Robert E. Wilson Award Speech

Hydrogen, Liquid Fuels, and R. E. Wilson

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I would like to thank the American Institute of Chemical Engineers and the Nuclear Engineering Division for honoring me with the Robert E. Wilson Award, which recognizes excellence in nuclear chemical engineering. While I could follow the tradition of the Oscars and spend 20 minutes thanking everyone, I thought it may be more useful to consider the career of Robert E. Wilson and its relevance to the many technical sessions at this meeting that have an emphasis on the use of nuclear energy to produce hydrogen. Robert Wilson was a well-known chemical engineer who became the president of Standard Oil of Indiana, and a member of the U.S. Atomic Energy Commission. His career combined interests in oil and nuclear energy—perhaps he was a little before his time. However, today that may be just the right mixture of technologies, as well as an accurate reflection of this meeting, with its many sessions on oil and production of hydrogen from nuclear energy.

This year may mark one of the most important events in the history of energy and oil: the year of peak oil production in the countries outside the former Soviet Union and the Organization of Petroleum Exporting Countries (OPEC). Oil is critical to the Western world. In the United States, about 40% of our total energy is from oil. Four economic recessions have been preceded by rapid rises in oil prices; thus, oil is very relevant to everyone.

Worldwide oil discoveries have been decreasing for about 40 years, while the demand has continued to grow. Since 1980, worldwide consumption of oil has exceeded discoveries of new oil. Because the total oil recovered from an oil field decreases with increased rates of extraction, oil extraction rates are limited by producers to maximize income. Except for some fields, the OPEC nations, most of the world's oil fields are producing oil at rates near their maximum extraction rates for long-term production. Future growth in oil production will depend primarily upon OPEC, with world production likely to peak within about two decades. Within OPEC, there are five countries with most of the oil: Saudi Arabia, Kuwait, the United Arab Republic, Iraq, and Iran.

There are serious questions about the reliability of these countries to supply oil. Saudi Arabia and Kuwait are absolute monarchies. Current reports suggest that these monarchs are about as popular among their subjects as King George the III of England was among his American subjects in 1776. The area of modern Iraq has the world's longest recorded history of conflict. Iran, unlike the rest of the Middle East, which is tribal, has had a unified culture since Cyrus the Great. The Iranians (i.e., the Persians), like the Japanese, will go their own way independent of anyone else.

In parallel, the demand for oil is accelerating—driven by the rapid economic growth in China and India. That economic growth is eliminating poverty at an extraordinary rate and must continue. However, it also implies the end of conventional oil as the basis of the world economy, because production can not keep up with rapidly rising demand over a period of several decades. Last year the United States produced 17 million cars while China produced 6 million cars. Almost all vehicles produced in the United States were replacement vehicles; thus, the growth rate in oil consumption in the United States is relatively slow. In contrast, most of China's 6-million new cars are additions to the total number of cars in China—which increases the need for roads, refineries, and other infrastructure as well as the rate of oil consumption. For most of recorded history, China has had the world's largest economy, with occasionally a few centuries of downtime. We may now be returning to the normal state of affairs in a world that simply does not have sufficient crude oil for such a large economy.

As chemical engineers, we all know that the end of conventional oil does not imply the end of automobiles or liquid fuels. Chemical engineers have built special refineries to produce liquid fuels from tar sands and coal. The largest construction projects in the world are those in Canada associated with expanding synthetic oil production from tar sands. However, these feedstocks have lower hydrogen-to-carbon ratios than gasoline, diesel, and jet fuel. To make liquid fuels, we must therefore add hydrogen or subtract carbon.

When carbon is subtracted from a hydrocarbon feedstock to produce liquid fuels (thermal cracking), the carbon is ultimately released to the atmosphere as carbon dioxide. When traditional steam reforming processes are used to produce hydrogen to add to a hydrocarbon feedstock, the by-product carbon dioxide is also released to the atmosphere. With all of our traditional processes, if we use heavier feedstocks to produce liquid fuels, we produce more carbon dioxide.

If gasoline or diesel is produced from coal rather than from light crude oil, we may more than double the carbon dioxide releases to the atmosphere per mile of vehicle travel. In a world concerned about climatic changes, our standard approaches to make synthetic transport fuels imply massive increases in carbon dioxide releases for the same amounts of liquid fuels and the same amount of travel. Because 40% of our energy is from oil, this strategy will rapidly increase the global carbon dioxide content of the atmosphere.

We now face a crisis similar to that faced by the oil industry in the early part of the 20^{th} century. Oil had originally been recovered for use in lamps. With the development of the car, there was a growing demand for gasoline. However, with crude stills, the gasoline yield from a barrel of oil was at most 20%. A radical change in technology was required. Otherwise, there would be insufficient oil to meet gasoline demands and many of the nation's rivers in oil producing areas would literally fill with refinery wastes. The radical change was the development of thermal cracking, which more than doubled gasoline yields per barrel of oil up to 45%. This was followed by hydrogen catalytic cracking, which further raised gasoline yields per barrel of oil by adding hydrogen to the feedstock.

Times have changed again, and we face a similar crisis. It's now time to consider new radical chemical engineering solutions, but solutions no more radical than the original introduction of thermal cracking to oil refining. I suggest today that the radical solution may be hydrogen produced by methods that that do not yield greenhouse gases. In this context, I would emphasize that the conversion to a hydrogen economy does not necessarily imply the abandonment of liquid hydrocarbon fuels. A hydrogen economy exists when a substantial fraction of the nation's energy is used to produce hydrogen—it is not defined by how that hydrogen is used. A hydrogen economy does not necessarily imply storing and using hydrogen in vehicles. The new hydrogen economy may be at a new type of refinery for liquid fuel production that may evolve in three stages.

1. *Hydrogen-rich liquid fuels.* Liquid fuels (gasoline, diesel fuel, and jet fuel) are defined by performance—not chemical composition. There is a variable range of hydrogen-to-carbon ratios for each of these fuels. If we can develop economic non-greenhouse-producing hydrogen production methods, the quantity of liquid fuel per barrel of oil can be increased by up to 20%. This is accomplished by maximizing the hydrogen-to-carbon ratio while maintaining the properties that define each of the liquid fuels.

2. *Synthetic liquid fuels from tar sands and coal without refinery greenhouse gas releases.* The minimum carbon dioxide release per gallon of liquid fuel is determined by the carbon content of the fuel. When converting oil, tar sands, or coal to liquid fuels, carbon dioxide releases from the refinery depend upon the sources of hydrogen and the sources of energy used to operate the refinery. If coal is used to produce hydrogen and energy for the refinery and the carbon dioxide is released to the atmosphere, the carbon dioxide released by the refinery can exceed that from

burning the liquid fuel. In contrast, if hydrogen and energy for the refinery come from non-greenhouse-emitting sources, we can today convert every atom of carbon in coal or tar sands into a liquid fuel. We need refineries that do not emit greenhouse gases to the atmosphere.

3. *Non-greenhouse liquid fuels*. Ultimately we may require liquid-fuels with no additions of greenhouse gases to the atmosphere. That is technical achievable. Liquid fuels can be produced from hydrogen and carbon dioxide with the carbon dioxide extracted from the atmosphere. The carbon dioxide can be extracted directly from the atmosphere or indirectly by the harvest of biomass. These routes to liquid fuels produce no net greenhouse gas releases—the options simply recycle the carbon dioxide in the atmosphere.

   There have been multiple studies on making liquid fuels using carbon dioxide from the air and hydrogen. Liquid fuels have been considered as a possible product for large fusion energy parks because of the ease of transporting liquid fuels versus electricity or hydrogen. Other studies have looked at naval fueling ships that produce their own fuel at sea using nuclear energy. This avoids the logistics problems of supplying a fleet with aviation and diesel fuel. The surprising fact is that about 80% of the energy input in liquid fuels production is for the hydrogen. Carbon dioxide extraction from the atmosphere is not the primary cost or energy driver.

   Alternatively, the carbon dioxide can be collected using biomass. Today, liquid fuels (primarily ethanol) are produced from corn and other forms of biomass. However, only a fraction of the carbon in the biomass becomes part of the liquid fuel. Much of the carbon is oxidized to carbon dioxide by the yeast to produce the alcohol or becomes part of the residual biomass after the fermentation process is complete. All of this carbon is ultimately returned to the atmosphere as carbon dioxide. There is an alternative energy future for biomass as a renewable, non-greenhouse source of carbon where outside sources of hydrogen are used to convert all the carbon to liquid fuels. This approach produces much larger quantities of liquid fuel per ton of biomass.

These alternative liquid-fuel hydrogen futures depend upon the cost of hydrogen and constraints on greenhouse gas releases. There are three candidates for non-greenhouse hydrogen production.

1. *Nuclear.* A wide variety of processes are being developed to convert water and heat (or heat and electricity) into hydrogen and oxygen. Because nuclear reactors can be built anywhere, a liquid fuels plant with nuclear hydrogen can also be built anywhere. Given the multiple sessions at this conference that address the many pathways to hydrogen production using nuclear energy, I will not address this topic in further detail.

2. *Fossil.* Hydrogen can be made by steam reforming of fossil fuels—the process used to produce almost all hydrogen today. The carbon dioxide from these processes can be released to the atmosphere or disposed of underground or in the oceans. While carbon dioxide sequestration can clearly be done on a small scale, it is unclear whether it can be done practically and economically on a large scale. The technological challenge is to isolate carbon dioxide for thousands to millions of years—depending upon the requirements. Carbon dioxide sequestration is a difficult technical, political, and multi-generational challenge.

3. *Solar*. Solar energy is the hydrogen production “wild card”. Current studies indicate that wind and solar cells are much more efficient for electricity production than hydrogen production; thus, these technologies are unlikely sources of large-scale hydrogen production. However, that situation changes if advancing technology (1) creates very low cost solar cells or (2) new solar technologies are developed that produce hydrogen directly.

I began this talk by referring to Robert E. Wilson and his dual career in oil and nuclear energy. We have now returned full circle to a point where nuclear energy may be the source of liquid fuels—be they gasoline, diesel, aviation fuel, methanol, ethanol, or some other combination of hydrogen and carbon. Thus, uranium, not crude oil, may prove to be the ultimate source of liquid fuels. Robert E. Wilson would be pleased.