History of
Rocketry and Astronautics

Proceedings of the Twelfth, Thirteenth and Fourteenth History Symposia of the International Academy of Astronautics

Dubrovnik, Yugoslavia, 1978

München, Federal Republic of Germany, 1979

Tokyo, Japan, 1980

Å. Ingemar Skoog, Volume Editor

R. Cargill Hall, Series Editor

AAS History Series, Volume 10

A Supplement to Advances in the Astronautical Sciences

IAA History Symposia, Volume 5

AAS Publications Office
P.O. Box 28130
San Diego, California 92198

Affiliated with the American Association for the Advancement of Science
Member of the International Astronautical Federation

First Printing 1990

ISSN 0730-3564

ISBN 0-87703-329-3 (Hard Cover)
ISBN 0-87703-330-7 (Soft Cover)

Published for the American Astronautical Society
by Univelt, Inc., P.O. Box 28130, San Diego, California 92198

Printed and Bound in the U.S.A.

Chapter 15

TECHNOLOGICAL STEPS TO LIQUID HYDROGEN PROPULSION*

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The history of flight contains many examples in which an innovative concept is proposed many years before the technology necessary for its accomplishment becomes available. Leonardo da Vinci's concept of a helicopter and the numerous concepts of manned space flight are examples. Another example, which is the focus of this paper, is the concept of using liquid hydrogen for manned space flight. This concept was first proposed by Constantin Tsiolkovskiy in 1903,[1] but over fifty years elapsed before it was adopted and became a reality with the Apollo Moon landing missions. Although the use of liquid hydrogen is not essential for manned space flight (U.S.S.R. flights attest to that), its use greatly facilitated the development of U.S. space vehicles, and was a major contributor to the successful manned lunar and unmanned planetary flights, and is the choice for the space shuttle. The purpose of this paper is to discuss some of the major technological steps that made feasible the use of liquid hydrogen for space vehicles.

Before discussing these technological advancements, however, let us ask: Why choose liquid hydrogen? To answer, let us consider some of the desirable properties of a fuel and how hydrogen measures up to these properties. The major performance criterion for a fuel is its ability to propel the rocket to sufficiently high velocity to achieve the desired space mission. This is dependent upon two primary factors - rocket exhaust velocity and low vehicle mass - and several secondary but important factors concerning cooling, combustion, and handling characteristics.

Tsiolkovskiy showed in 1903 that rocket vehicle velocity is directly proportional to the product of rocket exhaust velocity and the natural logarithm of the ratio of initial-to-final vehicle mass, (neglecting drag and gravitational velocity losses)[2]. Hydrogen, burned with oxidizers such as oxygen, fluorine, or ozone, produces the

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* Paper presented at the 14th History Symposium of the International Academy of Astronautics, Tokyo, Japan, September 1980.

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highest exhaust velocity of all chemical fuels by a combination of high heat of reaction and low molecular mass of the exhaust gases. Fuel characteristics also affect the vehicle structural (final) mass in the form of tankage, lines, and control equipment. Here liquid hydrogen's properties are a disadvantage, for it has the lowest density of all the fuels and hence requires more tankage mass than denser fuels.

Cooling rocket combustion chambers and nozzles is usually accomplished by using the fuel as the coolant prior to combustion. Liquid hydrogen, with its high specific heat and low critical pressure, excels as a coolant although this was not recognized and verified until the late 1940s. Hydrogen's high flame speed and wide flammability limits are advantages in achieving ignition and efficient combustion in a small volume.

Desirable handling and storage characteristics of a fuel are: low vapor pressure, low freezing point, high thermal stability, high ignition temperature, non-corrosive, and non-toxic. Although liquid hydrogen is non-toxic and non-corrosive, its very low liquid temperature and the ease with which gaseous hydrogen can be ignited in air makes for difficult handling.

With this background, let us now consider four related technological advancements which made practical the use of liquid hydrogen in unmanned and manned space vehicles. These are: 1) liquefaction of gases and their storage and handling; 2) demonstration that a liquefied gas can be used successfully in rocket flight; 3) development of lightweight and large rocket structures, and 4) aircraft and rocket experiments with liquid hydrogen that demonstrated its effectiveness.

LIQUEFACTION OF GASES AND THEIR STORAGE AND HANDLING

The liquefaction of gases began in the late 18th Century with the liquefaction of sulfur dioxide by Monge and Clouet. By 1844, Faraday was able to reach -110°C and had liquefied many gases, but six known gases remained: hydrogen, oxygen, nitrogen, nitric oxide, carbon monoxide, and methane. In 1889 Wroblewski became the first to achieve the static liquefaction of oxygen and air and these were used as cooling agents for liquefying other gases.

With these scientific successes, technology followed. In Germany Linde developed a commercial process for liquefying air on a large scale in 1895 and a year later, Hampton did the same thing in England. Gas liquefaction techniques involved three basic steps: 1) compressing the gas to a high pressure (50 to 200 atmospheres), 2) chilling the compressed gas to as low a temperature as possible, using various cooling methods, and 3) expanding the chilled, compressed gas from a high pressure to atmospheric pressure by means of a valve. The third step made use of the Joule-Thomson effect for gases where the gas is cooled by the expansion when below its inversion temperature.

Both the Linde and Hampton processes used regenerative cooling, an old idea first introduced by Siemens in 1857[2]. Regenerative cooling means using a fluid as the coolant in a process in which the fluid is itself involved.

Regenerative cooling proved to be the technological link needed to liquefy hydrogen. On 10 May 1898, Dewar used it to become the first to statically liquefy hydrogen. Using liquid nitrogen, he precooled gaseous hydrogen under 180 atmospheres pressure, then expanded it through a valve in an insulated vessel also cooled by liquid nitrogen. The expanded hydrogen further cooled the incoming high pressure gaseous hydrogen until liquid hydrogen was produced. Dewar produced about 20 cubic centimeters of liquid hydrogen[3] or about one percent of the hydrogen used.

Dewar used an insulated vacuum container flask he had developed earlier which became known as "Dewar flasks" - now simply, dewars. Dewars are multi-walled vessels with a vacuum in the annular space to minimize heat transfer by conduction and convection. The walls of the annular space are silvered to reflect radiant heat. The dewar was a very significant step in storing and transporting cryogenic or liquefied gases such as oxygen and hydrogen.

The same basic principles of liquefaction and vessel design are used today for the liquefaction, storing, and handling of liquid oxygen and liquid hydrogen, but additional technological developments and refinements that came with increased demand were necessary before liquid hydrogen became a practical fuel.

The development of liquid hydrogen technology in the early part of this century came from scientific research but the liquefaction capability on a laboratory scale was very small. One of the most significant advances was the discovery by Heisenberg in 1926 that the hydrogen molecule existed in two forms - orthohydrogen and parahydrogen[4]. Additional research showed that at room temperatures and above, ordinary hydrogen is 75 percent orthohydrogen and 25 percent parahydrogen. At the boiling point of liquid hydrogen, 20.3°K, the equilibrium composition is 99.8 percent parahydrogen. When gaseous hydrogen is liquefied, it will slowly and spontaneously seek equilibrium, with orthohydrogen changing to parahydrogen. At 20.3°K the conversion releases more heat (532 joules/gram) than is required to vaporize the liquid (453 joules/gram) and the liquefied normal hydrogen evaporates completely on conversion to parahydrogen, even in a perfectly insulated container - a situation Dewar did not foresee.

Interest in hydrogen liquefaction picked up with U.S. research on moderators for atomic weapons, and rapidly accelerated in the 1950s with thermonuclear research. Catalysts were developed to convert ortho- to parahydrogen as part of the liquefaction process so that hydrogen storage and transport in quantity became practical. Low-loss air transportable dewars and surface transportable dewars for liquid hydrogen were developed by the mid-1950s but the total hydrogen liquefaction capacity remained too low for propulsion use[5].

The incentive to increase liquefaction capacity significantly for an aircraft propulsion application came in 1956. In May of that year, the Air Force contracted to build a 680 kilogram-per-day liquid hydrogen plant in Painesville, Ohio. At the same time, a contract was awarded for a similar plant to be built in Bakersfield, California. The Painesville plant, built at a cost of $2 million, became operational in May 1957; the California plant, in the fall of 1957. A third plant with a capacity of

4,500 kilograms per day was built in Florida and was also in operation in the fall of 1957. A fourth plant, also in Florida, with a capacity of 27,200 kilograms per day was contracted for in 1957 for $27 million. This was the world's largest hydrogen liquefaction plant and, although it was built too late for its intended application, it served a very useful role in the space program that followed.

Concurrent with the building of the series of four hydrogen liquefaction plants, the Air Force developed over-the-highway trailers with a capacity of 26,500 liters of liquid hydrogen, with a loss rate of about 2 percent a day. The combination of hydrogen liquefaction plants and trailers for transporting liquid hydrogen was a large leap ahead in both liquid hydrogen availability and handling experience[6].

DEMONSTRATION THAT A LIQUEFIED GAS CAN BE USED SUCCESSFULLY IN ROCKET FLIGHT

Five years after Dewar first liquefied hydrogen, Tsiolkovskiy proposed its use with liquid oxygen in a manned space rocket (Figure 1a). He was apparently aware of the high energy content of hydrogen, first measured by Lavoisier and Laplace during the winter of 1783-84 and measured by a number of investigators during the 19th Century[7] and the capability of hydrogen-oxygen to produce a high rocket exhaust velocity. At first he saw no problems in hydrogen liquefaction but hedged his selection by noting that hydrogen could be replaced by liquid hydrocarbons. In later years he turned away from hydrogen in favor of liquid hydrocarbons because of difficulties he saw in liquefaction and in the problems of its low density. By 1930, Tsiolkovskiy was interested in rocket propelled aircraft in the belief that the way to space flight was to increase gradually the capability of aircraft to interplanetary flight. He noted the relatively unavailability of liquid hydrogen and noted that its density was a serious problem. By 1935, he concluded that liquid hydrogen was unsuitable as a fuel because of its low density and difficultly of storage. Tsiolkovskiy was a true theoretician and attempted no rocket experiments.

Another rocket pioneer, Robert Goddard, recognized the energy content of hydrogen-oxygen and in 1909 calculated that 45 kilograms of hydrogen-oxygen had enough energy to send a kilogram payload to infinity. Goddard's early work - and enthusiasm for hydrogen - revolved around using liquid hydrogen and solid oxygen but he undertook no experiments on this combination. He turned to fuels and oxidizers easier to handle and, for a while, was engrossed in developing a rocket using discrete charges of smokeless powder. This was a failure and he turned to liquid propellants. He soon chose gasoline-liquid oxygen and on 1 November 1923, he statically fired a rocket engine using this combination. On March 16, 1926 Goddard launched the world's first gasoline-liquid oxygen rocket which traveled 60 meters [184 feet] in 2 1/2 seconds[8-9]. Sixteen years later, on October 3, 1942, the Germans launched their flight of the 5000 kg A-4 (V-2) rocket at Peenemünde which travelled 192 kilometers. The V-2 used alcohol and liquid oxygen, and the approximately 1100 fired proved beyond any doubt the feasibility of large liquid-propellant rockets in general and the use of a liquefied gas - liquid oxygen - in particular.

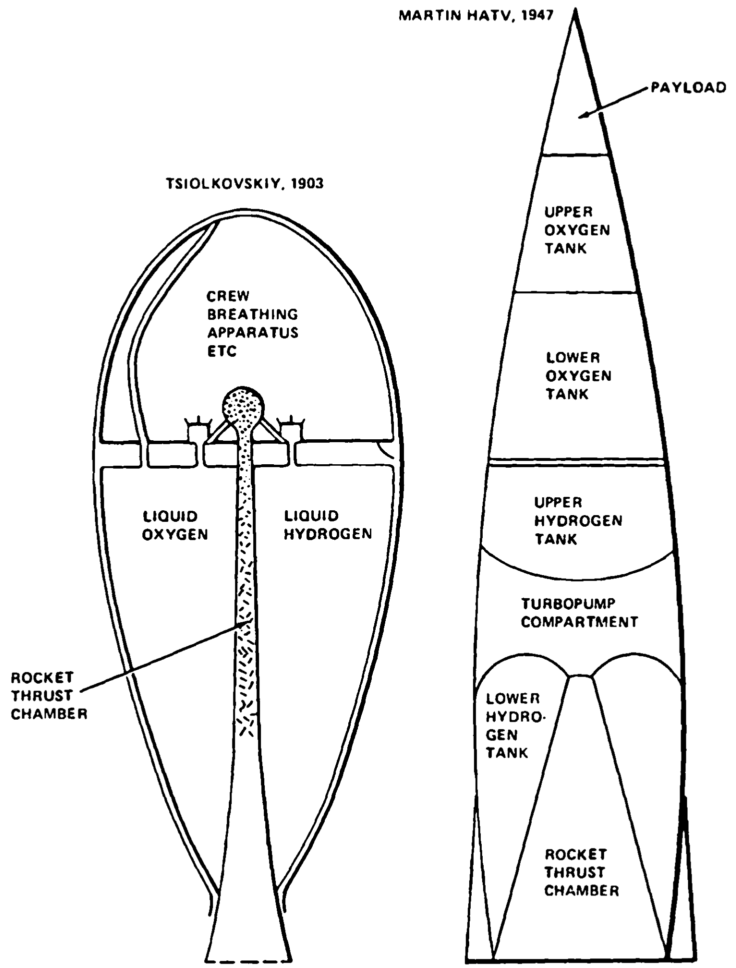

Figure 1 (a) Tsiolkovskiy's 1903 rocket using liquid hydrogen-oxygen
(b) Glenn L. Martin's design of a single stage to orbit using liquid hydrogen-oxygen in 1947. Note similarity to Tsiolkovskiy's design.

DEVELOPMENT OF LIGHTWEIGHT AND LARGE ROCKET STRUCTURES

In his *Die Rakete zu den Planetenraumen* in 1923, Hermann Oberth proposed a space rocket with the first stage using alcohol and oxygen and the second stage using liquid hydrogen-liquid oxygen. His reasoning was sound but the concept was ahead of the technology. He realized the problem of tank mass for low-density liquid hydrogen and proposed the use of a thin wall, pressure-stabilized tank. He checked his computations by putting linen sacks over thin rubber balloons, filling them with water and pressurizing the unit with weights. This concept, also ahead of its time, was proposed for use in liquid hydrogen rockets for the U.S. Navy by the North American Aviation Company and the Glenn L. Martin Company in 1946-1947 (Figure 1b). The North American Aviation and Martin designs were for single-stage-to-orbit vehicles where lightweight structures were essential. They too were not built[6].

The 1950s have been described as the golden age of missile development in the U.S., and with it came the development of intercontinental ballistic missiles, the Atlas and Titan, which advanced the technology of rocket vehicles. The predecessor of the Atlas missile was a contract let to Convair in 1946 by the U.S. Army Air Corps and identified as the MX-774. It was for a vehicle of 8,000 km range. Convair decided on a ballistic missile approach at a time of considerable skepticism over its feasibility. Lightweight design was crucial to achieving the long range required. The Convair engineers realized this but were handicapped by lack of weight data for practical designs. To meet this need the lead Convair engineer, Karl Bossart, built and flight-tested three vehicles with three innovations that were later used on the Atlas. One was the use of integral, thin-wall, pressure-stabilized tanks for minimum weight. This was the concept proposed by Oberth in 1923 and by North American and Martin in 1946-1947, but Bossart independently conceived the idea and was the first to build and test it successfully in flight. He calculated the internal pressure necessary to resist aerodynamic loads and compared it to the tank pressure needed to prevent cavitation at the inlet of the rocket pumps. He found the pressure needed for the pumps to be the higher value, which meant that a tank strong enough to withstand the pressure required would also be strong enough for the stiffening pressure needed for the tank to withstand aerodynamic forces. Bossart also dispensed with insulation for the liquid oxygen tank generally considered to be a necessary but weight handicap for using cryogenic fluids. The third innovation was to use swiveling rocket nozzles to control pitch, yaw, and roll of the rocket during flight. The flight tests were not a great success, falling short of the intended range of 185 km, but none of the failures were caused by Bossart's innovations.

In 1954 a breakthrough in nuclear weapons development reduced the payload requirement of intercontinental missiles to about 800 kg and Convair was given a contract for development of a scaled-down Atlas for this payload. The thin wall, integral, pressure-stabilized tank design with a single bulkhead separating fuel and oxidizer was a concern to the Air Force and, partly for this reason, it was specified that the design of the Titan for the same range and payload have a more conventional tank design. When the first Atlas flew in 1957, the hot exhaust gases from the turbopump burned through some control wires in the engine compartment and the vehicle lost stability while still in the atmosphere and began to tumble. The flight was a failure but those who viewed the film of the tumbling vehicle became believers in the pressurized tank concept. With aerodynamic loads far greater than in normal flight the tanks remained intact during the violent tumbling[6]. The Atlas was the first successful U.S. intercontinental ballistic missile and became part of the "stable" of initial boost vehicles for space activities of the 1960s, carrying John Glenn into orbit.

The lightweight, pressure-stabilized tank concept of the Atlas was adopted for the Centaur, the first vehicle to use liquid hydrogen-oxygen and still in use today as the workhorse of the U.S. planetary programs (Figure 2).

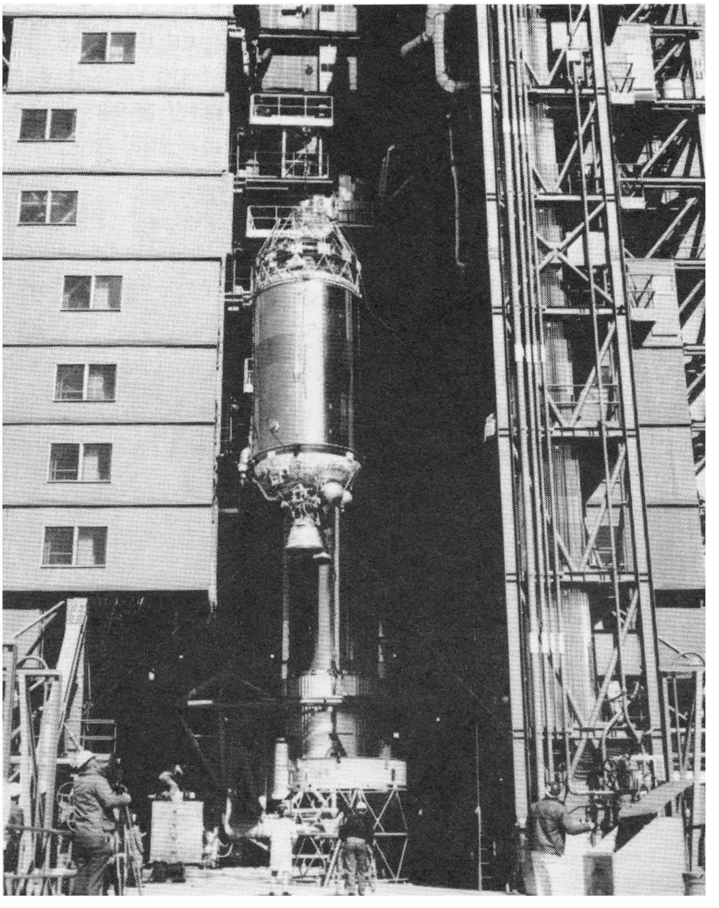

Figure 2 Centaur stage, first to use liquid hydrogen-oxygen.

AIRCRAFT AND ROCKET EXPERIMENTS WITH LIQUID HYDROGEN

Experiments with liquid hydrogen-liquid oxygen lagged considerably behind the proposals to use the combination. During the buildup of rocket research and development in Germany in the late 1930s, Walter Thiel experimented briefly with liquid hydrogen-liquid oxygen during 1937-1940, but Wernher von Braun noted there were considerable leaks and other problems. In the United States, experiments with hydrogen and oxygen began at Ohio State University and Aerojet Engineering Corporation in 1945; one sponsored by the Air Force, the other by the Navy. The Jet Propulsion Laboratory of the California Institute of Technology began experiments in 1949. The work at these laboratories showed that high performance could be realized, that liquid hydrogen could be used as a regenerative coolant, that liquid hydrogen could be pumped and that pump bearings would operate immersed in liquid hydrogen without conventional lubrication. The experiments were on a small scale, however, and the work phased out as the interest of the military sponsors turned to more conventional fuels for the ballistic missile program.

During the 1950s, the NACA Lewis laboratory began experiments with liquid hydrogen-liquid oxygen and with liquid hydrogen-liquid fluorine. The work showed that high performance could be obtained in flight-type rocket engines of a more practical size and that liquid hydrogen could be used successfully in cooling the thrust chambers (Figure 3).

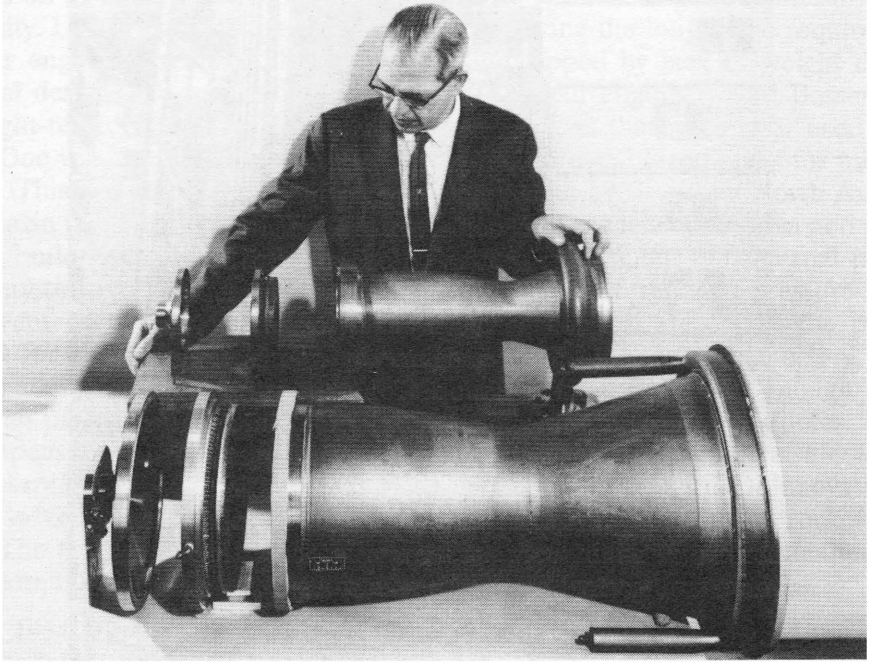

Figure 3 Experimental lightweight hydrogen-cooled thrust chambers at NACA's Lewis Research Center (circa 1957).

The staff at the NACA Lewis laboratory also became enthused over the potential of using liquid hydrogen for high-altitude aircraft. After an analysis of such aircraft possibilities was reported in April 1955, the laboratory, in cooperation with the Air Force, undertook a flight testing program in which one engine of a RB-57 twin engine bomber was modified to run on either its normal jet fuel or on liquid hydrogen. A liquid hydrogen fuel tank was designed and installed on one wing tip, and a heat exchanger for converting the liquid hydrogen to gaseous hydrogen and necessary control systems were installed. The hydrogen was pumped by using pressurized helium in tanks mounted on the opposite wing tip, but liquid hydrogen pumps were also designed and tested successfully. The first test on 23 December 1956 resulted in engine overspeeding and shut-down but no problems were encountered with handling liquid hydrogen (Figure 4). On 13 February 1957, the first of three successful flights was made and the system worked well. On 26 April 1957 a special conference on the successful flight experiments was held with 175 attendees hearing 7 papers by 19 members of the project team. They covered hydrogen consumption, fueling problems, airplane tankage, airplane fuel systems, and the flight experiments. Flight experiments with the liquid hydrogen pump extended into 1959 with three successful flights. These experiments demonstrated the feasibility of using liquid hydrogen in aircraft and, apparently, still remain the only aircraft flight propulsion experiments with liquid hydrogen.*

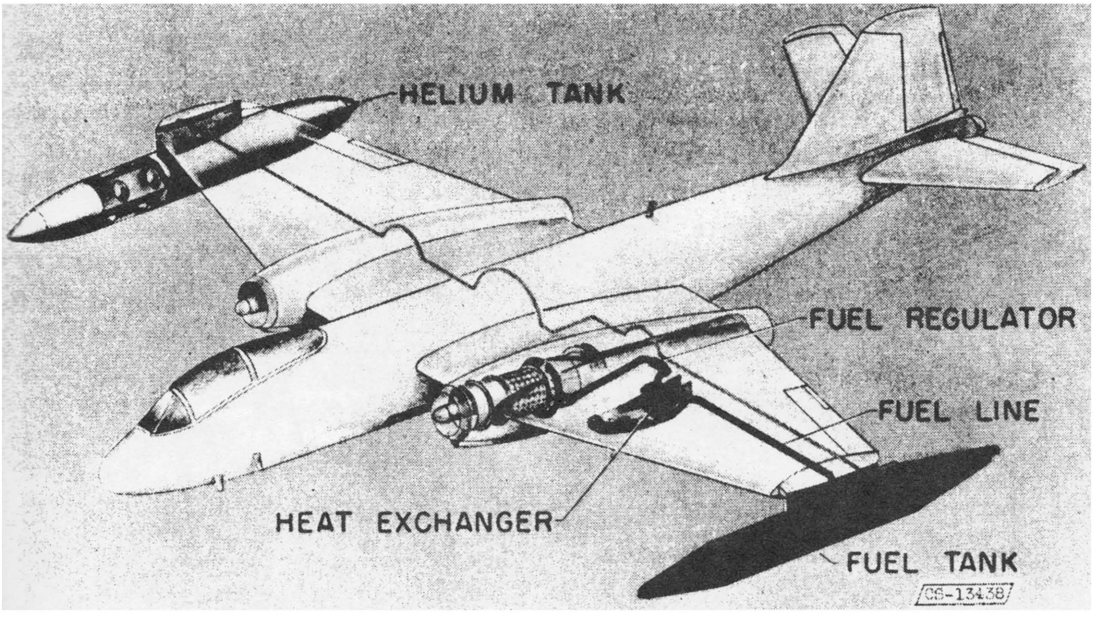

Figure 4 Top (a) Modifications to a RB-57 to use liquid hydrogen-oxygen in one engine (NACA Lewis Research Center, circa 1957).
Bottom (b) The modified RB-57 with liquid hydrogen tank in right pod. The smoke is normal for starting the unmodified engine.

* **Editor's Note**: Project Bee.

While NACA was experimenting with liquid hydrogen for rockets and aircraft in the 1950s, the Air Force was cooperating with NACA, but carrying on their own investigation as well. It started with the need for higher altitude flight in the early 1950s. In July 1953, three design contracts were let. One was to Martin to modify the RB-57 for higher altitude and the other two were to Fairchild and Bell for new high-altitude airplane designs. While these were underway Clarence L. (Kelly) Johnson of Lockheed Aircraft proposed a design for a high-altitude reconnaissance airplane. The Air Force turned Johnson down, but others in the government became interested and Johnson got the go-ahead in November 1954. His airplane, the famed U-2 reconnaissance airplane, became known to the world when Francis Gary Powers was shot down in his U-2 over the U.S.S.R. in May 1960.

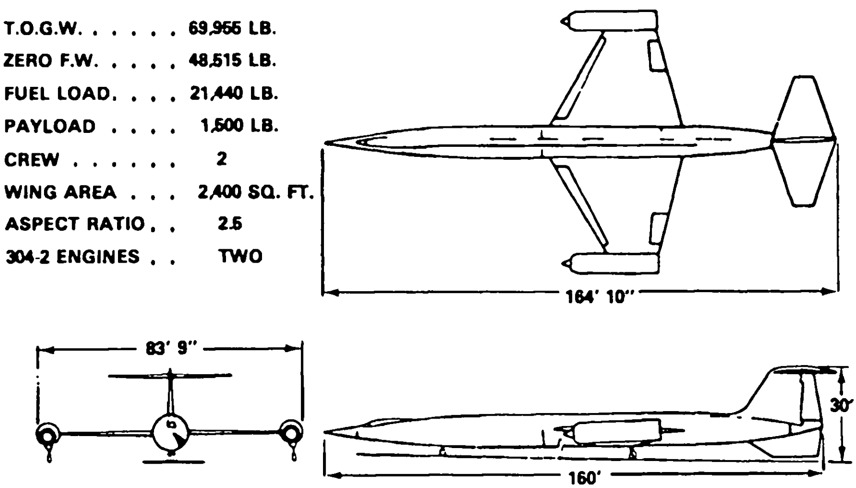

Figure 5 Kelly Johnson's CL-400 aircraft design using liquid hydrogen-oxygen (circa 1956).

In March 1954 a British-born inventor, Randolph Rae, submitted a proposal to the Air Force's Wright Field laboratories for an innovative high-altitude aircraft using a hydrogen-oxygen engine to drive a very large propeller*. The proposal generated interest in the propulsion concept but difficulties in contractual negotiations stalled conceptual work for some time. In the meantime, Kelly Johnson came back to the Air Force in early 1956 with his own proposal for a high-altitude reconnaissance airplane using liquid hydrogen as a fuel as a follow-on of the U-2 and capable of higher altitude and supersonic speeds†. The Air Force bought the concept, designated the CL-400 aircraft (Figure 5), and embarked on a large secret development, part of which involved building the four hydrogen liquefaction plants previously mentioned. Pratt & Whitney Aircraft was selected to build a hydrogen-fueled engine. Designated the Model 304, the P&WA engine was first tested in September 1957. The test period extended for a year with an accumulated time of over 25 hours operation with hydrogen (Figure 6).

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* **Editor's Note:** REX-1.

† **Editor's Note:** Project Suntan.

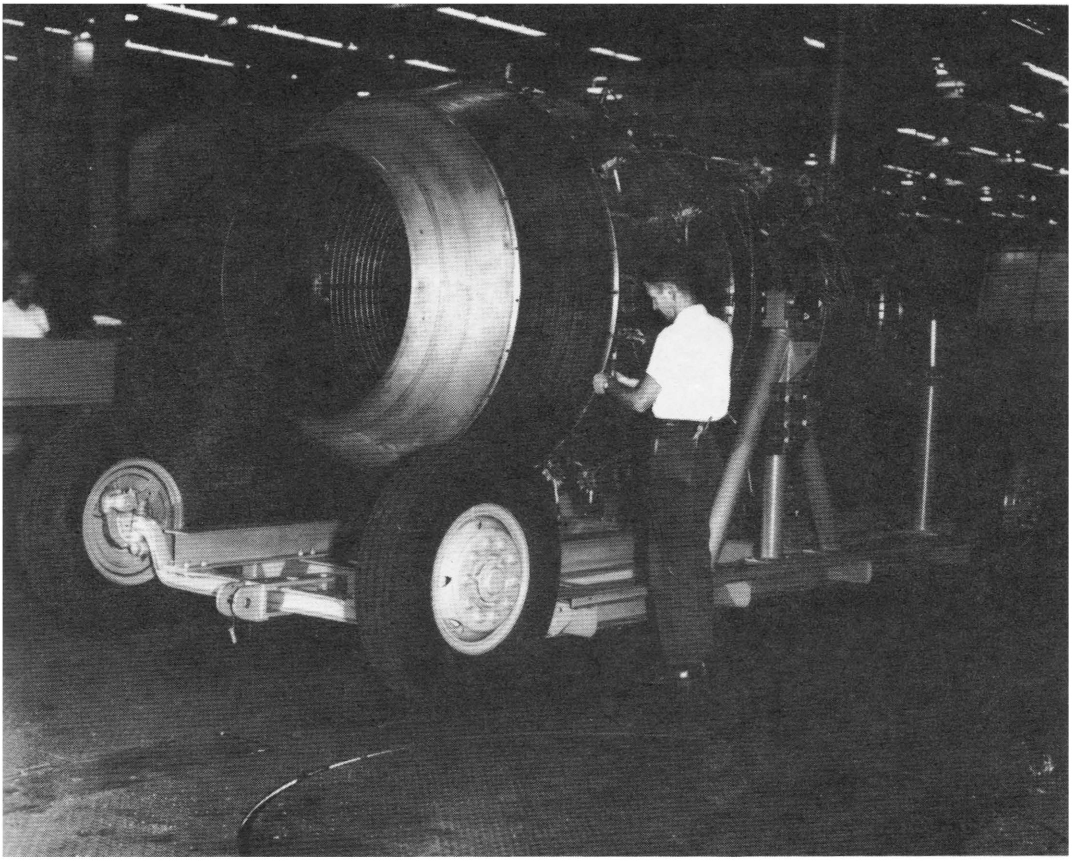

Figure 6 Pratt & Whitney's Model 304 engine using liquid hydrogen (circa 1957).

Johnson conducted tests on tanks and handling systems and satisfied himself that liquid hydrogen could be handled safely. As the work progressed, however, various conflicting views arose over the feasibility of the CL-400 and over whether it was the best way to accomplish reconnaissance. A difference of opinion arose over achievable range. The Air Force wanted a minimum radius to target of 2,800 kilometers but Johnson believed that 2,000 kilometers was about the best that could be achieved. Pratt & Whitney was not optimistic over performance growth potential of its engine. These factors, plus a lack of support by high Air Force officers and a budget squeeze, brought an end to the project in early 1959.

The effort by the Air Force on the hydrogen-fueled aircraft, however, was not in vain. At Air Force urging the Advanced Projects Research Agency approved in August 1958 the start of a hydrogen-oxygen upper stage for the Atlas, called the Centaur. The concept of Krafft Ehricke, Centaur tanks were the same thin wall, pressure-stabilized concept used on the Atlas. The engine development was given to Pratt & Whitney and they used the hydrogen liquefaction facilities adjacent to their Florida test facility to develop the first flight rocket engine to use liquid hydrogen-liquid oxygen, the RL-10 (Figure 7).

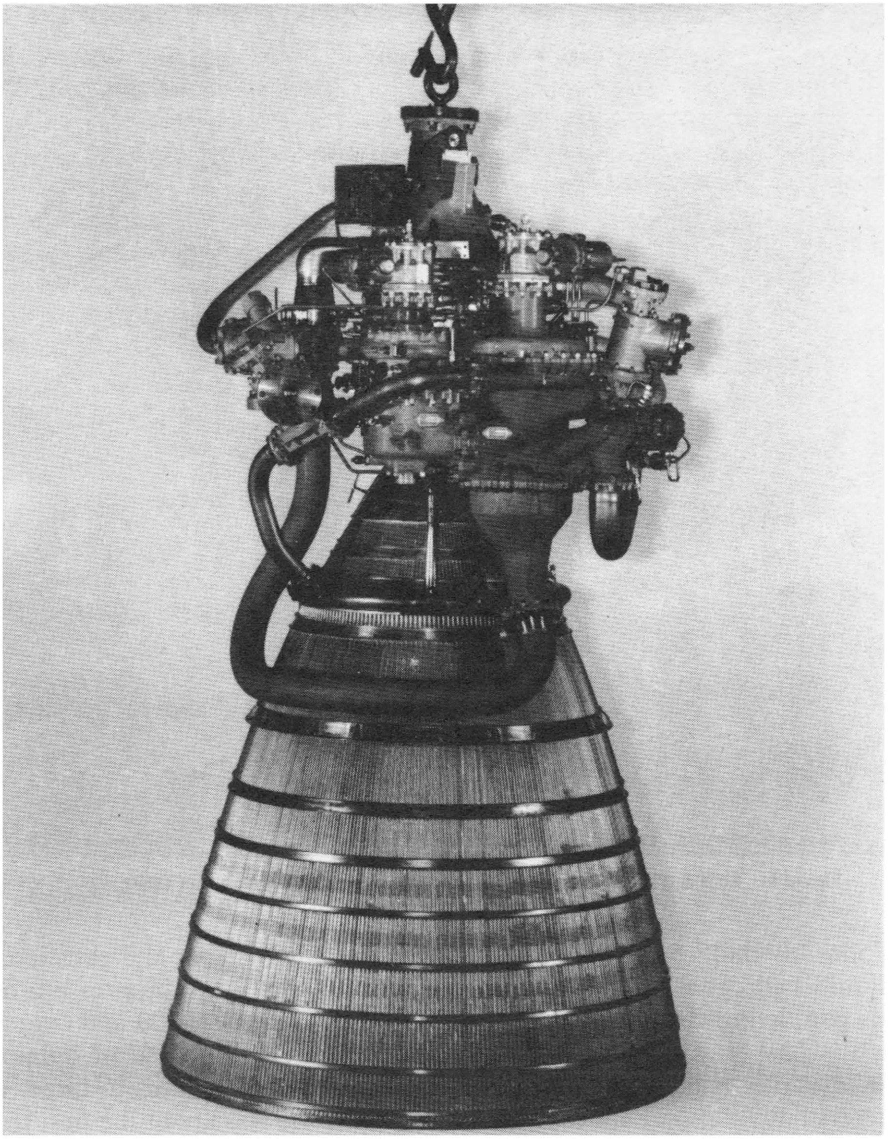

Figure 7 Pratt & Whitney's RL-10 rocket engine, the first liquid hydrogen-oxygen flight engine.

In 1959 a series of events took place in the U.S. regarding the building of large rocket vehicles to extend the capability of the "stable" of boosters based on intercontinental ballistic missiles. The newly designated space agency, NASA, the Air Force, and the Army, all had their favorite design for a large booster to catch up with Soviet booster capability. It was obvious that only one could be built, and a committee of NASA and Department of Defense officials decided in favor of the Army's Saturn for the first stage but left the decision on the upper stages open for a study by a team headed by Abe Silverstein of NASA and including Wernher von Braun, head of the Saturn team, Col. Norman Appold, the project leader for the

CL-400 hydrogen airplane, and others. Von Braun favored using the tried and proven kerosene-oxygen combination for the upper stages, but Silverstein, who was NASA's space flight director and who had led the hydrogen work at the NACA Lewis laboratory previously described, wanted to use liquid hydrogen-liquid oxygen. Silverstein persuaded von Braun and the others to his view which resulted in the decision to use liquid hydrogen-liquid oxygen in all the upper stages of Saturn vehicles[6]. The successful development and use of the Centaur and Saturn vehicles during the 1960s and 1970s is ample evidence of the soundness of the then bold decision to use the high-energy capability of liquid hydrogen-liquid oxygen.

In conclusion, what does the future hold for liquid hydrogen? It is still in use in the highly successful Centaur vehicle which has far exceeded its expected lifetime. It will be used in the space shuttle and is used in the third stage of the European Space Agency's Ariane booster. Many anticipate the use of liquid hydrogen for aircraft and eventually for cars, trucks, and buses. Proposals to generate hydrogen by nuclear or solar energy are also under study. Surely the future holds great promise for expanded use of this versatile fuel.

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