N77-33060

THE U.S. ARMY AIR CORPS JET PROPULSION RESEARCH PROJECT, GALCIT PROJECT No. 1, 1939-1946: A MEMOIR[+]

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I. INTRODUCTION

This memoir is a sequel to the one I wrote on the GALCIT (Guggenheim Aeronautical Laboratory, California Institute of Technology) Rocket Research Project 1936-38, for the First International Symposium on the History of Astronautics, organized by the International Academy of Astronautics at Belgrade on 25-26 September, 1967.[1] As I pointed out then, I fully recognize the fallibility of memory and the unavoidable injection of personal evaluations and judgements.

Whereas few written records for the period 1936-38 of rocket research at the California Institute of Technology (Caltech) remain, during the period 1939-46, numerous formal reports were prepared under contracts to agencies of the U.S. government, and are available to anyone interested. On the other hand, during the latter period our research work became secret, so that there are not many personal records of an intimate kind to turn to for aspects of developments that frequently are more interesting than cold, formal reports. It is a misfortune that minutes of the weekly research conferences held between 1939 and April 1944 are no longer to be found in the archives of the Jet Propulsion Laboratory (JPL).[+++] Secret classification of research also prohibited the free publication of results between 1940 and 1946. For this reason, some of these results are still not as well known as the more highly publicized activities of other groups during this period in the USA and in other countries, especially in Nazi Germany. This situation was aggravated

[+]Presented at Third History Symposium of the International Academy of Astronautics, Mar del Plata, Argentina, October 1969.

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[+++]Although the designation JPL was used for the first time in 1944, the work of JPL is considered to include rocket research at Caltech initiated by the Galcit Rocket Research Group from 1936 onwards.

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by the fact that several key persons who led the research at JPL dispersed after the end of the Second World War. Summaries of various aspects of this work, some published, can be found in References 2 to 10.

In September 1939, Nazi Germany invaded Poland and World War II began. This had a direct impact upon the rocket research plans of the GALCIT Rocket Research Group. Work toward our dreams of designing rockets for scientific research at high altitudes and for space flight had to be deferred for several years. We had anticipated the outbreak of war in Europe some time before it began, and our thoughts turned towards the use of rocket propulsion as an auxiliary to the propeller-piston engine power plants then in general use for aircraft. We had been authoritatively told by a senior officer of the U.S. Army Ordnance Department that there was little possibility of applying rocket propulsion in military missiles.[4]

Inter-service rivalry over rockets would appear several years later. As late as 1944, the Army Air Corps, by then called the Army Air Forces, readily allowed the Jet Propulsion Laboratory to undertake America's first research program on long range rocket missiles for the Army Ordnance Department. At the time, Army Air Forces foresaw little possibility of such missiles replacing many functions of bomber aircraft in warfare. It is surprising that Allied military intelligence had no inkling of the advanced state of military rocket development in Germany until 1943.

When General Henry H. Arnold, Chief of the Army Air Corps, visited Caltech[8, 9] in May 1938, Theodore von Kármán (1881-1963) (Figure 1) first learned that interest was developing in the use of rocket propulsion for military aircraft. I prepared a report in August for the Consolidated Aircraft Company (now called General Dynamics/Convair) at San Diego, California, on the possibility of using rocket propulsion for assisting the take-off of large aircraft, especially flying boats[11] (Figure 2). In early December, after giving a talk entitled "Facts and Fancies of Rockets" at a Caltech luncheon of the Society of the Sigma Xi, I was informed by von Kármán, Robert A. Millikan (1868-1953), and Max M. Mason, that I was to go to Washington, D.C., to give expert information on rocket propulsion to the National Academy of Sciences Committee on Army Air Corps Research. Mason was chairman and R. A. Millikan and von Kármán were members of the Committee.

General Arnold had asked the Academy for advice on a number of subjects, one of which was the possible use of rockets for the assisted take-off of heavily loaded aircraft. Some feared that sufficiently long runways would be unavailable in combat areas. (Later, others feared that the new jet engines would have low power on take-off and would require very long runways.) Actually, the bulldozer solved the problem on land, making long runways practical. Rocket-assisted take-off of aircraft on aircraft carriers, however, soon assumed importance to the U.S. Navy.

I prepared a study entitled "Report on Jet Propulsion for the National Academy of Sciences Committee on Air Corps Research," which contained the following parts:

Fig. 1
Theodore von Kármán in 1939 (circa)

(1) Fundamental concepts, (2) classification of types of jet propulsors, (3) possible applications of jet propulsion in connection with heavier-than-air craft, (4) present state of development of jet propulsion, and (5) a proposed research program for developing jet propulsion.[12] The word "rocket" was still in such bad repute in "serious" scientific circles in the USA at this time that von Kármán and I felt it advisable to follow the precedent of the Air Corps by dropping the use of the word. It did not return to our vocabulary until several years later, when the word "jet" had become part of the name of our laboratory (JPL), and of the Aerojet General Corporation.

I presented my report to the National Academy's Committee on December 28, 1938, and shortly thereafter the Academy accepted von Karman's proposal for a study by our GALCIT research group of the problem of the assisted take-off of aircraft as well as the preparation of a detailed plan for an extensive research program. The Academy provided a sum of $1,000 for this study, which was to be completed in about six months. Incidentally, when Caltech obtained this first government grant for rocket research, Jerome C. Hunsaker of the Massachusetts Institute of Technology agreed to study for the Air Corps the de-icing problem of windshields, then a serious aircraft problem, and told von Kármán: "You can have the Buck Roger's job."[9]

Fig. 2
Frank J. Malina in 1943 (circa)

John W. Parsons (1914-1952) (Figure 3) and Edward S. Forman were delighted when I returned from Washington with the news that our efforts during the previous three years were to be rewarded by financial support from the government, and that von Kármán would devote more of his time to the work. We could even expect to be paid for doing rocket research. Parsons, Forman and I were the only members of the original GALCIT research group at this time still carrying on at Caltech. We proceeded to collect more information on rockets for assisting the take-off of aircraft, and to accumulate experimental data on rocket motor performance with solid propellant rockets and with the gaseous propellant engines in a test stand we had constructed the previous year.

In May 1939, as part of his survey of aircraft development for the Army Air Corps, Charles A. Lindberg came to Caltech after visiting Robert H. Goddard at his New Mexico research station. Since von Kármán was away on one of his rather frequent trips, Clark B. Millikan (1903-1966) briefed Lindberg on aeronautical research at GALCIT, and I told him about our studies of the possible use of rocket propulsion for aircraft. He said

Fig 3
John W. Parsons in 1940

nothing about his visit with Goddard.[4] It is odd that none of the military services, to my knowledge, ever requested JPL to send copies of reports to Goddard, although we had a considerable mailing list of individuals and organizations. Similarly, none of Goddard's reports to governmental agencies were ever received at JPL.

About this time I learned that Eugen Sänger was carrying on rocket research in Germany in reply to a letter I had sent him in Vienna.[+] But information on rocket research in Nazi Germany that began in the early 1930's was unavailable to the Project until November 1943, when we received British intelligence reports on the V-2 missile work at Peenemunde. No information on rocket research in the USSR was available during the period of this memoir. Later, in September 1944, I went to England on a mission for the Ordnance Department where I obtained detailed information on British rocket research. I obtained further information during a second mission in the autumn of 1946. Some reports had been received by the project on British work beginning in 1940, and several British researchers visited us during the following years.

[+]See Irene Sänger-Bredt, "Memoir: The Silver Bird Story and the Development of the Aerospace Transporter," in this volume - Ed.

The studies and experiments we carried out in the spring of 1939 made us sufficiently confident of the possibility of developing both solid and liquid propellent rocket engines to the extent that we prepared a proposal to the National Academy for a $100,000 program of research and facilities construction for the fiscal year 1939-40, beginning on July 1, 1939. Von Kármán took the proposal to Washington only to find that our optimism was not shared either by the National Academy or by the Air Corps. In his autobiography, von Kármán recounts that while discussing the proposal with Major Benjamin Chidlaw (later Commanding General of the Air Material Command) he was asked "do you honestly believe that the Air Corps should spend as much as $10,000 for such a thing as rockets?" This amount turned out to be the maximum that could be obtained. It meant that our experimental work would have to be done either on the campus of Caltech, where our presence was not very popular, or with temporary portable setups in the Arroyo Seco river bed above Devil's Gate Dam on the western edge of Pasadena.

The contract, sponsored by the National Academy of Sciences, came into force on 1 July 1939, bringing into being the Army Air Corps Jet Propulsion Research Project. (A year later the Army Air Corps took over direct sponsorship of the Project.) Under its terms, studies were to be made of a number of basic problems connected with the development of rocket engines for application to the "super-performance" of aircraft. The term "super-performance" was defined to include: (a) shortening of the time and distance required to takeoff, (b) temporary increase of rate of climb, and (c) temporary increase of level flight speed. The contract also wisely authorized work to be done on both liquid- and solid-propellant rocket engines.

Von Kármán, then 58 years of age, became actively committed to the development of rocket propulsion by assuming direction of the Project. Parsons, Forman, and myself as chief engineer, formed the nucleus of the staff. He brought to our work his vast experience of utilizing mathematics and fundamental physical principles for the solution of difficult engineering problems, and a rare skill in negotiation and organization. Parsons was then 25; Forman and I were 27. While von Kármán was away, I chose the designation GALCIT Project No. 1 for the Air Corps research. When he returned he surprised me by frowning at the designation. He said I evidently did not know what House No. 1 meant in China. At the Air Material Command, Wright Field, Dayton, Ohio, the Project was known by the designation Aircraft Laboratory Project MX 121.

We carried out the experimental work partly on the campus of Caltech and partly in the Arroyo Seco above Devil's Gate Dam in Pasadena during the first year of the Project. In 1940, six acres on the western bank of the Arroyo Seco were leased from the Water Department of the City of Pasadena for the duration of World War II. Approximately 40 acres had been leased from the City by 1946 and this area is still a part of the tract on which the Jet Propulsion Laboratory is located. Most of the temporary structures for offices and testing have disappeared, since then replaced by permanent installations. Residents near the Project put up with the noise of rocket testing until the end of the war in 1946 but, thereafter, noisy experiments were shifted to other installations, for example, in the Mojave desert. Facilities of the Project in 1941, in 1945, and in 1969 are shown in Figures 4 (a) and (b), 5 and 6.

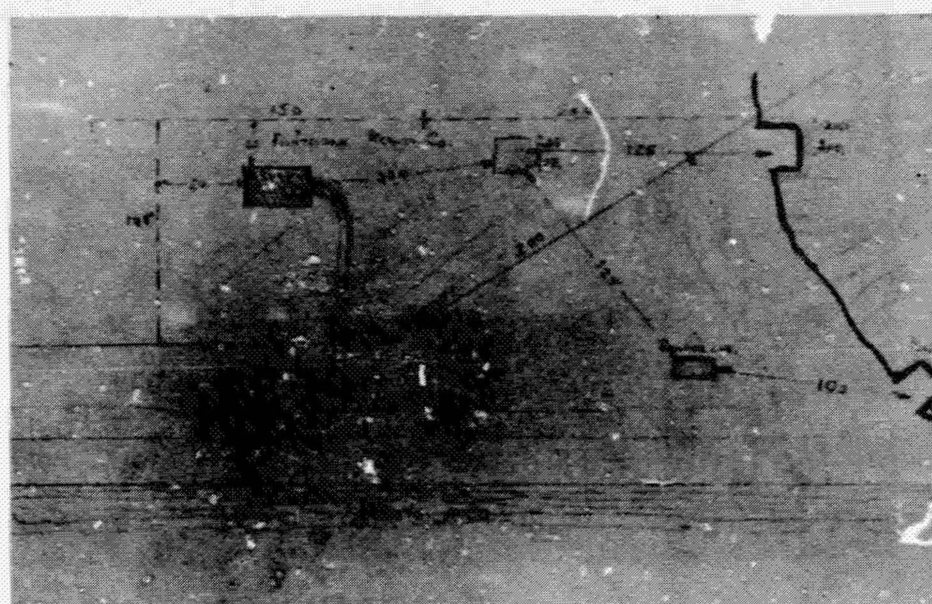

Fig. 4 (a)
Sketch in 1940 of Layout of First Project
Facilities to be Constructed at the
Arroyo Seco, Pasadena Site

The Project benefited greatly from the use of special Caltech laboratory equipment, and for advice from members of the faculty and staff. For example, Aladar Hollander, Linus A. Pauling, and Fritz Zwicky were frequently consulted. A Chemistry Group under the direction of Bruce H. Sage began working on chemical problems of propellants for the project in 1942. Also, several Caltech staff members served as senior research engineers for the Project on a part-time basis. The fact that Zwicky became one of our consultants in 1940 had ironic overtones. While working on the theory of rocket propulsion for my doctoral thesis in 1937,[13] I mentioned to him some difficulties I was having in my study. He exploded with the opinion that I was wasting my time on an impossible subject. For, he said, I must realize that a rocket could not operate in space as it required the atmosphere to push against to provide thrust! By 1940 he realized that he was mistaken.

It is not possible in this memoir to mention the many devoted men and women who carried out rocket research, assisted in the construction and testing of experimental

Fig. 4 (b)
View of Project Facilities in 1941

devices, made designs and computations, and helped with the administration of the Project. E. S. Forman and E. M. Pierce, Sr., were key persons in the first phase of the installation of buildings and facilities. Pierce, who was loved by all, was my administrative mainstay during the period covered by this memoir. It was no easy matter, in the midst of World War II, to assemble a qualified staff that grew in number each year. Obtaining scarce materials and equipment was a constant, frustrating trial. A group photograph of the Project personnel in 1945 is shown in Figure 7.

II. FUNDAMENTAL STUDIES OF ROCKET MOTORS

Characteristics and Performance Parameters of a Rocket Motor

H. S. Tsien and I began theoretical studies of the characteristics of an ideal rocket motor consisting of a chamber of fixed volume and an exhaust nozzle in 1936. The results of these studies up to the end of 1939 are given in References 13 and 14. I developed a universal ideal-thrust diagram showing the dependence of thrust on the expansion ratio of the exhaust nozzle, the ratio of chamber pressure to external pressure, the

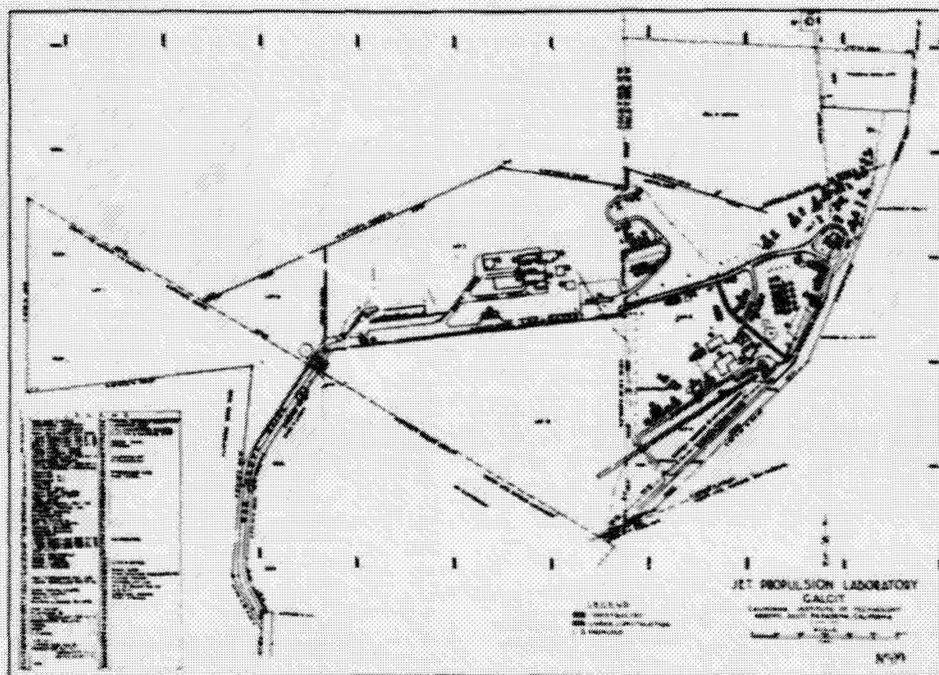

Fig. 5
Layout of the Facilities of the Jet Propulsion Laboratory, GALCIT in June 1945

exit angle of the exhaust nozzle and the specific heat ratio of the exhaust gas (Figure 8). A form of this diagram is now used for determining the ideal thrust coefficient, C_F, of a rocket motor. The effect of the angle of divergence of the exhaust nozzle on thrust under ideal conditions was calculated by Tsien.

Experimental studies of the characteristics of a rocket motor were carried out, beginning in 1938, by Parsons, Forman and myself with the gaseous propellants, oxygen and ethylene.[1] Data were first obtained with oxygen alone to check the test stand installation and to compare results with those reported by Bartocci in March 1938. These were followed by data obtained with the combustion of oxygen and ethylene.[13, 15] During one of the first series of tests with this combination, in March 1939, the oxygen line exploded, scattering parts of the apparatus over a large area. Though shaken, Parsons and Forman, who were conducting the test, were unhurt. A piece of the Bourdon tube of one of the pressure gauges buried itself in a wooden beam about where my head would have been if von Kármán had not called me away earlier.

Martin Summerfield joined the Project in July 1940 and continued these studies with an improved test installation (Figure 9). In particular, he determined the value of

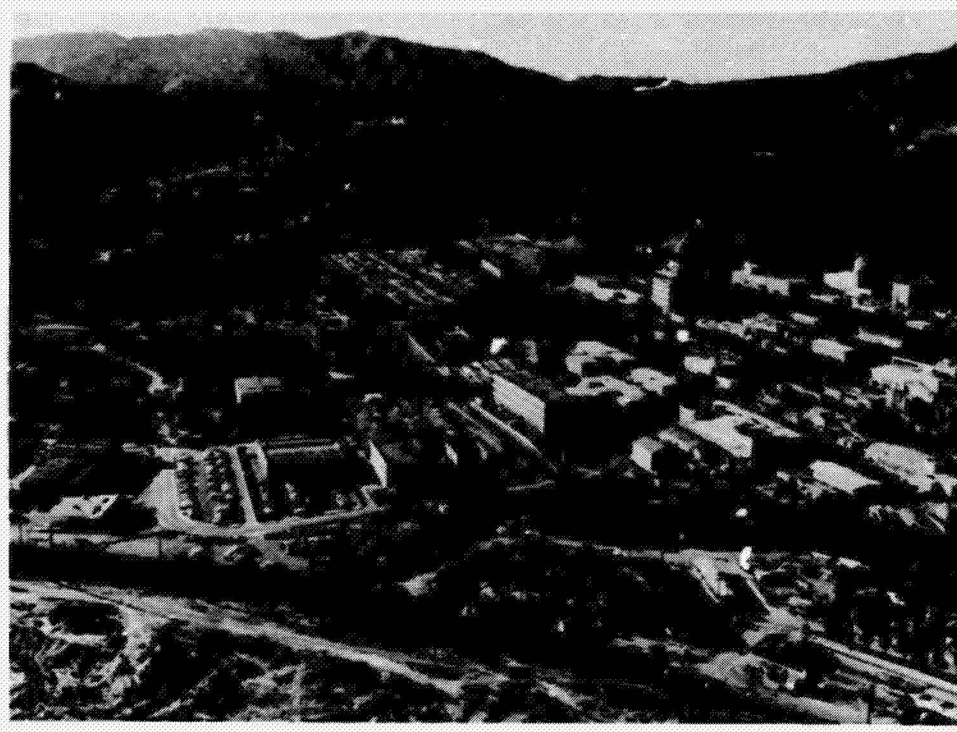

Fig. 6
Aerial View of the Jet Propulsion Laboratory
in 1965

the thrust coefficient under real conditions, as it was effected by the angle of divergence of the exhaust nozzle,[2] and he found that thrust augmentors gave little promise from a practical point of view.[5] He also investigated the significance of the ratio of the combustion chamber volume to [illegible] nozzle throat area, L*, proposed by Sänger for determining the required propellant [illegible]time in a combustion chamber. It is connected with chemical kinetics and affects combustion efficiency.[5]

While conducting experiments with liquid propellants in 1941, Walter B. Powell, following a discussion with Mark M. Mills, introduced a useful parameter called the characteristic velocity, c*, which is defined so as to give the effective exhaust velocity, c, as a product of the experimental coefficients, C_F AND c*. The characteristic velocity is determined only by the properties of the propellant and the nozzle throat area. Thus, it is independent of exit conditions and may be considered as the parameter indicating the efficacy of the combustion process.[2,5] At about this time another useful parameter, called the specific impulse, I_{sp}, came into use. It is ordinarily expressed in pounds thrust per pound of propellant consumed per second.

Fig. 7
Personnel of the Jet Propulsion Laboratory,
GALCIT in 1945 (circa)

Stability of Restricted Burning Solid Propellant Rocket Units

One of our first objectives was to develop a solid propellant rocket unit capable of delivering a constant thrust on the order of 1000 pounds for a period of 10 to 30 seconds. As far as was known, no black powder or smokeless power rocket had ever been constructed to meet these specifications of thrust and duration. Experts we consulted were very dubious about the possibility of doing so. Preliminary experiments made by Parsons and Forman with pressed solid propellant charges restricted to burn cigarette-fashion appeared to support this view.[15] It was generally believed that the combustion chamber pressure of a restricted burning solid rocket unit would continue to rise from the moment of ignition until any combustion chamber of reasonable weight would burst. In other words, it was thought that such combustion was inherently unstable. Von Kármán, in the spring of 1940, after listening both to the opinions of the experts and to the explosions of Parson's rockets, one evening at his home wrote down four differential equations describing the operation of an ideal restricted burning motor, and asked me to solve them (Figure 10). Much to our relief we found that, theoretically, a restricted burning unit would maintain a constant chamber pressure as long as the ratio of the area of the throat of the exhaust nozzle to the burning area of the propellant charge remained constant,

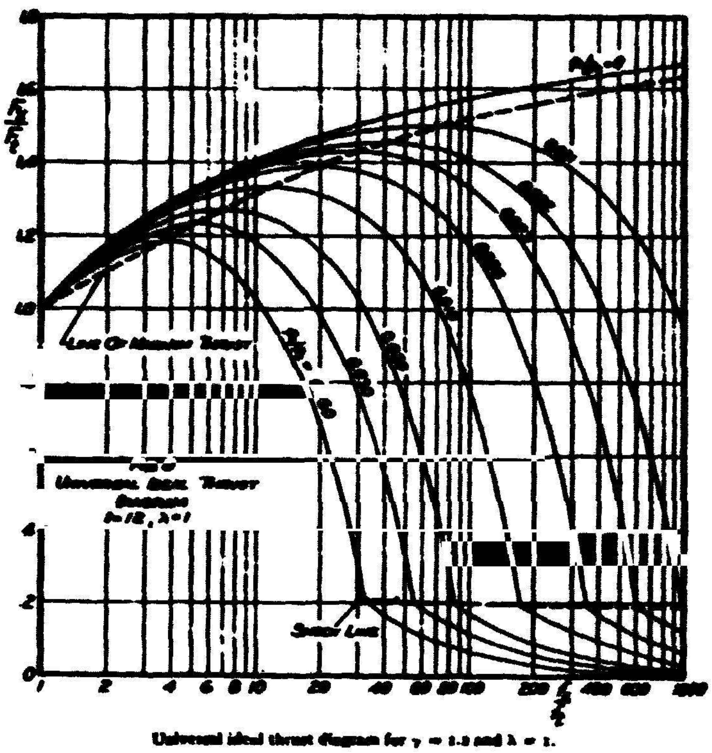

Fig. 8
Universal Ideal Thrust Diagram (cf. Ref. 14)

that is, the process is stable.[16,17] Experimental verification of the theory was soon obtained. (Cf. Section III). (It has been shown that the theory is correct provided the chamber frequency is low [that is L* is large]).

Cooling of Rocket Motors

A rocket motor operates under more severe conditions of high temperature and of continuous rate of heat release than any other heat engine utilizing chemical combustion. For these reasons, problems of heat transfer are among the most acute and important in rocket motor design. Rocket engines for the assisted take-off of aircraft require motors to operate for a maximum period of up to around 30 seconds. Tests made by various experimenters in the 1930s showed that for such a duration is was not necessary to cool the walls of the combustion chamber and exhaust nozzle. In an uncooled motor, thermal equilibrium in the materials of construction is not reached during the safe period of operation; if it were to be reached, the motor would become a molten mass. Work carried out

Fig. 9
Martin Summerfield and Edward G. Crofut in
Front of Gas Propellant Rocket
Test Stand in 1941

by the Project on the design and construction of uncooled solid propellant units and of liquid propellant motors is discussed in Sections IV and V below. The uncooled liquid propellant motor of 1999 lb. thrust used in the A-20A flight tests in 1942 had a safe operating period of 75 seconds, but it weighed 90 lbs.[18,19]

High performance, long duration rocket motors require the use of refractory liners or cooling of the walls in the case of liquid propellant motors by all or part of the propellants. In the 1930s, researchers demonstrated the feasibility of constructing regeneratively cooled motors in which the coolant liquid absorbs heat as it circulates around the motor in ducts and is then injected into the combustion chamber. Extensive studies of regeneratively cooled motors were begun in 1942 by Summerfield and Seifert.[2,20] When they began these studies, practically no information was available on the various aspects of regenerative cooling that would permit the design of a motor to meet the Air Corps performance specifications for various applications. There were, in fact, doubts

I. $$m_p = \Gamma f_t \frac{p_c}{\sqrt{R T_c}} + \frac{dm_c}{dt}$$

II. $$m_p = \frac{\rho_p R T_c}{p_c}\left(\frac{dm_c}{dt} - \frac{m_c}{p_c}\frac{dp_c}{dt} + \frac{m_c}{T_c}\frac{dT_c}{dt}\right)$$

III. $$m_p = \frac{m_c}{T_e - T_c}\frac{dT_c}{dt}$$

IV. $$m_p = (k + k_p p_c) f_c \rho_p$$

where

f_c = burning area of propellant

f_t = area of exhaust nozzle throat

k = propellant rate of burning coefficient

k_p = propellant rate of burning coefficient

m_p = mass of propellant burned per second

m_c = mass of gas in combustion chamber

p_c = combustion chamber pressure

R = universal gas constant

t = time, seconds

T_e = maximum possible combustion temperature

T_c = temperature of gases in combustion chamber

γ = ratio of specific heats of gas

$$\Gamma = \left(\frac{2}{\gamma+1}\right)^{(\gamma+1)/2(\gamma-1)}\sqrt{\gamma}$$

ρ_p = mass density of propellant

Fig. 10
Four Differential Equations That Describe the Operation of an Ideal Solid Propellant Rocket Motor

cast on the principle of regenerative cooling for motors operating at higher values of specific impulse because it appeared to be a "boot-strap" process. But theoretical and experimental studies showed that the principle was sound[9] and data were accumulated to permit the design of such motors.

Search for Materials

The high gas temperatures and velocities encountered in rocket motors and the unusual characteristics of chemicals used as liquid propellants posed special problems whose solution could not be found in other domains of heat-engine technology. Systematic studies of materials were begun by the Project in 1942, including the properties of steel, aluminum and magnesium alloys, ceramics and materials produced by means of powder metallurgy. It is comforting to note that humans, in cooperation with nature, provided the materials required by the designers of various types of rocket engines. The trials and tribulations of those that searched for materials are evident in the early reports by N. Kaplan and R. J. Andrus and by Mills,[21,22] in the monthly reports and in the conference minutes of the Project.[23, 24]

III. ROCKET PROPELLANTS

Liquid Propellants

When the development of a liquid propellant rocket unit for use aboard aircraft was discussed with the Air Corps, we decided that the project should attempt to use aviation gasoline as a fuel and something besides liquid oxygen (LOX) as an oxidizer. Liquid oxygen, the ideal oxidizer from a rocket performance point of view, had been used by Goddard, members of the American Rocket Society, and others. However, the problems of producing, transporting and storing LOX in 1939 (or at any time, as far as the military services were concerned) were considered so formidable that it should be avoided. In today's idiom, the Air Corps wanted rocket engines that utilized "storable propellants."

Parsons, in his report of June 1937,[25] suggested, among other storable oxidizers, a mixture of nitric acid and nitrogen pentoxyde. In 1939, he recommended the choice of red fuming nitric acid, a solution of nitric acid and nitrogen dioxyde, hereafter called RFNA. This oxidizer has poisonous properties and is very corrosive, requiring the use of stainless steel or aluminum to contain it. Nevertheless, it was more acceptable to the Air Corps than LOX. Just before Christmas, 1939, tests in an open crucible showed that RFNA would burn with gasoline and benzene. As pointed out in Section V, Summerfield and Powell subsequently found in testing actual rocket motors that RFNA and gasoline led to unstable combustion. The resulting pulses in some cases became so great that the combustion chamber exploded. The phenomenon of "throbbing" has not been completely cured to the present day.

A Chemistry Group, directed by Sage, was set up at Caltech at the beginning of 1941 to investigate the RFNA-gasoline reaction and the properties of other possible liquid propellants. We began to dream of the advantages of a fuel that would be spontaneously ignitible with RFNA. It would dispense with the need of an ignition system and might burn more satisfactorily with the oxidizer. In early February 1942, I visited the rocket research group at the Naval Engineering Experiment Station at Annapolis, Maryland, directed by an old friend, Lt. Robert C. Traux. While discussing the problem of RFNA-gasoline combustion with Ensign Ray C. Stiff, the chemical engineer of the group, I learned that he had found in the chemistry literature a reference to the property of aniline to ignite spontaneously with nitric acid. He wondered if it would be of any help to add aniline to gasoline.

During the overnight train trip from Annapolis to Dayton, Ohio, it occurred to me that we should try replacing gasoline entirely with aniline as a fuel. This would complicate Air Corps logistic problems, but it seemed it might be the necessary price to pay for an engine that would not explode unpredictably. Upon arriving in Dayton, I sent a telegram to Summerfield asking him to try the idea. When I returned to Pasadena a few days later, he greeted me with exultation. We had a reliable, storable, liquid propellant rocket engine!

Parsons and I filed a patent on 8 May 1943 for a reaction motor operable by liquid propellants and the method of operating it—a motor using spontaneously ignitable propellants.[26] Long after the war, I learned that Lutz and his collaborators in Germany had stumbled on what they called hypergolic propellants at about the same time. It is interesting to note that our patent included, among other suggestions, the use of hydrazine as a fuel with nitrogen dioxide. This is the basic combination used in the engines constructed by the Aerojet General Corporation for the Apollo Service Module, and by the Bell Aircraft Corporation for the Apollo Lunar Excursion Module, which so far have performed without fail in the flights of men to the Moon. The project initiated research on hydrazine and its compounds in 1945.

We encountered considerable resistance from the military services to the acceptance of the toxic aniline as a replacement for gasoline. The Air Material Command finally gave way when it became evident that the A-20A flight tests, scheduled to start within two months, could not be made without risk of catastrophe if gasoline was used as a fuel. The Navy Bureau of Aeronautics continued to resist the use of aniline by the Annapolis group for almost another year, when a violent explosion that wrecked their nitric acid-gasoline test stand made them accept it.

After completing the successful flight tests of the A-20A aircraft equipped with two uncooled 1000 lb. thrust, 25 seconds, RFNA-analine engines were completed (cf. Section VI), the project initiated detailed studies of the problems of propellant injection into the rocket motor, a search for other spontaneously ignitable propellant combinations—such as furfuryl alcohol and nitric acid not containing nitrogen dioxide or "white acid"—and of methods of cooling long-duration motors and of supplying propellants by means of gas pressure and of pumps (cf. Section V). Work was initiated on the development of engines utilizing liquid oxygen in October 1942.[23, 24, 27] The outlook of the project on liquid propellants in 1943 is described in Reference 28.

In 1944 studies of monopropellants, such as nitromethane and hydrogen peroxide, began. In 1937 Parsons already had listed tetranitromethane as a possible rocket propellant. The advantage of a monopropellant would be a much simpler engine, since only one propellant tank, one pump and one control valve would be required. Although nitromethane is comparatively easy to handle, it is sensitive to temperature, has a tendency to explode under impact or shock, and is difficult to ignite and sustain a reaction in a combustion chamber.[29] To the best of my knowledge, a satisfactory rocket engine utilizing nitromethane has not been developed.

Hydrogen peroxide, although it has found a place in presentday rocket technology, was regarded with fear and suspicion by the Project. This attitude arose when 60 pounds of H_2O_2 in a stainless steel tank exploded in the summer of 1944. The cause was not definitely determined; however, the summer atmospheric temperature of about 100°F and the possibility of foreign material in the tank were felt to have been contributing factors.[23]

Solid Propellants

Although there have been centuries of experience with black powder rockets, and several investigators used smokeless powker and Ballistite in rockets between about 1918 and 1939, none of these rockets had the thrust and duration required for the aircraft "superperformance" applications. Parsons and Forman in 1938 built and tested a smokeless powder constant-volume combustion motor similar to the one that had been used by Goddard.[1] We concluded after these tests that the mechanical complications of constructing an engine using successive impulses to obtain thrust durations of over 10 seconds was impractical. Upon Parsons' recommendation, we concentrated our efforts on the development of a motor provided with a restricted burning powder charge that would burn at one end only at constant pressure to provide a constant thrust.

Parsons started with the traditional sky rocket. This type of pyrotechnic device was propelled by a black powder charge pressed into a cardboard combustion chamber with a conical hole in its center. The gases escaped through a rounded clay orifice. Its efficiency was very, very low, but it was reliable. The conical hole in the charge was believed to be the secret that kept the charge from burning down the sides of the container to produce chamber pressures that would burst the container. The longest duration of thrust of this motor did not exceed about 1 second.

During 1939 and 1940, various mixtures based on black powder and mixtures of black powder with smokeless powder were tested in 1 in. and 3 in. diameter chambers. The charge for the 3 in. chamber was made up of 6 in. long pellets compressed at around 6,500 p.s.i. that were coated with various substances to form a solid or liquid seal between the charge and the walls of the chamber (Figure 3). The charge of the 1 in. chamber was pressed directly into the chamber in small increments at pressures between 7,700 and 12,000 p.s.i. Most of the tests of these charges ended in an explosion. Mechanical causes for failures, such as burning of the charge on the surface next to the wall because of leakage, transfer of heat down the walls sufficient to ignite the sides of the charge, and cracking of the charge under combustion pressure, were suspected. However, there were those who were convinced that the combustion process of a restricted burning charge in a rocket motor was basically unstable. It was only when the von Kármán-Malina analysis of the characteristics of the ideal solid propellant rocket motor was made in the spring of 1940 (Section II), that proved the process was stable, that a concentrated effort was made to study the mechanical causes of failure.[15, 16]

Hundreds of tests were then made with different powder mixtures, using black powder as the basic ingredient, with various loading techniques and with various motor designs. The dependence of chamber pressure on the ratio of chamber cross section area to nozzle throat area was determined for each specific powder mixture.

By the spring of 1941 results were sufficiently encouraging to schedule flight tests of an aircraft equipped with solid propellant rockets specially designed for it. (A discussion of the flight tests of the Ercoupe airplane is given in Section VI.)[30] The propellant charge used in the Ercoupe motors was a type of amide black powder designated as GALCIT 27. The 2 lb. charge was pressed into the combustion chamber, which had a blotting paper liner, in 22 increments by a plunger with a conical nose shape at a pressure of 18 tons. The diameter of the charge was 1.75 in. and its length varied between 10 and 11 in. The motor was designed to deliver about 28 lb. thrust for about 12 seconds (Figures 11(a) and 11(b)). Eighteen rocket motors were delivered every other day for the flight tests at March Field, California, about an hour's drive from the Project. During the first phase of the flight tests one motor failed explosively in a static test and one while the Ercoupe was in level flight. Thereafter, 152 motors were used in succession without explosive failure. The motors were prepared by Parsons, Forman, and Fred Miller.[30]

It was most fortunate that the flight tests were carried out close to the location of the Project, which permitted the rocket motors to be fired within a few days from the time they were charged with propellant. Following the flight tests, it was found that after the motors were exposed to simulated storage and temperature conditions over several days they exploded in most cases. It was evident that either the blotting paper liner or the mechanical characteristics of the propellant were unsatisfactory. But the Navy Department regarded the successful Ercoupe tests with much interest from the point of view of application of rockets for the assisted take-off of aircraft from aircraft carriers. Upon the urging of Lt. C. F. Fischer of the Bureau of Aeronautics, who had witnessed the tests, a contract was placed by the Navy with the Project in early 1942 for the development of a 200 lb. thrust, 8 second unit. The unit was designated by the acronym JATO for Jet Assisted Take-Off, and this designation is still used.

This Navy contract came in the midst of the explosive failures of the JATO unit developed for the Ercoupe tests. All efforts to improve the amide-black powder propellant and loading techniques of the motor developed for the Ercoupe tests failed to meet specified storage conditions ranging from Alaska to Africa. Investigations of motors using

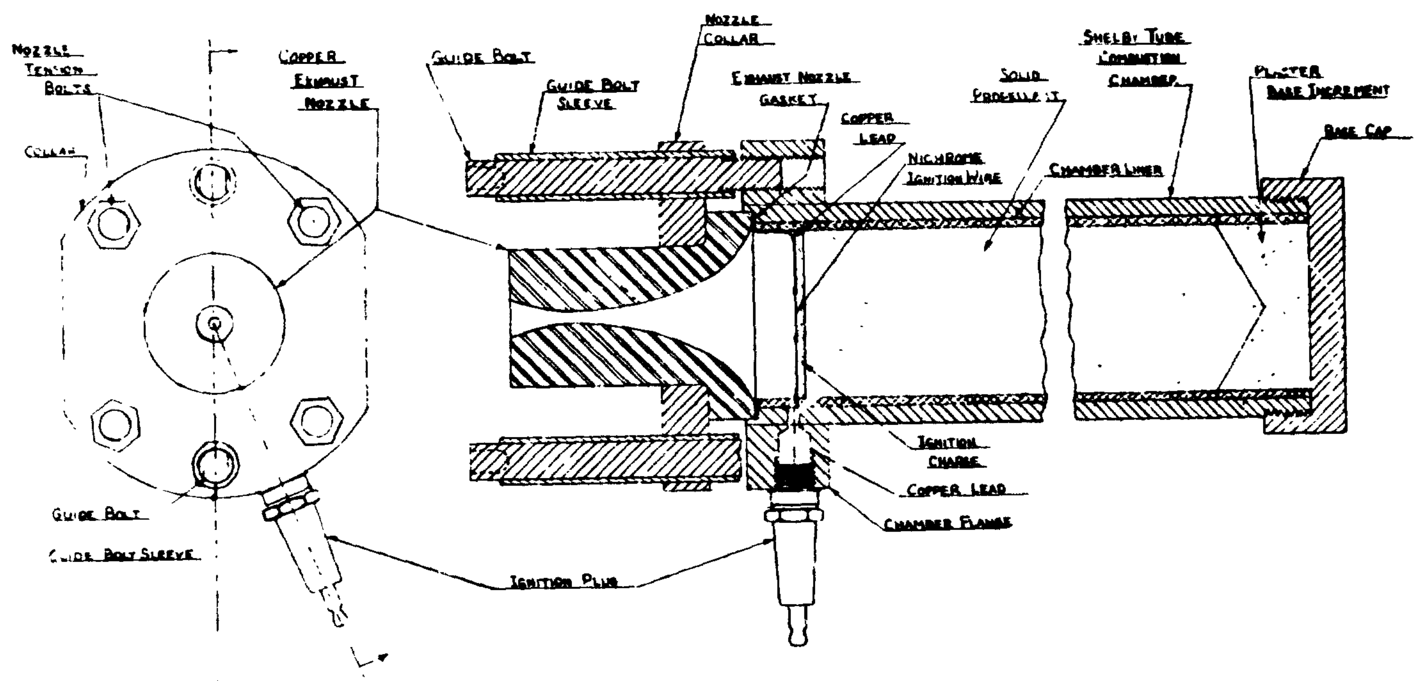

Fig. 11 (a)
Drawing of the 25 Lb. Thrust, 12 Second Solid-Propellant JATO Unit Used In The Ercoupe Flight Tests, August 1941

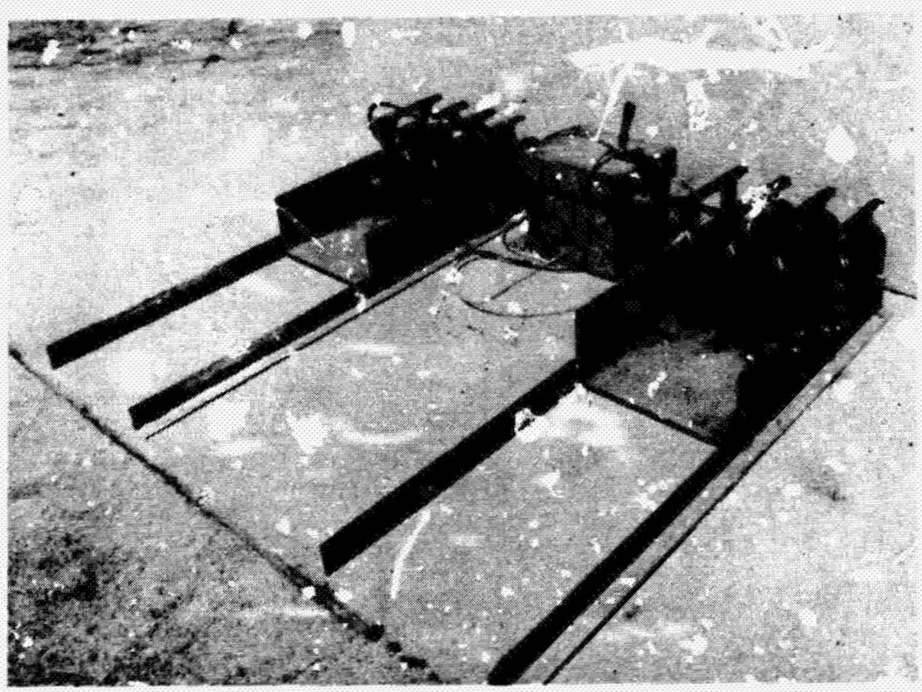

Fig. 11 (b)
View of Six JATO Units. Attachment Assemblies and Ignition System for Ercoupe Flight Tests

Ballistite, a compound essentially of nitrocellulose and nitroglycerine, also proved negative, mainly because of its ambient temperature sensitivity, that is, the variation of its rate of burning with ambient temperature. For example, a JATO unit designed to deliver 1,000 lb thrust at 90°F would deliver at most only 600 lb. thrust at 40°F. Though the duration of thrust at the lower temperature would be lengthened, an aircraft assisted under such a condition might fail to take off from a short runway.

Thus, the spring of 1942 was one of desperation for those concerned with development of a reliable solid propellant JATO unit. We know that theoretically it was possible to construct such an engine, but no one came forward with a promising idea until June, when Parsons, no doubt after communing with his [illegible] spirits, suggested trying a radical new propellant. It would consist of potassium perchlorate, as oxidizer, common asphalt used on roads as a binder and fuel, and be cast, after being mixed, into a combustion chamber. A test of the propellant, designated GALCIT 53, was quickly made and the results were so promising that work on other propellant types was dropped for a long time. Parsons was assisted in the development of the asphalt base propellant by Mills and Fred Miller.[31] After due study of the origin of the ideas for the new propellant, Parsons was recognized as its inventor and a patent was granted in his name.

At first, the Ordnance Department objected strongly to our use of potassium perchlorate as an oxidizer because it had proved unsafe in the past. Parsons realized that their objection was no longer valid, since ways had been found to produce the material with a minimum purity of 99%. Impurities in the form of dangerous chlorates had been practically eliminated. The ruling of the Ordnance Department was thereafter changed, allowing the use of this kind of solid oxidizer. The Navy contract for 100 JATO units delivering 200 lb. thrust for 8 seconds was successfully completed, with GALCIT 53 as the propellant.[32] (Figure 12) Production of service-type units for the Navy began shortly thereafter at the Aerojet Engineering Corporation (now Aerojet General Corporation, cf. Section VIII).

Fig. 12
View of 200 Lb. Thrust, 8 Second Solid-Propellant
JATO's Produced in 1942 For the U.S. Navy

The project carried out extensive studies on asphalt-base propellants (composite propellants, as they are now called) in the following years. A detailed report released in May 1944 on the propellant GALCIT 61-C by Mills can be found in Reference 32. GALCIT 61-C consisted of 76% potassium perchlorate and 24% fuel. The fuel component was 70%

Texaco No. 18 asphalt and 30% Union Oil Company Pure Penn SAE No. 10 lubricating oil. The fuel was liquified at about 275°F, the pulverized potassium perchlorate added to it, and the mixture thoroughly stirred. The mixture was then poured into the combustion chamber, which had been previously lined with a material similar to the fuel component, and allowed to cool and become hard. This propellant when burned at a chamber pressure of 2,000 p.s.i. had a chamber temperature of 3,000-3,500°F, a specific impulse of 186, and an exhaust velocity of about 5,900 ft. per sec. Storage temperature limits were from -9°F to 120°F. It was developed in 1943 and used in service JATO units by the Navy until the end of World War II.

Solid propellants utilizing potassium perchlorate as oxidizer produce dense clouds of white smoke (potassium chloride), which the Navy did not like at all. Some months after GALCIT 53 was developed, Parsons informed the Project weekly research conference that he had eliminated the smoke problem by replacing potassium perchlorate with ammonium perchlorate. Navy rocket experts were immediately invited to visit the Project for a demonstration. When they arrived we posted ourselves some distance from the test pit, the red flag was run up, and Parsons gave the order for his latest creation to be fired. We beheld a big cloud of white smoke and Parsons with a look of surprise on his face. He sheepishly explained that the smoke must have been caused by the humidity, for the air had been very dry on the days they had made tests before. Ammonium perchlorate does reduce the amount of smoke produced if the air is dry, but it produces undesirable chloride in the jet.

The project also studied the possible use of other fuels instead of asphalt, such as Napalm gelled hydrocarbon, gelled wax mixtures, and butyl rubber. A continuation of studies of the last material later led Charles Bartley, under the JPL-ORDCIT Project in 1945, to the discovery of the advantages of the castable elastomeric (polysulfide rubber) material called Thiokol. This discovery became the basis of solid propellant manufacture by the Thiokol Chemical Corporation. Air Force Material Command terminated work by the Project on solid propellant motors on June 30, 1944; the Ordnance Department continued the work for long range missile applications.

In concluding this part on the work of the Project in developing solid propellants for long duration rocket motors, it should be pointed out that two of the most important discoveries in the long history of solid rockets were made here. First it was theoretically proved by the Kármán-Malina analysis that a stable constant pressure, long duration solid propellant rocket motor was possible. Second, Parsons found a new kind of material, the asphalt-potassium perchlorate composite solid propellant, which initiated modern castable solid propellant rocket technology. The 200 lb. thrust JATO unit has grown into solid propellant rocket engines today delivering on the order of 1,000,000 lb. thrust.

IV. SOLID PROPELLANT MOTOR DESIGN

A solid propellant rocket motor consists of a combustion chamber containing the propellant charge, an ignitor, and an exhaust nozzle through which the combustion products escape to give thrust. In the first motor design made by the Project, the nozzle was attached to the combustion chamber by means of bolts that pulled apart at a chamber pressure considerably below the pressure that would shatter the walls of the chamber.[30] In 1942 Mills and I devised a pressure-release device or "safety plug" that considerably simplified motor design. A patent was granted to us for this device on 14 May 1946.[32,34]

Great care was taken to protect personnel involved in preparing solid propellants and in testing solid and liquid propellant engines. During the period of this memoir no serious injury was suffered by any member of the Project, in spite of the tendency of those daily working with explosives to develop a contempt for them through familiarity. Parsons was the fatal victim of this hazard in 1952 when he dropped some fulminate of mercury while moving his private laboratory from Pasadena to Mexico.[1]

The work of the Project concentrated on the design criteria for restricted burning motors that would be suitable for JATO units and, later for long range missiles. During the course of this research, engineers were provided with methods of motor component design when the following characteristics of the propellant to be used were known:

a. Sensitivity of the propellant to ambient temperature during combustion.
b. Combustion pressure limit below which the propellant burns in an irregular manner.
c. Combustion pressure limit above which the propellant burns in an unpredictable manner.
d. Storage characteristics of the propellant charge from the point of view of minimum and maximum ambient temperatures allowed and possible decomposition of the propellant with prolonged storage.
e. Ignition temperature of the propellant.
f. Rate of burning of the propellant as function of the combustion pressure.
g. Performance characteristics of the propellant to produce rocket thrust.

The great progress made in the scientific design of solid propellant rocket motors in comparison with the empirical, traditional, method used in previous centuries can be appreciated by reference to the text "Jet Propulsion"[2] prepared for the course at Caltech at the request of the Air Technical Service Command in 1943 and continued in following years (cf. Section IX). The development of the solid propellant JATO unit showed that for many applications it was superior to liquid propellant engines; because of its simplicity and reliability. The debate on the superiority of solid vs. liquid propellant rocket engines for boosters of space vehicles still rages today.

I would like to point out that it was the policy of the Project to concentrate efforts on fundamental research problems of rocket engine development, leaving pilot and service stage design problems to industry. Von Kármán and I were convinced that this was the appropriate stance to take for an educational and research institution such as Caltech. The fact that this policy was violated during later perioas in the history of JPL was due to special circumstances that prevailed in the U.S.A. at that time.

V. LIQUID PROPELLANT ENGINE DESIGN

When the Project initiated work on rocket engines for the "superperformance" of aircraft in 1939, it was not evident whether either a solid or a liquid propellant type could be constructed to meet service requirements. Therefore, we investigated both types. We realized that a solid propellant JATO unit would be simpler, lighter, and more practical logistically, even though it could not be stopped and restarted. On the other hand, for auxiliary propulsion in flight, the liquid propellant engine, with its higher specific impulse, possible longer burning duration, and controllable thrust, would have great advantages. The use of such an engine for the sole propulsion of an aircraft or of a missile was not at first contemplated in the program of the project. The study I prepared in October 1939 on the application of rocket propulsion to a radio-controlled flying torpedo was used by Captain (later Rear Admiral) D. S. Fahrney (then head of the guided missile project of the Bureau of Aeronautics of the Navy), as the basis for the design and production of America's first guided liquid propellant rocket missile in the U.S.A., the GORGON.[8,34]

RFNA - Gasoline Engine Research

A liquid propellant engine consists essentially of a rocket motor, propellant feed and control system, and propellant tanks (Figure 13). Summerfield initiated experiments directed toward the design and construction of a JATO unit using RFNA and gasoline on 1 July 1940 on the basis of experience that we had gained with tests of the gaseous oxygen-methyl alcohol motor in 1936, experiments with the gaseous oxygen-ethylene motor begun in 1937, various theoretical studies we had made, and the meager information available in the published literature.

The Project's first permanent installation or test pit for experiments on liquid propellant rocket engine components was completed in February 1941. Propellant was fed to a motor by regulated nitrogen gas pressure from standard commercial tanks. Tests were begun on an uncooled motor designed to deliver 200 lb. thrust at a combustion chamber pressure of about 300 p.s.i. The exhaust nozzle, which posed no special design problems, was made in a copper block and attached to the chamber by means of bolts that

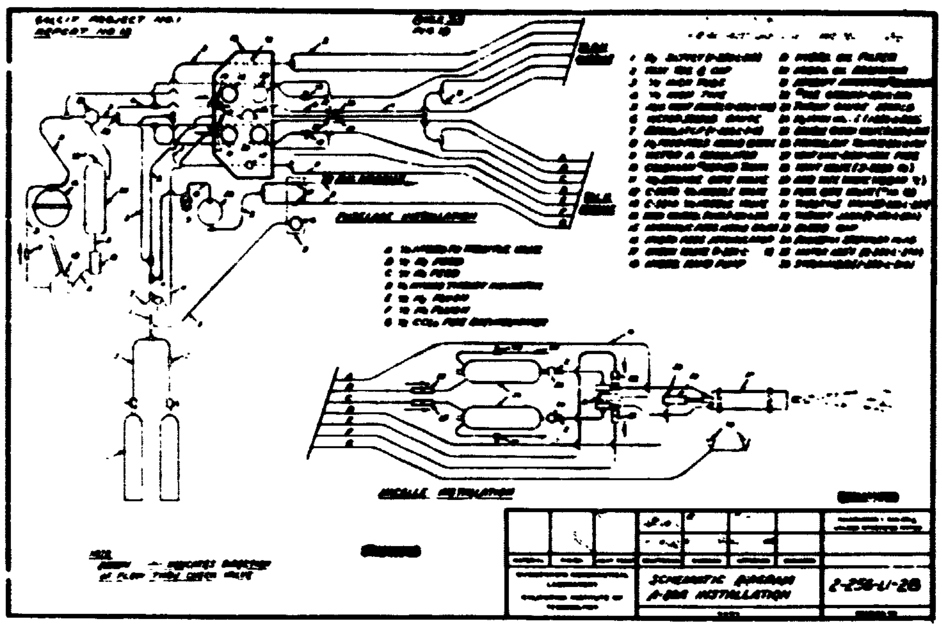

Fig. 13
Schematic Diagram of the Liquid Propellant
(RFNA-Aniline), Gas Pressure Supply
System JATO Engine Used in A-20A
Flight Tests

would break at a pressure below the bursting pressure of the chamber. The volume and shape of the chamber and the mode of injecting RFNA and gasoline into it to obtain regular, efficient combustion had to be determined as well as the method of obtaining ignition.

The first type tested had an impinging-stream injector with four orifices in a flat plate two for RFNA and two for gasoline, and a spark plug for ignition. Since the motor in a JATO unit would be placed in a horizontal position, it was so tested. Three motors were tried and all failed explosively. The third one, in May 1941, set fire to the railroad ties that made up the sides of the test pit and caused considerable damage to the test equipment. The test pits of the Project were deliberately built facing brush-covered hillsides in order to stop jets and flying metal. The brush, which during the long, dry Southern California season is highly flammable, was cleared near the pits. But we were constantly worried that one day the brush higher up would ignite in a big wind and that the fire would race up the mountains toward the Mt. Wilson Observatory above us. A fire did once break out, but it was stopped with the help of all hands at the Project. A sprinkler system was then installed on the hillsides and no further brush fires troubled us.

The chief cause of the liquid propellant motor failures was improper ignition. If ignition was not instantaneous, propellant accumulated in the chamber and, if it then ignited, an explosive reaction took place. It was concluded that the injector did not produce fine enough streams to obtain adequate mixing. A new injector was made with six impingement points; each was made up of a central gasoline stream and two RFNA streams from angled orifices. The spark plug was shielded to prevent short circuiting by spray. The motor with these modifications worked repeatedly without failure and led to tests of a similar, larger, motor designed to deliver 500 lb. thrust. Tests of this motor were also successful, except for one explosion which should have been a warning to us.

At this point we concluded that we knew notably the following, as reported by Summerfield and B. M. Forman (the cousin of E. S. Forman):[36]

a. How to introduce the propellants into the motor, including a satisfactory gas pressure propellant supply system and control valves.
b. The effect of RFNA-gasoline mixture ratio on combustion chamber temperature and the specific impulse of a motor.
c. How to reduce exhaust nozzle erosion by chrome plating the copper surface.

Tests on the 500 lb. thrust motor, which coincided with the successful Ercoupe flight tests at March Field (cf. Section VI), encouraged us, in September 1941, to make the following important decisions:

a. Design immediately a 1000 lb-thrust uncooled motor to operate for a minimum duration of 25 seconds.
b. Form two groups; the first to continue basic studies of engine design, and the second to begin the design of an experimental JATO unit suitable for installation on an aircraft.
c. Request the Army Air Forces (AAF) (formerly the Army Air Corps) to provide an aircraft for flight tests of the JATO unit (cf. Section VI).

Tests at the beginning of October of the first 1000 lb. thrust motor, provided with an injector with 15 impingement points and two shielded spark plugs, proved to be very disappointing. Sometimes ignition was so long delayed that a very "hard start" resulted; sometimes it failed altogether. What really disturbed us, however, was our first encounter with the unpleasant phenomenon of combustion pulsing or "throbbing" that has plagued rocket engineers for the past 30 years. Sporadically and unpredictably a motor begins to throb, slightly at first but with increasing intensity until, if not promptly shut off, it blows up.

For four months various attempts were made to overcome the phenomenon but without success. In the meantime, arrangements had been completed with the AAF for flight tests in the Spring of 1942. The JATO unit that was to be installed on the 14,000 lb. Douglas bi-motor bomber, the A-20A, was in final design stage. In early February 1942 sent the telegram to Summerfield from Dayton, Ohio to replace gasoline with aniline as a fuel. My suggestion worked. Throbbing was eliminated or rendered negligible (cf. Section III). The "throbbing" months drew von Karman, Summerfield, and the Sage Chemistry Group into a concerted theoretical and experimental attack on the problem. Von Kármán became so fascinated with the problems of liquid propellant combustion that he pursued them until his death in 1963; Summerfield is still working on them. Von Kármán broadened the field to include aerothermodynamics, and Summerfield subsequently branched off to include the combustion process of solid propellants.

Engine Research With RFNA and Spontaneously Igniting Fuel For the A-20-A Flight Tests

The property of aniline to ignite upon contact with nitric acid greatly simplified motor design. Auxiliary ignition methods could be dispensed with, and the danger of propellant accumulating in large quantities in a horizontally mounted motor was avoided—provided the propellant components arrived simultaneously at an appropriate mixture ratio. The short ignition lag when aniline comes into contact with RFNA, compared to gasoline, greatly helped to reduce throbbing and eliminated the destructive buildup of pulses. The importance of spontaneously igniting chemicals, or "hypergolic" propellants (a German term), for rocket engines opened up an aspect of chemical research that had been given very little attention in the past and this research contributed to a better understanding of the kinetics of chemical reactions.

The liquid propellant JATO unit group, consisting of Summerfield, Powell and E. G. Crofut incorporated the RFNA-aniline combination into a revised design. It was found that performance specifications established for the 100 lb. thrust motor using the storable propellants could be met by an injector with only four pairs of impinging streams. For the A-20A flight tests, no attempt was made to produce a lightweight unit but rather effort was concentrated on reliability and safety. The tail surfaces of the aircraft were estimated to be high enough to clear exhaust jets when the motors were mounted in the nacelle tail cones, where there was also sufficient space for the two propellant tanks and flow control valves. Standard commercial nitrogen tanks and pressure regulators were installed in the fuselage together with controls for starting and stopping the units, operable by a mechanic in the rear gunner's cockpit upon instructions from the pilot.[18, 37] A view of the installation in one of the nacelles is shown in Figure 14. The motor was mounted on slides and provided with hydraulic jacks, so that if an explosion separated the exhaust nozzle block, the remainder of the motor would not impose too great a shock on the aircraft nacelle structure.

The two JATO units performed satisfactorily during 44 successive firings on the A-20A. The propellant control valves, which were hydraulically operated, and the check

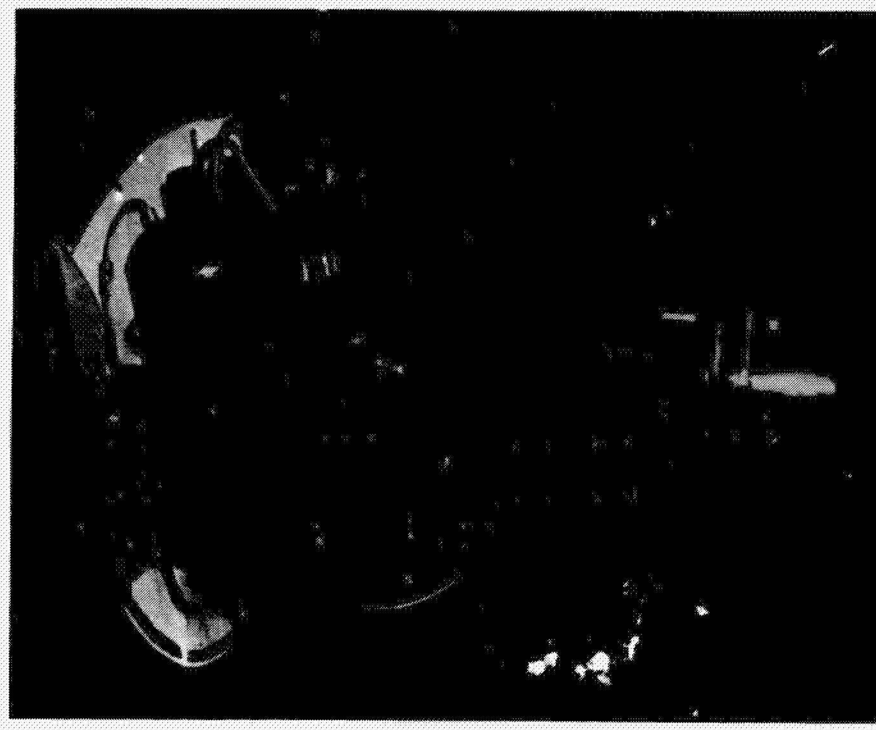

Fig. 14
View of the RFNA-Aniline JATO Engine Installed in
One of the Nacelles of A-20A Airplane

valves gave the most trouble. The check valves were removed at an early stage of ground testing. We had some malicious satisfaction when one of the conventional piston engines on the A-20A developed mechanical trouble and delayed the test program for two days. The highly successful tests of our experimental JATO units during the flight tests led the AAF to place a contract for the production of service-type units at the Aerojet Engineering Corporation--the newly formed company's first contract (cf. Section VIII). The Project, meantime, resumed basic research on rocket engine components.

Engine Research With Various Liquid Propellants After the A-20A Flight Tests

I prepared a review of developments in liquid propellant jet (rocket) propulsion at the Project and at Aerojet for a special meeting of the Office of Scientific Research and Development (OSRD) in Washington, D.C. on February 17, 1944.[38] It will be noted from the title of the report that at this time the term "rocket," in parenthesis, was used. The term was being rehabilitated in technical and military circles in the U.S.A. for the first time since the nineteenth century, when rifled guns replaced military rocket missiles. On the other hand, there was still general resistance to mentioning the use of rockets for space research and exploration, and none is made in the report, even though we were already reviving the studies we had interrupted in 1939.

Motors. A comprehensive memorandum on the state and direction of development of liquid propellant rocket motors by the Project and by other groups was prepared by Seifert and me for the May 29, 1945 meeting of the Coordinating Committee of the Guided Missile Program at the request of the Ordnance Department of the Army Service Forces.[39] (There was still no reference made to space research and exploration.)

An idea of the range of research on liquid propellant rocket motors and other engine components that was undertaken by the project at the end of the period covered in this memoir can be obtained from the following headings of Monthly Summary No. 1-54, 1 to 30 November 1946.[23] (Research on solid propellant rocket engines was taken over by the ORDCIT Project beginning on 1 July 1944):

A. Fundamental Research
  1. New Propellants
     Hydrogen peroxide
     (i) Performance with fuels
     Liquid oxygen
     (i) Performance with fuels
     Acid-hydrocarbon combinations
     (i) WFNA-Furfuryl alcohol
  2. Investigation and development of new materials
     a. Survey of the physical properties of ceramic materials
     b. Development of ceramic materials for use as turbine blades
     c. Preparation and properties of refractory chamber liners
     d. Development of porous materials for sweat cooling
  3. Temperature measurement and heat-transfer analysis
B. Engineering Development
  1. Injector and chamber designs
     a. Effect of injectors on performance, ignition and heat transfer (with nitromethane)
  2. Motor-cooling techniques
     a. Film cooling (with acid and hydrocarbons)
  3. Hydraulic measurements
     a. Characteristics of rocket components
        (i) Atomization
        (ii) Fluid metering

The same monthly summary contained a financial report showing that out of $944,000.00 available that year for research from the AAF, an estimated $954,211,52 had been spent! I do not remember who flew to the Air Material Command, Wright Field, Dayton, Ohio, to get more money, but it was obtained. I was then preparing for my two-year leave of absence from Caltech to go to Paris to work for international scientific cooperation at UNESCO, and I was turning over responsibility for the direction of JPL to my successor, Louis G. Dunn. As I write this memoir twenty-five years later, I am still in France, where I have been occupied since 1953 with non-governmental international cooperation in astronautics and visual fine art.

Propellant Feed Systems. The following types of feed systems were studied by the Project: the gas pressure feed system using stored air or nitrogen in tanks at around 2000 p.s.i., and using gas generators; centrifugal pumps with various drives; and the Centrojet principle proposed by Aerojet.[2, 38] The system using stored gas becomes excessively heavy if thrust durations exceeding about 60 seconds are required, and if combustion pressures higher than 300 p.s.i. are desired to obtain better specific impulse. The idea of providing gas at pressure by means of a chemical reaction to replace storage tanks sounded very good and, beginning in 1942, considerable effort was made to develop it; however, a practical system was not achieved by the end of 1946.[2, 23 & 24]

In 1942, the Project began the development of high speed centrifugal pumps. A satisfactory 10,000 r.p.m. aniline pump delivering 20 gallons per minute at 900 p.s.i. was developed in 1943. The construction of a nitric acid pump proved to be much more difficult because of the special materials this oxidizer requires. Drives such as electric motors and gas turbines were also investigated.[2, 38]

The Project undertook to test for Aerojet, during the Summer of 1943, two unusual proposals for supplying propellant to a long-duration rocket motor (30 minutes at idling thrust, 5 minutes at full thrust). The first would obtain pump drive from rotating rocket motors mounted so that a component of thrust would be made available for delivering torque - the system was called a Rotojet. The second used the principle of the Rotojet with a built-in centrifugal pump. A single combustion chamber was equipped with multiple angled exhaust nozzles. Cooling passages around the chamber walls served as pumping ducts when the whole assembly rotated—the system was called a Centrojet. Summerfield, at that time on leave from the Project, supervised the program at Aerojet. He believed that these systems were mainly the result of the interaction of the minds of William Van Dorn and Waldemar Mayer. It was decided to try them after a committee that included von Karman and Tsien asserted that they were the lightest and most efficient approaches, after reviewing a series of analytical studies of competitive schemes. (These included: gasoline-engine driven pumps, a gas turbine drive, a propellant steam jet pump, a direct combustion gas pressurization scheme, etc. The surviving scheme today is the propellant gas turbine drive. It was used successfully first by the German V-2 group in

1938 but this was not known to us.) Models of the Rotojet and Centrojet were constructed, but tests showed that, although the two systems worked in principle, the mechanical difficulties encountered were so great that there was little hope for them in practice.[2,40,41]

VI. FLIGHT TESTS OF ROCKET ENGINES

I pointed out earlier that the program of the Project was to develop solid and/or liquid propellant rocket engines for application to the "superperformance" of landplanes, including rocket assisted take-off, and abnormally large accelerations and increased flight velocities or rates of climb for only short periods of time. The program was launched on the basis of preliminary studies of the validity of using rocket engines for these purposes.[11, 12] C. B. Millikan and H. J. Stewart in January 1941 made a detailed analysis of the effect of auxiliary rocket propulsion on landplane performance.[42] A supplementary analysis was made by C. F. Fischer, a Navy officer, for his GALCIT master's thesis.[43] The predictions made by these analyses awaited experimental verification.

Ercoupe Flight Tests With Solid Propellant JATO Units

A message was sent to the Air Corps in the spring of 1941 that we were ready for flight tests of an aircraft equipped with solid propellant JATO's each delivering around 28 lb. thrust for about 12 seconds (cf. Section III). The Air Mate· al Command selected the Ercoupe low-wing monoplane, bearing the designation YO-55, for the tests and selected Homer A. Boushey, Jr. (then a Captain) as the test pilot. Boushey in 1941 was doing graduate work at GALCIT and also acted as liaison officer between the AAF and the Project. An analysis of the performance and flight characteristics of the Ercoupe and of the manner of installing multiple JATO units designed by the Project was made by C. F. Damberg and P. H. Dane of the Army Air Corps, as their GALCIT master's thesis.[44]

The Ercoupe was flown from Dayton, Ohio to March Field, California, at the end of July 1941, where modifications were made for installing the JATOs. The flight test group consisted of the following: (Project personnel) J. W. Parsons, E. S. Forman, F. S. Miller and myself, as director of the tests; (AAF personnel) Capt. H. ·. Boushey, Jr., Cpl. R. Hamilton and Pvt. Kobe (Figure 15). Von Kármán and C. B. Millikan joined the group at various stages of the program and some of the tests were witnessed by W. F. Durant, Chairman of N.A.C.A. Jet Propulsion Committee, and Fischer of the Bureau of Aeronautics of the Na·y Department.[30]

A front view of the Ercoupe is ·own in Figure 16 with three JATOs installed under the wing on each side of the fus· ·ge (cf. Figure 11). Each JATO was mounted on

Fig. 15
Ercoupe Flight Test Group: (Project Personnel,
Left to Right) F.S. Miller, J.W. Parsons,
E.S. Forman and F.J. Malina,
(AAF Personnel, Left to Right)
Capt. H.A. Boushey, Jr.,
Cpl. R. Hamilton and
Pvt. Kobe

slides and retained by cotter pins that sheared if the .TO failed and blew off the exhaust nozzle, in order not to transmit shock to the airplane wing. That is, the reaction of the nozzle moving backward would project the JATO combustion chamber forward. The test program began very cautiously, since we had to anticipate possible explosive failures of the JATOs, and it was not certain that the Ercoup would behave satisfactorily when rocket thrust wa pplied. Boushey, for one of the prel inary test flew the airplane equipped with one JATO on each side to an altitude of about 20 and ignited the rockets. We could not see the Ercoupe but our satisfact eeing a white jet trail appear in the sky wa ended in a few seconds when a big b reached us - one of the units had failed again. There were some anxious moments until we could see Boushey flying back and landing safely. Happily, the installation allowing for failure of the JATO without damage to the airplane had worked as planned.

On August 8, among the last ground tests conducted with six JATOs installed, one failed. Unfortunately, the exhaust nozzle rebounded from the runway and struck the

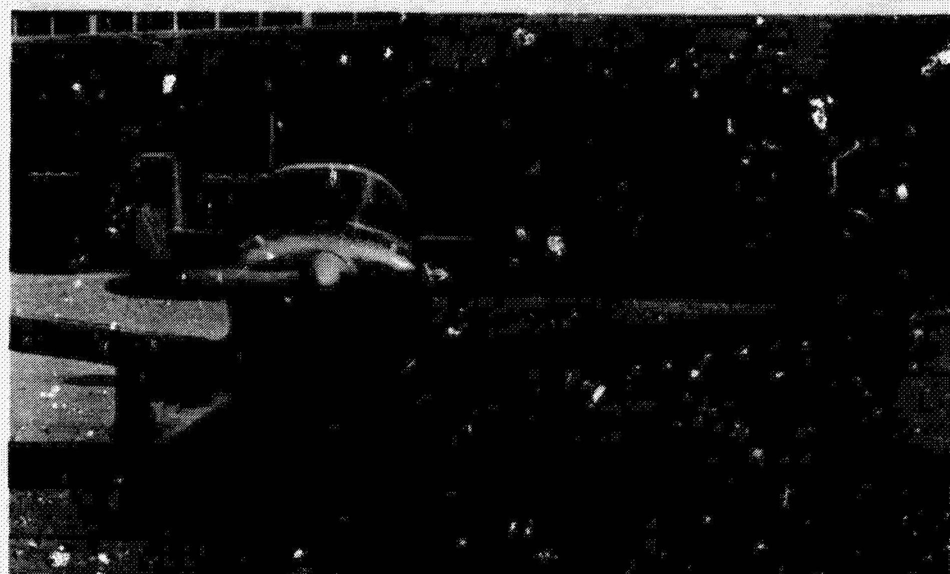

Fig. 16
Front View of Ercoupe With Three JATO's Attached
Under Each Wing

fuselage, ripping a 10 in. hole in the skin and shearing a bulkhe d. The combustion chamber flew about 100 ft. ahead of the airplane before hitting the ground. Some damage was also done to the attachment installation. The report on the flight tests[30] contains the following laconic comment: "The pilot deserv s credit for his willingness to continue flight tests as soon as the airplane was re red." Much to everyone's relief there were no further explosive failures of the JATOs for the remainder of the test program during which 152 units were fired.

On August 16, 1941, Boushey made the first take-off of the Ercoupe with six JATOs firing. A view of a take-off is shown in Figure 17. The salient results of the test program are summarized in Table I. They were found to be in easonable agreement with the theoretical predictions made by Millikan and Stewart. It will be noted that the use of JATOs reduced the take-off of the Ercoupe by about one-half of the distance normally required. The flight characteristics of the airplane were not significantly affected.

Fig. 17
View of Ercoupe Take-Off Assisted
By Six JATO Units

TABLE I

Item	Ercoupe without JATOs	JATO thrust lb.	New value of item	Percent saving
Take-off distance, ft.	580	170	300	48.3
Take-off time, sec.	13.1	170	7.5	42.8
Distance to clear 50 ft. obstacle, ft.	950	170	550	42.1
Distance to take-off with 285 lb. overload, ft.	905	166	438	51.6
Time to take-off with 285 lb. overload, sec.	18.8	166	9.5	40.4
Maximum indicated air speed at 11,400 ft. m.p.h.	62	171	97	56.5 (increase)

The first American manned flight of an aircraft propelled by rocket thrust alone was made by Boushey on August 23, 1941 (Figure 18). The propeller of the Ercoupe was removed and 12 JATO units installed, however, only 11 functioned. The Ercoupe was pulled by a truck to a speed of about 25 m.p.h. before the JATOs were ignited. The airplane left the ground and reached an altitude of about 20 ft.[30] This flight was not originally scheduled but we could not resist the opportunity to make the improvised demonstration of a future possibility of rocket propulsion.

Fig. 18
View of Ercoupe About To Take-Off With
Rocket Propulsion Alone

A-20A Flight Tests With Liquid Propellant JATO Units

We anticipated the flight tests of the RFNA-aniline rocket JATAs on the A-20A airplane with a degree of confidence, for we had gained much experience during the flight tests of the solid propellant JATOs on the Ercoupe. Nevertheless, with the lives of the pilot and the JATO operator in our hands, we proceeded with caution. The A-20A, after certain structural reinforcements had been made by the AAF Aircraft Laboratory at Wright Field, was flown by Major P. H. Dane to Lockheed Airport, Burbank, California, in March 1942. Here the JATOs were installed, whereupon the airplane was flown to the U.S. Air Force Bombing and Gunnery Range, Muroc, California.[37] The only difficulty that we encountered occurred during the first static tests; the unit in the starboard-side nacelle failed to deliver rated thrust. After several days of bafflement we found that the fault lay in the check valves of the propellant lines, which were thereupon eliminated in both units as unessential.[18]

The principal members of the flight test groups were the following: (Project personnel) M. Summerfield, W. B. Powell, E. G. Crofut, B. M. Forman, R. Terbeck and the author, director of the tests; (AAF personnel) Major P. H. Dane, M. G. Cassell and L. A. Brady and (Civil Aeronautics Administration) E. N. Fales, J. Matulaitis and N. N. Rubin. Key personnel in charge of the flight tests are shown in Figures 19 and 20, and the pilot and JATO operator in Figure 21. Von Kármán and C. B. Millikan joined the Project group during parts of the program and Fischer observed some of the flight tests for the Navy Bureau of Aeronautics.

Fig. 19
Personnel in Charge of A-20A Flight Tests
(Left to Right) M. Summerfield,
F.J. Malina, W.B. Powell,
Major Paul H. Dane and
Th. von Kármán

The take-off tests were made from the bed of Muroc Dry Lake, on which a stripe 3 ft. wide and 12,000 ft. long had been laid out to guide the pilot. Fischer flew in from his Navy base at San Diego, California, in the midst of the take-off tests one morning when von Kármán joined us. He asked von Kármán if he would like to see the equipment in the cockpit of a modern Navy fighter. Those of us who knew von Kármán's reputation for leaving experimental apparatus in a mess after visiting a laboratory wondered aloud if Fischer's invitation was a wise one. Von Kármán climbed into the cockpit, and Fischer explained the purpose of the various instruments while I stood on the lower wing and

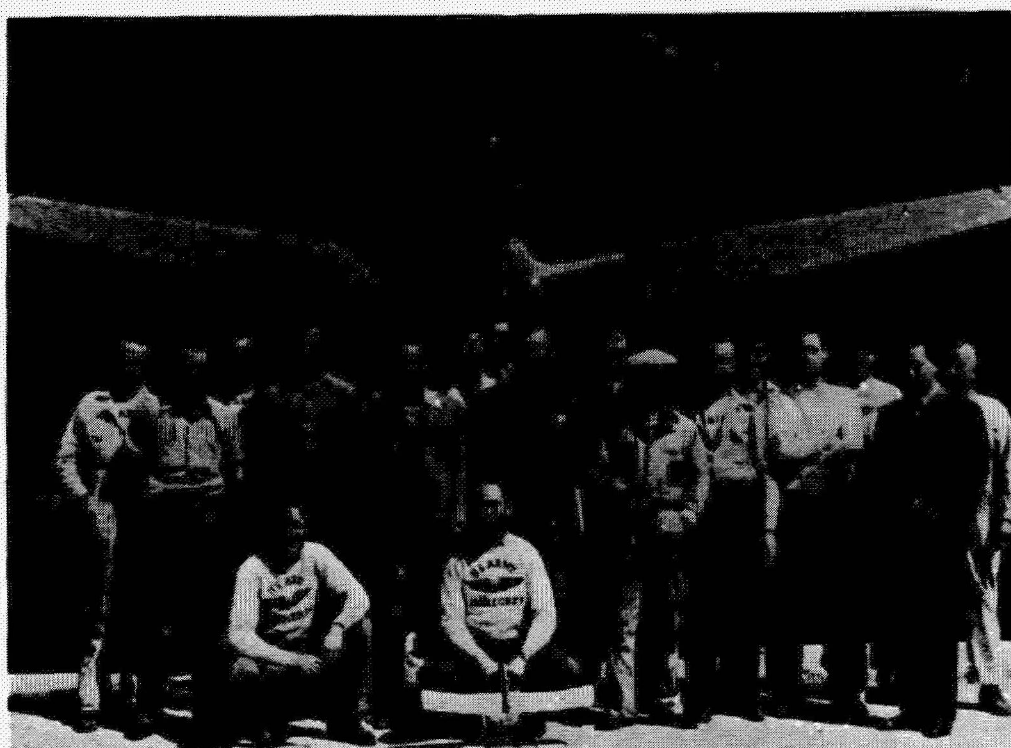

Fig. 20
A-20A Flight Test Personnel

watched. Von Kármán pointed at a handle by his foot and, as he asked what it was for, pulled the lever. I heard a crash behind me on the wing and scampered away from the airplane. When I looked back I saw a balloon under each tip of the upper wing slowly descend and inflate—von Kármán had released the water floatation gear. Fischer exclaimed: "My Lord, how will I explain this at my base—floatation gear activated in a desert!" We often wondered what story he told to his superiors to explain his desert floatation episode.

The first JATO assisted take-off of the A-20A was made on the afternoon of April 15, 1942. A view of a take-off is shown in Figure 22. During the flight tests the JATOs were fired 44 successive times without failure (cf. Section V). The principal results of the tests are summarized in Table II. They were found to be in good agreement with theoretical predictions.[37,42 & 43] The take-off distance, under various loading conditions, was reduced by about 30%. The flight characteristics of the airplane were not significantly affected.

Fig. 21
Major P.H. Dane, Pilot, and B.M. Forman, JATO Operator, During A-20A Flight Tests

Two tests were also made to measure the increase of indicated air speed in level flight with the JATOs ignited. At 5,000 ft., the speed increased from 252 to 300 m.p.h. or 19%, and at 10,000 ft. from 239 to 280 m.p.h. or 17.2%. The gross weight of the airplane was about 18,000 lb.

TABLE II

Item (A-20A at 20,000 lb. Gross weight)	A-20A without JATOs	JATO thrust lb.	New value of item	Percent saving
Take-off distance, ft.	2,320	2,000	1,570	32.3
Take-off time, sec.	25.1	2,000	16.8	33.1
Airborne distance to clear 50 ft. obstacle, ft.	1,630	2,000	1,120	33.3
Airborne time to clear 50 ft. obstacle, sec.	8.3	2,000	6.0	27.8

Fig. 22
View of A-20A Take-Off Assisted By 2 JATO Units

VII. ROCKET PROPULSION UNDER WATER

Qualitative experiments of rocket motors fired under water, made in the autumn of 1942, were reported upon by R. B. Canright. It was found that a RFNA-aniline motor started satisfactorily when submerged under 9 in. of water, even when water filled the motor and part of the propellant lines. Solid propellant units were tested when submerged at depths from 2 to 6 ft. of water in the lake formed at Morris Dam, California. The results showed that these engines could be operated under water as JATOs for flying boats, and for the propulsion of torpedoes. A patent for the application of rocket propulsion to water-borne vehicles was granted to Summerfield and the author.[46] The Armament Laboratory of the AAF Air Technical Service Command at Wright Field, upon hearing of these tests, requested the project to submit a proposal for development of a "hydrobomb." It was to be an air-launched torpedo, but, in order to circumvent the monopoly held by the Navy for the development of torpedoes, the AAF decided to call it by a different name. Propulsion of the missile was to start after it entered the water.

Von Kármán and I, in a memorandum dated February 20, 1943, proposed the design, construction and operation of a towing channel for underwater rocket propulsion research.[47] The proposal also included research on the design of a hydrobomb. When we explained the proposal to General Chidlow in Washington, D.C. his comment was: "The next time you come to see me you will want money to put rockets on my swivel chair." The proposal was accepted by the Armament Laboratory, and the work carried their designation: Project MX 363. Our designation for the work was GALCIT Project No. 2. An underwater Propulsion Section was established and placed in the charge of Dunn, who in 1944 became Assistant Director of JPL. Under Dunn's supervision, the towing channel or hydrodynamic tank was built. It had a length of 500 ft., a width of 12 ft., and a depth of 16 ft. (Figure 23).[3] The towing carriage was, at my suggestion, to be driven by a controllable RFNA-aniline engine delivering a maximum thrust of around 3,000 lb. to give a carriage speed of around 40 m.p.h.[48]

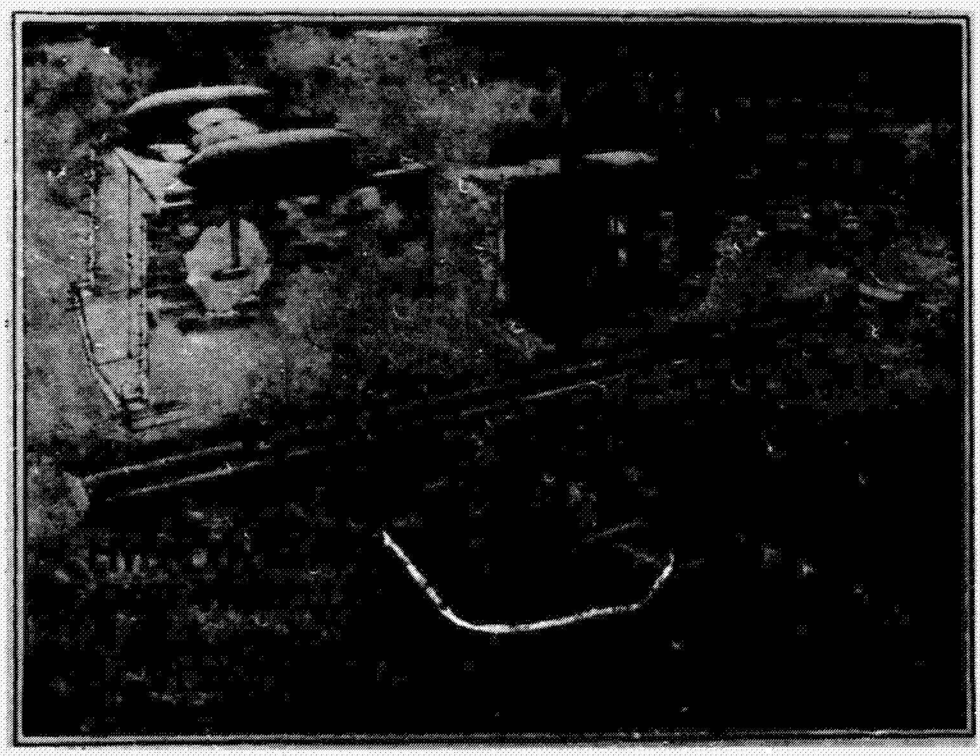

Fig. 23
Drawing of Hydrodynamic Tank Installation

The engine for this first rocket-propelled car in the U.S.A. was designed by Powell and Crofut.[49] The engine had three 1,000 lb. motors and a gas pressure propellant supply system. One memorable day in 1943 I was invited to watch a static test of the engine mounted in the completed towing carriage (Figure 24). George Emmerson, our brave photographer, and I posted ourselves to the rear and to one side of the carriage. We heard the order to fire the engine and to our horror, almost immediately saw one of the

Fig. 24
Static Test of Rocket-Propelled Towing Car

combustion chambers of a motor fly past us and flame envelop the carriage. The carriage, in a matter of seconds, was a burned out wreck because a violently "hard start" of the engine not only separated the parts of one of the motors but also broke the lines of the spontaneously ignitable propellant components. The carriage and the engine, with modifications, were rebuilt and used successfully during the preliminary phase of hydrobomb development. The rocket engine was later replaced by an electric motor drive that provided easier control of carriage speed. It is to be regretted that the first rocket propelled car was not saved, as it was the predecessor of rocket-propelled sleds now used for high speed experiments.

Two different prototype models of a hydrobomb were built by 1946 for the AAF; one by the Westinghouse Manufacturing Company and one by the United Shoe Machinery Company. The prototype by the latter company was about 10 ft. long, with a maximum diameter of 28 in. Designed to be launched at speeds up to 350 m.p.h. and to travel under water at 70 m.p.h., the missile was driven by a solid-propellant rocket unit delivering 2,200 lb. thrust for 30 sec. The range of the missile was 1,000 yd; gross weight was 3,200 lb., with a warhead weight of 1,250 lb.

The primary tasks were to obtain, on half-scale models, their hydrodynamic characteristics, the effect of rocket propulsion upon stability and performance, and the effect of the rocket jet upon cavitation. A special solid propellant and motor were designed by the Project for the full-scale hydrobomb that would withstand water impact when the missile was launched up to speeds of 400 m.p.h. Launching tests were made at the Torpedo Launching Range developed by Caltech for the Navy at Morris Dam, California.[50, 51]

VIII. FORMATION OF THE AEROJET ENGINEERING CORPORATION

It became evident in 1941, following the successful flight tests of the Ercoupe and with good progress being made in the development of a liquid-propellant JATO, that steps would soon have to be taken for the production of JATOs for the Air Force and the Navy. Caltech, being an institution for education and basic research, did not appear to us to be appropriate for undertaking engineering development and production on a large scale. Furthermore, I shared the opinion of Parsons and Forman that after the efforts we had made during the previous five years we should participate in the exploitation of our ideas. I proposed to von Kármán in September 1941 that we try to initiate the production phase of rocket engines, and found him sympathetic. He pointed out that since he and I were members of the faculty of Caltach, there probably would be objections made to our becoming businessmen and there certainly were some. Robert A. Millikan, with his usual broad outlook, expressed concern as to whether we could manage a commercial organization successfully.

To minimize these objections, the first plan was to try to get an existing aircraft company to set up a rocket engine division, with a special arrangement for our participation in its work and in the sharing of profits. Von Kármán describes in some detail in his autobiography[9] these unsuccessful efforts. Leaders of the aircraft industry in Southern California foresaw no future for rocket propulsion! Then, upon the counsel of Andrew G. Haley, von Kármán's attorney, we decided to found a company of our own, after a favorable discussion of the idea with General Frank C. Carroll at Wright Field.[52] The Aerojet Engineering Corporation, now called the Aerojet-General Corporation, was organized at the end of 1941 and formally incorporated on March 19, 1942, with the following officers: Von Kármán, President and Director; Malina, Treasurer and Director; Haley, Secretary and Director; Parsons, Forman and Summerfield, Vice-Presidents. Our first capital contribution to the company amounted to $200 each. Those of us who held patents assigned them to the company.

It was no easy matter to decide who of those connected with the Project should be invited to join us in the venture. After the company was underway, C. B. Millikan especially felt left out. A year later we decided to offer him some shares for purchase, which he bought, and then he actively aided with the development of the company. Parsons, Summerfield and Forman, by the end of 1942, spent much of their time at Aerojet, assisting with the transition from the experimental stage to pilot scale and to full-scale production of solid and liquid-propellant JATO units. In September, Haley took over as president of the company and von Kármán and I again concentrated our efforts on the continually expanding program at the JPL Air Corps Project.

This changeover was prompted, in part, by the attitude of the AAF to our becoming businessmen. Von Kármán has the following story in his autobiography.[9] We received word from Wright Field that the Air Force had decided not to renew the first contract of Aerojet for liquid-propellant JATOs. Somewhat annoyed, he and I flew to Washington, D.C., to find out what was wrong. Our old friend, General Ben Chidlaw, told him in no uncertain terms the following: "We like you very much, Doctor, but only in cap and gown to advise us what to do in science. The derby hat of the businessman does not befit you."

The problem of "hats" haunted us during the next years. At this time, von Kármán and I were actually alternating three hats - we were on the staff at Caltech, at the governmentally-owned JPL operated by Caltech, as well as officers of Aerojet. And von Kármán had several other hats; for example, he was retained as a consultant by the Northrop Aircraft Company. The more strenuous objections to possibilities of our having conflicting interests, however, were soft-pedalled because there were so few qualified persons in the country to deal with the required expansion of rocket propulsion development and production. Close technical liaison was maintained between the Project and Aerojet until 1944 when the General Tire and Rubber Company bought a majority interest in Aerojet from the founder shareholders. This sale was forced upon us because, as the government told us, we had by then the lowest ratio of invested capital to contracts of any company in the country. Thereafter, the company concentrated more and more on production rather than development and its relations with JPL became more and more tenuous.

IX. JET PROPULSION ENGINEERING EDUCATION

In 1943 von Kármán organized at Caltech for the AAF Material Command, the first graduate course in jet propulsion engineering in the U.S.A., utilizing the staffs at GALCIT and JPL. The course, at first, was limited to officers of the Army and Navy, but later opened to selected civilian students. Lectures in the course were collected in 1946 by the Air Technical Service Command under the title "Jet Propulsion".[2] The 799-page volume was edited by Tsien and contained contributions from: P. Chambre, J. V. Charyk, L. G. Dunn, A. Hollander, N. Kaplan, Th. von Kármán, F. J. Malina, C. B. Millikan, M. M. Mills, A. J. Phelan, W. D. Rannie, H. S. Seifert, H. J. Stewart, R. F. Tangren and H. S. Tsien.

This volume exhibits, especially, the great progress made between 1939 and 1946 in the U.S.A. in the development of jet propulsion engines of various types on a firm scientific basis. The popular conception has been built up that developments during this period in Nazi Germany far outdistanced American results of research on the fundamentals of rocket propulsion. That conception is false, for when we studied German developments after the war we found that, as far as liquid propellant rocket engines were concerned, they had more experience only with the practical aspects of large-thrust LOX engines. Developments in the U.S.A. of composite long-duration solid-propellant engines were much more advanced. The tendency in the U.S.A. to worship prophets from afar was well demonstrated in the case of rocket propulsion developments during this period, with some unhappy historical effects.

The approaching end of World War II posed serious policy decisions for Caltech as regards JPL. Some of the problems were brought to the fore by von Kármán in a memorandum he prepared in 1944 for the consideration of the Caltech Trustees on the possibilities of the establishment of a Jet Propulsion Laboratory owned by Caltech.[53] Von Kármán succeeded in convincing Caltech to accept the ORDCIT contract with the Ordnance Department, with concurrence of the AAF, to initiate the first research program on long-range rocket missiles in the U.S.A.[54] He was, however, also concerned with the postwar future of jet propulsion research on a permanent basis. He wrote: "It has now become known that one of the great changes in aviation equipment introduced by wartime research will consist in the use of jet propulsion as motive power. The present jet propulsion equipment is yet of a rather crude nature. However, certain very definite results have been obtained and promise wide possibilityes of application both in military and civilian aviation."

Von Kármán, Summerfield, Tsien, and the author performed a comparative study of jet propulsion systems as applied to missiles and transonic aircraft during the winter of 1944. We compared solid and liquid propellant rocket engines, and thermal jet engines such as the aeropulse, ramjet, and turbojet for various applications.[55] Under the contracts with the AAF and the Ordnance Department, the Laboratory soon involved itself with research on the full spectrum of jet propulsion engines. What is more, JPL became the largest single operation to be administrated by Caltech. The work I initiated with the GALCIT Rocket Research Project in 1936 had blossomed within eight years into a major activity of the Institute. The many problems arising from a private educational and research institution administrating large scale research for the government and for military applications after the war, ranging from using the staff of Caltech on such research, to allowing its staff members to become involved in industry, and to introducing within the curriculum the subject of jet propulsion engines, were all upon us.

Von Kármán took a leave of absence from Caltech at the end of 1944 to establish the AAF Scientific Advisory Group in Washington, D.C.[9] During 1945, I devoted more and more time to the problems of the Caltech-JPL relationship. I submitted, in November 1945, a memorandum on the future of jet propulsion research at Caltech.[56] My primary objective was to assure the survival of JPL within the structure of the Institute. To this end, I proposed that the Institute establish a Department of Jet Propulsion Engineering, with its own funds, and that JPL be operated as a government facility under the new department. The starting point of the department would have been the graduate Jet Propulsion Course begun in 1943. Although the proposals I submitted were not adopted in the way I envisaged, jet propulsion engineering education and research were added to Caltech's program, and JPL continued with a somewhat more tenuous link to the Institute.

At a meeting of the Society for the Promotion of Engineering Education at Berkeley, California on February 22, 1946,[57] I discussed the affect upon engineering education of jet propulsion and the beginnings of astronautics, and concluded with the following statement: "It appears that jet propulsion developments have served, in some measure, to increase the present pressure for a careful evaluation of the curricula and general spirit of engineering education. The need for men trained as research engineers to aid in bridging the gap between scientific research and useful application of new knowledge of nature has been critically appreciated by those given the responsibility for carrying out difficult phases of an urgently needed development during the war."

X. CONCLUDING REMARKS

I look forward to the opportunity of presenting at a future symposium of the International Academy of Astronautics my third and last Jet Propulsion Laboratory memoir. It will deal with the ORDCIT Project, from its inception in 1944 to the end of 1946. It was the first long-range rocket missile research undertaken in the U.S.A. and it also permitted resumption of rocket research for space exploration initiated at Caltech in 1936.

The help I received from Martin Summerfield and Walter B. Powell on technical parts of this memoir, and from George Emmerson in collecting photographs, is highly appreciated.

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