CFR 172.101 addresses the quantity of compressed hydrogen, compressed methane, or liquified hydrogen allowed in passenger aircraft or rail car. All three are forbidden for transport in passenger aircraft or rail car.

49 CFR 172.101 addresses the quantity of these materials allowed in cargo aircraft. Liquid hydrogen is forbidden. Compressed hydrogen and methane are limited to 150 kilogram per package. Compressed hydrogen and methane are treated identically as are mixtures of the two gases.

The Compressed Gas Association pamphlet CGA P-1-1991 entitled "Safe Handling of Compressed Gases in Containers" classifies gases by hazard class. Classification is based on the chemical and physical hazards of the gas. Three of the gases grouped together by their principal hazards are acetylene, hydrogen, and methane. The limiting capacity for gas containers (2500 ft³) stored inside industrial buildings at consumer sites is the same for all three gases. Though compressed hydrogen is specified as combining high pressure with flammable hazard, methane also combines the same two hazards.

SAE has addressed the subject of hydrogen usage as a vehicle fuel. This was done in SAE J 1297 entitled "Alternative Automotive Fuels". SAE's position was clearly stated "Safety and methods for storage of hydrogen fuel will require additional investigation". The references cited in the publication were all from the 1970's.

Four Areas of Potential Concern

The following four areas of potential concern were identified. This is not intended to be a comprehensive list as further investigation will likely identify additional areas for this list.

1. Odorants
2. Static Electricity
3. Leakage rate safety criteria
4. Tank permeability

Odorants

Odorants are required by all fuel gas specifications. Hydrogen fuel gas specifications will likely also require the use of odorants. The requirements are for odorant concentrations to be high enough to allow detection fuel gas concentrations of 1/5 the lean limit of combustion. These requirements exist for both natural gas and liquid petroleum gas.

SAE J 1616 "Recommended Practice for Compressed Natural Gas Vehicle Fuel" states "Natural gas introduced into any CNG fueling station or vehicle shall have a distinctive odor potent enough of its presence to be detected down to a concentration in air not over 1/5 of the lower limit of flammability.

NFPA 52 - 1992 edition "Standard for Compressed Natural Gas (CNG) Vehicular Fuel Systems" states "Natural gas introduced into any system covered by this standard shall have a distinctive odor potent enough for its presence to be detected down to a concentration in air of not over 1/5 of the lower limit of flammability".

NFPA 58 - 1989 edition "Standard for the Storage and Handling of Liquefied Petroleum Gases" states "All LP-gases shall be odorized prior to delivery to a distributing plant by the addition of a warning agent of such character that they are detectable, by a distinct odor, down to a concentration in air of not over one-fifth the lower limit of flammability".

The implementation of a similar requirement for hydrogen poses questions that will impact the cost of hydrogen as a vehicular fuel source. Odorants in current use (mercaptans, disulfides, and commercial odorants) contain sulfur. Internal combustion engines have been shown to be tolerant of the concentrations necessary for gas detection. Fuel cells are, on the other hand, sulfur intolerant. Technology to remove odorants, or new non-sulfur containing odorants will need to be used. Removal of odorants is usually accomplished with a zinc oxide sulfur polisher. The zinc oxide polisher is able to remove the mercaptans and disulfides. However; some commercial odorants contain THT (tetrahydrothiophene), more commonly known as thiophane, and require the addition of a hydrodesulfurizer before the zinc oxide catalyst bed. The hydrodesulfurizer uses hydrogen to convert the thiophane into H_2S which is easily removed by the zinc oxide polisher (Internet Web Page). The cost of sulfur removal is a function of the concentration of sulfur in the hydrogen.

The concentration of odorant in hydrogen gas is not well defined by the term "1/5 the lean limit of flammability". All fuel gases have two lean limits of flammability (see Table 1) (Lewis, 1987):

Table 1 - Lean Flammability Limits

	Upward propagating lean limit of combustion	Downward propagating lean limit of combustion
Propane	2.1% by volume	2.2% by volume
Methane	5.3% by volume	5.9% by volume
Hydrogen	4.1% by volume	10.0% by volume

Flames propagate upward with greater ease than they propagate downward. This is primarily due to natural convection of the hot burned gases in an upward direction. To propagate downward the flame speed must be high enough to overcome the upward gas motion due to natural convection. Note that for propane and methane the upward and downward propagating lean limit of combustion are approximately the same. They differ by a factor of 2.5 for hydrogen. The amount of odorant needed for use with hydrogen differs by the same factor depending on which lean limit is used as the basis for the requirement. As an example, if upward propagating lean limit is used, the odorant concentration in hydrogen would be 51% of that used for propane but 129% of that used for methane. If downward propagating lean limit is used, the odorant concentration in hydrogen would be 22% of that for propane and 59% of that for methane. Therefore, the proper odorant concentration for hydrogen needs to be determined.

Static Electricity

The second potential area of concern is the generation of static electricity. Hydrogen's ignition energy is as low as 0.017 millijoule for near stoichiometric mixtures, so the possibility of ignition by static electricity exists. This may well be the explanation for "spontaneous ignition" of hydrogen. Spontaneous ignition of hydrogen has been reported when venting at pressures higher than 2000 psi (1995 Proceedings). The source of this ignition may be traceable to the accumulation of static charge on the walls of the conduit through which the hydrogen is passing.

Static charge is an accumulation of electrons on a surface. Pure hydrogen will not carry electrons and cannot generate static charges by flowing through a conduit. However, if the hydrogen contains particles such as oxide flakes from the walls of pipes or containers to carry electrons, flowing hydrogen can generate static charges which may cause ignition if the hydrogen is mixed with air. For a vehicle, the installation of drag chains (drag straps) to bleed the static charge back to the road is not adequate to solve the problem (NFPA 77). The use of a filter to trap particles can increase the problem and produce from 10 to 200 times more charge than a system with no filter (API 2003). Filters have a large surface area due to the numerous small pores needed in their design. The large surface area allows static charge to accumulate more readily.

The potential for generation of static electricity is greatest for metal hydride systems where small particles of the hydride can be suspended in the hydrogen while it is flowing. It is anticipated that a safety publication will be needed to address the issue.

Leakage Rate Safety Criteria

The safety publications dealing with natural gas usage utilize volumetric leakage rates as performance criteria to assess the suitability of various devices (check valves, joints, connectors, etc.). Writing hydrogen standards based on the natural gas standards will require conversion of the natural gas leakage rate criteria values to values suitable for hydrogen.

How the conversion is made will determine whether or not existing hardware designed for natural gas will be suitable for hydrogen vehicles. If the conversion is made based on equivalent energy leakage rate for hydrogen compared to natural gas; hardware designed for natural gas will, in general, be suitable for usage with hydrogen systems without redesign. If, on the other hand, the conversion is made based on equivalent volumetric leakage rate it is probable that the hardware designed for natural gas will need to be redesigned for usage with hydrogen. Table 2 presents the reasons for this conclusion.

Table 2 - Hydrogen to Methane Leakage Ratios

Ratio of Hydrogen to Methane Leakage Flow Rate	Energy Flow Rate	Volumetric Flow Rate
Laminar	0.39	1.29
Turbulent	0.85	2.83
Sonic Throttled	0.88	2.93

Shown in Table 2 are the ratios of hydrogen flow rate divided by methane flow rate for the three types of leaks. They are calculated for the same pressure drop across the leak for both hydrogen and methane. The three types of leaks are characterized by the type flow within the leak. A laminar leak is normally a small leak that, by virtue of the small passageway, is characterized by laminar flow. Laminar flow is predominately viscous flow. Though hydrogen molecules are small, the dynamic viscosity of hydrogen is only slightly smaller than methane. Consequently the volumetric flow rate of hydrogen is only 29% larger than methane in a laminar leak. These relative flow rates were verified experimentally with test sections of natural gas lines removed from service due to leakage by People's Gas Company of Miami, FL. A turbulent leak occurs through a larger passageway when the leak flow is predominately turbulent.

Turbulent flow has a relatively thin viscous boundary layer and the flow rate is inversely proportional to the square root of gas density. Hydrogen's low density causes a much higher volumetric flow rate relative to methane. A sonic throttled leak occurs for large relatively unobstructed passageways and pressure ratios greater than two across the leak. The flow rates for turbulent and sonic throttled leaks are similar.

As can be seen in Table 2, performance criteria based on energy flow rate for hydrogen could be easily met with existing hardware. Hydrogen has inherently lower energy leakage rates than methane in a given leak at the same pressure. On the other hand, hydrogen performance criteria based on volumetric leakage flow rate will be difficult to meet with existing hardware. Hydrogen has inherently higher volumetric leakage rates than methane for all types of leaks.

Tank Permeability

ANSI/AGA NGV2-1992 "Basic Requirements for Compressed Natural Gas Vehicle (NGV) Fuel Containers" divides compressed natural gas containers of under 1000 liter capacity into four groups. They are as follows:

NGV2-1	All metal containers
NGV2-2	Metal liner "hoop wrapped"
NGV2-3	Metal liner "full wrapped"
NGV2-4	Non-metal liner "full wrapped"

In general, the standards could be applied to both natural gas and hydrogen. One area of concern does exist for NGV2-4. NGV2-4 states "The liner material and thickness shall be chosen such that the permeation of compressed natural gas through the wall of the finished container at service pressure is less than 0.25 normal cc per hour per liter water capacity of the container". Experience with polyethylene pipes (Swain, 1992) has shown that hydrogen's small molecular size does make permeability performance criteria difficult to meet. For polyethylene pipes the hydrogen volumetric permeation flow rate was on the order of 5.4 times that of methane at the same pipeline pressure. The ratio of hydrogen to methane energy flow rate, due to permeation, was on the order of 1.6. If the permeability of polyethylene pipe is an indicator of the permeability of non-metallic liners, then it may not be possible to meet the permeability performance criteria for hydrogen using existing containers with non-metallic liners. It will be more difficult to meet the permeability performance criteria if the conversion of NGV2 for natural gas to hydrogen is based on volumetric flow rate than if it is based in energy flow rate.

Hydrogen Fuel Delivery System

Figure 1 is a schematic of a hydrogen vehicle fuel delivery system. The components have been chosen to satisfy safety publications written for natural gas. The areas of concern when rewriting the safety publications for hydrogen usage were addressed in the previous section.

The relevant safety publications for natural gas are listed below with each of the fuel system components.

Fuel Container

ANSI/AGA NGV2-1992
AGA requirements No. 1-85
NFPA 52

ASME Boiler and Pressure Vessel Code Section VIII
Code of Federal Regulations, 49 CFR Parts 100 to 179 (US Department of Transportation)
Transportation of Dangerous Goods Regulations of Transport Canada

Pressure Gauge

UL 404
NFPA 52

Pressure Relief Device

CGA S1.1
CGA P-1-1991
ANSI/CGA standard V-9 1991
AGA requirements No. 1-85
49 CFR 173.34
NFPA 50A
NFPA 50B
NFPA 52
NFPA 58

Container Shut-off

ANSI/UL 429-1983

Pressure Regulator

UL 252
NFPA 52

Filler Connection

NFPA 52
ANSI/NFPA 30-A

Manual Shut-off

CGA P-1-1991
AGA requirements No. 1-85
NFPA 52
NFPA 58

Automatic Shut-off

NFPA 52

Hose, fuel line, connectors, adapters

SAE J 512
SAE J 1231
49 CFR 393 Subpart E
NFPA 52
ANSI/AGA NGV1-1994
CGA NGV1-1994
ASTM materials standards

Suggested Design Criteria

The following are two additional design criteria suggested for hydrogen fuelled vehicles. They are suggested for review and discussion by interested parties.

The first suggested design criteria is "vent upward". The intent of "vent upward" is to facilitate hydrogen's natural tendency to rise due to its low density. "Vent upward" would require pressure relief devices and other venting hardware to have an unimpeded path out of the top of the vehicle. "Vent upward" would include hydrogen vented or released due to an accident or damage to the fuel system. An unimpeded pathway should be provided such that hydrogen released can leave the accident scene in an upward direction due to natural buoyancy without being trapped by vehicle geometry. "Vent upward" would reduce the likelihood that leaking hydrogen, if ignited, would impinge on vehicle parts or occupants. The general concept of avoiding impingement is addressed in NFPA 50B and NFPA 58. It is also addressed in NFPA 30A for service stations and NFPA 59 for utility plants.

"Vent upward" also implies the use of a rain cap or cover over the upward facing vents to provide protection from the elements. NFPA 58 and NFPA 59 allude to the use of such devices. The rain cap or cover may function as a vent door for hydrogen combustion and should be sized as such. NFPA 68 and NFPA 52 provide some guidelines for this sizing. If the rain cap/cover is located in the rear of the vehicle the effect on rear visibility (SAE J 985) during deployment must also be addressed.

The second suggested design criteria concerns fuel container location. Safety publications addressing fuel container location in natural gas fuelled vehicles (49 CFR 393 Subpart E, and NFPA 52) restrict fuel container location in three ways. The container or associated equipment cannot extend beyond the vehicle, be located in front of the front axle or behind the rear bumper. It is suggested that these restrictions be tightened, to provide additional protection to the fuel system by the body of the vehicle. By analyzing the most frequent impact points (Fig.2) and crush (SAE J 1555) that occur during an accident, fuel system location and minimum crush distances around the fuel system can be specified to afford additional protection to the fuel system.

An Example Vehicle Configuration

The following is a potential vehicle configuration that would meet the design criteria previously discussed. The system includes a bank of compressed hydrogen fuel tanks surrounded by a fuel system compartment. The location of the fuel system, in the forward part of the trunk area, is consistent with both the desire to "vent upward" and provide adequate crush distances for protection during an accident. Placing the compressed gas cylinders in the forward part of the trunk still allows the tops of the containers to be located behind the rear window. This would allow upward venting to be accomplished by providing a panel above the containers that can be released if hydrogen is detected in the fuel compartment. The location at the front of the trunk provides a large crush distance between the fuel compartment and the rear bumper in case of an accident.

Applying these criteria to a 1992 Toyota Tercel, a storage system of 32; 4.35 inch OD compressed gas containers could be incorporated (Figure 3 and 4). The tank length is limited to 35 inches. The trunk would need to be lengthened 6.7 inches (Figure 5 and 6). The resulting vehicle would have an estimated range of 150 miles using 3000 psi storage pressure and 225 miles at 5000 psi storage pressure, assuming

0-60 MPH times of 11.2 seconds. The estimates are made from engine performance measured from operating hydrogen fueled engines in the IC Engines Lab at the University of Miami.

Sheet Metal Impingement

The vehicle configuration discussed above requires a fuel compartment to house the hydrogen fuel storage system (Figure 4). The compartment must be able to survive hydrogen flame impingement if hydrogen leaks and is ignited. An experimental study was conducted to investigate hydrogen flame impingement on vehicle body panels.

The testing began with an investigation of hydrogen flame impingement on a standard automobile fender (Photo 1). Hydrogen flow rate was initially 250 CFM. At the end of the test the vehicle fender was glowing visibly (Photo 2). Investigation after the fender returned to ambient temperature showed the paint at the center of the impingement area was barely oxidized but had a powdery consistency (Photo 3). The hydrogen jet contained a very rich mixture at the center of the impingement area and excluded oxygen from reaching the hot surface of the fender.

Testing continued with 4ft by 3ft sheets of cold rolled steel and higher flow rates of hydrogen. The tests with flat steel sheets showed that the peak temperature reached at the center of the sheet metal, during the burn, was a function of three parameters. They were hydrogen flow rate, distance between hydrogen source and the sheet steel, and the thickness of the sheet steel. The hydrogen flow rate during the test was a function of time. The flow rate decayed exponentially from an initial value of 1000 CFM to essentially 0 CFM. This is the behavior exhibited by a high pressure storage system breach. The volume of gas released in each test was 328 SCF of hydrogen.

Each test consisted of venting and igniting 328 SCF of hydrogen on a 3 ft by 4 ft sheet of cold rolled steel. Since the flow rate of hydrogen decreases throughout the test, the location of maximum flame temperature moves closer to the source with time. The rate of heat production also decreases throughout the test as hydrogen flow rate drops. Starting with a steel sheet test location far from the source, the peak surface temperature reached during the test initially increases as the test location is moved closer to the source. At locations far away from the source, the surface is far away from the location of maximum flame temperature for much of the burn and a lower peak temperature is reached. Moving closer, at some point the test location for highest peak surface temperature is reached. At locations closer to the source, than the location for highest peak temperature, the surface is shielded by the extremely rich core of the hydrogen jet. The rich mixture does not burn near the sheet but, after striking the sheet, is blown away from the surface by the rather high gas velocities from the hydrogen jet and burns at a point several inches away from the surface.

Figure 7 shows the temperature versus time plot for three tests, using 0.027 inch thick cold rolled steel, at 1.5, 2.0, and 3.0 feet from the hydrogen source. As can be seen the test location for maximum peak surface temperature is approximately 2.0 feet. These tests were all run by venting 328 SCF of hydrogen at an initial flow rate of 1000 CFM. The temperature measurements shown in figure 7 were made at the center of the flame impingement. For the sheets at a distance of 2 or 3 feet from the hydrogen source a much larger area of the sheet was heated during the early, high flow rate portion of the burn. This allowed a continuing temperature rise later in the burn that was not displayed in the data for 1.5 feet away from the hydrogen source. The continuing temperature late in the burn occurred as heat was transferred from the hottest portion of the sheet which was a ring around the center of impingement.

Figure 8 shows the temperature versus time plot for two steel sheet tests at 2.0 feet, with material thicknesses of 0.027 inch and 0.037 inch. The temperature profiles vary only slightly with material thickness. The 328 SCF of hydrogen vented during a test released 88,250 BTU's, calculated using the lower heating value of hydrogen. Since the entire sheet of 4ft by 3ft by 0.027 inch cold rolled steel could be heated to 1500 °F with 2,062 BTU's, it is apparent that the heat capacity represents a small portion of the total heat liberated by the burning hydrogen. The temperature rise in the steel sheet is principally the difference between the heat transfer into the impingement surface and the heat transfer out of the non-impingement surface. The heat transfer in and out of the steel sheet is virtually identical for both sheets and a small function of sheet thickness.

Photo 4 shows the initiation of the type of test just discussed. The hydrogen flow rate is 1000 CFM, the steel sheet is 0.027 inches thick, 4 ft by 3 ft, and at a distance of 2.0 feet from the hydrogen source. Photo 5 shows the sheet when the surface temperature in the center has reached 1500 °F. Photo 6 shows the sheet with the hydrogen flow interrupted in the middle of the test. The sheet is glowing, but it was not possible to "burn through" the sheet metal during these tests. The over rich portion of the hydrogen prevented large scale oxidation of the material and the peak temperatures were not high enough to simply melt the steel sheet. Radiation from the glowing 1500 °F surface was, however, sufficient to ignite some materials used in the interior of automobiles and potentially harm vehicle occupants.

In an effort to reduce the likelihood of occupant injury, a series of tests were conducted to investigate the feasibility of using a double layer of cold rolled steel sheet to prevent heat transfer through the firewall. Firewalls constructed from two layers of 0.027 inch thick sheet steel were tested. The first sheet withstood the hydrogen flame impingement and the second sheet acted as a radiation shield. The surface temperature of the second plate was significantly lower than the first unless the sheets came in contact with one another. Unfortunately, the first sheet tended to warp when the hydrogen flame impinged on it and it expanded. The sheet bowed away from the flame and therefore moved closer to the second sheet. The two sheets very often did come in contact and this negated the effectiveness of the second sheet as a radiation shield. Preventing contact, particularly in an vehicle accident scenario, involved a relatively complicated array of stand-offs and was deemed impractical.

Firewall Material Impingement

In an attempt to find a light weight, inexpensive material for lining and insulating the fuel compartment, a polypropylene fiber reinforced cement foam was tested. This material was tested under the same conditions as the steel sheet; 328 SCF of hydrogen vented and ignited with an initial 1000 CFM flow rate. Tests were run with 2 ft by 3 ft sheets of the cement foam with 1 ft by 3 ft steel sheets on either side to complete the standard 4 ft by 3 ft test section. Data for the test is shown in Table 3. The values for temperature rise during burn are measured on the non-impingement side of the cement foam during the hydrogen burn. The peak temperature rise was measured on the non-impingement side 15 to 20 minutes after the test when the cement foam sheet had reached equilibrium. The temperature rise measured was very small. An investigation of the material after the test showed that the polypropylene fibers had been melted to only a depth of 0.075 inch.

Table 3 - Temperature Rise versus Material Thickness

Material Thickness	Temperature Rise During Burn	Peak Temperature Rise
2.0 inch	4.2 °F (2.6 °C)	24.6 °F (13.7 °C)
1.5 inch	4.6 °F (2.6 °C)	30.6 °F (17.0 °C)
1.0 inch	5.3 °F (2.9 °C)	35.8 °F (19.9 °C)

Vehicle Test

The full-scale fuel system leak test consisted of releasing and igniting the contents of a compressed hydrogen fuel system. This experiment was a simulation of a fuel system breach that released hydrogen at the bottom of the fuel system compartment. 984 SCF of hydrogen was released at an initial flow rate of approximately 3000 CFM (Photo 7). A 1986 Mercury Cougar was chosen for the experiment. The choice of vehicle was not critical. The 1986 Cougar had, however, a vertical rear window which presents an approximate worst case for heat transfer into the passenger area. The hydrogen was released inside a prototype fuel system container mounted in the trunk area of the test vehicle (Photo 8). The fuel system container was designed to include a fire wall on all sides of the compressed hydrogen gas fuel tanks. The fuel system container was constructed of 0.027 inch thick steel sheet and lined with 0.5 inch thick polypropylene fiber reinforced cement foam to provide an effective fire wall. Figure 9 shows the placement of the fuel system container in the test vehicle. Thermocouples were placed inside the passenger area and in the trunk area. The temperature at each thermocouple location was recorded with a National Instruments DACPad data acquisition system. The highest temperature (145 °F) was reached on the sheet metal which forms the trunk lid just behind the fuel compartment (Figure 10). The temperature at the top of the rear window (Figure 10) almost reached 145 °F. The heating at the top of the rear window occurred late in the burn when the hydrogen flow rate had diminished to the point that wind (from the rear of the vehicle) was able to redirect the flame toward the rear window (Photo 9).

Weight and cost of the fuel compartment are critical design criteria. The weight of the fuel compartment for the previously discussed 1992 Toyota Tercel would be 31.6 pounds for the sheet metal for the fuel compartment and 42.0 pounds for the polypropylene fiber reinforced cement foam. This assumes the foam is 0.5 inches thick as it was during the testing for this work. Investigation of cross sections of the foam after testing have led to the conclusion that the foam thickness could probably be reduced 70%. This would mean a foam thickness of 0.15 inch. The weight of the foam would be reduced from 42.0 pounds to 12.6 pounds and the cost would be reduced from \$4.80 to \$1.44.

Conclusions

- I. The same terminology may take on different meaning in different safety publications. Care needs to be taken when comparisons are made between various safety publications.
- II. Minor differences exist in the fuel specifications for natural gas in existing publications.

- III. Safety publications presently deal with natural gas and hydrogen in the same manner.
- IV. Four areas of potential concern exist in the conversion of natural gas safety publications to hydrogen safety publications. They are:
  - 1. The use of odorants
  - 2. Ignition by static electricity
  - 3. Conversion of natural gas leakage rates to hydrogen leakage rates
  - 4. Conversion of natural gas permeation rates to hydrogen permeation rates
- V. Fuel delivery systems used for natural gas can be used as guidelines for hydrogen fuel delivery systems.
- VI. Two additional design criteria are suggested for hydrogen. They are:
  - 1. Vent upward
  - 2. Restrict hydrogen container vehicle location.
- VII. Light weight, low cost firewalls to resist hydrogen flame impingement can be designed.

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Safety Publications

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ANSI/AGA NGV1-1994 "Compressed Natural Gas Vehicle (NGV) Fueling Connection Devices"

ANSI/AGA NGV2-1992 "Basic Requirements for Compressed Natural Gas Vehicle (NGV) Fuel Containers"

ANSI/CGA standard V-9, 1991 "Standard for Compressed Gas Cylinder Valves"

ANSI/NFPA 30A "Automotive and Marine Service Station Code" 1990 Edition

ANSI/UL 429-1983 "Standard for Electrically Operated Valves"

API 2003-Fifth Edition, Dec 1991 "Protection Against Ignitions Arising Out of Static, Lightning, and Stray Currents"

ASME Boiler and Pressure Vessel Code Section VIII

ASTM A213/A213M-92 "Standard Specifications for Seamless Ferritic and Austenitic Alloy-Steel Boiler, Superheater, and Heat-Exchanger Tubes"

ASTM A47-90 "Standard Specification for Ferritic Malleable Iron Castings"

ASTM A105/A105M-92 "Standard Specifications for Forgings, Carbon Steel, for Piping Components"

ASTM A106-91 "Standard Specifications for Seamless Carbon Steel Pipe for High-Temperature Service"

ASTM A182/A 182M-92a "Standard Specifications for Forged or Rolled Alloy-Steel Pipe Flanges, Forged Fittings, and Valves and Parts for High-Temperature Service"

ASTM A216/A216M-89 "Standard Specifications for Steel Castings, Carbon, Suitable for Fusion Welding, for High-Temperature Service"

49 CFR 171.8 "Definitions and Abbreviations"

49 CFR 172 "Hazardous Materials Table, Special Provisions, Hazardous Materials Communications, Emergency Response Information, and Training Requirements"

49 CFR 172.101 "Purpose and Use of Hazardous Materials Table"

49 CFR 173.34 "Qualification, Maintenance, and Use of Cylinders"

49 CFR 173.115 "Class 2, Divisions 2.1, 2.2, and 2.3 - Definitions"

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Figure 1 - Schematic of Fuel System

Figure 2 - Distribution of Collision Impact Point Locations

Figure 3 - Cut Away of Hydrogen Vehicle

Figure 4 - Hydrogen Fuel Compartment

Figure 5 - Unconverted Gasoline Vehicle

Figure 6 - Hydrogen Powered Vehicle

Photo 1 - 250 CFM Hydrogen Impingement on Fender

Photo 2 - Fender Partially Glowing

Photo 3 - Fender After Returning to Ambient Temperature

Figure 7 - Temperature as a Function of Distance to Hydrogen Source

Figure 8 - Temperature as a Function of Sheet Steel Thickness

Photo 4 - 1000 CFM Hydrogen Impingement on Sheet Steel

Photo 5 - Sheet Steel at 1500 °F

Photo 6 - Sheet Steel with Hydrogen Flow Interrupted

Photo 7 - 3000 CFM Hydrogen Leak from Bottom of Fuel Compartment

Photo 8 - Fuel Compartment after Testing

Figure 9 - Location of Fuel Compartment in Test Vehicle

Figure 10 - Temperature at Two Locations on Test Vehicle

Photo 9 - Hydrogen Flame Near End of Testing