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RESEARCH MEMORANDUM

GAS-TURBINE-ENGINE OPERATION WITH VARIABLE-AREA FUEL NOZZLES

By Harold Gold and David M. Straight

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RESEARCH MEMORANDUM

GAS-TURBINE-ENGINE OPERATION WITH VARIABLE-AREA FUEL NOZZLES

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SUMMARY

The characteristics of variable-area and fixed-area atomizing nozzles are discussed in relation to use in aircraft gas-turbine engines. A variable-area fuel nozzle and a fuel-distribution control that were used in the experimental operation of a turbojet engine are described. Photographs are presented of the spray produced by the variable-area fuel nozzle and by the fixed-area fuel nozzle that is currently in use on the engine. The variable-area fuel nozzle produced a finer fuel spray in the lower half of the required fuel-flow range and operated at a reduced fuel-system pressure at the maximum required fuel-flow rate.

A comparison is also made between sea-level performance characteristics at zero ram of a full-scale turbojet engine equipped with variable-area fuel nozzles and the performance characteristics of the engine equipped with fixed-area fuel nozzles. The reduced thrust specific fuel consumption in the lower half of the fuel-flow range and the improved starting characteristics obtained when the engine was equipped with the variable-area fuel nozzles is correlated with the finer fuel spray.

INTRODUCTION

The power range over which the aircraft gas-turbine engine is operated requires a wide range of fuel-flow rates. The ratio of maximum to minimum fuel-flow rates employed in current gas-turbine engines is approximately 10 to 1 and ratios as great as 100 to 1 are contemplated for future engines. The problem of fuel atomization that has resulted from these wide flow ranges has presented two difficulties: that of providing a fine spray at minimum flow rates, and that of avoiding excessively high fuel-pump pressures at maximum flow rates. This investigation at the NACA Cleveland laboratory consisted of a study of a possible solution to both of these difficulties.

In the pressure-type atomizing nozzle, the energy for breaking up the liquid into small droplets is derived from the pressure drop across the nozzle. The pressure drop across a fixed-area nozzle increases in proportion to the square of the rate of flow so that, even when reasonably high fuel-system pressures can be tolerated at the maximum flow rate, over a wide portion of the flow range the nozzle pressure drop may be relatively low and the atomization consequently poor.

The relation between flow and pressure drop of the pressure-type atomizing nozzle can be altered by varying the effective discharge area of the nozzle. When the effective discharge area is varied, a pressure drop high enough for good atomization can be employed at the minimum flow rate without requiring excessively high fuel-system pressures at the maximum flow rate. The relation between flow and pressure drop of the variable-area nozzle can be essentially a straight line, and the pressure drop over a wide flow range can be kept substantially constant.

Large variations can occur in the flow resistances of variable-area nozzles that operate at nearly constant pressure drop. This variation of flow resistance precludes the use of these nozzles with the simple manifold fuel-distribution system. The development, however, at the NACA Cleveland laboratory of a fuel-distribution control (references 1 and 2) presents a possible means of using variable-area nozzles that operate at nearly constant pressure drop without the disadvantage of irregular nozzle-to-nozzle fuel distribution.

Accordingly, a set of 14 constant-pressure-drop variable-area fuel nozzles were designed and built at the Cleveland laboratory for operation with the fuel-distribution control. The nozzles and the control were used in the operation of a turbojet engine on a sea-level-static stand. A comparison is made between the atomization produced by the variable-area fuel nozzles and the fixed-area fuel nozzles currently in use on the test engine. The starting and operating performance of the test engine when equipped with variable-area and with fixed-area fuel nozzles is also compared. The accuracy with which this fuel-distribution control can maintain equal rates of flow to the variable-area fuel nozzles during actual engine operation was studied. The starting runs were made in conjunction with a general turbojet engine-starting investigation, the results of which are reported in reference 3. The same variable-area fuel nozzles and fuel-distribution control were used in both of these investigations.

During preliminary bench studies of the fuel-distribution control, two modifications of the distribution control were made. In the first modification, the pilot system of the fuel-distribution control (described in references 1 and 2) was altered in order to obtain more consistent control accuracy when operating with variable-area nozzles. The second modification was the addition to the distribution control of an automatic valve for shutting off flow in individual fuel-nozzle lines in the event of line breakage. The automatic valve, which presents a possible means of decreasing the hazards of nozzle-line breakage such as might be caused by battle damage, is described in the appendix.

APPARATUS AND METHODS

Variable-Area Fuel Nozzle

The variable-area fuel nozzles used in this investigation were of the vortex type. The vortex-type nozzle essentially consists of a cylindrical swirl chamber into which the fuel flows tangentially and a circular orifice, concentric with the cylindrical chamber, through which the rotating mass of fuel is discharged. The spray resulting from this type of nozzle is in the form of a hollow cone.

Conventional vortex nozzles such as are currently used on the engine of this investigation have a fixed discharge orifice and fixed tangential openings into the cylindrical swirl chamber. Variable-area fuel nozzles of the type investigated have a fixed discharge orifice, but the area of the tangential openings into the cylindrical swirl chamber is varied by a pressure-sensitive means.

A cutaway drawing of the experimental variable-area fuel nozzle is shown in figure 1. Fuel flows into the nozzle as indicated by the arrows. The pressure-sensitive element is a bronze bellows, the spring rate of which is augmented by a helical spring. Fuel pressure acts on the outside of the bellows; the inside of the bellows is vented to the engine combustion chamber. As the fuel pressure increases, the bellows is compressed and the plunger is drawn upward, progressively uncovering the holes that are tangentially drilled into the swirl chamber. In operation, the differential between fuel pressure and combustion-chamber pressure that acts on the effective area of the bellows is balanced by the spring load. The spring is selected to exert a nearly constant force at all operating positions of the plunger. The fuel pressure drop through the nozzle is thereby maintained substantially constant over a range of flow rates and is independent of the combustion-chamber pressure. For fuel flow cut-off at the nozzle upon shutdown, the plunger is provided with a ball end, which seats in the discharge orifice. A photograph of the front and the rear of the nozzle is shown in figure 2.

The operating pressures of the nozzles were adjusted by moving the plunger on the threaded stem of the bellows shaft. The 14 nozzles used were so adjusted that, at a flow of 50 pounds per hour, the nozzle pressure drops were within the limits of 45 to 52 pounds per square inch.

Fuel-Distribution Control

The fuel-distribution control used to regulate the flow of fuel to the variable-area nozzles was basically similar to the control described in references 1 and 2 but had a modified pilot system.

In the fuel-distribution control described in reference 2, the pilot resistance valve was preset for a fixed flow resistance to match the pressure-drop characteristics of the fixed-area fuel nozzles. If a similar pilot system were used with variable-area fuel nozzles, the pilot resistance valve would have to be arranged to offer a varying flow resistance to match the pressure-drop characteristics of the variable-area fuel nozzles. This system was tried with a spring-loaded pilot resistance valve, but the results were inconsistent because of the inconstancy and the irregularity of the resistances of both the variable-area fuel nozzles and the spring-loaded pilot resistance valve.

The fuel-distribution control was therefore 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 3, 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 whose resistance is highest.

The pilot element is used to feed one of the 14 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. A photograph of the fuel-distribution control used in the investigation is shown in figure 4.

Engine Installation

An I-40-9 turbojet engine mounted on a sea-level static stand was used in this investigation. The fuel-distribution control was mounted on the engine and individual rotameters were installed in each line carrying fuel from the control to the engine fuel nozzles. The rotameters used covered a range from 50 to 350 pounds per hour. The variable-area fuel nozzles were installed in the engine air adapter in the conventional location. The spark plugs were set back radially 3/4 inch from the conventional location to accommodate the wider cone angle of the fuel spray produced by the variable-area fuel nozzles at the starting fuel-flow rate. A rotameter covering a range from 500 to 7000 pounds per hour was used to measure rate of total fuel flow to the engine. Engine thrust was measured with a calibrated strain gage having a range of 50 to 5000 pounds. Engine-starting data were obtained with the recording instruments described in reference 3. The manual fuel control was of the two-lever type, having a throttle lever and a stopcock lever. An adjustable bypass around the throttle was provided so that, with the throttle closed and the stopcock open, a fuel-flow rate sufficient for engine idle speed was maintained.

Engine Operating Conditions

All engine runs were made at ambient temperatures between 40° and 60° F. The engine was operated through a range of speeds

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from 4000 to 11,500 rpm. The total fuel-flow rate, the fuel-flow rate to each nozzle, and the static thrust were recorded.

Runs were made with the variable-area fuel nozzles in the engine and also with the fixed-area fuel nozzles currently being used in service for a comparison of engine performance. The variable-area fuel-nozzle runs and the fixed-area fuel-nozzle runs were made alternately to avoid errors due to engine or instrument deterioration. The fuel-distribution control was used with both types of fuel nozzle during the runs made for a comparison of engine performance. In order to obtain data for a comparison of fuel-system pressures, one set of runs was made using the manifold fuel system currently in use on the engine. Kerosene fuel, AN-F-32, was used for all engine operation.

RESULTS AND DISCUSSION

The results of the investigation are discussed with respect to nozzle characteristics and fuel distribution, effect of atomization on engine operating characteristics, and fuel-system characteristics during engine operation.

Nozzle Characteristics and Fuel Distribution

Relation of flow and pressure drop. - The relation of flow and pressure drop of the variable-area and the fixed-area fuel nozzles used in the engine investigation are shown in figure 5(a). At low flow rates, the pressure drop across the fixed-area nozzle is very low. Because of the low pressure drop, very little energy is available to break up the liquid fuel and the atomization is consequently poor. The pressure drop across the fixed-area nozzle increases in proportion to the square of the flow rate, resulting in a relatively high pressure at the maximum rate of flow.

The relation between flow and pressure drop of the variable-area nozzle used in the engine runs (fig. 5(a)) was essentially a straight line up to 240 pounds per hour and the pressure drop was substantially constant. Above 240 pounds per hour the pressure drop increased sharply. This sudden increase in pressure drop was a result of insufficient tangential-hole area in the nozzle. After the engine runs were completed, more tangential holes were drilled in the nozzle and the straight-line relation was extended to a flow rate of 500 pounds per hour (fig. 5(b)). Nearly as high a pressure drop can therefore be used at the lowest flow rate as will be required at the highest flow rate. Sufficient energy can thereby be provided for good atomization over the full range of fuel-flow rates without excessively high fuel-system pressures at the maximum flow rate. The variable-area fuel nozzles of the type used in this investigation were found to be capable of producing a finely atomized spray over a flow range from 30 to 500 pounds per hour with a corresponding pressure range from 50 to 70 pounds per square inch.

Visual comparison of fuel sprays. - Photographs of the spray produced by the variable-area and the fixed-area nozzles that were used in the engine runs are shown in figure 6. The flow rates shown are 40, 65, 80, 125, 150, and 200 pounds per hour. The finer atomization produced by the variable-area nozzle in the low-flow range because of the greater pressure drop is readily apparent. The lower flow-rate limit at which the variable-area fuel nozzle produced a fine spray similar to that shown at 40 pounds per hour (fig. 6(a)) was approximately 30 pounds per hour.

Calibration of variable-area fuel nozzles. - From the spread of calibrations of the 14 variable-area nozzles used in the engine runs (fig. 7), it can be seen, by tracing a line of equal pressure drop, that if the nozzles were fed from a common manifold as in current turbojet-engine fuel systems, the distribution would be very erratic. The poor distribution would be due primarily to the constant pressure-drop characteristic of the nozzles, as a result of which large differences in flow rate can exist between nozzles at the same pressure drop.

Fuel distribution during engine operation. - The rate of flow from the fuel-distribution control to each variable-area nozzle as measured with rotameters during engine runs is shown in figure 8. Over the range of nozzle flow rates from 65 to 311 pounds per hour, the maximum deviation from the mean flow rate was 3.3 percent, including a possible random rotameter error (reference 2) of ± 3 pounds per hour at all flow rates. This distribution accuracy is somewhat better than that obtained with fixed-area fuel nozzles and with a fixed pilot-nozzle resistance on the fuel-distribution control (reference 2). This improvement in distribution-control performance is probably due to the modified pilot system in which the pilot-nozzle resistance is automatically adjusted at all times to equal the greatest resistance of any of the 14 nozzles.

Effect of Atomization on Engine Operating Characteristics

Engine performance. - The thrust specific fuel consumption of the turbojet engine when operating with the variable-area fuel nozzles and with the fixed-area fuel nozzles is shown in figure 9. The data were obtained from several runs on one engine made alternately with the variable-area and the fixed-area fuel nozzles. A definite decrease in the thrust specific fuel consumption was obtained with the variable-area fuel nozzles. The reduction in thrust specific fuel consumption shown in figure 9 was the result of both an increase in engine thrust and a decrease in fuel consumption at a given speed. These data are plotted in figures 10 and 11, respectively. At the lowest engine speed of 4000 rpm, where the fuel-flow rate is lowest and the difference in the atomizing performance of the two types of nozzle is greatest (fig. 6(a)), the decrease in thrust specific fuel consumption is greatest (fig. 9). At higher engine speeds, with the accompanying higher fuel-flow rates, the thrust-specific-fuel-consumption curves converge. The point of convergence of the two curves is at an engine speed of approximately 9500 rpm. This speed corresponds to an engine fuel-flow rate of 2630 pounds per hour (fig. 11) and therefore to a nozzle flow rate of approximately 190 pounds per hour, which coincides with the point of convergence of the nozzle pressure-drop curves, as shown in figure 5(a).

Under a wide range of altitude operating conditions, the engine fuel-flow rates will be below 2630 pounds per hour for the full range of engine speeds. Improved atomization, such as obtained in this investigation with the variable-area fuel nozzles, therefore may possibly result in improved engine performance at altitude over the full range of engine speeds.

Engine starting. - The engine when equipped with the variable-area fuel nozzles was started consistently at a constant fuel-flow rate of 580 pounds per hour as compared to approximately 1000 pounds per hour required for a short period with the fixed-area fuel nozzles (reference 3). The ability to start on a reduced and constant flow rate simplified the operational procedure.

During the engine starts with the variable-area fuel nozzles, the constant rate of 580 pounds per hour was maintained by the idle bypass in the manual fuel control. (See section entitled "Engine installation.") This bypass permitted the throttle lever to be left closed during starting; only the opening of the fuel stopcock was required. With this procedure, approximately 30 engine starts were made, in all of which combustion occurred within a few seconds after the nozzle-opening pressure was reached. After combustion occurred, the engine speed rose to approximately 3000 rpm without any manipulation of the throttle. Above a speed of 3000 rpm, the operator had good control of the engine with the throttle lever. All starts were made at ambient temperatures between 40° and 60° F with the engine being driven by the starter motor at a speed of approximately 1000 rpm. In all the starts made with this procedure, the peak tail-cone gas temperature was between 1400° and 1650° F. A record of a typical start is shown in figure 12.

The fuel stopcock was a quick-opening valve, so linked to the hand lever that only a small percentage of the lever's travel was in the throttling range of the valve. The time required for the fuel pressure to build up to the opening pressure of the variable-area nozzles (approximately 5 sec) was longer than the time required to pass the stopcock hand lever through the throttling range when the lever was moved with normal speed. For all practical purposes, therefore, the speed with which the stopcock hand lever was moved had no effect on the rate of fuel flow. With fixed-area nozzles, careful manipulation of the throttle lever is necessary during the starting operation (reference 3).

In reference 3, the accumulation of fuel in the combustion chambers before combustion occurred was found to result in poor control of temperature during starting. This accumulation of fuel was caused by poorly atomized fuel sprays. The effect of fuel accumulation on engine starting with variable-area nozzles was investigated by delaying the closing of the ignition circuit until sometime after the fuel began to flow. The ignition was delayed progressively 5, 15, and 34 seconds (during which time the rate of fuel flow was 580 lb/hr) without appreciable effect on tail-cone gas temperature. The time-temperature record of these starts is shown in figure 13. During the ignition delay, a thick fog of fuel blowing out of the engine tail pipe was observed. The fog stopped the instant the combustion rumble could be heard. Apparently, the spray produced by the variable-area fuel nozzles was fine enough to remain suspended in the air stream and pass out of the engine until combustion occurred.

Fuel-System Characteristics During Engine Operation

Carbon formation on variable-area fuel nozzles. - The orifice of the variable-area fuel nozzle is recessed in the discharge face of the nozzle (figs. 1 and 2). Examination of the nozzles after engine runs showed that although carbon built up on the ridge of the recess, only a thin film of carbon formed around the orifice. Possibly the recessing of the orifice served to shield the orifice from heavier carbon formation that would have disrupted the spray. A study of the spray produced by the carboned nozzles showed that at the engine starting flow rate of 580 pounds per hour (41 lb/hr nozzle flow rate) some of the spray impinged on the heavier carbon that formed on the ridge of the recess; most of the spray, however, was unaffected. At flow rates above 50 pounds per hour, the cone angle of the spray narrowed slightly and there was no interference. By proper adjustment of the depth of the recess, disruption of the spray by carbon formation might be entirely avoided. The carbon interference that occurred during engine operation was not great enough to prevent engine starting at the constant flow rate of 580 pounds per hour; however, an examination of the data showed that the carbon formation caused somewhat higher tail-cone gas temperatures during starting. The highest tail-cone gas temperature reached during starting with carboned variable-area fuel nozzles was 1650° F. The engine performance data showed no effect due to the carbon formation, which confirms the observation that there was no interference above 50 pounds per hour.

Fuel-system pressures. - As shown previously (fig. 5), the variable-area fuel nozzles used in this investigation allow operation with considerably reduced fuel pressure at the maximum rate of flow, as compared with that required with fixed-area nozzles currently in use on the engine used in this investigation. This reduction can be accompanied by a reduction in fuel-pump pressure. The actual reduction in fuel-pump pressure cannot be accurately predicted, however, because it would also depend on the design of other fuel-system components. A comparison of throttle-outlet pressures can serve to indicate, nevertheless, the significance of the possible pressure reduction. The variation of throttle-outlet pressure with engine fuel-flow rate during sea-level static engine operation for the turbojet engine with the distribution control and the variable-area fuel nozzles and with the current manifold fuel system and the fixed-area fuel nozzles is shown in figure 14. Similarly plotted are the throttle-outlet pressures required with the improved variable-area fuel nozzle (fig. 5(b)) as calculated from bench and engine data. The variable-area nozzle and the distribution-control system reduced the maximum throttle-outlet pressure approximately 130 pounds per square inch from that of the current fuel system to a pressure of 200 pounds per square inch gage and the improved variable-area nozzle may bring the maximum throttle-outlet pressure down to approximately 175 pounds per square inch gage.

Engine shutdown. - When the pressure supplied to the variable-area fuel nozzle drops below the opening-pressure setting as in shutdown, the plunger (fig. 1) moves downward, seating the ball end in the orifice. The fuel is thereby shut off at the combustion chamber. No afterburning was observed throughout the entire period of the investigation. No significant collection of fuel from the combustion-chamber drain valve occurred during this period.

SUMMARY OF RESULTS

From an investigation of the sea-level performance characteristics at zero ram pressure of a turbojet engine equipped with a fuel-distribution control with variable-area fuel nozzles and with fixed-area fuel nozzles, the following results were obtained:

1. The variable-area fuel nozzles of the type used in this investigation were found to be capable of producing a finely atomized spray over a flow rate range of 30 to 500 pounds per hour with a corresponding pressure range of 50 to 70 pounds per square inch.

2. The fuel spray produced by the variable-area fuel nozzle was visibly finer than that produced by the fixed-area fuel nozzle currently in use on the turbojet engine in the range of nozzle fuel-flow rates of 30 to approximately 190 pounds per hour. Above 190 pounds per hour, there was no visible difference in the spray produced by the two nozzles.

3. The fuel-distribution control regulated the rate of flow to the 14 variable-area fuel nozzles with a maximum deviation from uniform distribution of 3.3 percent (including the possible random rotameter error of ±3 lb/hr) over a range of nozzle fuel-flow rates of 65 to 311 pounds per hour.

4. With variable-area fuel nozzles, in the range of nozzle fuel-flow rates below 190 pounds per hour, the thrust specific fuel consumption of the engine was definitely lower than when operating with the fixed-area nozzles. Above 190 pounds per hour, there was no appreciable difference in the thrust specific fuel consumption of the engine with either nozzle.

5. The engine was started consistently with a constant engine fuel-flow rate of 580 pounds per hour when equipped with variable-area fuel nozzles. In each of approximately 30 starts, the peak tail-cone gas temperature was between 1400° and 1650° F.

6. With variable-area fuel nozzles, ignition delay during starting had no appreciable effect on the peak tail-cone gas temperature. The fuel spray was apparently fine enough to be blown out of the engine before ignition.

7. The maximum throttle-outlet pressure, which occurred at maximum sea-level static power, was 200 pounds per square inch gage when variable-area fuel nozzles were used.

8. On engine shutdown, the variable-area fuel nozzles shut off the fuel at the burners, with the immediate end of combustion and the elimination of the draining of residual fuel into the combustion chambers. No burning of fuel after shutdown was observed during the entire investigation.

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APPENDIX - DAMAGE-CONTROL VALVE

Purpose of valve. - In gas-turbine-engine fuel systems in which a fuel manifold is employed, the breaking of any one branch line that feeds a nozzle could result in the starving of the remaining nozzles. If a fuel-distribution control such as that described in this report is used, the possibility of starving the remaining nozzles when a branch line is broken is eliminated. The control, however, would maintain normal branch fuel flow through the broken line, constituting a serious fire hazard. In order to eliminate the fire hazard, an automatic valve was designed at the Cleveland laboratory for use with the fuel-distribution control. The automatic valve functions to shut off the flow in any branch line (other than the pilot) in the event of line breakage.

Control method. - A schematic diagram showing the combination of fuel-distribution control, fuel nozzles, and damage-control valve is shown in figure 15. Fuel flows from the distribution control through the valve seat and into the valve chamber from which it flows through the branch line to the variable-area nozzle. The check valves of the pressure selector are vented downstream of the damage-control valve and transmit the highest branch-line pressure to chamber C in the manner discussed in connection with figure 3. Chamber C is also vented to the diaphragm chamber of each damage-control valve. A spring acts on the valve stem exerting a force in the direction of the valve opening.

Before starting, the pressures on both sides of the damage-control-valve diaphragm are zero gage and the spring maintains the valve open. During starting, the branch-line pressures build up at nearly equal rates so that there is, at most, only a small closing force acting on the valve, which is resisted by the spring. With variable-area nozzles, the branch line is at a substantial pressure at all flow rates, so that the spring can be set to resist a reasonable pressure differential between the diaphragm chamber and the valve chamber of the damage-control valve. As long as the variable-area fuel nozzles are functioning properly, this pressure differential will be small in relation to the pressure level, and the spring will maintain the valve open. In the event of branch-line breakage, the pressure in the broken line drops to zero gage and the resulting large pressure differential closes the valve against the spring. The shutting off of flow in any branch line does not affect the flow to the remaining branch lines as regulated by the fuel-distribution control. If the flow in the pilot line is shut off, however, the fuel-distribution control will cease to function properly. For this reason, a damage-control valve cannot be placed in the pilot line.

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Description and performance of experimental model. - A photograph of an experimental model of the damage-control valve mounted on a section of the fuel-distribution control is shown in figure 16. The minimum operating pressure of the variable-area fuel nozzles used in this investigation was 45 pounds per square inch. The valve spring was accordingly set to resist up to a 35-pound-per-square-inch pressure differential. This high spring load eliminated any tendency of the valve to close prematurely. Upon line breakage the valve shut instantaneously. The performance of the fuel-distribution control was unaffected by the damage-control valve.

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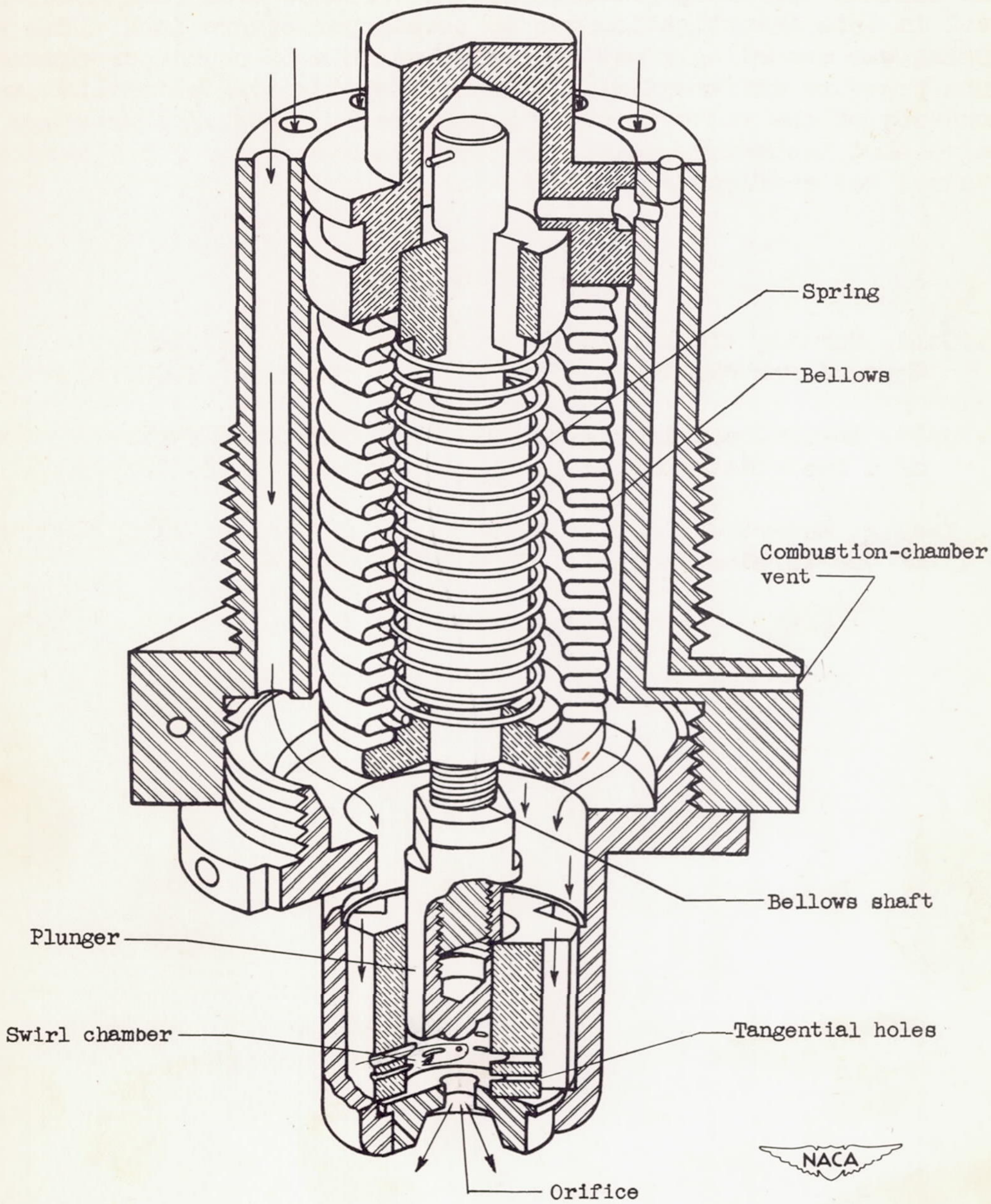

Figure 1. - Cutaway drawing of experimental variable-area fuel nozzle for gas-turbine engine.

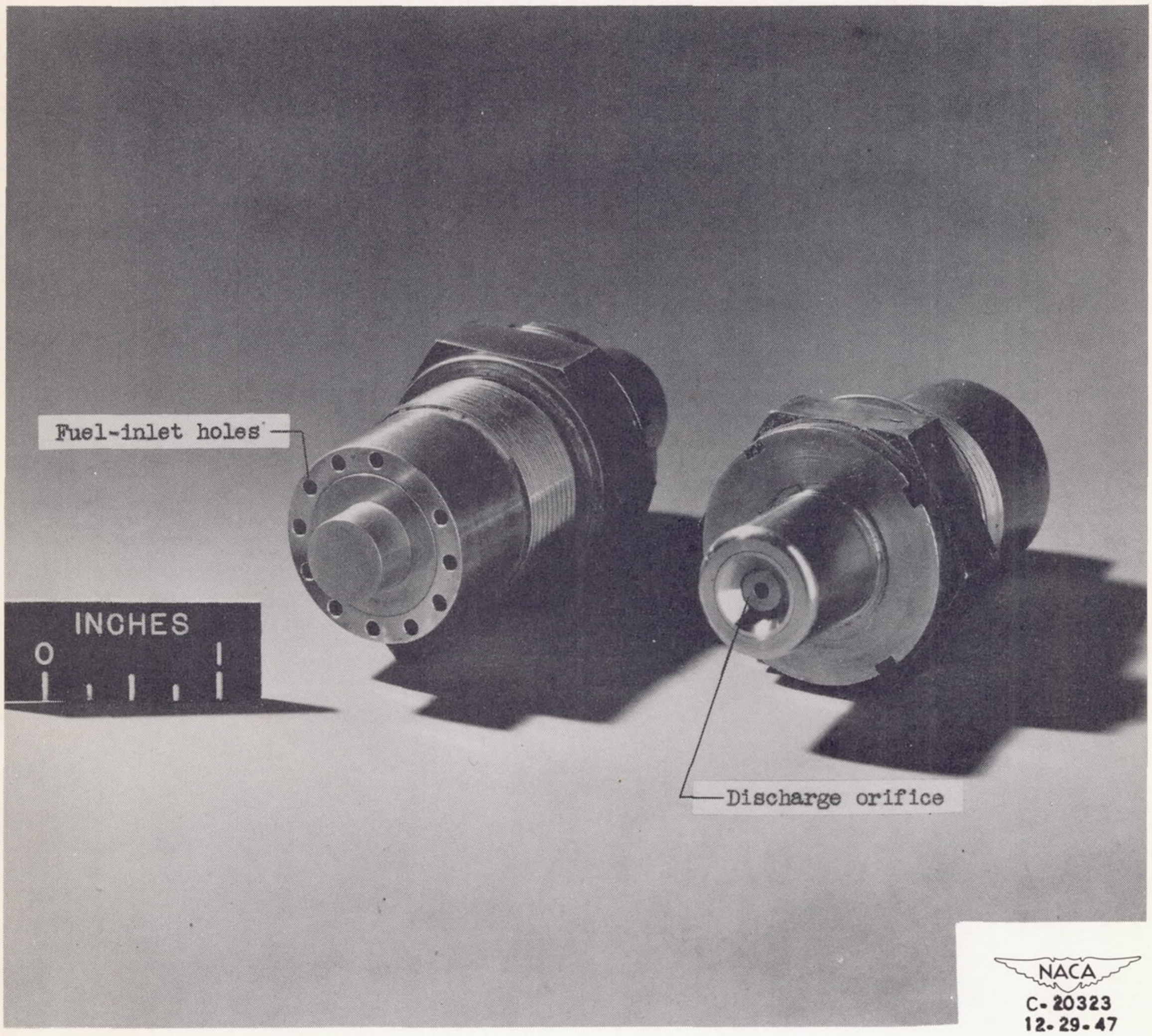

Figure 2. - Experimental variable-area fuel nozzle for gas-turbine engine.

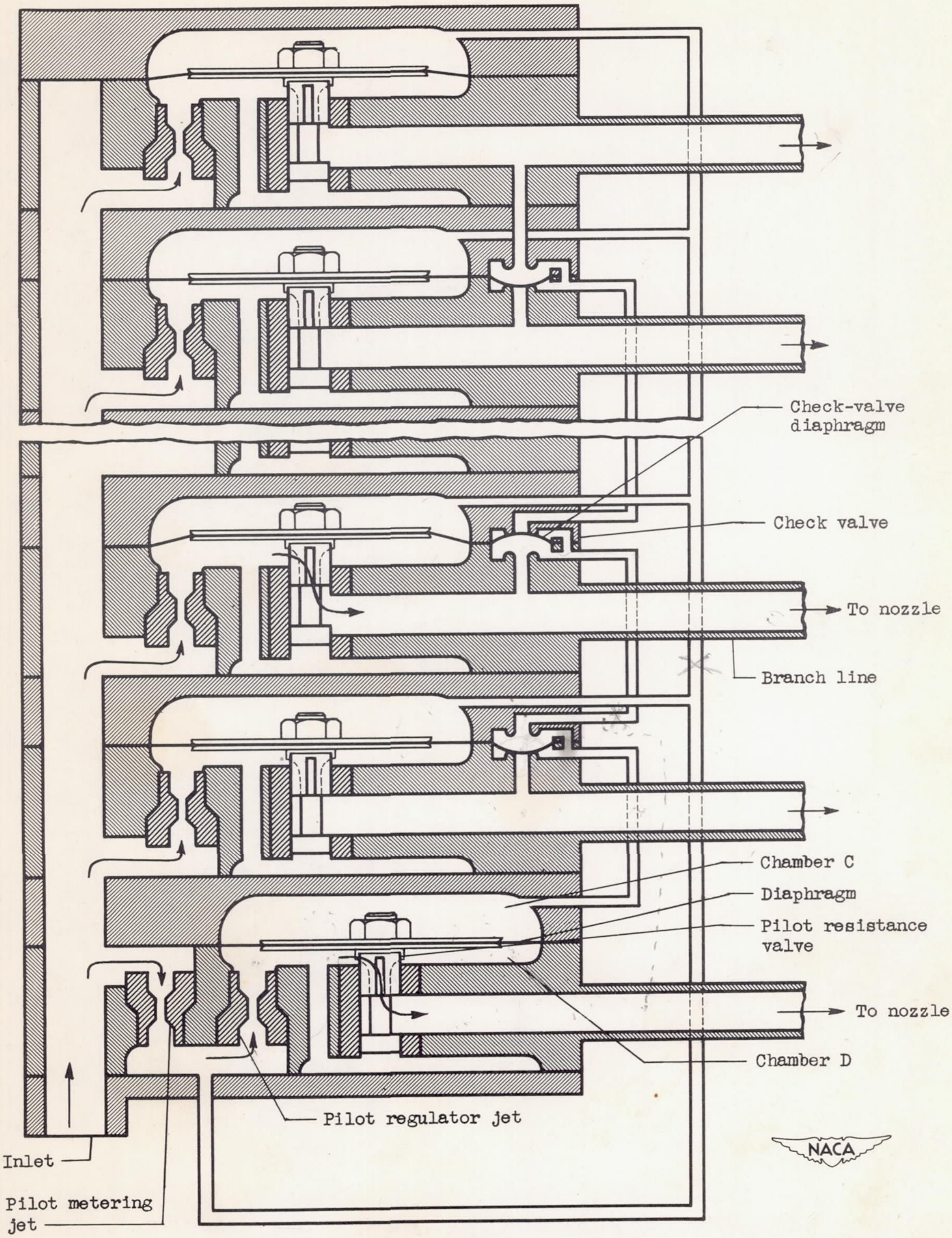

Figure 3. - Schematic diagram of fuel-distribution control for use with variable-area fuel nozzles.

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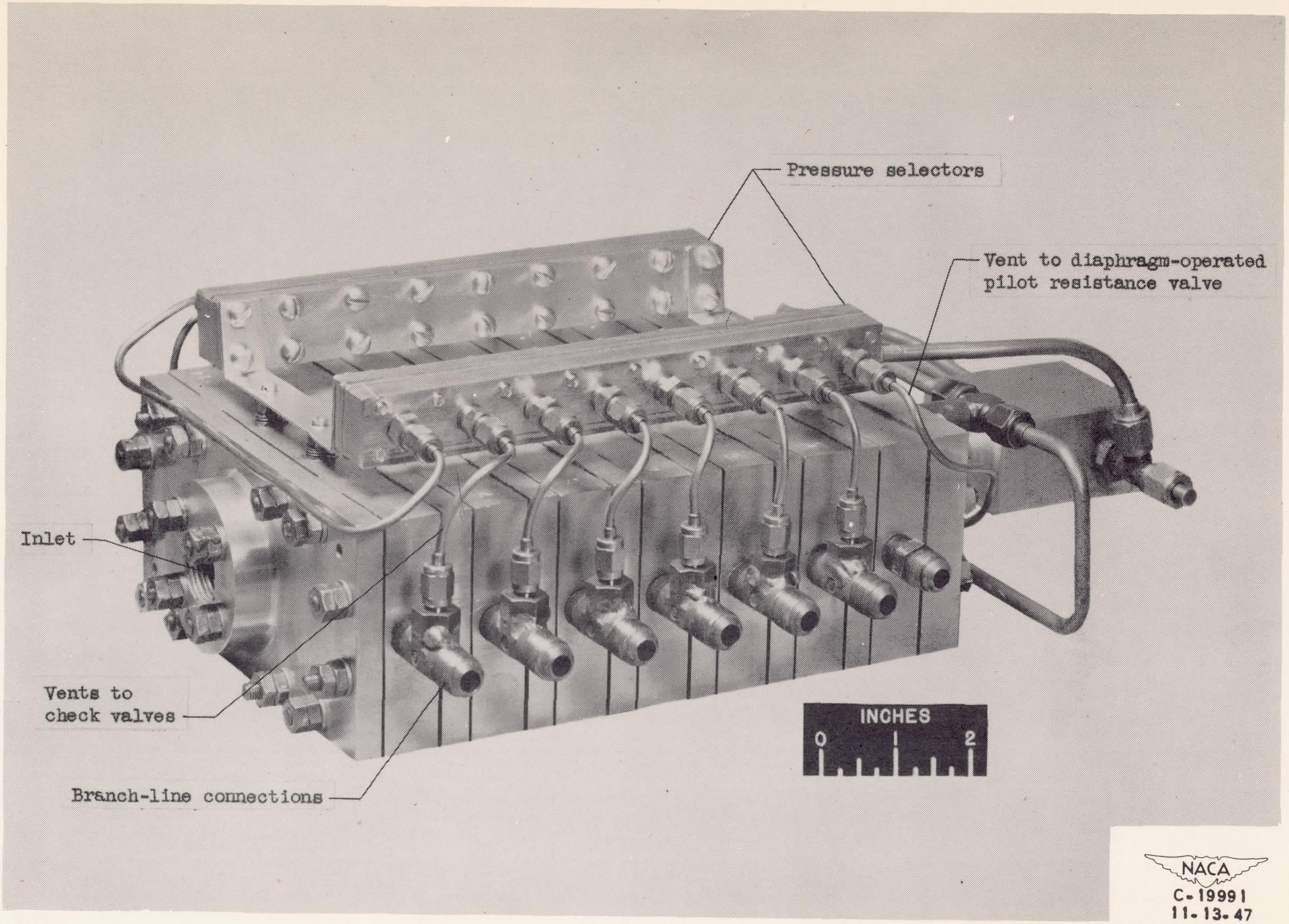

Figure 4. - Fuel-distribution control used in gas-turbine-engine operation with variable-area fuel nozzles.

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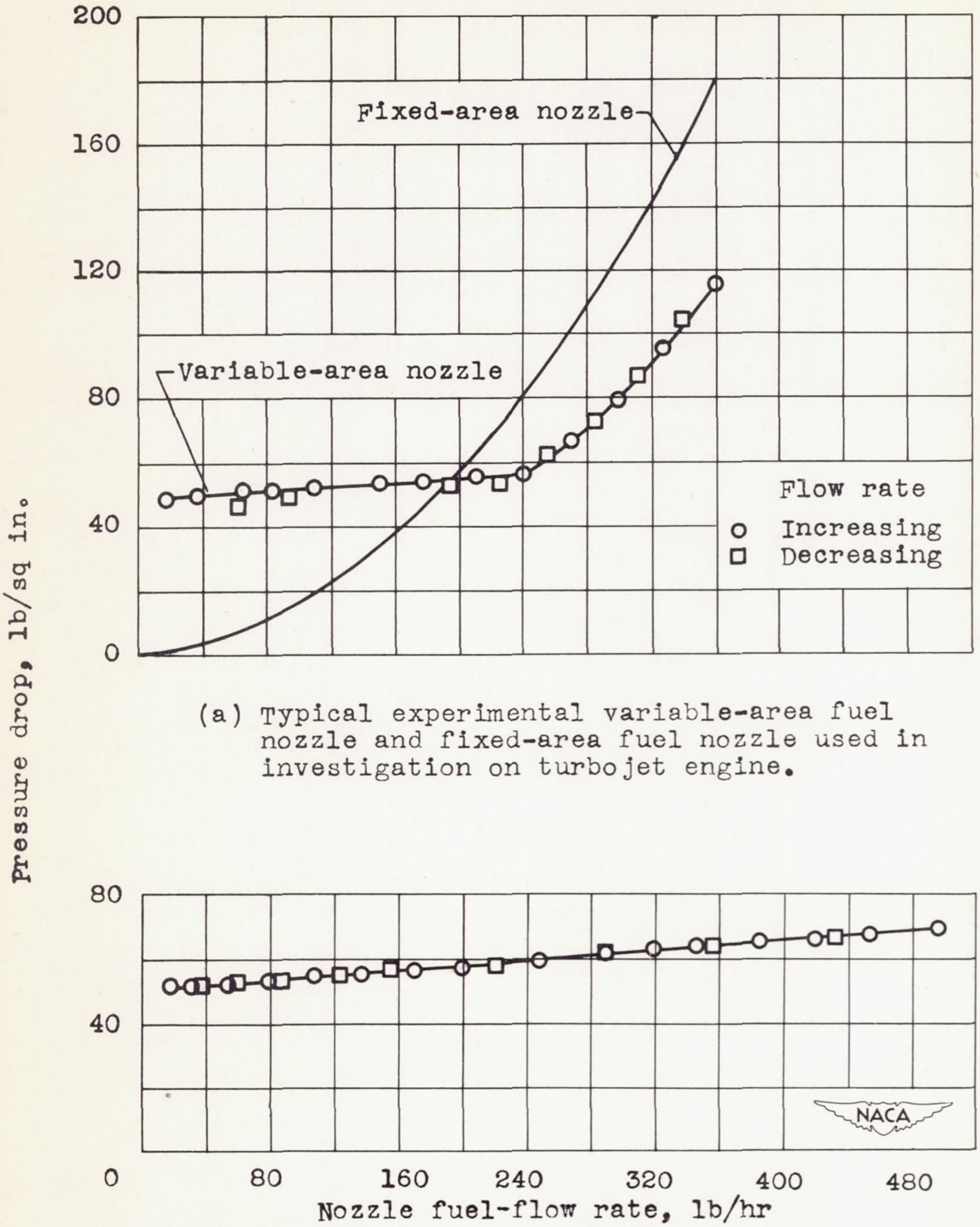

(a) Typical experimental variable-area fuel nozzle and fixed-area fuel nozzle used in investigation on turbojet engine.

(b) Variable-area fuel nozzle with additional tangential holes.

Figure 5. - Relation between flow and pressure drop for variable-area and fixed-area fuel nozzles. Fuel, AN-F-32.

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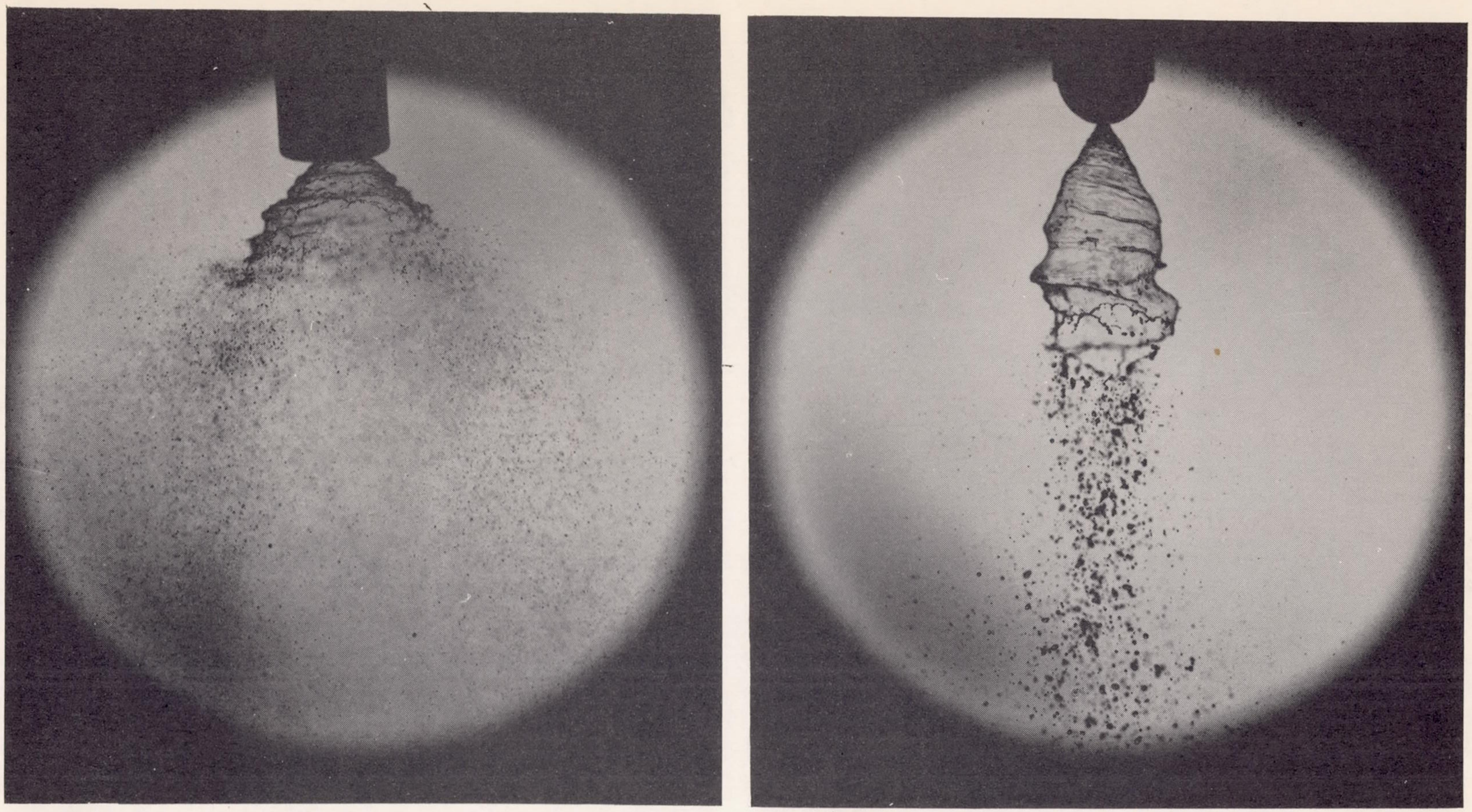

Variable-area fuel nozzle

Fixed-area fuel nozzle

NACA
C-21120
4-12-48

(a) Flow rate, 40 pounds per hour.

Figure 6. - Photographs of spray produced by variable-area and fixed-area fuel nozzles used in operation of turbojet engine. Fuel, AN-F-32.

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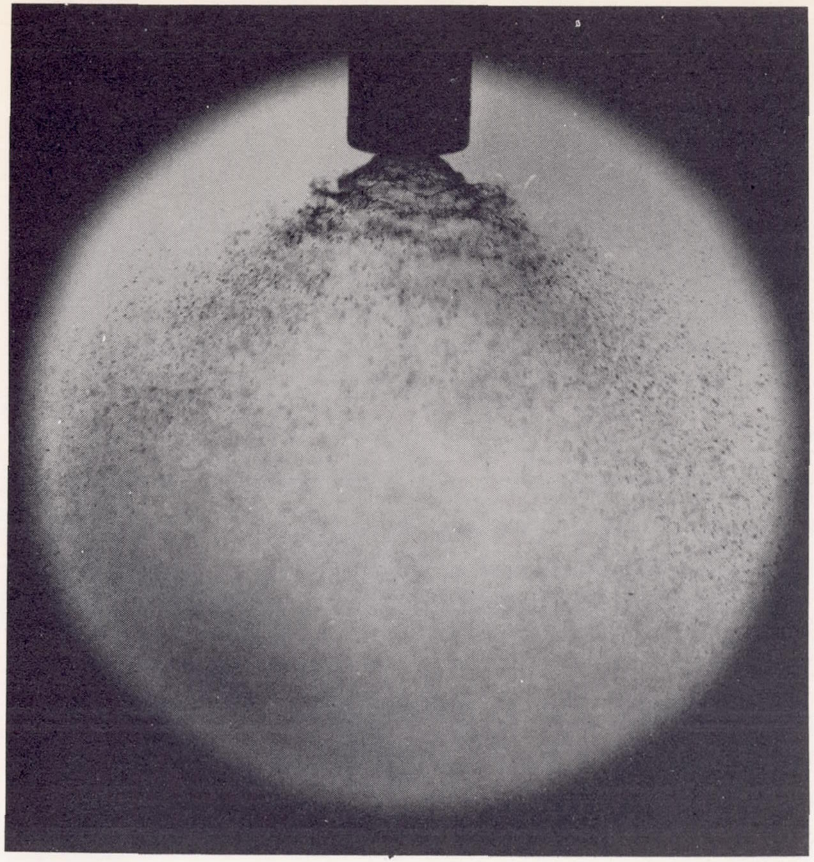
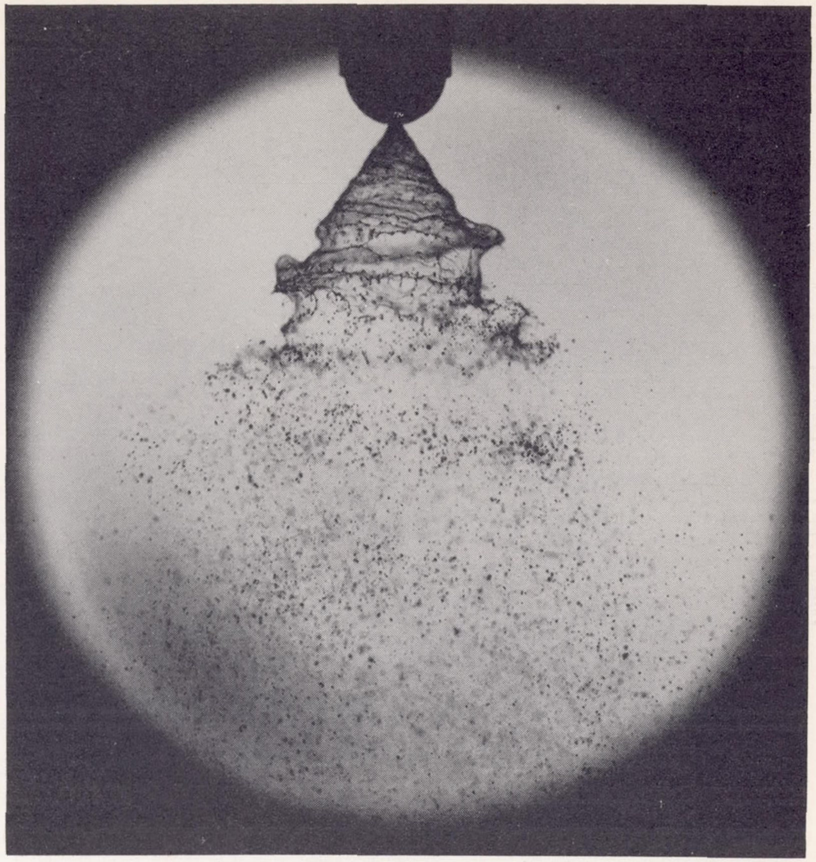


Variable-area fuel nozzle



Fixed-area fuel nozzle

C-21121
4-12-48

(b) Flow rate, 65 pounds per hour.

Figure 6. - Continued. Photographs of spray produced by variable-area and fixed-area fuel nozzles used in operation of turbojet engine. Fuel, AN-F-32.

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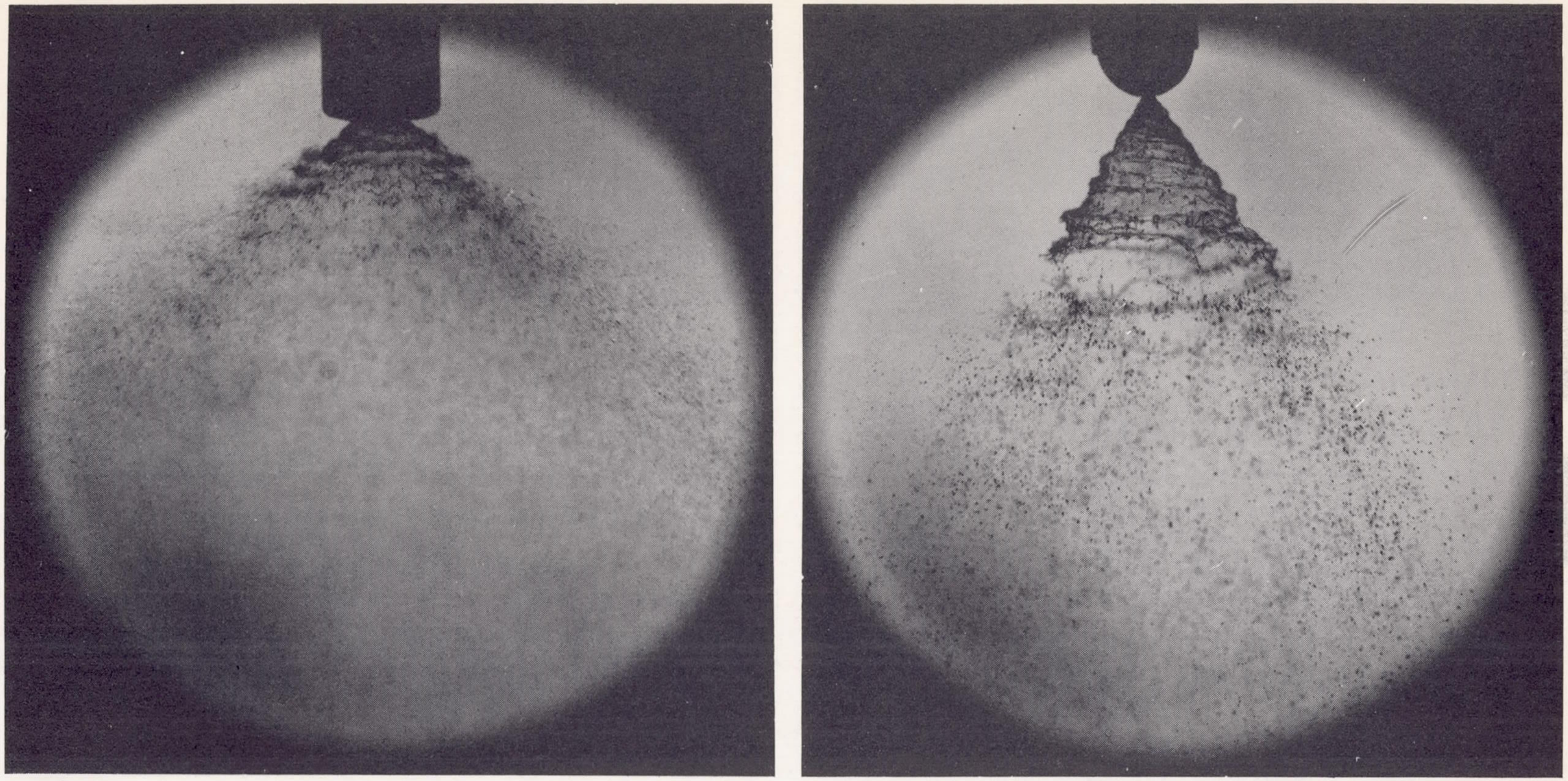

Variable-area fuel nozzle

Fixed-area fuel nozzle

NACA
C-21122
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(c) Flow rate, 80 pounds per hour.

Figure 6. - Continued. Photographs of spray produced by variable-area and fixed-area fuel nozzles used in operation of turbojet engine. Fuel, AN-F-32.

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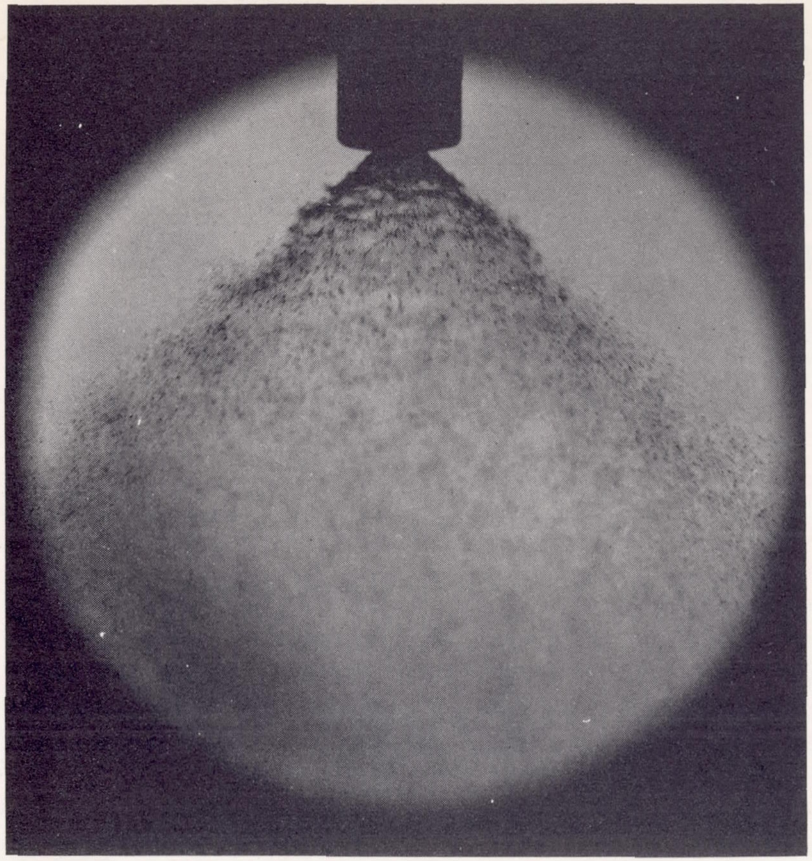
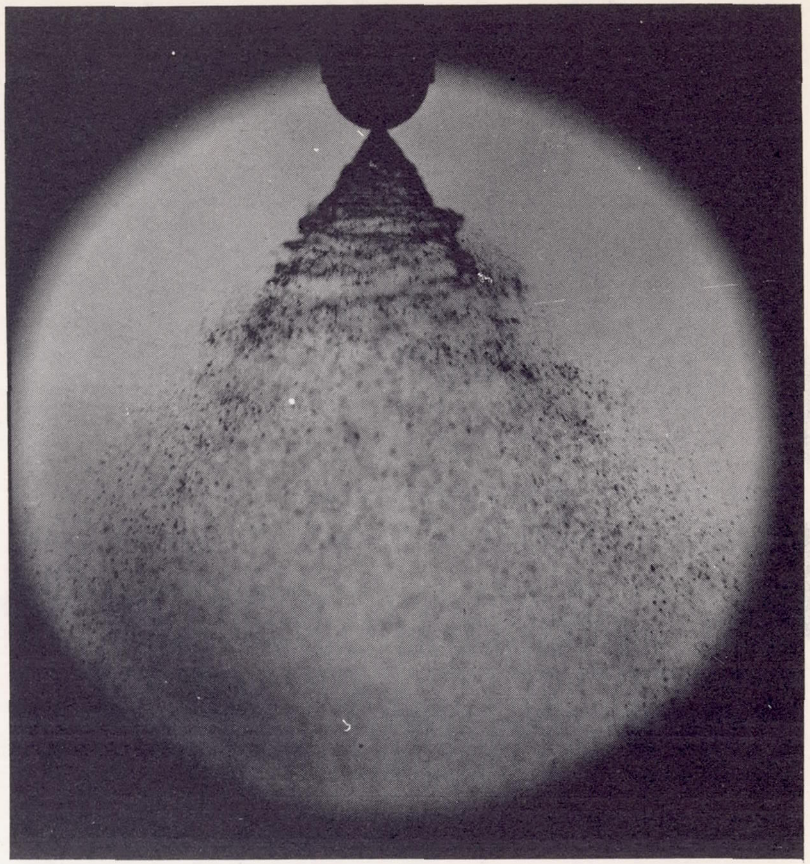


Variable-area fuel nozzle



Fixed-area fuel nozzle

NACA
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4-12-48

(d) Flow rate, 125 pounds per hour.

Figure 6. - Continued. Photographs of spray produced by variable-area and fixed-area fuel nozzles used in operation of turbojet engine. Fuel, AN-F-32.

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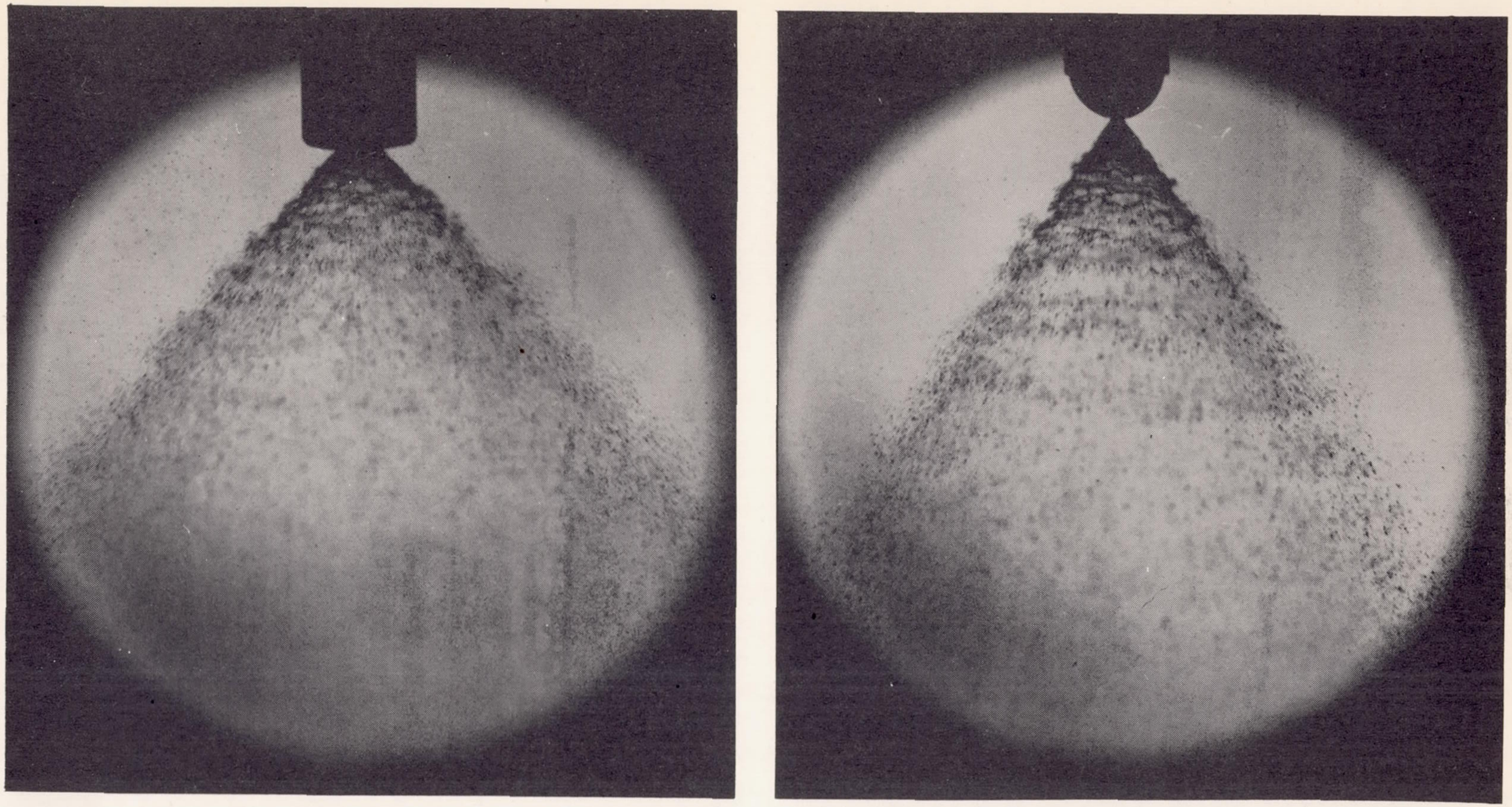

Variable-area fuel nozzle

Fixed-area fuel nozzle

NACA
C-21124
4-12-48

(e) Flow rate, 150 pounds per hour.

Figure 6. - Continued. Photographs of spray produced by variable-area and fixed-area fuel nozzles used in operation of turbojet engine. Fuel, AN-F-32.

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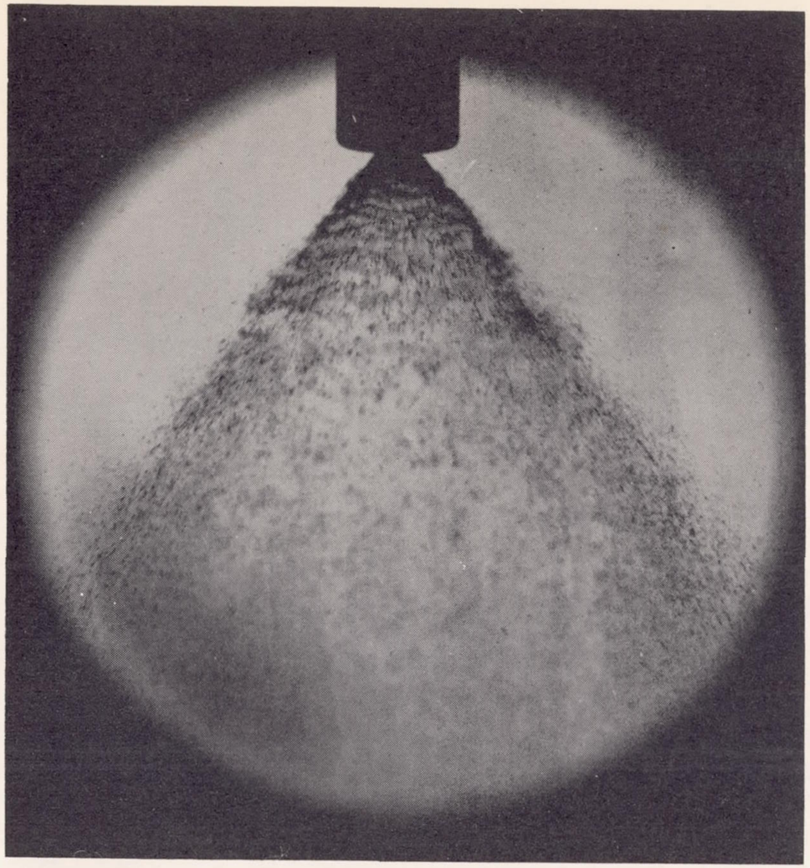
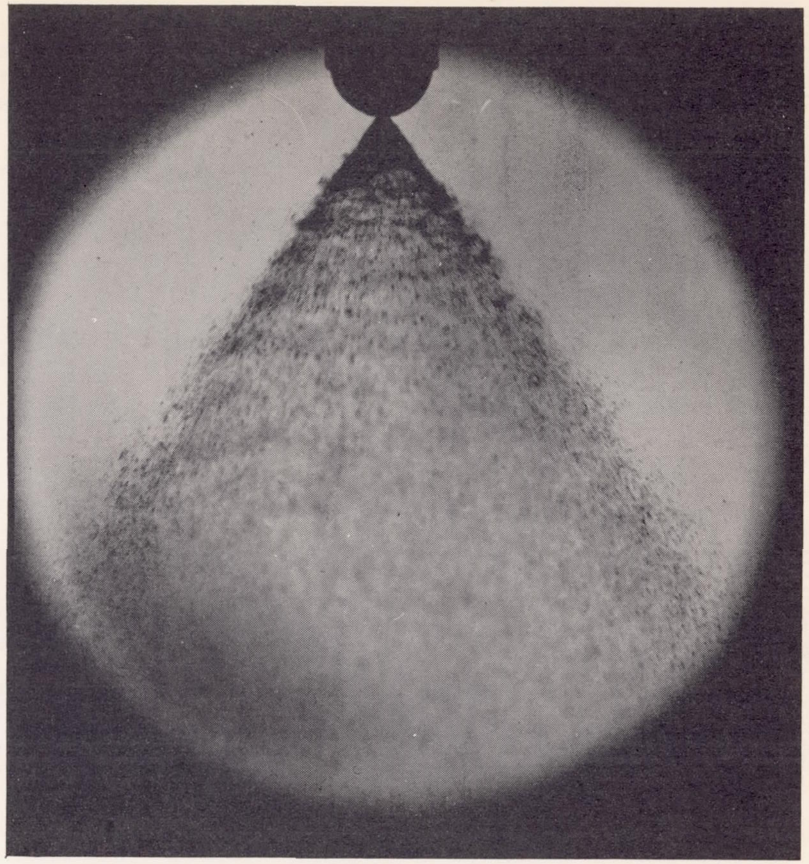


Variable-area fuel nozzle



Fixed-area fuel nozzle

NACA

C-21125
4-12-48

(f) Flow rate, 200 pounds per hour.

Figure 6. - Concluded. Photographs of spray produced by variable-area and fixed-area fuel nozzles used in operation of turbojet engine. Fuel, AN-F-32.

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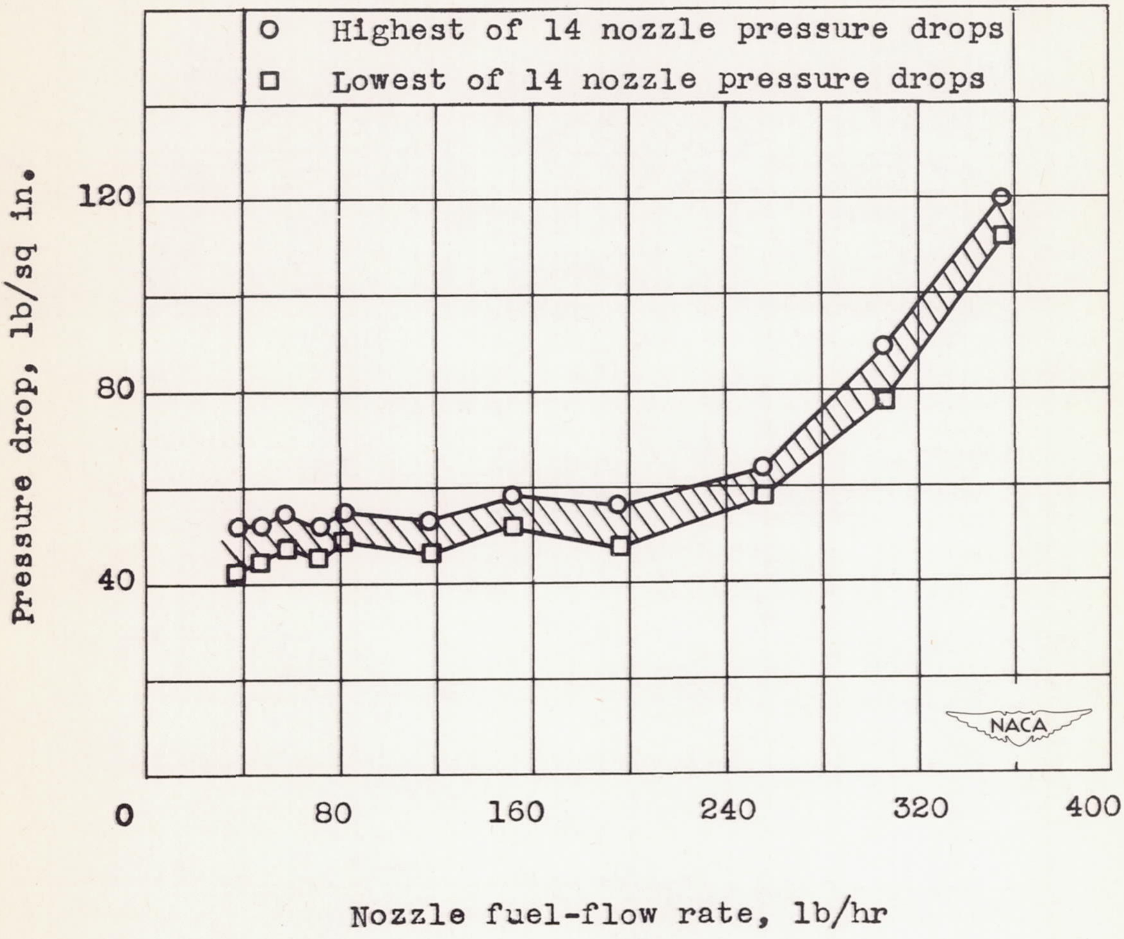

Figure 7. - Calibration spread of variable-area fuel nozzles used in turbojet-engine investigation. Fuel, AN-F-32.

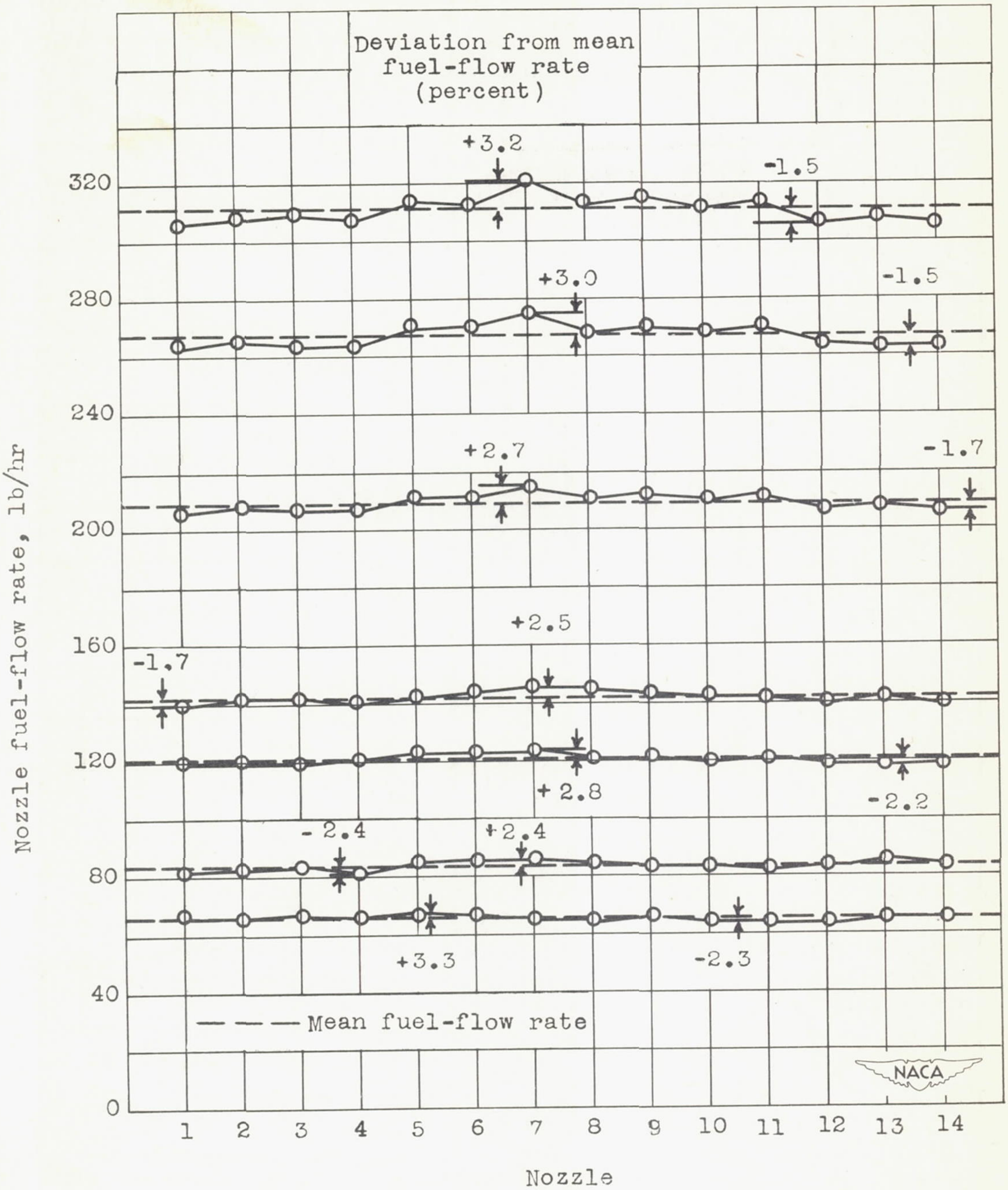

Figure 8. - Deviation from mean fuel flow at various flow rates. Variable-area fuel nozzles with fuel-distribution control operating on turbojet engine.

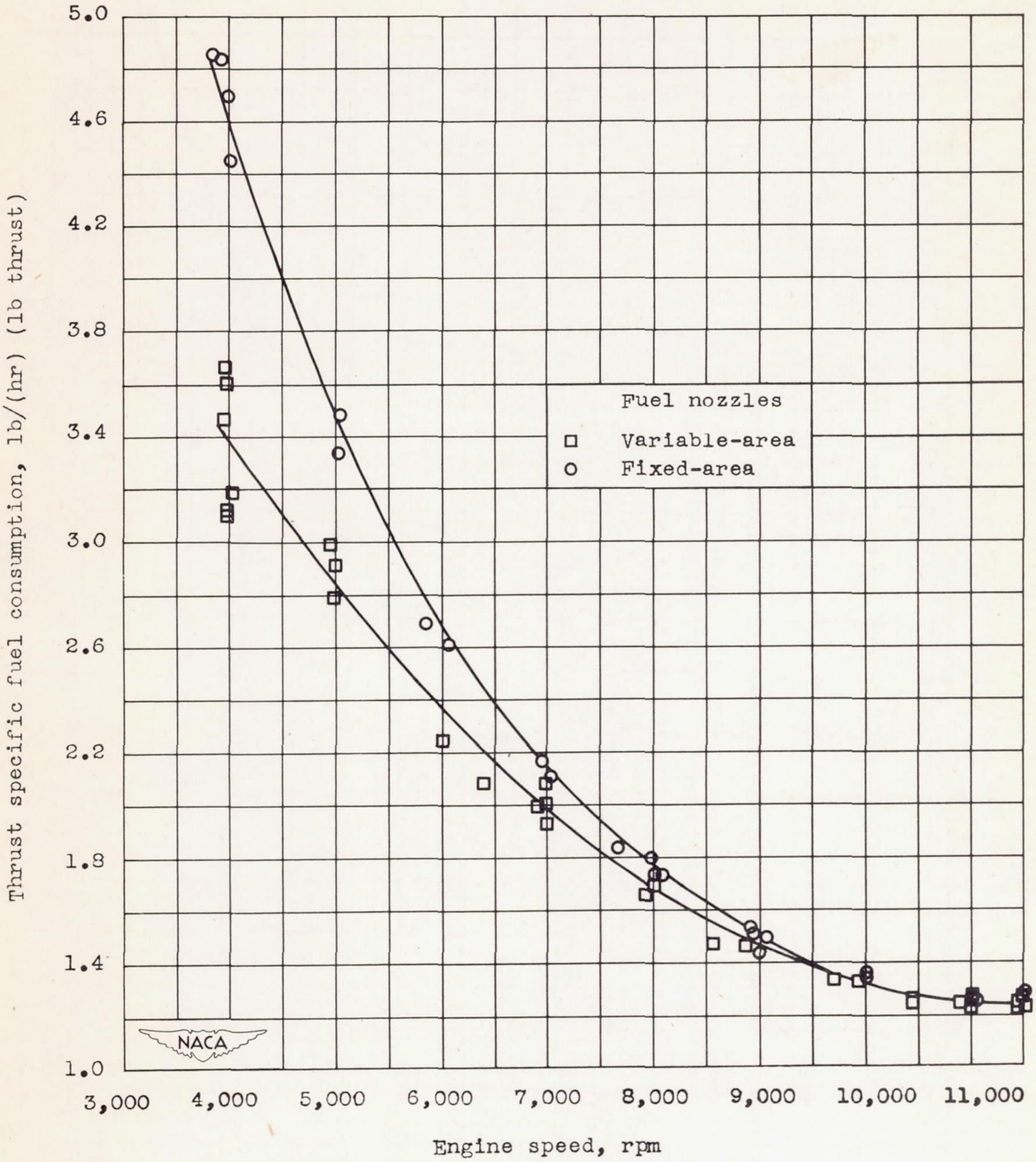

Figure 9. - Sea-level static thrust specific fuel consumption for turbojet engine operating with variable-area fuel nozzles and with fixed-area fuel nozzles; data corrected to standard sea-level conditions.

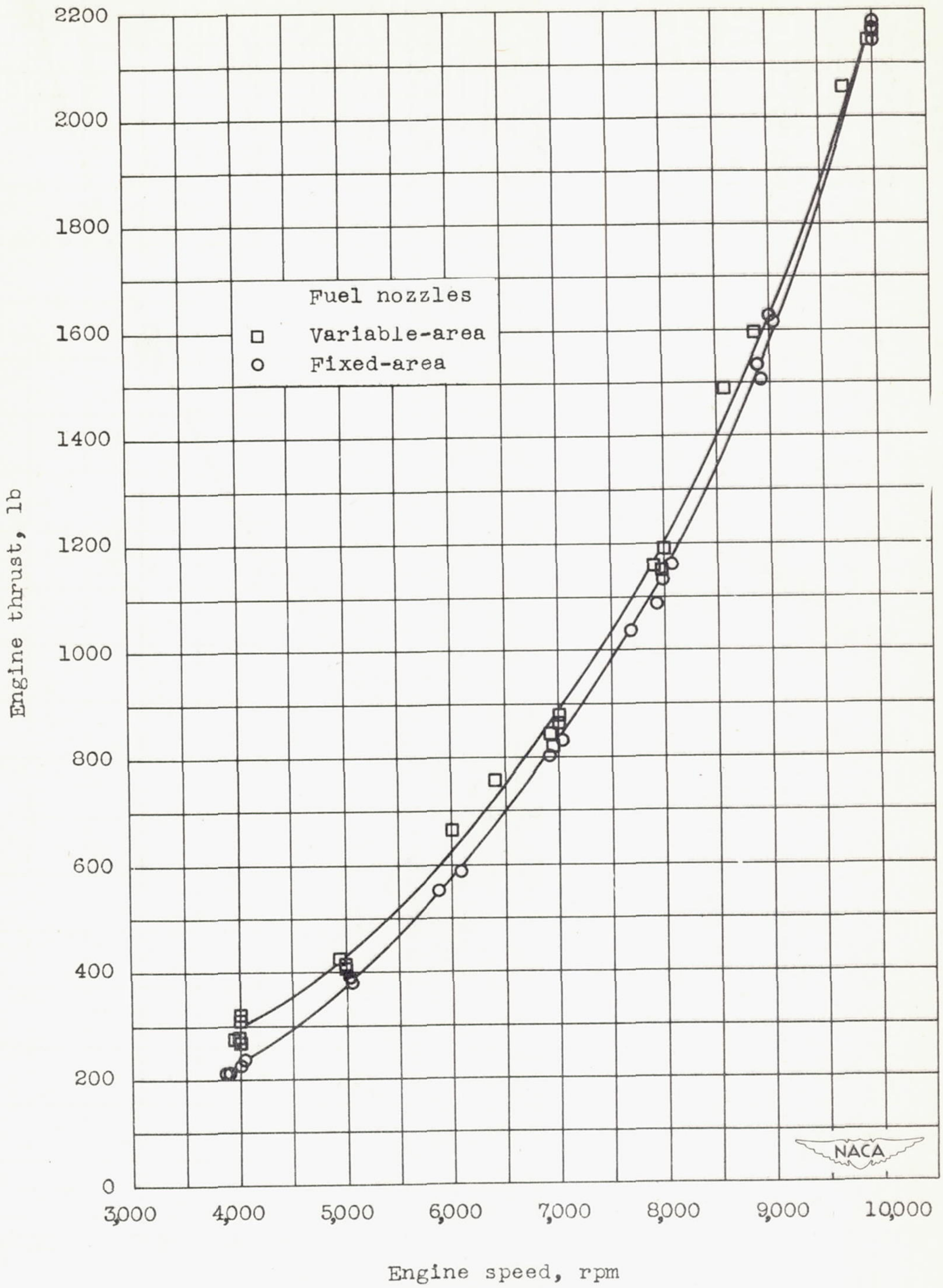

Figure 10. - Sea-level static thrust for a turbojet engine operating with variable-area fuel nozzles and with fixed-area fuel nozzles; data corrected to standard sea-level conditions.

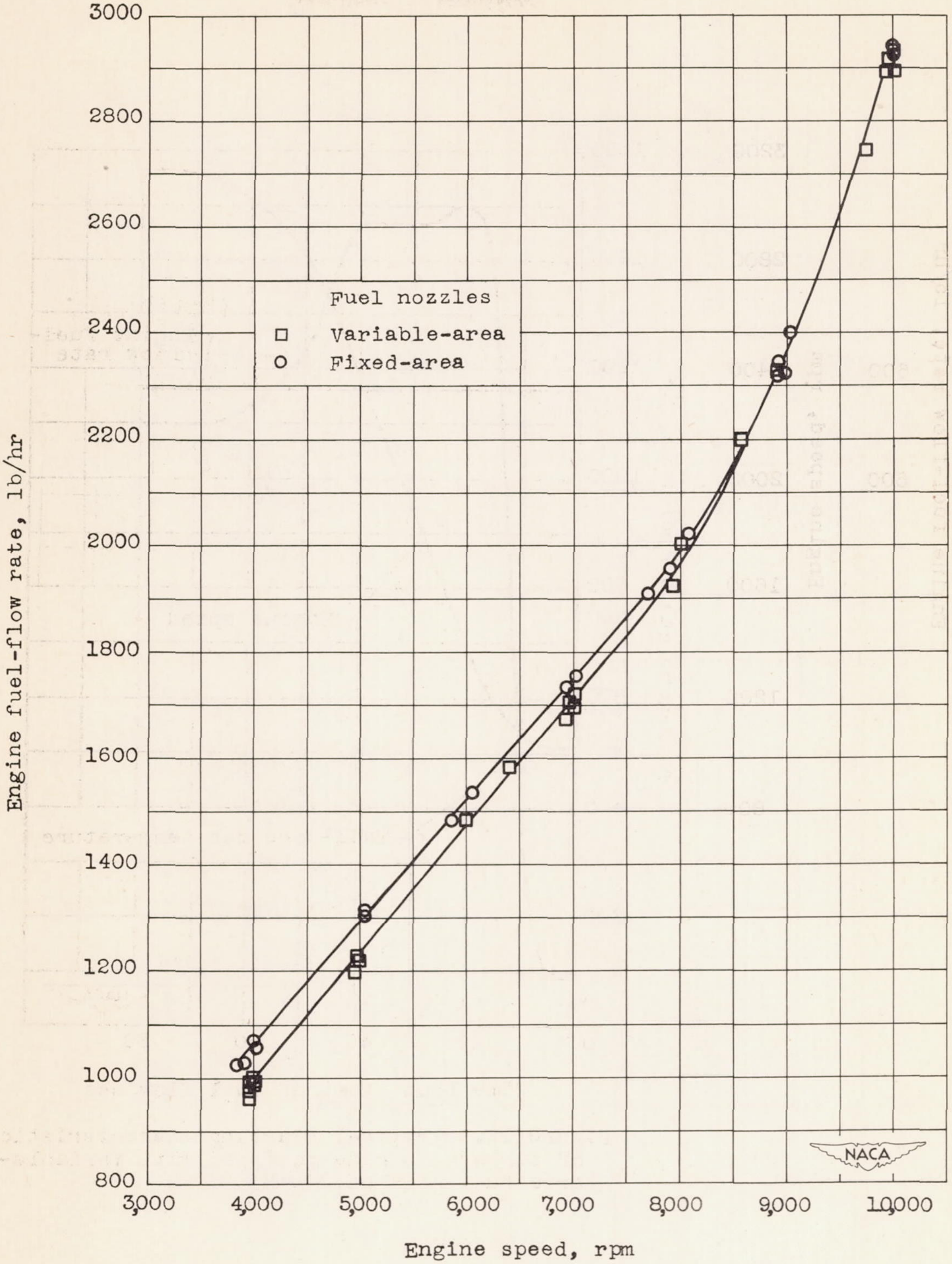

Figure 11. - Sea-level static fuel consumption for turbojet engine operating with variable-area fuel nozzles and with fixed-area fuel nozzles; data corrected to standard sea-level conditions.

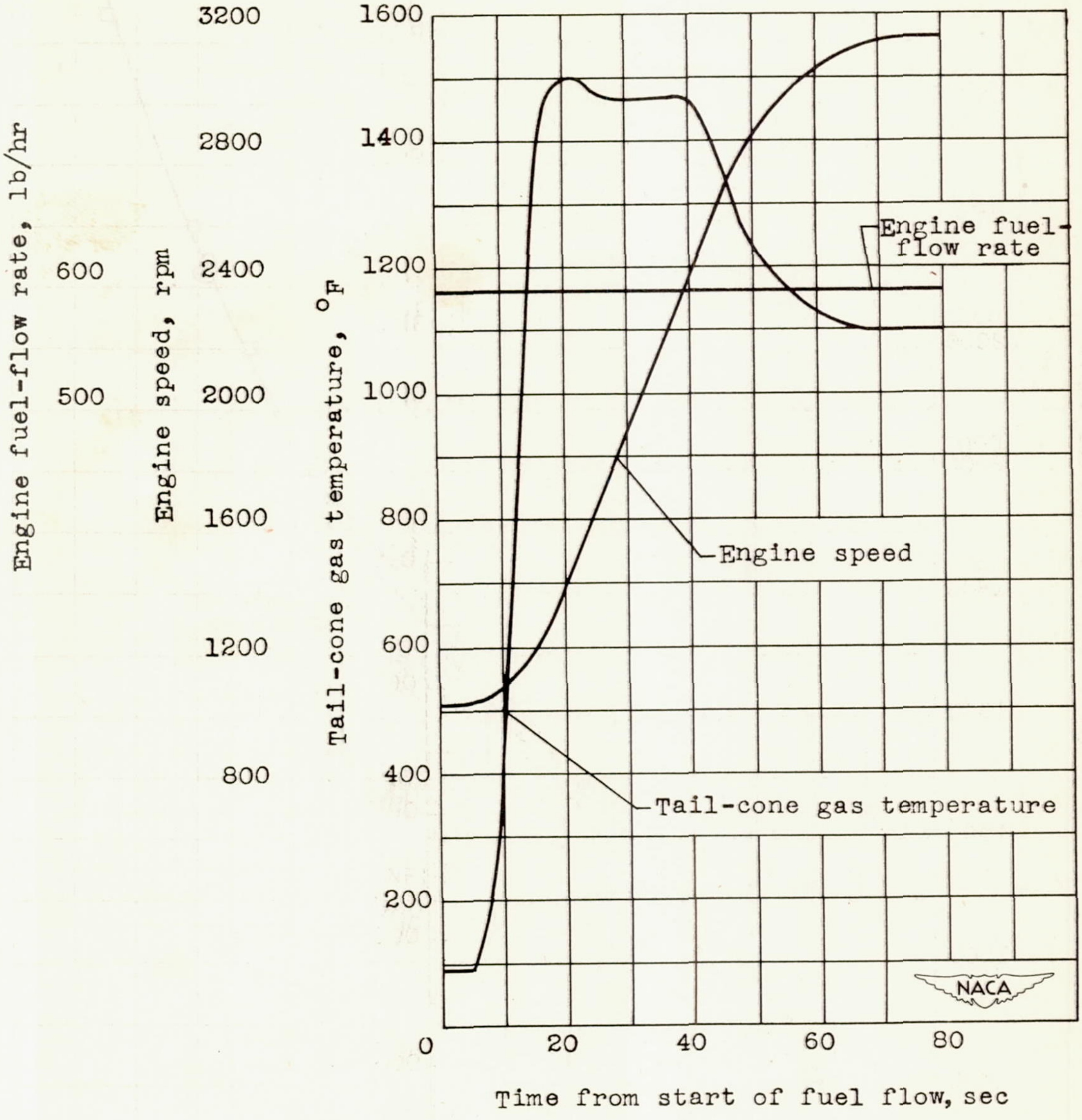

Figure 12. - Typical starting characteristics of turbojet engine equipped with variable-area fuel nozzles.

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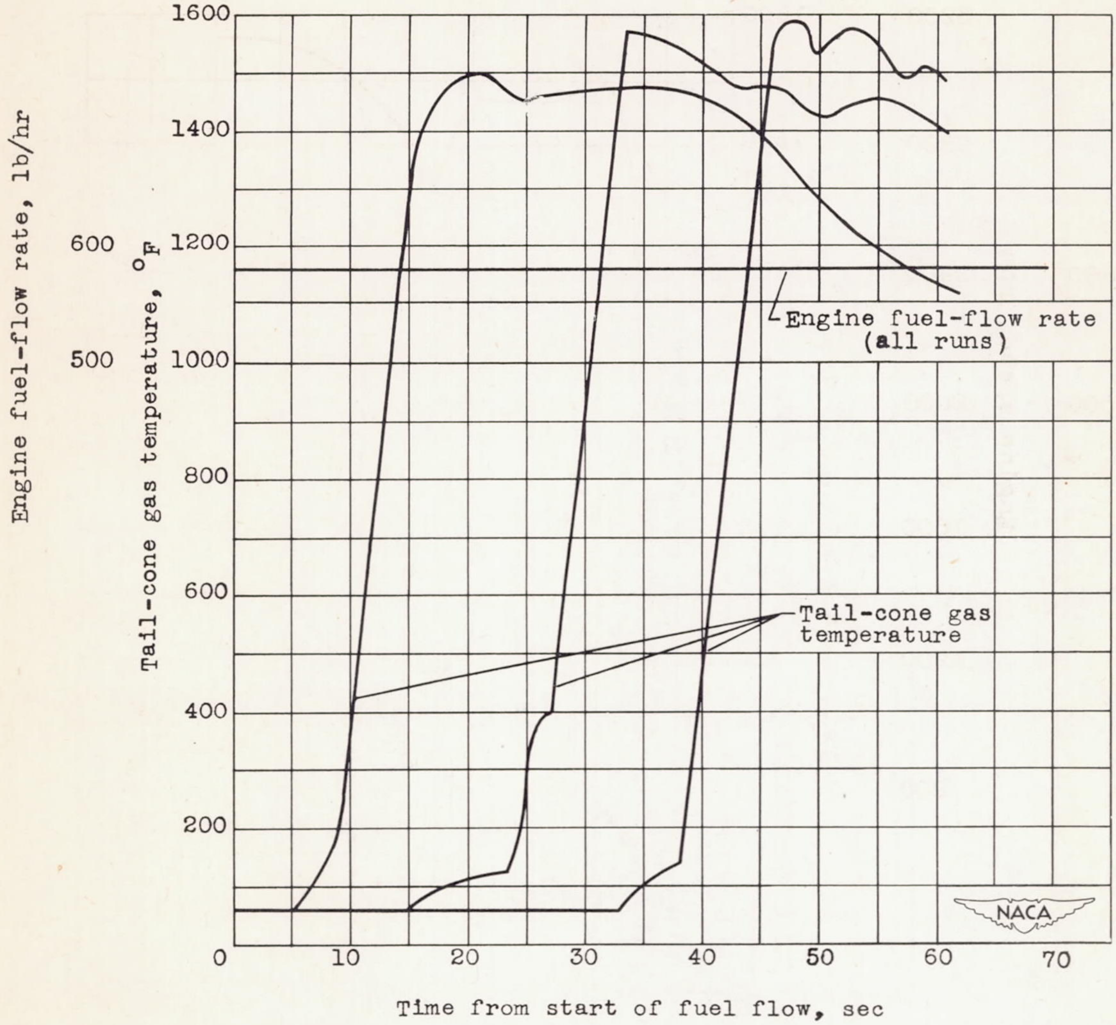

Figure 13. - Time record of delayed ignition starts of turbojet engine equipped with variable-area fuel nozzles.

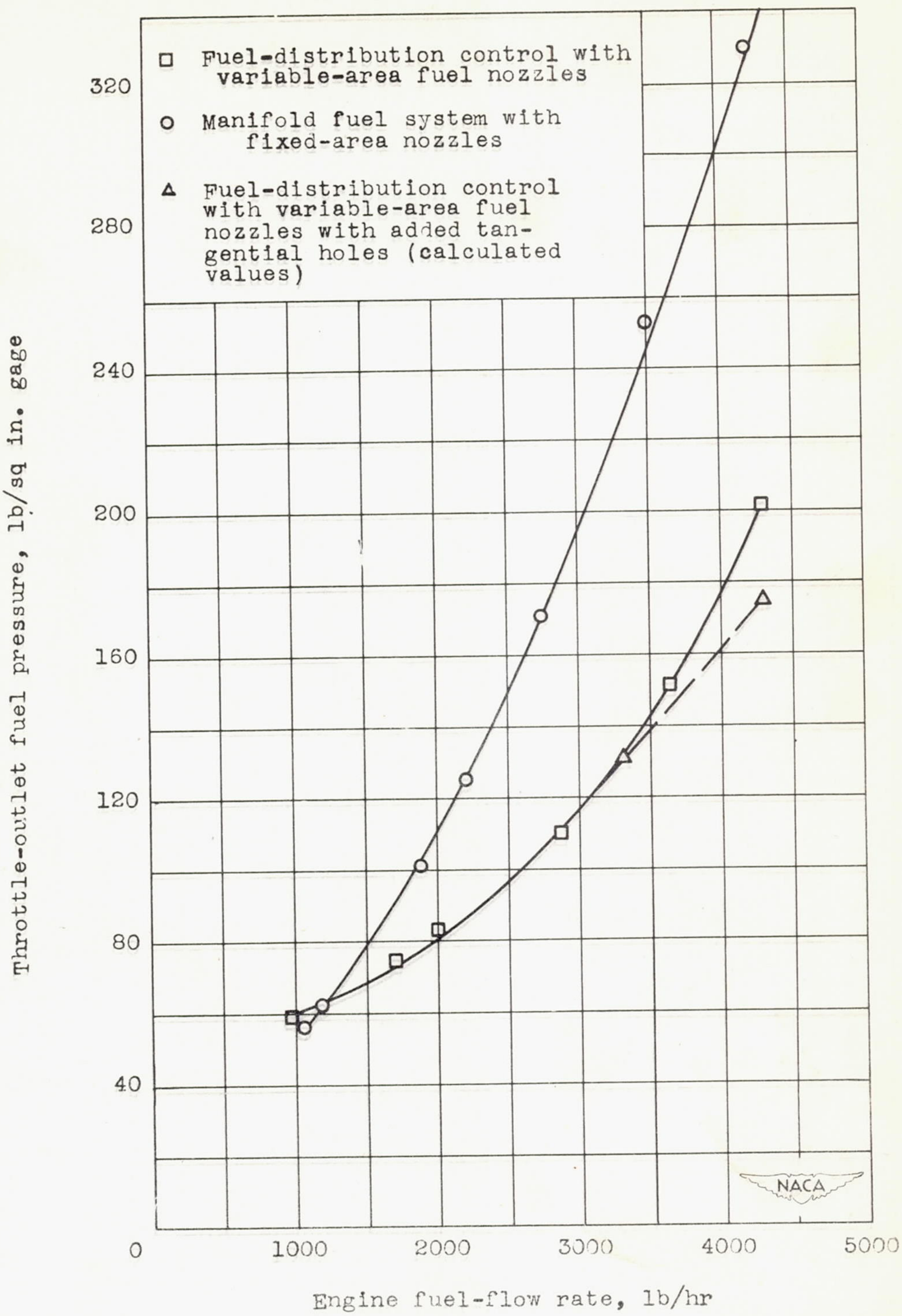

Figure 14. - Throttle-outlet fuel pressures required on a turbojet engine, operating at sea-level static conditions, with distribution control and variable-area fuel nozzles and with manifold fuel system and fixed-area fuel nozzles.

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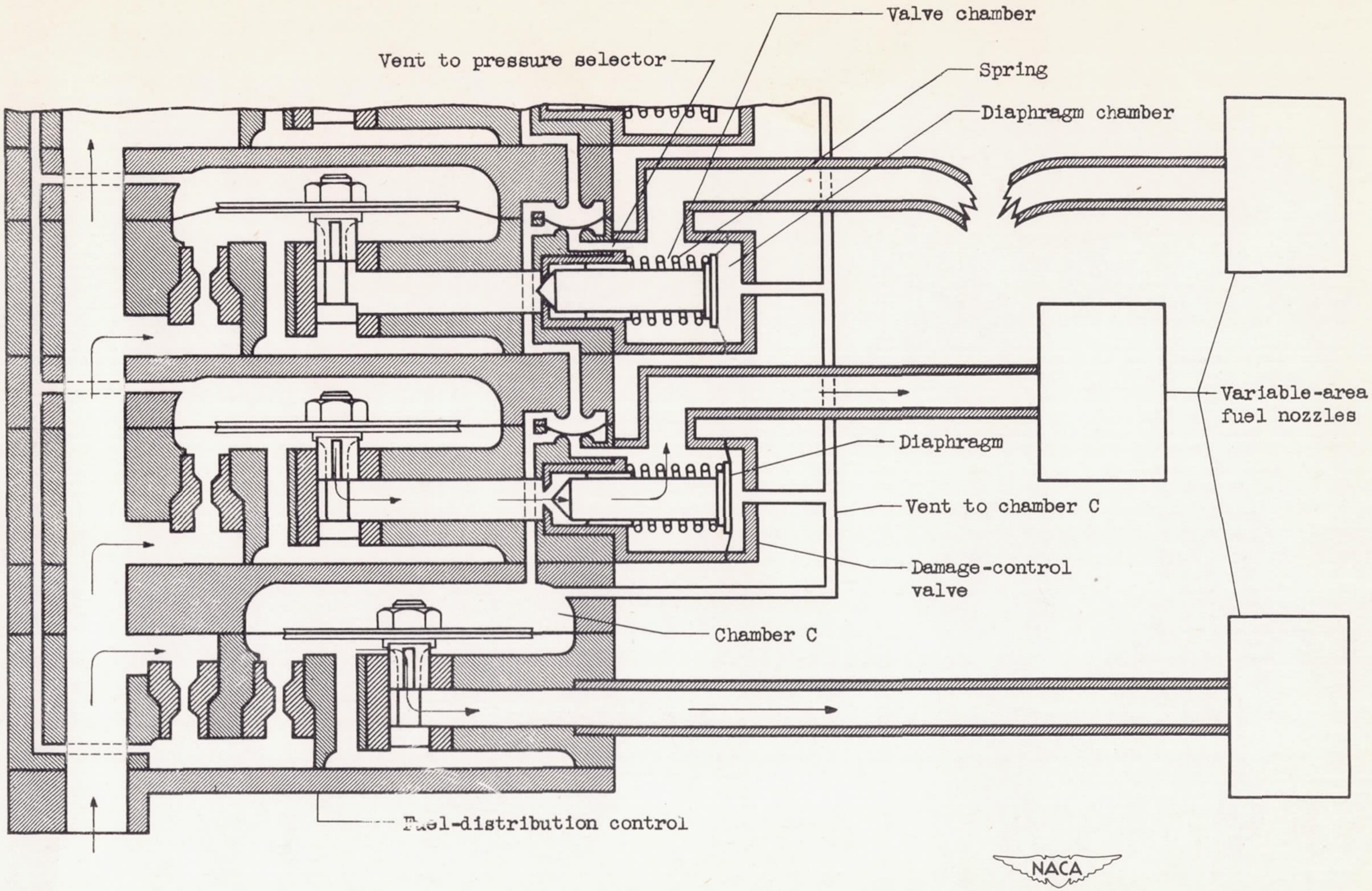

Figure 15. - Schematic diagram of damage-control valve operating in conjunction with the fuel-distribution control.

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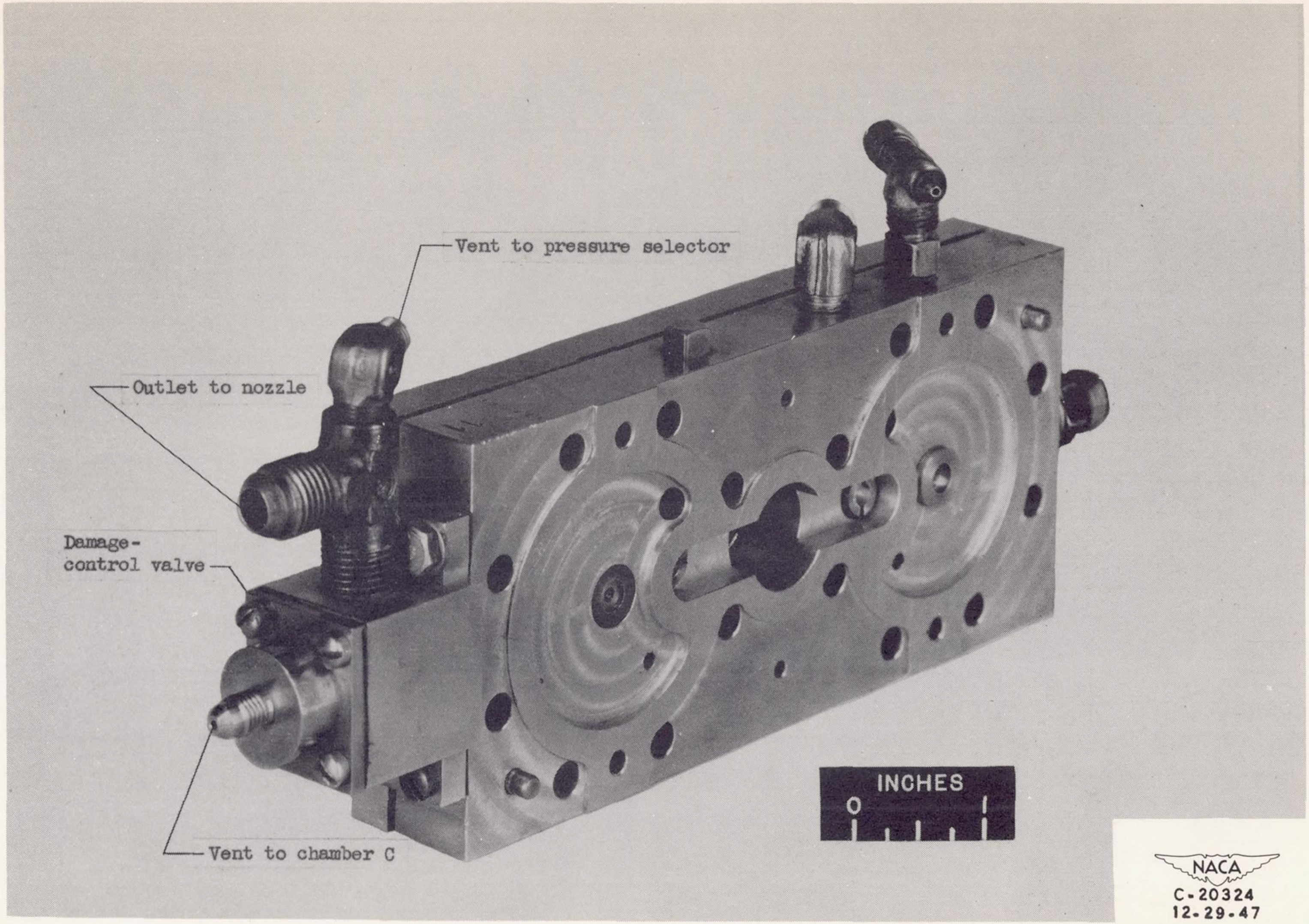

Figure 16. - Photograph of experimental model of damage-control valve mounted on section of fuel-distribution control.