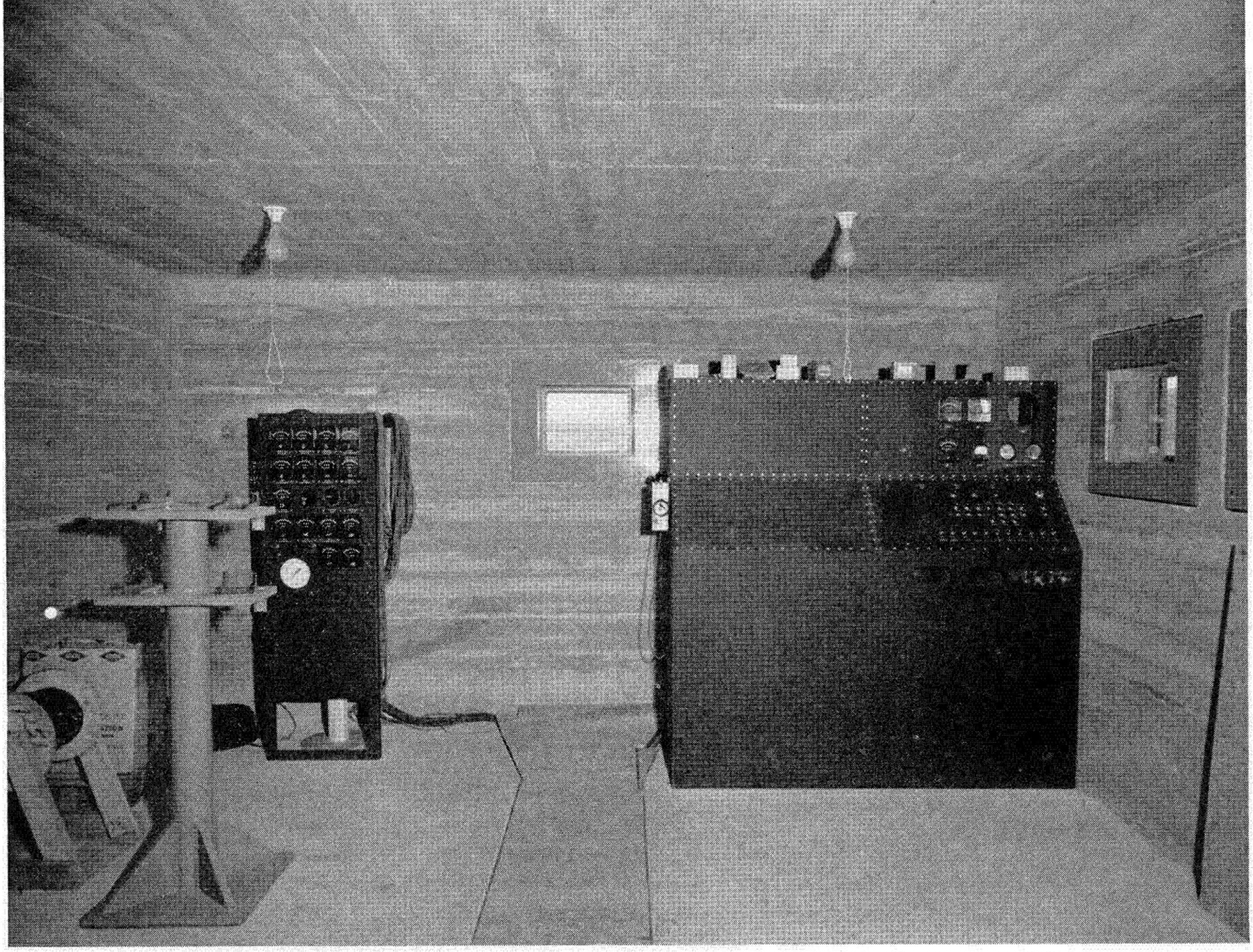


FIG. 1. The Muroc Test Station control room at the Muroc Army Air base, California.

THE Jet Propulsion Laboratory is located within a fenced enclosure covering approximately forty acres near the western limits of the city of Pasadena, California. Within the enclosure are more than eighty structures of widely-varied types. Dominating the entrance is the Administration Building. Beyond it are numerous test pits for the development of propulsion systems for solid and liquid-propellant rockets, and for ramjets and turbojet engines; laboratories for research in high-temperature resistant materials, and the processing of solid propellants; a towing channel for research on underwater missiles; and machine, sheet metal, and welding shops.

Under construction is a compressor house to supply highly-compressed air for thermojet research.

The staff at the Laboratory numbers more than 385. The facilities with equipment are valued approximately at $3,000,000.

Various laboratories on the campus of the California Institute of Technology also are utilized; for example, the 10-foot wind tunnel of the Guggenheim Aeronautical Laboratory. Expert consultation on special problems is provided by staff members in several departments. A Chemistry Group, under the direction of Dr. B. H. Sage of the Department of Chemical Engineering, has been conducting special research for the Laboratory for several years.

A test station for the investigation of large, liquid-propellant rocket units is being operated by the Laboratory for the A.S.F. Ordnance Department at the Muroc Army Air Base, California, parts of which are shown in *Fig. 1* and *Fig. 2*.

Numerous contracts under the different research projects have been placed with industrial organizations in various parts of the United States, including many companies throughout the Los Angeles area.

JATO STUDY BEGUN

The research begun in 1939 on Jet-Assisted Take-Off for Aircraft under the auspices of the National Academy of Science, continued the modest work that had been initiated in 1936. It was understood, as it continues to be, that the Laboratory primarily should be concerned with the solution of basic research problems, to enable the Armed Services to develop equipment of novel type.

One of the immediate objectives of Frank J. Malina, John W. Parsons and Edward S. Forman, appointed to carry out the research program for the first year, was to develop two types of rocket motors; one, utilizing the energy of a solid propellant, the other, a liquid propellant. Both types had to be capable of delivering a constant and sufficient thrust for a period long enough to assist a plane to take off and reach an altitude considered safe to continue its flight unassisted. The period specified was of the order of ten to thirty seconds.

The first year was devoted mainly to a survey of early experience in the field and to study of the fundamental properties of propellants. Little information was available on powder rockets with duration longer than one second. Two ways suggested themselves to solve the problem of delivering a prolonged thrust. The first was to install in a plane a group of motors loaded with fast-burning solid charges, and to fire them one at a time in quick succession so as to produce a prolonged thrust. Experiments conducted by a number of investigators were discouraging in that successive firing at split-second intervals was not dependable; hence thrust was delivered not constantly but by fits and starts, strenuous on pilot and plane alike. The second way that suggested itself was to develop a restricted-burning propellant that would burn at one end only, like a cigarette, in order to produce a constant, prolonged thrust. Profiting by knowledge of the difficulties encountered in attempts to develop the first method, the Project directed its efforts toward development of the second.

The first experiments were conducted with commercial stick powders, made to specification. The experimental motor was built of steel tubing two feet long and one inch thick. The inside diameter was three inches. One end was plugged; the other end was fitted with a pipe flange eight inches in diameter. The motor nozzle also was fitted to a flange to match the one on the motor so that the nozzle and motor were connected by bolting the two flanges together. The bolts, made of relatively soft steel, were of a diameter calculated to give way when pressure inside the motor became dangerously high; thus the nozzle was permitted to fly off and save shattering the motor. Powder charges were ignited at the nozzle end of the motor by an electric squib; near the nozzle end, also, the motor was tapped to permit pressure measurements.

One of the dangers anticipated in the operation of the experimental motor was that, under the pressure created, the gaseous flame at the end of the solid powder stick might strike down between the charge and the chamber wall. If it did, the whole charge would burn so rapidly that the result might be an explosion. Or, possibly, the transfer of heat down the walls of the chamber might ignite the whole charge. To prevent such possibilities, experiments were conducted with various types of liners whose function it was to seal off effectively the space between the powder and the chamber walls so as to restrict burning to the end of the stick.

Over a two-year period, with personnel augmented only in the second year, the Project made many hundreds of tests. Different powder combinations were tried with various loading techniques, and with dissimilar nozzles. By the summer of 1941, a dependable, small-scale motor and a propellant had been developed and put into limited production for experimental purposes. The motor delivered a maximum thrust of 28 pounds for 12 seconds. Unloaded, the unit weighed 10.7 pounds; the powder charge weighed approximately 2 pounds.

The propellant developed, named GALCIT 27, was an amide powder prepared from commercial ingredients. Each two-pound charge had to be pressed into the combustion chamber of the motor in a series of 22 separate increments, each under a pressure of 18 tons. Loading with large, hence fewer, increments, or loading under lighter pressure, produced powder sticks that were likely to explode.

THE ERCOUPE FLIGHT TESTS

Calculations had revealed that the combined thrust of six of the new motors was sufficient to justify their application to a light airplane. It was feasible, moreover, to fire six of the units simultaneously.

The Germans already had used jet propulsion to assist gliders into the air. We Americans had not. Our knowledge was limited to calculations based upon theory. Obviously, data based on actual tests were much needed to check against theoretical predictions of the distance jet propulsion could shorten take-off, with and without overloading a plane. If experiment proved the theoretical calculations to be sound, then they could be relied upon to predict the performance of any airplane equipped with jets. It was desirable to know, too, what effect the jet thrust would have upon the stability and control of an airplane, and what effect the hot jet blasts would have upon the plane structure.

For flight tests, therefore, the Air Materiel Command made available to the Project a low-wing monoplane, known as the Ercoupe. Its weight, empty, was 753 pounds. Captain H. A. Boushey, Jr., the test pilot, flew the plane from Wright Field, Dayton, Ohio, to March Field, near Riverside, California. Two identical assemblies, each incorporating three rocket units, were installed on the plane, one assembly under each wing. As a safety precaution in case of explosion, each unit was designed so that both the exhaust nozzle and the combustion chamber were free to fly clear of the plane.

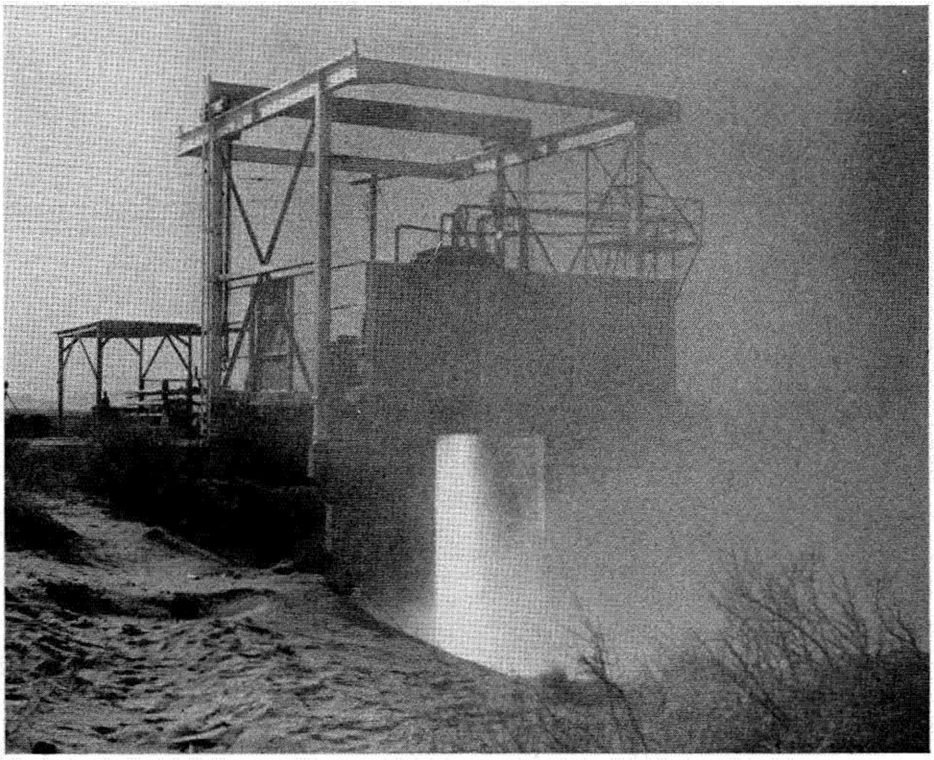


FIG. 2. The Corporal E motor in operation at the Muroc test station. In designing the Corporal E a new method of fabrication and assembly had to be introduced.

FIG. 3. Ercoupe take-off assisted, versus Porterfield take-off unassisted.

An electrical switch, mounted on the control panel, controlled ignition of the rocket motors.

The test program was conducted at March Field, August 6 to August 23, 1941. Witnesses, including both Army and Navy personnel, viewed the first take-off in the United States of an airplane assisted by jet propulsion. With the exception of several failures in preliminary trials, the tests were successful, the experimental results checking satisfactorily the theoretical predictions.

With jet assistance, shown in *Fig. 3*, the distance required for the plane to take off was shortened from 580 feet to 300 feet, a saving of 48.3 per cent. The time required to take off was shortened from 13.1 seconds to 7.5 seconds, a saving of 42.8 per cent. With an overload of 285 pounds, the distance was shortened from 905 feet to 438 feet, a saving of 51.6 per cent. The time was shortened from 18.8 seconds to 9.5 seconds, a saving of 49.4 per cent.

The operation of the jet units, 152 being operated in succession without the failure of a motor, had no adverse effect upon either stability or control or upon the plane structure. The pilot remarked, in fact, that the auxiliary thrust had made easier the handling of the plane throughout the take-off run. In short, results of the flight tests fully justified proceeding with plans to develop and test both solid and liquid-propellant jet motors designed to deliver 1,000-pound thrust.

LATER DEVELOPMENTS OF JATO

Simulating a period of twenty-eight days, tests were run to determine the keeping qualities or storage life of the new propellant, GALCIT 27. Under test it deteriorated too fast for use in the services. Shrinkage of the powder stick tended to draw it away from the liner, thus breaking the seal of the propellant across the diameter of the combustion chamber and permitting flame to penetrate below the surface and cause an explosion. In September an experimental program was started to improve both liner and powder.

Early in 1942, while the program was still in progress, the report of the Navy Officer who had witnessed the Ercoupe flight led to action. The Navy contracted with the Project to develop for experimental purposes a jet unit, with acceptable storage life, to deliver 200-pound thrust for eight seconds, shown in *Fig. 4*. The Project planned to incorporate in the unit the improvements expected to result from the program in progress. In May a greatly improved solid propellant and a suitable motor were ready for testing. The improved propellant was designated as GALCIT 46.

Meantime, the Project had been investigating the whole subject of solid propellants with the intent to develop one better than GALCIT 46. The latter had good storage life, but good only within too narrow a range of ambient temperatures for use in global warfare, which demands propellants suitable for use anywhere from Alaska to Africa.

To determine chances for success with any formula combining ingredients essential to all types of propellant like GALCIT 46, an investigation was made of the crystalline properties and the thermal expansion rates of such ingredients. The investigation suggested that both crystalline changes and expansion rates, over a wide range of temperatures, varied so that probably any compound would crack and disintegrate in burning.

After exhausting other possibilities, the investigators turned to a radically different type of propellant made by a different process, namely casting the ingredients in a mold rather than compressing them. What they turned up with was designated as GALCIT 53, the number being suggestive of the amount of developmental work the Project had done on solid propellants.

First tests of the molded propellant were made in June, 1942—by coincidence while the test program on GALCIT 46 was still running its course. GALCIT 53 showed such promise that the Project decided to give it priority over the other, to hasten its full development.

The oxidizer in GALCIT 53 was potassium perchlorate, in form a white powder. In addition to being plentiful, it combines the optimum in available oxygen, heat of combustion, and chemical and physical stability. The fuel in the new propellant was a special type of asphalt; added to it was a small percentage of oil with an asphalt base.

The mixture was prepared by heating the asphalt and oil in a mixing kettle to a temperature of 350°F., then stirring in the perchlorate. Before the combustion chambers were loaded with the finished propellant, they were lined with a hot mixture of asphalt and oil. When the propellant had cooled sufficiently, it was scooped into the combustion chambers, which were bounced a few times to assure uniform settling, then set aside for the propellant to harden.

In its finished form, GALCIT 53 is a black plastic, at ordinary temperatures resembling stiff paving tar. It can be detonated with difficulty if at all. Only with patience can it be ignited with a match flame; but once ignited it burns fiercely, emitting a white light and dense white smoke. Burning in a combustion chamber under pressure of 1,800 pounds per square inch, the propellant gives an average exhaust velocity of 5,300 feet per second at an average burning rate of 1.25 inches per second.

The new asphalt-base propellant had several advantages over all the earlier ones. It was easier to prepare, and ingredients were more readily available; it could be stored at wider temperature limits, and within those limits it could be stored indefinitely without deteriorating, whereas the earlier propellants had a tendency in storage to pull away from the liner, leaving tiny cracks, which led to explosions.

Units loaded with the new propellant were recommended to be fired at temperatures between 40°F. and 110°F. Much above the recommended temperature it became viscous and flowed. Therefore, it was imperative that invariably the JATO units be stored right side up, as they are in *Fig. 4*.

The rocket motor designed for use with GALCIT 53 was constructed to meet specifications set by the Bureau of Aeronautics, Navy Department. It was approximately thirteen inches long and five and one-half inches in diameter. The nozzle plate, which was screwed into the end of the combustion chamber, was equipped with a nozzle, an ignition squib, and a safety device, called a blow-out plug. The plug was a copper disk designed to blow out at a pressure approximately of 3,000 pounds per square inch, thus permitting excess gases to escape. To prevent danger from flying pieces and temporary excessive thrust of the jet unit at the instant of failure, a cap with four holes in its side walls was screwed over the disk. The holes in the cap permitted the gas flow to emerge in four jets which mutually canceled thrust in any one direction.

In 1943 the Navy, having a greater use for jet-assisted take-off than the Army, began placing large orders for motors delivering not only 200, but 500 and then 1,000-pound thrust.

RED FUMING NITRIC ACID AS AN OXIDIZER

As part of their work between 1936 and 1939, the GALCIT Research Group had made some preliminary study of liquid oxidizers, starting with a review of the data their predecessors had made available. After four months of work in 1939, they had reduced to four the compounds that recommended themselves for further study. Within an additional six weeks, by still more rigorous process of elimination, they had reduced the four to one; namely, red fuming nitric acid, a solution of nitric acid and nitrogen dioxide, with the chemical formula HNO_3NO_2.

The Project celebrated its first birthday, July 1, 1940, by initiating a program for the development of nitric acid as an oxidizer. For the time being at least, the many difficulties inherent in the development of liquid oxygen could be forgotten. The way was open to develop, as directed by the Army Air Corps, a liquid-propellant rocket unit to deliver 1,000-pound thrust for approximately one minute.

THE FIRST 1,000-POUND THRUST MOTOR

Engineering practice suggested that the development of the projected motor and its assembly should proceed, not in a single step from a small model to the full-size one, but through intermediate models graduated in size, in order to minimize the difficulties likely to arise as scale increases. Another reason for making haste slowly was that manpower and facilities were strictly limited. As a starter, then, the Project designed a unit to deliver thrust of 200 pounds.

Time out to clear ground and construct buildings during the summer of 1940 delayed development of the projected unit. But late in February, 1941, it was assembled in the new test pit designed to house it. One end of

FIG. 4. Motors with 200 pound thrust, 8 second duration, ready for delivery to the U. S. Navy.

FIG. 5. A bi-motor Douglas bomber, the A-20A, takes off assisted by two 1,000 pound thrust, 25 second duration liquid motors.

the structure was left open to expedite the escape of fumes. The open end faced into a hillside, where the solid earth should act as a cushion for flying missiles in case of explosions. As an added precaution, walls were built of heavy railroad ties set upright like the timbers in a stockade.

The chief difficulty in tests on the unit was with ignition. Unless it was instantaneous—and often it was not—such quantities of propellants collected in the chamber that, when they did ignite, the motor blew up.

The first tests were a decided disappointment. Sometimes ignition was delayed; sometimes it failed altogether. And in addition a new trouble appeared. Sporadically, the motor began to pulse, slightly at first but increasing in intensity until at the fourth or fifth throb, if not shut off, it would blow up.

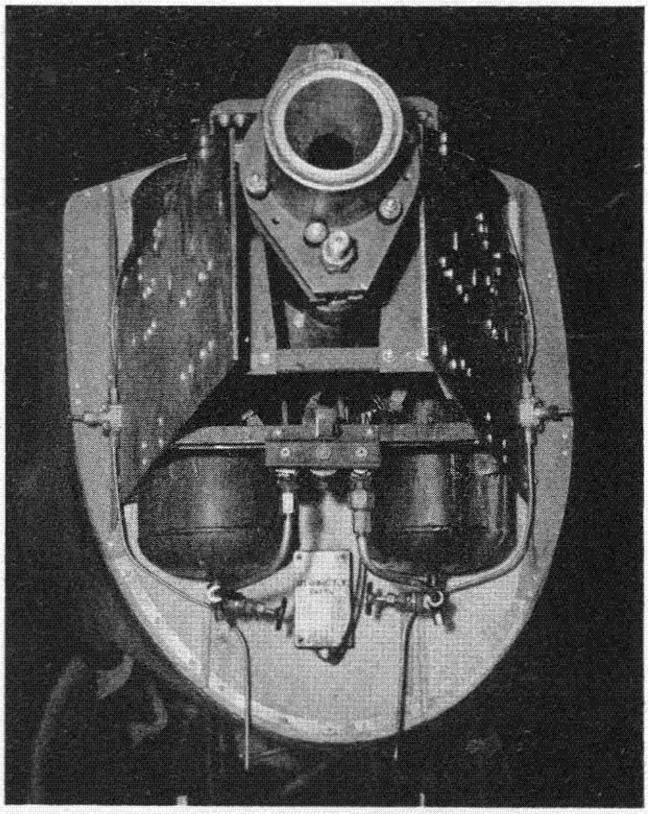


FIG. 6. A 1,000 pound A.T.O. unit on an A-20A airplane with the nacelle cone removed.

For four months the Motor Group labored to improve ignition and combustion, and to stop throbbing. In the end, though ignition was improved so that it worked possibly 80 per cent of the time, throbbing still presented a baffling problem.

ANILINE AS A FUEL

At the Naval Experiment Station, Annapolis, Maryland, another group of investigators had been having trouble with the combustion of nitric acid and gasoline. They suggested, talking it over with Dr. Malina who was visiting the Station, that perhaps the addition of aniline to the gasoline might help. Dr. Malina telegraphed his group in Pasadena, suggesting aniline, not simply as an additive to gasoline but as a substitute for it.

Put into practice, the suggestion worked. Not only did it work, but it led to the discovery in the United States that aniline is spontaneously combustible with red fuming nitric acid. Thus, at once, ignition, combustion, and throbbing problems were solved.

But there was still a serious question to be decided. Should the attempt be abandoned to develop gasoline as a fuel in favor of aniline? Gasoline has a great advantage for military operations in that it is available, as are facilities for handling it and operators who know how. Aniline, on the other hand, though available, is a toxic liquid that affects the blood, and it is readily absorbed through the pores of the skin. If adopted, facilities for handling it would have to be developed, and crews would have to be taught how to use it properly. But the decision was made, in the end, to adopt aniline.

THE A-20A FLIGHT TESTS

The chief purpose of the projected flight tests was to gain information about air-borne equipment and control devices essential for practical application to liquid-propellant rocket units.

The choice of an airplane suitable for mounting and testing a pair of units, each with 1,000-pound thrust for a duration of approximately 25 seconds, settled upon a bi-motor Douglas bomber, the A-20A which is shown taking off in *Fig. 5*. The weight of the plane, empty, was 14,000 pounds. Its tail surfaces were high enough to clear the jets from the motors; and the nacelle tail cones, which projected rearwards well behind the wings, provided ample space to house a unit. This space is used sometimes to mount a machine gun firing aft.

The Design and Control Group was responsible for all installations. Early in the winter of 1941, the Group was engaged in preparing a complete mockup, or dummy, of the motor and all the equipment, exactly as the assembly would be mounted in the A-20A. The work was expedited in January when the A.A.F. sent detailed drawings of the plane and an actual nacelle cone to work with. *Fig. 6* shows a 1,000-pound JATO unit on an A-20A airplane, nacelle cone removed.

A simplified description of the assembly and its installation in the plane is as follows: the nitrogen tanks to supply pressure for the propellants were located in the forward bomb bay, with a line leading to each nacelle cone. In each cone were located a motor, two propellant tanks, and a valve—actuated by hydraulic pressure —to control the propellant supply. The end of each cone was cut off in order to give the exhaust nozzle necessary clearance. In the rear cockpit were six pressure gauges to measure the performance of the installation, and eleven controls, all accessible to the operator stationed there.

Among the numerous safety precautions taken, two especially deserve notice. Each motor, mounted on slides, was restrained by hydraulic thrust jacks in order to permit recoil so that, if there was an explosion, the plane would not have to absorb the forward thrust of the combustion chamber. The purpose of the second precaution was to avoid destructive thrust if the nozzle was blown off. It was coupled to the motor body by a pair of shock absorbers so that the two units could react upon one another instead of one of them reacting on the plane; moreover, both of them would be brought to a full stop within a few inches.

The flight tests with the A-20A were conducted at the A.A.F. Bombing and Gunnery Range at Muroc, California, April 7 to April 24, 1942. The pilot was Major P. H. Dane. During the tests forty-four successive runs were made without any misfires or explosions. For the first time in the United States, an airplane had taken off, assisted by liquid-propellant rocket units.

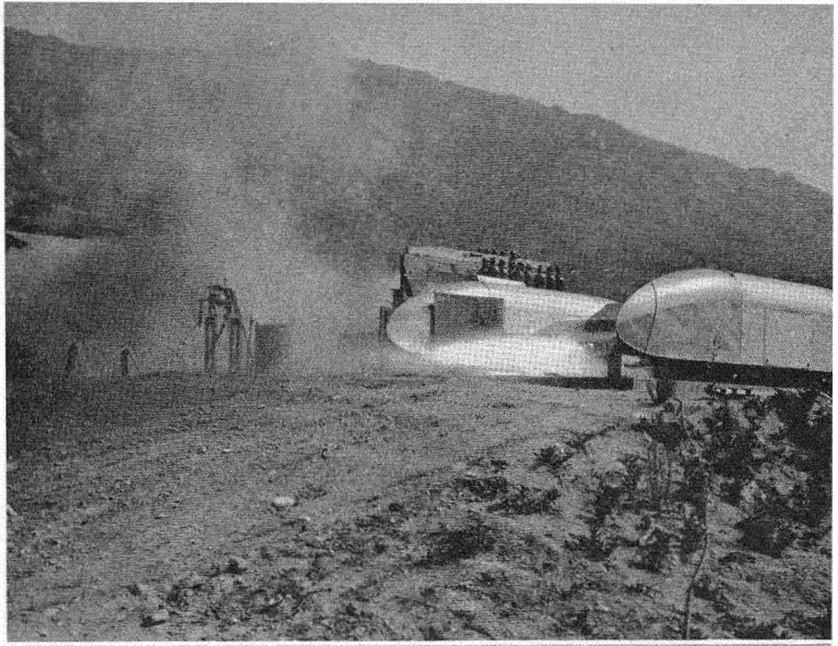
Like the earlier tests with the Ercoupe, those with the A-20A were highly successful. Reduction in distances required to take off were very close to those predicted. And the experience gained in the development of the experimental unit cleared the way for the design and manufacture of a service type.

THE HYDROBOMB

In 1943, the Armament Laboratory of the A.A.F. arranged with the Jet Propulsion Laboratory, GALCIT to develop a missile to be launched from a bombing plane and to be propelled at high speed under water by means either of solid- or liquid-propellant rocket units.

The missile at present under development is called the hydrobomb. Two different prototype models have been built for the A.A.F.; one by the Westinghouse Manufacturing Company, and one by the United Shoe Machinery Company. The Laboratory has designed and constructed half-scale models of these prototypes.

A full-scale model, constructed by the United Shoe Machinery Company, and reproduced in *Fig. 8* is more than 10 feet long, with a maximum diameter of 28 inches. Designed to be launched at speeds up to 350 miles per hour, and to travel under water at 70 miles per hour, the missile is driven by a solid-propellant rocket unit delivering 2,200-pound thrust for 30 seconds. The range of the missile is 1,000 yards; gross weight, approximately 3,200 pounds; and the weight of the warhead, 1,250 pounds.



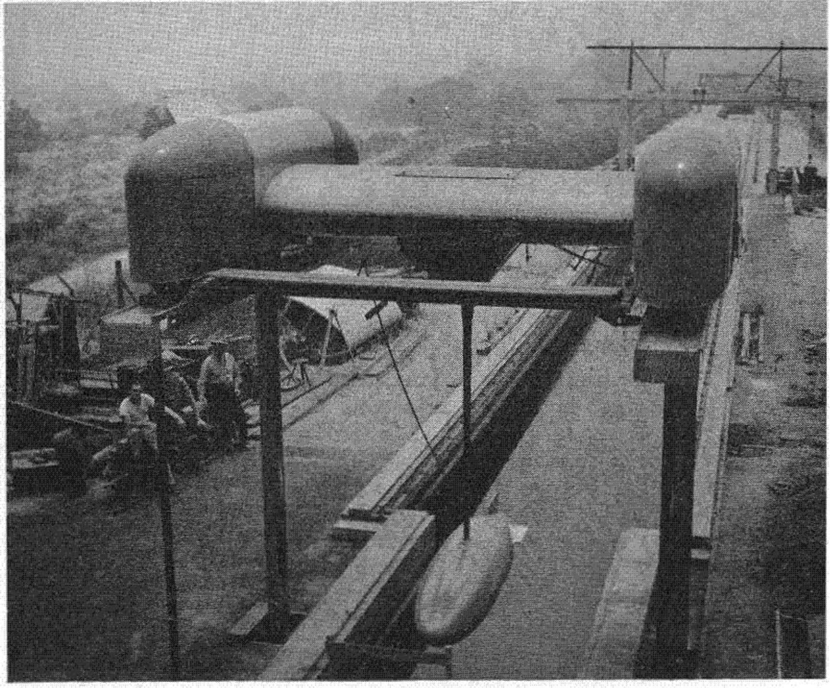


FIG. 7. (Top): Static test of rocket-propelled towing car.
FIG. 8. (Bottom): Full scale model of Hydrobomb constructed by the United Shoe Machinery Company.

FACILITIES FOR RESEARCH

Of fundamental importance in the research program undertaken to develop the hydrobomb was basic information upon the hydrodynamic characteristics of the proposed missile. It was imperative to know, for example, the effect of jet propulsion upon stability and performance of an underwater missile, and the effect of jet propulsion upon cavitation, a phenomenon well known to designers of high-speed underwater craft.

The experimental part of the research program set up to develop the hydrobomb demanded elaborate apparatus, useful also in other investigations of propulsion under water. This apparatus is a towing channel equipped with facilities for observing and measuring the behavior under water either of models or of full-scale craft.