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# HYDROGEN AS A FUEL FOR FUEL CELL VEHICLES: A TECHNICAL AND ECONOMIC COMPARISON

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## Abstract

All fuel cells currently being developed for near term use in vehicles require hydrogen as a fuel. Hydrogen can be stored directly or produced onboard the vehicle by reforming methanol, ethanol or hydrocarbon fuels derived from crude oil (e.g. Diesel, gasoline or middle distillates). The vehicle design is simpler with direct hydrogen storage, but requires developing a more complex refueling infrastructure.

In this paper, we compare three leading options for fuel storage onboard fuel cell vehicles:

* compressed gas hydrogen storage

* onboard steam reforming of methanol

* onboard partial oxidation (POX) of hydrocarbon fuels derived from crude oil

Equilibrium, kinetic and heat integrated system (ASPEN) models have been developed to estimate the performance of onboard steam reforming and POX fuel processors. These results have been incorporated into a fuel cell vehicle model, allowing us to compare the vehicle performance, fuel economy, weight, and cost for various fuel storage choices and driving cycles. A range of technical and economic parameters were considered.

The infrastructure requirements are also compared for gaseous hydrogen, methanol and hydrocarbon fuels from crude oil, including the added costs of fuel production, storage, distribution and refueling stations.

Considering both vehicle and infrastructure issues, we compare hydrogen to other fuel cell vehicle fuels. Technical and economic goals for fuel cell vehicle and hydrogen technologies are discussed. Potential roles for hydrogen in the commercialization of fuel cell vehicles are sketched.

## Introduction

All fuel cells currently being developed for near term use in vehicles require hydrogen as a fuel. Hydrogen can be stored directly or produced onboard the vehicle by reforming methanol or hydrocarbon fuels derived from crude oil (e.g. Diesel, gasoline or middle distillates). The vehicle design is simpler with direct hydrogen storage, but requires developing a more complex refueling infrastructure.

While most in the fuel cell vehicle community would agree that widespread public use of hydrogen fuel cell cars is the ultimate aim, there is an ongoing debate about the most direct path to this goal. Much of this debate centers around which fuel to use and when to use it.

In this paper, we compare three leading options for fuel storage onboard fuel cell vehicles (see Figure 1):

* compressed gas hydrogen storage
* onboard steam reforming of methanol
* onboard partial oxidation (POX) of hydrocarbon fuels derived from crude oil

with respect to vehicle performance, fuel economy and cost, and infrastructure requirements.

To examine vehicle design trade-offs, models of onboard fuel processors have been developed. These have been coupled to Princeton's fuel cell vehicle simulation model. This allows us to calculate vehicle performance, fuel economy and cost for a variety of cases.

Capital costs for hydrogen refueling infrastructure development are estimated for various near term hydrogen supply options, and the cost of delivered hydrogen to the consumer is calculated. The overall infrastructure costs per car (including both onboard fuel processors and off-board refueling systems) are compared.

Finally, potential roles for hydrogen in the development of fuel cell vehicles are discussed.

## Comparison Of Alternative Designs For Fuel Cell Vehicles

### Model Of Fuel Cell Vehicles

A computer model for proton exchange membrane fuel cell vehicles has been developed (Steinbugler 1996, Steinbugler and Ogden 1996, Steinbugler 1997). This program allows us to estimate the performance, fuel economy and cost of alternative fuel cell vehicle designs.

Input parameters to the model include:

* the driving schedule [the Federal Urban Driving Schedule (FUDS), Federal Highway Driving Schedule (FHDS) or others may be used]
* vehicle parameters (the base vehicle weight without the power train, the aerodynamic drag, the rolling resistance, vehicle frontal area, accessory loads),

* fuel cell system parameters (fuel cell current-voltage characteristic, fuel cell system weight),

* peak power battery characteristics (behavior on charging and discharging, weight), and

* fuel processor parameters (conversion efficiency, response time, weight, hydrogen utilization in the fuel cell).

First, the fuel cell system and peak power device are sized according to the following criteria:

* The fuel cell system alone must provide enough power to sustain a speed of 55 mph on a 6.5% grade.

* The output of the fuel cell system plus the peak power device must allow acceleration for high speed passing of 3 mph/sec at 65 mph.

These criteria are consistent with the goals set by the Partnership for a New Generation of Vehicles (PNGV).

Once the components are sized, the vehicle weight is calculated, (accounting for any extra structural weight needed on the vehicle to support the power system). Then the fuel economy is calculated for a desired driving schedule. At each time step of the driving schedule the road load equation [1] is solved to find the total power $P_D$ needed from the vehicle's electrical power system (fuel cell plus peak power device).

$$P_D = P_{aux} + (mav + mgC_Rv + 0.5\ \rho\ C_D\ A_F\ v^3)/\eta \qquad [1]$$

where:

$P_D$ = total electrical power demanded of vehicle's power system (Watts)
$P_{aux}$ = power needed for accessories such as lights and wipers (Watts)
m = vehicle mass (kg)
a = vehicle acceleration ($m/s^2$)
v = vehicle velocity (m/s)
g = acceleration of gravity = 9.8 $m/s^2$
$C_R$ = rolling resistance
$\rho$ = density of air ($kg/m^3$)
$C_D$ = aerodynamic drag coefficient
$A_F$ = vehicle frontal area ($m^2$)
$\eta$ = efficiency of electric motor, controller and gearing

If the fuel cell alone cannot supply the power needed, the peak power battery is called upon. Power demanded is allocated between the fuel cell and battery in a way that both accounts for fuel processor response time and aims to maintain the battery at a target state of charge. (The program is set up to keep the battery near its ideal state of charge, by recharging from the fuel cell during driving.) Knowing the fuel processor efficiency, the fuel consumed in each time step can be estimated. Fuel consumption is summed over the drive cycle and divided into the distance travelled to give a fuel economy, expressed in miles per equivalent gallon of gasoline.

*Fuel Storage Capacity and Range*

The vehicle range is allowed to vary, but all fuel storage systems are assumed to weigh 50 kg. We assume that 7.5% hydrogen by weight can be stored in a compressed gas tank at 5000 psia. For gasoline and methanol, 13 gallons of fuel are stored in a 12 kg tank.

*Model of Fuel Cell System*

The fuel cell is modelled based on current-voltage curves for existing PEM fuel cells (Steinbugler and Ogden 1996). For hydrogen-air fuel cells operated at 3 atm, with cathode stoichiometry of 2, the voltage current relation is given by [Steinbugler 1997]:

$$V = 0.787 - 0.0533 \log i - 0.148\, i + V_{comp/exp} - V_{reformate} \qquad [2]$$

where:

V = voltage output in volts
i = current density is amps/cm$^2$

$V_{comp/exp}$ = voltage correction for power consumed/generated by net air compression/expansion.
= -0.08 for hydrogen
= +0.067 for methanol steam reforming
= 0 for gasoline POX

$V_{reformate}$ = voltage penalty due to $H_2$ dilution when operating on reformate
= 0 (hydrogen)
= 0.06 i for methanol reformate
= 0.128 i for gasoline/POX

This expression is valid for $0 < i < 1.5$ amps/cm$^2$.

Both the power produced by the fuel cell and the power required for cathode air compression are proportional to the flow of hydrogen through the fuel cell (or the current drawn from it.) Thus in order to properly account for the net auxiliary power (compression-expansion) we apply a constant voltage drop of $V_{comp/exp}$ to the polarization curve, as shown in Eq. 1.

The output of PEM fuel cells varies with the concentration of hydrogen in the anode feed gas. For compressed gas hydrogen storage, the feed gas to the fuel cell anode is pure hydrogen. For the case of methanol steam reforming, the hydrogen content is about 75% by volume and for gasoline partial oxidation about 35%. The voltage and power output of the fuel cell on different anode feed gases is shown in Figure 2. The peak power output is highest on pure hydrogen. The higher the hydrogen content, the better the fuel cell performance, and the greater its power density.

*Model of Peak Power Battery*

We have modelled our peak power battery as a thin film, spiral wound, lead-acid technology, based on data from the Bolder Battery company (Juergens 1995, Keating 1996, Plichta 1995). The battery system specific weight is assumed to be 1.0 kg/kW. To ensure a long lifetime, the battery is kept near its initial state of charge of 50% by recharging from the fuel cell during driving. The battery charge and discharge rates depend on the battery power demand, the state of charge and on the battery resistance. The charging current is limited to 30 amps.

It is assumed that energy is recaptured via regenerative braking, up to the battery's maximum charge rate. When the battery state of charge exceeds its nominal value of 50%, the program demands more power from the battery and less from the fuel cell, in order to bring the battery state of charge back down to the nominal 50% level.

*Models Of Onboard Fuel Processors*

Onboard fuel processors convert a liquid fuel (methanol or gasoline) to a hydrogen rich gas for use in the fuel cell.

Heat integrated methanol steam reformer and gasoline partial oxidation systems have been modelled using ASPEN-plus software (Kreutz, Steinbugler and Ogden 1996, Kartha, Fischer and Kreutz 1996). Configurations for a methanol steam reformer /fuel cell system and a gasoline partial oxidation/fuel cell system are shown in Figures 3 and 4.

For the methanol steam reformer, the fuel cell anode exhaust gas is used as fuel in the reformer burner. The energy is recovered as heat input to the steam reforming reaction. The critical feedback loop, in which the anode exhaust is burned to partially satisfy the heat requirements for the steam reforming reaction, complicates a clear definition of the steam reformer efficiency independent of the fuel cell. As a gauge of system efficiency we employ the product of the steam reformer efficiency (HHV of hydrogen produced/HHV of methanol feed) times the hydrogen utilization in the fuel cell. This yields a system fuel reformer efficiency corresponding to the (HHV of the hydrogen consumed in the fuel cell)/(HHV of the methanol feed) = 62%. However, the expander work significantly exceeds that required for air compression, accounted for by a $V_{comp/exp}$=0.067 or on average an 8% increase in the DC output of the system.

In contrast to methanol steam reforming, which requires heat input, partial oxidation is an exothermic reaction. A well heat integrated POX reformer has no need for the energy contained in the anode exhaust. Some of the energy in the anode exhaust gas can be recovered for uses other than the POX reaction. For example, anode exhaust can be burned to vaporize the incoming gasoline and also to provide expander work to offset the required air compressor work. The expander work exceeds power demands for compression, but the excess power produced (<1 kWe) is not sufficient to warrant a separate generator. The conversion efficiency for the POX reactor is well defined (HHV H2 out/HHV gasoline in) and has been measured as the near-equilibrium value of 86.7% (Mitchell 1996).

For comparison with the steam reformer efficiency note that the product of the POX efficiency times the 80% hydrogen utilization in the fuel cell gives a POX system efficiency = (HHV H2 consumed/HHV gasoline in) of 69.4%.

Plotting the power demand $P_D$ from Eq. 1, we see that the demands on the power system change rapidly over a typical drving cycle. This is shown in Figure 5, where the power required by the Federal Urban Driving Schedule is plotted vs. time. (When $P_D$ is negative, the vehicle is braking.)

In a hydrogen fuel cell vehicle, the fuel cell should be able to follow the rapidly changing demands of the driving schedule. However, onboard fuel processors can have a longer response time, as it can take many seconds or even minutes to change the gas output of the reformer. It may be difficult for the fuel processor/fuel cell system to follow the rapidly changing demands.

For POX reactors this may not be much of an issue, as the response time is expected to be quite fast. For steam reformers, it may be longer, on the order of several seconds or more. To model the effect of response time, we assumed that the fuel processor tries to follow the demands of the driving cycle, reaching the desired level in a characteristic response time. Meanwhile, the peak power battery supplies the power needed by the drive cycle, until the fuel processor can "catch up". The peak power battery is recharged while driving from the fuel cell, when the power is lower, or from regenerative braking.

The drive cycle power demand and the output of the fuel cell system are plotted in Figure 6 for fuel processor cases with 1 and 5 second response times. The fuel cell output matches the power demand well for the 1 second case, but lags the power demand significantly for the 5 second case. The battery state of charge is also shown for each case. For the 5 second response time, the battery is used more often and the battery state of charge has larger excursions away from its target value. The amount of energy routed through the battery is shown in Figure 7 as a function of fuel processor response time for the FUDS and FHDS cycles. The longer the response time, the more the battery must be used. For a 5 second response time 40-50% of the energy reaching the wheels on the FUDS cycle has been routed through the battery.

## Model Results: Vehicle Performance, Fuel Economy and Cost for Alternative Fuel Cell Vehicle Designs

We now apply the model to compare alternative designs for fuel cell vehicles. Table 1 summarizes the assumptions used in our calculations. Table 2 shows the results for vehicle mass,the required size for the fuel cell and peaking battery, the fuel economy and range for alternative fuel cell vehicle designs.

### *Vehicle Weight*

The vehicle mass varies with the vehicle type. The various components' contributions to the total vehicle mass are shown for hydrogen, methanol and gasoline fuel cells cars in Figure 8. Vehicles with onboard fuel processors are heavier for several reasons. First, the fuel processor adds weight. Second, the fuel cell/fuel processor system is less energy efficient than a pure hydrogen system, so a larger fuel cell is needed to provide the same power output, if the fuel cell is run on reformate. Third, the mass of the vehicle support structure is increased by 15% of the additional weight it carries. The methanol fuel cell vehicle weighs about 10% more than the hydrogen vehicle, the gasoline POX vehicle about 19% more.

### *Power Requirements for the Fuel Cell and Peak Power Device*

The peak power required is shown in Table 2 for various fuel cell vehicle designs. Roughly, the fuel cell and battery each provide about half the peak power. For hydrogen, a lower peak power output is needed because the vehicle is lighter. In Figure 9, we have plotted a histogram showing the power demands of the FUDS and FHDS cycles (fraction of the time a certain power is demanded vs. power). The power required by the FUDS and FHDS cycles is considerably less than the fuel cell power, when the fuel cell is sized for sustained hill climbing. However, the long fuel processor response time means that the battery is used even during the FUDS cycle.

### *Fuel Economy*

The fuel economy is shown for the FUDS, FHDS, and combined driving cycles. The combined driving cycle fuel economy is defined as:

mpg (combined) = 1/(.55/mpg FUDS + .45/mpg FHDS)

The energy efficiency of the methanol and gasoline fuel cell vehicles is about 2/3 that of the hydrogen fuel cell vehicle. The loss of efficiency is due to several effects, as shown in Figure 10. First is the 15-25% energy loss in converting methanol or gasoline to hydrogen. Second, operation on reformate means that the fuel cell has a lower efficiency. Third, the vehicle weighs 10-20% more with an onboard fuel processor. Finally, for the methanol steam reformer, the 5 second response time means that a significant fraction (40-50%) of the energy must be routed through the battery, with attendant losses in charging and discharging.

### *Range*

The vehicle range exceeds the PNGV goal of 380 miles, for all the fuel cell vehicle cases considered in Table 2.

### *Vehicle Cost*

The cost of alternative fuel cell vehicles is shown in Figure 11. Table 3 summarizes our cost assumptions for fuel cell vehicle components in high volume mass production. Two sets of cases are shown, one corresponding to a low range of values for fuel cell, fuel processor, battery and hydrogen storage mass produced costs, the other to a high range of values. We see that the first cost of fuel cell vehicles with onboard methanol steam reformers would be higher than that for hydrogen fuel cell vehicles by about $400-430/car. We estimate gasoline POX fuel cell cars would cost $660-870/car than hydrogen vehicles.

For comparison the manufacturing cost of corresponding parts for a gasoline internal combustion engine vehicle (e.g. the engine, transmission, electrical system, fuel and tank, and emission control systems) might be about $39/kW (Steinbugler 1997). For a gasoline IC engine car with an 94 kW engine (the estimated power for an aluminum intensive Ford Sable), this would be about $3666/car. To achieve a first cost similar to that of today's gasoline ICEVs, fuel cell vehicle components must meet stringent cost goals.

### *Summary*

In summary, for the same performance, hydrogen fuel cell vehicles are likely to be simpler in design, lighter, more energy efficient, and less expensive than methanol or gasoline fuel cell vehicles. And the tailpipe emissions will be strictly zero.

## Refueling Infrastructure Requirements for Fuel Cell Vehicles

### Developing a Refueling Infrastructure for Hydrogen Vehicles

The relative simplicity of vehicle design for the hydrogen fuel cell vehicle must be weighed against the added complexity and cost of developing a hydrogen refueling infrastructure. Indeed, hydrogen infrastructure is often seen as a "show-stopper" for hydrogen fuel cell vehicles.

- We have assessed the technical feasibility and economics of developing a hydrogen vehicle refueling infrastructure (Ogden, Dennis, Steinbugler and Strohbehn 1995, Ogden, Cox and White 1996, Ogden 1997). A number of near term possibilities for producing and delivering gaseous hydrogen transportation fuel were considered (using commercial or near commercial technologies for hydrogen production, storage and distribution). These include (see Figure 12):

  * hydrogen produced from natural gas in a large, centralized steam reforming plant, and truck delivered as a liquid to refueling stations,

  * hydrogen produced at the refueling station via small scale steam reforming of natural gas, (in either a conventional steam reformer or an advanced steam reformer of the type developed as part of fuel cell cogeneration systems)

  * hydrogen produced in a large, centralized steam reforming plant, and delivered via small scale hydrogen gas pipeline to refueling stations,

  * hydrogen produced via small scale electrolysis at the refueling station,

  * hydrogen from chemical industry sources (e.g. excess capacity in ammonia plants, refineries which have recently upgraded their hydrogen production capacity, etc.), with pipeline delivery to a refuelingstation.

## Economics Of Hydrogen Production And Delivery

### *Delivered cost of hydrogen transportation fuel*

The delivered (levelized) cost of hydrogen transportation fuel (to the vehicle) from these sources is estimated in Figure 13. Delivered fuel costs are given in $/GJ. (On a higher heating value basis, the energy cost of $1/gallon gasoline is equivalent to $7.7/GJ -- see Table 0.) In this example, we have used energy prices in the Los Angeles area, where the natural gas cost is low ($2.8/GJ), and the cost of off-peak power is relatively high (3 cents/kWh). A capital recovery factor of 15% is assumed. (For other assumptions, the delivered costs will vary.) The cost contributions of various factors are shown for each technology over a range of refueling station sizes from 0.1 to 2.0 million scf/day (e.g. stations capable of refueling about 80-1600 fuel cell cars/day or 8-160 fuel cell buses/day). Although all the supply options are roughly competitive, several points are readily apparent.

* Onsite production of hydrogen via small scale steam reforming of natural gas is economically attractive and has the advantage that no hydrogen distribution system is required. Delivered hydrogen costs are shown for onsite reforming of natural gas based on: 1) conventional small steam reformer systems and 2) advanced low cost reformers, which have just been introduced for stationary hydrogen production (Farris 1996, Halvorson et.al 1997). With conventional reformer technology, hydrogen is expensive at small station sizes, but is economically attractive at larger station sizes. As discussed in a recent report (Ogden et.al. 1996), adopting lower cost, advanced steam methane reformer designs based on fuel cell reformers could substantially reduce the delivered cost of hydrogen especially at small station size. With advanced reformers, onsite

reforming is competitive with liquid hydrogen truck delivery and pipeline delivery over the whole range of station sizes considered.

* Truck delivered liquid hydrogen gives a delivered hydrogen cost of $20-30/GJ, depending on the station size. This alternative would be also attractive for early demonstration projects, as the capital requirements for the refueling station would be relatively small (Ogden et.al. 1995, Ogden et.al. 1996), and no pipeline infrastructure development would be required.

* Under certain conditions, a local pipeline bringing centrally produced hydrogen to users could offer low delivered costs. Centrally produced hydrogen ranges in cost from $3/GJ (for refinery excess) to $5-9/GJ for large scale steam reforming to $8-10/GJ for hydrogen from biomass, coal or MSW). If the cost of hydrogen production is low, higher pipeline costs could be tolerated. Still, for pipeline hydrogen to be competitive with truck delivery or onsite reforming, pipeline costs can be no more than a few $/GJ. For a small scale hydrogen pipeline system to be economically competitive a large, fairly localized demand would be required. Alternatively, a small demand might be served by a nearby, low cost supply of hydrogen.

* It appears that onsite electrolysis would be somewhat more expensive than other options, largely because of the relatively high cost of off-peak power (3 cents/kWh) assumed in the study. If the cost of off-peak power were reduced from 3 cents/kWh to 1-1.5 cents/kWh, hydrogen costs would become much more competitive.

*Capital cost of building a hydrogen refueling infrastructure*

The capital cost of building a hydrogen refueling infrastructure is often cited as a serious impediment to use of hydrogen in vehicles. In Figure 14 and Tables 4a and 4b, we show the capital cost of building a hydrogen refueling infrastructure for the various options discussed in the previous section. We consider two levels of infrastructure development.

* Early development of distribution system and refueling stations to bring excess hydrogen from existing hydrogen capacity to users. We assume that no new centralized hydrogen production capacity is needed. Two refueling stations serve a total fleet of 13,000 cars, each station dispensing 1 million scf H2/day to 800 cars/day. The options for providing hydrogen include: 1) Liquid hydrogen delivery via truck from existing capacity, 2) pipeline hydrogen delivery from a nearby large hydrogen plant or refinery, 3) onsite production from steam reforming of natural gas and 4) onsite production from electrolysis

* Development of new hydrogen production, delivery and refueling capacity to meet growing demands for hydrogen transportation fuel. The system serves a total fleet of 1 million cars, each station dispensing 1 million scf H2/day to 800 cars/day. Options for providing hydrogen are: 1) liquid hydrogen delivery via truck from new centralized steam reformer capacity, 2) pipeline hydrogen delivery from a new centralized hydrogen plant, 3) onsite production from steam reforming of natural gas and 4) onsite production from electrolysis.

The range of infrastructure capital costs for a system serving 13,000 fuel cell cars, is about $1.4-11.4 million or $100-900/car. The range of infrastructure capital costs for a system serving 1 million fuel cell cars, is about $400-900 million or $400-900/car.

It is important to keep in mind the results of Figure 13 for the total delivered cost of hydrogen transportation fuel, as well as the capital cost of infrastructure. Some of the lower capital cost options such as liquid hydrogen delivery, can give a higher delivered fuel cost than pipeline delivery or onsite reforming. Onsite small scale steam reforming is attractive as having both a relatively low capital cost (for fuel cell type reformers), and a low delivered fuel cost.

## Developing a Refueling Infrastructure for Methanol Fuel Cell Vehicles

A modest distribution system for chemical methanol exists at present. To service a significant number of fuel cell cars, this network would have to be expanded in some places. To bring methanol to millions of fuel cell cars might involve increases in methanol production capacity as well.

The cost of truck delivery is estimated to be about the same for methanol and gasoline on a volumetric basis. Given the lower energy density of methanol, truck delivery would cost about $1.9/GJ, as compared to $1.0/GJ for gasoline (Ogden, Larson and Delucchi 1994).

The capital cost of retrofitting a refueling station from gasoline to methanol use has been estimated at about $20,000 per station. If a new methanol refueling station were built, the cost should be comparable to that for a new gasoline station, so no incremental cost as compared to gasoline is would be expected.

The costs to develop methanol refueling infrastructure should be relatively small compared to hydrogen infrastructure costs. As a first approximation, we assume additional infrastructure costs for methanol are zero.

## Cost of Infrastructure for Gasoline Fuel Cell Vehicles

For this study, we have assumed that there is no extra capital cost for developing gasoline infrastructure for fuel cell vehicles. This may be an oversimplification. For example, if a new type of gasoline (e.g. very low sulfur) is needed for gasoline/POX fuel cell vehicles, this would entail extra costs at the refinery. Environmental effects of gasoline refueling stations are not considered (e.g. remediation of pollution from leaking underground storage tanks). The costs of maintaining the existing gasoline infrastructure are not considered.

## Total Infrastructure Costs (On And Off The Vehicle) For Fuel Cell Vehicles: Hydrogen Compared To Methanol And Gasoline

It is often stated that use of methanol or gasoline with onboard reformers would greatly reduce (for methanol) or eliminate (for gasoline) the problem of developing a new fuel infrastructure. How does the capital cost of building a hydrogen refueling infrastructure compare to the capital cost of infrastructure development for methanol or gasoline fuel cell vehicles?

Defining "infrastructure" to mean all the equipment (both on and off the vehicle) required to bring hydrogen to the fuel cell, it is clear that gasoline and methanol fuel cell vehicles also entail extra costs -- largely for onboard fuel processing. In the case of hydrogen, the infrastructure development capital cost is paid by the fuel producer (and passed along to the consumer as a higher fuel cost). In the case of methanol or gasoline fuel cell vehicles, the capital cost is paid by the consumer buying the car.

In Figure 15 we combine our estimates of the cost of alternative fuel cell vehicles (Figure 11) and off-board refueling infrastructure (Figure 14). Our estimates show that gasoline POX fuel cell vehicles are likely to cost $660-870 more than comparable hydrogen fuel cell vehicles. The added cost of off-board refueling infrastructure for hydrogen is in the range $500-900/vehicle. The total cost for infrastructure on and off the vehicle would be comparable for hydrogen and gasoline fuel cell vehicles.

A recent study by Directed Technologies, Inc. also concluded that when the total infrastructure cost (on and off the vehicle) is considered, hydrogen infrastructure capital costs are comparable to those for methanol and gasoline (Thomas 1996).

## Discussion: Is Hydrogen Refueling Infrastructure A "Show-Stopper" For Hydrogen Fuel Cell Vehicles

Our study suggests several reasons why hydrogen infrastructure development may not be an insurmountable obstacle to introducing hydrogen fuel cell vehicles.

* The technologies to produce, deliver and dispense hydrogen are well known. There appear to be no major technical hurdles to providing hydrogen transportation fuel.

* The capital cost of building a hydrogen refueling infrastructure off the vehicle appears to be comparable to the added cost of putting individual small hydrogen production systems (fuel processors) onboard each vehicle.

* There are ample resources for making hydrogen. For the next few decades, hydrogen from natural gas appears to be the least expensive option in many locations. In the longer term, gasification of biomass, municipal solid waste or coal (with sequestration of the $CO_2$) may offer relatively low hydrogen costs. Onsite electrolysis in areas with low cost off-peak power may be attractive as well. (Ogden, Cox and White 1996).

* In a recent case study of potential hydrogen supply and demand in the Los Angeles area (Ogden, Cox and White 1996, Ogden 1997), we found that it would be possible to introduce significant numbers of fuel cell vehicles, even without building any new hydrogen production capacity. The excess hydrogen capacity available from industrial suppliers and refineries in LA today might fuel 700-2000 PEM fuel cell buses or 30,000-100,000 PEM fuel cell cars.

Of course, hydrogen faces the same "chicken and egg" problem as any non-gasoline alternative automotive fuel, in moving beyond centrally refueled niche markets into general public refueling. More than the cost of hydrogen instructure (which appears to be comparable to the added vehicle cost of using onboard fuel processors), the issue may be getting enough hydrogen fuel cell vehicles on the road to reduce the cost of fuel cells via mass production, thereby opening the way to general automotive markets.

## Strategies For Developing Fuel Cell Vehicles: The Role Of Hydrogen

### Hydrogen in Early Fuel Cell Fleet Demonstrations

Hydrogen is likely to play an important role in early fuel cell vehicle demonstrations. The first fuel cell vehicle fleets may be hydrogen fueled PEM fuel cell buses, for several reasons:

* Ballard will be demonstrating hydrogen fueled PEMFC buses in several cities starting in 1997, with commercialization planned for 1998.

* Refueling with hydrogen or any alternative fuel is easier at centralized fleet locations such as bus garages.

* The daily demand for hydrogen for a bus depot would be large enough to bring the delivered cost of hydrogen down somewhat because of economies of scale, especially for stations based on small scale reformers.

* Fuel cells might be economically competitive first in bus markets, where cost goals are not as stringent as for automobiles.

Early fuel cell fleet demonstrations offer an excellent opportunity to demonstrate hydrogen refueling systems as well. We recommend that hydrogen infrastructure demonstrations be an important part of hydrogen fuel cell bus projects. Demonstrations of small scale methane reformers may be of particular interest. (A fleet of about 8 PEMFC buses could be refueled daily using a small scale reformer producing 100,000 scf H2/day. Rapid developments in small scale reformer technology are making this an increasingly attractive supply option. (Halvorson, Victor and Farris 1997)

### Introduction of Fuel Cell Automobiles

Several major automobile manufacturers are conducting R&D on PEM fuel cell cars (including Chrysler, GM, Ford, Daimler-Benz, Mazda, Toyota, and Honda). A PEMFC mini-van using compressed hydrogen gas storage was demonstrated in May 1996 by Daimler-Benz, and it is likely that the first mid-size PEMFC automobiles may be demonstrated before the year 2000. The first mass-produced commercial models might be available a few years later in the 2004-2010 time frame. Chrysler has announced plans to demonstrate a gasoline POX fuel cell vehicle, with commercialization possible around 2005.

If onboard partial oxidation of gasoline is perfected, this might allow a rapid introduction of fuel cell cars to the general public, with attendant lowering of fuel cell costs in mass production. But onboard POX vehicles appear to have penalties in terms of vehicle cost, complexity, efficiency and emissions, which may make hydrogen vehicles an extremely attractive successor or alternative. Given the lower first costs for hydrogen fuel cell vehicles (see Figure 11), there may be a strong incentive to switch to hydrogen fuel, even if large numbers of gasoline/POX fuel cell cars are introduced first, bringing the cost of fuel cells down via mass production. [Recent studies by Directed Technologies, Inc. suggest that the most economically attractive route to fuel cell vehicle commercialization may be starting with hydrogen fuel cell vehicles rather than gasoline (Thomas 1997).]

We recommend that demonstrations of hydrogen refueling systems (especially small scale reformers) be conducted as part of hydrogen vehicle demonstrations (bus and automotive fleets) over the next few years. (In fleet applications hydrogen fuel cell vehicles may be preferred from the beginning for reasons of vehicle simplicity and cost.) As vehicle demonstrations progress, design issues for various types of fuel cell vehicles will be better understood and the path to commercialization should become clearer.

## Conclusions

Simulation programs of fuel cell vehicles and onboard fuel processors have been developed. For the same performance, we found that hydrogen fuel cell vehicles are simpler in design, lighter weight, more energy efficient and lower cost than those with onboard fuel processors.

Vehicles with onboard steam reforming of methanol or partial oxidation of gasoline have about two thirds the fuel economy of direct hydrogen vehicles. The efficiency is lower because of the conversion losses in the fuel processor (losses in making hydrogen from another fuel), reduced fuel cell performance on reformate, added weight of fuel processor compents, and effects of fuel processor response time.

For mid-size automobiles with PNGV type characteristics (base vehicle weight of 800 kg -- e.g. weight without the power train and fuel storage, aerodynamic drag of 0.20, and rolling resistance of 0.007), fuel economies (on the combined FUDS/FHDS drving cycle) are projected to be about 106 mpeg for hydrogen fuel cell vehicles, 69 mpeg for fuel cell vehicles with onboard methanol steam reforming, and 71 mpeg for onboard gasoline partial oxidation.

Based on projections for mass produced fuel cell vehicles, methanol fuel cell automobiles are projected to cost about $400-430 more than comparable hydrogen fuel cell vehicles. Gasoline/POX fuel cell automobiles are projected to cost $660-870 more than hydrogen fuel cell vehicles.

The cost of developing hydrogen refueling infrastructure based on near term technologies would be about $500-900/car depending on the type of hydrogen supply. No extra costs are assumed for developing gasoline or methanol infrastructure.

Defining "infrastructure" to mean all the equipment (both on and off the vehicle) required to bring hydrogen to the fuel cell, we find that the cost is comparable for hydrogen, methanol and gasoline POX fuel cell vehicles.

Hydrogen is the prefered fuel for fuel cell vehicles, for reasons of vehicle design, cost and efficiency, as well as potential energy supply and environmental benefits. The cost of developing hydrogen refueling infrastructure is comparable to the total cost (on and off the vehicle) for gasoline fuel cell vehicles. Like CNG or methanol, hydrogen faces the issue of reaching beyond centrally refueled fleet markets. Valuable experience can be gained in the near term by building the refueling systems for centrally refueled hydrogen fuel cell vehicle demonstrations, and investing now in technologies which could play a role in a future hydrogen infrastructure.

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## Figures



## Tables

**Table 0. Conversion Factors And Economic Assumptions**

1 GJ (Gigajoule) = $10^9$ Joules = 0.95 Million BTU
1 EJ (Exajoule) = $10^{18}$ Joules = 0.95 Quadrillion ($10^{15}$) BTUs

1 million standard cubic feet (scf) = 28,300 Normal cubic meters ($m_N^3$) = 362 GJ (HHV)
1 million scf/day = 2.80 tons/day = 4.19 MW $H_2$ (based on the HHV of hydrogen)

1 scf $H_2$ = 362 kJ (HHV) = 344 BTU (HHV); 1 lb $H_2$ = 64.4 MJ (HHV) = 61.4 kBTU (HHV) = 178.5 scf
1 $m_N^3$ = 12.8 MJ (HHV); 1 kg $H_2$ =141.9 MJ (HHV) = 393 scf

1 gallon gasoline = 130.8 MJ (HHV); $1/gallon gasoline = $7.67/GJ (HHV)

All costs are given in constant $1993.

Capital recovery factor for hydrogen production systems, distribution systems and refueling stations = 15%

**Table 1. Parameters Used in Fuel Cell Vehicle Modelling**

| | |
|---|---|
| **Vehicle Parameters** | |
| Glider Weight (= vehicle - power train)[a] | 800 kg |
| Drag Coefficient[a] | 0.20 |
| Rolling Resistance[b] | 0.007 |
| Frontal Area[a] | 2.0 $m^2$ |
| Accessory Load[c] | 0.4 kW |
| Structural Weight Compounding Factor[d] | 15% |
| **Fuel Cell System** | |
| Operating pressure | 3 atm |
| Cathode Stoichiometry | 2 |
| System weight (including air handling, thermal and water management)[e] | 4.0 kg/kW |
| **Fuel Processor Systems** | |
| ***Methanol Steam Reformer*** | |
| Gross efficiency (HHV H2 consumed in fuel cell/HHV MeOH in) | 62% |
| $V_{comp/exp}$ | 0.067 Volts |
| Hydrogen utilization[g] | 80% |
| Voltage Penalty for reformate operation[h] | 0.06 x current (amp/$cm^2$) |
| Weight of system[i] | 32 kg+1.1 kg/kW |
| Response time | 5 sec |
| Reformate Composition | 70% $H_2$, 24% $CO_2$, 6% $N_2$ |
| ***Gasoline POX*** | |
| Efficiency (HHV H2 consumed/HHV gasoline in)[j] | 69.4% |
| Hydrogen utilization[g] | 80% |
| Voltage Penalty for reformate operation[h] | 0.128 x current (amp/$cm^2$) |
| Weight of system[i] | 32 kg+1.1 kg/kW |
| Response time | 1 sec |
| Reformate Composition | 42% $N_2$, 38% $H_2$, 18% $CO_2$, 2% $CH_4$ |
| **Peak Power Battery** | |
| Battery type | Spiral wound, thin film, lead-acid |
| System weight[k] | 1.0 kg/kW |
| Maximum charge rate | 30 amps |
| Nominal state of charge[k] | 50% |
| Energy stored[k] | 15 Wh/kg |
| **Motor and Controller** | |
| Overall efficiency[b] | 77% |
| Overall weight[l] | 2.0 kg/kW |
| **Fuel Storage** | |
| Hydrogen[d] | 5000 psi compressed gas tank total weight 50 kg, 7.5% H2 by weight |
| Methanol, Gasoline | 12 kg tank, 13 gallon capacity total weight 50 kg |
| **Driving schedules** | FUDS, FHDS |
| **Regenerative braking recovered up to battery capabilities** | |

Notes for Table 1

a. Based on PNGV targets. (Source: CALSTART website. http://www.calstart.org/about/pngv/pngv_ta.html)

b. Energy and Environmental Analysis, "Analysis of Fuel Economy Boundary for 2010 and Comparison to Prototypes," p. 4-11, prepared for Martin Marietta Energy Systems, Contract No. 11X-SB0824, November 1990.

c. Ross, M. and W. Wu, "Fuel Economy Analysis for a Hybrid Concept Car Based on a Buffered Fuel-Engine Operating at a Single Point," SAE Paper No. 950958, presented at the SAE Interantional Exposition, Detroit, MI, Feb 27-March 2, 1995.

d. C.E. Thomas and R. Sims, "Overview of Onboard Liquid Fuel Storage and Reforming Systems," "Fueling Aspects of Hydrogen Fuel Cell Powered Vehicles," Society of Automotive Engineers, Proceedings, Fuel Cells for Transportation TOPTEC, April 1-2, 1996, Arlington, VA.

e. Based on a Ballard-type PEM fuel cell system with a stack power density of 1 kg/kW. Other weight is due to auxiliaries for heat and water management equipment and air compression.

f.Arthur D. Little 1994. "Multi-Fuel Reformers for Fuel Cells Used in Transportation, Multi-Fuel Reformers, Phase I Final Report," USDOE Office of Transportation Technologies, Contract No. DE-AC02-92-CE50343-2.

g. This estimate was verified with fuel cell developers.

h. The voltage penalty for operation on reformate is based on models by Shimson Gottesfeld at Los Alamos National Laboratory.

i. William Mitchell, Arthur D. Little, private communications, 1997.

j. Mitchell, W. April 2, 1996. "Development of a Partial Oxidation Reformer for Liquid Fuels," Society of Automotive Engineers, Proceedings, Fuel Cells for Transportation TOPTEC, Arlington, VA.

k. Keating, J., B. Schroeder and R. Nelson 1996. "Development of a Valve-Regulated, Lead/Acid Battery for Power-Assist Hybrid Electric Vehicle Use," Bolder Technologies Corporation, Wheat Ridge, CO.

l. Chang, L. "Recent Developments of Electric Vehicles and Their Propulsion Systems," Proceedings of the 28th Intersociety Engineering Conference, vol. 2, pp. 2.205-2.210, American Chemical Society, 1993.

**Table 2.**
**Model Results: Comparison of Alternative Fuel Cell Vehicle Designs**

| Fuel Storage/ H2 Generation System | Vehicle mass (kg) | Peak Power (kW) (FC/Battery) | FUDS mpeg | FHDS mpeg | Combined 55% FUDS 45% FHDS mpeg | range (mi) |
|---|---|---|---|---|---|---|
| Direct H2 | 1170 | 77.5 (34.4/43.1) | 100 | 115 | 106 | 425 |
| Methanol Steam Reformer | 1287 | 83.7 (37.0/46.7) | 62 | 79 | 69 | 460 |
| Gasoline POX | 1395 | 89.4 (39.4/50.0) | 65 | 80 | 71 | 940 |

For the assumptions in Table 1.

**Table 3. Cost Estimates for Mass Produced Fuel Cell Vehicle Components**

| Component | High estimate | Low estimate |
|---|---|---|
| Fuel cell system[a] | $100/kW | $50/kW |
| Fuel processor system [b] | $25/kW | $15/kW |
| Hydrogen storage cylinder rated at 5000 psia[c] | $1000 | $500 |
| Motor and controller[d] | $26/kW | $13/kW |
| Peak power battery[e] | $20/kW | $10/kW |
| Extra structural support | $1/kg | $1/kg |
| Cost of 12 kg gasoline or methanol tank | $100 | $100 |

a. Based on a range of estimates found in the literature. For example, GM/Allison projects a fuel cell "electrochemical engine" cost of $3899 for a 60 kW system including the fuel cell, fuel processor (methanol reformer), heat and water management. This is about $65/kW (at the rated power of 60 kW) or $46/kWpeak. About 45% of the cost per peak kW ($21/kW) is for the fuel cell stack, 28% ($13/kW) for the methanol reformer and the rest for auxiliaries. This cost assumes large scale mass production. (Allison Gas Turbine Division of General Motors December 16, 1992).

Mark Delucchi of Institute of Transportation Studies at UC Davis estimates a retail cost of $2954 for a mass produced 25 kW hydrogen/air PEM fuel cell system or about $120/kW. (The manufacturing cost is $59/kW, with a materials costs for the fuel cell stack plus auxiliaries estimated to be $41/kW, and the labor cost $18/kW. ) (J. M. Ogden, E.D. Larson and M.A. Delucchi May 1994).

A study by Directed Technologies for the USDOE estimated a cost in mass production of $2712 for a hydrogen/air fuel cell plus auxiliaries with net output of 85 kW power (about $32/kW). Directed Technologies is now working with Ford Motor Company on fuel cell vehicles as part of the PNGV program. (Ref: B.D. James, G.N. Baum and I.F. Kuhn, Directed Technologies, Inc. "Technology Development Goals for Automotive Fuel Cell Power Systems," prepared for the Electrochemical Technology Division, Argonne National Laboratory, Contract No. W-31-109-Eng-28, February 1994.)

Chrysler estimates that even with current fuel cell manufacturing technology, mass produced costs would be $200/kW (Chris Boroni-Bird, private communications 1997).

b. W. Mitchell, J. Thijssen, J.M. Bentley, "Development of a Catalytic Partial Oxidation Ethanol Reformer for Fuel Cell Applications," Society of Automotive Engineers, Paper No. 9527611, 1995.

c. C.E. Thomas and R. Sims, "Overview of Onboard Liquid Fuel Storage and Reforming Systems," "Fueling Aspects of Hydrogen Fuel Cell Powered Vehicles," Society of Automotive Engineers, Proceedings, Fuel Cells for Transportation TOPTEC, April 1-2, 1996, Arlington, VA.

d. Derived from estimates in B. James, G. Baum, I. Kuhn, "Development Goals for Automotive Fuel Cell Power Systems," ANL-94/44, August 1994.

e. Based on PNGV goals

**Table 4a. Capital Cost for Developing New Hydrogen Delivery and Refueling Station Infrastructure Serving a Total Fleet of 13,000 FCV Cars, Delivering 2 million scf $H_2$/day (assuming that existing production capacity is used)**

| | Centralized Production via Steam Reforming of Natural Gas w/LH2 Delivery | Centralized Production via Steam Reforming of Natural Gas w/Pipeline Delivery | Onsite Steam Reforming of Natural Gas: Conventional Steam Methane Reformer | Onsite Steam Reforming of Natural Gas: Fuel Cell Steam Methane Reformer | Onsite Advanced Electrolysis Using Off-Peak Power |
|---|---|---|---|---|---|
| Centralized Hydrogen Production | 0 (assumed that existing capacity is used) | 0 (assumed that existing capacity is used) | | | |
| Hydrogen Distribution | 0 (assumed that existing trucks are used) | 10 km pipeline = $6.2 million (at $1 million per mile) | | | |
| 2 Refueling Stations each serving 800 cars/day | $1.4 million ($0.7 per station) | $3.4 million ($1.7 million per station) | $10.8 million ($5.4 million per station) | $6.8 million ($3.4 million per station) | $11.4 million ($5.7 million per station) |
| TOTAL | $1.4 million | $9.6 million | $10.8 million | $6.8 million | $11.4 million |
| infrastructure cost per car | $105 | $740 | $830 | $520 | $880 |

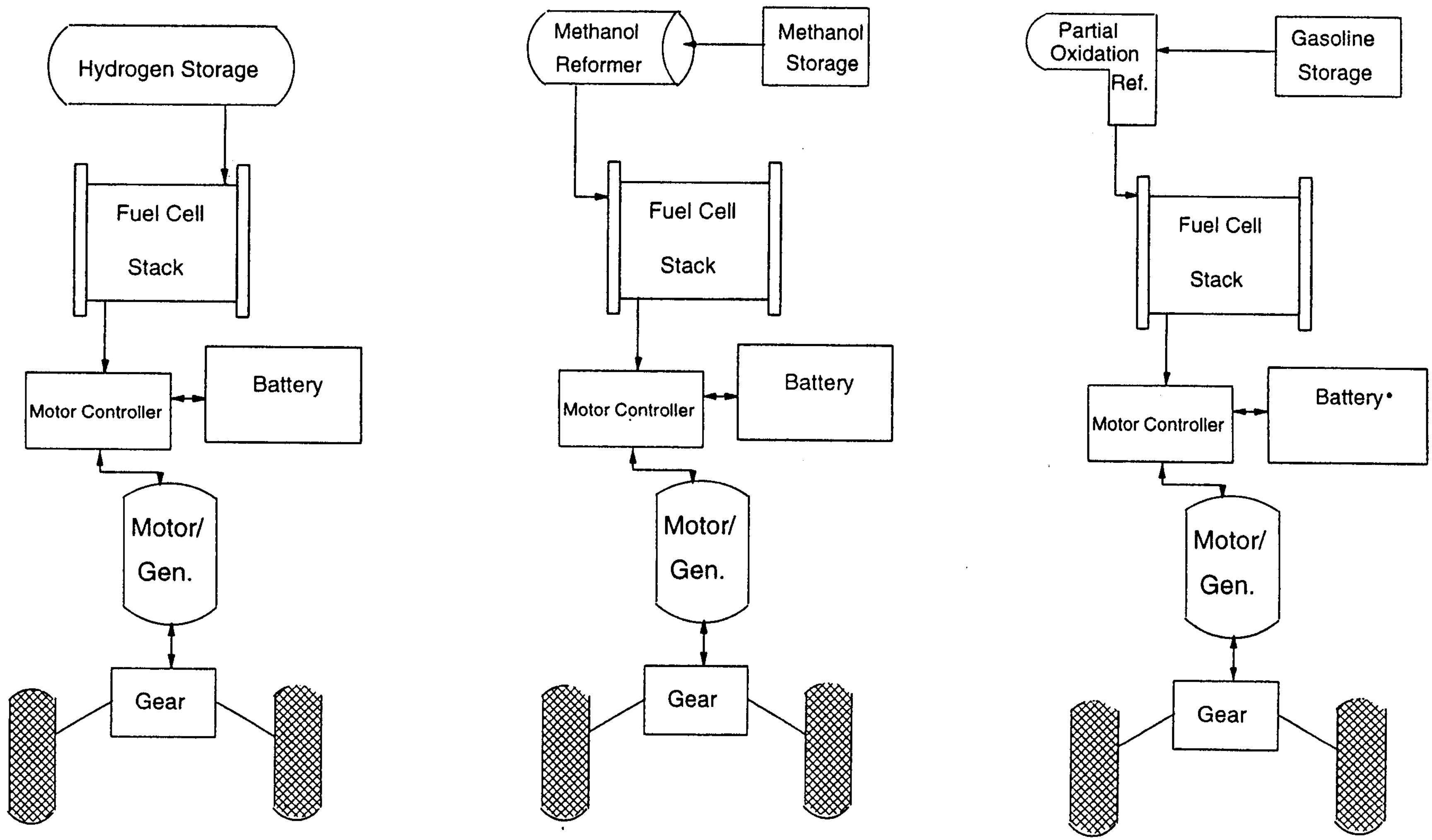
Adapted from Ogden, Kreutz, Iwan and Kartha 1996.

**Table 4b. Capital Cost for Developing New Hydrogen Production, Delivery and Refueling Station Infrastructure Serving a Total Fleet of 1 million Fuel Cell Cars, Delivering 153 million scf $H_2$/day**

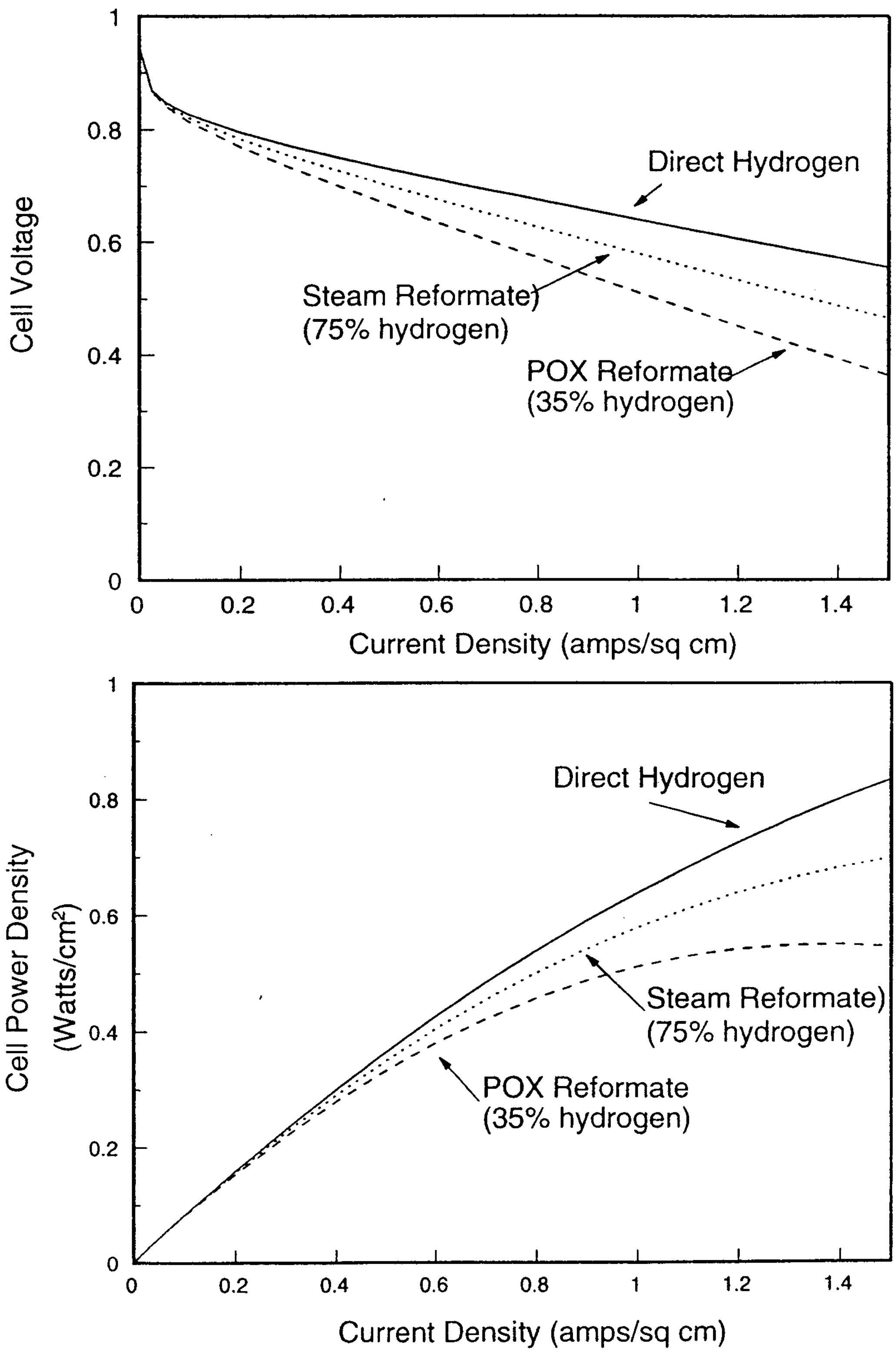
| | Centralized Production via Steam Reforming of Natural Gas w/LH2 Delivery | Centralized Production via Steam Reforming of Natural Gas w/Pipeline Delivery | Onsite Steam Reforming of Natural Gas: Conventional Steam Methane Reformer | Onsite Steam Reforming of Natural Gas: Fuel Cell Steam Methane Reformer | Onsite Advanced Electrolysis Using Off-Peak Power |
|---|---|---|---|---|---|
| Centralized Hydrogen Production | $100 million for reformer + $ 200 million for liquefier + LH2 storage | $170 million for reformer + $H_2$ compressor | | | |
| Hydrogen Distribution | 80 LH2 trucks each with a 3 tonne capacity, each making 2 local deliveries/day = $40 million | 600 km pipeline = $380 million (at $1 million per mile) | | | |
| 153 1 million scf H2/day Refueling Stations each serving 800 cars/day | $104 million ($0.7 million per station) | $260 million ($1.7 million per station) | $830 million ($5.4 million per station) | $516 million ($3.4 million per station) | $870 million $5.7 million per station) |
| TOTAL | $440 million | $810 million | $830 million | $516 million | $870 million |
| Infrastructure Cost per Car | $440 | $810 | $830 | $516 | $870 |

Adapted from Ogden, Kreutz, Iwan and Kartha 1996.

Figure 1: Possible Fuel Cell Vehicle Configurations



# Figure 2: Fuel Cell Model Polarization and Power Curves



# Methanol Steam Reformer System

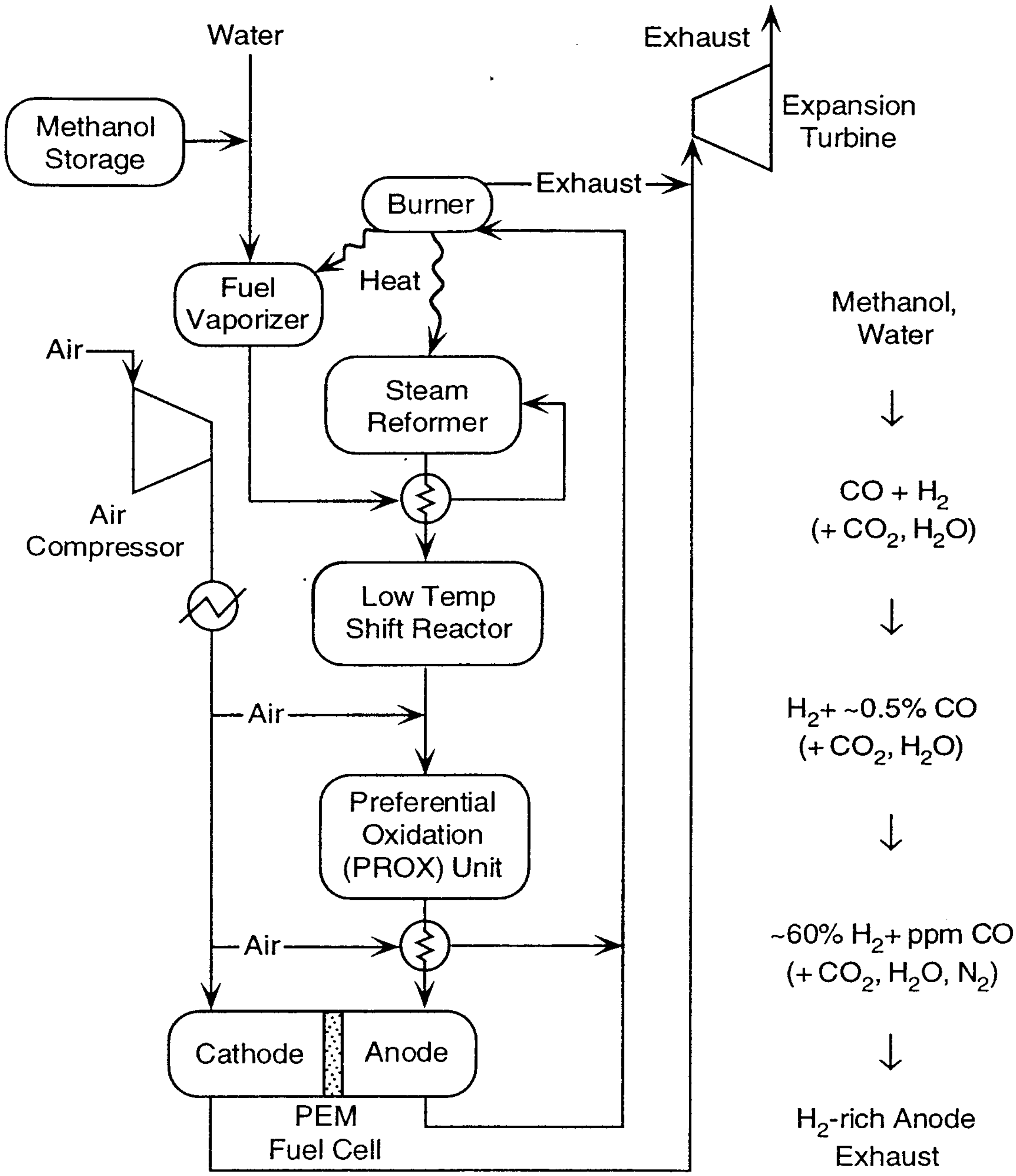



*Figure 3.* Schematic on-board methanol steam reforming system.

# POX Reformer System

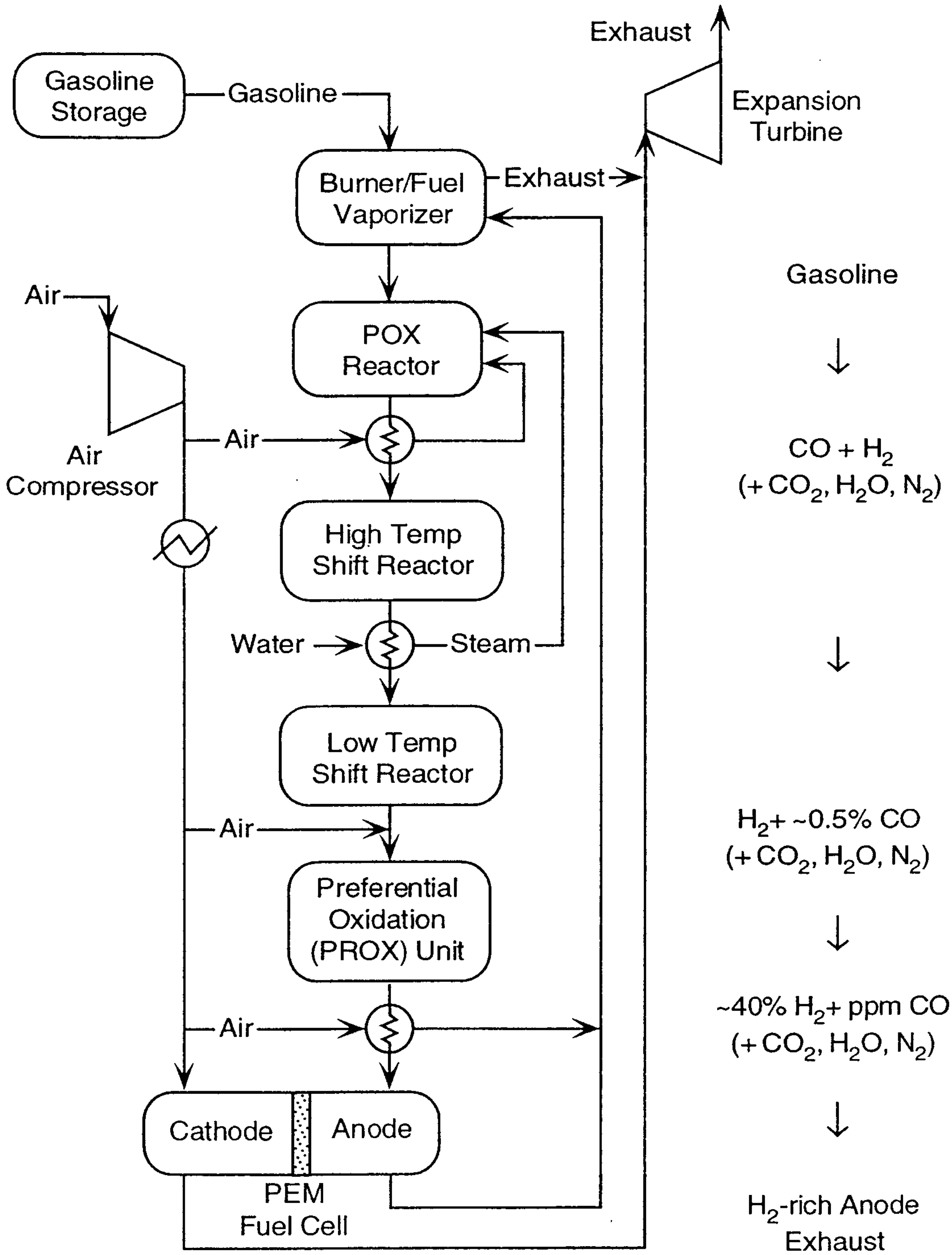



*Figure 4.* Schematic on-board gasoline partial oxidation (POX) reforming system.

# Cycle Power Requirements and System Response

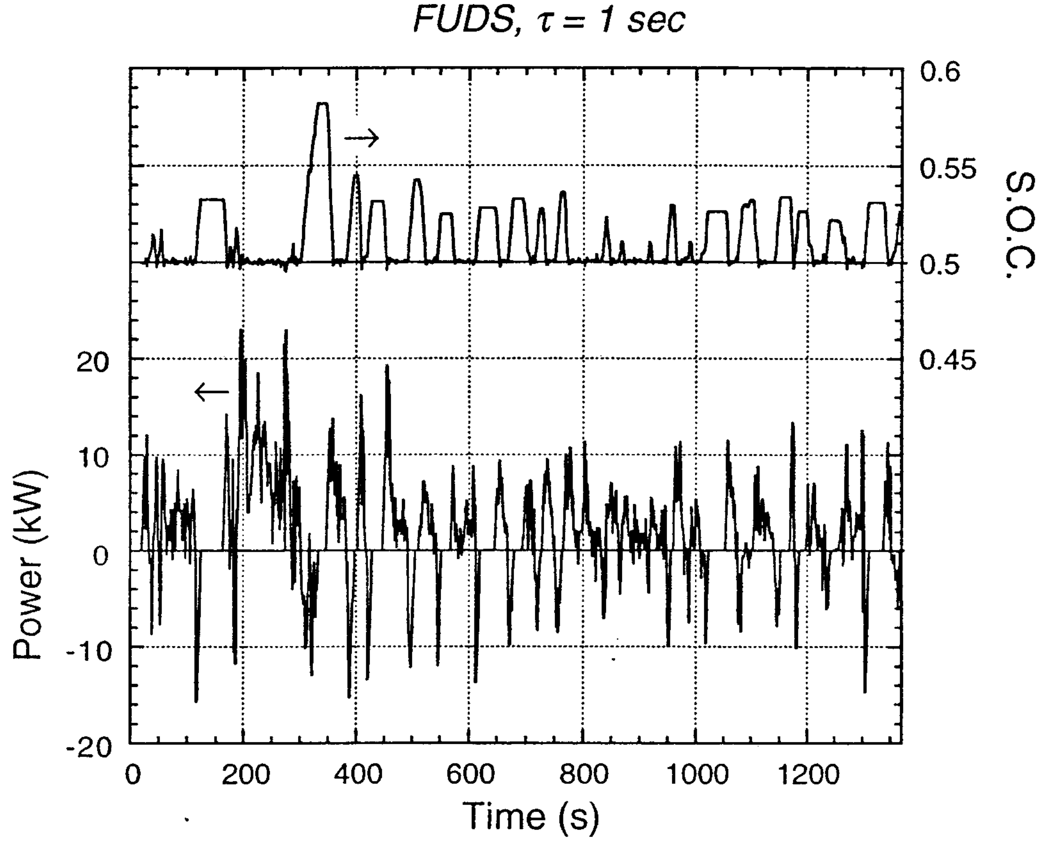



*Figure 5.* The power required of the fuel processor/fuel cell system during the FUDS cycle, and the resulting fractional battery state-of-charge (SOC). Conditions: 1000 kg vehicle mass, 1 sec fuel processor time constant, 0.36 kWh battery, 1 sec characteristic time for battery recharging, 28.9 kW baseload power, 0.77 motor/controller efficiency.

# Time Constant Effects

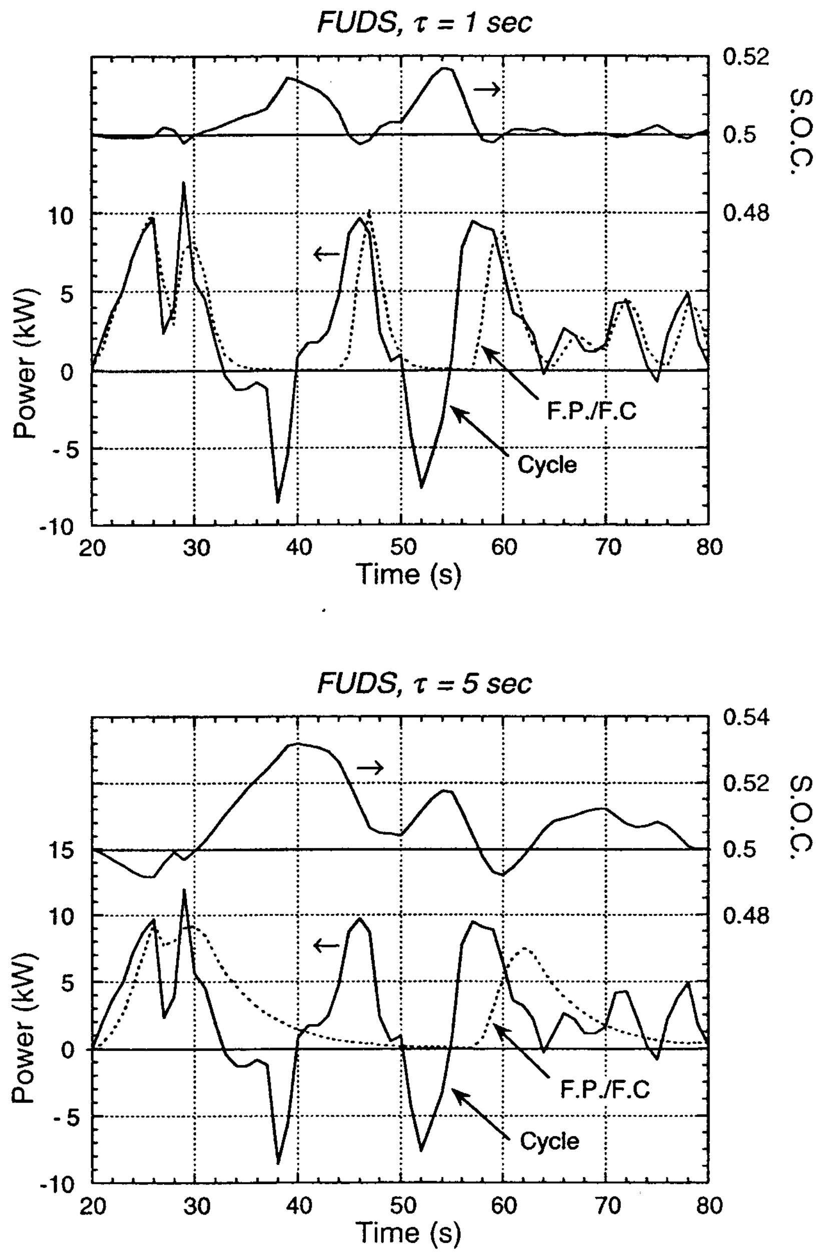



*Figure 6.* The power provided by the fuel processor/fuel cell - for both 1 and 5 second time constants - as a function of time in response to the power demanded by a portion of the FUDS cycle. The resulting battery fractional state of charge (SOC) is also shown, oscillating about its target value of 50%. Conditions: 1000 kg vehicle mass, 0.36 kWh battery, 1 sec characteristic time for battery recharging, 28.9 kW baseload power, 0.77 motor/controller efficiency.

# Time Constant Effects:

## Energy Routed Through Battery

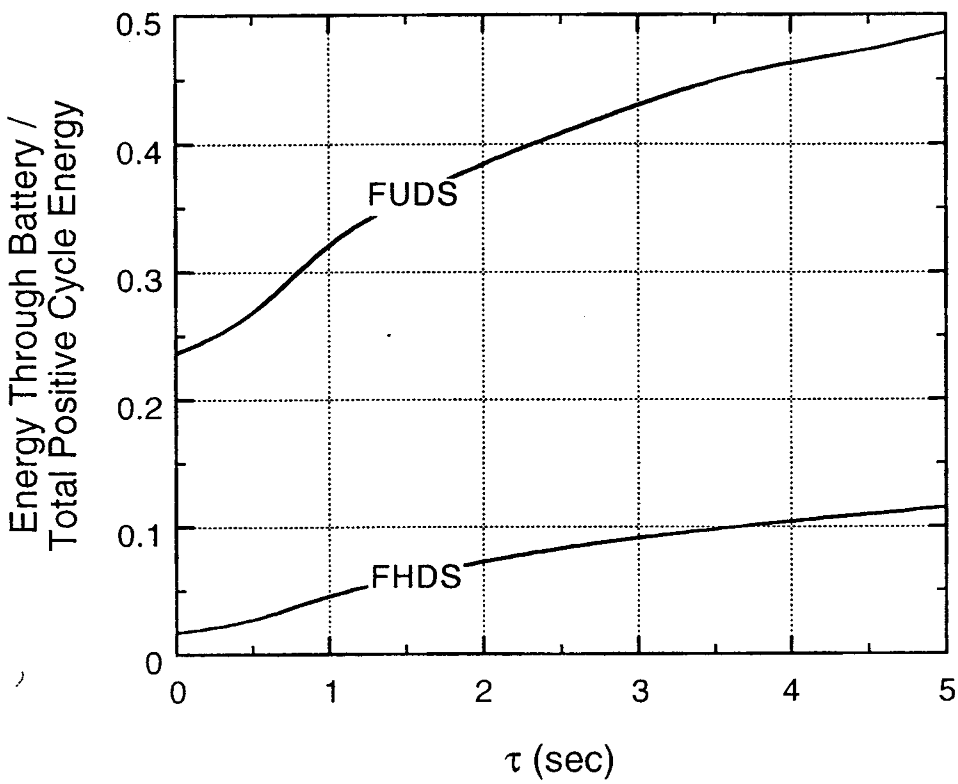
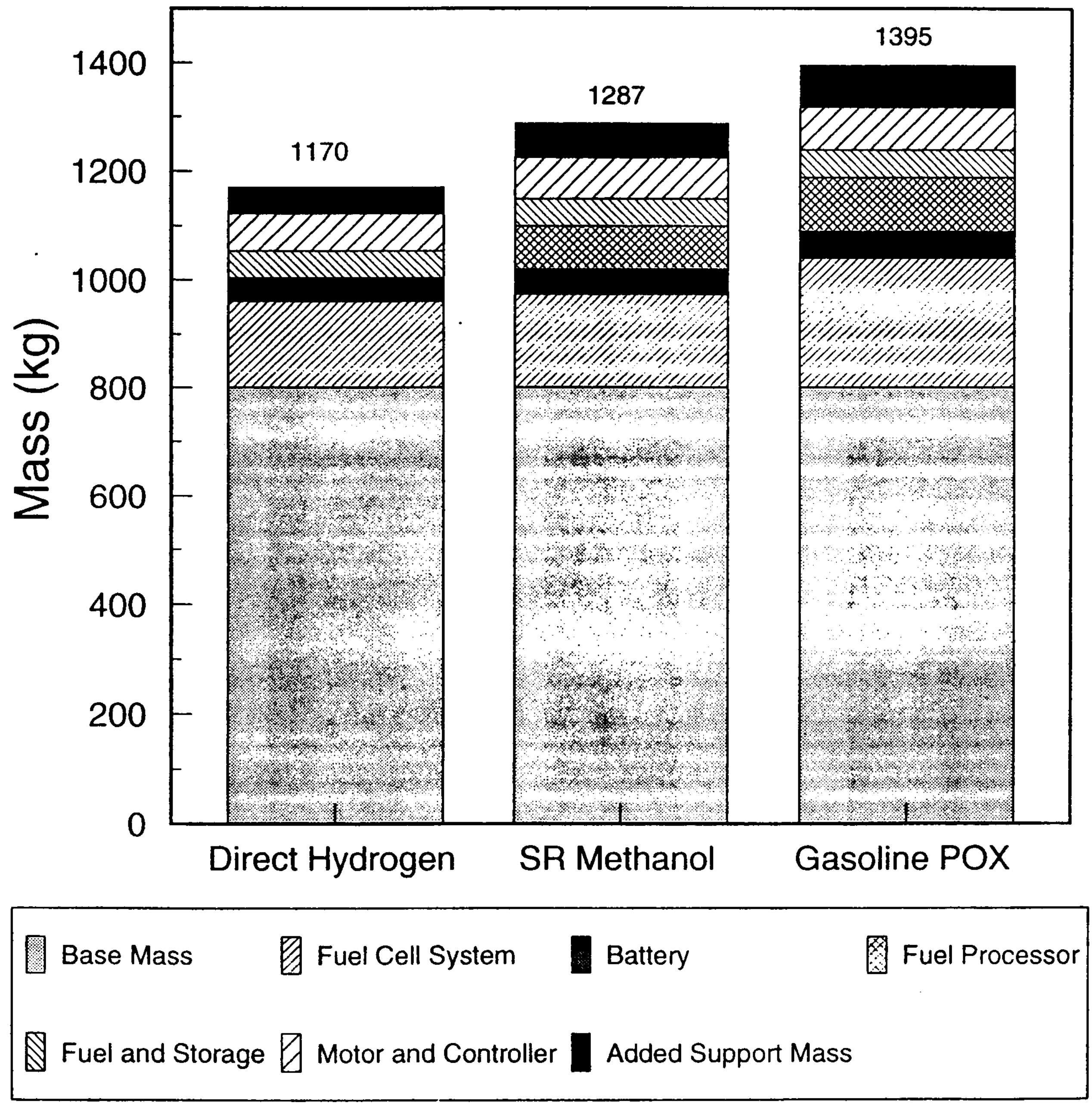



*Figure 7.* The fraction of the total positive cycle energy, for both the FUDS and FHDS driving cycles, that passes through the peaking device (e.g. battery), which acts as a buffer between the fuel processor/fuel cell system and the rapidly fluctuating demands of the driving cycle. Conditions: 1000 kg vehicle mass, 0.36 kWh battery, 1 sec characteristic time for battery recharging, 28.9 kW baseload power, 0.77 motor/controller efficiency.

# Figure 8: Contributions to Vehicle Weight



# Required vs. Available Power

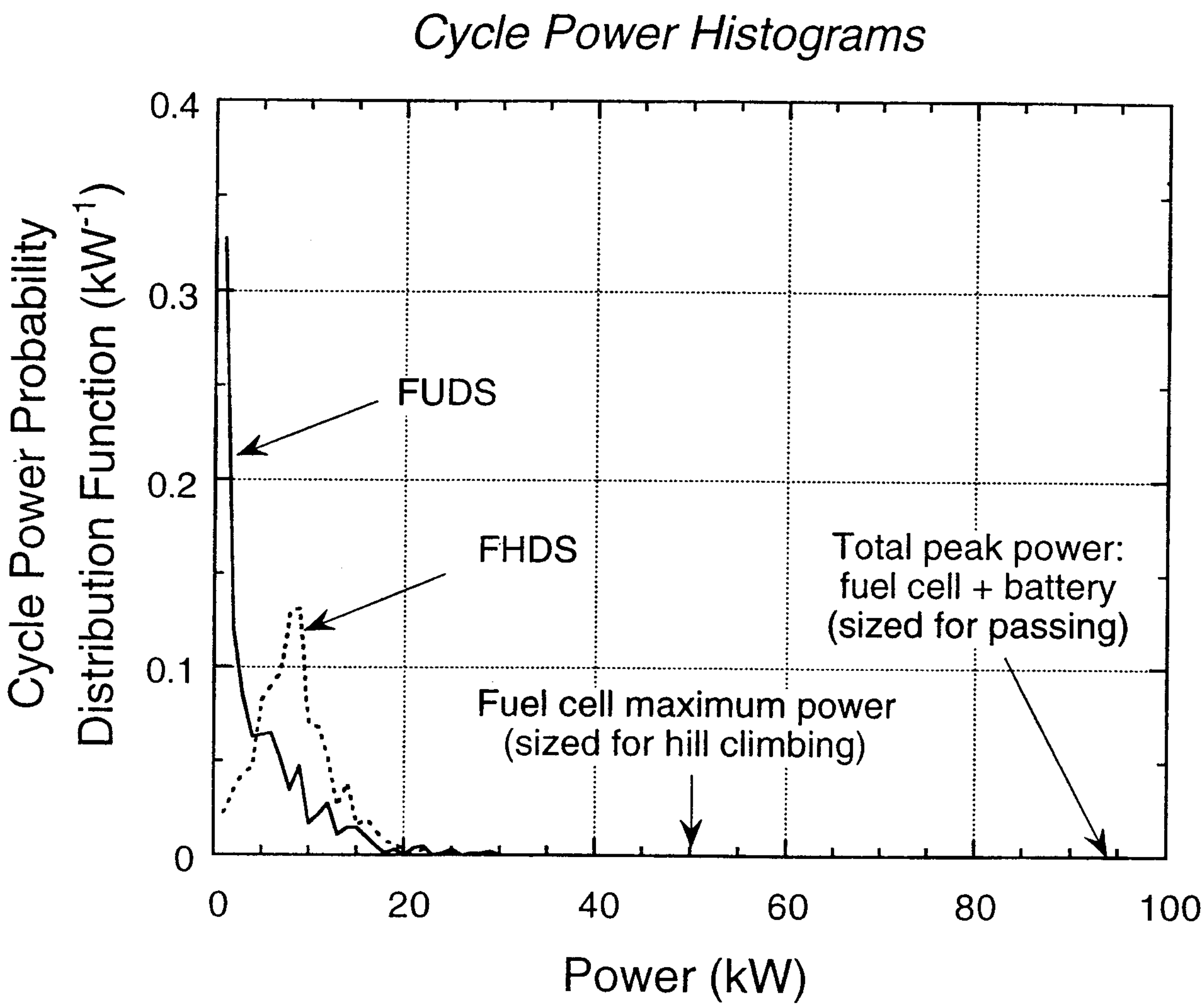



*Figure 9.* Histograms of the power required by the fuel processor/fuel cell system on the FUDS and FHDS driving cycles. As a result of the stiff performance requirements which govern the size of the fuel cell and the battery, much much more power is available than is usually called for under 'normal' driving conditions. Conditions: 1000 kg vehicle mass, 0.36 kWh battery, 1 sec characteristic time for battery recharging, 28.9 kW baseload power, 0.77 motor/controller efficiency.

*Figure 10*

# ***Fuel Economy Penalties From On-Board Fuel Processing***

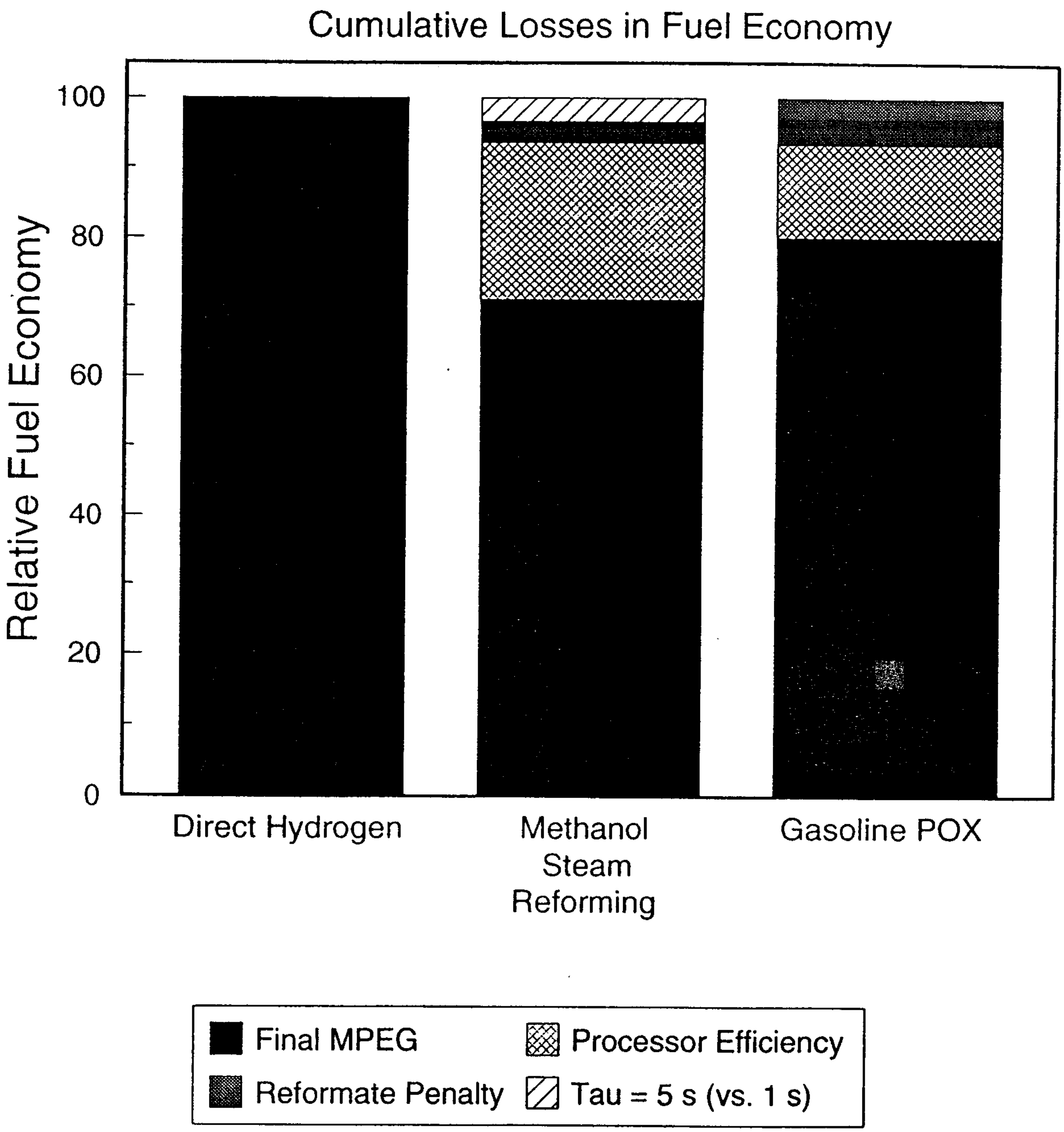
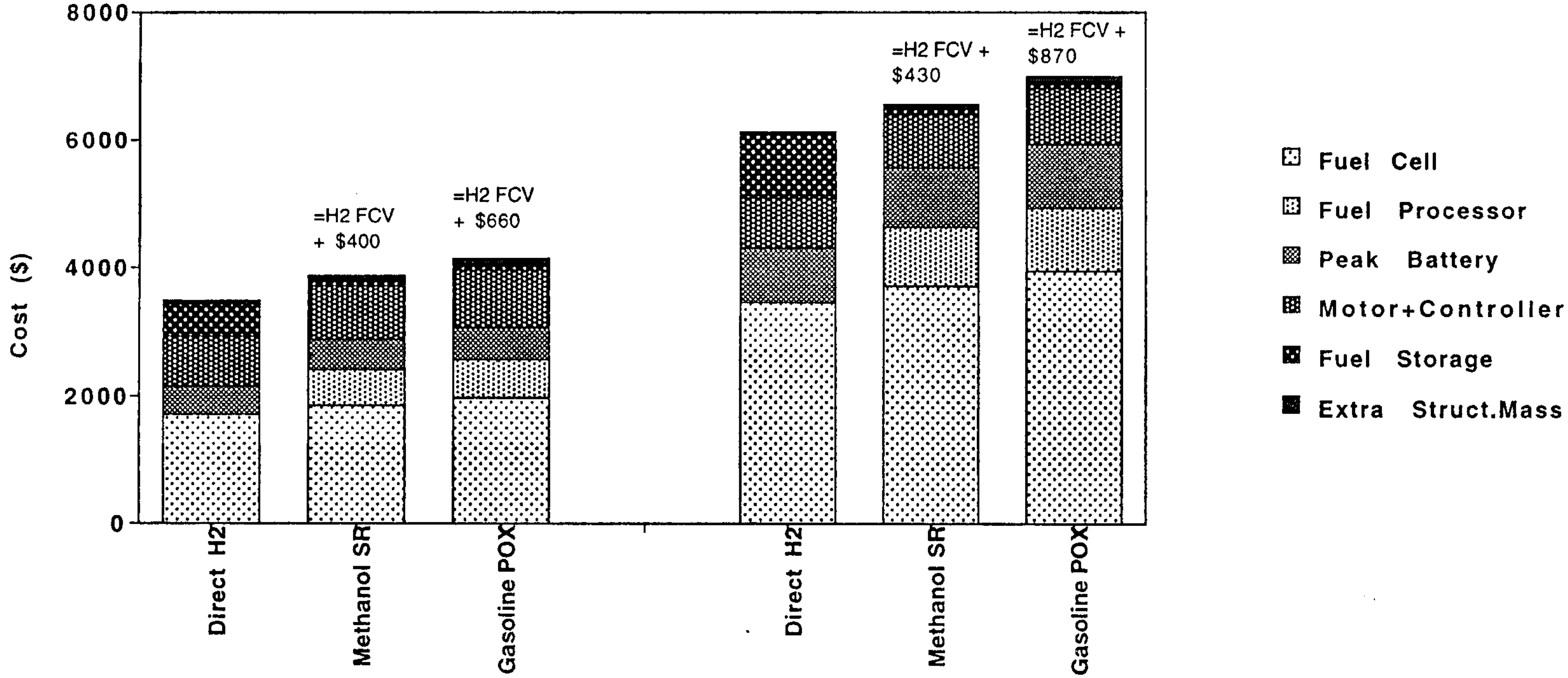


Fig. 11 Cost of Components in Alternative Fuel Cell Automobiles




Fuel Cell = $50/kW
Fuel Processor = $15/kW
Peak Battery = $10/kW
H2 cylinder = $500
Motor+Controller=$13/kW
Gasoline or MeOH Tank =$100
Extra Struct. Mass = $1/kg

Fuel Cell = $100/kW
Fuel Processor = $25/kW
Peak Battery = $20/kW
H2 cylinder = $1000
Motor+Controller=$13/kW
Gasoline or MeOH Tank =$100
Extra Struct. Mass = $1/kg

FIG 12. NEAR TERM GASEOUS H2 SUPPLY OPTIONS

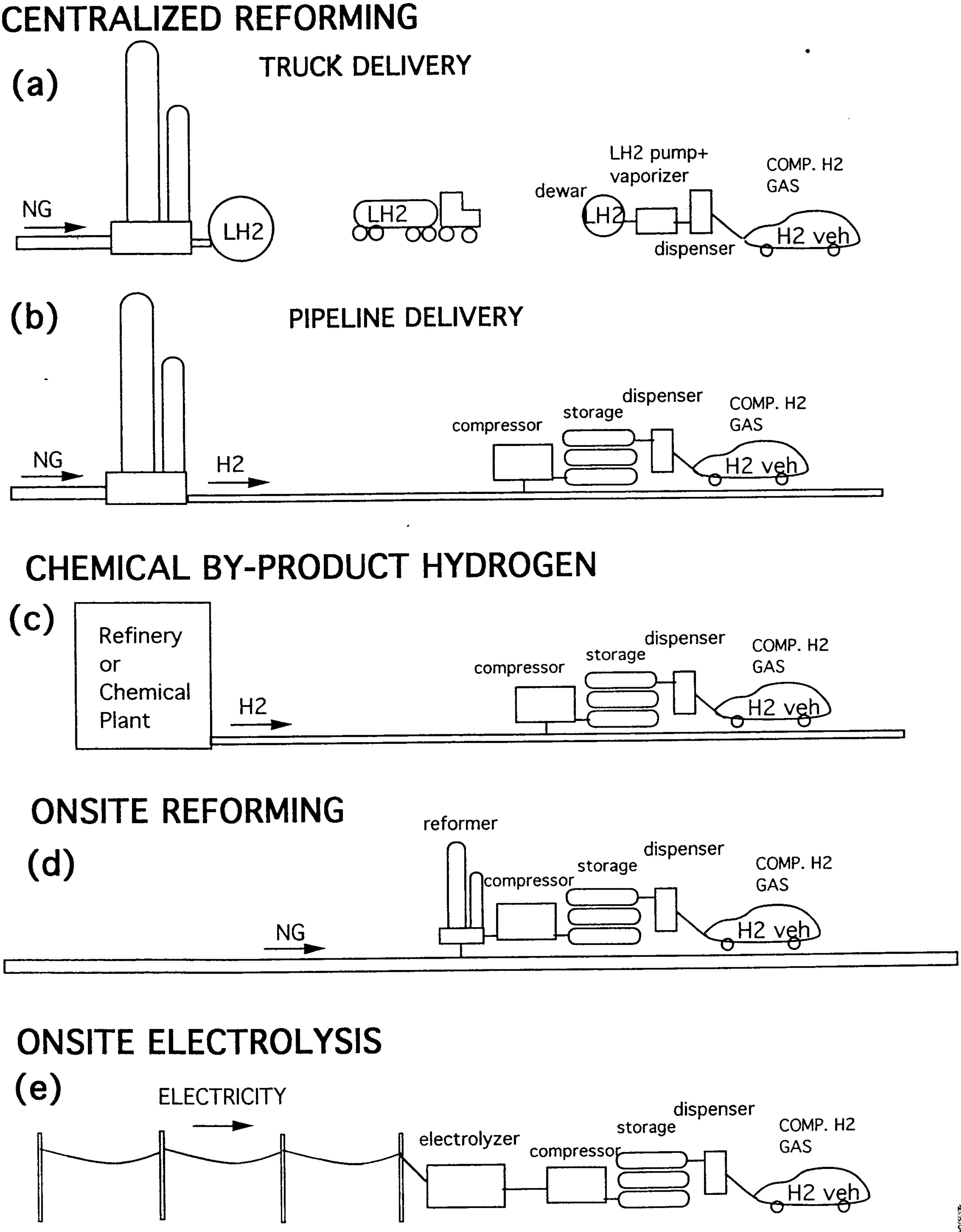


**Figure 13. Delivered Cost of Hydrogen Transportation Fuel ($/GJ) vs. Station Size**

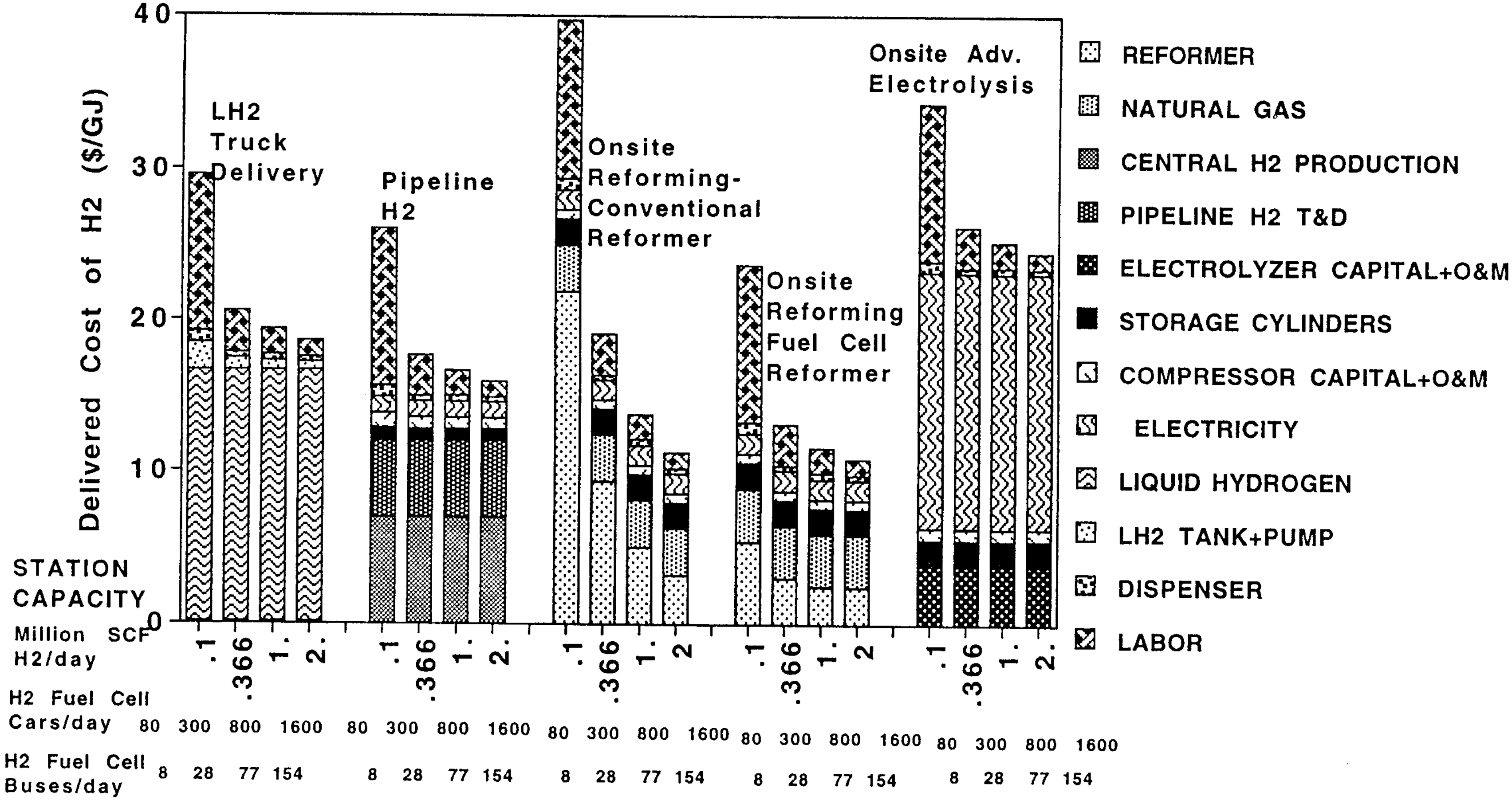
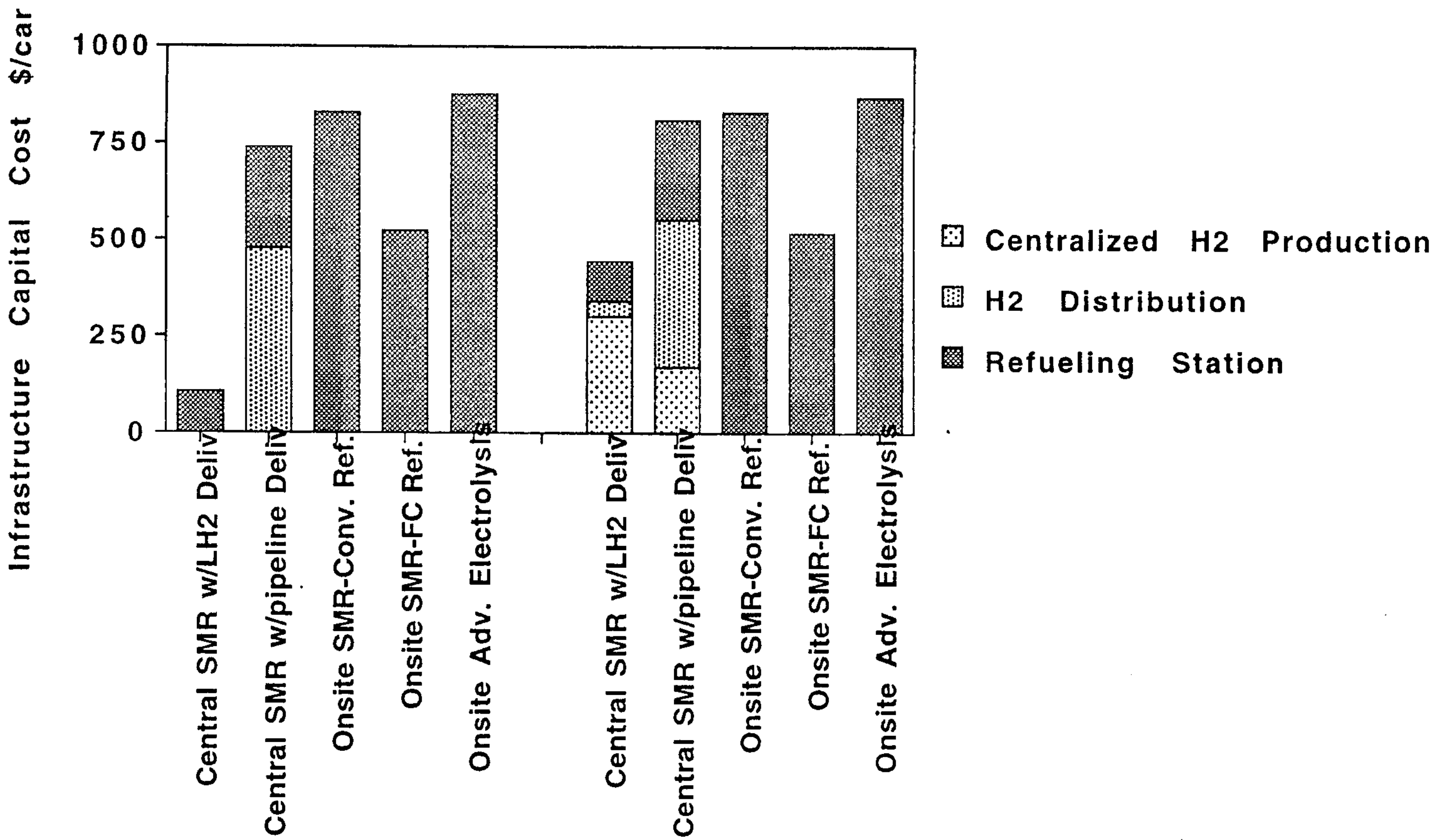


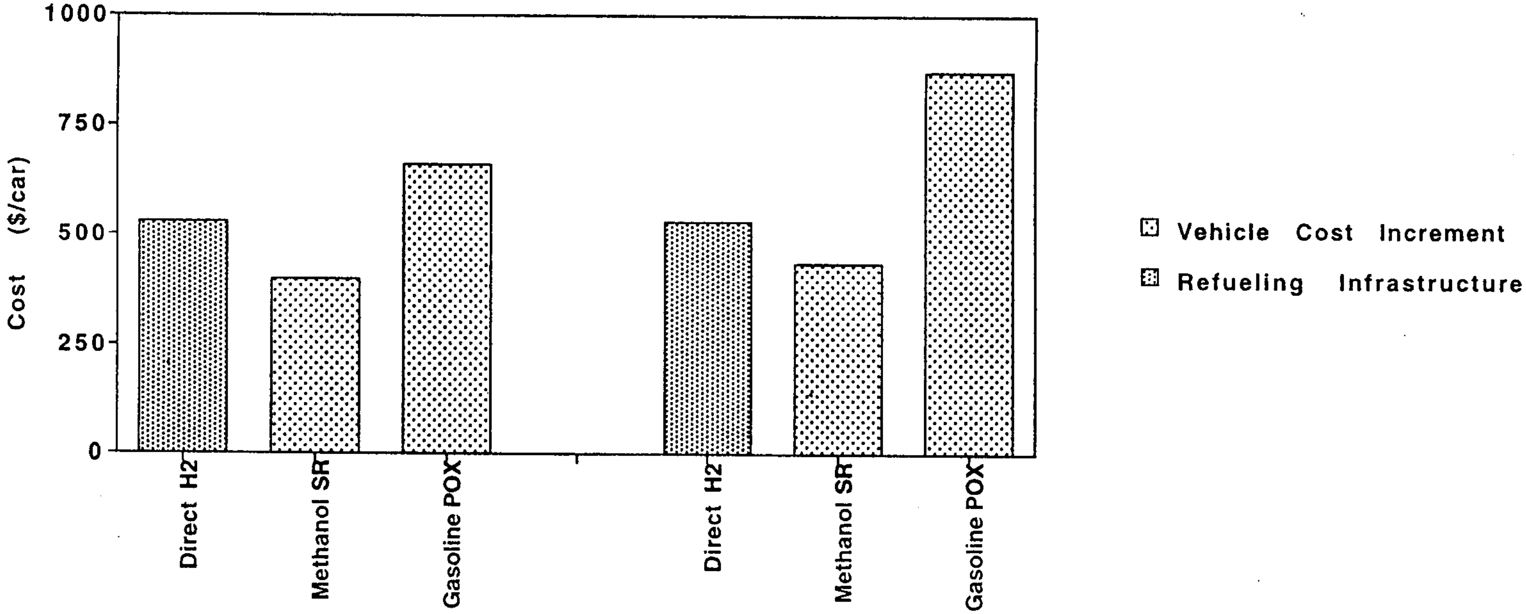
Figure 14. Capital Cost of Hydrogen Infrastructure




Early Development : Total fleet of 13,000 fuel cell cars. Centralized Options use Existing H2 Production Capacity

Extensive infrastructure development: Total fleet of 1 million fuel cell cars. Centralized options use new H2 Production Capacity

## Fig. 15. Comparison of Incremental Costs for Vehicles (Compared to H2 Fuel Cell Vehicle) and Infrastructure (Compared to Gasoline)




Fuel Cell = \$50/kW
Fuel Processor = \$15/kW
Peak Battery = \$10/kW
H2 cylinder = \$500
Motor+Controller=\$13/kW
Gasoline or MeOH Tank =\$100
Extra Struct. Mass = \$1/kg

Fuel Cell = \$100/kW
Fuel Processor = \$25/kW
Peak Battery = \$20/kW
H2 cylinder = \$1000
Motor+Controller=\$13/kW
Gasoline or MeOH Tank =\$100
Extra Struct. Mass = \$1/kg

H2 Refueling Infrastructure = \$530/car (onsite reforming)
No extra infrastructure cost for gasoline