2
Air Force Research on Hydrogen

The origins of Air Force interest in liquid hydrogen as a fuel are obscure, but researchers were well aware of hydrogen from general studies and from occasional external suggestions. One of the latter came to Robert V. Kerley on a warm July day in 1942 and, at the time, made no sense to him. As chief of Wright Field's fuels and oil branch, Kerley was the Air Force's leading expert on aviation fuels and its representative on the fuels and lubricants subcommittee of the National Advisory Committee for Aeronautics (NACA). The subcommittee, under the chairmanship of Professor W.G. Whitman of the Massachusetts Institute of Technology, played a key role at the beginning of the war by coordinating aviation fuel needs and stressing the imperative of increased production.*

Kerley's branch at Wright Field had a long tradition of leadership in improving aviation fuels. Although fuels research can be traced to the establishment of the aeronautical engineering laboratory at McCook Field in 1917, the first systematic fuels research program dates from 1928 when studies were started to determine the relationship between fuel composition, engine performance, and knock. As engine designers sought increased power output per unit volume of engine piston displacement, fuels had to be improved to keep pace. During the 1930s, the fuels and oil branch at Wright Field was the recognized leader in promoting research and production of improved aviation fuels. As a result, the United States was the only one of the Allies at the beginning of the war having a significant capacity for producing high-performance aviation fuel.

Kerley was up to his ears in practical problems of increasing aviation fuel production and operating problems in July 1942 when he was requested to comment on a British suggestion forwarded by the NACA. It was a ten-page proposal by F. Simon to use—of all fuels—liquid hydrogen as a means for increasing aircraft range. Kerley knew that hydrogen produced knock; further, hydrogen liquefaction capacity in the United States was on the order of a few hundred liters per day, and those plants were in scientific laboratories. If the exasperated Kerley considered Simon a nut and his suggestion ridiculous, it would be understandable. Although the suggestion was

*In July 1940, when President Roosevelt announced a goal of 50000 airplanes, the subcommittee estimated that current production of 100-octane aviation fuel must be increased twelvefold but could not convince the military services, who agreed only to a fourfold increase. By war's end, Allied production of 100-octane aviation fuel was 40 times greater than in 1940. Sam D. Heron, "Development of Aviation Fuels," in *Development of Aircraft Engines and Fuels* (Elmsford, NY: Maxwell Reprint, 1970), pp. 631–34.

impractical at the time and indicated Simon's naiveté with respect to fuel production and aviation, he was anything but a nut. F. Simon was Franc Eugen Simon (1893–1956), a thermodynamicist and ingenious experimenter with liquid hydrogen at Oxford University. He had earned his doctorate under the famous Nernst and worked in Germany on low-temperature phenomena until 1933 when, disturbed by rising Nazi power, he accepted an invitation from F.A. Lindemann (Lord Cherwell) to come to Oxford. Simon managed to bring a hydrogen liquefier with him and was instrumental in building an outstanding low-temperature laboratory at Clarendon; in August 1940, he was placed in charge of isotope separation research in Britain's nuclear fission effort.[1]

Kerley immediately recognized the utter impracticability of Simon's suggestion to use liquid hydrogen, but was not so pressed that he could not respond with a bit of humor:

Now F. Simon went a-hunting
  With a lot of gaseous pride
We say his purpose does appear
  To take US for a long sleigh ride

Hydrogen is a knocking fuel
  And is plenty good for heating
But what good is a B T U
  When horsepower goes a-fleeting?

After several more verses, the doggerel ended:

If morals one must always sing
  To Ally Simon we'd sing thus
'Keep working on a simple thing
  And shut off all this goddam fuss!'[2]

Simon, who had an impish sense of humor and laughed at jokes on himself, would have been delighted with the verses, if not the disposal of his suggestion.

Simon was not alone in considering hydrogen for aviation fuel. Much earlier, P. Meyer had written an article entitled "Is There Any Available Source of Heat Energy Lighter than Gasoline?" which the NACA translated as Technical Note 136 in the early 1920s. Meyer noted that hydrogen had a greater heat content than any other known fuel. Apparently considering it only in gaseous form under pressure, he also noted that the containers had to be strong and heavy, which counterbalanced the energy advantage.

Both Meyer and Simon, therefore, found that hydrogen in any form was an aviation fuel whose time had not come. Interest in hydrogen, however, was not lost entirely and surfaced when war pressures eased in late 1944 and 1945 and the men at Wright Field began to think again about future projects. Opie Chenoweth, chief civilian engineer of the power plant laboratory, suggested that research be sponsored on increasing the energy content of aviation fuels.[3] Hydrogen was not a good fuel for piston engines because of the tendency to knock, but what about using it in jet engines? Over at Ohio

State University in nearby Columbus was a professor who had built a cryogenics laboratory during the war and was one of a few experts in liquefying hydrogen and studying its properties. Why not have him study liquid hydrogen for aircraft and rockets? The professor's name was Herrick L. Johnston.

The Cryogenics Laboratory at Ohio State University

Soon after his arrival at Ohio State University in 1929 as an assistant professor of chemistry, Herrick L. Johnston (1898–1965) prepared plans for a cryogenics laboratory to match that of his preceptor, William F. Giauque of the University of California at Berkeley. This was ambitious planning, for Giauque's laboratory and one at the Bureau of Standards in Washington were among the very few in the country capable of research at the temperatures of liquid hydrogen. Giauque and Johnston had just published their revolutionary discovery that atmospheric oxygen contains atoms of mass 17 and 18, as well as 16, a discovery that set into motion a chain of experiments leading to the discovery of heavy hydrogen by Harold C. Urey in 1939 (appendix A-3).

Unfortunately for Johnston, his move to Ohio took him out of the mainstream of the swiftly moving research of low-temperature phenomena, and his dream of a cryogenics laboratory lay dormant a decade for lack of funding. In 1939, Johnston, a full professor and still pushing for his cryogenics laboratory, got a big break. The year before, William McPherson, a former head of the chemistry department, was called out of retirement to be acting president of the university. The first annual alumni development fund drive in 1939 included plans for a cryogenics laboratory and McPherson personally contributed the first $1000. This amount was augmented by $5000 from the university budget and Johnston was quick to start spending it. He ordered a hydrogen compressor and other equipment needed for a liquefier but soon encountered another obstacle—no space for the equipment. This problem was solved when federal funds—part of a plan to involve universities in war research—became available for a building. It was bluntly named the War Research Building. Johnston was initially allocated part of the first floor for a cryogenics laboratory, but later he took over the first two floors.[4]

Construction of the building began about mid-1942, but before the foundation and framework were completed, another crisis threatened to shatter Johnston's dreams for a laboratory. The government had decided to push forward the research necessary to build and test an atomic bomb. Part of the urgently needed research was for more information on hydrogen and deuterium as likely moderators. The university received word that its low-temperature equipment was needed elsewhere for war research, and Johnston was requested to set up and direct a cryogenics laboratory in the East. By some remarkably fast footwork and persuasion, university officials and Johnston managed to get the government to locate the cryogenics laboratory at Ohio State University. By mid-November, Johnston had a research contract.

Johnston worked best under pressure and short deadlines. He quickly recruited a staff including Gwynne A. Wright, an engineer who was to remain with him for 16 years, and Dr. Thor A. Rubin, a research chemist and another pupil of Giauque. Wright was placed in charge of installing the liquefier equipment. Typically, Johnston drove himself and his men hard. During December and most of January they worked

in overcoats, for the building was still under construction and without heat. On 2 February 1943, Johnston and Wright produced their first batch of liquid hydrogen (fig. 1) and Rubin lost no time in making use of it in an experiment.[5]

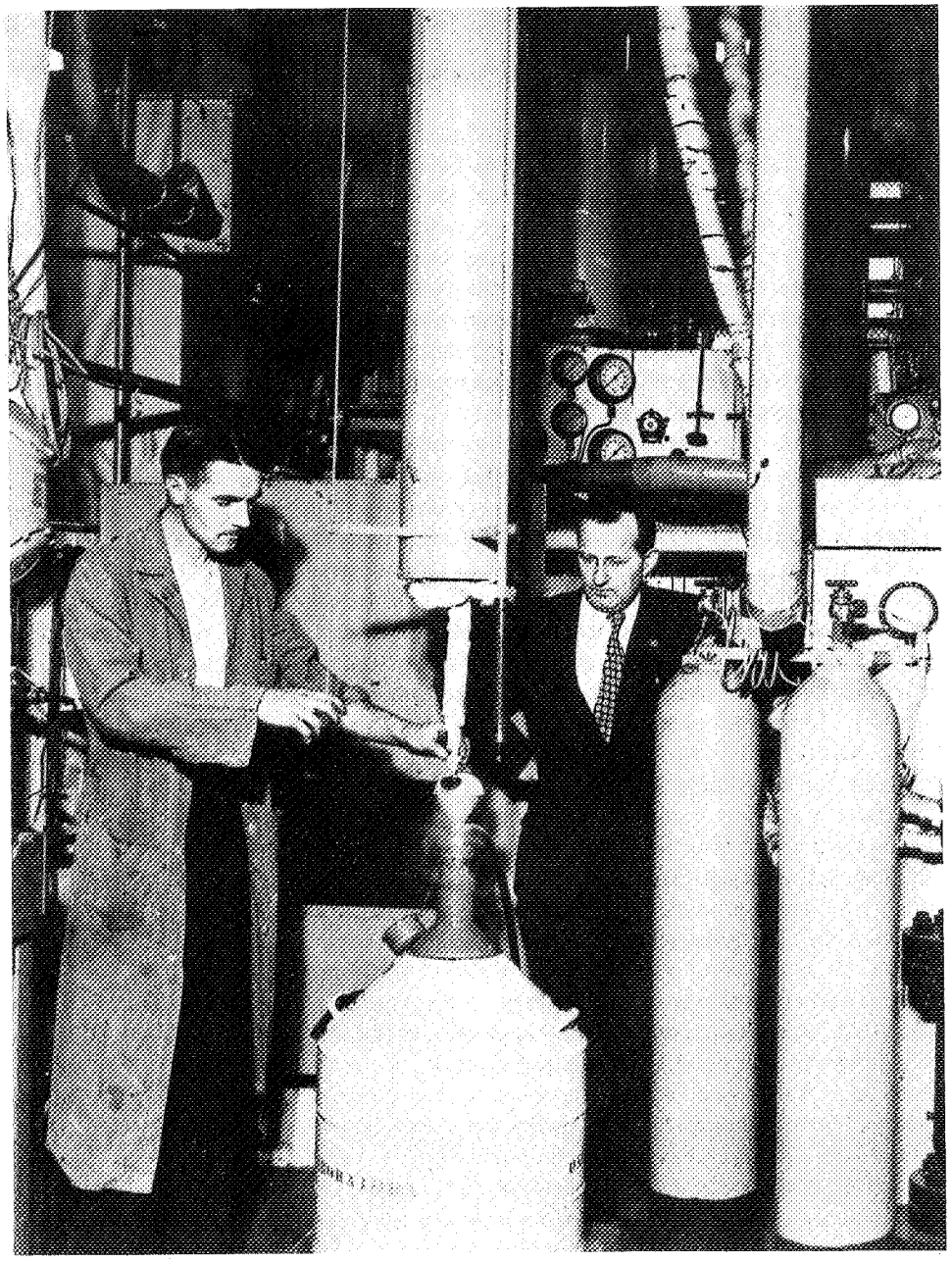


Fig. 1. Gwynne A. Wright, left, operating Professor Herrick L. Johnston's first hydrogen liquefier at Ohio State University, as Johnston observes, ca. 1943. (Courtesy of G. A. Wright.)

By the end of his Manhattan Project research contract in 1946, Johnston had a fine cryogenics laboratory. Included were air, hydrogen, and helium liquefiers and other low-temperature equipment. He organized five sublaboratories—calorimetric, high pressure, spectroscopic, electrical and magnetic, and high temperature. The last, capable of reaching temperatures up to 2700 K, indicates that Johnston viewed a cryogenics laboratory in very broad terms.

The hydrogen system comprised five major components. Gaseous hydrogen was generated by electrolysis of water and the equipment was capable of producing 2 cubic meters per hour. The hydrogen was purified by a series of steps including heating to 570 K to remove oxygen, chilling to remove moisture, and use of a liquid-air trap to remove other condensable impurities. The third component was a three-stage compressor with an output of 1.7 cubic meters per minute at 300 atmospheres pressure. The hydrogen liquefier, a group of heat exchangers, was capable of 25 liters of hydrogen per hour. A large vacuum pump, capable of handling 5 cubic meters at a vacuum of 0.03 atmosphere, comprised the last component.

The hydrogen liquefier was modeled after the one developed by Giauque which was, in turn, a refinement of the basic process of regenerative cooling used by James Dewar in the first liquefaction of hydrogen in 1898. The process consisted of cooling high-pressure gaseous hydrogen as close as possible to the boiling point of liquid hydrogen (20.3 K) and then expanding the gas through a valve. Expansion provided the final cooling needed to liquefy part of the gas. Dewar used boiling liquid air for part of the hydrogen cooling and passed the cold, expanded hydrogen gas through a coil containing the incoming high-pressure gas on its way to the expansion valve. Giauque and Johnston did the same, although they used a total of eight heat exchangers to increase liquefaction efficiency. The liquefier (fig. 2) was diagramed and described by Johnston in 1946.

In steady-state operation, liquid hydrogen was in the left column (fig. 3). This column had four heat exchangers: the three upper ones, A′, B, and F, used escaping cold gaseous hydrogen as a coolant; the bottom heat exchanger, G, was immersed in the liquid hydrogen, which served as a coolant. The right column also had four heat exchangers; the two upper ones, A and C, used escaping cold gaseous nitrogen and oxygen, from liquid air boiling under reduced pressure, as coolants. The two lower heat exchangers, E and D, were immersed in liquid air as coolant. The liquid air was in two containers connected by a float valve, to ensure that the escaping gases were nitrogen-rich. (If the gas were oxygen-rich, it would burn when in contact with the oil of the pump.)

Incoming hydrogen gas at room temperature and a pressure of about 125 atmospheres was split between the two columns and received its first cooling in heat exchangers A and A′. The two hydrogen streams then combined and passed, successively, through heat exchangers B, C, D, E, F, and G, getting progressively colder until (at G) the gas was near the boiling point of liquid hydrogen, 20.3 K. Finally, the high pressure, cold hydrogen gas expanded through valve H and about 20 percent of it liquefied. The rest passed up through the heat exchangers and cooled the incoming high pressure hydrogen as previously mentioned. The liquefier produced about 25 liters per hour.

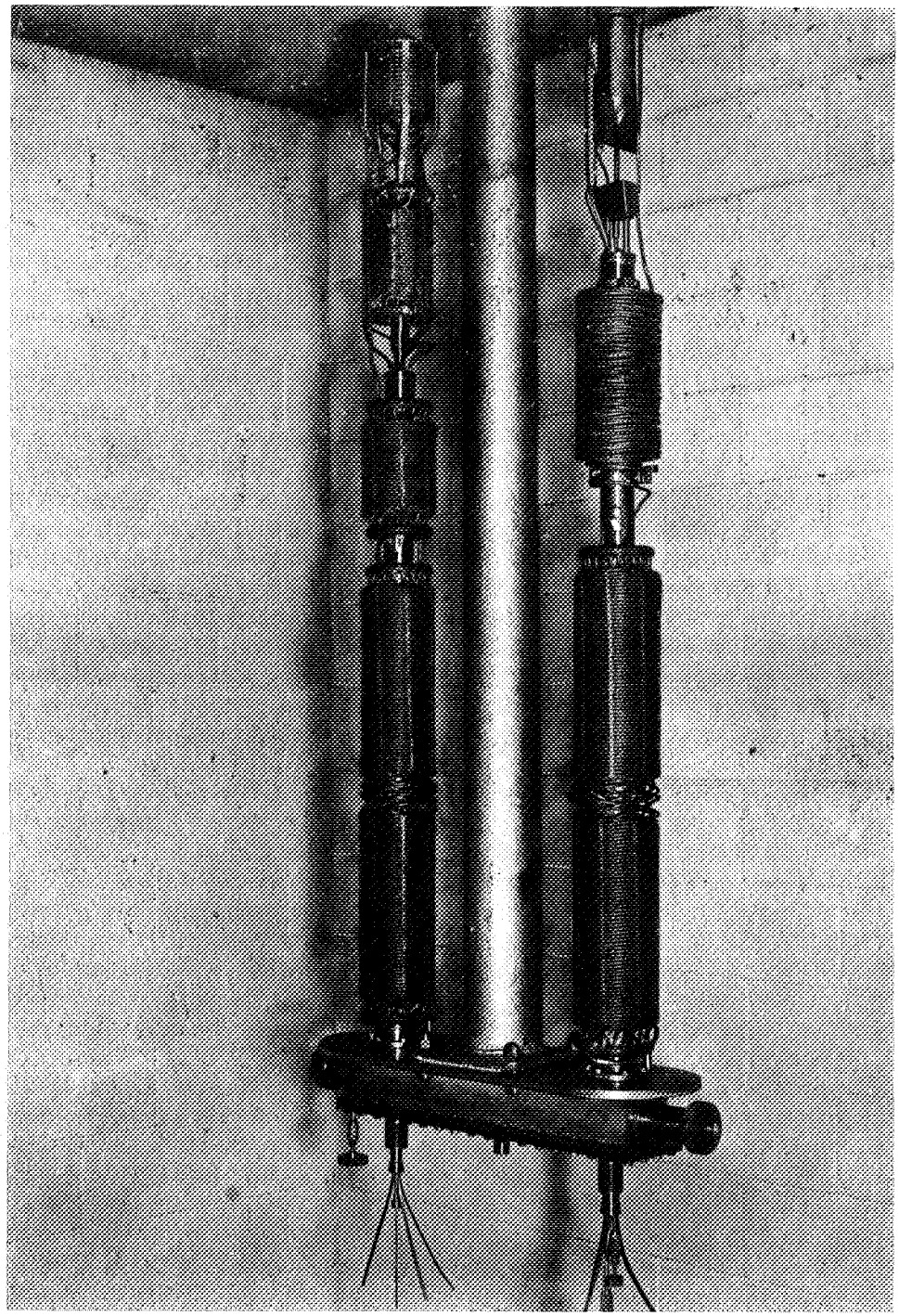


Fig. 2. The several heat exchangers (shell removed) of H. L. Johnston's hydrogen liquefier, ca. 1946. (Courtesy of W. V. Johnston.)

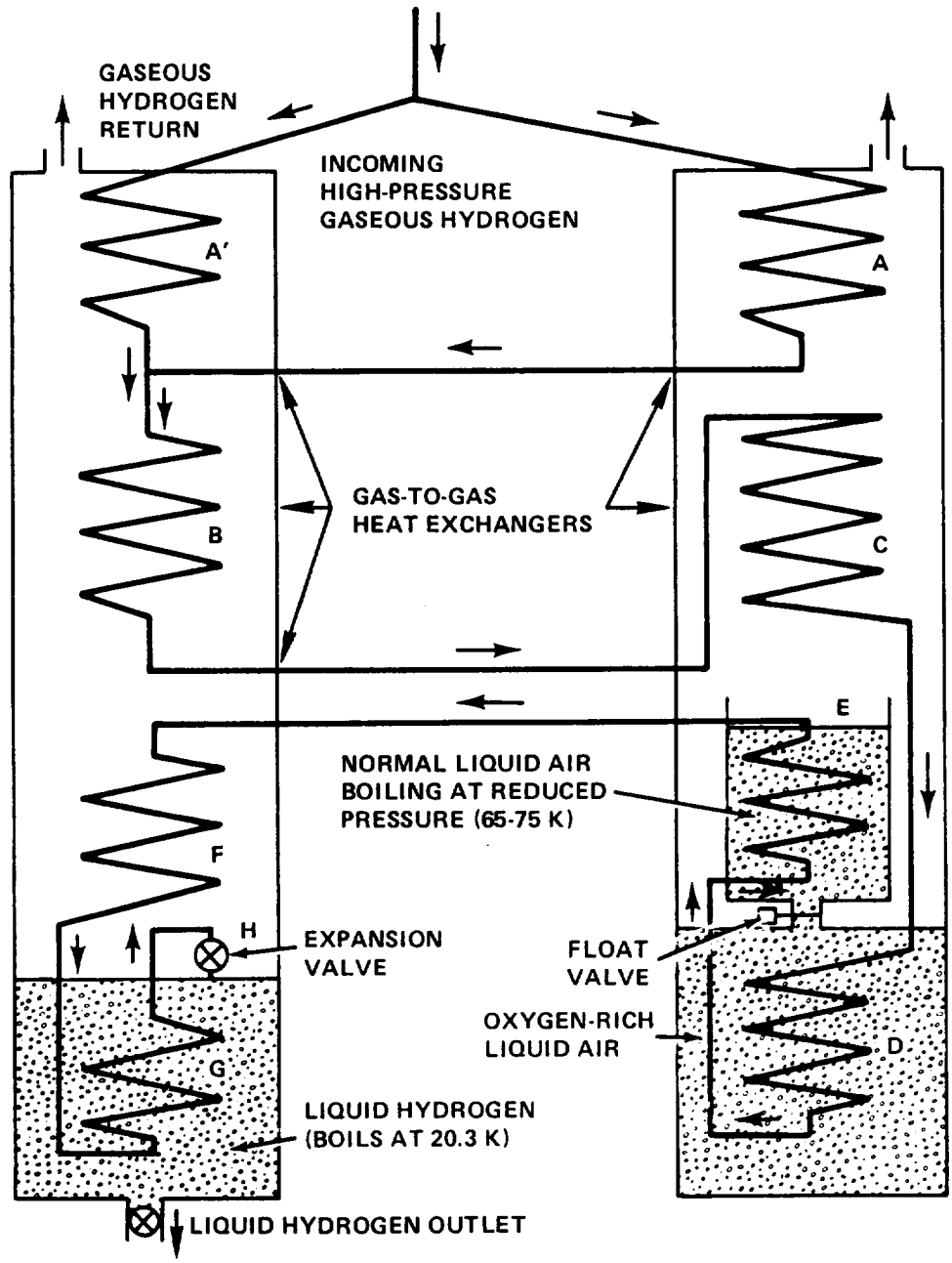


Fig. 3. Diagram of hydrogen liquefier, Cryogenic Laboratory, Ohio State University, 1946. Professor H. L. Johnston modeled this liquefier after one developed by Professor Giauque of the University of California.

Hydrogen for Aircraft and Rockets

By early 1945, the pace of war-needed military research had slackened. The government's laboratory at Los Alamos, New Mexico, was preparing for the first atomic bomb test in July. Johnston needed new support for his cryogenic laboratory and was receptive when the men in charge of fuels research at Wright Field approached him in the spring; agreement was soon reached on a contract, the first on hydrogen for aircraft and rockets in the United States.

Starting on 1 July 1945, the contract covered two major types of investigations. The first was hydrogen as a fuel for aircraft and rockets and was essentially engineering research. The second dealt with measurements of the physical, chemical, and thermochemical properties of hydrogen and the effect of very low temperatures on the properties of metals. This was science, the kind of work Johnston was most familiar with and which provided the research opportunities academicians seek for their graduate students. In 1948, both types of work were continued but under separate contracts. The fuel contract ended in December 1951, but the scientific properties contract continued. The contracts required bimonthly progress reports and annual summaries. In addition, special reports were written and the scientific work appeared in numerous doctoral theses and papers in scientific journals.[6]

The properties research contributed to the propulsion research by providing basic data needed for the theoretical aspects of propulsion research, such as thermochemical calculations of performance at various fuel/oxidant mixtures and combustion pressures, the composition of the exhaust gas and its properties for heat transfer calculations, and the properties of liquid hydrogen as a coolant.

Johnston devoted most of his time to his specialty, low-temperature equipment and properties research. The propulsion work was delegated largely to a group of engineers and technicians assisted by engineering students, all in the charge of a chief engineer. Three chief engineers served during the course of the propulsion work: Marvin L. Stary from early in the contract until 1949; Willard P. Berggren from 1949 to 1950; and William L. Doyle from 1950 to 1951. The rocket work involved, at one time or another, 18 research engineers, 21 students, 13 technicians, 7 administrative personnel, and 3 consultants. Figure 4 is a photograph of the rocket laboratory staff about 1950 and shows a typical mix of skills: 3 engineers, 3 engineering students, and 5 technicians.

Many aspects of the hydrogen work at Ohio State are beyond the scope of our subject, and only the work directly related to propulsion will be described. This is divided into five topics: hydrogen-air experiments, hydrogen-oxygen rocket performance, hydrogen-oxygen rocket cooling, pumping liquid hydrogen, and hydrogen-fluorine rocket performance.

Hydrogen-Air

In the initial days of the contract, the studies of hydrogen as a fuel related to its ignition and burning in air for possible application to jet engines. The work began with 67 tests of gaseous hydrogen injected, ignited, and burned in an air stream. No data were published, but presumably there were no problems. In the next series of experiments, liquid hydrogen was injected in open air ahead of a stream of air from a

small pipe (about 7.5 cm in diameter), and later the liquid hydrogen was injected in the air flowing within the pipe. The liquid hydrogen flow was very small (about 2 grams per second) and when the liquid hydrogen was directed as a straight jet, an icicle—from moisture in the air—formed on the injector and impeded the flow. A splash plate was placed in front of the liquid hydrogen jet to spread it radially into the air stream and this gave better results. Combustion was maintained over a wide range of hydrogen-air mixture ratios.[8]

An unsuccessful attempt was made to use hydrogen in a pulsejet engine, the type of engine used in the German V-1. The inlet of a pulsejet consists of a number of flapper, or one-way, valves. When air enters through these, fuel is injected and the mixture ignited. The rise in pressure from combustion closes the flapper valves and the hot gases flow rearward through the nozzle, producing thrust. When operated on gasoline, the rapid series of explosive bursts was very noisy—as anyone can attest who experienced them popping along overhead in World War II. The Ohio State investigators obtained a tiny pulsejet engine marketed for model airplanes and substituted hydrogen for the fuel. It would not work because the very wide flammability limits of hydrogen resulted in continuous, rather than intermittent, burning. The investigators concluded that the narrow range of flammability of gasoline was responsible for establishing cyclic combustion by flaming out at lean and rich mixtures; it was these characteristics that made the pulsejet work.

Fig. 4. Staff of Ohio State University's rocket laboratory, ca. 1950. First row, L to R: Lester Cox, shop supervisor; Darwin Robinette, student; James Pierce, student; Arthur Brooke, test mechanic; William L. Doyle, chief engineer; Philip Petre, student. Standing: Lawrence Anthony, rocket shop supervisor; Ross Justus, machinist; Harold Smeck, engineer; James Sweet, test mechanic; William Strauss, engineer; unidentified. (Courtesy of Arthur Brooke.)

In the latter part of 1948, large-scale equipment was built to investigate hydrogen as a fuel for ramjets. A few tests were made, but were discontinued when the facilities were needed to test a liquid-hydrogen pump.

To sum up the hydrogen-air burning experiments, they were qualitative observations and verified only what was already well known—hydrogen burns in air over a wide range of conditions. The nature of the experiments and their cessation in favor of another project indicated a lack of interest in hydrogen as a fuel for air-breathing engines.

Other hydrogen-air experiments were made to assess the hazards of handling hydrogen. Tests of hydrogen-air explosions were made using a liter of liquid hydrogen in an open-mouth dewar. Ignition of the evaporating hydrogen resulted in a quiet flame, whereas hydrogen containing 10 percent solid air exploded with violence. Johnston was well aware of these characteristics as the following incident, part of the legend about him, illustrates.

Johnston supplied liquid hydrogen not only for his own experiments but also for the low-temperature experiments of other groups on the campus. One day a fire broke out at the top of a liquid hydrogen dewar of about 25 liters capacity being used for some materials testing. The fire department was called and the dewar was hurriedly rolled out into a parking lot. The firemen and a crowd were standing in a circle about the dewar, obviously puzzled about what to do next, when a passing car suddenly stopped in the middle of the street and a man got out. He pushed through the crowd, approached the dewar, pulled out his handkerchief and used it to snuff out the flame. He returned to his car and departed without having said a word. None in the crowd recognized Professor Johnston.[8]

Hydrogen-Oxygen Rocket

Experiments with hydrogen and oxygen in a rocket began at Ohio State University on 2 April 1947 and ended 29 May 1950. Similar tests were also underway at Aerojet General Corporation in California from 1945 to 1949 and at the Jet Propulsion Laboratory of the California Institute of Technology from 1948 to 1949, which will be described in the next chapter.

At Ohio State, the first twelve tests were made with liquid hydrogen and gaseous oxygen, because the installation of a liquid-oxygen tank at the test cell had been delayed. On 13 June 1947, Stary and his staff made the first rocket engine test in the United States using liquid hydrogen and liquid oxygen. The engine produced 471 newtons (106 lb of thrust) at a chamber pressure of 21.1 atmospheres with an oxygen-to-hydrogen mass ratio of 4.2. Exhaust velocity was 2405 meters per second, or 82 percent of the theoretical performance for that ratio (according to the theoretical performance given in the Lemmon report). Following this, an additional 118 runs were made with the same engine, and beginning in September 1948, 38 runs were made with an engine five times larger. One of the most significant accomplishments was a series of 37 runs at the smaller thrust using an engine regeneratively cooled with liquid hydrogen, starting of 26 August 1949. These will be discussed later.

An early problem for all rocket experimenters was satisfactory instrumentation to measure thrust, mass flow rates of fuel and oxidizer, and combustion pressure. From

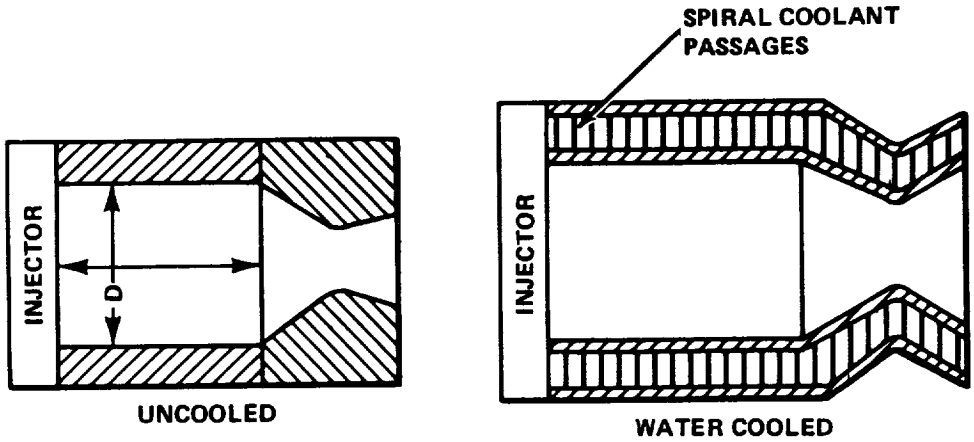
these the exhaust velocity at a given mixture ratio can be obtained and compared with theoretical calculations.* Of these measurements, the mass flow rate of liquid hydrogen was of most concern. It was determined by measuring the pressure differential across a sharp-edged orifice—a time-honored method of measuring flow rates. The accuracy depends upon the density of the fluid being measured; for liquid hydrogen, the large density changes with temperature are lessened at the high pressures used in rocket experiments. Measurements of hydrogen properties by Johnston, David White, and others were going on in parallel with the rocket work. Using Ohio State's temperature-density data, Johnston and Doyle reported that if the temperature of liquid hydrogen in a tank increased from its normal boiling point to the critical point at 25 atmospheres, the flow measurement would be approximately 10 percent too high. For this reason and because improvements in measurements were made as the tests progressed, strict comparisons of the various runs were not made, but qualitative comparisons were made to show trends.

The major design element affecting high performance is the propellant injector. Stary came to Ohio State from Aerojet General Corporation where impinging jet injectors had been successfully used with other propellants. In this type of injector, streams of propellant are directed so as to impinge on each other to break up the liquid stream into fine droplets and mix the fuel and oxidizer (fig. 5). This was the prevailing design philosophy of the period, and it is not surprising that major emphasis was placed on this type of injector for hydrogen-oxygen at Ohio State. In fact, 18 out of 20 injectors at Ohio State used impinging jets for at least one, and usually both, propellants. The two exceptions, a concentric tube and a "showerhead," were not tested. Ironically, these were later found by the Aerojet team and other investigators to be best for liquid hydrogen.

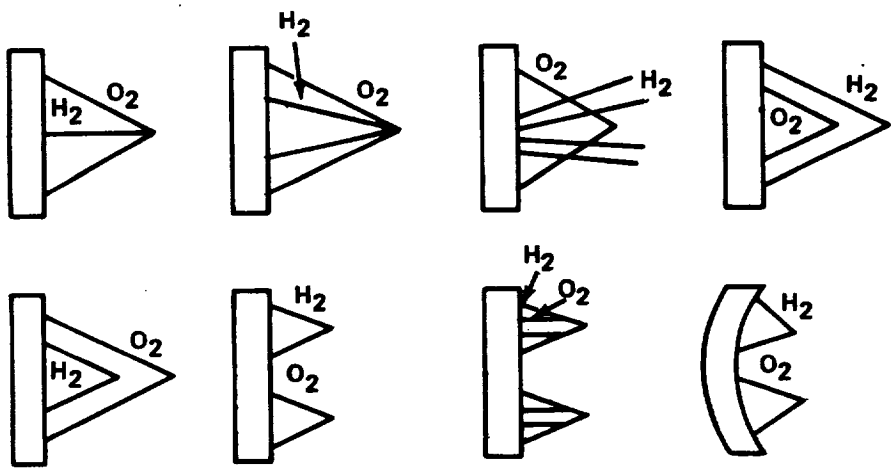
Rocket-Engine Cooling

In rocket experiments, the measurement of the heat flowing from the combustion gases to the engine walls and the use of this information to devise satisfactory cooling of the engine are second only to obtaining maximum performance. Without cooling, a flight-weight rocket engine would be heated to its melting point in a second or two. Major factors affecting this heat transfer are gas temperature, density, and velocity; all three of these are much higher in rocket engines than in other internal combustion engines. These factors, plus gas composition, are functions of the propellants, engine design, and operating conditions. The particular fuel and oxidizer, the proportions used, combustion pressure, and combustion efficiency determine gas composition, temperature, and density. Injector design, propellant proportions, mass flow, and combustion chamber design affect gas velocity. The rocket engineer seeks a design giving both high performance and a cooling method for steady-state operation. He is aided by combustion characteristics, for peak performance usually occurs at a fuel-rich mixture where the heat transfer is lower than at a leaner mixture.

*Rocket experiments used specific impulse (thrust divided by total propellant flow rate) for determining performance, which is equivalent to exhaust velocity used in this text (appendix B).



	445 N	2.2 kN
D, cm	4.4	8.7
L, cm	6.4	17 (UNCOOLED)
		10.3(COOLED)



VARIOUS HYDROGEN-OXYGEN IMPINGING-JET INJECTORS

Fig. 5. Experimental rocket engines using hydrogen-oxygen, Ohio State University, 1947–1950.

Heat transfer measurements at Ohio State used two techniques common in rocket experiments. In the "heat-sink" method, the combustion chamber and nozzle are made from a high-conductivity material, usually copper, in which a thermocouple to measure temperature is buried in the thick, uncooled wall. During rocket operation, the high thermal conductivity of the copper keeps the inside wall from melting as the heat rapidly flows into the interior of the mass. This allows a rocket to operate for a few seconds, and sometimes as long as 30 seconds. After the run, the temperature of the copper mass comes to equilibrium and by measuring this temperature, the total amount of heat absorbed can be calculated from the known mass and specific heat of the copper. In the second method, a water jacket surrounds comparatively thin engine walls and a high-velocity water flow keeps the walls cool. The average heat transfer can be obtained by measuring the water flow and its temperature rise. Using these methods, Ohio State measured average heat transfer rates of about 1.6 joules per second per square meter (1 Btu/sec-sq in) for the combustion chamber and about twice that for the nozzle. These values were on the same order as found in high-performance rocket engines using other propellants, but are several times higher than heat transfer rates in other types of internal combustion engines and are, for example, from 20 to 200 times higher than in steam plants.

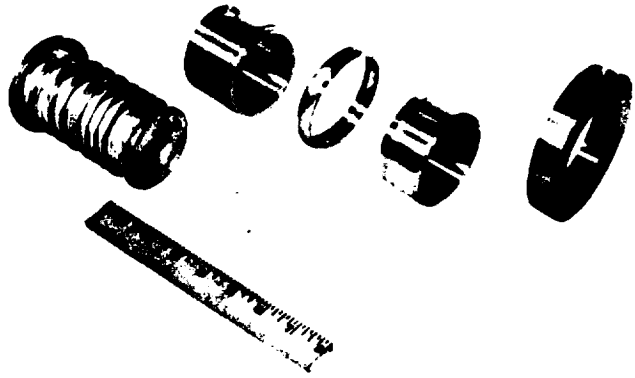
In mid-1948 a mechanical engineer from Aerojet, Irwin J. Weisenberg, joined the Ohio State rocket staff under Stary and specialized in heat transfer and cooling experiments. The first attempt to use hydrogen as a coolant was to employ a porous combustion chamber wall and force hydrogen through the wall into the combustion chamber.[10] This type of cooling, called transpiration or "sweat" cooling, was popular at the time and work with it was under way at several other rocket laboratories.

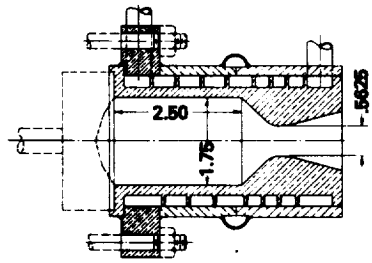
In the first part of 1949, another engineer at the Ohio State rocket laboratory, Clair M. Beighley, made a theoretical analysis in which a temperature ratio involving combustion gas temperature, wall temperature, and coolant temperature was related to dimensionless flow parameters. A porous combustion chamber was tested later and the experimental data agreed with the theoretical predictions. Porous wall chambers with uniform permeability were difficult to make, however, and the Ohio State rocket engineers turned to regenerative cooling when an analysis showed it to be feasible. In this method, hydrogen is circulated in coolant passages surrounding the engine prior to injection and burning.

In the midst of preparations to try it experimentally (in June 1949) Stary returned to Aerojet and still another Aerojet engineer, Dr. Willard P. Berggren, arrived at Ohio State as the new chief engineer for rocket experiments.[11]

The experimental thrust chamber for regenerative cooling was designed to produce 445 newtons at a chamber pressure of 20.4 atmospheres (fig. 6). Liquid hydrogen in the coolant jacket would be well above this value and hence far above its critical pressure of 12.8 atmospheres so that no boiling could occur in the coolant passages. The first successful regenerative cooling run was on 26 August 1949, when the thrust chamber operated for 60 seconds at an oxygen-to-hydrogen mass ratio of 4.1 and produced an exhaust velocity of 3190 meters per second—about 93 percent of theoretical performance.

In all, 33 successful runs were made, over half of which operated for 60 or more seconds; one operated for 159 seconds. The runs covered a range of mixture ratios and





100 LB. THRUST REGENERATIVE MOTOR

Fig. 6. Rocket thrust chamber of 445 newtons designed to use liquid hydrogen-oxygen and be regeneratively cooled by the liquid hydrogen. Ohio State University, 1949. Scale and dimensions are inches. (Courtesy of I. J. Weisenberg.)

the maximum exhaust velocity for the series was 3270 meters per second.* In general, performance with the regeneratively-cooled engine was considerably higher than that obtained with the water-cooled chambers. The experimenters attributed this not only to the elimination of heat losses, but also to a lower-density hydrogen entering the combustion chamber, which produced improved mixing and higher combustion efficiency. Figure 7 shows the regeneratively-cooled rocket operating in December 1949 during the series of tests. The frost on the chamber indicates that it was well cooled.[12]

*The highest performance run lasted 90 seconds at a fuel-rich mixture (O/F,4.7), 21 atm, and a relatively low overall heat transfer rate of 2.1 $J/s \cdot m^2$. In contrast, the longest run (159 sec.) was at the stoichiometric mixture (O/F,8), 19.6 atm, much lower exhaust velocity (2800 m/s), but almost triple the overall heat transfer rate (5.2 $J/s \cdot m^2$). The comparison illustrates that peak performance does not come at the same operating conditions as maximum heat transfer. It also shows that hydrogen cooling handled the higher heat load.

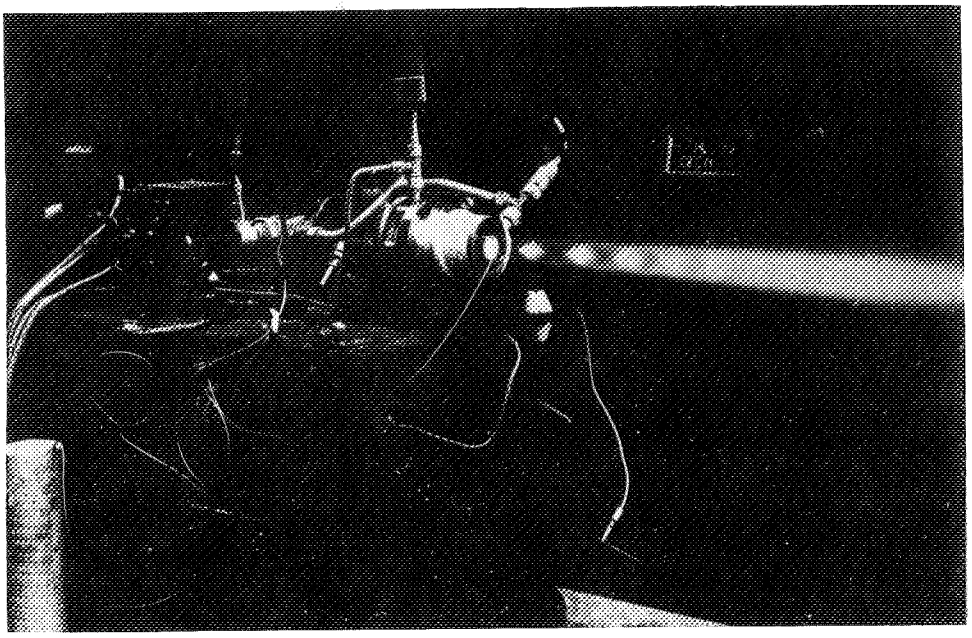


Fig. 7. Liquid hydrogen–oxygen rocket engine regeneratively cooled by the hydrogen, Ohio State University, December 1949. Note the frost on the outside of the rocket chamber and the shock diamonds in the exhaust. (Courtesy of I.J. Weisenberg.)

Pumping Liquid Hydrogen

By 1947, the scope of rocket research at Ohio State had broadened to study pumping of liquid hydrogen, which was carried out by Leroy F. Florant with the assistance of another engineer, Harold F. Snider. They were aware of the German development of a pump for liquid oxygen and of parallel work on liquid hydrogen at Aerojet General beginning in 1948, but their research was the most comprehensive analytical and experimental investigation of liquid hydrogen pumping of the period. They built two facilities—one for using fluids normally liquid at room temperature and the other for low-temperature fluids. They used water and isopentane in the first and liquid nitrogen and liquid hydrogen in the second. In the low-temperature facility the tanks, lines, and valves were vacuum jacketed for insulation. After initial troubleshooting, the system worked well, although there were high liquid hydrogen losses from the conversion of orthohydrogen to parahydrogen (pp. 266–67).

Florant and Snider designed, built, and tested two types of centrifugal liquid hydrogen pumps. They also investigated bearings and seals at speeds up to 10000 RPM. They concluded that centrifugal pumps were a desirable and practical way of pumping liquid hydrogen for rocket engines. They found that water was a satisfactory test fluid for determining and verifying pump design parameters for liquid hydrogen pumps. This facilitated testing and greatly reduced its cost.[13]

One of the most significant results the two investigators obtained was that properly mounted, precision ball bearings would operate satisfactorily in liquid hydrogen at

speeds up to 10000 RPM. The bearings were cooled by the liquid hydrogen and required no lubrication. This useful information was to be rediscovered by Richard Mulready of Pratt & Whitney in 1958 in developing the first flight-model liquid hydrogen–oxygen rocket engine.

Hydrogen and Fluorine

Early in 1949 William L. Doyle, a chemist engaged in rocket propellant research at North American Aviation, made a deal with Herrick Johnston. Doyle would come to work at the Ohio State University Rocket Laboratory if given a free hand to investigate the performance of liquid hydrogen with his favorite oxidizer, liquid fluorine.*

In February 1949, Doyle reported for duty at the Ohio State laboratory. He did not like the experimental equipment, the operations, or the procedures, so he began to make changes.

William Doyle was a dynamic young man who knew what he wanted and just how to do it. The antithesis of the desk-bound supervisor and paper shuffler, he liked to be part of the action. He found his right environment at Ohio State where a senior engineer was responsible for his entire project—from inception, through design, fabrication, installation, operation, data analysis, and writing up the results. Doyle found this situation ideal and he made the most ot it.

Doyle's interest in the hydrogen-fluorine combination was natural. It represented the combination of the ultimate fuel and the ultimate oxidizer, with a higher theoretical performance than hydrogen and oxygen. In addition, the mixture of 6 percent hydrogen and 94 percent fluorine by weight not only resulted in near-maximum performance, but also meant higher average propellant density for the combination. Doyle visited the men in the fuels and oil branch at Wright Field and convinced them to modify the Ohio State contract to include the work he wanted to do.

One of Ohio State's rocket test facilities was rebuilt to handle liquid hydrogen and liquid fluorine. The hydrogen flow system was encased in a vacuum jacket for insulation. A series of problems with maintaining the vacuum were solved. The flow of liquid hydrogen was measured by a dual system: the conventional way of measuring the pressure differential across a sharp-edged orifice as well as continuous measurement of the hydrogen tank mass. Once the hydrogen system was functioning, it gave little more trouble, but many problems were encountered in the fluorine system. The fluorine gas, procured commercially as a compressed gas, was condensed in the

*Doyle had become interested in fluorine at North American Aviation when he was assigned to take over an experimental rocket project. Doyle redesigned the equipment and the test rig to his own liking and proceeded to investigate the burning of hydrazine and fluorine. On 8 Nov. 1947, Doyle successfully operated the first rocket to use fluorine, the most powerful of all stable oxidizers. He found that fluorine quickly decomposed Teflon, at the time the favorite "inert" material for gaskets and sealants in rocket experiments. Fluorine will also combine with moisture and impurities and once a reaction starts, the heat generated makes it quick to attack and burn metals. It is also highly toxic, and Doyle's parking-lot operation became a matter of some concern by the time he was ready to head for Ohio. Interview with William L. Doyle, Redondo Beach, CA, 26 Apr. 1974.

propellant tank by immersing it in a liquid air bath. Liquid fluorine flow was measured by the same methods used for hydrogen.

Doyle made his first liquid hydrogen–liquid fluorine run on 15 June 1950. He first operated the injector alone to see if the hydrogen and fluorine would ignite readily and spontaneously, which they did. He followed this experiment with rocket engine tests. By the first part of August, nine runs had been made and Doyle felt confident enough to invite his sponsors from Wright Field to witness a test. Judging from the mishaps reported for the first eight runs, Doyle was displaying a considerable amount of confidence. Don Kennedy arrived in response to the invitation and witnessed the tenth test on 11 August 1950. The run was perfect in Doyle's view, with a measured exhaust velocity of about 3600 meters per second at 20 atmospheres. Kennedy was greatly impressed and reported the results to his boss, Weldon Worth. Doyle continued the experiments and in mid-January 1951, Kennedy informed him that a group of high officials at Wright Field would visit Ohio State to witness a run with hydrogen-fluorine. Soon after the call, Doyle made a run at a high pressure (38 atmospheres) and measured an exhaust velocity of over 4300 meters per second. On 29 January, 14 people from Wright Field's Power Plant Laboratory arrived in terrible weather—a sheet of ice compounded by mist and drizzle. Icing difficulties delayed the run for an hour, but it was a success, lasting over a minute. Performance, however, was lower than obtained in earlier runs.[14]

One measurement necessary to determine performance—fluorine flow—had bothered Doyle from the start. Whereas the two flow measurements for liquid hydrogen checked with each other, the fluorine flow as measured by the orifice was lower than that measured by weighing the propellant tank. The difference was consistent—about 18 percent lower for the orifice. Five design changes were made to improve the orifice measurement, but the discrepancy remained.

Doyle was not the only experimenter having difficulty measuring the flow rate of liquid fluorine. Aerojet was having the same difficulty and investigators there began to suspect that the density of fluorine might somehow be wrong. This was heresy, for a number of eminent scientists had measured the density of fluorine and they all agreed. James Dewar and Henri Moissan had first measured it in 1897 and found it to be close to 1.14 grams per cubic centimeter at 83 K. The value in use in the 1950s was 1.13 grams per cubic centimeter at 77 K, determined by E. Kanda in 1937.

Near the end of April 1951, Kennedy telephoned Doyle that Aerojet, using a hydrometer, found that the density of liquid fluorine was 1.55 grams per cubic centimeter, considerably higher than the published value. Doyle used the Aerojet value with his orifice measurements and found that the 18 percent discrepancy with the weighing measurement disappeared! The greater density of liquid fluorine was an exciting discovery to rocket engineers, for it meant the oxidizer was even more attractive than first realized.*

*The specific gravity of liquid fluorine, 1.54 at 77 K, reported by Kilner, Randolph, and Gillispie (*J. Am. Chem. Soc.* 74:1086) in 1952 was verified by Elverum and Doescher the same year (*J. Chem. Physics* 20:1834). See also National Bureau of Standards Technical Note 392, rev., 1973. Some contributors to chemical handbooks were slow in noting the change.

Doyle made his 48th and last hydrogen-fluorine run in mid-April 1951 and turned his attention to the ammonia-fluorine combination. This ended the Ohio State rocket experiments with liquid hydrogen, although the properties work continued, as well as some small-scale combustion research of a fundamental nature.

Significance

The first experimental investigation of liquid hydrogen as a fuel for aircraft and rockets was started in 1945 by the research arm of the Air Force, as part of a long tradition of searching for new and improved fuels. Hydrogen, the ultimate fuel in energy content, needed to be investigated for its potential application in air-breathing and rocket engines. The availability of hydrogen liquefaction equipment and the experts at Ohio State University provided the catalyst for starting the experimental investigation.

The Ohio State research on hydrogen for air-breathing engines never progressed beyond a few exploratory experiments. These showed that hydrogen burned readily over a wide range of conditions—a result that could have been predicted from earlier work. That more was not done with hydrogen for air-breathing engines could have come from one or more of the following: (1) hydrogen's low density, long its outstanding disadvantage for aircraft applications, as pointed out by Tsiolkovskiy in 1930; (2) rising interest in boron compounds as high-energy fuels for ramjets, as sponsored by the Navy; (3) greater interest in rocket applications by Wright Field; and (4) lack of equipment needed for research on air-breathing engines.

Ohio State University investigators focused their engine research on rocket engines and made many contributions to liquid hydrogen technology. The high performance potential of liquid hydrogen–liquid oxygen was verified, and it was also found that liquid hydrogen was a satisfactory regenerative coolant. Research established that centrifugal pumps were capable of pumping liquid hydrogen to the high pressures needed for rocket engines. It was also found that ball bearings for pumps would operate satisfactorily when immersed in liquid hydrogen without the usual oil lubrication, showing that design of practical pumps was feasible. Pump tests with water produced data that were valid in predicting performance with liquid hydrogen—a decided convenience in determining several design parameters. Finally, it was shown that the performance of liquid hydrogen–liquid fluorine was higher than for liquid hydrogen–liquid oxygen, and density was higher also.

With such significant results with liquid hydrogen, then, why did Air Force interest in sponsoring further research begin to wane in the late 1940s? Several possible reasons come to mind, one being the shift in Air Force interest from rockets to air-breathing propulsion in the late 1940s. Another possibility is that the Air Force managers may have felt the exploratory research had fulfilled all of its objectives and without an application, there was no need for further work. There is, also, the ever-present possibility that the sum of all of hydrogen's disadvantages—formidable for military applications—may have overwhelmed Wright Field's attraction to the high energy of hydrogen in the same manner experienced earlier by both Tsiolkovskiy and Goddard.

The scientific and technological progress made at Ohio State with liquid hydrogen served as the foundation for contributions by other groups. Running parallel to Air

Force interest in hydrogen as a fuel was Navy interest, which also faded by the end of the 1940s. Unlike the Air Force, however, the Navy had a specific application in mind and its efforts to secure approval to develop a hydrogen-oxygen rocket will be discussed next.