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Chapter 7

GENESIS OF LIQUID HYDROGEN PROPULSION THROUGH 1945*

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Experimental research using liquid hydrogen as fuel for aircraft and rockets began in the United States in 1945 and continued sporadically during the 1950s. In 1958 and 1959, decisions were made to develop a rocket engine and upper stages of launch vehicles using liquid hydrogen. The subsequent developments of Centaur and Saturn launch vehicles were key elements in the success of American manned and unmanned space missions and transformed liquid hydrogen into a practical fuel with a great potential for wider energy applications.

The decisions to use liquid hydrogen would not have surprised the great Russian rocket pioneer Konstantin E. Tsiolkovsky (Figure 1), for he proposed a liquid hydrogen-liquid oxygen space rocket in 1903, five years after the first liquefaction of hydrogen by James Dewar. This paper is concerned with the origins of U.S. interest and experiments with liquid hydrogen, the possible links with earlier work, and why liquid hydrogen was not used earlier as a propulsion fuel [1].

Of Tsiolkovsky's many contributions to rocket technology, perhaps the best known is his theory of rocket flight based on the laws of motion. The Tsiolkovsky equation helps to explain the advantages and disadvantages of using liquid hydrogen. Tsiolkovsky showed that the velocity of a rocket vehicle is directly proportional to the velocity of the exhaust. Hydrogen excelled over all other stable chemical fuels in achieving high exhaust velocity, an advantage quickly realized by Tsiolkovsky and others who followed him.

The Tsiolkovsky equation also has a term containing the ratio of initial to final mass of the vehicle. In this term, hydrogen appears as a disadvantage because its low density requires a large-volume tank which adds to the final mass and penalizes performance. Thus, hydrogen's advantage of high exhaust velocity is partially offset by an increase in the final mass because of its low density.

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During his career, Tsiolkovsky's enthusiasm for using hydrogen waned, especially when he became engrossed in rocket-powered aircraft, which are volume-limited. A year before his death in 1935, he discussed rocket fuels and concluded that "hydrogen is unsuitable because of its low density and storage difficulties when in liquid form [2]."

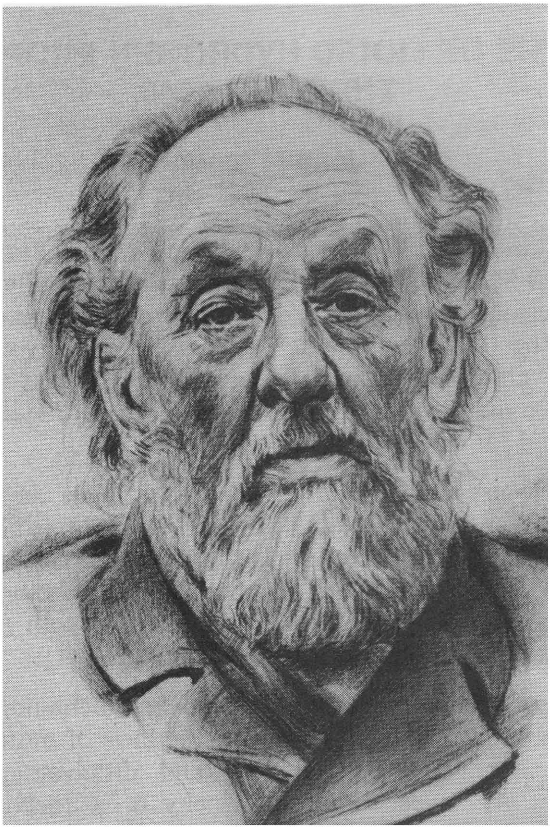

Figure 1 Konstantin E. Tsiolkovsky

Another rocket pioneer, Robert H. Goddard (Figure 2), was also attracted to hydrogen-oxygen because of its high-energy potential. In 1909, he calculated that the energy released from 45 kilograms of hydrogen-oxygen was sufficient to propel a 1-kg payload to infinity. In 1910, he wrote about producing hydrogen-oxygen on the Moon. Goddard, however, was considering the combination in the same way as a solid propellant; that is, burning discrete charges. When he began experimenting with continuous burning in 1921, the practicality of the gasoline-liquid oxygen combination attracted him. By 1923, he had operated a test rocket with gasoline-liquid oxygen and three years later became the first to fly a liquid-fueled rocket. His achievement clearly demonstrated the feasibility of using a cryogenic fluid -- liquid oxygen -- in flight. He did not experiment with liquid hydrogen, however, because of its low availability and handling problems. For the same reasons, he was amazed to learn in 1939 that the National Advisory Committee for Aeronautics (NACA) was considering liquid hydrogen for a flight application [3]. NACA, however, did not get around to such experiments until the 1950s.

Figure 2 Robert H. Goddard

Returning to the 1920s, still another rocket pioneer, Hermann Oberth (Figure 3), published the first of his series of books on interplanetary flight in 1923. He proposed a multistage vehicle using alcohol-water with liquid oxygen in the first stage and liquid hydrogen-liquid oxygen in the upper stages. He also proposed the use of pressure-stabilized, thin-wall tanks as a practical means of achieving low tank mass for liquid hydrogen. Both his upper-stage propellants and the thin-walled tanks were adopted in the U.S. space program. Oberth was primarily a theoretician but apparently he experimented with a gaseous hydrogen-oxygen burner though not with liquid hydrogen [4].

To sum up, all three rocket pioneers -- Tsiolkovsky, Goddard, and Oberth -- were attracted to and proposed the use of liquid hydrogen-liquid oxygen because of its high heat content, but theoretician and experimentalist alike saw the disadvantages of hydrogen's low density, limited availability, and handling difficulties.

Parallel to rocket considerations there were other activities that used hydrogen. The best known was in lighter-than-air flight, the first practical application of gaseous hydrogen that started in 1783. From 1900 to 1937, thousands of passengers were carried in large hydrogen-filled dirigibles yet there were accidents and these ended the era of the giants. The last and best remembered was the Hindenburg, filled with 200,000 m^3 of hydrogen, which burst into flames after a transatlantic flight to the United States. Thirty-six people lost their lives in the accident.

Figure 3 Hermann Oberth

Not so well known were early attempts to use dirigible buoyancy gas as fuel in its engines instead of venting it. Paul Haenlein patented this concept in 1872 and successfully used coal gas in a Lenoir engine in the first flight using an internal combustion engine the same year. Haenlein also considered hydrogen, but no record has been found that he tried it. Others did, however, following World War I, in Italy, Great Britain, Germany, and the United States. These were of limited success as hydrogen has a tendency to produce detonations or knock in piston engines [5]. These lighter-than-air applications added to the technology of generating, storing, and handling hydrogen which was further enhanced by the greatly expanded use of hydrogen in hydrogenation processes.

A second parallel activity involving hydrogen was scientific investigations of low-temperature phenomena that began to move more rapidly during the second half of the 19th Century with the race to liquefy the so-called permanent gases. Hydrogen was liquefied in 1898 by Dewar and helium in 1908 by Kamerlingh Onnes. Dewar also developed an efficient cryogenic storage vessel bearing his name. From these and other low-temperature experiments, liquefiers were developed which made liquid hydrogen available in small quantities.

The earliest rocket experimenter to use liquid hydrogen appears to have been Walter Thiel at Kummersdorf in Germany, during the 1937-1940 period. According to recollections of Wernher von Braun, Thiel tried a number of propellant combinations, among them liquid hydrogen-liquid oxygen and liquid hydrogen-liquid oxygen and fluorine mixtures in a small (200 newton) engine:

> "As to Thiel's liquid hydrogen tests with this set-up, I remember seeing liquefied (outside) air dripping from the supercold liquid hydrogen line. In discussing liquid hydrogen's potential, Thiel fully endorsed Oberth's earlier optimism, but pointed out that tightness of plumbing connections was a critical problem and the ever-present explosion hazard caused by the accumulation of leaked-out hydrogen gas in an unvented structural pocket would require extreme care in the design of a liquid hydrogen-powered rocket or rocket stage [6]."

The exploratory work with hydrogen went no further as development concentrated on the A series of rockets. Thiel transferred to Peenemünde to work for von Braun and was killed in 1943 during a British air raid. The German A-4 (V-2), using Oberth's alcohol-water mixture with liquid oxygen, established beyond all doubt the feasibility of using a cryogenic fluid in a rocket vehicle.

A parallel flight activity influencing interest in fuels other than high-octane gasoline was the development of jet engines for aircraft. Hans von Ohain was the first to use hydrogen in a turbojet engine. Employed by Heinkel in 1936 to develop a turbojet and pressed for time, von Ohain used gaseous hydrogen as a fuel of convenience. In early 1937, tests showed that the engine ran "outstandingly well with respect to quick throttle changes (almost like a piston engine) [7]." The test impressed Heinkel and gave von Ohain time to develop a gasoline combustor for his engine. Whether or not this transient use of hydrogen in a turbojet stirred interest elsewhere is not known. It is conceivable, however, that it may have influenced NACA's 1939 interest in liquid hydrogen with atmospheric air which so surprised Goddard.

The advent of German V-weapons and the effectiveness of a small number of jet interceptors against Allied bombers brought swift realization to the United States of how far behind it was in these new technologies. Part of the lag in developing jet aircraft was a decision to concentrate on the mass production of tried and proven piston engine planes rather than rely on the potentially superior but untried jet engine. Teams of Allied scientists and engineers followed in the wake of advancing armies in Europe, gathering technical data from documents and interrogations of Germans involved. Among those interrogated was Wernher von Braun and his concepts of future space missions caused considerable interest [8]. Less known was another interrogation of von Braun in which he discussed Thiel's brief experiments with liquid hydrogen and problems from plumbing leakage [9].

In late 1944 and early 1945, as war pressures on U.S. aeronautical laboratories began to ease, fuel researchers at the Army Air Force's Wright Field began to plan long-range projects. How much they may have been influenced by prior work is conjecture. They were well aware of hydrogen's advantages and disadvantages from general studies and from occasional research studies or suggestions. In the early 1920s, for example, the NACA translated a German paper by P. Meyer on fuels lighter than gasoline [10]. Meyer discussed hydrogen but apparently only considered it in gaseous form for he concluded that the heavy tanks required would not be feasible for aircraft. They were also aware of a British suggestion forwarded to them in 1942 by the NACA. It was written by F.E. Simon, a physicist who fled Germany before the war and had brought a hydrogen liquefier to Oxford's Clarendon laboratory. Simon proposed to use liquid hydrogen as a means for increasing aircraft range [11]. As the total hydrogen liquefaction capacity in the United States was only a few hundred liters per day, Simon's suggestion was dismissed as utterly impractical, particularly in wartime.

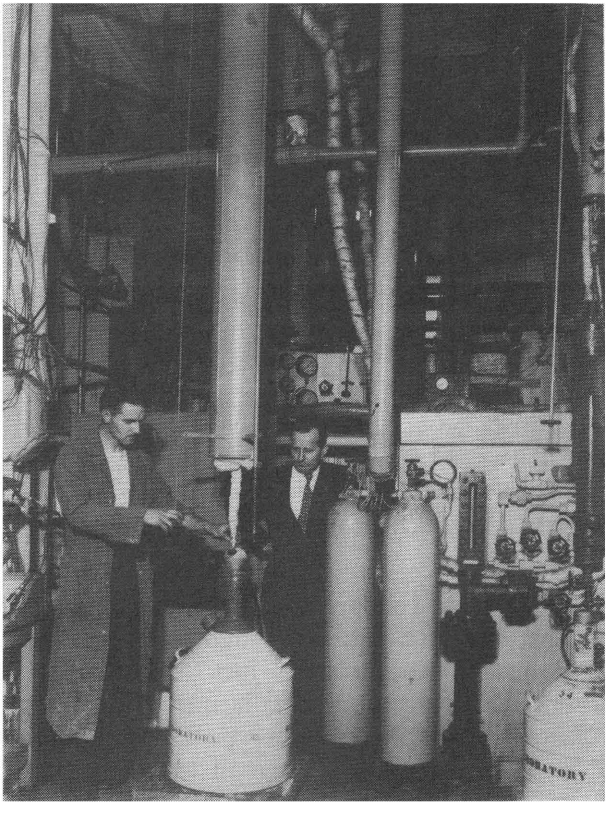

Figure 4 Professor Herrick L. Johnston (right) and Gwynne A. Wright with hydrogen liquefier at Ohio State University, ca. 1945

In the long-range planning at Wright Field, the chief civilian engineer of the power plants laboratory, Opie Chenoweth, suggested to his colleagues that research be undertaken to increase the energy content of aviation fuels. Although hydrogen was not a good fuel for piston engines because of its tendency to cause knock, jet engines did not have this restriction. At Ohio State University in nearby Columbus, Professor Herrick Johnston had a fine cryogenics laboratory and was a leading authority on liquefying hydrogen (Figure 4). He had a liquefier capable of producing 25 l of hydrogen per hour. Which of the several researchers involved at Wright Field put all these together is not known, but on 1 July 1945, Ohio State University began a study of liquid hydrogen for aircraft and rockets under contract to Wright Field [12]. From interviews and communications with several of the principals involved, a reasonable conclusion is that this hydrogen research was initiated as a normal consequence of the laboratory's research operations, evolving from group considerations rather than from the inspiration of an individual or reaction to a new piece of information [13]. Initial studies led to successful testing of liquid hydrogen-liquid oxygen experimental rocket engines (Figure 5).

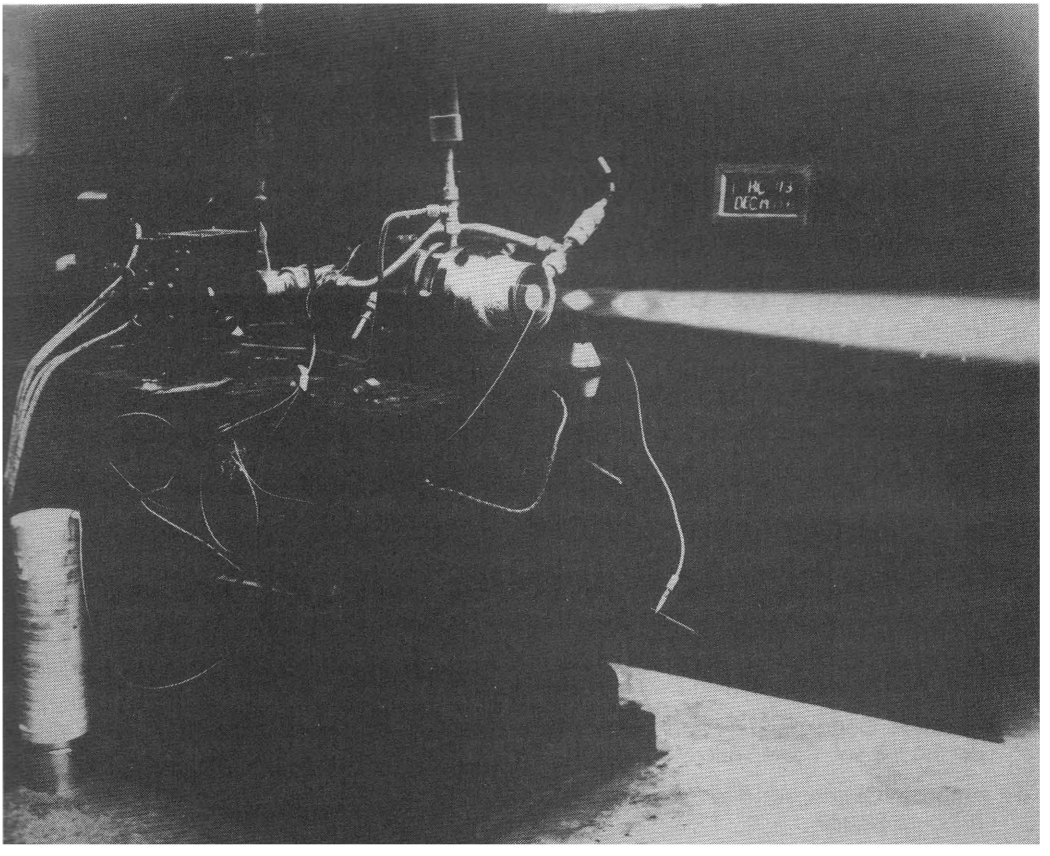

Figure 5 Liquid hydrogen-liquid oxygen experimental rocket engine regeneratively cooled by liquid hydrogen, Ohio State University, December 1949. Note frost on outside of rocket combustion chamber.

Like the Army Air Force, the Navy was stirred by German jet propulsion developments. In one action, it sponsored a study of fuels for jet propulsion by Alexis W. Lemmon, Jr., which he reported in May 1945 [14]. Lemmon found that hydrogen-oxygen gave the highest exhaust velocity of any propellant combination he studied but he rejected it because of its low density.

In July 1945, a young Marine lieutenant, Abraham Hyatt, reported to the Navy's Bureau of Aeronautics after completing a technical intelligence mission. Hyatt brought along German technical documents, including von Braun's space predictions, which stimulated the staff, particularly Lt. Robert Haviland and Cmdr. Harvey Hall. Both began studies of space projects and made proposals for satellites but they took different courses on the launch vehicles. Hall, who had a doctorate in physics, began educating himself in rocket theory. He worked out the Tsiolkovsky equation from the laws of motion and began to explore the extremes of exhaust velocity and mass ratio. At the time he was unaware of the newly-issued Lemmon report. He simply went to his chemistry textbooks in search of high-energy reactions and there he found hydrogen and oxygen, whose heat of combustion had been measured by Lavoisier and Laplace in the 18th Century and by others many times since. Hall was also totally unaware that he was repeating the same steps that Tsiolkovsky had taken almost a half century earlier and arriving at the same conclusion; that is, an initial enthusiasm to use liquid hydrogen [15]. As a result of Hall's initiatives, the Navy let a contract with the Aerojet Engineering Corporation for an experimental investigation of a liquid hydrogen-liquid oxygen rocket [16]. Unlike the Air Force contract with Ohio State, which was a general investigation, the Navy contract was directed toward using liquid hydrogen-liquid oxygen in a single-stage-to-orbit booster for a satellite.

In conclusion, the U.S. Air Force and Navy became interested in liquid hydrogen as a rocket fuel in 1945, both independent of each other and of other work, as well as for different reasons. Consideration of liquid hydrogen is a logical outcome of any study of high-energy fuels; low density, low availability, and handling difficulties were the chief obstacles which prevented an application from the time Tsiolkovsky first suggested it until after Sputnik.

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