Our Hydrogen Energy Future: Do We Have One?

By Robert Mauro, General Manager, PATH

I have ignored worrying about the path for our hydrogen energy future for several years. It seemed reasonable to assume that with the Federal government and industry engaged in the process of developing that future that practicality and experiment would fine tune the path that we were on to that future. However, the critique of government and industry efforts by the National Academy of Sciences (NAS) has caused me to refocus my attention on this issue. As I thought about the NAS study, I felt that they pointed out serious short-comings in the program without providing solutions. The caused me to ask what it would take, given today's technology, to produce a renewable hydrogen vehicle and infrastructure.

The major point that I agreed with in the NAS report was the need for more fundamental research at universities on a global basis. I also agreed with the comment about focusing on hydrogen production from renewables and the cost associated with that production. Most of my comments will focus on the three most important parameters in the DOE program: hydrogen, on-board storage and the fuel cell.

Hydrogen production from wind electrolysis, which I will use as my benchmark, will probably be over $20/million btu. For my benchmark, I will use $24/million btu. This is about $3/kg hydrogen at the 'wellhead' so to speak. This is roughly equivalent to the energy content of a gallon of gasoline. There are still costs for transmitting, storing, distributing, storing and dispensing the hydrogen. The total distribution costs are certainly more than $2/million btu, but probably less than $8/million btu. So, in large scale production hydrogen gas is at $3/kg to $4/kg. If the hydrogen is liquefied, the price increases by another $1/kg or $8/million btu. No one really knows what a liquid hydrogen infrastructure would look like or has determined its cost. Back in the early 1990's, when I was doing a hydrogen study for NASA, liquid hydrogen produced from natural gas (with low natural gas prices) delivered by tanker truck to the Kennedy Space Center was $1.25/lb. or $2.75/kg. The cost of liquid hydrogen delivered by barge to NASA's Marshall Facility was $.90/lb or about $2/kg. I do not know what those cost are today. However, at that time, I estimated the cost of liquefaction at about $8/million btu in bulk, and don't believe that cost of the liquefaction process has changed a great deal. The point to keep in mind with a fuel cell powered car is that you need half as much energy in the hydrogen stored on-board as is needed in a vehicle powered by an internal combustion engine operating on gasoline. Treating a kg as the approximate equivalent in energy content to a gallon of gasoline, one can afford to pay twice as much for a kg of hydrogen as for a gallon of gasoline.

For hydrogen to compete with gasoline on price, the measure that matters is the cost of a fill-up for a light duty vehicle to go 400 miles plus or minus 10%. To go that distance in a light duty vehicle, requires let us say 16 gallons of gasoline. This should only take the equivalent of 6 kg of hydrogen in an efficient fuel cell vehicle. However, let's assume hydrogen fuel cell vehicle is twice as efficient and requires 8 kg of hydrogen stored on-board the vehicle. Therefore the hydrogen can cost twice as much as gasoline to break-even. At $2/gallon for gasoline, hydrogen's break-even cost is $4/kg. At $4/gallon for gasoline, hydrogen's break-even cost is $8/kg. Remember without infrastructure renewable hydrogen is $3/kg at the 'well head'. Delivered to the vehicle, compressed hydrogen gas is less than $5/kg. In other words, $3/gallon gasoline is more expensive per fill-up than renewable produced compressed hydrogen gas. I can also argue with some confidence that $5/gallon gasoline is likely to be more expensive per fill-up than renewably produced and liquefied hydrogen delivered to the vehicle. It may be that $4/gallon gasoline is near the break-even for renewably produced liquefied hydrogen in a fuel cell vehicle. Gasoline price at the pump contains significant state and local taxes which would have to be subtracted from the pump price for a fair comparison. However, the U.S. is not close to summer and the average price of gasoline is about $2/gallon with taxes in the Western United States. It is possible that the price of gasoline will top $2/gallon this summer after removing state and federal taxes. Increased demand for gasoline from Asia will only increase price pressure over the next decade and drive prices up to the levels that I am discussing in this article.

Let’s turn to storage, in my view the National Academy of Sciences too quickly dismiss on-board compressed gas and liquid hydrogen storage. I am going to focus on liquid hydrogen for three reasons. First, we are used to having our cars filled with a liquid. Second, the infrastructure is similar to that of gasoline with the addition of refrigeration. Third, there are significant on-board advantages over any other storage system. Finally, we know how to overcome the disadvantages at least conceptually. In term of infrastructure, delivery would be by truck to an insulated tank. This is similar to delivery of gasoline today. The pipelines for liquid hydrogen would have to be refrigerated. This will require the development of magnetic refrigeration to reduce energy costs associated with hydrogen liquefaction and allow for distributed smaller refrigeration systems. We understand the theory and science of creating magnetic refrigeration. The application of the necessary technology (engineering) eludes us.

If we are going to have a hydrogen economy, then we are going to have aircraft using hydrogen as fuel in combustion turbines. The hydrogen will be liquefied and so we will have to develop the technology anyway. Why not have all hydrogen fuel in the same state, liquid, for all major transportation applications. For a light duty vehicle to go the same distance as a comparable gasoline fueled vehicle will require a liquid hydrogen tank with twice the volume of a gasoline tank. This represents less than a 30% increase in each of the linear dimensions of the tank. A composite insulated liquid hydrogen tank filled should weigh substantially less than the equivalent filled gasoline tank to travel the same distance. Even empty the liquid hydrogen tank should only be 10 or 15 kg heavier than the empty gasoline tank. At 20 degrees Kelvin, the boiling point of liquid hydrogen every impurity is frozen and the vapor going into the fuel system of the vehicle is extremely pure. Finally for safety, vehicles will have to be fueled automatically. I would remind you that for most of the first 75 years of internal combustion vehicles, it was illegal for a person to refuel his/her vehicle himself/herself at a service station in almost all of the United States.

The final major issue is the fuel cell as a propulsion device. The goal is to produce a unit with the performance, price and life of an internal combustion engine. The NAS study spoke about material, catalysis and membrane research. You certainly need research in each of those areas. What is unique about the light duty vehicle fuel cell that is unnecessary in any other application is that you must increase the fuel cell life by a factor of four while you reduce the amount of platinum catalyst by 99%. The platinum is in the fuel cells to speed the rate of the reactions. Over time it ceases to perform its function and the fuel cell’s heat rate begins to increase as more heat is produced and less electricity until it becomes unacceptable and the stack is replaced. The reason why reducing platinum content is so important is first that so little is produced annually and an expanding vehicle market will use it up at a time when demand for it in catalytic converters is also expanding. Second, in order for the fuel cell to have any possibility of reaching $50/kW, the amount of platinum must be reduced to as low as possible, $2/kW or less, from current levels which are estimated to be about 10 times that. Other fuel cell applications are not on the scale of vehicles or require the same low per kilowatt costs as vehicle propulsion.

In the NAS report and as stated more strongly in the American Physical Society study, it is not at all clear that performance and cost targets can be met with a PEM fuel cell. It seems to me that unless internal combustion engines double in efficiency and remain nearly at that efficiency for at least 150,000 miles of operation they are not a suitable fuel cell propulsion replacement. It is always possible that there could be breakthrough in PEM fuel cells or hydrogen IC engines that make my comments moot, but until then we should explore other avenues as well as the ones that are being followed. Let me indicate three additional activities to address this problem in addition to continuing to work on reducing platinum while increasing PEM life or developing a highly efficient internal combustion engine.

The first thing to do is to scan the field and see whether there are technologies and activities in micro fuel cells that are attractive. This includes looking at battery replacement technologies for personal electronic devices (PEDs) and military battery replacements. If fuel cells are developed for PEDs, then they will be capable of being manufactured in the millions and they will be relatively inexpensive. Military fuel cell systems will have to rugged and reliable in harsh operating environments.

The second thing that might be considered is raising the temperature of the PEM significantly to increase its kinetics. This may impact start-up performance, but it is a means of reducing catalyst and increasing reaction rates. Early efforts are underway to explore this option within the DOE program.

Finally, I would take the comments of the NAS to heart on hydrogen production from electrolysis. The other electrolysis product which you would capture is oxygen. Why not put another liquid tank on the vehicle and run a hydrogen oxygen fuel cell? It will cost money, but you can dial way back on the amount of platinum catalyst used, increase catalyst life and virtually eliminate poisoning as an option. This is not an option for fossil fuel produced hydrogen, but it is for renewably produced hydrogen from electrolysis. I think that today you could, with current platinum loading, produce a fuel cell that operates for significantly more than 5,000 hours. The original Gemini fuel cell had endurance tests on hydrogen and oxygen well in excess of 5,000 hours operating in 1962 with inferior materials and membranes compared to what we have today and much higher platinum loadings. I think this is worth considering in a renewable environment. If you can not do this what make you think that you can ever produce an air breathing fuel cell with 5,000 hours of life. Once you have your baseline you can start reducing your platinum loading by material improvements that reduce internal resistance within the cells.

So my light duty hydrogen vehicle operates with a sealed PEM fuel cell on hydrogen and oxygen with two on-board liquid tanks. It is refueled automatically with hydrogen produced using a renewable electrolysis process. The hydrogen is liquefied using magnetic or conventional refrigeration. The fuel cell can probably reduce its platinum loading by 50% to 80% per kilowatt with today’s technology. The fuel cell will be expensive while the rest of the car would probably not be. The infrastructure would very likely be expensive. The large environmental issue will be hydrogen releases to the atmosphere during transfer and cooling down of tanks. Renewably produced hydrogen and oxygen would be cost competitive with gasoline at about $6 per gallon.