HYDROGEN TODAY

The current status of H2 and Fuel Cells
and
a review of alternatives.

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Introduction:

Hydrogen holds considerable promise as the element that will free mankind from fossil fuels. It is virtually the only technology that has the potential to eliminate or substantially reduce our reliance on oil for transportation while also playing a role in generating electricity.

The President's emphasis on technology and on developing a hydrogen powered automobile by around 2020[1] provides an aggressive time line for the development of hydrogen as a substitute for oil. Strategically it identifies the direction for long range US energy development. Tactically, it puts oil producing nations on notice that the higher they drive the price of oil the faster America will work to develop the hydrogen alternative.[2]

Unfortunately, some absurd things have been written in books and the media about the prospects for a hydrogen economy that create unfounded expectations or are designed to advance an agenda. The only realistic conclusion today is that hydrogen can not begin to significantly displace fossil fuels in the near future: Definitely not before 2020 and probably not until much later.

As a nation we need to be realistic and well informed so we can take actions that ensure an ample supply of electricity[3] and oil over the next several decades while the hydrogen economy emerges. This means a reliance on fossil or nuclear generated electricity; and oil for transportation.

There are several reasons why the hydrogen economy may be delayed well into the future. They include:

- The world is not running out of cheap oil, which means that the cost of gasoline and diesel fuels will remain low: This will make it difficult for hydrogen to be economically competitive for many years to come. The USGS survey in 2000 indicated that there are about 2120 billion barrels of oil (1471 bbl of proven and another 649 bbl yet to be discovered reserves) available outside the United States. This compares with the 539 billion barrels of oil produced outside the US over the past 100 years.[4]
- Internal combustion engines are being constantly improved so that pollution is declining and gas mileage is improving.
- The development of hybrids using a combination of an internal combustion engine and electric motors creates an alternative to hydrogen propelled vehicles.
- Improved internal combustion engines and hybrids create a moving cost target making it ever more difficult for hydrogen propelled vehicles to compete.
- The vast amounts of coal and improving technologies for the clean burning of coal will make it difficult for fuel cells to compete in the generation of electricity.
- Gas turbines, including micro gas turbines, are far more efficient than fuel cells for generating electricity: Why convert natural gas to hydrogen when natural gas by itself can do the job at less cost?
- Nuclear[5], which generates electricity at a lower per KwHr cost than coal and which is as air quality friendly as hydrogen, could make hydrogen a less desirable alternative for power generation: Or, conversely, could contribute to the hydrogen economy by producing low cost bulk hydrogen.

This paper attempts to put the hydrogen economy into perspective and explores the obstacles that must be overcome, the current status of key technologies and some sense as to when various facets of the hydrogen economy may emerge. There is no guarantee that hydrogen will emerge as the replacement for fossil fuels though this paper assumes that the hydrogen age will eventually emerge.

Currently, there do not appear to be any technical or physical showstoppers that would preclude using hydrogen as a fuel for transportation or for power generation: All of the technical issues seem to relate to cost, which will be the ultimate hurdle before hydrogen can successfully displace fossil fuels.

The technical and cost issues can be categorized as follows[6]:

- Production
- Delivery (Transporting of hydrogen.)
- Storage
- Usage (Conversion of hydrogen to useful work.)
- Safety

It would appear that the relative importance of these issues differ in so far as they relate to the use of hydrogen for transportation (e.g., automobiles) or for the generation of electricity.

1. For automobiles (and other transportation vehicles) it would appear that producing hydrogen would take place external to the vehicle so that the vehicle itself carries pure hydrogen. The exception would be if methanol or other liquid (including gasoline, which seems counter productive) was used in the vehicle as the hydrogen source.
2. For the generation of electricity it would appear as though the source gas (methane) can be piped directly to a fuel cell used for power generation, where the hydrogen is extracted from the source gas by a reformer that is an integral part of the power generation unit.

In the first instance production of hydrogen takes place external to the vehicle. In the second instance production takes place within the stationary power generation unit.

In the first instance the issue of transporting hydrogen is resolved if production takes place at the point of fueling the vehicle. In the second instance transportation could be as simple as using natural gas already piped to buildings (where reforming takes place inside the stationary power generation unit).

In the first instance storage of hydrogen on the vehicle (and at fueling stations) is a problem while storage in the second instance is essentially accomplished by the pipelines transporting natural gas.

In both instances usage of hydrogen is probably accomplished by using a fuel cell, though internal combustion engines are an alternative.

It is difficult to chronicle with absolute certainty the latest technologies available to resolve each of these issues as much of the work is being done by the private sector where detailed information is proprietary. Fuel cell companies and others are rightfully concerned about protecting their investment in their unique technologies. Enough information is forthcoming, however, to allow educated conclusions regarding these issues.

Production.

The process of extracting hydrogen from chemical compounds is called reforming. Currently accepted methods of reforming[7] are:

- Steam methane
- Partial oxidation
- Electrolysis

Other methods being explored in laboratories are:

- Thermochemical water splitting using nuclear or solar heat.
- Photolytic using solid state solar photochemical electrolysis.
- Biological techniques using algae and bacteria.

Currently nearly all the 9 million tons of hydrogen produced each year are used in the chemical, refining and metals industries, with 95% of the hydrogen produced by the steam methane process.

A major obstacle facing the production of hydrogen is that the cost per unit of energy produced using hydrogen reformate is greater than the cost of the same unit of energy from the hydrocarbon source itself.

No matter how it is done, producing hydrogen is currently far more costly than producing gasoline. Where the hydrogen is produced also affects overall costs. If it is produced in bulk some distance from the point of usage, transportation of hydrogen will add to total costs.

Producing hydrogen from water using electrolysis is ten times more costly than natural gas and three times more costly than gasoline per BTU.[8]

Using renewable energy sources to produce the electricity needed to separate the hydrogen from water using electrolysis is simply not feasible. Wind power is the lowest cost renewable energy source other than hydro and it would require 300,000 wind turbines rated 2MW (currently the largest production units) occupying an area of roughly 40,000 square miles to produce enough hydrogen to power 1/3 of the automobiles currently on the road in the US[9]. Compare this with the largest number of wind turbines ever installed in the United States in one year, which was 1000.

Without integrating the reformer with the fuel cell, the hydrogen needs to be produced separately and then delivered to the point of usage…or produced at the point of usage and transferred to the vehicle using a fueling station. Current prototype fueling stations look much like a typical gasoline pump: An electrolyzer or steam methane reformer is used to produce the hydrogen which is stored in the fueling station under pressure; and then by using a hose and nozzle device the hydrogen is transferred (under pressure) to the vehicle.

Demonstration electrolysis units (electrolyzers) intended for fueling vehicles at dispersed locations (such as the corner gas station) have been installed at several locations.[10]

The alternative to electrolyzers for producing hydrogen locally at fueling stations is small steam methane reformers using natural gas. One flow of natural gas is burned to generate the steam that is then used with a second flow of natural gas to strip it of hydrogen. These natural gas reformers suitable for installation in service stations are currently under development.

It would appear that electrolyzers can be scaled to small sizes appropriate for fueling a small number of vehicles daily while the natural gas reformers are difficult to economically scale to small sizes and are more suitable for fueling a larger numbers of vehicles.

Incorporating the reformer with a fuel cell allows an integrated unit to be installed in homes and commercial centers using natural gas piped into homes and office buildings. As an intermediate step a reformer capable of extracting hydrogen from methanol or propane would permit the installation of an integrated reformer and fuel cell in an automobile or bus.

With a reformer on board, a fuel cell car has essentially the same efficiency as a car using an internal combustion engine (ICE); while a fuel cell vehicle (FCV) that uses pure hydrogen, generated external to the vehicle, is about twice as efficient as an ICE car.

Undesirable by-products are produced by the steam methane and partial oxidation processes. The small natural gas reformers under development appear to resolve this issue. Electrolysis produces hydrogen with no undesirable by-products. All three of these methods consume more energy than can be derived from the hydrogen produced by the process.

In the final analysis cost is likely to be the greatest stumbling block in using hydrogen in any application.

Delivery.

Hydrogen gas has low energy density which means it contains a small amount of energy per unit volume. To be a practical fuel source it must be compressed, liquefied or stored in a transfer medium such as a metal hydride or carbon structure that acts like a sponge.

At present, compressed hydrogen is the simplest and least costly approach.

Liquefied hydrogen does not appear to be a practical alternative except for special applications, such as rockets, and possibly as a method for transporting large amounts of hydrogen. However, some car manufacturers are pursuing this approach.[11] Hydrogen does not become liquid until its temperature is lowered below -423 degrees F. Refrigerating hydrogen to this temperature uses the equivalent of approximately 25% of hydrogen's energy content; which is a large penalty to pay in overall terms of energy usage.[12]

Hydrides currently store little energy per unit weight. The current research objective is to develop a hydride that will have a high energy density where the hydrogen can be quickly released. Quick release of hydrogen from the hydride is required for the fuel cell (or internal combustion engine) to respond to rapid changes in load.

Compressed hydrogen, liquefied hydrogen and hydrogen in a hydride can be transported using rail or trucks. Hydrogen is delivered using high-pressure cylinders and tube trailers when the distances are less than a few hundred miles. Long distance distribution usually requires using cryogenic highway tank trucks, rail or barge.

Hydrogen gas can be transported in dedicated pipe lines separate from natural gas pipelines.

An important aspect of delivery is the ability to fill the vehicle's tank with hydrogen. The process must be simple (similar in ease to filling a car with gasoline) and safe. Several prototype fueling stations have been developed (see above) and have successfully demonstrated that the technology itself is not an issue: Cost remains the core issue.

Storage

To a certain extent storage and delivery issues are inherently similar. Much of what has been said about delivery also applies to storage.

Hydrogen can be stored as a compressed gas (such as at 5000 psi), as a liquid at -423 degrees F, in a hydride form or in carbon structures.[13] Some test vehicles have used hydrogen stored in cryogenic (thermos bottles) mounted in the car.[14]

Storage will be required at vehicle fueling stations and also on vehicles themselves. Storage will also be required to supply stationary fuel cells, used for power generation, where the fuel cell does not use methane (natural gas) piped directly to the unit or where the hydrogen is produced separately in a small natural gas reformer.

The key criteria for hydrogen storage on vehicles is the ability to store sufficient hydrogen in the limited space available on a vehicle to provide an acceptable range (300 to 400 miles for automobiles and 100 to 150 miles for busses) before refueling; without adding an inordinate amount of weight. Traditional steel cylinders are inappropriate due to their weight.

These ranges translate into an ability to store approximately 3 kg (8 pounds) of hydrogen on a bus and 5 kg (13.4 pounds) on an automobile when these vehicles are powered by a fuel cell.

One approach has been the development of carbon fiber-wrapped composite tanks that are reasonably light weight and hold hydrogen at 5000 psi. (A 10,000 psi tank to afford a range of 300 miles is currently being tested by GM[15].) A Ford conceptual fuel cell car proposed using three such tanks to hold 8 pounds of hydrogen, sufficient to allow the car to have a range of over 300 miles. (The car was not built so the concept was never proven.)

Fleet operated vehicles, such as city busses, typically operate on a predetermined schedule where the distances are known and where fueling can be done on a predictable schedule at a central fueling station.

It should be noted that fuel cells can also use liquids (such as gasoline and methanol) and gasses (such as propane) as a source of hydrogen. These do not appear to be long term solutions though they may provide interim solutions while the structure of the hydrogen economy is emerging.

Usage.

Converting hydrogen into useful work can be accomplished by using internal combustion (reciprocating) engines, gas turbines or fuel cells supplying electricity to motors.

Gas turbines already burn natural gas and are used around the world for power generation, either singly or in a combined heat and power installation. There seems little reason to operate gas turbines on pure hydrogen except in very special situations.

Internal combustion engines can be adapted to burn hydrogen rather than gasoline. Because internal combustion engine technology is already available and plants already exist for their manufacture, they may be a logical intermediate step in the development of the hydrogen economy. Internal combustion engines can be used for transportation and for stationary power generation. Burning pure hydrogen in an internal combustion engine produces water, about the same amount of NOx as a gasoline ICE and possibly somewhat more soot particles than a gasoline ICE..

Fuel cells are believed to be the eventual preferred method for converting hydrogen into work: However, fuel cells are currently ten times more expensive than internal combustion engines.

Fuel cells of various types[16] have been under development for many years and have been used successfully in the space program and in stationary power generation. Commercial fuel cells are on the market today for power generation, either as back up power, remote stand alone power plants or cogeneration. Micro fuel cells for powering hand tools and smaller items are also under development.

Proton Exchange Membrane (PEM) Fuel Cells that operate at relatively low temperatures seem to be the type receiving the most attention at this time for possible use in vehicles and in residential applications.

Safety.

A major impediment to the development of a workable hydrogen economy is the development of standards. In the same way that the UL label indicates that electrical products have met required standards, a system of standards must evolve that demonstrates the safety of various hydrogen products. Governments at all levels must either develop standards or accept the standards of a central testing and regulating body similar to UL. Until these standards have been developed and agreed upon and then incorporated in all the building and regulatory codes throughout the United States, it is impossible for the hydrogen economy to take shape.

The complexity of this issue can not be overstated. Not only are there many professional standards bodies involved with establishing standards, but there are myriad governing bodies (Federal, State, City, County, International etc.) with which to contend as well as numerous components (valves, gaskets, piping, etc.) and sub systems that must be certified as safe.

Acceptance by the public depends on such a system of standards and certification. For example, most people will require that vehicles be crash tested to prove that the hydrogen, its storage system and fuel cell will be safe in the event of an accident.

While natural gas includes an additive that produces an odor when it escapes, it is not yet possible to add such an ingredient to hydrogen; substances that provide an odor attack the fuel cell. Natural gas in homes is accepted by nearly everyone as being safe; partly because the odor identifies leaks. Whether hydrogen detectors, similar to smoke alarms, are acceptable to the public is yet to be determined. Until this question is answered the idea of installing reformers in homes for fueling vehicles is strictly conjecture. Fuel cells for power generation that have integrated reformers and where the hydrogen is used as it is produced may be acceptable for in home installation; but regulators still need to address this issue.

Economic Considerations.

No one, at this point, can estimate with any degree of certainty the ultimate composition of an economy using hydrogen in place of oil. However, some observations are appropriate.

It would appear that generating hydrogen locally at the point of usage (i.e., in filling stations) will be more cost effective than generating hydrogen centrally and then transporting it to the point of usage. Transportation costs, the cost of storage (probably cryogenic) and hydrogen losses (e.g., boil off) would seem to more than offset the probable higher cost of distributed reformers. New hydrogen pipelines duplicating existing natural gas pipelines are a possibility, but would seem to be expensive and inflexible.

Producing hydrogen locally has certain implications. If electrolyzers are used, it will require increasing the electric utility infrastructure to generate, transmit and distribute the necessary electricity; while if small natural gas reformers are used, it will require increasing the infrastructure for producing, transmitting and distributing natural gas.

Using small natural gas reformers would also put an additional demand on natural gas reserves and require increased exploration and drilling in the United States and Canada; or, importing liquid natural gas (LNG) from overseas.

It has been suggested that a hydrogen economy will result in overall savings to the economy. This suggestion is based on the hydrogen infrastructure being inherently less costly than maintaining and growing the existing oil production, refining and distribution infrastructure.[17] Though the economy as a whole may enjoy reduced investment, the cost of implementing the hydrogen infrastructure will be borne by different companies; some of whom may enjoy no offsetting savings.

If the oil companies invest in the fueling stations they can expect to save on not having to spend as much on their existing petroleum infrastructure: This frees up cash for investing in the hydrogen infrastructure. The gas companies and electric utilities will have no such offsetting savings so the necessary growth in their investments must come from additional funds over and above those required by the economy without hydrogen production.

The ultimate magnitude of these investments is huge.

There are roughly 180,000 filling stations in the United States and it has been estimated that at least 30% of these must have hydrogen fueling stations before fuel cell vehicles can enjoy wide usage.

At quantity 1, the cost of the small natural gas reformer is around $750,000. Assuming a 95% learning curve the average cost of each of 60,000 units will be approximately $375,000. The total investment (assuming one fueling station per location) will be around $23 billion. Assuming that each station can support 1400 cars this investment would support approximately 80 million fuel cell cars.[18] For comparison, there were approximately 135 million cars on the road in the United States in 2000.

All of the above economic considerations are speculative (though based on current data) and, naturally, the investment in fueling stations and additional natural gas or electric infrastructure would be made over a period of time.

Conclusion:

There is currently no simple road map for a hydrogen economy: There are too many unresolved issues and too many alternatives to be explored before settling on an appropriate road map.

Today, the primary motivation for developing the hydrogen economy is to free the United States from dependency on foreign oil, though activists are promoting hydrogen to forestall global warming[19].

It will be many decades before hydrogen and fuel cells will be economically competitive with fossil fuels for transportation or the generation of electricity. Roughly speaking, the cost of fuel cells and hydrogen needs to come down to around 10% of their current costs before hydrogen will be competitive with fossil fuels. It is estimated that a fuel cell car currently costs around $1 million while a fueling station suitable for handling the same number of cars as a traditional gas pump currently costs around $750,000; and hydrogen, on an energy for energy basis, costs around $4 per gallon of gasoline. (It should be noted that these estimated costs vary widely depending on the source.)

Current internal combustion engines are being constantly improved, making it ever more difficult for hydrogen to compete in the transportation arena. There is also the problem of establishing a hydrogen fuel infrastructure where fueling stations are conveniently located for refueling vehicles.

Coal will remain cheap for decades to come and the burning of coal cleanly is also being constantly improved so as to reduce pollutants. Natural gas fired gas turbines are extremely efficient and don’t require extracting hydrogen from the natural gas.

Virtually all the technical issues relating to producing, shipping, storage and use of hydrogen relate to cost and safety. Cost issues are formidable while the complexities of establishing and enforcing safety standards are daunting.

Attempting to develop renewable energy sources to produce hydrogen is a fool’s errand.

In the transportation sector, the most likely scenario is for hydrogen to be used in fleets of vehicles, such as municipal busses, where fueling is done centrally, distances between refueling are relatively low, the cost of the fuel cell is relatively low compared to the total cost of the vehicle and local air quality is a compelling reason for using fuel cells. Hydrogen fueled automobiles using fuel cells will be produced in very limited quantity for at least the next dozen years. Again, fleets of vehicles (taxi’s, service vans etc.) will be the most likely first users of hydrogen.

Vehicles with internal combustion engines using hydrogen (H2 ICE vehicles) could help stimulate the development of the fueling infrastructure and provide a logical way to transition to the hydrogen economy while waiting for the development of low cost fuel cells.

Fuel cells for power generation will continue to be used for backup power and other special applications. The widespread use of fuel cells in residential and commercial settings is unlikely for decades to come. Coal and gas are plentiful in the United States and will be very hard to displace as the primary source of power generation.

Given these factors it is unlikely that hydrogen will significantly displace fossil fuels any time soon. There is always the possibility that technical breakthroughs could dramatically lower costs so that hydrogen could become competitive more quickly: And, if the ultimate objective is to free the United States from foreign oil, funds for hydrogen R&D for transportation are well spent.

Glossary of terms frequently encountered when reading about hydrogen.

AFV = Alternative Fuel Vehicles
BPEV's = Battery Powered Electric Vehicles
CaFCP = California Fuel Cell Project
CNG = compressed natural gas
FCV = Fuel Cell Vehicle
GHG = Green House Gasses
ICE= Internal Combustion Engine
ISO = International Standards Organization
LHV = Lower Heating Value
NOx= Nitrous Oxide
SDO = Standard Development Organization
ZEV = Zero Emission Vehicles

Notes:

1. President Bush in his state of the union speech said “that the first car driven by a child born today could be powered by hydrogen and pollution-free”. Depending on when a child born today could legally drive, the year might be 2018 or somewhat later.
2. Conversely the OPEC strategy has been to keep the price of oil low enough to deter our development of alternatives to Mid East oil.
3. Renewable energy sources include wind power, biomass, solar, geothermal and hydro power. These sources can not replace fossil fuels for the generation of electricity. Combined, all these renewable energy sources will produce no more than 4% of all the electric power needs of the United States by 2020. See “The False Promise of Renewable Energy (for power generation)” at www.tsaugust.org.
4. USGS world Petroleum Assessment 2000. See USGS Fact Sheet FS-070-00 April 2000.
5. New Pebble reactors may offer nuclear power acceptable to most people.
6. The Department of energy defines these categories as production, delivery, storage, conversion and applications. Conversion refers to the process by which hydrogen is converted to useful work, i.e., electricity, mechanical or thermal. Application refers to the issues faced by consumers such as safety, affordability, convenience etc. We have combined conversion and application into a single “usage” category.
7. The objective of reforming is to remove as much hydrogen as possible from the source medium with as few undesirable by products as possible.

   Reforming Methanol CH_3OH. Liquid methanol and water are vaporized using heat with the vapor fed across a catalyst in a heated vessel. The methanol molecules are split into carbon monoxide (CO) and hydrogen gas (H_2). The chemical process is denoted as $CH_3OH \Rightarrow CO + 2H_2$ The water vapor splits into hydrogen gas and oxygen with the oxygen combining with the carbon monoxide (CO) to form CO2. Some CO is released by this process. The chemical process is denoted as $H_2O + CO \Rightarrow CO_2 + H_2$

   Reforming Natural Gas (which is mostly methane) CH_4. Methane and water are vaporized using heat with the vapor fed across a catalyst in a heated vessel. Methane in the natural gas reacts with water vapor to form carbon monoxide and hydrogen gas. The chemical process is denoted as $CH_4 + H_2O \Rightarrow CO + 3H_2$.

   These reactions are not perfect and result in both CO and CO2 as by products. It is important to remove the CO as it can reduce a fuel cell’s performance if it is allowed to pass through the fuel cell and second, as a regulated pollutant, it should not be allowed into the exhaust of a car except in small quantities.
8. Cost structure and conversion data:
   a. Producing one cubic foot of hydrogen gas from water by electrolysis requires 0.14 KWhr of electricity; Or 1 KwHr of electricity would theoretically produce about 3412 BTU of hydrogen.
   b. Cost of producing hydrogen by electrolysis (including conversion costs, inefficiencies and handling) is approximately $30 per million BTU.
   c. Cost of natural gas (wellhead price) is approximately $3 per million BTU.
   d. Gasoline at $1.10 per gallon is equivalent to approximately $9 per million BTU.

e. Gasoline: 1 Gallon = 125,000 BTU
f. Gasoline: 1 Gallon = 6.17 lbs
g. Propane: 1 Gallon = 90,000 BTU
h. Propane: 1 Cu ft = 2,500 BTU
i. Propane: 1 gallon = 4.237 lb.
j. Natural Gas: 1 Cu ft Methane = 1,000 BTU
k. Electricity: 1 Kilowatt-hours = 3,412 BTU
l. Hydrogen: 1 Cu ft = 325 BTU

9. This calculation is based on a spacing between units of seven times the rotor diameter as suggested by the Danish Wind Energy association with a resulting 9 turbines per square mile. Empirical data suggests that this calculation is optimistic and the number of turbines will be closer to 480,000 on an area occupying roughly 100,000 square miles.

   Using empirical data, several scientists have estimated that 5 kw per acre are generated by the typical wind farm. This translates into 29,074,040 KwHrs of electricity per square mile per year from the typical wind farm, while 9 wind turbines per square mile produces 47,336,400 KwHrs per year. Empirical evidence would seem to indicate that terrain and other factors reduces the amount of power that might otherwise be generated by a wind farm by reducing the number of turbines that can be installed per square mile.

   GE has produced a unit rated 3.5 MW which may go into production in the near future. Larger units may reduce the number of wind turbines required to generate the needed electricity for producing hydrogen but the area will remain the same as the spacing of the turbines needs to be increased

10. The California Fuel Cell Partnership has installed about a half-dozen hydrogen stations. Aided by state and local government subsidies, more than a dozen others are planned in the next few years. GM and Royal Dutch/Shell Group said they plan to launch a fuel-cell-demonstration project in the Washington area in 2003.

11. GM and BMW have teamed up to develop a fueling system and nozzle for dispensing liquid hydrogen. Their intent is for the system to become the industry standard.

12. To cool one pound of hydrogen to -423 degrees F requires 5 KWhr of electrical energy.

13. Underground storage for large quantities of hydrogen is also possible in a cavern having suitable cap rock, though the cushion gas that remains at the end of the discharge cycle can be as much as 50% of the working volume.

14. Mercedes Benz Necar.

15. The system being developed by GM consists of two carbon composite tanks. It was approved last year by Germany's top safety institute, (Technischer berwachungsverein - TÜV) in accordance with common industry standards in Europe and North America. The TriShield™ tank design features a one-piece permeation-resistant seamless liner, a high-performance carbon composite over-wrap for strength and a proprietary, impact-resistant outer shell.

16. Principle fuel cell types.
    - **Phosphoric Acid Fuel Cells (PAFC)**
      Phosphoric acid fuel cells have been field tested as early as the 1970s. These systems operate at temperatures between 150°C and 200°C. The principal use of these systems has been for mid-sized (200kW) stationary power generation applications.
    - **Molten Carbonate Fuel Cells (MCFC)**
      Molten carbonate fuel cells operate at very high temperatures (650°C) that allow them to use fuel directly without the need for a fuel processor. They require significant time to reach operating temperature and to respond to changes in electricity demand, and therefore are best suited for the provision of constant power in large utility applications.
    - **Solid Oxide Fuel Cells (SOFC)**
      Solid oxide fuel cells operate at extremely high temperatures, approximately 800C. As a result, they can tolerate relatively impure fuels. Their relatively simple design combined with the significant time required to reach operating temperature and to respond to changes in electricity demand make them suitable for large to very large stationary power applications.
    - **Proton Exchange Membrane (PEM) Fuel Cells**
      PEM fuel cells operate at relatively low temperatures, about 80 C, have high power density, can vary their output quickly to meet shifts in power demand, and are suited for applications where a quick startup is required.
    - **Direct Methanol (DMFC) Fuel Cells.**

      Draws the hydrogen directly from liquid methanol thereby eliminating need for reformer.
17. Dr. C. E. Thomas, President of H2Gen Innovations Inc., in his paper Hydrogen and Fuel Cells: Pathways to a Sustainable Energy Future; estimates that the global economy as a whole would save an estimated $840 billion over the next 37 years (2003 through 2040) based on infrastructure investments required for a hydrogen transportation system using natural gas reformers versus the infrastructure investment required to support an equal number of gasoline powered vehicles.
18. ibid It should be noted that information about the cost and capabilities of electrolyzers is not included in this paper. It is not known whether they have comparable capacities or economics though Dr. Thomas infers that electrolyzers are better suited for fueling small numbers of vehicles and that the cost of hydrogen produced by electrolyzers is higher than when hydrogen is produced using small natural gas reformers being developed by his company.
19. ***"Considering the uncertainties of long range predictions and judging solely by lowest life-cycle energy use and greenhouse gas (GHG) releases, there is no current basis for preferring either fuel cell (FC) or internal combustion engine (ICE) hybrid power plants for mid-size automobiles over the next 20 years or so using fuels derived from petroleum or natural gas."*** Comparative Assessment of Fuel Cell Cars February 2003, MIT Laboratory for Energy and the Environment, 77 Massachusetts Avenue, Cambridge MA 02139-4307