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RESEARCH MEMORANDUM

PREFLIGHT AND FLIGHT-TEST INVESTIGATION OF A 50-PERCENT-MAGNESIUM 50-PERCENT JP-4 SLURRY FUEL IN A TWIN-ENGINE RAM-JET VEHICLE

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NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS
WASHINGTON

May 31, 1956
Declassified November 8, 1957

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PREFLIGHT AND FLIGHT-TEST INVESTIGATION OF A 50-PERCENT-MAGNESIUM 50-PERCENT JP-4 SLURRY FUEL IN A TWIN-ENGINE RAM-JET VEHICLE

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SUMMARY

An investigation was conducted by means of preflight and flight tests to determine the performance of a 50-percent-magnesium 50-percent JP-4 slurry fuel in a twin-engine ram-jet test vehicle. Data were obtained over an equivalence-ratio range of 0.25 to 0.9 at Mach numbers of 1.84, 2.06, and 2.21 in free-jet tests. The flight test was used to obtain performance data at altitudes of 3,320 to 37,940 feet at Mach numbers of 2.03 to 2.56. Flight data indicated that the thrust coefficient varied from 0.540 to 0.664 over the corresponding Mach number range. Performance during the flight test was below that obtained in the preflight tests, and below theoretical values. Additional research and development is needed on this type of fuel to achieve performance superior to that of the hydrocarbon fuels now in use.

INTRODUCTION

Because of the ever-increasing need for better performance from ram-jet and turbojet combustors over a wider range of operating conditions, a number of the high-energy metals such as aluminum, magnesium, and boron have been investigated for use as fuels. The results of these investigations are reported in reference 1. One of the more promising of the fuels evolving from this investigation is composed of 50-percent magnesium suspended in a hydrocarbon fuel. The National Advisory Committee for Aeronautics has investigated this slurry-type fuel; the results are reported in references 1, 2, 3, and 4. As part of an overall program on high-energy fuels, a flight test was made to determine performance over a wider range of conditions and to determine its operating characteristics in flight.

The NACA twin-engine test vehicle described in references 5 and 6 has been found satisfactory for this program, having the advantages of small size, accessibility, and a self-pressurized fuel system. The fuel system was modified to use the burners and the slurry fuel developed and supplied by the Lewis Flight Propulsion Laboratory. Although ground tests on the fuel and burner had been conducted by the Lewis Flight Propulsion Laboratory (refs. 1, 2, and 3), it was necessary to make preflight tests to obtain starting characteristics and to test fuel-system operation in the type of engine used in the test vehicle. The purpose of this paper is to report the results of flight and preflight tests of the 50-percent-magnesium slurry fuel by the Langley Aeronautical Laboratory.

SYMBOLS

t_f	time measured from take-off, sec
p	static pressure, lb/sq in. abs
T	static temperature, $^{\circ}R$
M	Mach number
S_a	air specific impulse, $\frac{\text{Pounds of jet thrust}}{\text{Pounds of air/sec}}$
C_t	thrust coefficient based on combustion-chamber area
$\frac{f}{a}$	fuel-air ratio; weight rate of fuel flow to weight rate of air flow
ϕ	equivalence ratio, $\frac{\text{Fuel-air ratio}}{\text{Stoichiometric fuel-air ratio}}$

APPARATUS

Test Vehicle

The test vehicle with twin ram-jet engines installed on the tail surfaces is shown in figure 1(a). The model-booster combination is shown in launching position in figure 1(b). The vehicle weighed 327.0 pounds including 60 pounds of 50-percent-magnesium slurry fuel. The vehicle configuration was identical to that described in references 5 and 6. Figure 2 presents configuration drawings of the model, along with pertinent dimensions. In order to adapt the model to slurry fuel, changes were necessary in the fuel control system, the fuel tank, the burners, and the exit nozzles; additional details of these are described in the following section.

Ram-Jet Engines

The ram-jet engines used on the test vehicle were similar to those described in references 6 and 7, having identical inlet and diffuser designs. Each engine weighed 44.5 pounds and was 51.35 inches long and 6.6 inches in diameter. A sectional view of a ram-jet engine is presented in figure 3(a). The exit nozzle had a minimum throat diameter of 6.0 inches, giving it a ratio of 0.852 between the cross-sectional area of the nozzle throat and the cross-sectional area of the combustion chamber, and a ratio of 1.174 between the cross-sectional area of the nozzle throat and the cross-sectional area of the nozzle exit. Burnout disks were provided just ahead of the exit nozzles to facilitate starting the engines during flight. The burnout disks blocked 40 percent of the combustion-chamber area and burned out 0.7 second after engine ignition. The burners (see fig. 3(b)) are similar to those described in references 3 and 4, each weighing 10.5 pounds including the ignition flare. The ignition flare, located in the center of the burner, had a burning time of approximately 20 seconds and was ignited 5 seconds prior to booster firing in the flight test.

DESCRIPTION OF FUEL

The slurry fuel used in the flight test was provided by the Lewis Flight Propulsion Laboratory and consisted of 50.7 percent solids by weight suspended in commercial JP-4 turbojet fuel. The solid portion of the fuel consisted of 93.1-percent free magnesium by weight, 3.5-percent free aluminum; and the remainder was mainly magnesium oxide. The mean particle size of the solid particles in the fuel was 0.6 micron.

The Brookfield viscosity of the fuel was approximately 8,000 centipoises. No mixing was done on the fuel after it was loaded in the flight-test vehicle 95 minutes before the flight test; however, the fuel was mixed for approximately four hours before being transferred to the flight-test vehicle.

FUEL SYSTEM

The fuel control system consisted of a pressurized fuel tank, an electrically fired squib valve, and a distribution system having a fixed calibrated orifice to meter the fuel to each engine. A diagram of the fuel system is presented in figure 4. The fuel tank was pressurized to 1,100 pounds per square inch with helium, and no boundary was provided between the helium and the fuel. While the model was being accelerated, the fuel remained in the rearward end of the fuel tank. A trap was provided in the rearward section of the fuel tank in order that short periods of deceleration would not interrupt the fuel flow. The electrically operated squib valve permitted the fuel flow to be started 1.0 second after take-off.

Metering orifices provided a predetermined fuel flow to the engines during the flight test. Because of the increasing volume and decreasing pressure of the helium, a decreasing fuel rate was obtained as altitude increased during the flight test.

PREFLIGHT INSTRUMENTATION AND METHODS

Preflight tests on a single ram-jet engine were conducted at $M = 1.84$ and 2.06 in the 8-inch-diameter free jet, and a twin-engine test was performed in the 12- by 12-inch free jet at $M = 2.21$ at the preflight jet of the Pilotless Aircraft Research Station at Wallops Island, Va. The preflight jet unit is described in detail in reference 8. Prior to flight testing, the engines were mounted in the 12- by 12-inch free jet as shown in figure 5. The strain-gage beam balance used in the free-jet test measured thrust in excess of drag during the engine operation. Diffuser-exit static pressure and combustion-chamber pressure were measured from pressure-gages on the engine. The differential pressure across the fuel metering orifices was measured for use in calculating fuel-flow rates. The metering orifices were calibrated with the same type of fuel prior to the tests. The fuel system was set up to simulate the system in the flight vehicle as nearly as possible. All fuel lines were made the same length and size as those in the flight vehicle.

FLIGHT INSTRUMENTATION

An NACA eight-channel telemeter was used to transmit meaurements of longitudinal acceleration, pitot stagnation pressure, left- and right-engine diffuser pressure, right-engine combustion-chamber pressure, left- and right-engine fuel differential pressure, and fuel-tank pressure.

An NACA modified SCR 584 tracking radar was used to obtain the flight path of the test vehicle during the flight, and continuous-wave CW Doppler radar was used to measure velocity. A balloon carrying a radiosonde transmitter was released at the time of the flight test to obtain atmospheric conditions and wind velocities aloft throughout the altitude range traversed by the model. Atmospheric pressure and temperature are presented in figure 6.

RESULTS AND DISCUSSION

Preflight Tests

The 50-percent-magnesium slurry fuel was tested in single-engine tests at $M = 1.84$ and 2.06 in order to obtain performance and starting characteristics and to develop techniques in the use and handling of this fuel. From measured data, values of air specific impulse and thrust coefficient were calculated by methods presented in references 8 and 9. Figure 7 presents air specific impulse plotted against equivalence ratio for the single-engine tests. The average values of air specific impulse from the preflight tests are compared with the theoretical impulse for 100-percent combustion efficiency and the average values obtained in closed duct tests at Lewis Laboratory. Performance in the free-jet tests was lower than in the Lewis Laboratory closed-duct tests and the theoretical values. Reference 10 shows that ram jets operated in open- and closed-duct tests may produce entirely different performance results. Free-stream stagnation temperatures of 830° to 900° F absolute were maintained in the preflight tests as compared with the Lewis Flight Propulsion Laboratory tests which were made at 830° F absolute.

Before the flight test, the two flight ram-jet engines were mounted in the 12- by 12-inch free jet at $M = 2.21$ to obtain the gross thrust coefficient of the engine. The fuel system from the model was used to duplicate the fuel-system operation and starting conditions in flight. Increased equivalence ratios produced corresponding increases in thrust over the range tested. Figure 8 presents gross thrust coefficient as a function of equivalence ratio for the twin-engine preflight tests over an equivalence-ratio range of 0.25 to 0.75 as compared with the single-engine tests. Sufficient fuel was not available to obtain starting characteristics over a wide range of equivalence ratios. Operation of the engines and fuel control system proved satisfactory in the twin-engine preflight tests.

Flight Test

The flight test was conducted at the Pilotless Aircraft Research Station at Wallops Island, Va. The model-booster combination as shown in figure 1(b) was launched at a 50° elevation and was accelerated to $M = 2.23$ at a 3,320-foot altitude by the booster rocket. From 3,320 to 37,940 feet, the ram-jet vehicle continued under its own power for 28 seconds after take-off; at that time, the fuel supply was exhausted. Figure 9 presents a Mach number time history of the flight test. Ignition flares in the ram-jet engines were ignited 5 seconds before take-off. Conditions of free-stream pressure and temperature for the flight test are presented in figure 6. Figure 10 presents a plot of altitude plotted against horizontal range of the model during the powered portion of the flight.

The test vehicle decelerated to $M = 2.03$ after leaving the booster and then accelerated until it reached a maximum of $M = 2.56$ at 27 seconds after take-off, as shown in figure 9. Velocity was determined by three methods: by CW Doppler radar, by integration of the longitudinal accelerations, and from total-pressure measurements on the model. Velocities obtained from CW Doppler radar and by integration of the longitudinal accelerations agreed within 1.0 percent, and velocities obtained from the total-pressure measurements agreed within 2.0 percent of the other two methods. The CW Doppler radar was effective for only the first 13 seconds of the flight; after this time, its readings became erratic because of the metallic exhaust of the engines.

Fuel flow during the flight test was measured by means of fixed orifices which were calibrated prior to the flight test. Figure 11 presents equivalence ratio as a function of time for the flight test. Combustion in the left engine was erratic for the first 4 seconds after booster separation. This erratic combustion caused a loss in Mach number, producing higher equivalence ratios than expected for the remainder of the flight.

Figure 12 presents a time history of air specific impulse of the engines during the flight test. Impulse was low for the first 4 seconds after separation. The engines performed satisfactorily from 7.5 to 11.5 seconds, during which time the thrust decreased abruptly for 0.9 second; after this interval they performed satisfactorily until the fuel supply was exhausted at 28 seconds. It is believed that the abrupt decrease in thrust of the engines at 11.5 seconds was due to clogging in the main fuel line. The fuel, in this case, was in storage for approximately one month before use. It was remixed on a drum roller and passed through a 16-mesh screen before use in the flight model. Although stoppage of the fuel in the lines did not occur in the preflight tests, its occurrence in the flight test indicates that more thorough preparation of the fuel is necessary if it is kept in storage for long periods of time before use.

Figure 13 also presents the variation of air specific impulse as a function of equivalence ratio for the flight test as compared with the preflight tests. Air specific impulse for the flight test was lower than in the preflight tests. Although the reasons for the low values of air specific impulse are not definitely known, previous tests on turbojets and ram-jet combustors indicate that combustion efficiency decreases with altitude. The low impulses obtained in these tests indicate the need for additional research and development if the optimum performance of this slurry-type fuel is to be realized.

Figure 14 presents a time history of the gross thrust coefficient for the flight test. Figure 15 presents a comparison of gross thrust coefficient, as a function of equivalence ratio, for the preflight and flight tests. Gross thrust coefficients were lower in the flight test than in the preflight tests. Thrust values were obtained from the longitudinal acceleration and the model weight for any given time. Values of air specific impulse and thrust coefficient were calculated from measured data by methods presented in reference 9.

CONCLUDING REMARKS

An investigation conducted by means of preflight and flight tests on a 50-percent-magnesium 50-percent JP-4 slurry-type fuel in a twin-engine ram-jet vehicle indicates the following results:

Although a successful flight test was made with the twin-engine ram-jet vehicle for Mach numbers from 2.03 to 2.56 while the test vehicle was climbing from an altitude of 3,320 to 37,940 feet, performance was below that obtained from preflight tests and below theoretical values.

Because of the low performance and poor starting characteristics of this type of fuel in its present state of development, additional research and development will be needed on the fuel and the burners to achieve the potential performance available from this slurry-type fuel.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., February 23, 1956.

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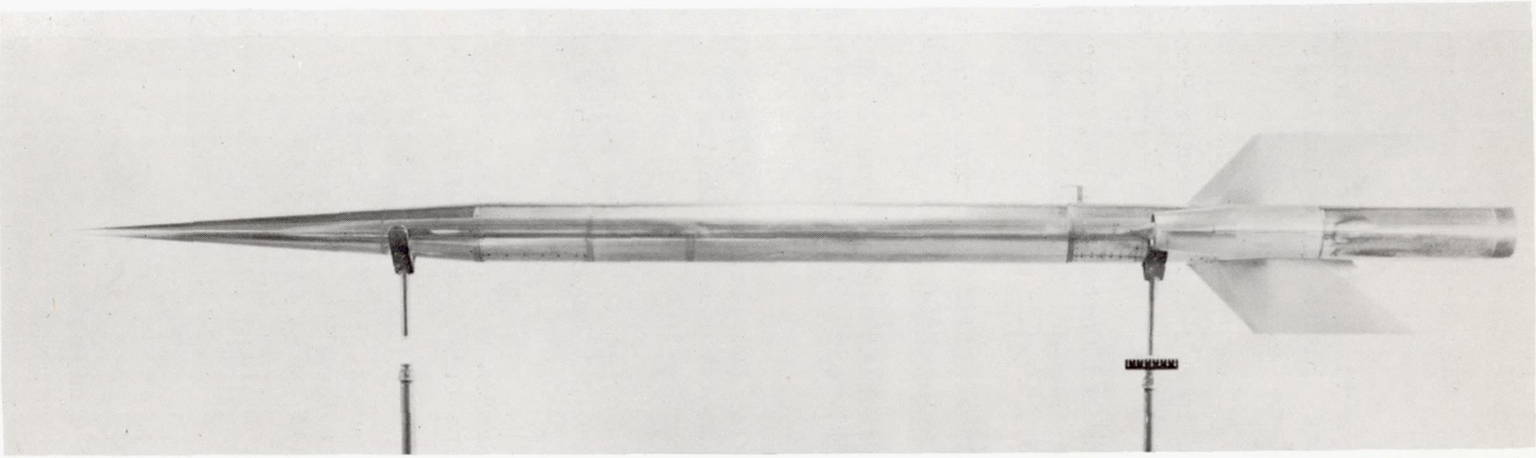

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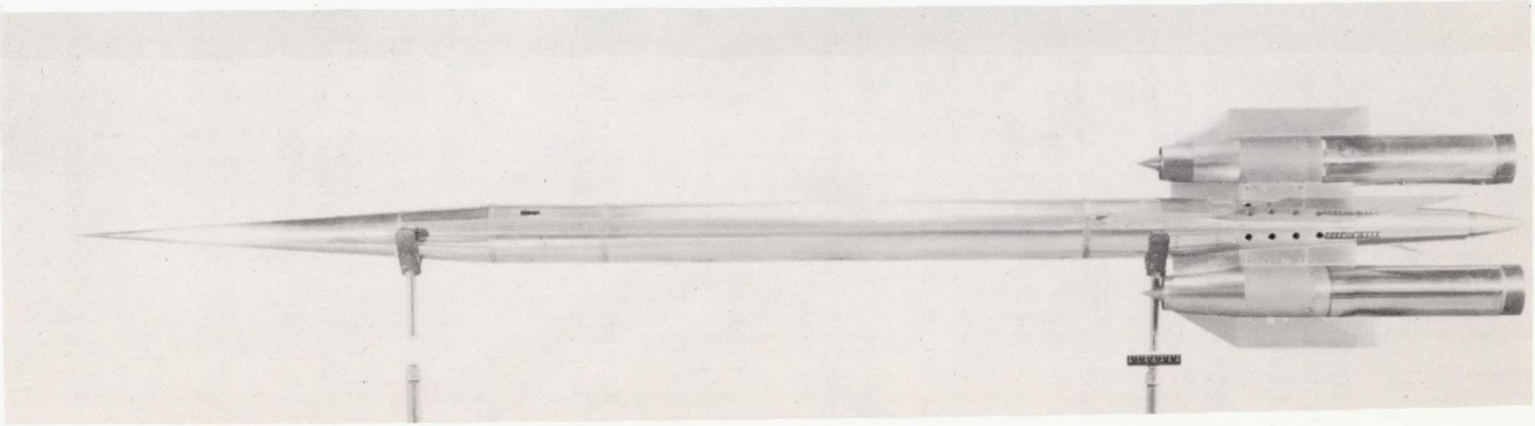

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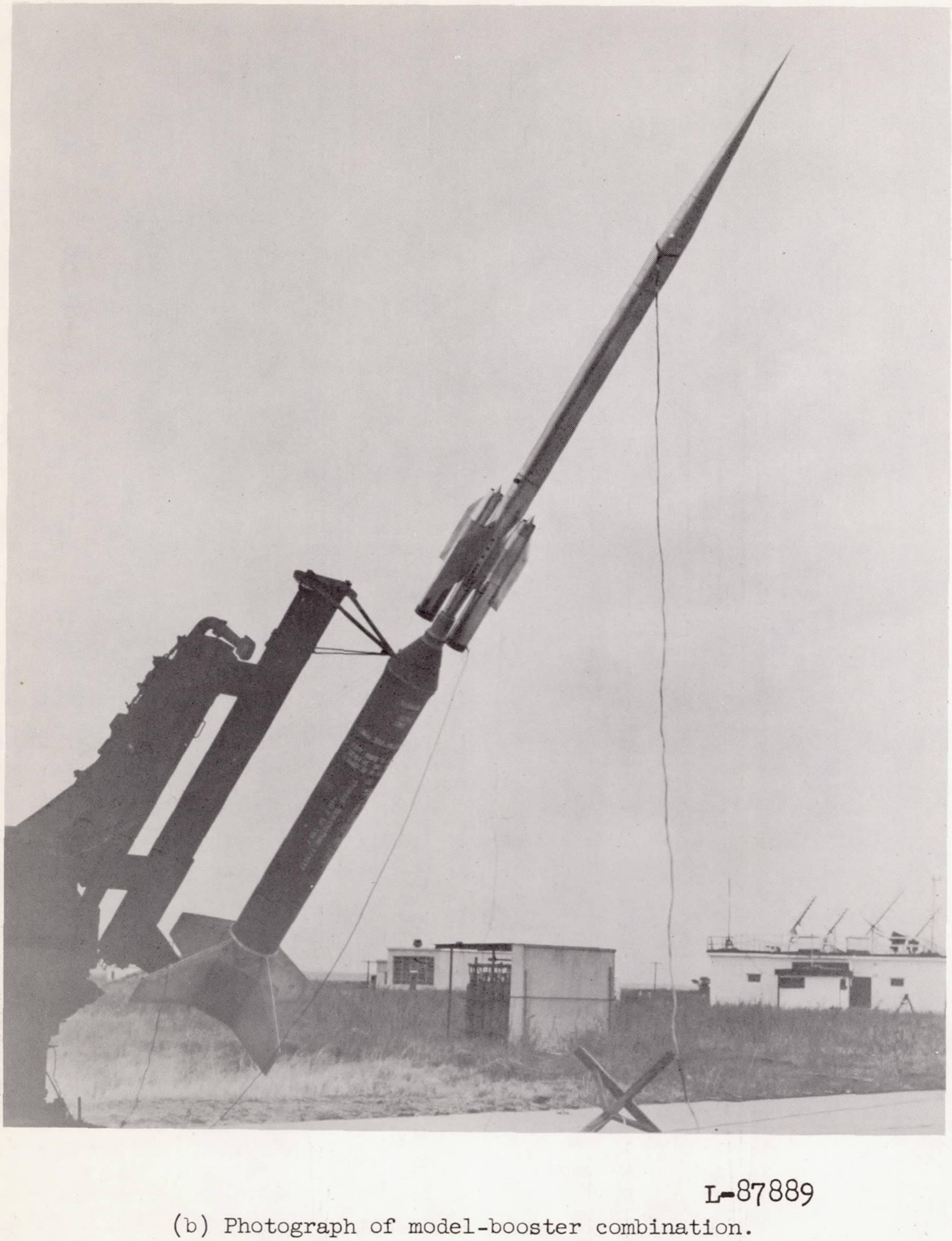
(a) Test vehicle in verticle and horizontal positions about center line.

Figure 1.- Photographs of test vehicle and model-booster combination.



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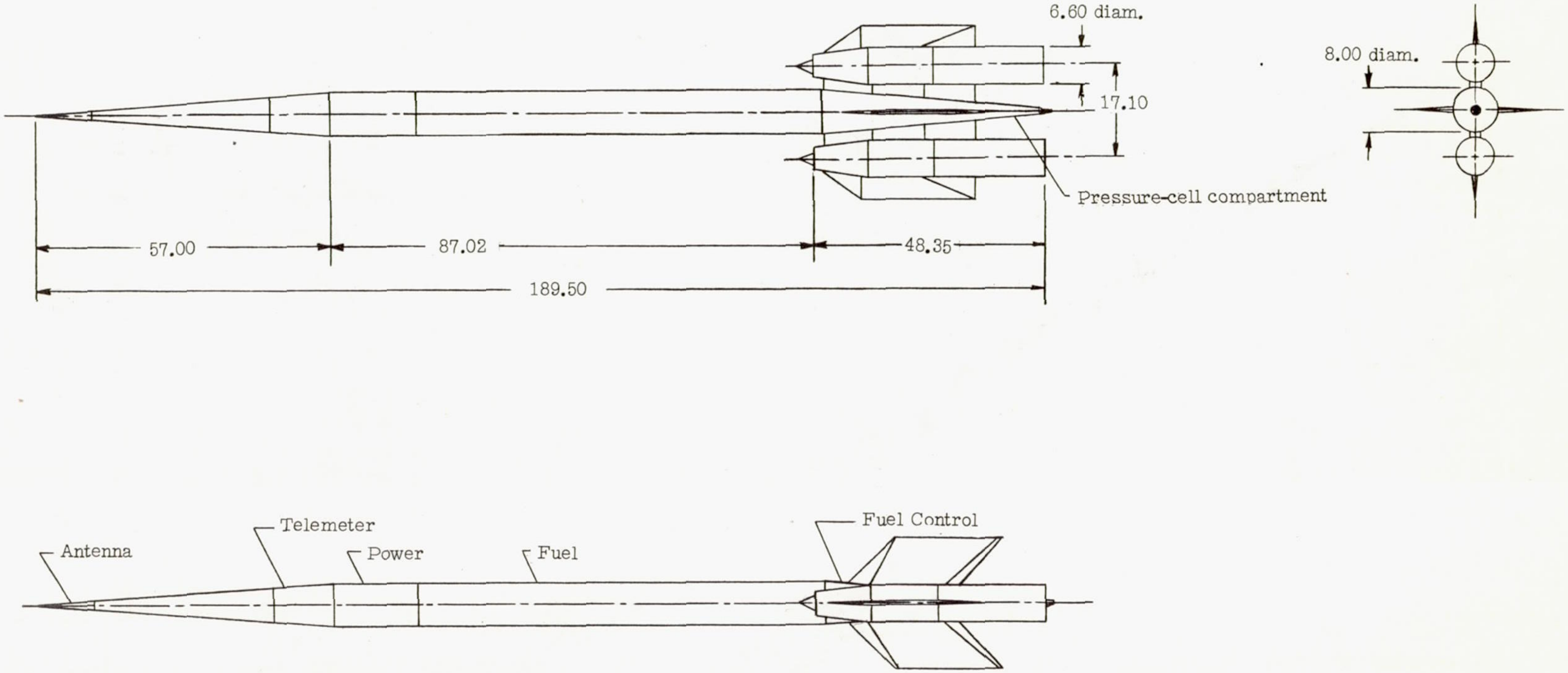
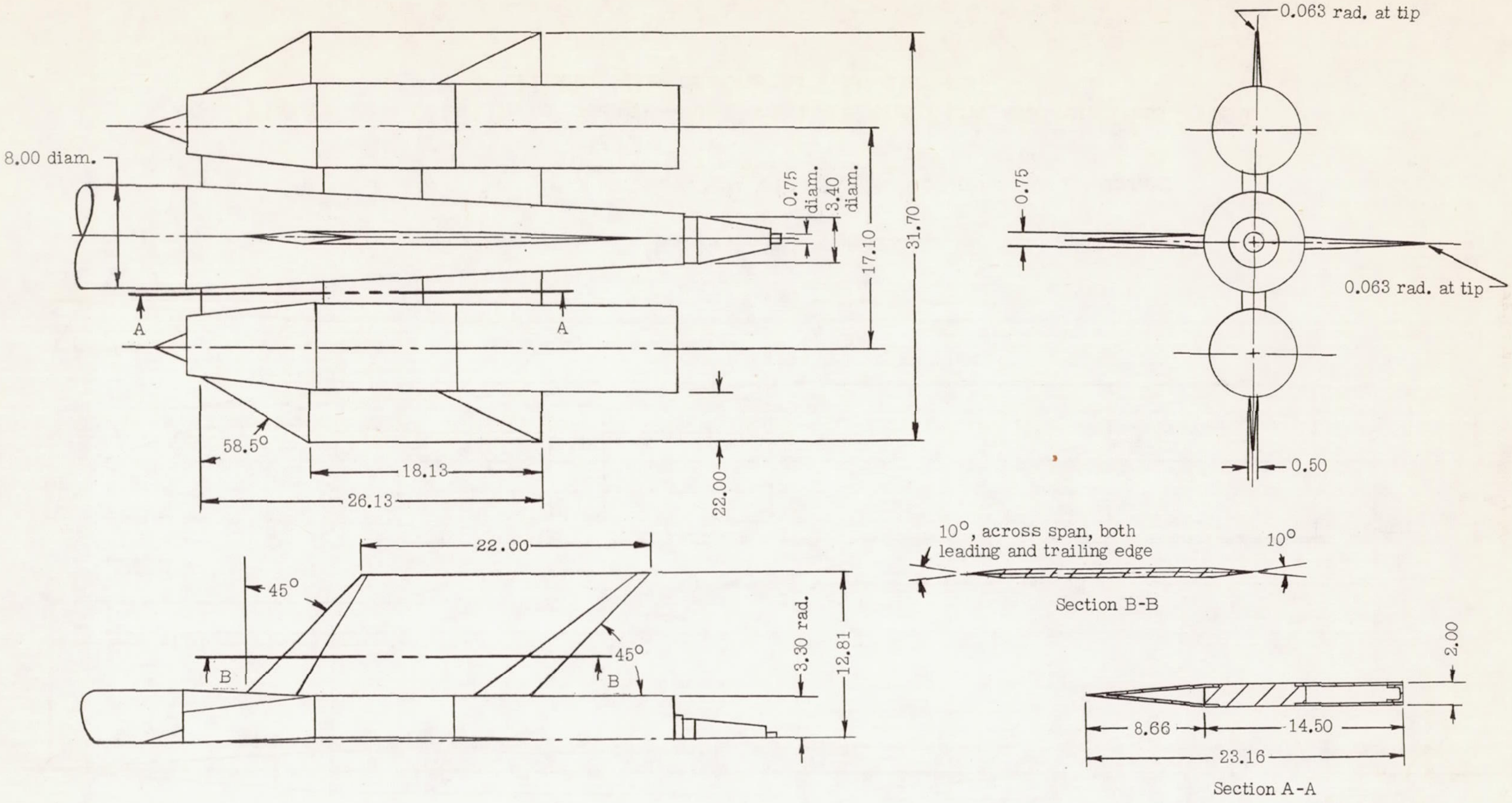
(b) Photograph of model-booster combination.

Figure 1.- Concluded.



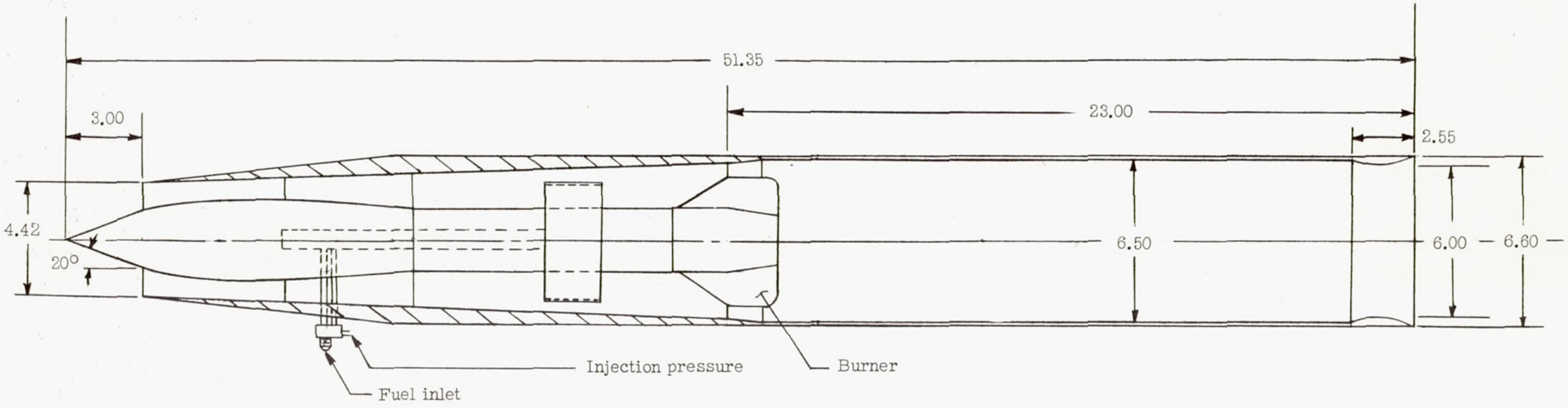
(a) Flight test vehicle.

Figure 2.- Details of flight test vehicle and fins and engines. All linear dimensions are in inches.



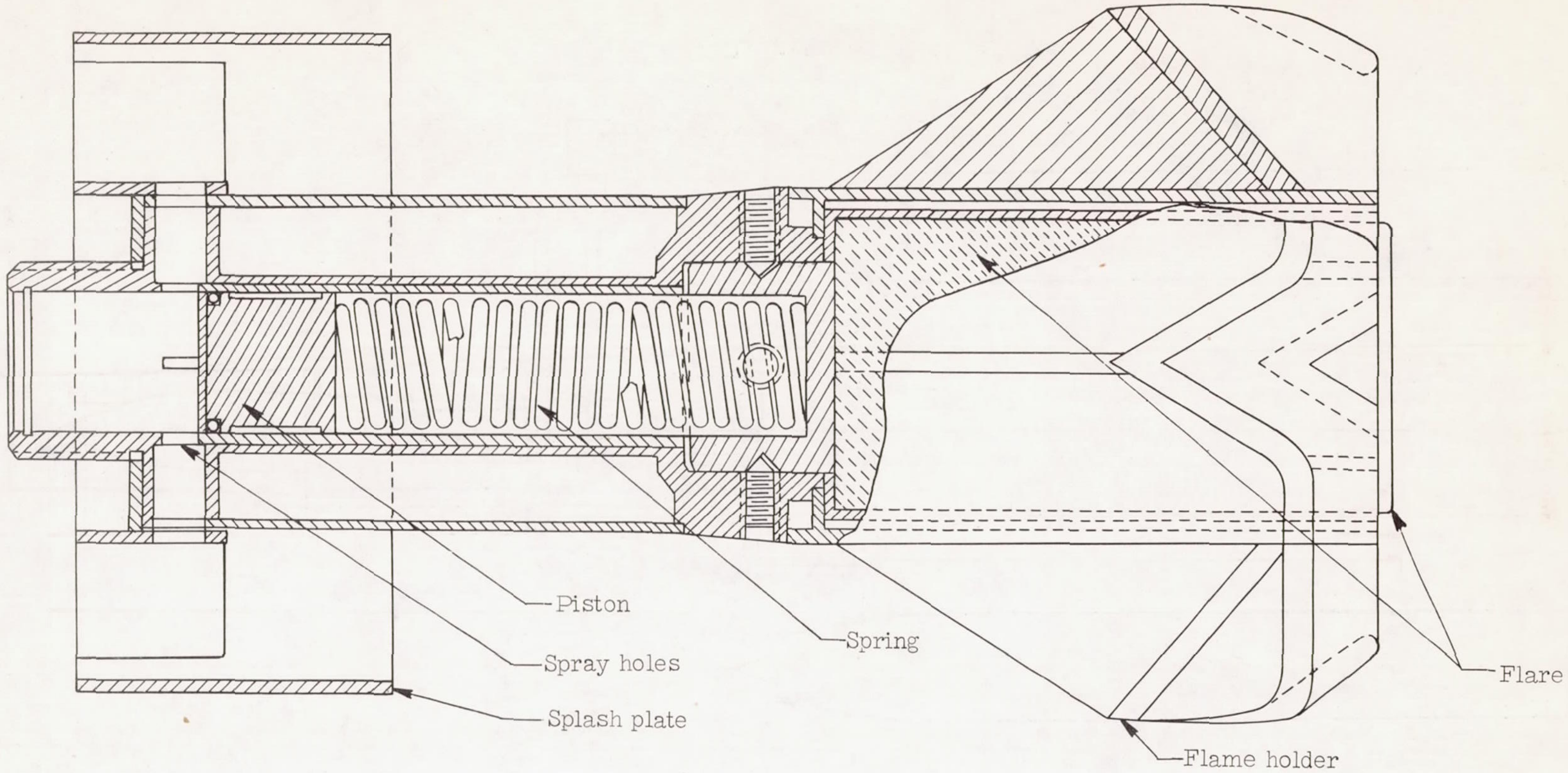
(b) Engines and fins of flight test vehicle.

Figure 2.- Concluded.



(a) Ram-jet engine.

Figure 3.- Sectional view of ram-jet engine and burner.



(b) Burner.

Figure 3.- Concluded.

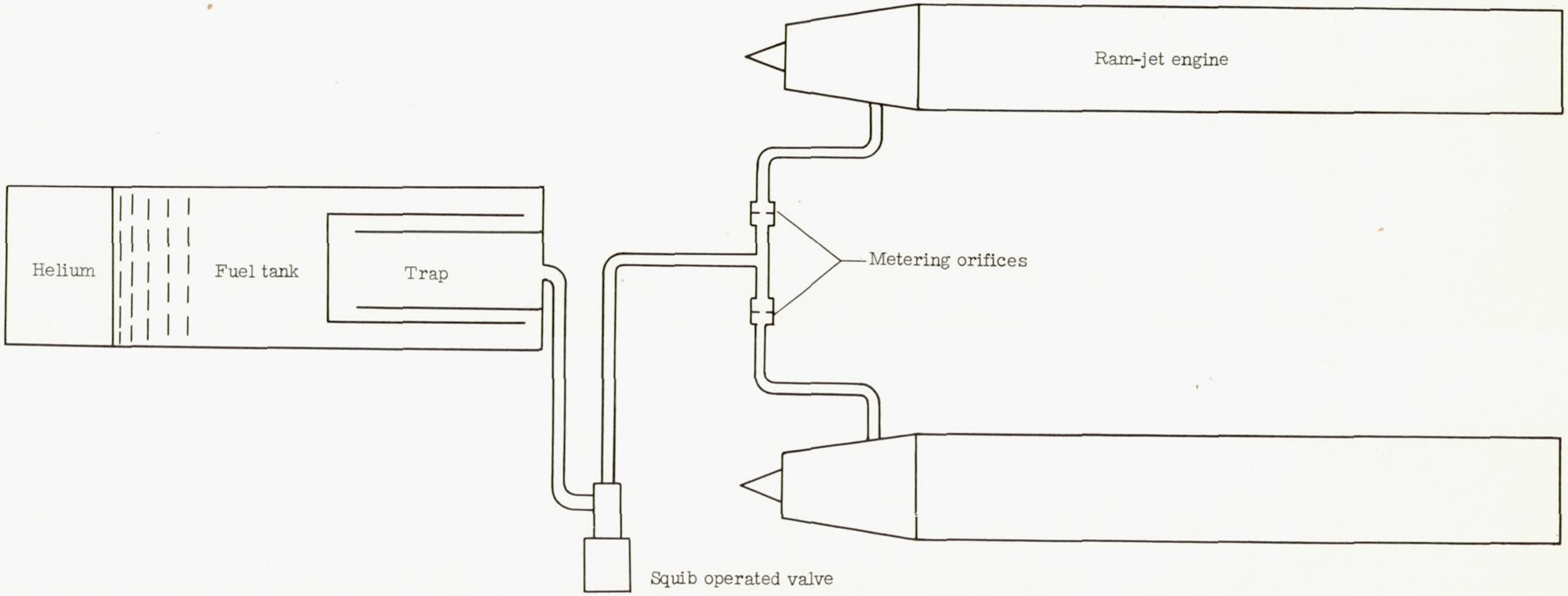


Figure 4.- Diagram of fuel system.

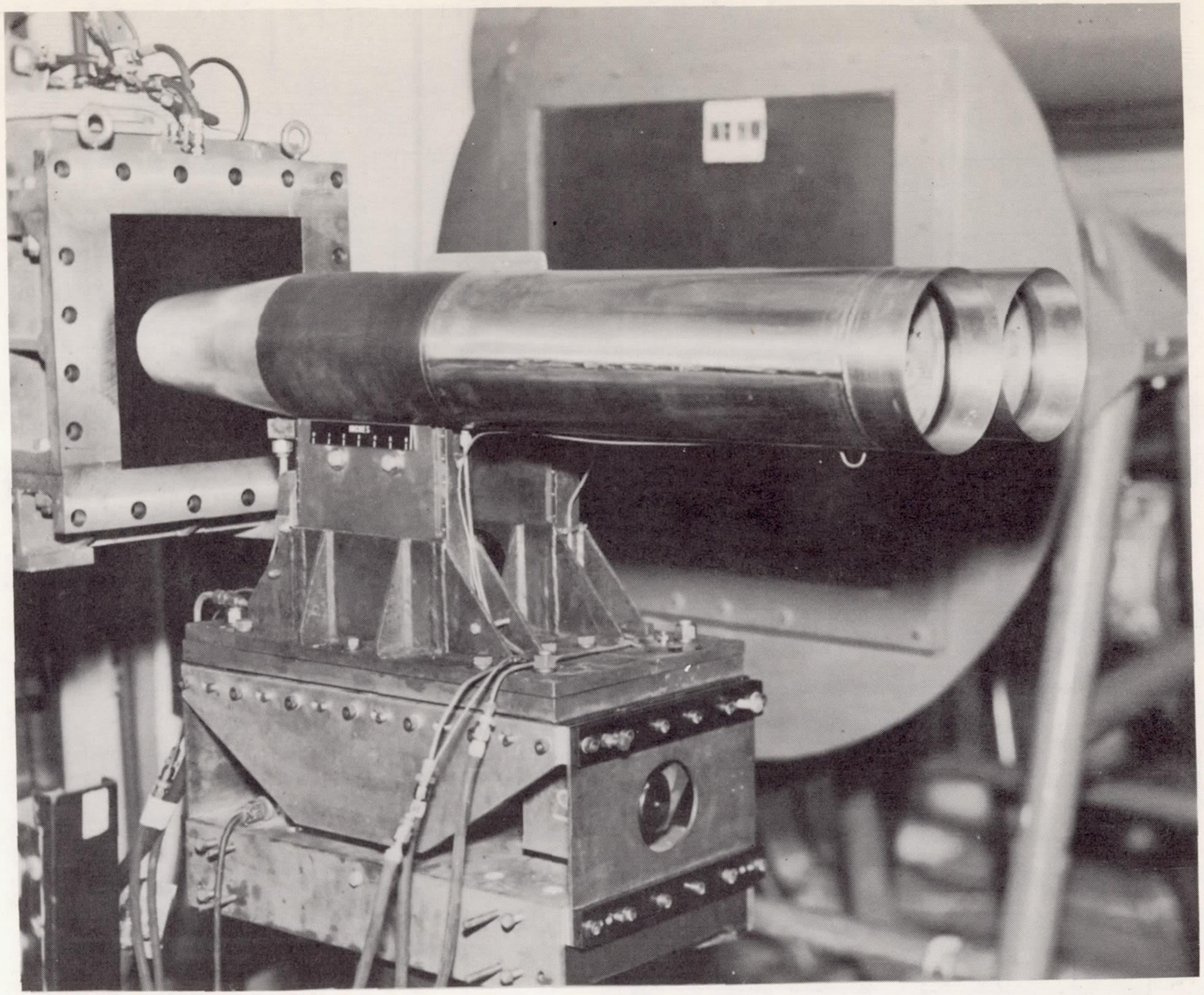


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Figure 5.- Photograph of twin ram-jet engines mounted in preflight jet.

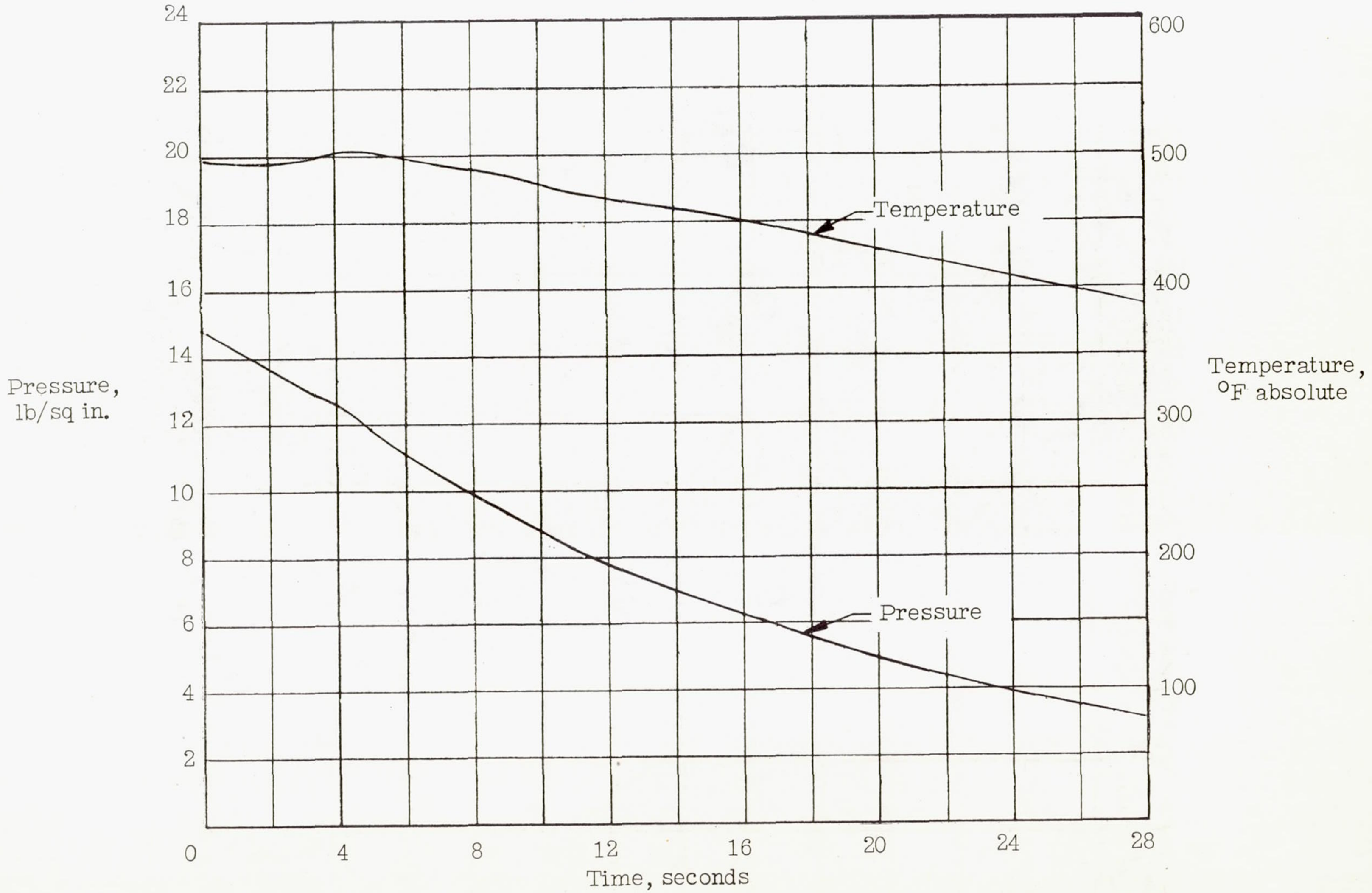

Figure 6.- Free-stream pressure and temperature plotted against time for flight test.

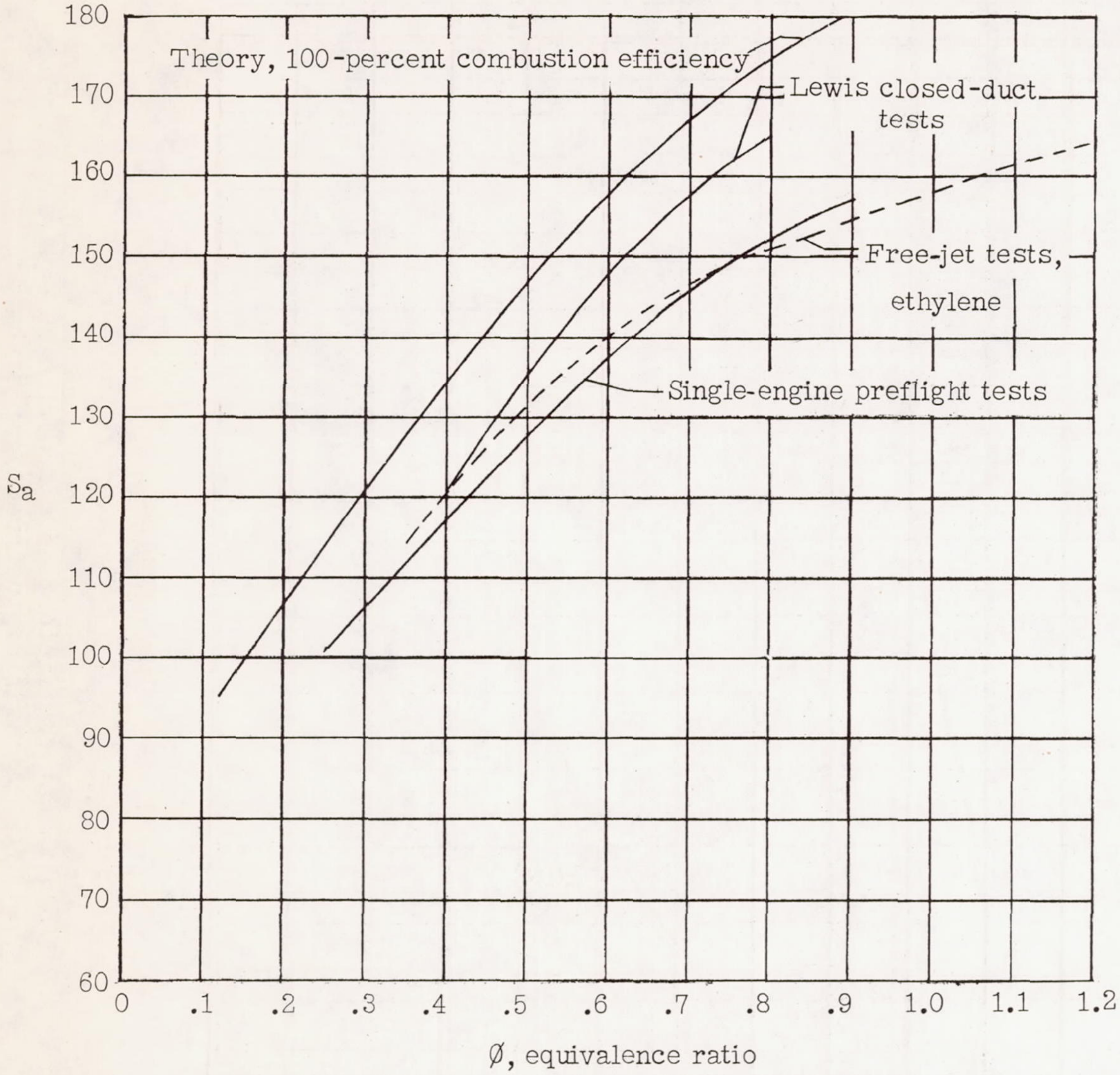

Figure 7.- Air specific impulse plotted against equivalence ratio for preflight tests.

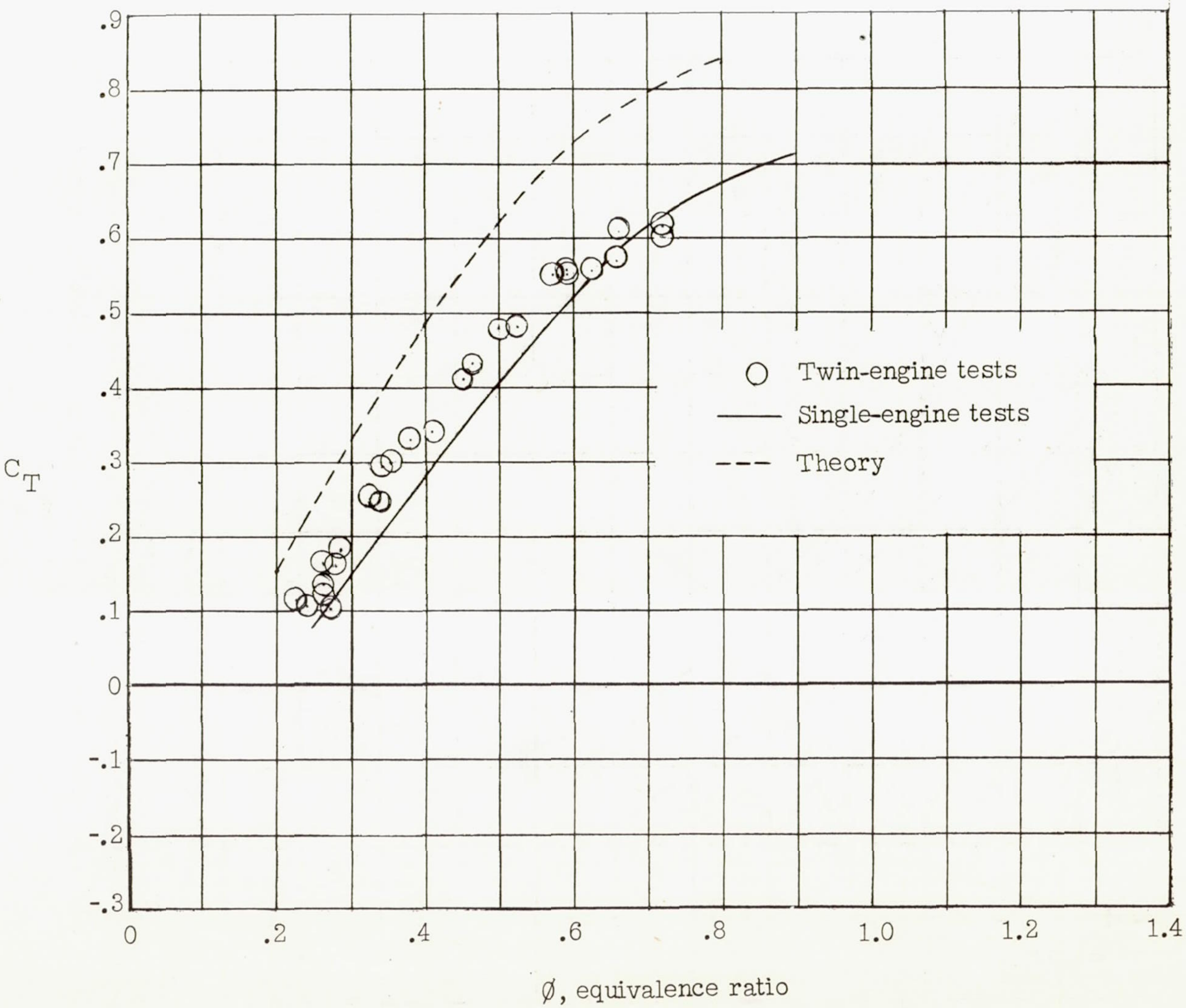

Figure 8.- Gross thrust coefficient as a function of equivalence ratio for the twin-engine preflight tests.

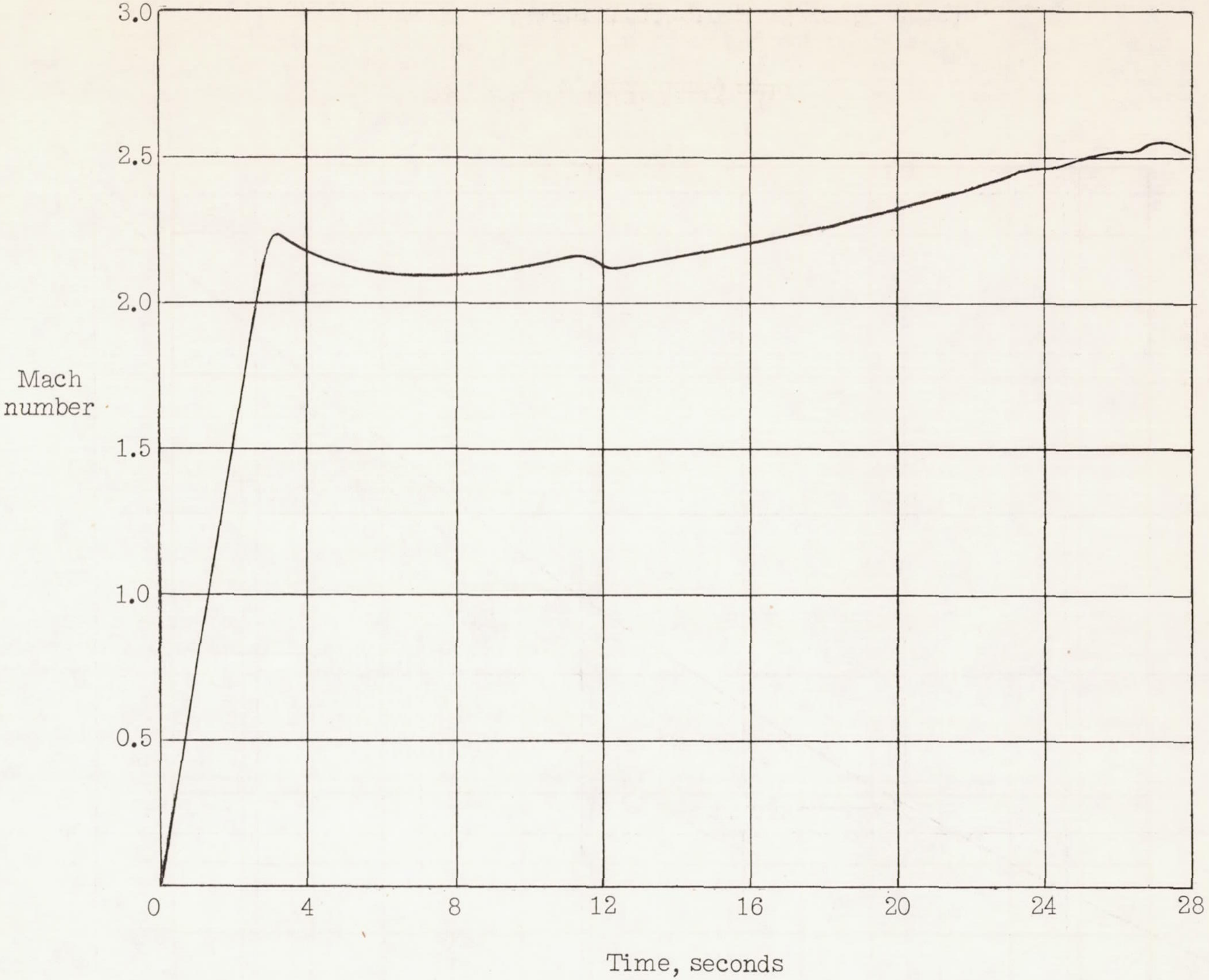

Figure 9.- Mach number time history of flight test.

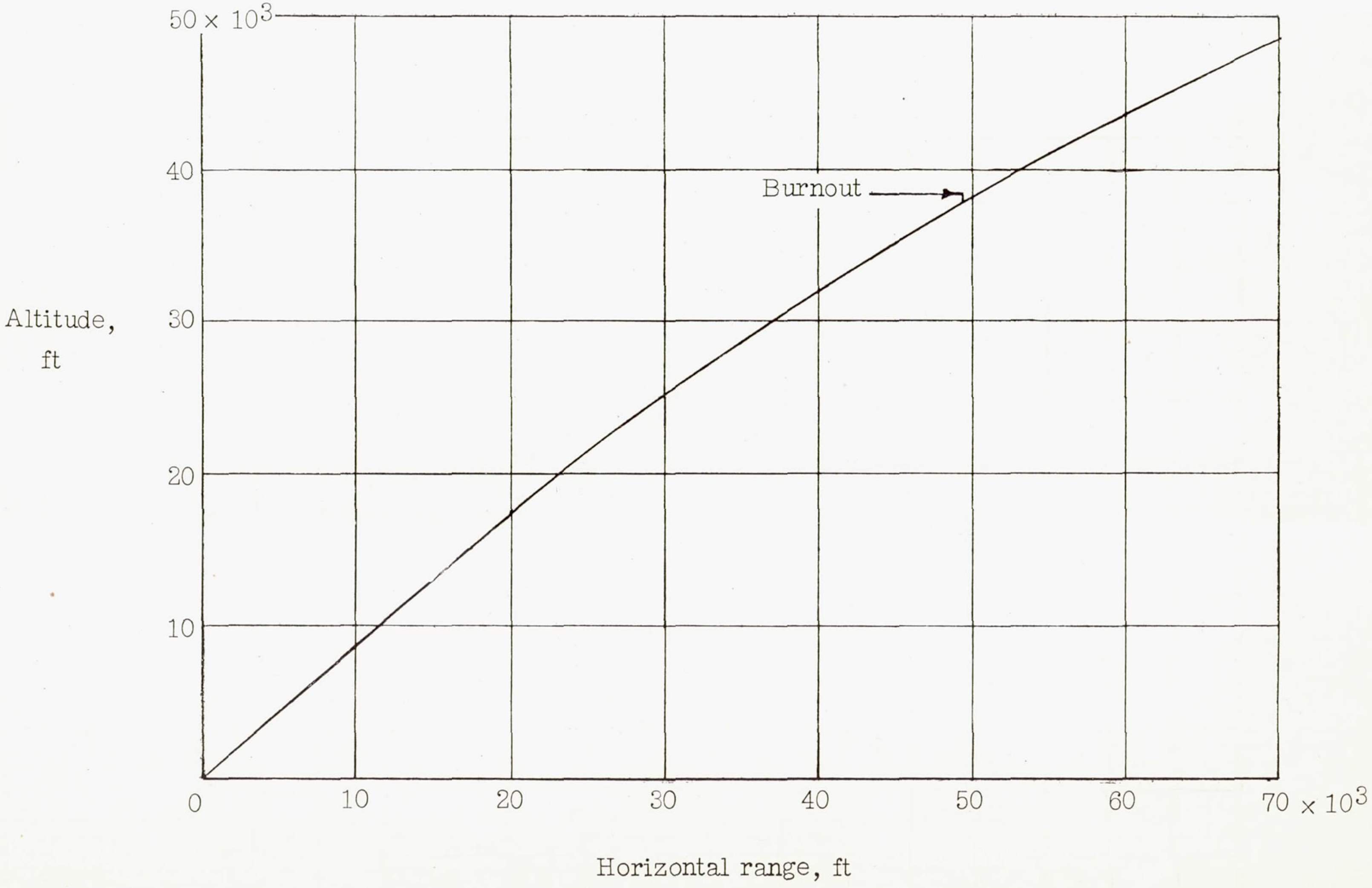

Figure 10.- Flight trajectory of test vehicle.

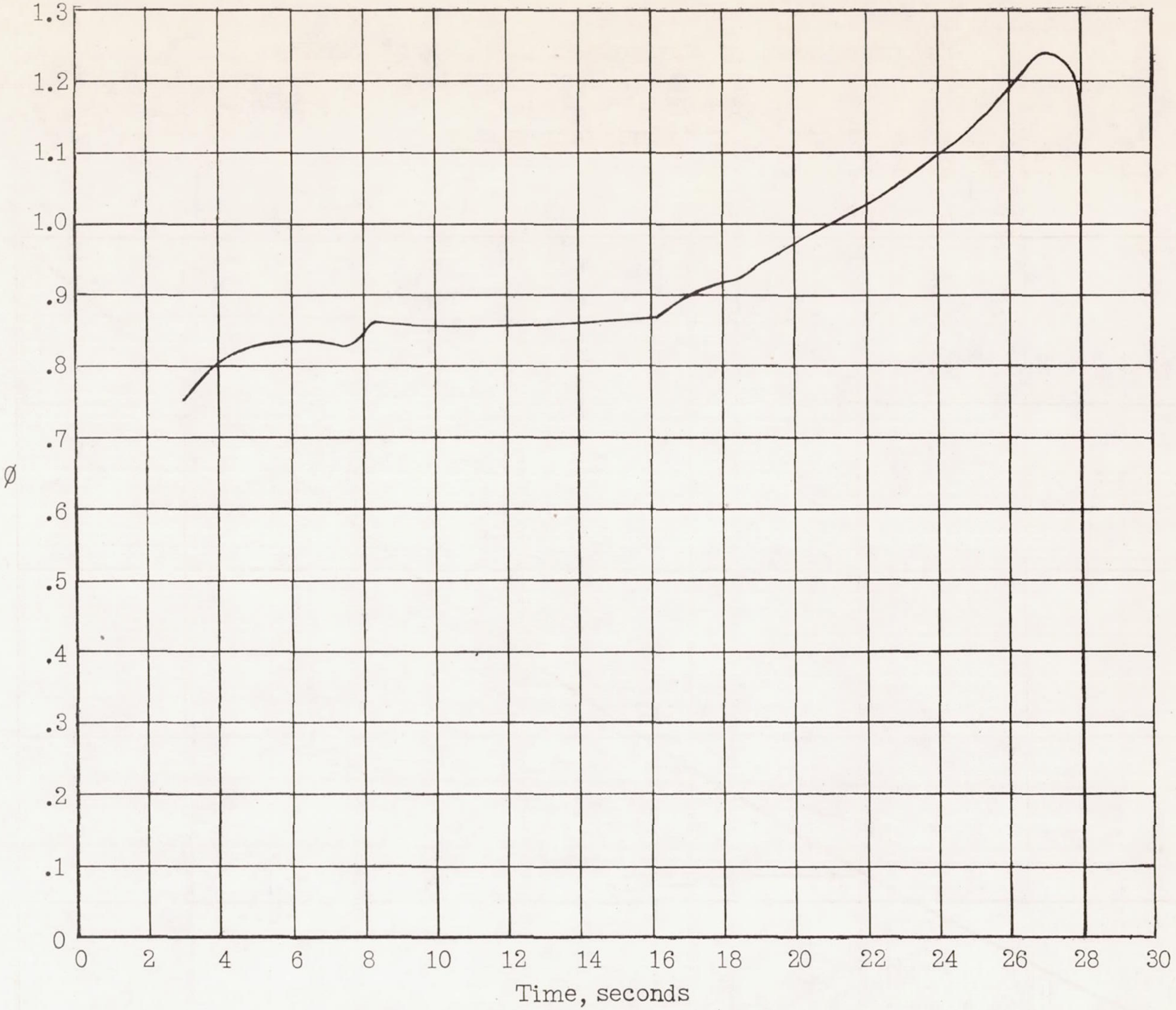

Figure 11.- Variation of equivalence ratio with time for flight test.

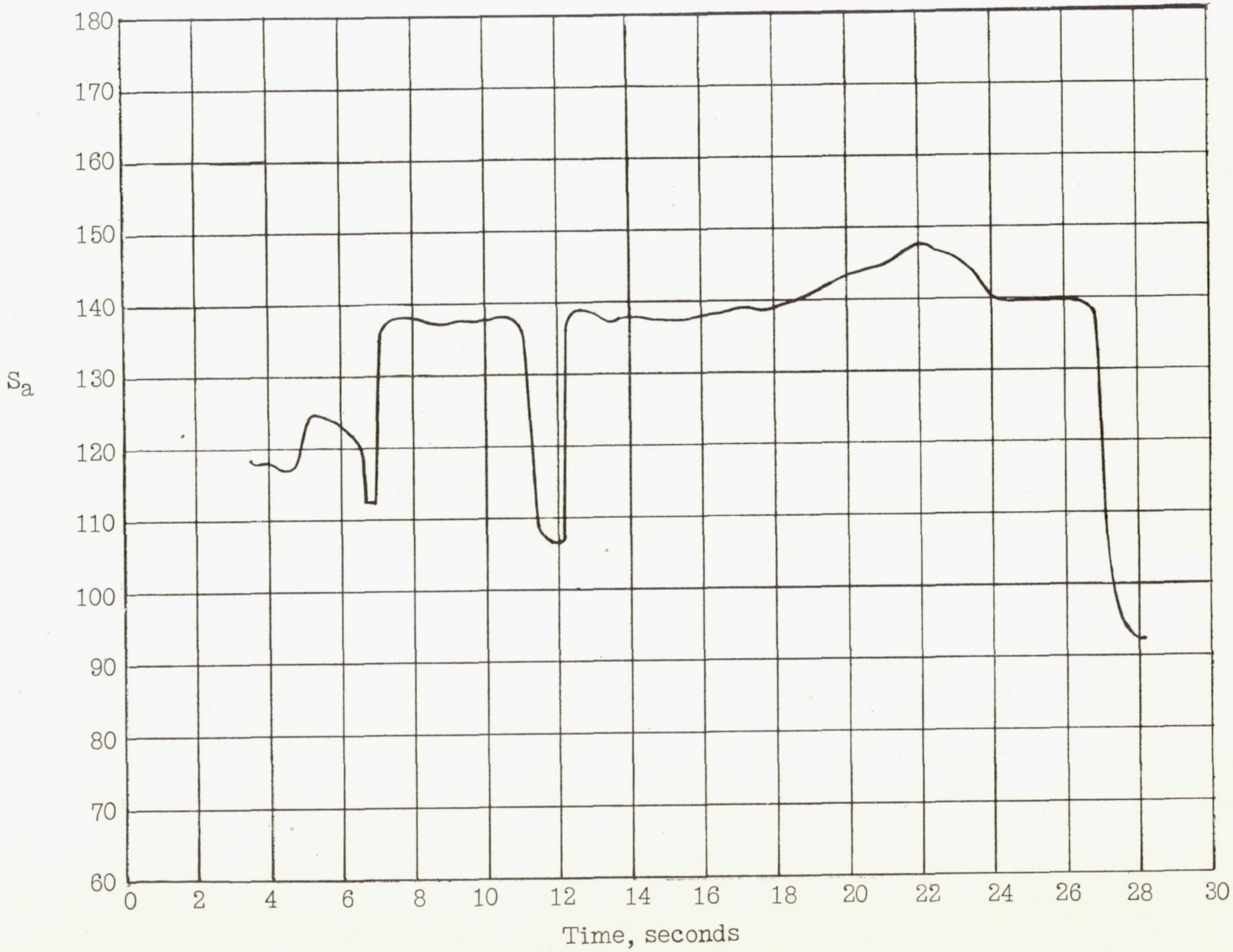

Figure 12.- Variation of air specific impulse with time for flight test.

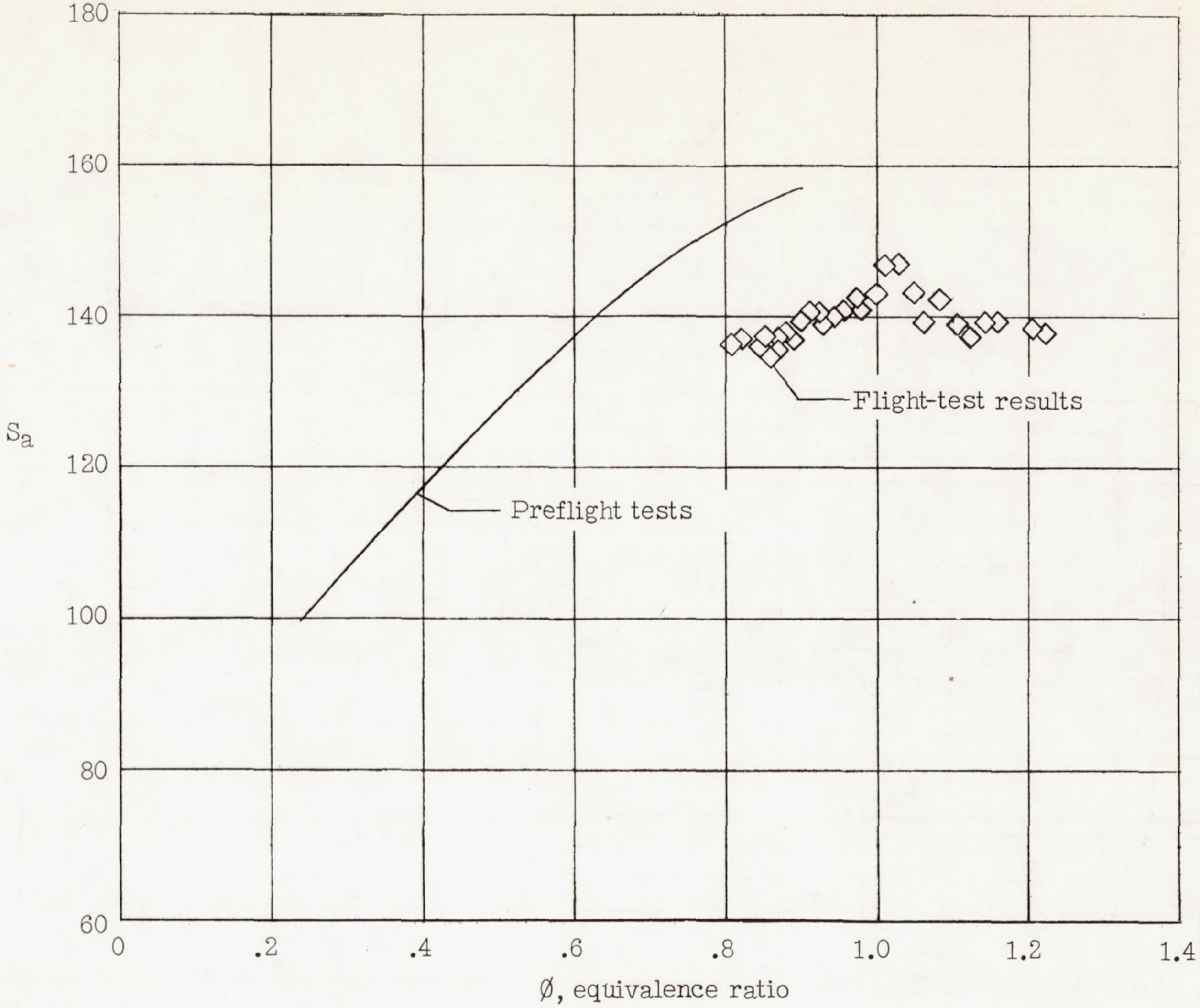

Figure 13.- Variation of air specific impulse with equivalence ratio for flight test.

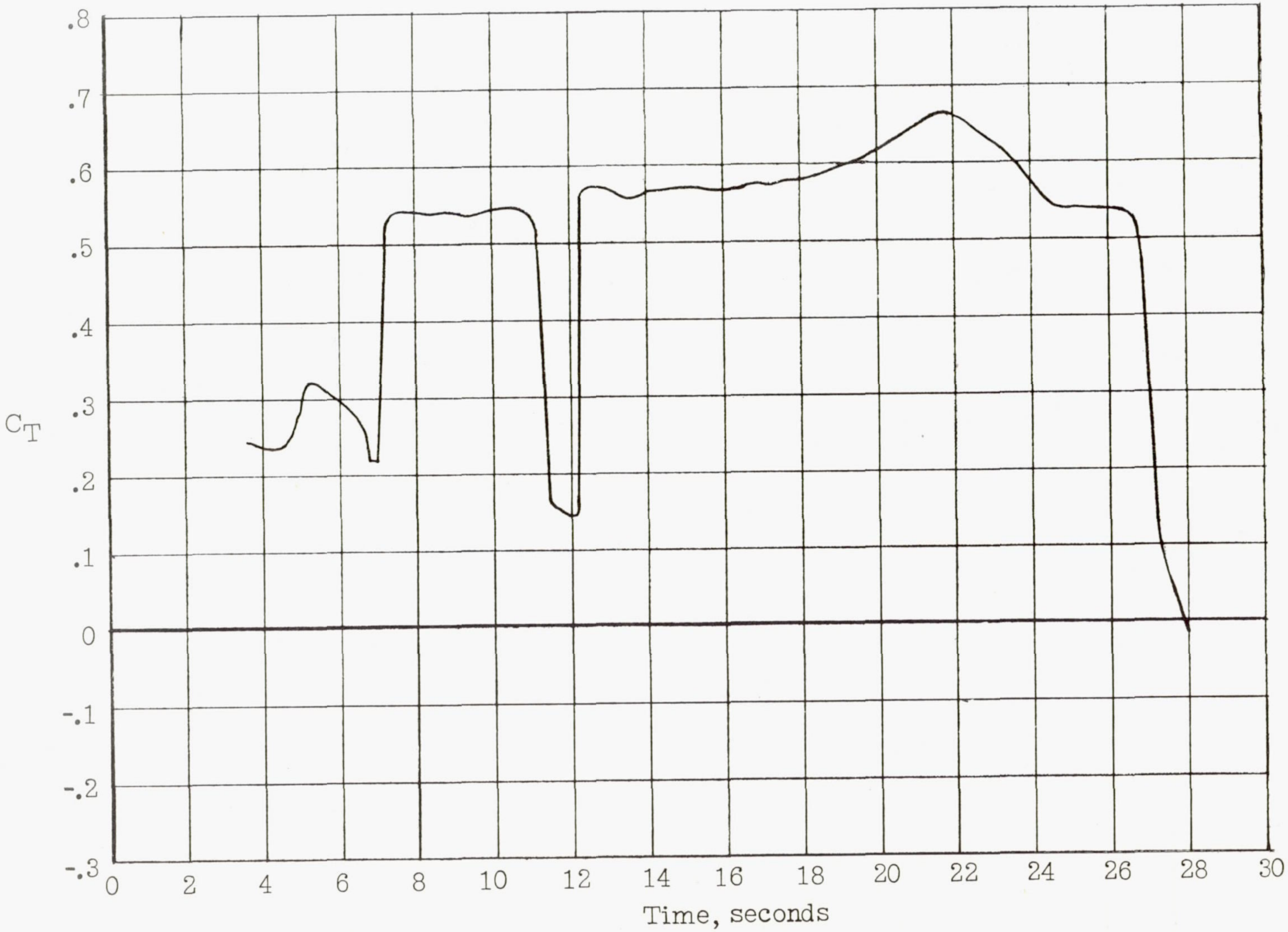

Figure 14.- Gross thrust coefficient plotted against time for flight test.

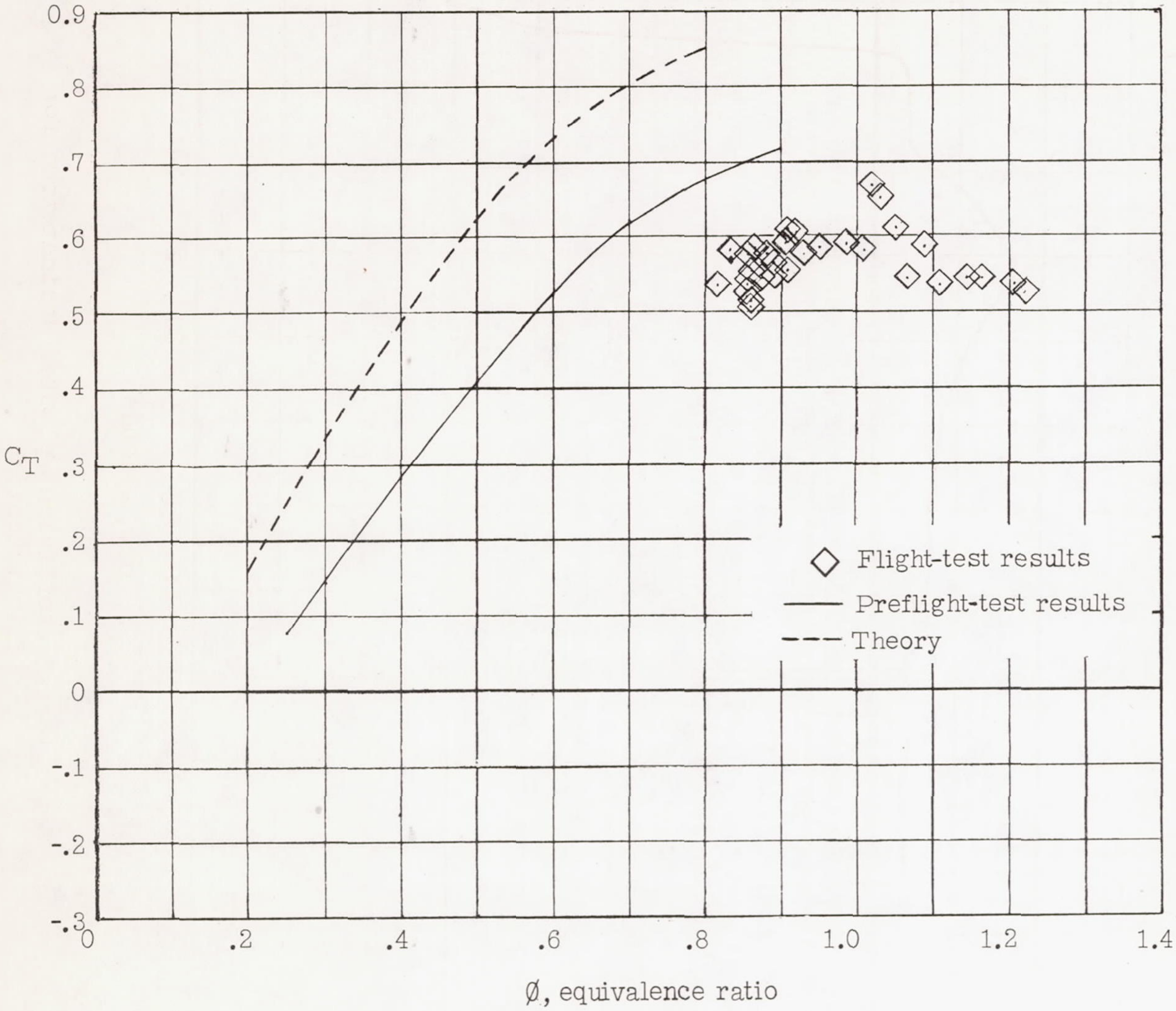

Figure 15.- Gross thrust coefficient plotted against equivalence ratio for flight test.

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