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The mirage of the H_2 economy

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In a recent paper (1) I analyzed the new "hydrogen economy" and explained why for most uses it makes no sense to convert fuels, electricity or any other form of energy to hydrogen, only to use the hydrogen as a fuel for fuel cells. Since H_2 is not a resource but an inefficient energy carrier, it would appear that the H_2 economy is just a mirage. If alternative energy sources are ever developed, an economy based on electricity would be cheaper (by a factor of three) and much easier to adopt than H_2. Oddly, I had covered the same topic twenty years ago in a paper that analyzed the hydrogen economy of the 1970s (2). Then, the investment in H_2 research was about 10 billion wasted dollars before it was phased out. In this column I will try to explain why the scientific establishment engages in such obviously futile behavior and why this mirage attracts so many followers.

In the mid 1970s I became aware of a strange phenomenon. Many leading scientific journals were suddenly giving enormous coverage to hydrogen, the fuel of the future; a new term, hydrogen economy, was born. International meetings attracted thousands of participants and the U.S., Germany, and Japan funded the necessary development with vast resources. The central idea, put forward by the International Atomic Energy Research Center in Vienna, utilized a high temperature nuclear reactor as the heat source. In this reactor, pressurized helium was used as the coolant. To generate electricity, the hot helium was first expanded through a turbine and then used for steam generation before being fed back to the reactor.

The "thermochemical cycle", the name applied to this new process, does not include a turbine, and the heat from cooling the hot helium is used to drive a set of closed-cycle chemical reactions; the net result is that water is split into hydrogen and oxygen.

Following is a hypothetical example of such a reaction:

$$\begin{aligned} &MeO + Heat \rightarrow Me + \tfrac{1}{2}O_2 \\ &Me + H_2O \rightarrow H_2 + MeO + Heat \end{aligned} \quad (1)$$

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where Me is any metal. No such reaction was ever discovered and all cycles proposed were quite complex. One does not need to be an experienced cost estimator to realize that such a cycle would be very expensive and have a low thermal efficiency.

The H_2 was supposed to be used to replace natural gas in existing pipelines. Several obvious questions were not asked:

1. A pipeline for methane cannot be used to transport H_2. To avoid leakage one needs totally different valves and connectors. Furthermore, as the volume of H_2 is triple than that of methane, one needs larger pipes and different compressors. Of course, the same factors would apply to the distribution of the gases to customers. None of the valves or controls would be tight enough, and all burners would have to be changed.
2. Since nuclear reactors are available, why not use electricity instead of methane for most applications? Electricity is far more efficient than H_2 or methane (by a factor of two) for most uses. Let me illustrate. Today, in the USA and the world, a large amount of electricity is generated from natural gas. This electricity, on a BTU basis, costs by a factor of about 2.2 more than the natural gas feed. The fact that we do it obviously means that electricity is more valuable than natural gas. At the same price it would have driven out natural gas. H_2 as a fuel has even a lower value than natural gas. If we now convert electricity to H_2, we again lose at least 1/3 of the energy. Thus H_2 made from electricity has a value about four times lower than the electricity. This simple calculation illustrates the stupidity of the idea to convert nuclear or solar energy to hydrogen. At that time, no one was foolhardy enough to suggest using H_2 generated by a nuclear reactor as fuel for a fuel cell. Furthermore, an electricity distribution system is already in place and can grow with demand.
3. Why not make H_2 by electrolysis, a well-known process? Nobody asked why -in contradiction to our cumulative technical experience- a set of chemical reactions should generate a large increase in ΔT more cheaply or efficiently than electrolysis. The main item in the cost of electricity is the nuclear reactor and if a thermochemical cycle is less efficient it is inherently more expensive.
4. The cost of switching to hydrogen is astronomical. To produce the equivalent of one million BTU of hydrogen per day by elecrolysis would require a 25 kilowatt nuclear reactor at an investment cost of $150,000. That

means that a standard nuclear reactor of one gigawatt costing 6 billion dollars will be able to supply 40000 million BTU/day of H_2 the equivalent of 6700 barrels of oils. Building the capacity for supplying a new pipeline that could carry 12% of the current U.S. capacity of natural gas would have to be built from the start at a cost of close to 1 trillion dollars. For thermochemical cycles the cost would be significantly higher. All this must be invested before a pipeline can be started. The same energy needs could be supplied by electrical energy at only one-quarter the cost since electrical energy has a higher efficiency for almost all purposes. The investment for electricity can be spread over many years since a grid is already in existence. Furthermore, just the energy from the nuclear reactions would cost \$50 per million BTU H_2.

5. The most dangerous of all fuels, pressurized H_2, ignites with an invisible flame. Its explosive limits are very wide, and its minimum ignition energy is ten times smaller than that of any other gaseous fuel. This problem occurs not only when H_2 is being distributed or used, but even more so when it is generated in a thermochemical cycle. When H_2 is produced by electrolysis, one can locate the plant far away from the nuclear reactor generating the electricity. But this is not true for helium which must be pumped in such large quantities, as it cannot be sent over long distances at reasonable cost. Society has accepted the risks of explosion in conventional fuels but tries to limit exposure. Thus, even a small propane storage tank may not be transported through a tunnel. But, what level of risk from a potential explosion at a nuclear power plant complex is acceptable? None of these critical questions were asked then – nor are they being asked today.

These questions have been on my mind for a long time. In the "age of technology" how could the scientific community have been misled by such obvious nonsense? And why had so many engineering firms and large companies come up with totally unrealistic cost, at least by a magnitude too low, and thermal efficiency estimates that are unrealistically high?

The intellectual climate of the time can be illustrated by a small story. Science carried a six-page article, featured on the cover, about a new cycle developed by General Electric that promised to produce H_2 at \$2.50/ million BTU H_2 (at that time it would have cost \$7.00/million BTU to produce H_2 from oil). For fun I flow-sheeted the process and published the mass and heat balance in a letter to Science (3) suggesting that if GE can reduce costs to \$2.50, they should forget about hydrogen and change the economy. Buy comparison, we poor chemical engineers could not achieve such results at a cost of \$250/million BTU H_2. Three months later I was invited to GE's central laboratory where the Director of Chemical Research offered me a consulting job. The head to the lab was a chemist who had read about the need for a thermochemical cycle and he actually developed the first one that worked. His engineers had given him this cost estimate. When my letter was published he asked Corporate Engineering to make their own estimate and they confirmed my numbers. This story illustrates a key aspect of the hydrogen economy. Many excellent scientists lack the skills needed to deal with economics and costs. Later, I published another paper demonstrating from elementary design principles that any thermochemical process must by necessity, cost much more than electrolysis (2).

It is true that many scientists could have erred because they were not knowledgeable about process economics. But, I also came to realize that other forces were driving the program. Even though they are inherently safer, high temperature nuclear reactors of the type required by thermochemical cycles were deemed less competitive and more costly than boiling water reactors. This created an opportunity for their developers to seek more government support. A large nuclear research community was hungry for grants and contracts.

Interestingly and unfortunately the episode of the 1970s has been ignored or forgotten. But, before we place large national resources behind an effort to deal again with such major problems as renewable energy, global warming and energy independence, we have to understand what went wrong the first time a so-called "hydrogen economy" was attempted.

The paper I just published is about the reincarnation of the hydrogen economy. This time all the proposed processes are feasible but the program itself seems to make even less sense. As before, the main emphasis is on the replacement of conventional fuels with a national distribution system of H_2 at a tremendous loss in efficiency in the production and transmission steps. As before, the same intractable safety and cost problems still persist.

Similar driving forces remain at work. Large research budgets are projected to find a use for a technology in which DOE has invested huge sums of money to little or no avail. This time it is fuel cells powered by hydrogen, a technology that is good for space applications, where $H_2$is used as a rocket fuel and therefore available in small quantities, and other specialty applications, but useless for applications which couple H_2 generation with the generation of electricity. Such systems have half the efficiency of combined cycle turbines, cost over five times more (1, 2, 3, 4) and create at least double the green house emission, probably much more.

Today, there even is talk about switching cars from gasoline to H_2 and this makes the transition problem even more difficult as the new supplying system cannot start locally, and this would also require the use of pressurized H_2 at 6000 psi, a pressure very seldom used in industry. Nobody mentions that in industry, a H_2 tank with the capacity proposed for a family car requires storage in a special room with a blowout wall. Any technician approaching such a pressurized tank to check the valves swings a wooden broom to prevent being fried by an invisible flame which may come from a leaking valve, as above 1500 psi a H_2 leak is self-igniting (1). For a gas station, a minimum-sized storage tank would have the explosive power of two thousand tons of TNT or two of the largest bombs used by the Air Force. A terrorist could just open a valve and detonate a small bomb after 20 seconds.

The most obvious fallacy of the new H_2 economy, however, is that it solves all of our problems (6, 7). For those of us who accept the first and second laws of thermodynamics it is obvious that the use of H_2 would increase the use of other energy resources. Arguments are made that once we have a hydrogen distribution system we could capture the CO_2 produced and sequester it. But we have no idea how to sequester such vast amounts of CO_2safely. A successful policy can only be formulated after all the elements are solved and a good deal is known about costs. At present, the U.S. releases 100 million tons of sequestered CO_2 back into the atmosphere each year.

In a system in which the basic science is known, costs are reduced by innovative ideas which arise during the implementation stage of a project rather than by more research. The cost of liquid natural gas plants and combined cycle power plants decreased in the last ten years by a factor of two, even though the basic technology did not change because many were built to compete in the market. So, research, in order to be effective, needs to be coupled with a clear plan for implementation.

In order to promote the use of fuel cells, or other new technologies, which are by one to two orders of magnitude more expensive than available technologies, the research community has invented the myth of "learning curves". In the last 40 years, computers became through miniaturization cheaper by several magnitudes, but this option does not apply to energy systems. In the last 20 years the cost of solar cells was reduced by less than a factor of two despite a tremendous research budget. Better engineering and mass production can reduce the cost of most new technologies by a factor of two to three. But, this would require the building of large plants based on competitive bidding, not a new research breakthrough. Large research budgets over the past 40 years have not made cost of fuel cells more competitive.

The alternative sources that really reduce CO_2emissions include solar and nuclear energy and biomass. The use of H_2 just makes everyone of these options several times more expensive. Solar and nuclear energy produce electricity, and for most purposes electricity is far more efficient to use than H_2. To provide electricity to the motor in a H_2 car requires three to four times the solar or nuclear capacity required for providing the electricity directly via a battery. While we don't have good electric cars yet, Toyota has just come out with a hybrid car with a plug-in battery large enough for a 40-mile drive. Such a car could reduce total gasoline consumption by 80%. But electric cars would only reduce green house emissions if the electricity were generated by solar energy. As for biomass, which is a valuable but limited future resource, conversion by fermentation to alcohol followed by conversion to gasoline or diesel is far cheaper and thermally more efficient than conversion to hydrogen.

In the early nineties an Israeli company, Luz (5), built solar electric power plants using a high temperature heat transfer fluid, and which included sufficient storage to supply Los Angeles with 300 megawatts electricity on a reliable basis. The Luz plant had another major advantage; the design allowed for conventional fuel to be used as a backup because, even in the desert, 10% of the days may be rainy. To be profitable, all Luz needed was a 50% tax break on the investment. When Luz became large the tax breaks were taken away. If Luz had been allowed to build a few gigawatts, the price would have come down and other companies would have come in; we might have had affordable solar energy today.

Today we have the resources and the technology to do something useful about global warming if we really had the resolve. For example, for 50 billion dollars a year over twenty years, we could replace 40% of coal power plants with solar power plants using proven technology; we just have to engineer them better and provide them with sufficient storage capacity. We are the only western nation who has enough sun and area for solar power. Alternatively, we could eliminate about 80% of our gasoline used for cars. We could easily afford to do both, but we have to realize that no research can make solar, nuclear or other alternative energy competitive with cheap oil or gas.

Our society has solved far more difficult large-scale technical problems successfully, e.g., space travel, and the most advanced defense weapons in the world. Applying our capabilities to global warming or to resource depletion to preserve a livable world to our grandchildren would require not only conviction but a strong political will to do so.

To give a recent example, thirty years ago we faced the problem of increasing pollution from our coal power plants. We had the technology (scrubbers) to reduce the pollution substantially. It would have cost about 20–30 billion dollars. But politics and the influence of senators from coal producing states prevented the adoption of such a solution. Instead we spent twenty billion dollars on "clean coal" research programs that failed to produce results that could help solve this problem. But the "clean coal" effort did provide large research budgets along with the illusion that we were accomplishing something. Thirty years later the same plants are producing more electricity and consuming more coal—still poisoning the fish we eat with mercury, causing smog that blocks us from seeing the sky, destroying our forests and most importantly, impairing the health of all of us more than any other form of pollution.

The private car is another example of the obstacles that a serious national policy faces. In the 1970's, in response to the Arab oil embargo, oil price increases and an alleged likelihood that the oil resource base would become depleted within the next several decades, Presidents Nixon, Ford, and Carter proposed new energy policy initiatives which included the goal of improving auto fuel economy. These resulted in the Corporate Average Fuel Economy standards (CAFÉ), which required that the fleet fuel economy of new light duty vehicles (5500 lbs or less) reach 27.5 mpg by a certain date, reaching a 30% reduction in gasoline demand. This limited the ability of the companies to produce large cars and station wagons. The same provision set lower standards in mileage and emissions for light duty trucks weighing less than 5500 lbs.

Nine years ago the car industry realized that one could produce large cars (SUV's) that fit all the definitions of a light truck, such that one should be able to fold all seats to the floor to provide a major space occupying the car and several others. It was a great success. As light trucks convertible to luxury passenger cars do not count as passenger cars for the CAFE laws and are not considered in the fleet average, this allowed car companies again to produce gas-guzzlers. Eight years later 30% of the passenger cars sold in the U.S. are SUV's and all the efficiency gains of 30 years have been wiped out.

As we face the potential of global warming and resource depletion that might endanger the future of our grandchildren we escape our responsibilities by pretending that all problems can be solved better and at lower cost through the mirage of more research. Thus the H_2 mirage allows car companies to continue to produce gas guzzling, highly polluting SUV's while touting the glorious future a "H_2" car that will miraculously be energy efficient and pollution free. And, as in the 70's, thousands in the scientific and political communities are promoting this mirage to the public.

Thus mirages like the "hydrogen economy" play an important psychological function in our society and many in the technical community play along. The role engineers and scientists should be playing today is to educate the public and the politicians about the real options. We should be reminded of an old cartoon in the Pogo series that bears the caption "We have met the enemy and he is us."

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