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RESEARCH MEMORANDUM

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INVESTIGATION OF ALTITUDE STARTING AND ACCELERATION CHARACTERISTICS OF J47 TURBOJET ENGINE

By Richard L. Golladay and Harry E. Bloomer

Lewis Flight Propulsion Laboratory
Cleveland, Ohio

NATIONAL ADVISORY COMMITTEE
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INVESTIGATION OF ALTITUDE STARTING AND ACCELERATION CHARACTERISTICS OF J47 TURBOJET ENGINE

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SUMMARY

An investigation was conducted on an axial-flow-compressor-type turbojet engine in the NACA Lewis altitude wind tunnel to determine the operational characteristics of several ignition systems, cross-fire-tube configurations, and fuel systems over a range of simulated flight conditions.

The opposite-polarity-type spark plug provided the most satisfactory ignition. Increasing the cross-fire-tube diameter improved intercombustor flame propagation. At high windmilling speeds, accelerations to approximately 6200 rpm could be made at a preset constant throttle position. Between engine speeds of 4000 and 5000 rpm, careful manipulation of the throttle was required during manual acceleration in order to avoid combustion blow-out. Use of a variable-area exhaust nozzle reduced acceleration time.

INTRODUCTION

It is often necessary to start turbojet engines at altitude after combustion blow-out has occurred or when some of the engines of a multiengine aircraft have been inoperative during cruise. Starting and acceleration of turbojet engines is more difficult at high altitude than at sea level because the low combustor pressures and temperatures and the poor fuel spray encountered at high altitude are detrimental to fuel ignition and flame propagation. The decreased density of the air at high altitude also reduces the energy available for acceleration, whereas the inertia of the rotating parts remains constant.

A general program is being conducted at the NACA Lewis laboratory to study the problem of altitude starting and to investigate methods of improving the altitude operational characteristics. As part of this program, an investigation was made in the Lewis altitude wind tunnel to study the high-altitude starting and acceleration characteristics of an axial-flow turbojet engine to be used in an airplane powered principally by reciprocating engines. Dependable starting at altitude was required because the operating plans for the airplane called for cruising with the jet engines inoperative. An effort was made to improve the fuel-ignition system, the flame-propagation system, and the technique for engine acceleration. A preliminary investigation of operational characteristics at lower altitudes is presented in reference 1.

The effects of these improvements on the starting and acceleration characteristics of the engine were investigated over a range of altitudes from 35,000 to 60,000 feet, simulated airspeeds from 250 to 585 miles per hour, and inlet-air temperatures of approximately -40° F and are presented herein. The effect of four different fuels on ignition characteristics was also investigated.

DESCRIPTION OF APPARATUS

Installation. - The engine was installed on a wing spanning the test section of the altitude wind tunnel (fig. 1). During the entire program, dry refrigerated air was supplied to the engine from the tunnel make-up air system through a duct connected to the engine inlet by means of a labyrinth seal. The air flow through the duct was throttled from approximately sea-level pressure to a total pressure at the engine inlet corresponding to the desired flight Mach number while the static pressure in the tunnel test section was maintained to simulate the desired altitude.

Engine. - The J47 turbojet engine used in the altitude-wind-tunnel investigation has a sea-level static thrust rating of 5200 pounds at an engine speed of 7950 rpm and a turbine-outlet temperature of 1275° F. The engine has a 12-stage axial-flow compressor, eight cylindrical direct-flow-type combustors, a single-stage impulse turbine, and a tail pipe. A fixed-area exhaust nozzle having an outlet area of 280 square inches was used during half of the investigation. A manually controlled clam-shell-type variable-area exhaust nozzle having a maximum outlet area of 452 square inches and a minimum outlet area of 257 square inches was used during the remainder of the investigation. The over-all length of the engine excluding the exhaust nozzle is 143 inches, the maximum diameter is approximately 37 inches, and the total weight is 2475 pounds.

Instrumentation. - Instrumentation was installed at five stations in the engine for measuring temperatures and pressures during transient conditions (fig. 2). Engine variables were transmitted to gages on a panel, which was photographed by a movie camera at the rate of 1 frame per second (fig. 3). The panel instruments are identified in the following table:

Photo panel number	Instrument	Engine station where measured
1	Timer	
2	Compressor-outlet total pressure	3
3	Airspeed	1
4, 7, 18, 19	Compressor-inlet total pressure	1
5	Tachometer	
6	Compressor-outlet temperature	3
8	Exhaust-gas temperature	6
9	Compressor-inlet temperature	1
10	VS-2 regulator sensing compressor-outlet pressure	3
11	Altimeter	
12, 13	Nozzle-inlet total pressure	7
14-17	Turbine-outlet temperature	5
20	Clock	
21	Ignition voltage - primary	
22	Fuel-return pressure	
23, 24	Variable-control oil pressure	
25-32	Current across ignition systems	
33, 34, 45	Small-slot fuel pressure	
35	Large-slot fuel pressure	
36	Throttle-position indicator	
37	Fuel flow	
38	Main-pump discharge pressure	
39	Turbine-outlet static pressure	5
40	Starter amperes	
41 (not installed)	Compressor-outlet bleed-valve position	
42	Starter volts	
43	Nozzle-position indicator	
44	Regulator-case pressure	

Ignition systems. - The three types of ignition system that were furnished by the engine manufacturer are shown in figure 4. The standard ignition unit supplied with the J47 engine consisted of a vibrator and an ignition coil enclosed in one package. The vibrator changed the 24-volt steady direct-current supply to a pulsating direct current in the primary winding of the coil and a 20,000-volt current in the secondary winding.

The dual-synchronous system employed two vibrators in one unit and a separate ignition coil. The vibrator units operated in parallel but slightly out of phase with one another. The use of two vibrators allowed a larger current flow through the coil than was possible with the standard system. The increased current resulted in approximately 40 percent more energy to the spark plug.

The opposite-polarity ignition system consisted of two ignition coils and one vibrator unit. The primary windings of the two coils were in series but were connected to generate opposite-polarity impulses in the secondary windings. With the leads from the secondary windings connected to insulated plugs, a potential difference approximately twice as high as that produced by the standard system existed across the spark gap.

Spark plugs for these ignition systems were also supplied by the engine manufacturer. The four plugs shown in figure 5 were used with the standard and dual-synchronous systems. The electrodes of the standard plug extended into the combustors approximately 2 inches. The corresponding lengths of the electrodes of the other three plugs were 3 inches, $3\frac{1}{2}$ inches, and $4\frac{1}{8}$ inches (as measured from the spark-plug flange to the tips of the electrodes). The gap setting of each of these plugs was 0.130 inch. The ground electrodes of the four plugs were hollow and were cooled by primary combustion air. The center electrodes of the $3\frac{1}{2}$- and $4\frac{1}{8}$-inch plugs were hollow and were cooled with primary combustion air by the aspirator action of the ground electrode.

The opposite-polarity type plugs (fig. 6), which were intended for use with the opposite-polarity ignition system, were also used with the standard and dual-synchronous ignition units. When used with these ignition systems, one of the two plugs was connected to the high-tension lead from the coil and the other plug was grounded. Gaps between the plugs of 1/2 and 13/16 inch were used with the opposite-polarity ignition system and 1/4 inch with the standard and dual-synchronous ignition systems. These larger gaps were possible because the design of the opposite-polarity plug greatly reduced the "ladder effect" encountered with the standard plug. The opposite-polarity twin plug (with a gap of 1 in.) (figs. 7 and 8) was used only with the opposite-polarity ignition system. The electrodes of the opposite-polarity plugs were hollow and were cooled by compressor discharge air.

Cross-fire tubes. - Cross-fire tubes used in this investigation included the standard size (1-in. diameter) and three large sizes, $1\frac{3}{16}$, $1\frac{7}{16}$, and $2\frac{3}{8}$ inches in diameter (fig. 9). The 1-, $1\frac{3}{16}$-, and $1\frac{7}{16}$-inch tubes, which were furnished by the manufacturer, were installed in the standard location. The $1\frac{7}{16}$-inch tube was made by removing the liner from the $1\frac{3}{16}$-inch tube. The $2\frac{3}{8}$-inch tubes were installed at the closest point between combustors at the position of the standard cross-fire tubes (fig. 8). Because of installation difficulties, the cross-fire tube between combustors 4 and 5 was omitted.

For two configurations, cross-fire tubes were installed 3 inches forward of the standard location so that the domes of adjacent combustors were connected (fig. 10). The two configurations differed in that the cross-fire-tube diameters were 1 inch and $1\frac{3}{16}$ inches.

Fuel systems. - For the first part of this investigation, the standard engine fuel system was used (fig. 11(a)). The main components of this system consist of a fuel regulator, gear-type fuel pump, fuel-control valve, flow divider, and duplex fuel nozzles. Fuel is supplied to the main fuel pump by means of a booster pump. The main fuel pump is of the constant-displacement type having a pumping capacity that is greater than the fuel requirements of the engine. The fuel-pump discharge pressure is varied by bypassing a portion of the fuel back to the pump inlet. The position of the fuel-control valve in the bypass circuit is governed by the variable-control oil pressure supplied by the fuel regulator. The fuel-regulator variable-control oil pressure is a function of throttle position, compressor-discharge pressure, and engine speed. The regulator includes a wide-range speed governor, which operates effectively at engine speeds above 3000 rpm, maintains constant engine speed for a given throttle position and flight condition, and also provides overspeed protection. At engine speeds below 3000 rpm, fuel flow is controlled by manual operation of the stopcock.

A bypass was installed around the stopcock for making starts at preselected fuel flows. Later in the first part of the investigation, the fuel was regulated by a supplementary throttle installed in the line feeding the large slots of the fuel nozzles in order to prevent combustion blow-out caused by sudden surges of fuel flow when the flow divider opened.

For the second part of the investigation, the fuel system was modified as shown in figure 11(b). The fuel line to the small-slot manifold was closed and all the fuel was supplied to the fuel nozzles through a fuel-distribution control (fig. 12). The control meters equal amounts of fuel to the large slots of each of the eight fuel nozzles regardless of the total fuel flow. A more detailed description of the fuel-distribution control is presented in appendix A. The spray angle and the large-slot orifice diameter of the fuel nozzles used with this system were larger than those of the standard nozzles. A needle valve was installed in a bypass around the flow divider to simulate the restriction of the small slots so that the fuel-regulator schedule would be unaffected. For this part of the investigation, a supplementary throttle installed in the fuel-outlet line of the oil cooler provided a microadjustment for the fuel at low flows.

Fuels. - Because the airplane in which this type of engine was to be installed carried only gasoline in its tanks, the main part of the investigation was conducted with this fuel. For most of the investigation, weathered unleaded gasoline AN-F-48b, grade 115/145, base stock with a Reid vapor pressure of 4.2 pounds per square inch was used. Weathered gasoline was used to simulate that fuel which is left in airplane tanks after it has climbed to high altitude. Parts of the investigation, however, were conducted with leaded gasoline AN-F-48b, grade 115/145, with a Reid vapor pressure of 6.2 pounds per square inch, weathered leaded gasoline AN-F-48b, grade 115/145 base stock with a Reid vapor pressure of 4.2 pounds per square inch, and the readily available fuel AN-F-58.

Oxygen-injection system. - The oxygen-injection system consisted of a stainless-steel tube connected to each combustor in the position shown in figure 13. The tubes were of 3/16-inch inside diameter and were immersed 1/4 inch inside the combustor liner. When initial results indicated that insufficient penetration was achieved, the inside diameter of the tubes was decreased to 3/32 inch and the immersion was increased to 1/2 inch. The oxygen was injected into the combustors at pressures ranging from 15 to 35 pounds per square inch.

PROCEDURE

Engine operational characteristics were investigated over a range of pressure altitudes from 35,000 to 60,000 feet and simulated airspeeds from 250 to 585 miles per hour, which correspond to flight Mach numbers from 0.37 to 0.88, and engine windmilling speeds from approximately 1200 to 3000 rpm (fig. 14). The compressor-inlet air temperature was maintained at approximately -40° F (420° R) at each simulated flight condition.

All attempts to accomplish ignition were made while the engine was windmilling without starter-motor assistance. During the starting cycle, the fuel flow was set at a predetermined value before the ignition system was energized. After flame propagated to all the combustors, the engine was accelerated with the throttle.

Some starts and accelerations were made with the standard engine fuel system, as indicated in tables I to III. For most of the investigation, however, the modified fuel system was used.

Two techniques were employed in starting and accelerating the engine. Manual accelerations from all windmilling speeds investigated were accomplished by governing the rate of throttle advance to maintain a turbine-outlet gas temperature of 1600° F until an engine speed of approximately 4000 rpm was reached. In order to avoid combustion blow-out, the throttle position was held fixed until the engine accelerated to 5000 rpm and the exhaust-gas temperature decreased to 1100° F. The exhaust-gas temperature was then gradually increased to 1600° F by advancing the throttle until rated engine speed was reached.

"Automatic" starts and accelerations were made only at windmilling speeds of approximately 2000 rpm. It was possible to preset the throttle to give a fuel flow such that, when the ignition was turned on, the engine started and accelerated to an engine speed of approximately 6200 rpm, from which speed it was further accelerated to rated speed by advancing the throttle from its preset position. During the time the throttle position was constant, the fuel flow increased because of increased output of the fuel pump with engine speed. This method of starting and accelerating an engine would be particularly useful in flight where more than one engine must be put into operation.

RESULTS AND DISCUSSION

Ignition in a gas-turbine engine at high altitudes can be obtained when the following conditions are established: (1) The spark-plug electrodes must be located in the combustor where a combustible mixture exists; (2) the pressure level in the combustor should be as high as possible and the air velocity as low as possible; (3) the spark energy level must be sufficient to produce ignition at reduced mixture densities; and (4) the fuel entering the combustor should be highly volatile and at as high a temperature as possible. The effects of some of these factors on the starting characteristics of a full-scale turbojet engine for a range of altitudes and airspeeds are shown and discussed herein.

Determination of Fuel-Flow Requirements

Successful ignition and flame propagation throughout the engine combustors can be obtained for only a limited range of fuel-air ratios. Thus, as the engine air flow varies with changes in altitude or airspeed, the fuel flow must also be varied in order that the resulting fuel-air ratio be within the combustible range. Minimum and maximum fuel flows were determined by the trial-and-error method. The range of fuel flows for which ignition and flame propagation were accomplished are shown in the following table for both fuel systems at all flight conditions investigated. Fewer starts were made at a simulated airspeed of 355 miles per hour than at the other airspeeds at all three altitudes; therefore, the fuel-flow limits are not believed to be as accurate for this condition as for other conditions.

Altitude	Simulated airspeed (mph)	Fuel flow (lb/hr)	
		Standard fuel system	Fuel-distributor system
35,000	250	200-575	290-800
35,000	355	300-390	460-750
35,000	410	270-630	450-900
40,000	250	200-350	350-690
40,000	355	280-345	400-700
40,000	410	220-425	400-870
45,000	250	130-380	290-740
45,000	355	210-450	295-610
45,000	410	270	390-760

It is noted that the engine required more fuel as the altitude pressure and airspeed were increased. When the engine was equipped with the fuel-distribution control, more fuel was required for ignition and propagation than with the standard fuel system. For the dome-to-dome location of cross-fire tubes, it was necessary to drop the fuel flow to the lower limit in order to obtain satisfactory propagation.

Ignition

The reliability of an ignition system can be evaluated at a particular flight condition by consideration of the time required to obtain initial ignition and the number of successful starts obtained with respect to the total number of attempts made. After the predetermined correct fuel flow is set and the ignition is turned on, the ignition time (time required for initial ignition to occur) depends on the probability of a combustible mixture existing in the region of the spark plug. Thus the primary solution to obtaining reliable ignition in the shortest time interval is to locate the spark gap in a region of the combustor where the probability of the existence of a combustible mixture is the greatest.

A comparison of the performance of several of the ignition systems investigated is shown in table I. Ignition times of 5, 10, and 20 seconds were arbitrarily established as the basis for comparison. Changes in the fuel system had no apparent effect on ignition time when the same ignition system was used.

The performance of the standard ignition system with 2-inch spark plugs was poor. At altitudes of 35,000 and 40,000 feet and an airspeed of 250 miles per hour, only 25 percent of the attempted starts resulted in ignition within 20 seconds.

Three other lengths of the standard-type spark plug (3, $3\frac{1}{2}$, and $4\frac{1}{8}$ in. (fig. 5)) were used with the standard and dual-synchronous ignition systems. Of these combinations, the most satisfactory performance was obtained with the dual-synchronous ignition coil and the 3-inch spark plug, as shown in table I. Although the performance was slightly better than that of the standard ignition system for the same flight conditions, ignition within 20 seconds could not be obtained at airspeeds higher than 250 miles per hour at an altitude of 40,000 feet or at any airspeed at an altitude of 45,000 feet.

When the opposite-polarity igntion system was used with a spark-plug gap of 13/16 inch at the same flight conditions, ignition was obtained more consistently and generally within a shorter time. Although some starts were obtained at an airspeed of 410 miles per hour at altitudes of 40,000 and 45,000 feet, the average time for ignition was longer than 20 seconds. The rapidity with which ignitions could be obtained with the opposite-polarity system was greatly improved by decreasing the spark-plug gap from 13/16 inch to 1/2 inch. Ignition was obtained consistently at all flight conditions investigated and for the majority of attempts made ignition was obtained in 10 seconds or less.

In an effort to maintain the improved ignition system as close as possible to the standard system, the standard ignition coils were used with the opposite-polarity plugs having a 1/4-inch gap. The results obtained with this configuration at most conditions were as good as those obtained with the best configuration using the opposite-polarity coils. At altitudes of 35,000, 40,000, and 45,000 feet, at least 83 percent of ignitions at 250 miles per hour and at least 50 percent of ignitions at 410 miles per hour were accomplished in 10 seconds or less.

It is therefore apparent that the opposite-polarity plugs were responsible for most of the improvement in the starting characteristics, rather than coil design or length of spark plug.

In addition to the data presented in table I, ignitions were obtained with the fuel-distributor system at airspeeds greater than 410 miles per hour or at altitudes higher than 45,000 feet. All attempts resulted in ignition. At an altitude of 45,000 feet and an airspeed of 585 miles per hour, five ignitions were obtained in 25 seconds or less using each of two systems, the opposite-polarity ignition system with 1/2-inch spark gap and the standard coil with opposite-polarity plugs and 1/4-inch spark gap. At an altitude of 50,000 feet, three ignitions were obtained in 20 seconds or less at 250 miles per hour with the opposite-polarity ignition and 1/2-inch spark gap. The opposite-polarity system with 1/2-inch spark-plug gap was also effective at 60,000 feet and 315 miles per hour where two ignitions were obtained in 30 seconds or less.

Flame Propagation

In the design of a turbojet engine having several individual combustors, it is general practice to install spark plugs in only two diametrically opposite combustors, thus providing a simplification and a saving in weight as compared to a system where each combustor would have a separate ignition system. Ignition in the remaining combustors is dependent on flame propagation through interconnecting cross-fire tubes. Aside from obtaining reliable ignition in the combustors containing spark plugs, successful starting of a turbojet engine depends on the ability of the flame to propagate rapidly throughout the remaining combustors. Flame propagation may be affected by the diameter and the length of the cross-fire tube and the lengthwise location of the tube on the combustor.

The flame-propagation performance of several cross-fire-tube configurations is presented in table II for altitudes of 35,000, 40,000, and 45,000 feet and a range of airspeeds at each altitude. The flame-propagation time was recorded from the time that ignition occurred in one combustor until all combustors were ignited.

Flame propagation with the standard cross-fire tubes (1 in. in diameter) was unsatisfactory at all flight conditions investigated. An increase in cross-fire-tube diameter to $1\frac{3}{16}$ inches resulted in some improvement in flame propagation, but the percentage of propagations obtained was low, particularly at altitudes of 40,000 and 45,000 feet. A further increase in tube diameter to $1\frac{7}{16}$ inches greatly improved flame propagation at all altitudes and airspeeds. In at least 80 percent of the attempts, flame propagation was obtained in 20 seconds or less at all altitudes and airspeeds except 45,000 feet and 410 miles per hour.

Increasing the diameter of the cross-fire tubes apparently improved flame propagation. Consequently, tubes were fabricated with a diameter of $2\frac{3}{8}$ inches and were installed at the shortest distance between combustors. In order to include this configuration in the investigation, it was fabricated rapidly. A loose fit between cross-fire tubes and combustor liner to allow for expansion, the protrusion of the cross-fire tubes through the liners, and omission of the cross-fire tube between combustors 4 and 5 because of installation difficulties probably explain the reduced performance of this configuration compared with the smaller $1\frac{7}{16}$-inch-diameter cross-fire tubes.

Two sets of cross-fire tubes having diameters of 1 and $1\frac{3}{16}$ inches were installed in the dome of the combustors 3 inches forward of the standard position. The 1-inch-diameter dome-to-dome cross-fire tubes gave satisfactory propagation at an altitude of 35,000 feet and an airspeed of 255 miles per hour. These results are not presented in table II. By increasing the diameter to $1\frac{3}{16}$ inches, in 67 percent of the attempts propagations were made in 10 seconds and 100 percent in 20 seconds at altitudes of 35,000 and

40,000 feet at a simulated airspeed of 250 miles per hour. At higher airspeeds and an altitude of 45,000 feet, however, performance was very poor. As shown in table II, a limited amount of data was obtained using the $1\frac{3}{16}$-inch-diameter cross-fire tube with both the standard and the fuel-distribution control fuel systems. The data indicate that the change in fuel system did not appreciably affect propagation time.

Acceleration

Numerous accelerations were made using the manual and automatic techniques with the variable-area exhaust nozzle open and in the standard-area position. The average time for these accelerations is shown in table III. The time given in the table was recorded from the completion of propagation to the time rated speed was reached.

Attempts to accelerate with the standard fuel system at 40,000 and 45,000 feet at an airspeed of 250 miles per hour, were unsuccessful because of combustion blow-out.

In order to improve the acceleration characteristics of the engine, the standard fuel system was replaced by the fuel-distribution control system. This system was designed to distribute the fuel equally to all combustors at all fuel flows and also spray larger drops of fuel into the combustors because fuel was injected through only the large slots. An improvement in acceleration time was noted at every condition and, at some conditions, accelerations were made with the fuel-distribution control that were impossible to make with the standard fuel system. With the use of the fuel distributor at engine windmilling speeds of approximately 2000 rpm, it was possible for the engine to accelerate "automatically" at constant throttle position to approximately 6200 rpm, from which point the throttle could be advanced rapidly. As shown in table III, the manual acceleration was, in general, faster than the automatic acceleration because the turbine-outlet temperature could be kept closer to 1600° F. A sudden change in fuel flow by throttle motion during the acceleration to approximately 6200 rpm, particularly between 4000 and 5000 rpm, however, was likely to cause combustion blow-out. Although not as rapid, the automatic-type acceleration is valuable, inasmuch as it practically eliminates pilot throttle technique and combustion blow-out. A comparison of the automatic and manual type of acceleration is presented in figure 15 for an altitude of 40,000 feet at an airspeed of 410 miles per hour. It can be noted that the fuel pressure and turbine-outlet temperature are generally higher for the manual acceleration.

Decreasing the turbine-outlet pressure by increasing the exhaust-nozzle area with a variable-area nozzle decreased the acceleration time an average of 50 percent of the time required with the standard nozzle area, except at an altitude of 45,000 feet and an airspeed of 410 miles per hour where only one acceleration was made with the nozzle open (table III). A time history of an acceleration with the nozzle open at 40,000 feet and an airspeed of 410 miles per hour is also presented in figure 15. The manual acceleration time to 7600 rpm is 23 seconds compared with 40 seconds for the manual acceleration with the standard-area exhaust nozzle. The reduced pressure at the turbine outlet with the exhaust nozzle open, although it reduces acceleration time, actually increases time for ignition and propagation. For this reason, the best procedure to shorten starting time for operation with a variable-area nozzle is to keep the nozzle in the closed position until ignition and propagation are completed and then to open the nozzle until the acceleration is completed.

Effect of Fuel

Several fuels were used in the investigation in an effort to determine the effect on high-altitude ignition. During this part of the investigation the engine was equipped with the standard and opposite-polarity ignition systems, opposite-polarity-type spark plugs, and the fuel-distribution control. It was thought that the higher volatility fuels would ignite faster, but examination of the limited data available indicated that the effect of fuel volatility within the range investigated was negligible.

Effect of Oxygen Injection

In order to aid ignition and propagation, oxygen was injected into the combustors at altitudes of 45,000 and 50,000 feet. A definite decrease in time for ignitions and propagations was noted when oxygen was injected. During one start, combustors that had ignited went out when the oxygen flow was stopped. Even though oxygen injection improves ignition and propagation, its use in a flight installation might be objectionable because of the extra weight of injection equipment.

SUMMARY OF RESULTS

The following results were obtained during an investigation of the high-altitude starting and acceleration characteristics of a J47 turbojet engine in the NACA Lewis altitude wind tunnel:

1. The ignition systems that performed most reliably were the opposite-polarity coils combined with the opposite-polarity spark plugs with a 1/2-inch gap, and the standard coil with opposite-polarity spark plugs with 1/4-inch gap. Reliable ignition was obtained at simulated airspeeds up to 410 miles per hour and altitudes up to 45,000 feet. Several successful ignitions were obtained at an altitude of 60,000 feet at an airspeed of 315 miles per hour and at airspeeds as high as 585 miles per hour at an altitude of 45,000 feet.

2. Intercombustor flame propagation improved as the cross-fire-tube diameter was increased from 1 inch to $1\frac{7}{16}$ inches.

3. Acceleration characteristics were improved through the use of the fuel-distribution control, which made it possible to use larger fuel flows at ignition and during the early stages of acceleration. At altitudes from 35,000 to 45,000 feet and an airspeed of approximately 410 miles per hour, corresponding to an engine windmilling speed of 2000 rpm, accelerations were made to 6200 rpm at a preset constant throttle position. Between engine speeds of 4000 and 5000 rpm, careful manipulation of the throttle was required during manual acceleration in order to avoid combustion blow-out.

4. Average time for accelerations with the variable-area exhaust nozzle was reduced to 50 percent of the time required with the standard area nozzle.

Lewis Flight Propulsion Laboratory,
National Advisory Committee for Aeronautics,
Cleveland, Ohio.

APPENDIX A

FUEL-DISTRIBUTION CONTROL

The fuel-distribution control equalizes the flow to the fuel nozzles independently of nozzle flow resistance by controlling equal pressure drops across fixed-area orifices. One of these orifices feeds each nozzle. The fuel-distribution control used in this investigation was basically similar to the control described in reference 2. The control was modified by using a springless, diaphragm-operated pilot resistance valve that was automatically vented by a multiple pressure selector to the branch line feeding the nozzle having the highest resistance. In this manner, the pilot resistance valve automatically adjusted to the pressure-drop characteristics of the nozzles. As schematically shown in figure 16, each branch line feeding a nozzle is vented to a diaphragm-operated check valve. If the pressure in a branch line is higher than the pressure being transmitted to the opposite port of the check valve, the check-valve diaphragm is moved upward and the branch pressure is transmitted downward. If the pressure in a branch line is lower than the pressure transmitted to the opposite port of the check valve, the diaphragm is moved downward and the higher pressure entering the upper port is transmitted downward. In this manner the highest pressure existing in any of the branch lines is transmitted downward to chamber C. The diaphragm-operated pilot resistance valve positions itself to maintain the pressure in chamber D equal to that in chamber C. The pilot regulator jet therefore always discharges into a pressure equal to that existing in the branch line feeding the nozzle having the highest resistance. 1365

The pilot element is used to feed one of the eight engine fuel nozzles. If this nozzle should have the highest resistance, the diaphragm-operated pilot resistance valve moves to a wide-open position and the pilot regulator jet again discharges into a pressure equal to that existing in the branch line feeding the nozzle with the highest resistance.

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APPENDIX B

CALCULATIONS

Symbols

The following symbols are used in this report:

g	acceleration due to gravity, 32.2 ft/sec^2
P	total pressure, lb/sq ft absolute
p	static pressure, lb/sq ft absolute
R	gas constant, 53.3 ft-lb/(lb)(°R)
T	total temperature, °R
T_i	indicated temperature, °R
t	static temperature, °R
V	velocity, ft/sec
γ	ratio of specific heats

Subscripts:

0	free-air stream
1	engine inlet

Methods of Calculation

In the calculation of the desired parameters, arithmetic-average values of temperature and pressure were used.

Temperatures. - Static temperatures were determined from indicated temperatures with the following relation:

$$t = \frac{T_i}{1 + 0.85\left[\left(\frac{P}{p}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]}$$

Airspeed. - Simulated airspeed was calculated from ram pressure ratio by the following equation assuming complete pressure recovery at the engine inlet:

$$V_0 = \sqrt{\frac{2\gamma}{\gamma-1} gR \left[\frac{T_1}{\left(\frac{P_1}{p_0}\right)^{\frac{\gamma-1}{\gamma}}}\right]\left[\left(\frac{P_1}{p_0}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]}$$

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2. Gold, Harold, and Straight, David M.: A Fuel Distribution Control for Gas-Turbine Engines. NACA RM E8C08, 1948.

TABLE I - IGNITION

Altitude (ft)	Simulated airspeed (mph)	Time (sec)	Ignition									
			Standard fuel system				Fuel-distribution system					
			Standard ignition, 2-in. plug		Dual-synchronous ignition, 3-in. plug		Opposite-polarity ignition, 13/16-in. gap		Opposite-polarity ignition, 1/2-in. gap		Standard ignition, opposite-polarity plug, 1/4-in. gap	
			Successful ignitions (percent)	Total attempts	Successful ignitions (percent)	Total attempts	Successful ignitions (percent)	Total attempts	Successful ignitions (percent)	Total attempts	Successful ignitions (percent)	Total attempts
35,000	250	5	0		10		0		43		68	
		10	0		60		0		100		100	
		20	25	4	90	10	63	8	100	7	100	6
35,000	355	5	(a)		0		0		100		100	
		10	(a)		0		50		100		100	
		20	(a)		0	1	100	2	100	1	100	2
35,000	410	5	0		0		0		50		60	
		10	0		0		50		50		100	
		20	0	2	29	7	100	2	100	2	100	5
40,000	250	5	0		0		42		38		90	
		10	0		38		75		50		90	
		20	25	4	38	8	100	12	100	8	100	10
40,000	355	5	(a)		0		0		100		100	
		10	(a)		0		0		100		100	
		20	(a)		0	4	50	2	100	10	100	8
40,000	410	5	(a)		0		0		63		56	
		10	(a)		0		0		100		78	
		20	(a)		0	2	40	5	100	8	100	9
45,000	250	5	0		0		0		33		33	
		10	0		0		0		83		83	
		20	0	1	0	4	14	7	100	6	100	6
45,000	355	5	(a)		0		0		33		0	
		10	(a)		0		0		100		100	
		20	(a)		0	2	0	3	100	3	100	1
45,000	410	5	(a)		(a)		0		42		0	
		10	(a)		(a)		0		75		50	
		20	(a)		(a)		25	4	100	12	50	4

---

[a] Data not obtained.

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TABLE II - FLAME PROPAGATION

Altitude (ft)	Simulated airspeed (mph)	Time (sec)	Flame propagation											
			Standard fuel system				Fuel-distribution system							
			1-in.-diam. standard cross-fire tube		$1\frac{3}{16}$-in.-diam. cross-fire tube		$1\frac{3}{16}$-in.-diam. cross-fire tube		$1\frac{7}{16}$-in.-diam. cross-fire tube		$2\frac{3}{8}$-in.-diam. revised cross-fire tube		Dome-to-dome $1\frac{3}{16}$-in. diam.	
			Successful starts (percent)	Total starts	Successful starts (percent)	Total starts	Successful starts (percent)	Total starts	Successful starts (percent)	Total starts	Successful starts (percent)	Total starts	Successful starts (percent)	Total starts
35,000	250	10	0	19	0	1	50	8	80	5	75	4	67	3
		20	16		0		63		80		75		100	
35,000	355	10	0	3	(a)		0	5	100	2	50	2	0	1
		20	0		(a)		0		100		50		0	
35,000	410	10	0	7	60	5	33	9	100	3	100	6	0	4
		20	0		100		44		100		100		75	
40,000	250	10	0	17	25	8	25	16	100	7	50	6	67	3
		20	0		37		37		100		67		100	
40,000	355	10	0	1	50	4	25	4	82	11	(a)		0	6
		20	0		50		25		82		(a)		0	
40,000	410	10	(a)		0	5	0	22	100	9	(a)		0	2
		20	(a)		0		5		100		(a)		0	
45,000	250	10	0	1	20	10	18	17	80	5	43	7	0	4
		20	0		20		24		80		43		0	
45,000	355	10	(a)		0	3	0	1	33	3	(a)		[illegible]	2
		20	(a)		0		0		100		(a)		0	
45,000	410	10	(a)		0	1	0	14	19	16	0	1	(a)	
		20	(a)		0		7		50		0		(a)	

[a] Data not obtained

TABLE III - ACCELERATIONS

Altitude (ft)	Simulated airspeed (mph)	Approximate windmilling speed (rpm)	Approximate speed at start of acceleration (rpm)	Acceleration time (sec)									
				Standard fuel system		Fuel-distribution control							
						Manual				Automatic			
				Fixed-standard-area nozzle		Standard-area nozzle		Nozzle open		Standard-area nozzle		Nozzle open	
				Limits and average	Total runs	Limits and average	Total runs	Limits and average	Total runs	Limits and average	Total runs	Limits and average	Total runs
35,000	250	1225	1300	120-270 170	3	103-150 131	5	64-65 64	3	(a)		(a)	
35,000	355	1700	1750	(a)		40-60 52	3	(a)		149 149	1	(a)	
35,000	410	2100	2425	45-90 60	3	30-75 43	4	(a)		26-93 59	2	29-40 33	3
40,000	250	1225	1400	(b)		100-244 180	8	93-106 99	2	(a)		(a)	
40,000	355	1600	1725	(a)		95-118 106	2	43 43	1	(a)		(a)	
40,000	410	2000	2550	85-102 92	3	30-140 59	10	21-35 27	3	44-73 58	4	(a)	
45,000	250	1200	1450	(b)		210-313 257	4	160 160	1	(a)		(a)	
45,000	355	1600	1675	(a)		101 101	1	62 62	1	(a)		(a)	
45,000	410	1900	2750	(a)		38-54 45	4	53 53	1	88-113 100	5	41 41	1

[a] Data not obtained.

[b] Engine failed to reach top speed.

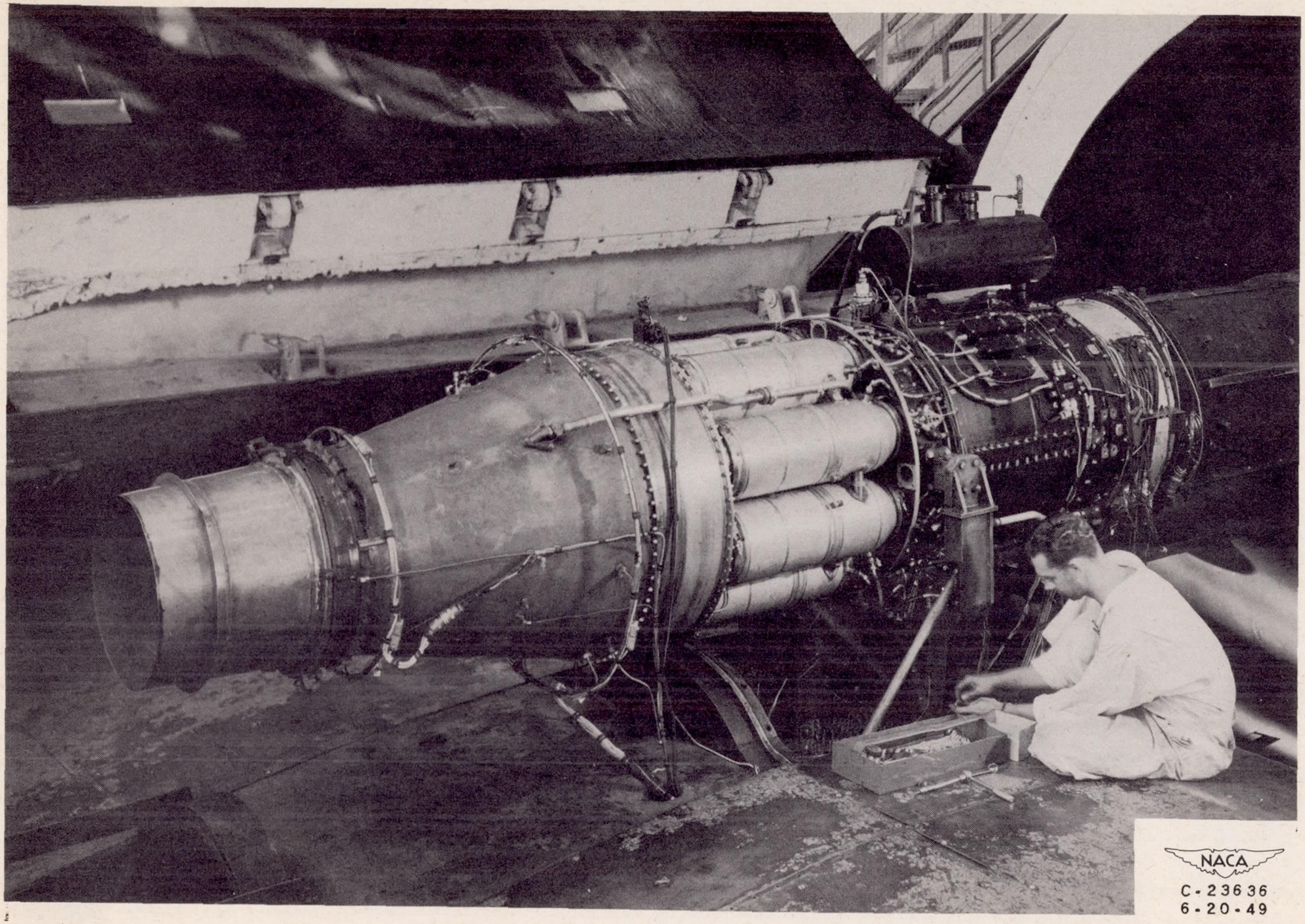
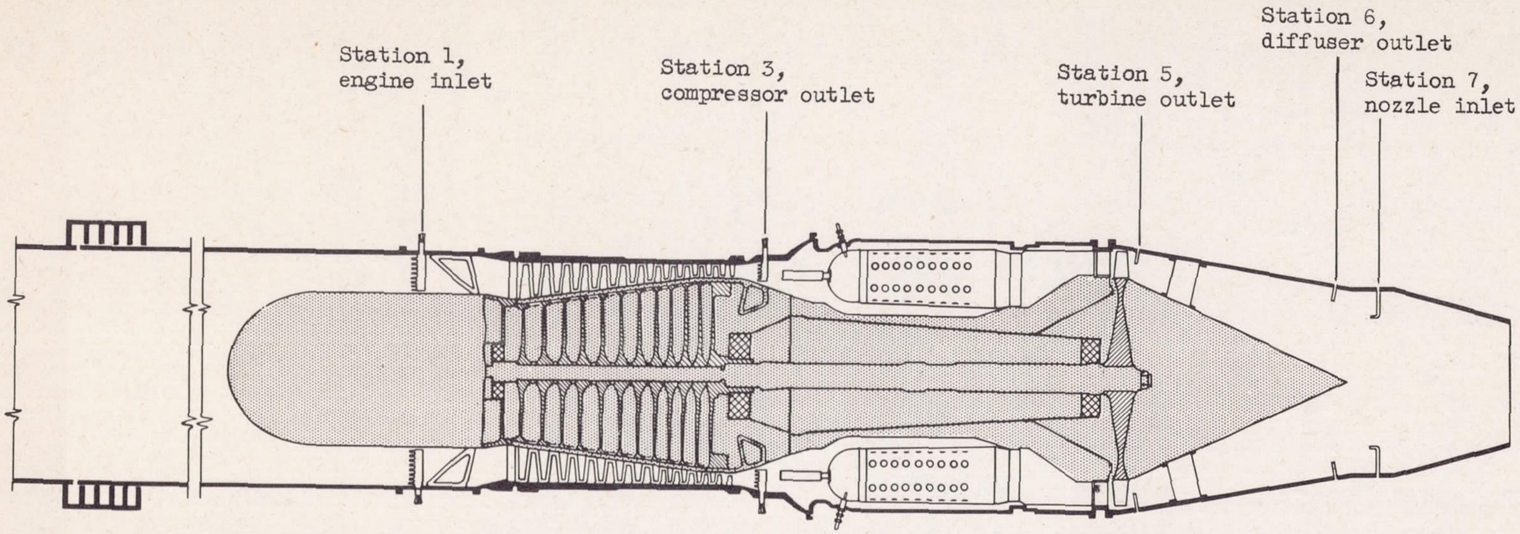


Figure 1. - Installation of turbojet engine in altitude wind tunnel.



Station	Total-pressure tubes	Static-pressure tubes	Thermocouples	Wall static-pressure orifices
1	47	4	8	
3	26		6	4
5			8	
6			4	
7	2			

Figure 2. - Cross section of turbojet-engine installation showing instrumentation stations.

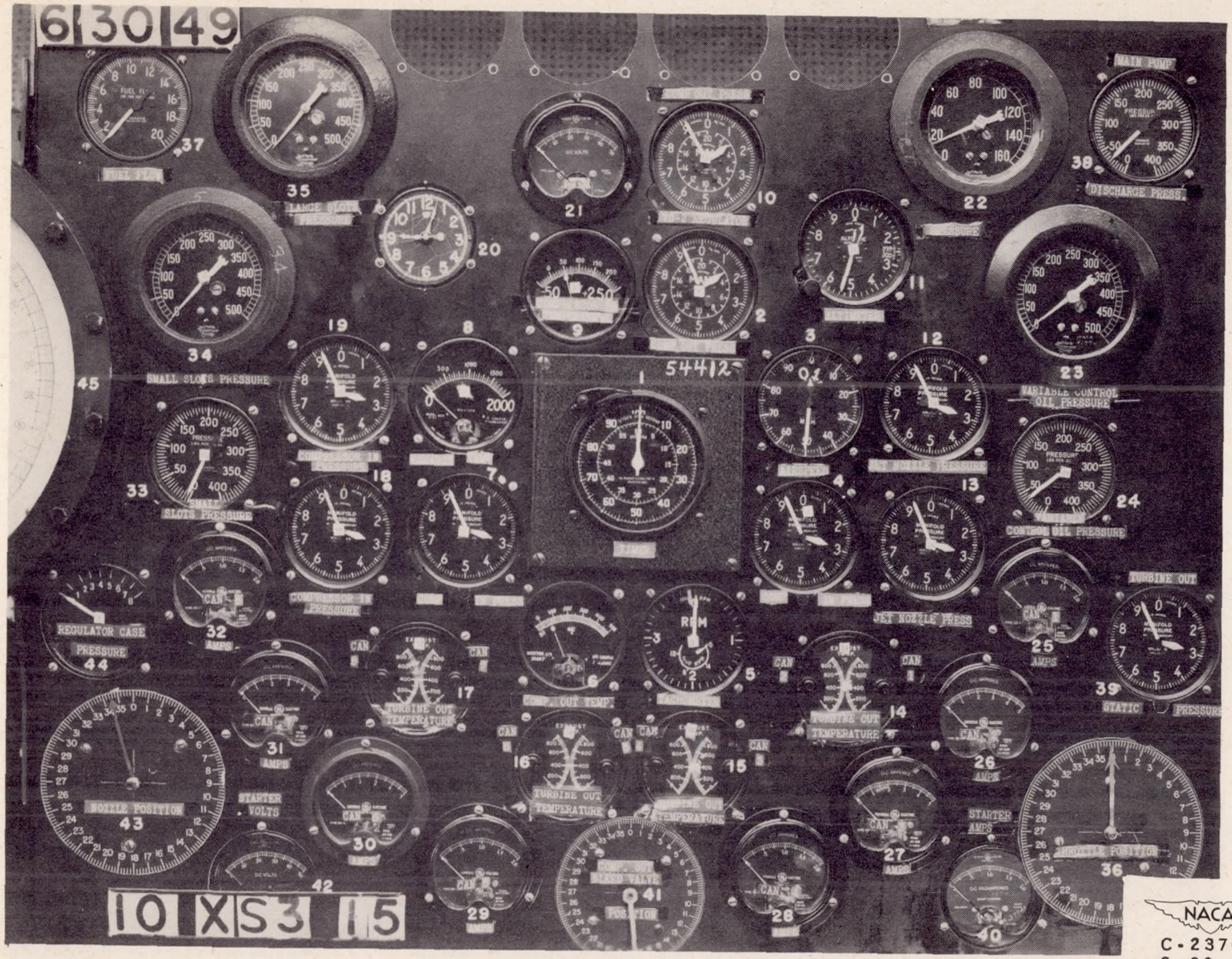


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Figure 3. - Photo panel of instruments recorded by movie camera during transient conditions.

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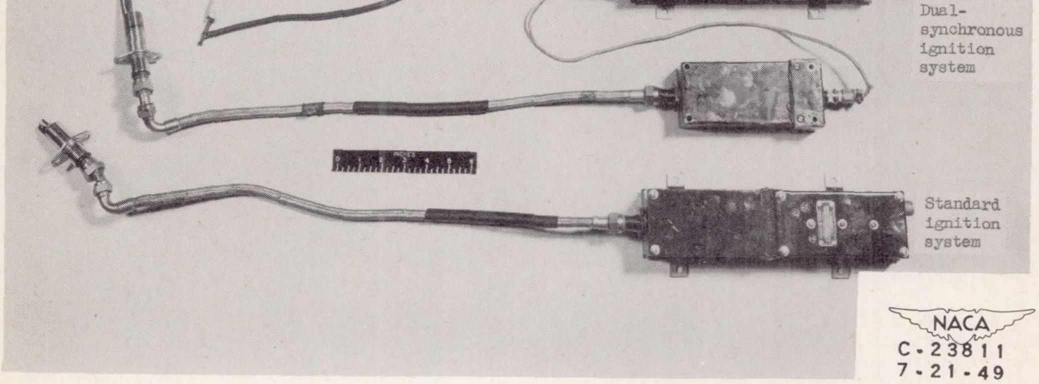


Figure 4. - Ignition systems employed during altitude-starting investigation.

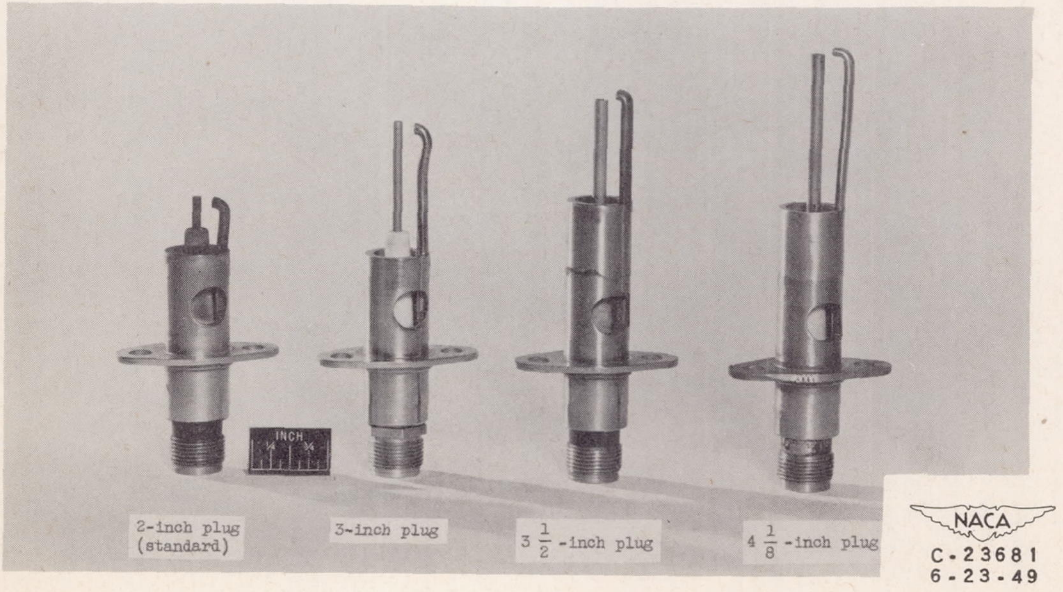
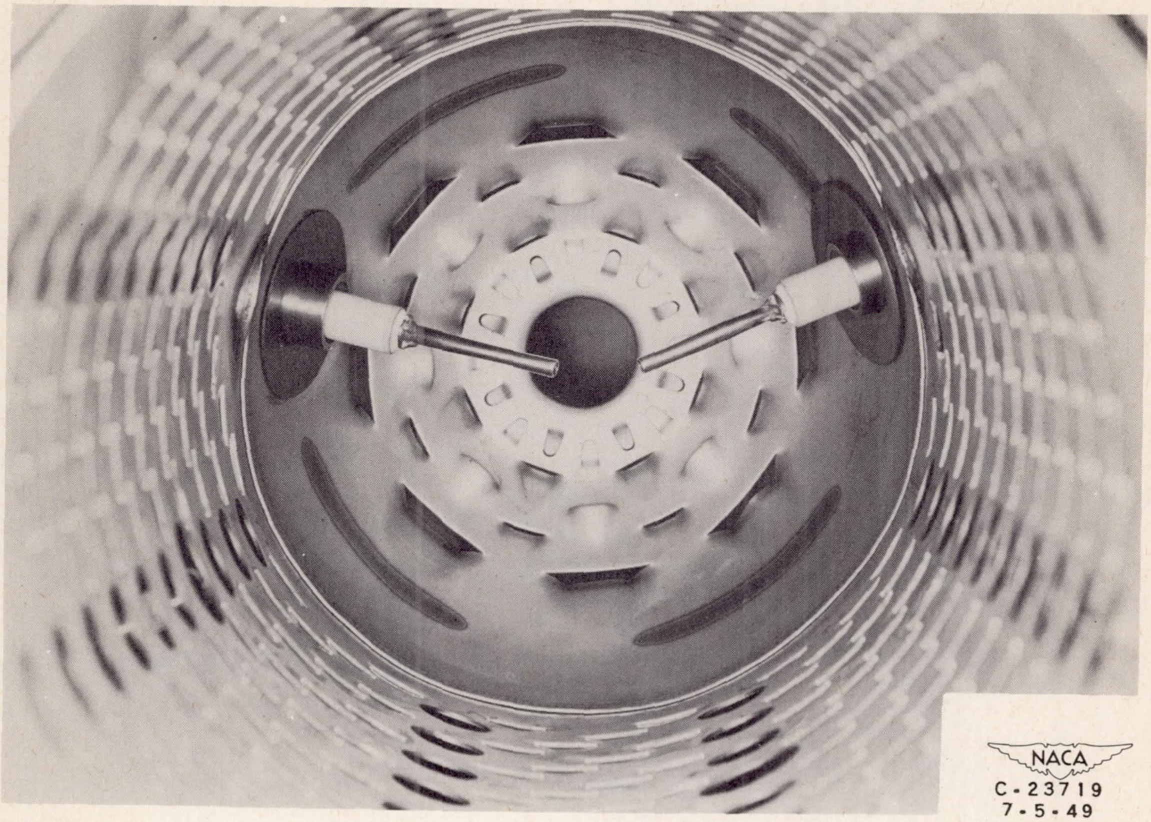


Figure 5. - Four spark plugs used with standard and dual-synchronous ignition units.



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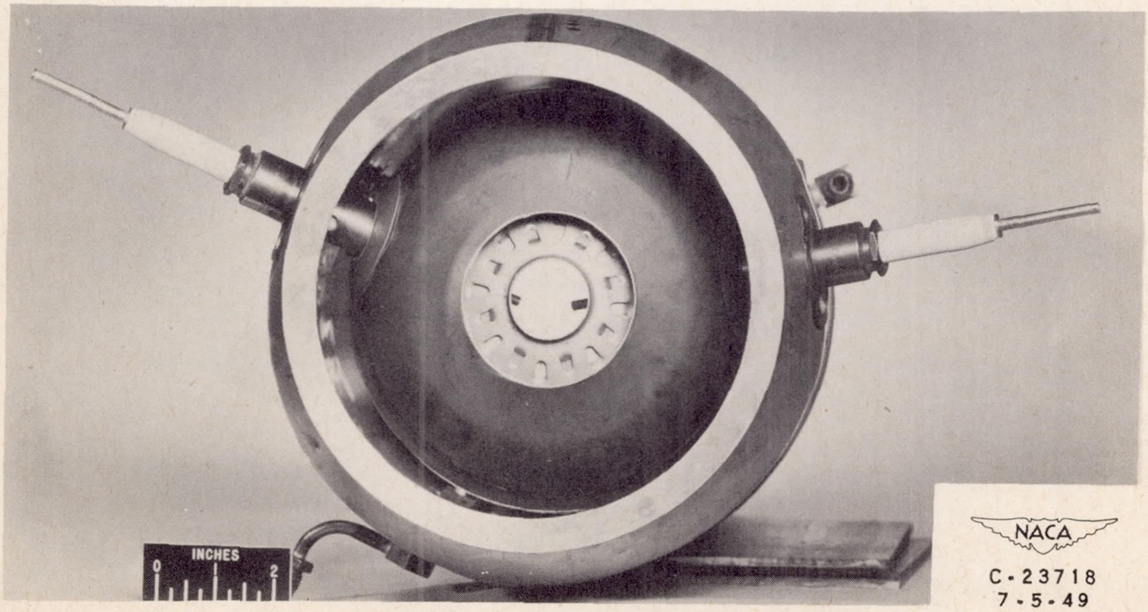
(a) View from inside of combustor.



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(b) View from outside of combustor.

Figure 6. - Opposite-polarity-type spark plugs installed in combustor.

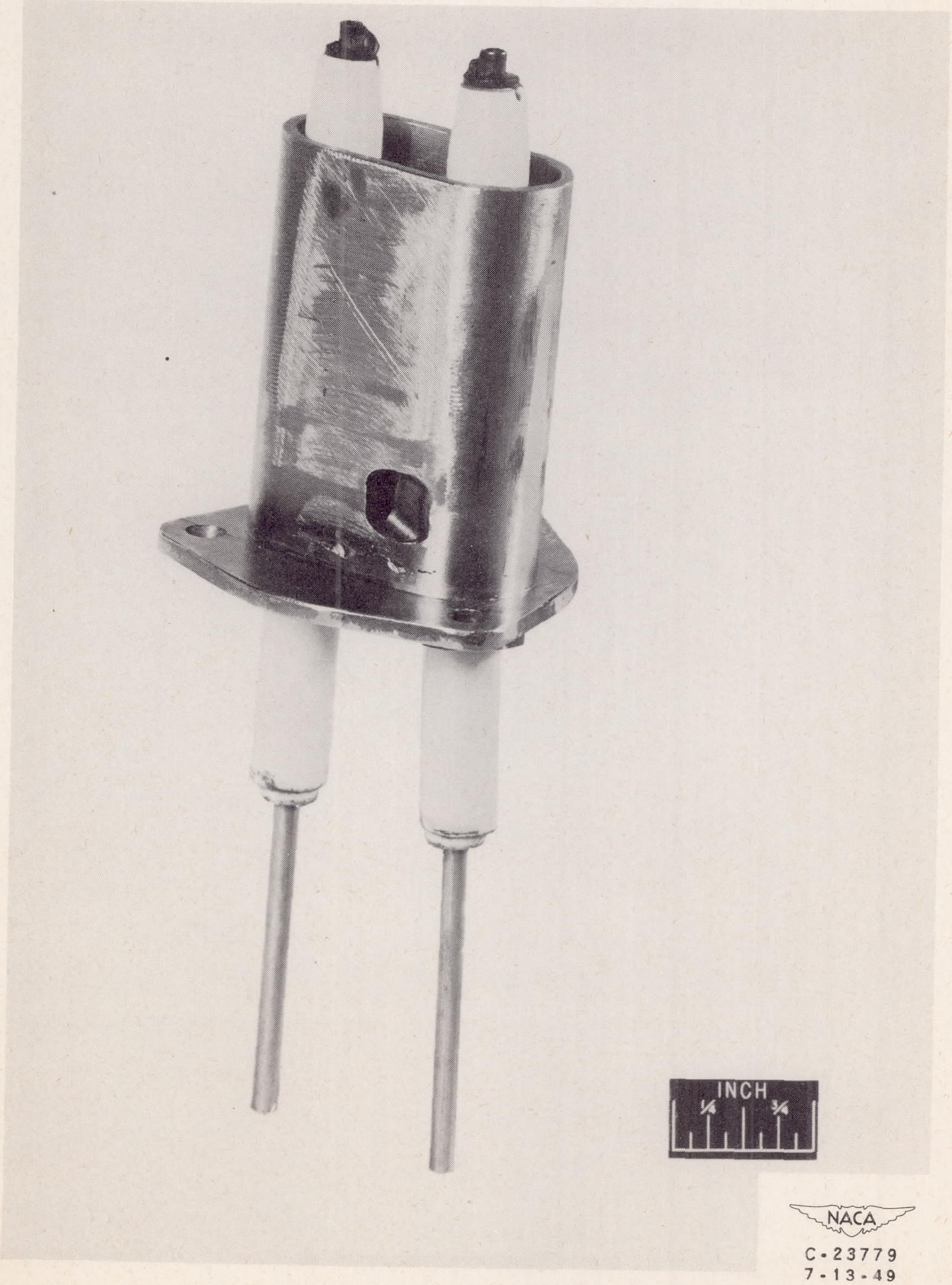

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Figure 7. - Opposite-polarity twin plug.

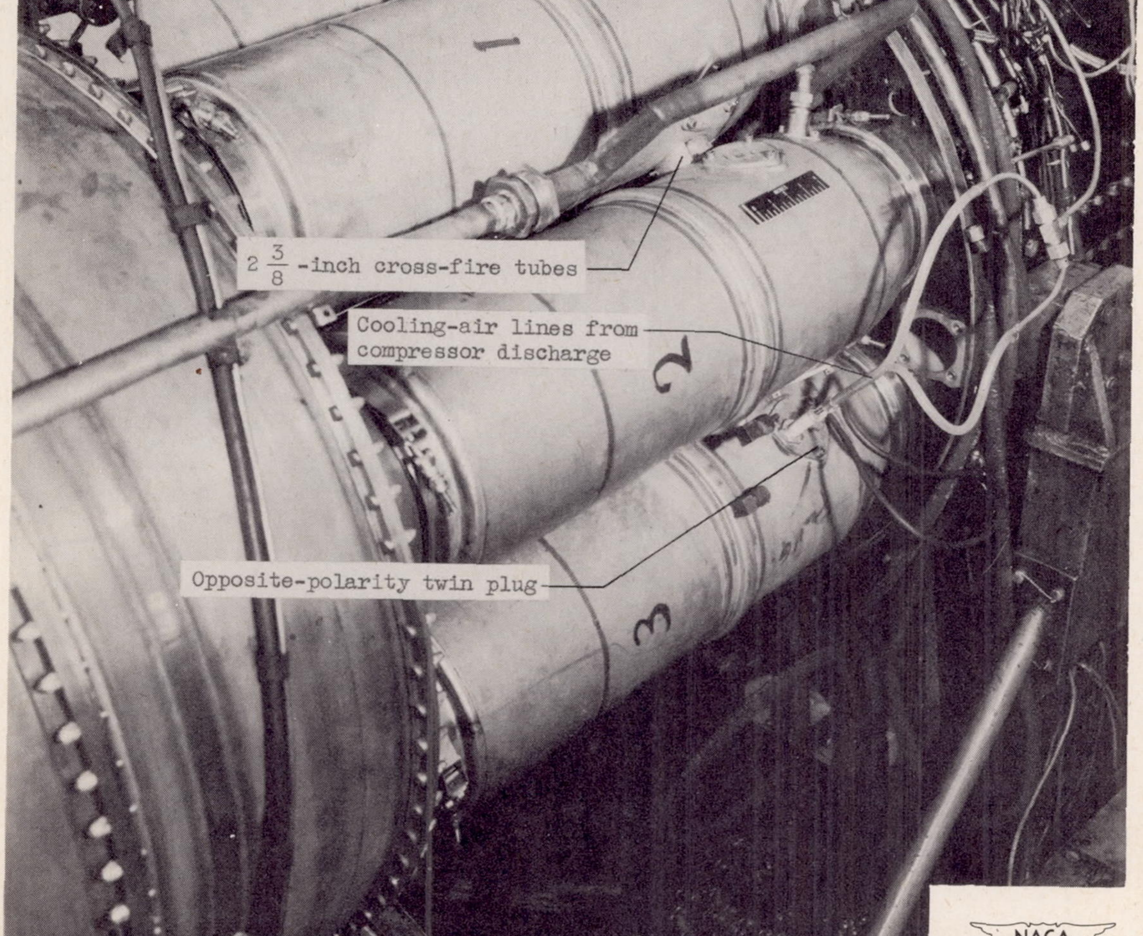

Figure 8. - Installation of $2\frac{3}{8}$-inch cross-fire tubes at shortest distance between combustors and opposite-polarity twin plug.

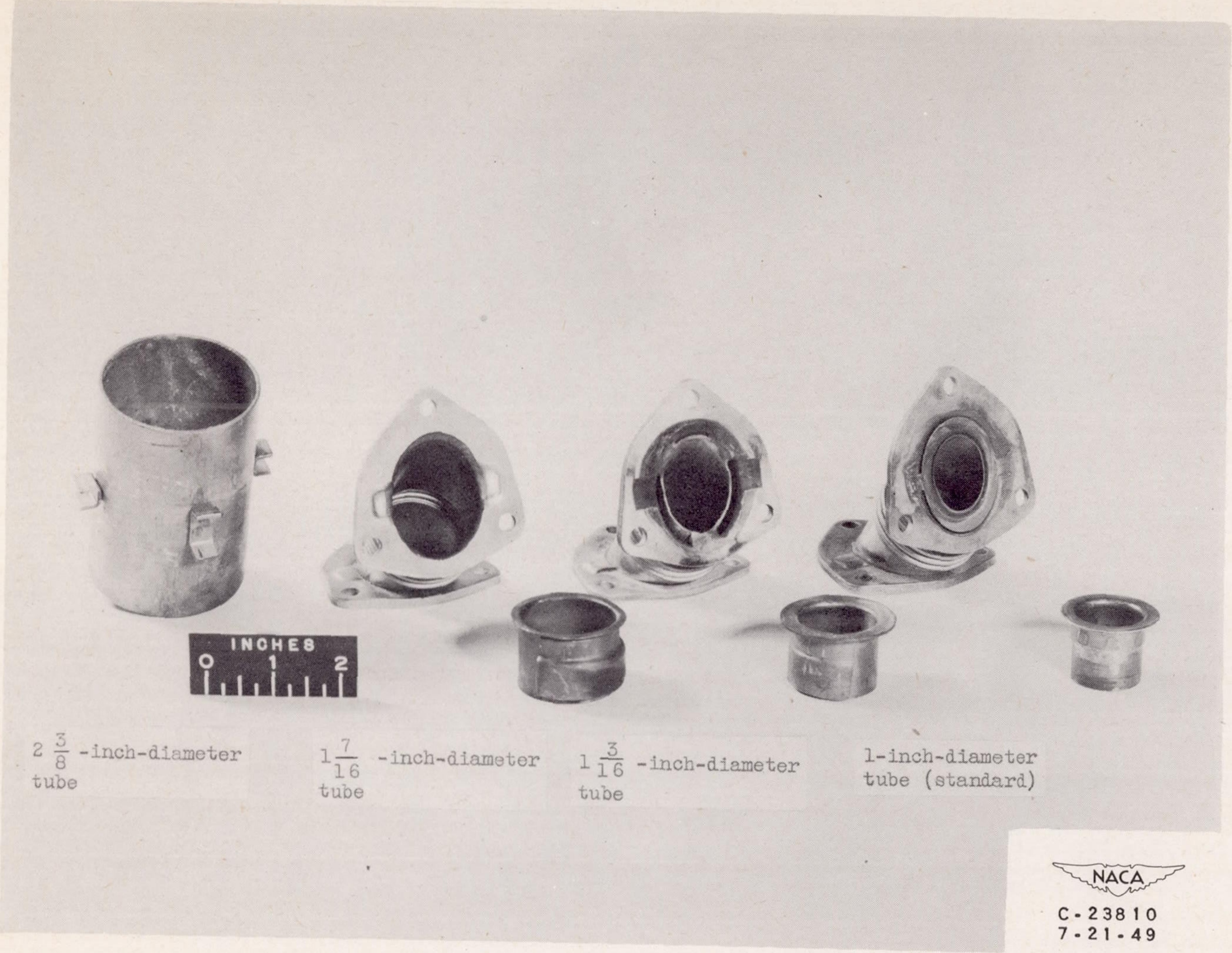

Figure 9. - Cross-fire tubes in order of decreasing diameter.

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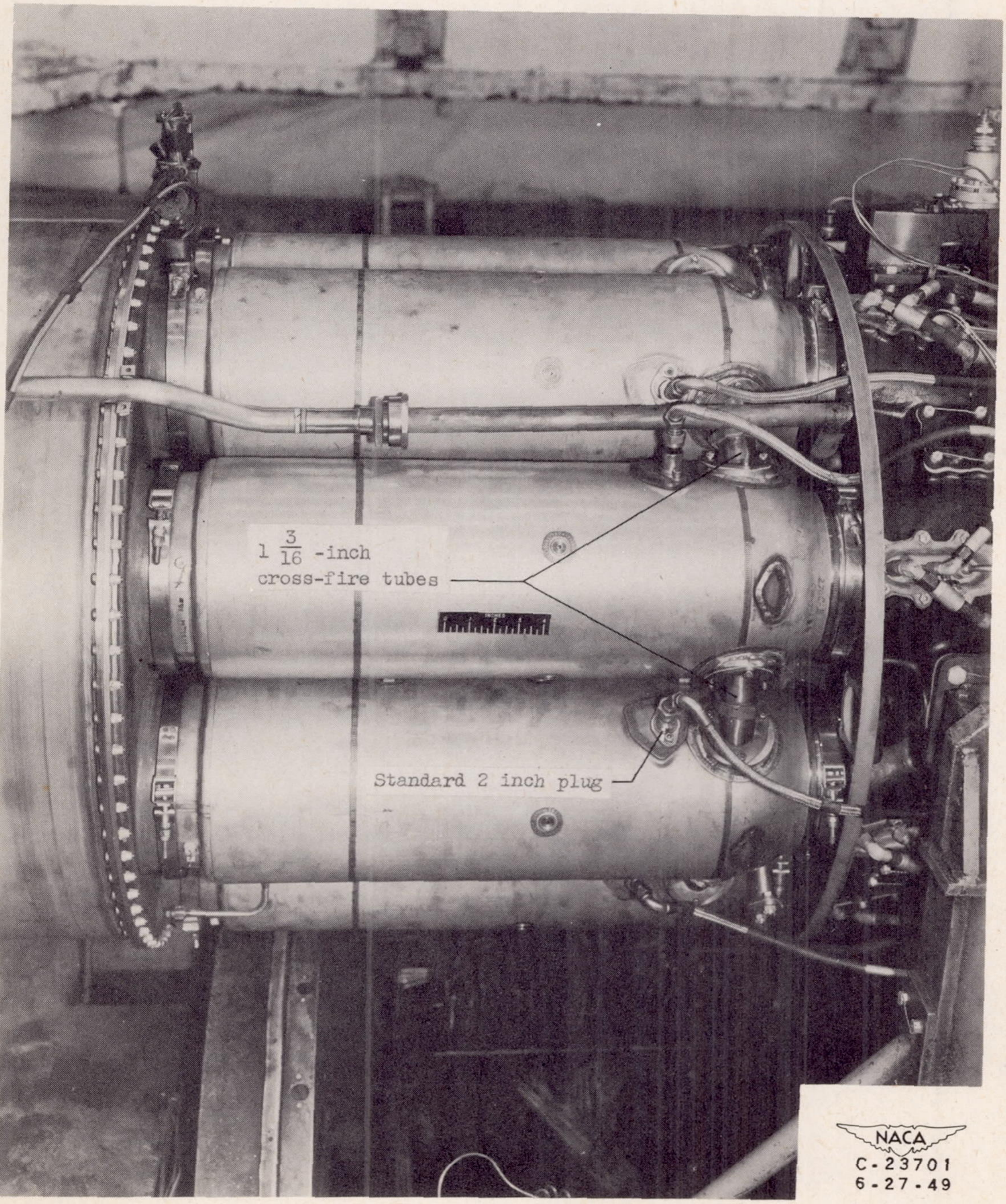
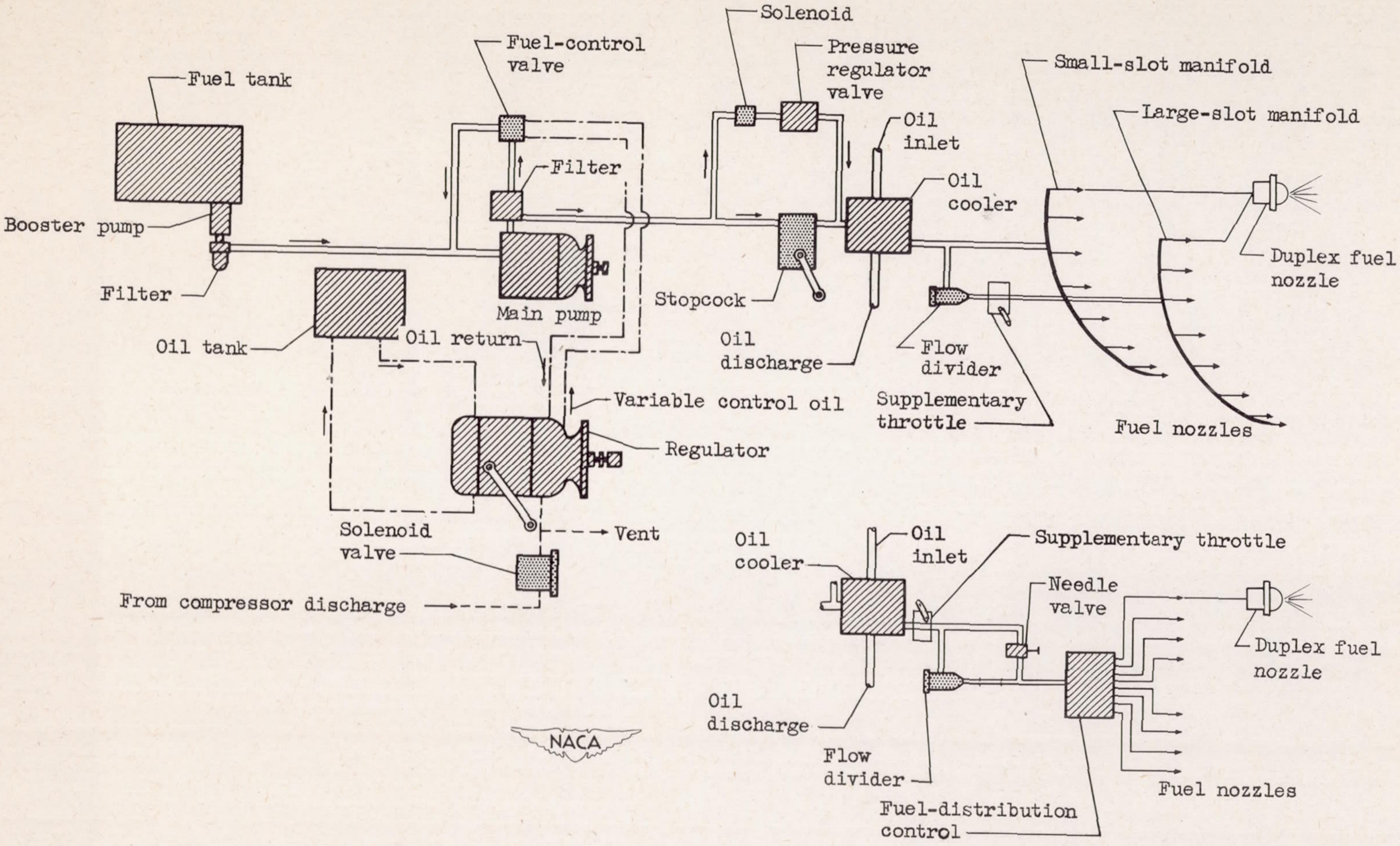


Figure 10. - Installation of dome-to-dome position cross-fire tubes.



(a) Standard fuel system.

(b) Modified fuel system.

Figure 11. - Diagrammatic sketch of standard and modified fuel systems.

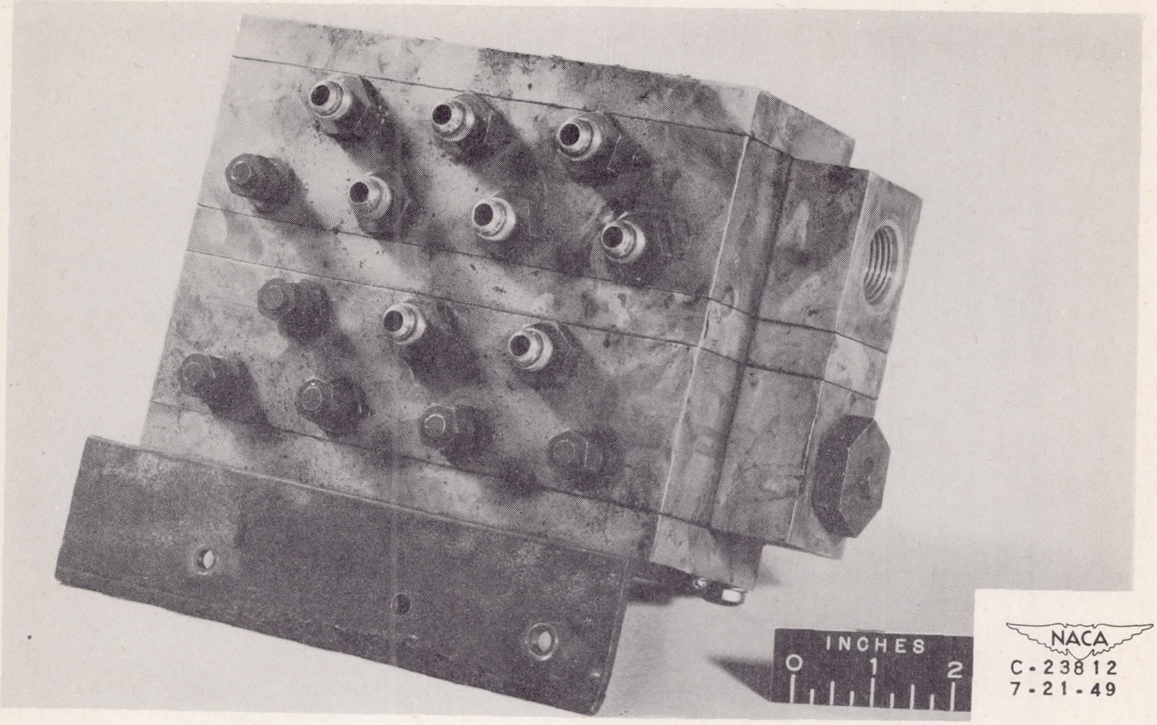


Figure 12. - Experimental fuel-distribution control used during altitude-starting investigation.

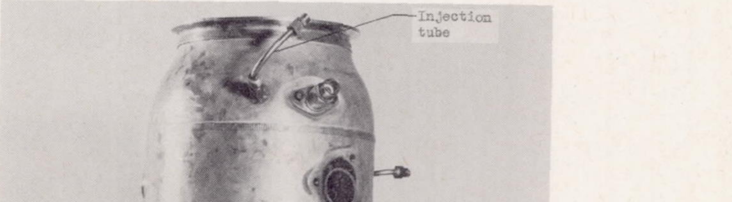


Figure 13. - Location of oxygen-injection tubes on combustor.

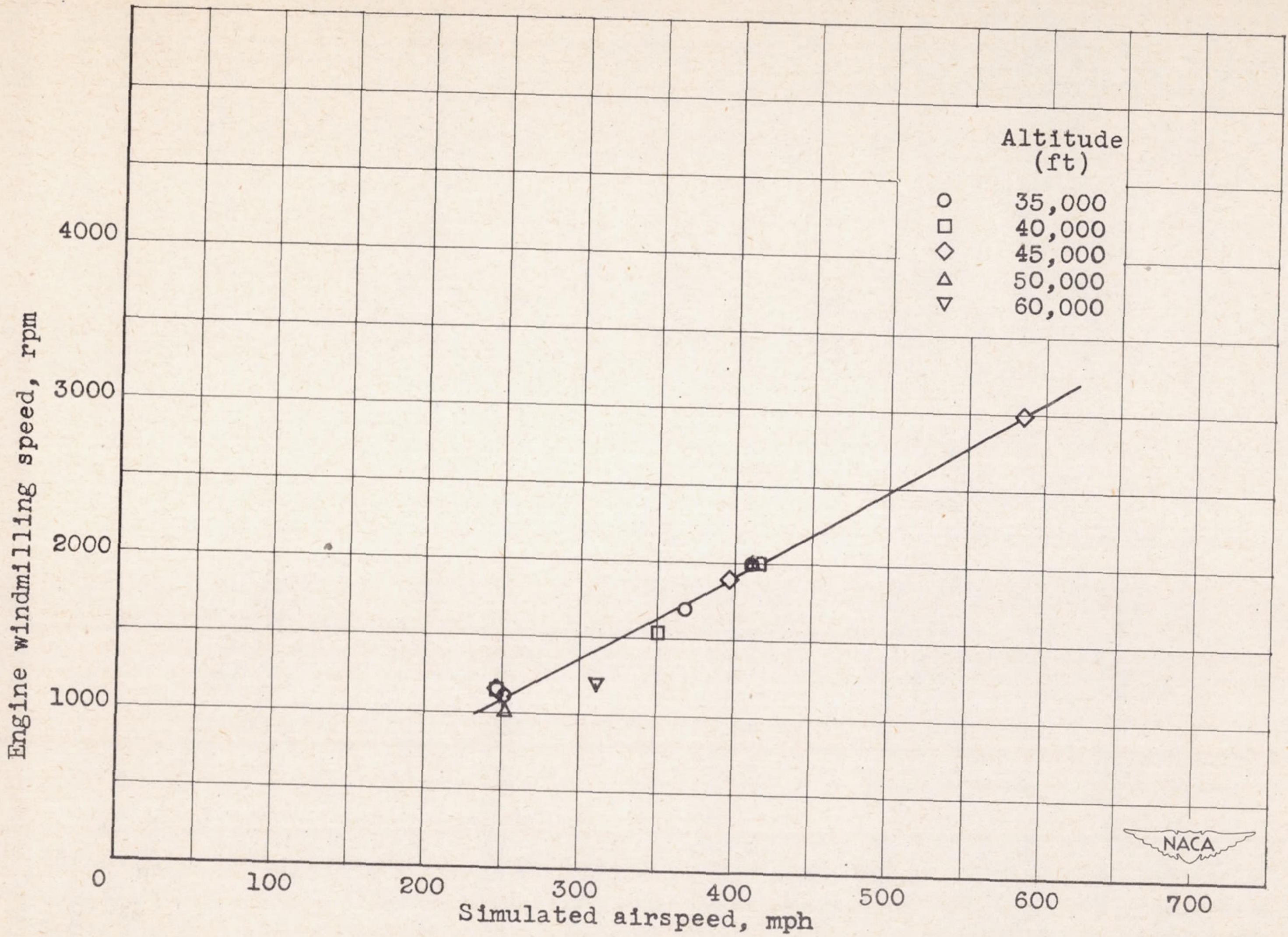


Figure 14. - Variation of engine windmilling speed with simulated airspeed at altitudes from 35,000 to 60,000 feet. Exhaust-nozzle-outlet area, 280 square inches.

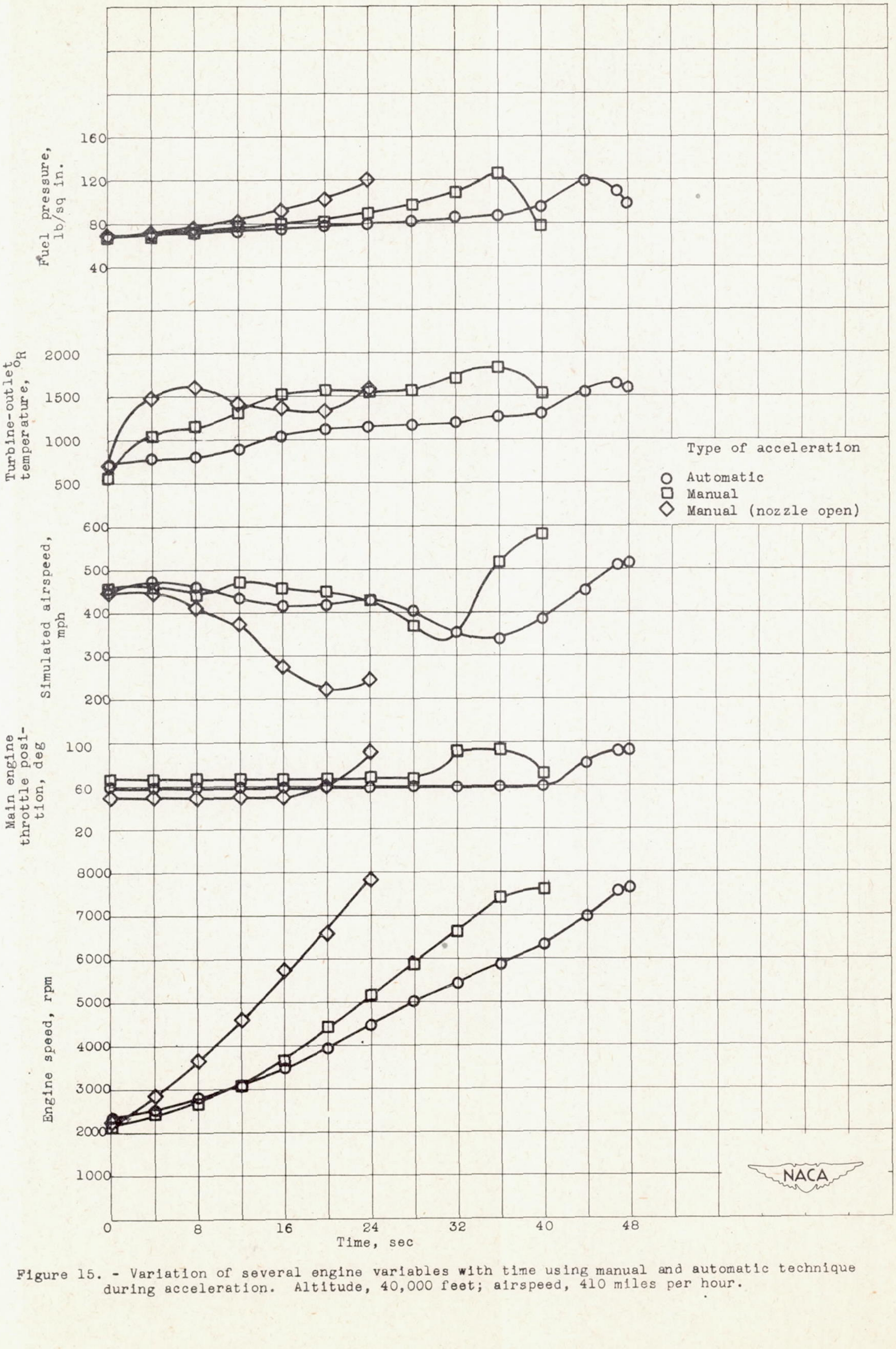


Figure 15. - Variation of several engine variables with time using manual and automatic technique during acceleration. Altitude, 40,000 feet; airspeed, 410 miles per hour.

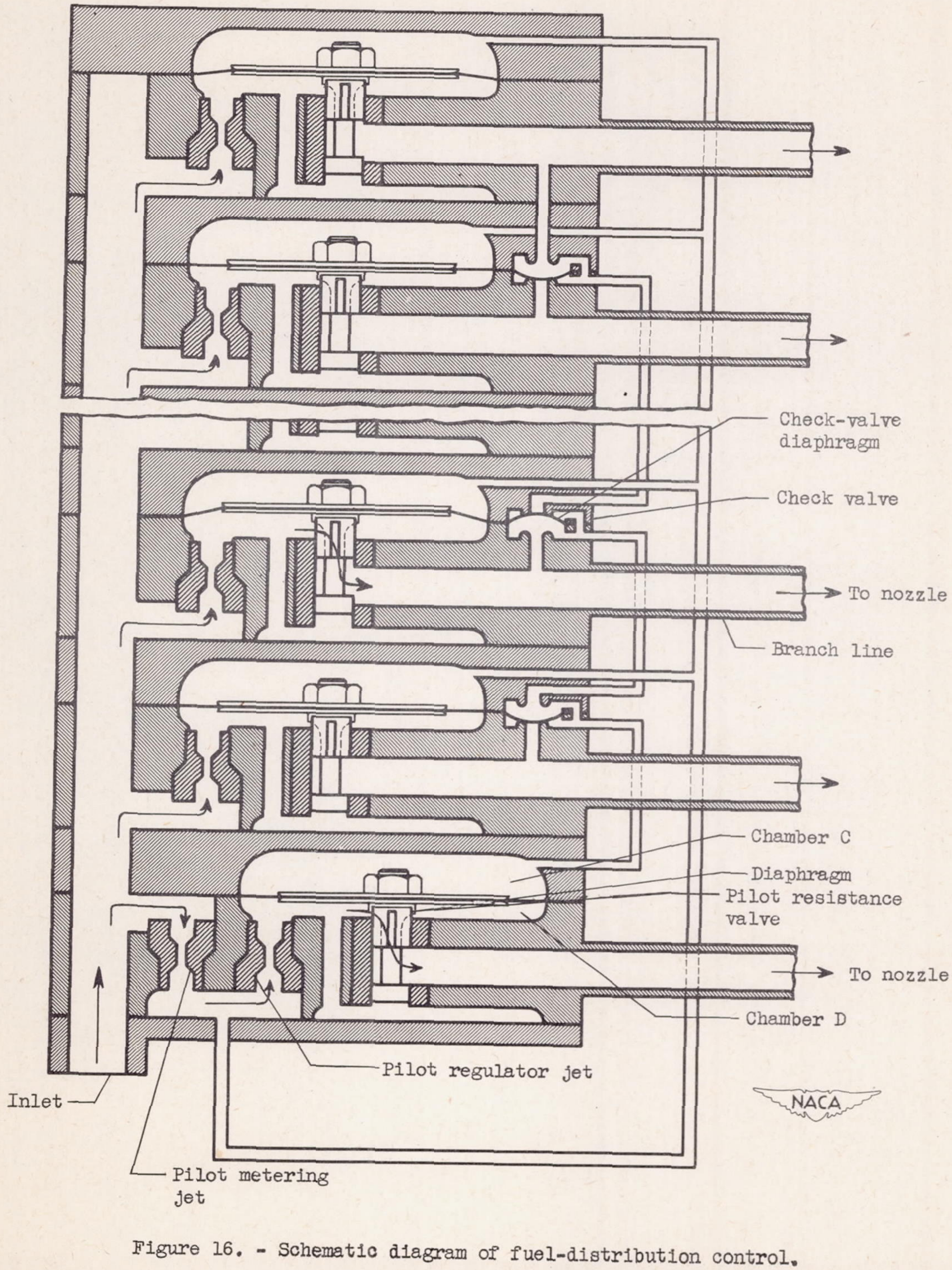


Figure 16. - Schematic diagram of fuel-distribution control.