HYDROGEN AS A TRANSPORT FUEL: PAST AND PRESENT USAGE

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Summary

Interest in hydrogen as an internal combustion engine fuel is not new. In fact, it was the fuel for the first self-sustaining ICE, developed by Cecil in England in the 1820s. Current activity stems largely from efforts initiated about 1970. The US space program

(1960s) led to renewed interest and usage of fuel cells and the use of hydrogen therein. Several automotive firms now have hydrogen-powered vehicles that demonstrate the promise of hydrogen as an automotive fuel. Hydrogen also offers great potential for use in aircraft, especially for supersonic and hypersonic operations.

Great reduction in air pollution, significant reduction in carbon dioxide in the atmosphere (thus combatting the "greenhouse" warming effect), and realization that petroleum reserves will be exhausted at some time in the future, all argue for the use of hydrogen at the earliest possible date.

Rigorous experimental study of the safety aspects of hydrogen usage indicates about the same degree of risk as with natural gas. With proper handling, hydrogen is far safer than propane or butane or, it can be argued, gasoline. The problem of onboard storage of the quantity of hydrogen desired remains a serious one, simply because of the density of hydrogen, and it requires further attention. Lightweight, high-pressure tanks of composite materials offer high promise.

The last decade of the twentieth century saw remarkable advances in fuel cell development. The relatively new concept of the PEM (proton exchange membrane) fuel cell offers the possibility of powering automotive vehicles without generating toxic emissions—a true ZEV. Several buses have been modified to be powered with fuel cells and are demonstrating the concept. The significantly greater efficiency of the fuel cell also reduces the onboard storage problem.

1. Introduction

Interest in hydrogen as an engine fuel is not new. Indeed, hydrogen fueled the first self-sustaining internal combustion engine, developed by the Reverend William Cecil in the early 1800s and reported by him to the Cambridge Philosophical Society in 1820. To fully appreciate the potential significance of Cecil's contribution, it must be noted that the engines of the day were either the waterwheel or the still-primitive steam engine. As Cecil pointed out, the former had to be located near a large, flowing source of water, while the latter took all day to warm up. Still, while Cecil's engine surmounted these difficulties, it did not lead to the immediate development of internal combustion engines, although it did stimulate a few further attempts. Cecil himself devoted the rest of his life to the Church of England.

More current interest in hydrogen as an engine fuel has been stimulated by the need to minimize the pollution of the atmosphere due to the use of hydrocarbon fuels, and by the recognition that the availability of these fuels is not infinite. Fortunately, earlier predictions of petroleum's depletion have turned out to be overly pessimistic. The question remains, however, of *when*, rather than *will* supplies become exhausted.

The matter of air pollution and its effect on public health, however, must be recognized as the dominant factor in the increasing recognition of the use of hydrogen as the fuel offering the greatest promise of improvement—even elimination—of this problem. In areas suffering severe air pollution, such as the Los Angeles area of California, more than one-half of the pollution is due to emissions from engines using hydrocarbon fuels.

Despite the impressive results achieved in reducing the toxic emissions per vehicle, the continuing increase in the number of vehicles conspires to make atmospheric pollution a serious problem. The problem is far more than an annoyance. It is hazardous to the health of the public and damages agricultural crops to the extent of several billion dollars annually.

Clearly, the use of hydrogen would generate none of the noxious emissions of carbon dioxide, carbon monoxide, or unburned hydrocarbons. Its only direct product of combustion is water vapor. The air used for combustion of hydrogen can generate oxides of nitrogen (generally referred to as NOX), depending on the flame temperature permitted. In the case of fuel cells, the reaction temperature might be reduced approximately to atmospheric temperature and the NOX generated to essentially zero.

Further, there is considerable concern over the carbon dioxide *blanket* developing in the atmosphere, potentially leading to an increase in the Earth's temperature. Consequent, dreadful effects can be readily visualized; the melting of a significant fraction of icebergs and the polar cap, for example, would result in a heightened *sea level* and flooding of coastal areas. No matter how clean burning fuels based on fossil fuels might become, they would continue to dump carbon dioxide into the atmosphere and contribute to this *blanket effect*.

Thus, three major concerns direct attention to the use of hydrogen as the engine fuel of the future: the highly significant reduction of atmospheric pollution, the arrest of the *carbon blanket* problem, and the inevitable demise of petroleum resources.

As with any fuel, there are potential problems with the use of hydrogen. Chief of these is storage onboard the vehicle it would propel. Hydrogen is the lightest of the elements and, simply put, a comparatively large volume is required to contain a significant amount of it. Safety, again, as with any fuel, is axiomatically of great concern. This is perhaps especially true in the case of hydrogen, with the unfortunate image it still has in the aftermath of the Hindenburg tragedy (1937) for which it is erroneously blamed. The production of hydrogen in large quantities is another challenge. It does not occur in nature to any significant degree in its pure form so it must be produced from its *bound state*—water, for example. These concerns are not prohibitive, as will be apparent from the following discussion.

2. Historical Review of Efforts Leading to the Hydrogen-Fueled Engine

2.1. Prior to 1875

A review of man's attempts to convert thermal energy to useful work from the middle 1600s on makes interesting reading, and one marvels at the novelty, variety, and cleverness of the ideas suggested. Although many patents were issued, only a few working models were constructed, and none could sustain operation on their own. The distinction of self-sustaining operation was reserved for the Reverend William Cecil's hydrogen-fueled engine described in his paper of 1820. The title of his paper leaves no doubt of his interest in hydrogen as the intended fuel: "On the Application of Hydrogen Gas to Produce a Moving Power in Machinery; with a Description of an Engine Which is Moved by the Pressure of the Atmosphere upon a Vacuum Caused by Explosion of Hydrogen Gas and Atmospheric Air."

The next highly significant contributions to the development of the internal combustion engine were due to Barsanti and Mateucci over the decade from 1854 to 1864. Their work "closed an era of necessary, but financially unrewarding, searching and experimenting." They developed a free piston engine, which was built and sold commercially. In general, it was used to power machine tools. A second, improved version was designed, and efforts were initiated to form a company and go into commercial production. There seems little doubt that they would have been the founders of the internal combustion engine industry had not fate intervened. Mateucci was forced to resign from the enterprise in 1862 due to ill health. Barsanti carried on alone, and was close to completing arrangements for production and further development work, when he himself fell ill of typhus. He died in 1864, at age 42. Had he lived, the probability seems high that much of the recognition and credit accorded Otto would have been his.

2.2. From 1875 to 1950

Nicolas Otto began his work with engines in 1861, with the inventor's usual enthusiasm coupled with a scarcity of funds. It is not clear just what led to Otto's meeting with Eugen Langen in 1864, but it was surely a most fortuitous event, not only for Otto, but for mankind. On witnessing the running of Otto's first atmospheric engine, Langen decided to invest in its future. Within a few weeks, he had raised funds, chiefly from his father and several business friends, sufficient to start a company for furthering Otto's work. By 1867, the company had improved the engine to the point of displaying and demonstrating it at the Paris Exposition of the same year. The display was a success, and the company began receiving orders for the engine in sufficient number to assure further engine development. The addition of Gottlieb Daimler to the design group was significant, and he was largely responsible for the four-stroke engine that became the source of propulsion of the automobile that in turn changed society's way of life.

While Otto's engine was not fueled by pure hydrogen, it did use a *town gas*, rich in hydrogen, probably more than 50%. Incidentally, Otto tried a liquid fuel, with explosively disastrous results, and he immediately declared liquid fuels far too dangerous to merit their use. At about the turn of the century, the carburetor was invented and a liquid fuel, benzene (or gasoline), became the fuel of choice for internal combustion engines. It is noteworthy that fuel once considered too dangerous for practical usage has now been used routinely for 100 years. One can visualize a similar destiny for hydrogen.

Development of the internal combustion engine (ICE) continued steadily after the great success of Otto and his associates, though with little regard for hydrogen, per se, as the fuel. It was not until the 1920s, in fact, (just 100 years after Cecil's hydrogen-fueled engine) that Ricardo, in England, reintroduced the notion of hydrogen as an ICE fuel. And, in 1925, Burstall of Cambridge University reported results of engine performance using hydrogen. Both reported indicated thermal efficiencies of more than 40%, and both noted the problem of backflash, or firing back, or as Ricardo put it, "popping back into the carburetor," which, of course, limited performance. About the same time, Rudolph Erren, in Germany, was converting engines to operate with hydrogen and devising methods of fuel injection to overcome the problem of backflash.

Weil in 1972 noted that considerable, serious thought was given to the use of hydrogen as the fuel for lighter-than-air craft under construction in England and Germany. Since hydrogen was to provide the necessary buoyant force, there would be no additional storage problem. It seemed an appealing and promising suggestion. In 1968 Ricardo also alluded to it in his autobiography and inferred that political considerations rather than technical problems overruled it.

Erren continued his efforts in England during the 1930s, working with Hastings-Campbell. Their 1933 paper remains good reading today. In addition to its technical content, it stresses the nonpolluting nature of hydrogen, as well as the need to become independent of foreign sources of fuel. In particular, it suggested the conversion of buses to run on hydrogen, which would be stored in banks of cylindrical tanks at a relatively high pressure. Erren later developed such a bus, as he continued to convert cars and trucks to run on hydrogen; he estimated that he had made more than 1000 such conversions.

Interest in hydrogen as an internal combustion engine fuel continued through the decade of the 1940s, much of it stimulated by military needs arising in World War II. A hydrogen-oxygen system, for example, offered the possibility of submarine and torpedo propulsion free of a traceable wake. The idea, apparently due to Erren, seems to have been rejected by the British Admiralty, but was pursued by the German Navy. The work was done in secrecy, of course, and technical reports have not appeared in the open literature. In an interview, Erren (who was interned by the British during the war) spoke of German submarines captured by the Allies, who were using the system with considerable success. The major thrust of Oemichen's work in Germany in 1942 was directed toward solving the backflash problem via direct cylinder injection of the hydrogen.

2.3. From 1950 to 2000

Interest in hydrogen seems to have waned considerably after World War II, with the return of plentiful, cheap gasoline. R.O. King, then at the University of Toronto, carried out an extensive investigation of hydrogen performance, especially on the problems of pre-ignition and backfire.

The US space program of the 1960s led to the development of considerable hydrogen technology in rocket engines, particularly with the Apollo program. The remarkable safety record of this program should be noted here and serves as reassurance of the acceptable safety of the use of hydrogen as an engine fuel. During the 1960s, a key contribution to the potential use of hydrogen was made by Reilly and Wiswall with their work on the use of metallic hydrides as a storage medium for gaseous hydrogen.

A marked increase in research and development directed toward the potential use of hydrogen as an engine fuel for vehicular use took place in the 1970s. Indeed, approximately 50 major research centers were so involved, either with direct or supporting activity. This was probably due to two factors: increasing concern over air pollution and the verification of the major role of automotive emissions in generating it, and the great reduction in petroleum shipments to the US.

The year 1972 was a turning point, or the stimulus for one. The Urban Vehicle Design Contest was held in the US that year, attracting many entries and publicly demonstrating the viability of the hydrogen car concept. The entries of UCLA (Lynch, Finegold, and Baker) and Brigham Young University (Billings) were notably successful. In addition to the novelty of cars actually running on hydrogen and performing the standard road tests, the contest offered an appreciation of the reduction in air pollution possible with the use of hydrogen. At a time when the proposed automobile emission standards for the State of California (probably the most severe in the world at the time) were 1 g/mi for unburned hydrocarbons, 2.4 g/mi for carbon monoxide, and 1.5 g/mi for oxides of nitrogen, the figures for the UCLA car were .09 g/mi, 0.15 g/mi, and 0.04 g/mi, respectively. Ironically, it was later recognized that these figures were probably higher than actual performance, because sampling was done in an enclosed facility and reflected background concentrations. Recognizing the billions of dollars annual damage done to agriculture and forest products by air pollution due in large measure to automotive emissions, one cannot resist speculating about the cost of **not** using hydrogen as an engine fuel.

The 7th Intersociety Energy Conversion Engineering Conference, held in San Diego, California, in 1972, also contributed to stimulating interest in the hydrogen-fueled engine, devoting a session to the subject. The late Professor Kurt Weil reacquainted the technological community with hydrogen engines and speculated on promises for the future in recognition of the emerging need for improvement, nationally and internationally, in the energy/transportation/environment system. The (modern) pioneering work of Murray and Schoeppel of Oklahoma State University and that of Swain and Adt of Miami University were presented.

UCLA’s work with hydrogen engines continued with emphasis on the greater efficiency obtainable with hydrogen, the recycle of exhaust gas to reduce emissions of the oxides of nitrogen, and the development of a cryogenic, liquid hydrogen system. Buchner and Saufferer of Daimler-Benz also made significant contributions, as did Peschka and Carpetitis working with BMW. The former emphasized the use of metallic hydride storage systems and demonstrated their promise by modifying several Mercedes vehicles to utilize them. The latter devised a cryogenic system to contain liquid hydrogen and modified a BMW automobile to operate in this mode; they also developed a liquid hydrogen “filling-station” pump to demonstrate the potential ease of filling the automobile’s fuel tank with liquid hydrogen. Not only were these contributions important in themselves, but the fact that Daimler-Benz and BMW supported them gave credibility to the outlook for the ultimate practicality of hydrogen-fueled vehicles.

Yet another event took place in the 1970s that is worthy of note. This was a rally held in 1975 designed to demonstrate the fuel economy of various engine-fuel systems. It started at the Canadian border on the West Coast of the US and terminated in Los Angeles, covering a distance of 2800 km. One entry was fueled with liquid hydrogen. This was a vehicle developed by Professor Furuhama and his group at the Musashi Institute of Technology in Tokyo. As Furuhama stated, the event was not without problems, but the fact that his car completed the course satisfactorily gave much needed evidence that the hydrogen car concept was more than a laboratory curiosity. It was an accomplishment that should have been much more recognized, but unfortunately, the rally itself was not widely publicized. Fortunately, Furuhama's group has been able to continue work on liquid hydrogen-fueled engines and cryogenic storage systems; they have also developed a liquid hydrogen fuel pump with the objective of injecting hydrogen still in the liquid state into the engine.

Other work in Japan includes that of Ikegami at Kyoto University on the operation of diesel engines with hydrogen. There had been some question about the suitability of hydrogen as a fuel for the diesel cycle due largely to uncertainties about its auto-ignition characteristics and the higher pressures involved. De Boer of Cornell University investigated the auto-ignition phenomenon specifically using a single-cylinder, variable-compression engine. He reported no auto-ignition up to compression ratios as high as 29, but found this no deterrent to the use of hydrogen in the diesel cycle, as he reported that ignition took place readily with a "glowplug" device providing the ignition source. Ikegami's work further demonstrated the feasibility of diesel engine operation with hydrogen.

About the middle of the 1970s, the availability and cost of gasoline in the US returned to normal, and financial support for work on hydrogen-fueled engines diminished significantly. There were, fortunately, notable exceptions. Swain conducted an extensive study of the performance of some 19 engines that had been modified to run on hydrogen. The overall objective was to develop a broad database relative to the engine of the future designed to operate with hydrogen—in contrast to gasoline engines modified to use hydrogen.

Daimler-Benz also made a major contribution during this period. Five passenger cars and five delivery vans, each powered with hydrogen-fueled engines, were put into regular service in Berlin, with two commercial fleet operations. The vehicles were put on regular duty, serviced by the the Mercedes-Benz Berlin branch and with hydrogen supplied at a central fueling station. The results of one and a half years of testing were quite positive and have stimulated interest in hydrogen-powered vehicles globally.

Mention must also be made of the efforts of Bockris in establishing a hydrogen research center at Texas A&M University. Now the Center for Electrochemical Systems and Hydrogen Research, it has been particularly active, and successful, in fuel cell research.

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Biographical Sketches

William D. Van Vorst is professor emeritus of chemical engineering at the Los Angeles Campus of the University of California (UCLA). His earlier education was in chemical engineering at Rice University, where he received the professional degree of Ch.E. He earned the S.M. in chemical engineering practice at M.I.T. After a few years in jet propulsion research in industry, he entered the Ph.D. program at UCLA and received the degree. He accepted appointment to the faculty at UCLA and has served there ever since. His interest in hydrogen as an engine fuel dates to 1972, when he joined the hydrogen car project as a faculty cosponsor.

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