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RESEARCH MEMORANDUM

ALTITUDE-WIND-TUNNEL INVESTIGATION OF A 4000-POUND-THRUST AXIAL-FLOW TURBOJET ENGINE

II - OPERATIONAL CHARACTERISTICS

By William A. Fleming

Flight Propulsion Research Laboratory
Cleveland, Ohio

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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SUMMARY

An investigation was conducted in the Cleveland altitude wind tunnel to determine the operational characteristics of an axial-flow-type turbojet engine with a 4000-pound-thrust rating over a range of pressure altitudes from 5000 to 50,000 feet, ram pressure ratios from 1.00 to 1.86, and temperatures from 60° to -50° F. The low-flow (standard) compressor with which the engine was originally equipped was replaced by a high-flow compressor for part of the investigation. The effects of altitude and airspeed on such operating characteristics as operating range, stability of combustion, acceleration, starting, operation of fuel-control system, and bearing cooling were investigated.

With the low-flow compressor, the engine could be operated at full speed without serious burner unbalance at altitudes up to 50,000 feet. Increasing the altitude and airspeed greatly reduced the operable speed range of the engine by raising the minimum operating speed of the engine. In several runs with the high-flow compressor the maximum engine speed was limited to less than 7600 rpm by combustion blow-out, high tail-pipe temperatures, and compressor stall. Acceleration of the engine was relatively slow and the time required for acceleration increased with altitude. At maximum engine speed a sudden reduction in jet-nozzle area resulted in an immediate increase in thrust. The engine started normally and easily below 20,000 feet with each configuration. The use of a high-voltage ignition system made possible starts at a pressure altitude of 40,000 feet; but on these starts the tail-pipe temperatures were very high, a great deal of fuel burned in and behind the tail pipe, and acceleration was very slow. Operation of the engine was similar with both fuel regulators except that the

modified fuel regulator restricted the fuel flow in such a manner that the acceleration above 6000 rpm was very slow. The bearings did not cool properly at high altitudes and high engine speeds with a low-flow compressor, and bearing cooling was even poorer with a high-flow compressor.

INTRODUCTION

An investigation has been conducted in the NACA Cleveland altitude wind tunnel to determine the operational and performance characteristics of an axial-flow-type 4000-pound-thrust turbojet engine. The performance characteristics of the engine in the standard configuration are included in reference 1. Engine operational data obtained with the engine in the standard configuration and with various modifications to the standard configuration is presented herein. The modifications investigated include changes in the compressor, the combustion chambers, the turbine, the turbine nozzle, the tail pipe, the jet nozzle, the ignition system, and the fuel regulator. The following operational characteristics were investigated: operating speed range, combustion stability, acceleration, starting, operation of the fuel control system, and bearing cooling. Damage that occurred to several parts of the engine during the runs is discussed.

The high-flow compressor unit considered herein does not represent any engine contemplated for production by the engine manufacturer, but does represent the initial attempt of the engine manufacturer to obtain increased performance by modifying the standard unit with the quickest and simplest methods available at the time of the 4000-pound-thrust axial-flow turbojet engine wind-tunnel test program.

Two inlet configurations were used in the investigation. For the static tests the engine air was taken from the tunnel test section in a normal manner; for the ram tests the air was introduced into the engine through a duct at pressures above the tunnel-test-section pressure in order to simulate various flight speeds. The tests were conducted over a range of ram pressure ratios from 1.00 to 1.86 and pressure altitudes from 5000 to 50,000 feet with approximately corresponding standard air temperatures.

WIND-TUNNEL INSTALLATION AND ENGINE CONFIGURATIONS

Description of Engine

The J35 engine investigated has a sea-level rating of 4000 pounds static thrust at an engine speed of 7600 rpm. At this rating the air

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flow is approximately 75 pounds per second and the fuel flow 4400 pounds per hour. The over-all length of the engine is about 14 feet; the maximum diameter, 36 inches; and the total weight, 2300 pounds. Both compressors have 11 axial-flow stages. The low-flow compressor provides a pressure ratio of approximately 4 and the high-flow compressor provides a pressure ratio of approximately 4.5 at rated engine speed. On the engine are eight individual combustion chambers. Two of the chambers contain a spark plug to ignite the fuel when starting the engine. Fuel in the other six combustion chambers is cross-ignited through the small interconnecting tubes that join the burners together. A single-stage turbine drives the compressor.

In order to obtain satisfactory starting and idling characteristics, each combustion chamber was equipped with a duplex fuel nozzle to which fuel was supplied through two lines. The low-flow or primary line supplied fuel to the small slots of the nozzles at all operating conditions and the high-flow or secondary line supplied fuel to the large slots when the engine was operating at high fuel rates. With the duplex nozzles, a well-balanced spray pattern could be maintained in the combustion chambers throughout the entire range of fuel flows.

Installation and Procedure

The engine was supported on a 7-foot-chord airfoil installed in the 20-foot-diameter test section of the wind tunnel, as shown in figure 1. The cowling extended only to the rear of the compressor; thus the burners and the tail pipe were cooled by the movement of the air in the test section. Air was supplied to the engine by two methods. For the static tests a wooden cowling was attached to the engine inlet and air was supplied to the engine from the tunnel test section in a normal manner. For the ram tests inlet pressures corresponding to flight at high speed were obtained by introducing dry refrigerated air from the tunnel make-up air system at approximately sea-level pressure. The air was throttled to the desired pressure at the engine inlet while the wind-tunnel pressure and temperature corresponding to the test altitude were maintained. The make-up air duct was connected to the engine intake by means of a slip joint located 40 feet upstream of the engine. (See fig. 2, station X.) The tunnel drive motor was not operated in these tests, but a velocity from 40 to 100 feet per second was induced in the tunnel test section by the ejector effect of the jet and by the tunnel-exhauster scoop located immediately downstream of the test section.

The engine was extensively instrumented as shown in figure 3. Temperature and pressure measurements of the air and gases were taken at eight stations throughout the engine in order to obtain information on the individual components and the over-all operating characteristics.

Vibration pickups were installed on the engine to determine the amplitude of the horizontal and vertical vibration of the engine at the front flange of the compressor casing and the rear flange of the turbine casing. The amplitude of vibration was indicated by a vibration meter in the control room.

Engine Configurations

Investigations were made of 13 configurations of the engine. (See table I.) The total time logged for the engine during the runs was 97.1 hours.

Two compressors designated low-flow and high-flow were investigated. The low-flow compressor, which was the standard compressor for the engine, has a sea-level air-flow rate of about 70 pounds of air per second at 7600 rpm. The high-flow compressor has the same dimensions as the low-flow compressor, but the blade angle of the rotor and stator blades is approximately 5° greater in order to give a higher air flow.

Three types of combustion chamber, designated A, B, and C, were investigated (fig. 4). The principal dimensions of the three chambers are the same, but they differ in the manner in which air is introduced into the primary burning zone. On the dome of the type A combustion chamber are three rows of louvers pushed outward to scoop the air into the primary burning zone. The type B chamber is similar to type A except that the center row of louvers is pushed in so that air is blown upstream along the inner surface of the dome. This modification was made to improve the starting characteristics of the engine. The type C combustion chamber has a hood over the dome to ram more air through the louvers, which are pushed in instead of raised as in types A and B. A vertical motion of the air is introduced on the inner surface of the dome by means of two rows of louvers bent to induce circumferential flow in opposite directions. This modification was designed to provide a higher upper blow-out limit for high-altitude operation.

Three turbine nozzles with different areas were investigated; they are referred to in table I as small, standard, and large nozzles. The nozzles became eroded and warped during runs and the nozzle areas were changed as follows: the small nozzle, from 101.9 to 97.7 square inches; the standard nozzle, from 106.8 to 108 square inches; and the large nozzle, from 121 to 119.9 square inches.

Five different turbine wheels were used. The initial runs of the engine in the standard configuration with the low-flow compressor were made with a turbine having cast buckets; this wheel was limited in speed to 6650 rpm because of a weak turbine disk. This turbine wheel was replaced by a similar wheel fitted with cast buckets, but the disk was strengthened and the rated engine speed of 7600 rpm could be reached. Two of the turbine blades developed cracks near the roots after 20 hours of operation and the wheel was removed. A turbine wheel with forged blades was then installed and tests were continued for approximately 46 hours before cracks in four of the turbine blades near the root necessitated the removal of the wheel. Another turbine wheel with forged blades was then installed and was removed after approximately 12 hours of operation because the radial clearance between the turbine shroud ring and the outer race was excessive. A forged wheel of the same construction having the proper clearance was then used for $6\frac{1}{4}$ hours without failure.

Four tail pipes were used during the tests, as indicated in table I. The tail pipe supplied with the original engine failed after 6 hours of operation. The inner cone collapsed and the outer shell was severely warped over almost its entire length. A tail pipe the same as the first was then installed and was removed after $6\frac{1}{2}$ hours of operation as the result of a partial failure similar to that of the first. The inner cone of the third tail pipe was reinforced and vented in order to equalize more rapidly the pressure on the inner and outer surfaces of the tail cone and the outer shell was strengthened. Operation of the engine for 54 hours caused the outer shell of the tail pipe directly behind the turbine to warp and buckle slightly. The fourth tail pipe investigated was identical in construction to the third; however, straightening vanes were added in an attempt to remove the swirl from the gases leaving the turbine wheel. After 30 hours of testing, the straightening vanes were warped and the outer shell of the tail pipe directly behind the turbine outlet was warped in the same manner as the third tail pipe.

Jet nozzles with circular-outlet diameters of $16\frac{1}{4}$, $16\frac{3}{4}$, 18, and $19\frac{1}{2}$ inches were investigated. A special rectangular nozzle with a variable outlet area was also constructed for some of the runs. (See fig. 5.) The outlet area of this nozzle was varied by two compressed-air pistons operating hinged doors that formed the sides of the nozzle. The nozzle could be used in only two positions, open and closed. In the closed position, the area of the 15- by $15\frac{3}{4}$-inch rectangular outlet was equivalent to that of a $17\frac{1}{2}$-inch-diameter circular jet nozzle; with the doors open, the area was equivalent to that of a $21\frac{1}{2}$-inch-diameter circular jet nozzle. 532

Three types of spark plug were used on the engine during the investigation. The two original spark plugs used with the low-flow compressor had two electrodes that protruded into the combustion chamber with a spark gap of about 0.60 inch. When the high-flow compressor was installed, these spark plugs were replaced by two spark plugs designed to make it possible to start the engine at higher altitudes than before. The two new spark plugs had the same spark gap and were similar in design to the original type of spark plug except that provision was made to discharge a jet of oxygen through the core of the spark plug into the zone of the spark (configurations 6 and 7). Oxygen was supplied from a bottle in the control room through a $\frac{1}{4}$-inch tube and the oxygen flow was manually controlled during the starts. One of the oxygen spark plugs was later replaced by a spark plug connected to a transformer having a higher voltage than the one previously used (configurations 8 to 13). The high-voltage spark plug had heavier electrodes than the original type spark plug and the spark gap was approximately 0.120 inch.

When the high-flow compressor was installed in the engine, the original fuel regulator was replaced with a modified regulator. The modified regulator used the compressor-outlet static pressure as a reference pressure for the barometric bellows. This regulator was also set so that the rate of increase in fuel flow when a rapid acceleration was made would not be great enough to overheat the engine.

RESULTS AND DISCUSSION

Operating Range

Low-flow compressor. - The initial runs with the low-flow compressor (configurations 1 to 5, table I) indicated that the engine could be operated at rated speed without serious combustion-chamber temperature unbalance at pressure altitudes up to 50,000 feet. The minimum operating speed without ram varied from 2000 rpm at a pressure altitude of 5000 feet to 4000 rpm at 40,000 feet. (See fig. 6.) The minimum speed at 50,000 feet was not determined. Without ram at 5000 feet the engine could be idled below 2000 rpm; however, the temperature distribution between the combustion chambers was unbalanced, the tail-pipe temperatures were high, and acceleration was sluggish. Below 2000 rpm the engine could be accelerated only by exceeding the tail-pipe temperature limit of 1500° F for acceleration.

The engine could be operated at slightly less than 4000 rpm at 40,000 feet, but idling the engine at so low a speed necessitated closing the throttle in very small increments in order to decrease the fuel pressure only 1 or 2 pounds per square inch at any one time. At an engine speed of 4000 rpm the tail-pipe temperature was approximately 400° F, at which point a sudden decrease in fuel flow caused combustion to cease.

Increasing the ram pressure ratio at the engine inlet resulted in a higher minimum operating speed at all altitudes. (See fig. 6.) At high altitudes with ram, temperatures as low as 275° to 350° F were measured in the tail pipe at the minimum speed just before combustion failure.

Combustion was stable except when the engine was operating near the minimum speed above 20,000 feet. Slow deceleration of the engine was required near the minimum operable speeds because rapid deceleration in the low-speed range often caused several or all of the combustion chambers to blow out. Usually a lower operating speed could be reached with a very slow deceleration than with a rapid deceleration.

High-flow compressor. - In several runs with the high-flow compressor (configurations 6 to 8, 10 and 11), the maximum engine speed was limited by combustion blow-out, high tail-pipe temperature, and compressor stall, as shown in figure 7. Configurations 6 and 7 were investigated at an indicated airspeed between 200 and 300 miles per hour and configuration 8 was investigated at static conditions. At pressure altitudes below 20,000 feet, slow acceleration of the engine to full speed (7600 rpm) was possible without encountering combustion blow-out. At pressure altitudes of 30,000 and 40,000 feet, the maximum engine speed with configurations 6 to 8 was limited by combustion blow-out between 7300 and 7500 rpm during normal accelerations. In order to reach full speed at these high altitudes, it was necessary to accelerate the engine very slowly above 7000 rpm.

When combustion blow-out occurred, a yellow flame about 5 feet long shot out of the jet nozzle for a few seconds, the engine speed began to decrease, the tail-pipe temperatures began to rise rapidly, and combustion suddenly ceased. Combustion blow-out was encountered at pressure altitudes of 30,000 and 40,000 feet, indicated airspeeds from 0 to 300 miles per hour, compressor-inlet temperatures from -15° to -30° F, and engine speeds from 7300 to 7500 rpm.

At a pressure altitude of 40,000 feet with an indicated airspeed of 250 miles per hour and a compressor-inlet temperature of -40° F, combustion blow-out was encountered at an engine speed of approximately 7400 rpm when the engine was slowly accelerated. The combustion chambers were allowed to blow out several times at about 7400 rpm, and each time they could be relighted by turning on the ignition at engine speeds between 6500 and 7000 rpm. In order to determine whether the spark plug was relighting the chambers or whether some burning continued when the engine speed began to decrease, the ignition was not immediately turned on in one case after the combustion chambers blew out. The engine speed then continued to fall below 6000 rpm; at 4000 rpm the ignition was turned on, but the combustion chambers would not relight at this or lower speeds while the rotor was coasting.

After the change from type B to type C combustion chamber (configuration 9), full speed could be reached at a pressure altitude of 30,000 feet and an indicated airspeed of 400 miles per hour. The only attempt to accelerate the engine to full speed with configuration 9 was made at this altitude; when the engine speed reached 7600 rpm, the tail-pipe temperature suddently increased and reached a peak of 1650° F before the engine speed could be reduced. At 6200 rpm, the tail-pipe temperatures varied from 1250° to 1300° F. An immediate inspection of the engine revealed that several of the transition sections between the rear of the combustion chambers and the turbine nozzles had failed and choked off part of the area. (See fig. 8.) These transition sections were changed several times because they were continually collapsing and breaking off. After several failures they were tack-welded to the turbine nozzle and this procedure kept them intact for the rest of the runs. An inspection later disclosed that the transition sections installed while the compressor was being changed were slightly larger than the original ones and had no clearance between them for expansion.

Replacing the standard turbine nozzles with the small nozzles (configuration 10) resulted in much poorer performance of the engine. Static tests were made with this configuration at pressure altitudes from 1500 to 37,500 feet. Combustion blow-out was not encountered but, when the maximum speed at which the engine would operate was reached (fig. 7), fuel began to burn in the tail pipe, the compressor-outlet static pressure dropped about 25 percent, the airflow rate fell markedly, the engine speed decreased about 500 rpm, and the tail-pipe temperatures rapidly increased. Apparently the compressor blades were stalling as a result of excessive choking in the small turbine nozzles used in configuration 10. This condition limited the maximum engine speed to approximately 6300 rpm at a pressure altitude of 1500 feet and approximately 4400 rpm at a pressure altitude of 37,500 feet. When an engine speed of 6300 rpm was reached at a pressure altitude of 1500 feet, a single burst of yellow flame about 10 feet long was emitted at the tail pipe and was followed by several rapid bursts of a pulsating yellow flame about 10 feet long, which continued until the throttle was retarded. Operation of the engine at 40,000 feet with this configuration was impossible owing to excessively high tail-pipe temperatures.

Replacement of the small turbine nozzles with the large nozzles (configuration 11) made possible operation of the engine at higher speeds. (See fig. 7.) Static tests were made with this configuration at pressure altitudes from 5000 to 40,000 feet. The maximum speed of the engine with this configuration was limited by high tail-pipe temperatures resulting from excessive fuel flow. The maximum engine speed at 5000 feet was 6500 rpm, with tail-pipe temperatures between 1150° and 1300° F. A maximum engine speed of 7000 rpm was reached at 40,000 feet with a tail-pipe temperature of 1300° F. Slow acceleration to the maximum engine speed was required in order to avoid blow-out of the combustion chambers. Combustion blow-out was encountered at 5400 rpm with a pressure altitude of 30,000 feet and at 6400 rpm with a pressure altitude of 40,000 feet during rapid accelerations.

Replacing the 18-inch-diameter jet nozzle with a $19\frac{1}{2}$-inch-diameter nozzle and replacing the turbine wheel having excessive radial clearance with one having proper radial clearance (configurations 12 and 13) made possible operation of the engine at full speed. (See fig. 7.) Configuration 12 was investigated at indicated airspeeds from 250 to 300 miles per hour and configuration 13 was investigated at static conditions. Both configurations were investigated over a range of pressure altitudes from 5000 to 40,000 feet. With these configurations, the tail-pipe temperature at full speed was between 1000° and 1100° F at all altitudes.

Distribution of Temperatures at Turbine Outlet

The temperatures measured behind each combustion chamber at the turbine outlet were very well balanced for both type A and type B combustion chambers; usually they did not vary more than 50° F at any engine speed or altitude. Operation with the type C combustion chamber resulted in an unbalanced temperature distribution among the chambers. This unbalance may have been caused by a set of unmatched fuel nozzles. With the type C combustion chamber, the difference between the highest and lowest temperatures measured at the turbine outlet was usually 100° to 200° F at any engine speed and at all altitudes. Replacement of the type B combustion chamber for runs with configurations 12 and 13 resulted in one chamber running hotter and one running cooler than the others. The temperatures of the other combustion chambers were well-balanced.

Acceleration

Low-flow compressor. - With the low-flow compressor (configurations 1 and 5) at pressure altitudes from 5000 to 25,000 feet and temperatures from 29° to -41° F, the engine was started and accelerated to a normal operating speed. The time required to start the engine from a windmilling speed of approximately 500 rpm and accelerate to 4000 rpm increased from 47 seconds at 5000 feet to 72 seconds at 25,000 feet. (See fig. 9.) The time required to accelerate from 3000 to 6000 rpm increased from 13 seconds at 5000 feet to 44 seconds at 30,000 feet (fig. 10). Between 12 and 18 seconds were required to ignite the combustion chambers at all altitudes. The increase in acceleration time with altitude resulted from the decreased accelerating force exerted on the turbine blades by the low-density gases at high altitude. The results of experimental and calculated data to determine the ratio of the time to accelerate at altitude to the time to accelerate at sea level are shown in figure 11. In order to determine the calculated curve, the assumption was made that the turbine-inlet temperature was the same at all altitudes during acceleration. The ratio of time to accelerate at altitude to time to accelerate at sea level was then found to be inversely proportional to the ratio of the respective densities of the inlet air.

Careful handling of the throttle was required when starting the engine or when accelerating from low engine speeds. The throttle had to be opened slowly to hold the tail-pipe temperature below the limit of 1500° F. Acceleration from idling speed required more careful manipulation of the throttle at high altitudes than at low altitudes because of high tail-pipe temperatures and compressor surge.

In acceleration tests with the low-flow compressor at a pressure altitude of 20,000 feet (configuration 1), a violent surge of the compressor was encountered during a rapid acceleration. The engine stopped accelerating at approximately 5300 rpm, a violent pulsation was set up in the engine, and a yellow flame about 10 feet long was usually emitted at the tail pipe. The fuel flow rapidly increased and rapid fluctuation of compressor-outlet and tail-pipe pressures occurred. The tail-pipe temperature rapidly increased and further acceleration was impossible. In order to recover from the compressor surge, deceleration to 5000 rpm or lower was necessary. When the tail-pipe temperature was maintained below 1200° F during acceleration at a pressure altitude of 20,000 feet, no compressor surge was encountered.

Compressor surge was also encountered during rapid accelerations at pressure altitudes of 30,000 and 40,000 feet. During accelerations at 40,000 feet with tail-pipe temperatures slightly below 1200° F, the compressor surge occurred on three occasions. The first time, the engine speed was reduced to 4800 rpm, from which speed the engine could be accelerated more slowly through the critical range. The second and third times, the compressor surge encountered was more violent and resulted in blow-out of several combustion chambers. As soon as some of the combustion chambers blew out, the temperature in the tail pipe behind the chambers that remained lighted began to rise rapidly, but the chambers did not cross-ignite nor would the ignition relight them. Inasmuch as the tail-pipe temperatures were becoming excessive and the engine speed continued to decrease, operation of the engine had to be discontinued.

<u>High-flow compressor.</u> - Acceleration characteristics with the high-flow compressor (configurations 6 to 8) were poorer than with the low-flow compressor (configurations 1 to 5). Only slow accelerations could be made with configurations 6 to 8 without encountering combustion blow-out.

The installation of the small turbine nozzle (configuration 10) resulted in much poorer acceleration characteristics than with configurations 6 to 8. Attempts to accelerate rapidly resulted in an increase in engine speed of only 200 to 600 rpm before the compressor stalled. When the compressor stalled, the tail-pipe temperature rose rapidly and a yellow flame was usually emitted at the tail pipe; the flame turned to a blue haze and did not disappear until the throttle was retarded. When an attempt was made to accelerate rapidly from approximately 3000 rpm at a pressure altitude of 10,000 feet, the compressor stalled and a yellow flame fringed with a blue haze shot from 6 to 8 feet out of the tail pipe for several seconds.

Neither burning in the tail pipe nor combustion blow-out occurred during accelerations at pressure altitudes of 5000, 10,000, and 20,000 feet in runs with the large turbine nozzles and the 18-inch-diameter jet nozzle (configuration 11). The combustion chambers blew out at 5400 rpm with a pressure altitude of 30,000 feet and at 6400 rpm with a pressure altitude of 40,000 feet during rapid accelerations. Combustion completely ceased in both cases and the chambers were not immediately relighted.

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Starting and acceleration tests were made with the large turbine nozzles and a $19\frac{1}{2}$-inch-diameter jet nozzle (configuration 13) at pressure altitudes from 5000 to 40,000 feet and inlet temperatures from 25° to -34° F. Combustion blow-out was not encountered below a pressure altitude of 20,000 feet during rapid accelerations. The revised fuel regulator contained a restricting orifice that limited the rate at which the fuel flow could be increased. During accelerations a tail-pipe temperature of 1500° F could be maintained until the engine speed reached approximately 5500 rpm. From this point the fuel regulator controlled the rate at which the fuel flow was changed to such an extent that the acceleration from 6000 to 7000 rpm with the throttle wide open was only from one-third to one-half as fast as the acceleration from 5000 to 6000 rpm. This restricting orifice was responsible for a greater accelerating time from 6000 to 7000 rpm than would normally be encountered. (See figs. 12 and 13.) The variation in the two acceleration curves at a pressure altitude of 5000 feet is attributed to an excess of fuel sprayed into the burners during the run represented by the upper curve. The excess of fuel caused very high tail-pipe temperatures and considerable burning of fuel in and behind the tail pipe, which resulted in a slower acceleration below 3000 rpm.

In one run at a pressure altitude of 20,000 feet during a rapid acceleration from 3000 to 7000 rpm, one combustion chamber blew out at 4000 rpm and relighted between 5500 and 6000 rpm. The engine continued to accelerate while the chamber was out, but the acceleration time was greater than when all the chambers were lighted. During three rapid accelerations from 3000 rpm at a pressure altitude of 30,000 feet, several combustion chambers blew out between 4000 and 5000 rpm and the engine speed began to decrease. The throttle was retarded and the chambers were relighted by means of the cross-fire tubes. All the combustion chambers blew out at 6300 rpm at a pressure altitude of 40,000 feet during a rapid acceleration from 4000 rpm.

Acceleration tests were made at pressure altitudes of 30,000 and 40,000 feet with the engine operating on 62-octane unleaded gasoline. During two rapid accelerations from 3000 rpm at a pressure altitude of 30,000 feet, several combustion chambers blew out, which caused the engine speed to decrease suddenly. The throttle was retarded and the combustion chambers were relighted by means of the cross-fire tubes. During a rapid acceleration from 4000 rpm at a pressure altitude of 40,000 feet, all the combustion chambers blew out at 4200 rpm. The acceleration characteristics of the engine were about the same with gasoline as they were with kerosene.

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Variable-area jet nozzle. - Because acceleration of the engine was relatively slow, investigations were conducted with the high-flow compressor at pressure altitudes of 5000, 10,000, 20,000, 30,000, and 40,000 feet using a variable-area jet nozzle (configuration 8). These investigations were made to determine the rate and extent of increase in thrust when the exit area was suddenly reduced. (See table II.) With the engine operating on the governor control at 7600 rpm, a sudden reduction in the nozzle area from 137 percent normal area to normal area resulted in an immediate increase in thrust of 37 to 47 percent and a decrease in engine speed of 100 to 200 rpm. If the governor control had held the engine speed constant, the increase in thrust would have been approximately 50 to 60 percent. At pressure altitudes up to 20,000 feet the engine speed was controlled by the governor at 7600 rpm, but above a pressure altitude of 20,000 feet the engine was operating on the fuel-regulator control at full speed. When the engine speed was set at 7600 rpm with the engine operating on the fuel-regulator control, a sudden reduction of the jet-nozzle area resulted in an increase in thrust, during which time the engine speed was decreasing. The engine speed finally stabilized at approximately 6800 rpm with a total increase in thrust of about 10 to 15 percent. In order to maintain constant engine speed with the engine operating on the fuel-regulator control the throttle had to be advanced when the jet-nozzle area was reduced.

Starting

The easiest method of starting the engine from rest was to apply the starter, then to open the throttle about halfway and turn on the ignition as soon as the control oil pressure of the fuel regulator had reached approximately 90 pounds per square inch. The small-slot fuel pressure reached about 80 or 90 pounds per square inch by the time the starter had cranked the engine to 900 rpm. As soon as the burners lighted, the small-slot fuel pressure was reduced to 40 or 50 pounds per square inch by partly closing the throttle and the ignition was turned off. The starter was left engaged until an engine speed of 2000 rpm was reached in order to help the engine accelerate more rapidly. By this procedure, tail-pipe temperatures could be maintained below 1300° F during the start provided that the fuel ignited as soon as the small-slot fuel pressure had reached 80 or 90 pounds per square inch. If the fuel did not ignite, the combustion chambers and tail pipe became loaded with fuel. When the fuel then ignited, a yellow flame 10 to 15 feet long burned out of the tail pipe and gradually disappeared as the engine speed was increased. With the engine being turned by the starter, a small-slot fuel pressure of approximately 120 pounds per square inch could be obtained by completely opening the throttle, but starting the engine at this high fuel pressure resulted in tail-pipe temperatures of 1400° to 1700° F when the combustion chambers lighted.

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Original ignition system. - During the runs with the original spark plugs on the engine, no difficulty was encountered in starting the engine from rest or from a low windmilling speed at pressure altitudes below 20,000 feet. The engine was started at a pressure altitude of 25,000 feet with considerable burning in and behind the tail pipe and with high tail-pipe temperatures.

No successful starts were made at a pressure altitude of 30,000 feet with the original spark plugs and ignition system. On several attempts to start at this altitude without ram, the combustion chambers had to be loaded with fuel at about 800 rpm before they would light and then one of the top chambers did not light. Inspection of the engine revealed that this combustion chamber failed to light because the cross-fire tubes had shifted out of position. When the combustion chambers lighted at 30,000 feet, a yellow flame 10 feet long was emitted from the tail pipe. With seven chambers lighted and the starter engaged, the engine speed could not be raised above 2200 rpm and disengaging the starter caused the engine speed to decrease slowly. An attempt was made for 5 minutes to raise the speed above 2200 rpm. Operation of the engine was then discontinued because the tail-pipe temperatures were between 1200° and 1500° F.

Starts at pressure altitudes of 20,000 and 25,000 feet at any ram pressure were also accompanied by a yellow flame. When the engine speed had been increased to between 2000 and 2500 rpm, the flame withdrew into the combustion chambers. The engine could not be started with the low-flow compressor and original ignition system at any altitude when windmilling above 1600 rpm. The fuel could not be ignited at a pressure altitude of 32,000 feet or in several of the attempts made at 30,000 feet.

Oxygen spark plug. - After installation of the spark plugs in which a jet of oxygen was discharged into the zone of the spark, one start was made at a pressure altitude of 37,000 feet from a windmilling speed of 800 rpm; the compressor-inlet temperature was -40° F and the indicated airspeed was 140 miles per hour. Engaging the starter increased the engine speed to approximately 1250 rpm and the fuel was ignited at a small-slot fuel pressure of 100 pounds per square inch. A yellow flame about 30 feet long was emitted from the tail pipe, but the turbine-outlet temperatures were less than 100° F and the tail-pipe temperature approximately 4 feet behind the turbine was only about 100° F. Fuel was burning in the jet nozzle and behind the nozzle in the air stream. When the small-slot fuel pressure was reduced to about 50 or 60 pounds per square inch, the combustion chambers lighted one at a time. When the engine speed had increased to 1700 rpm all the combustion chambers were lighted and a blue flame about 10 feet long was still burning out of the tail pipe. The flame disappeared into the tail pipe at 3000 rpm, the starter was disengaged, and acceleration was normal. The characteristics of this start were typical of all starts made above a pressure altitude of 30,000 feet.

The engine was started several times between pressure altitudes of 20,000 and 30,000 feet with the starter and the oxygen jet in use. During each of these starts, a flame was emitted at the tail pipe until the engine speed exceeded 2000 rpm.

<u>Oxygen spark plug and high-voltage spark plug.</u> - With one spark plug using an oxygen jet and one spark plug connected to a high-voltage transformer, the fuel was ignited several times at a pressure altitude of 40,000 feet both with and without ram. During the starts without ram, a flame about 15 feet long extended from the tail pipe and the combustion chambers again failed to light until the fuel had ignited in the tail pipe and was burning in the air stream. The small-slot fuel pressure was reduced to about 50 pounds per square inch before the flame withdrew into the combustion chambers. In several starts without ram at a pressure altitude of 40,000 feet, the maximum engine speed obtainable was between 1500 and 1800 rpm with all the combustion chambers lighted and the starter engaged. At these engine speeds, the maximum turbine-outlet temperature was approximately 1800° F and operation of the engine had to be discontinued.

In one start at a pressure altitude of 40,000 feet with a pressure of 30 pounds per square inch in the oxygen line to one spark plug, the fuel was ignited at an engine speed of 1000 rpm. Approximately 4 minutes from the time the attempt to start was begun, the engine speed had increased to 4000 rpm. During acceleration of the engine the temperatures about 4 feet behind the turbine were higher than the temperatures at the turbine outlet and a flame was burning out of the tail pipe. Several attempts to start at pressure altitudes from 40,000 feet were made, but the fuel could not be ignited.

A series of windmilling starting runs were conducted with the two types of spark plug (configuration 12) in order to determine the maximum windmilling speed at which the engine would start. During one attempt to start the engine at a windmilling speed of 2050 rpm and a pressure altitude of 40,000 feet, a blue flame momentarily shot out of the tail pipe, but the fuel would not reignite. At a windmilling speed of 1600 rpm at a pressure altitude of 40,000 feet, the engine was started and accelerated with the aid of the starter. The maximum windmilling speed at which the engine could be started at a pressure altitude of 30,000 feet was 2000 rpm. During two windmilling starts at a pressure altitude of 20,000 feet and an engine speed of 2800 rpm, a blue flame shot out of the tail pipe at almost explosive velocity and the engine speed increased from 2800 to 4000 rpm in approximately 1 or 2 seconds. The maximum tail-pipe temperature indicated during these starts was approximately 450° F.

A summary of the conditions at which windmilling starts were attempted is given in table III and the maximum windmilling speeds and true airspeeds at which the engine could be started at each altitude are shown in figures 14 and 15. Acceleration of the engine was more rapid in starts at high airspeeds.

Operation of Fuel-Control System

Original fuel regulator. - Trouble was encountered in obtaining sufficient fuel flow through the original regulator, used with configurations 1 to 5, to operate the engine at full speed. The regulator had been set for full speed at sea level but, in order to obtain full speed at altitude, a pressure of 5 to 40 inches of mercury above tunnel static pressure was required on the atmospheric side of the bellows in the barometric control.

When the throttle was opened or closed during an acceleration or deceleration, a lag in the controls occurred between 6000 and 7000 rpm during which a movement of the throttle did not change the speeds. During acceleration the lag occurred between the points at which the fuel regulator no longer had control and at which the speed governor took over the control. The total throttle travel was 120°; when the transition from fuel regulator to governor control occurred, no change in engine speed resulted from movement of the throttle between the 60° and 90° positions.

When the speed governor took over the control, a sudden surge of the fuel pressure and fuel flow occurred. A rapid change in speed while the engine was operating on the governor caused the fuel pressure and fuel flow to change with a surge instead of smoothly as they did when the engine was operating on the fuel regulator. When the fuel regulator had control, the small-slot fuel pressure did not fluctuate; however, when the governor controlled the fuel flow, the needle on the small-slot fuel-pressure gage oscillated rapidly over a range of 8 to 10 pounds per square inch.

When the engine operation was controlled by the fuel regulator, the altitude compensator allowed the engine speed to increase slightly as the altitude was increased and the rate of increase in engine speed became greater at high altitudes. The engine speed increased from 5000 to 5200 rpm with a change in pressure altitude from 10,000 to 20,000 feet, from 5200 to 5500 rpm with a change in pressure altitude from 20,000 to 30,000 feet, and from 6100 to 6900 rpm with a change in pressure altitude from 38,000 to 50,000 feet.

Modified fuel regulator. - The modified fuel regulator, which replaced the original fuel regulator when the high-flow compressor was installed in the engine, so restricted the fuel flow during acceleration that above 6000 rpm acceleration was very slow (figs. 12 and 13). The original fuel regulator controlled the fuel flow up to an engine speed of approximately 6800 rpm where the variable-speed governor began to control the fuel flow. The modified regulator, however, controlled the fuel flow up to an engine speed of about 7000 rpm at a pressure altitude of 5000 feet. With the modified fuel regulator an increase in altitude resulted in an increase in the engine speed at which the governor took control of the fuel flow. At pressure altitudes above 20,000 feet the revised fuel regulator controlled the fuel flow up to 7600 rpm. The maximum small-slot fuel pressure obtainable when starting was 90 pounds per square inch with the modified fuel regulator as compared with 120 pounds per square inch with the original fuel regulator.

Bearing Cooling

During runs with the low-flow compressor (configurations 1 to 5), the bearings did not cool properly at engine speeds higher than 7000 rpm above a pressure altitude of 30,000 feet. At 7600 rpm above a pressure altitude of 30,000 feet, the temperatures of the mid bearing (bearing 2) and the rear bearing (bearing 4) did not stabilize but were permitted to rise until a temperature between

300° and 340° F was reached; then the engine speed was reduced in order to allow the bearings to cool. The maximum allowable bearing temperature was 350° F and extended operation with bearing temperatures above 300° F was not advisable.

The bearing cooling was worse with the high-flow compressor (configurations 6 to 13) than with the low-flow compressor. With the high-flow compressor the engine could not be operated above 7000 rpm for more than 10 or 15 minutes before the temperatures of the mid bearing and the rear bearing reached 320° to 340° F and they were still increasing at the rate of 2° to 4° per minute.

Failure of the bearings to cool properly at high pressure altitudes and high engine speeds was attributed not only to the reduced density of the air at high altitude but also to the fact that at high engine speeds the bearing cooling-air flow decreased with increasing engine speed. Representative data showing the comparison of bearing cooling-air flow with the low-flow and high-flow compressors at a pressure altitude of 30,000 feet are presented in figure 16. The decrease in bearing cooling-air flow at high engine speeds was more rapid with the high-flow compressor than with the low-flow compressor. At maximum engine speed the high-flow compressor delivered from 15 to 25 percent less cooling air to the bearings at all altitudes than the low-flow compressor.

The decrease in bearing cooling-air flow at high engine speeds was attributed to a corresponding decrease in the compressor fourth-stage static pressure, the stage from which the cooling air was bled. A comparison of the fourth-stage static pressures of the low-flow and high-flow compressors at a pressure altitude of 30,000 feet is shown in figure 17.

The temperature rise between the compressor inlet and the bearing cooling-air discharge at all altitudes was from 10 to 20 percent greater with the high-flow compressor than with the low-flow compressor. A comparison of this temperature rise for the low-flow and high-flow compressors at a pressure altitude of 30,000 feet is shown in figure 18.

Inspection of the low-flow compressor after disassembly showed that some of the holes in the compressor casing for bleeding off the bearing cooling air did not line up with the holes in the pads leading the air from the compressor. The bearings were thus deprived of some of the cooling air they should have received.

After 54 hours of testing with the low-flow compressor, the mid bearing, which is located at the rear of the compressor, failed. The engine had been operating for several minutes at a pressure altitude of 50,000 feet and engine speeds near 7000 rpm with the mid-bearing temperatures ranging from 275° to 335° F. The engine speed was increased and was being stabilized at 7450 rpm when the mid-bearing temperature reached 340° F and continued to rise rapidly. The fuel was shut off as quickly as possible, but the mid-bearing temperature immediately reached 392° F and soon rose to a maximum of 410° F. The temperature of the rear bearing just ahead of the turbine wheel reached a maximum of 360° F soon after operation of the engine was discontinued. The high temperature of the rear bearing was probably caused by heat transfer from the turbine wheel, which was still hot. While the engine was windmilling immediately after the fuel had been shut off, the amplitude of vibration of the engine indicated on the vibration meter greatly exceeded the allowable limit of 0.005 inch for normal operation.

An inspection of the mid bearing after the engine was disassembled revealed that all the plastic cages that held the balls in place had been ground into small pieces. Operation of the bearing at high temperatures had probably weakened the plastic cages and one of them failed, which enabled the balls to move about and crush the remaining cages. The tips of the rotor and stator blades on the rear stages of the compressor had rubbed after the mid bearing failed. Views of the compressor rotor and case after the blades rubbed are shown in figures 19 and 20.

Damage to Accessory Dome and Air Guide

During performance runs at ram pressure ratios up to 1.8 at 40,000 feet, the dome over the accessories collapsed. The dome was repaired and a stiffening ring was riveted around the inside. The dome again collapsed at high ram conditions and was replaced with one made of heavier gage aluminum, which proved satisfactory. The dome afterbody and the vanes in the air guide at the inlet were badly torn during the tests owing to the high ram pressures. The damaged dome and dome afterbody are shown in figure 21. A steel dome afterbody and steel guide vanes were constructed to replace the damaged ones.

SUMMARY OF RESULTS

The following operational characteristics were observed during an altitude-wind-tunnel investigation of a 4000-pound-thrust axial-flow turbojet engine for a range of altitudes from 5000 to 50,000 feet and ram pressure ratios from 1.00 to 1.86.

1. With the low-flow compressor, the engine could be operated at full speed without serious burner unbalance at altitudes up to 50,000 feet. The minimum operating speed without ram varied from 2000 rpm at a pressure altitude of 5000 feet to 4000 rpm at 40,000 feet. At a true airspeed of 635 miles per hour at 40,000 feet, the minimum operating speed was increased to 6300 rpm.

2. In several runs with the high-flow compressor installed (configurations 6 to 8, 10, and 11), the maximum engine speed was limited to less than 7600 rpm by combustion blow-out, high tail-pipe temperatures, and compressor stall. These maximum speed limits were removed by installing turbine nozzles and a tail-pipe nozzle that had greater nozzle areas; however, the tail-pipe temperatures at full speed were then approximately 200° F lower than the desired operating temperature.

3. Acceleration of the engine was slow, approximately 13 seconds being required to accelerate from 3000 to 6000 rpm at a pressure altitude of 5000 feet with the standard engine configuration and the low-flow compressor. Acceleration was slower at high altitudes; 44 seconds were required to accelerate from 3000 to 6000 rpm at 30,000 feet.

4. At maximum engine speed a sudden reduction in jet-nozzle area from 137 percent normal area to normal area immediately increased the thrust by 37 to 47 percent and decreased the engine speed by 100 to 200 rpm.

5. The engine started normally and easily below 20,000 feet with each configuration. The maximum pressure altitude at which the engine could be regularly started was increased from 25,000 to 40,000 feet by installing the revised ignition system and high-voltage transformer. Starts above 20,000 feet in each case were accompanied by a great deal of burning in and behind the tail pipe, high tail-pipe temperatures, and very slow acceleration. The maximum engine windmilling speed and the corresponding true airspeeds at which the engine could be started ranged from 2800 rpm at 550 miles per hour and 20,000 feet to 1600 rpm at 300 miles per hour and 40,000 feet.

6. Operation of the engine was similar with both fuel regulators except that the modified fuel regulator restricted the fuel flow in such a manner that the acceleration above 6000 rpm was very slow.

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7. High temperatures of the mid bearing (bearing 2) and the rear bearing (bearing 4) were encountered in the runs with the low-flow compressor at engine speeds higher than 7000 rpm at pressure altitudes above 30,000 feet. The bearing cooling was worse with the high-flow compressor than with the low-flow compressor. The high bearing temperatures were caused in part by the reduction in bearing cooling-air flow at high engine speeds.

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

REFERENCE

1. Fleming, William A.: Altitude-Wind-Tunnel Investigation of a 4000-Pound-Thrust Axial-Flow Turbojet Engine. I - Performance and Windmilling Drag Characteristics. NACA RM No. E8F09, 1948.

TABLE I - TEST CONFIGURATIONS OF 4000-POUND-THRUST AXIAL-FLOW TURBOJET ENGINE

Configuration	Operating time (hr)	Compressor	Combustion chambers	Turbine nozzle	Turbine wheel		Tail pipe		Jet-nozzle diameter (in.)	Ignition	Fuel regulator	Inlet condition
					Number	Description	Number	Description				
1	12.5	Low flow	7 type A; 1 type B[a]	Small	1	6650 rpm; cast	1, 2	Standard	$16\frac{1}{4}$	Original	Original	Cowl
2	7.3	--do------	Type B	Standard	2	Full speed; cast	3	Strengthened	$16\frac{1}{4}$	--do----------	--do-----	Ram pipe
3	12.7	--do------	--do------	--do----	2	--do--------	3	--do--------	$16\frac{3}{4}$	--do----------	--do-----	Do.
4	16.3	--do------	--do------	--do----	3	Full speed; forged	3	--do--------	$16\frac{3}{4}$	--do----------	--do-----	Do.
5	5.1	--do------	--do------	--do----	3	--do--------	3	--do--------	$16\frac{3}{4}$	--do----------	--do-----	Cowl
6	12.6	High flow	--do------	--do----	3	--do--------	3	--do--------	18	Oxygen to both plugs	Modified	Ram pipe
7	7.0	--do------	--do------	--do----	3	--do--------	4	Vaned	18	--do----------	--do-----	Do.
8	5.2	--do------	--do------	--do----	3	--do--------	4	--do--------	Variable area	1 oxygen plug; 1 high voltage	--do-----	Cowl
9	.6	--do------	Type C	--do----	4	--do--------	4	--do--------	18	--do----------	--do-----	Ram pipe
10	5.5	--do------	--do------	Small	4	--do--------	4	--do--------	18	--do----------	--do-----	Cowl
11	5.9	--do------	--do------	Large	4	--do--------	4	--do--------	18	--do----------	--do-----	Do.
12	5.1	--do------	Type B	--do----	5	--do--------	4	--do--------	$19\frac{1}{2}$	--do----------	--do-----	Ram pipe
13	1.3	--do------	--do------	--do----	5	--do--------	4	--do--------	$19\frac{1}{2}$	--do----------	--do-----	Cowl
Total--	97.1											

[a]Contained one spark plug.

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TABLE II - RUNS OF 4000-POUND-THRUST AXIAL-FLOW TURBOJET ENGINE

WITH VARIABLE-AREA JET NOZZLE (CONFIGURATION 8)

Pressure altitude (ft)	Initial engine speed (rpm)	Initial thrust (lb)	Engine speed after closing jet nozzle (rpm)	Thrust (lb)			
				After closing jet nozzle	Percentage increase	At initial engine speed with jet nozzle closed	Percentage increase
5,000	7594	1940	7400	2660	37.0	2740	41.2
10,000	7594	1735	7500	2425	39.8	----------	--------
10,000	7594	1745	6900	2050	17.5	----------	--------
20,000	7594	1230	7400	1815	47.5	1850	50.5
20,000	7594	1205	7400	1775	47.3	1815	50.6
[a]30,000	7594	805	6700	910	13.0	1210	50.4
[a]30,000	7594	815	6700	940	15.3	1225	50.3
[a]40,000	7594	530	-------	-------	--------	830	56.7
[a]40,000	7594	515	-------	-------	--------	835	62.1
[a]50,000	7594	340	-------	-------	--------	500	47.0

[a]The engine was operating on the fuel regulator without governor control at full speed above 20,000 feet.

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TABLE III - WINDMILLING STARTING TESTS OF 4000-POUND-THRUST AXIAL-FLOW TURBOJET ENGINE WITH HIGH-FLOW COMPRESSOR (CONFIGURATION 12)

Altitude (ft)	Wind-milling speed (rpm)	Indicated air-speed (mph)	Cowl inlet temperature (°F)	Compressor outlet static pressure (lb/sq in. absolute)	Oxygen pressure to spark plug (lb/sq in. gage)	Successful ignition	Maximum tail-pipe temperature (°F)	Small-slot fuel pressure (lb/sq in. absolute)	Remarks
40,000	2800	270	-26	3.9	0	No			
40,000	2600	270	-26	3.9	20	No			
40,000	2600	270	-26	3.9	40	No			
40,000	2050	210	-24	3.8	20	No			
40,000	2050	210	-24	3.8	40	No			Puff of blue flame
40,000	2050	210	-24	3.8	60	No			
40,000	1600	155	-24	3.7	20	Yes	1750	100-120	Starter used
40,000	1550	140	-24	3.7	0	Yes	1775	100-120	--------do.--------
30,000	2950	365	-20	5.9	20	No			
30,000	3000	365	-20	5.9	40	No			
30,000	2000	250	-20	4.9	0	Yes	710	100-120	No starter used
30,000	2450	300	-20	5.2	0	No			
30,000	2450	300	-20	5.2	20	No			
30,000	2450	300	-20	5.2	40	No			
30,000	2000	230	-20	5.0	0	Yes	1400	100-120	--------do.--------
30,000	1800	225	-20	5.0	20	Yes	1450	100-120	--------do.--------
20,000	2800	410	-12	8.4	0	No			
20,000	2800	410	-12	8.4	20	Yes	375	80-100	No starter used; violent surge and rapid acceleration
20,000	2800	415	-12	8.5	0	Yes	450	80-100	--------do.--------

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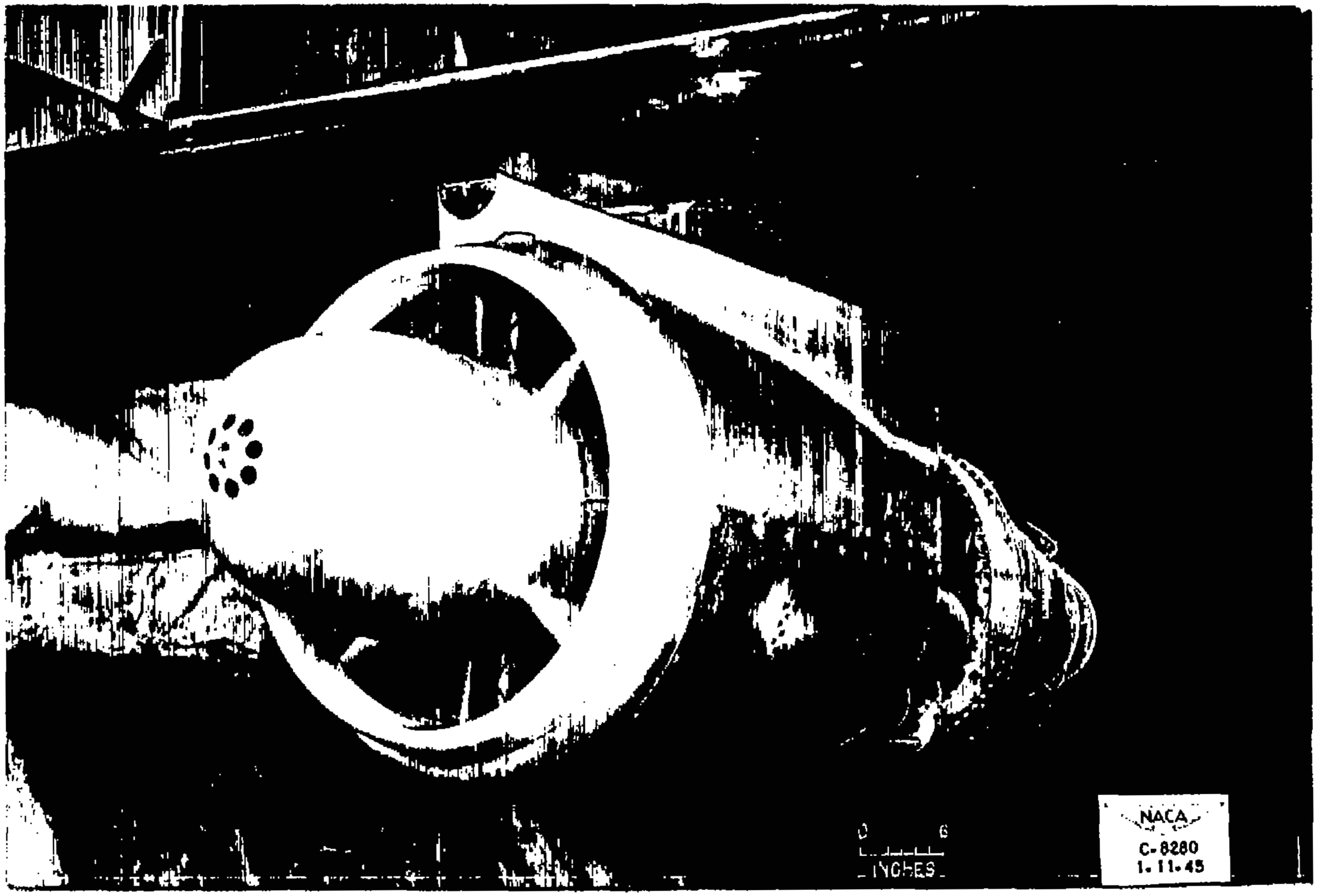
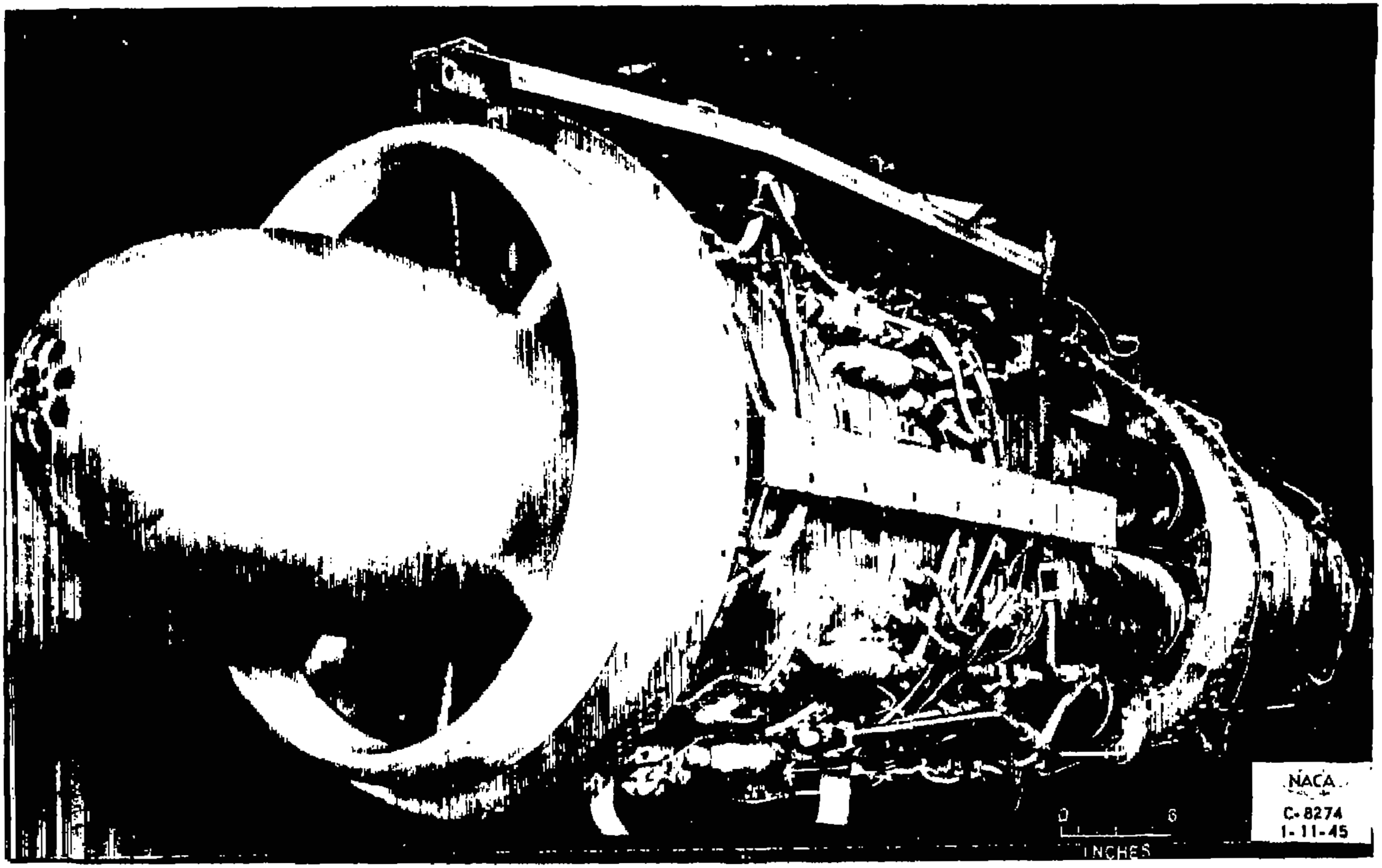


(a) Left-side view with cowling installed.

Figure 1. - Installation of 4000-pound-thrust axial-flow turbojet engine in altitude wind tunnel.



(b) Left-side view with cowling removed.

Figure I. – Concluded.

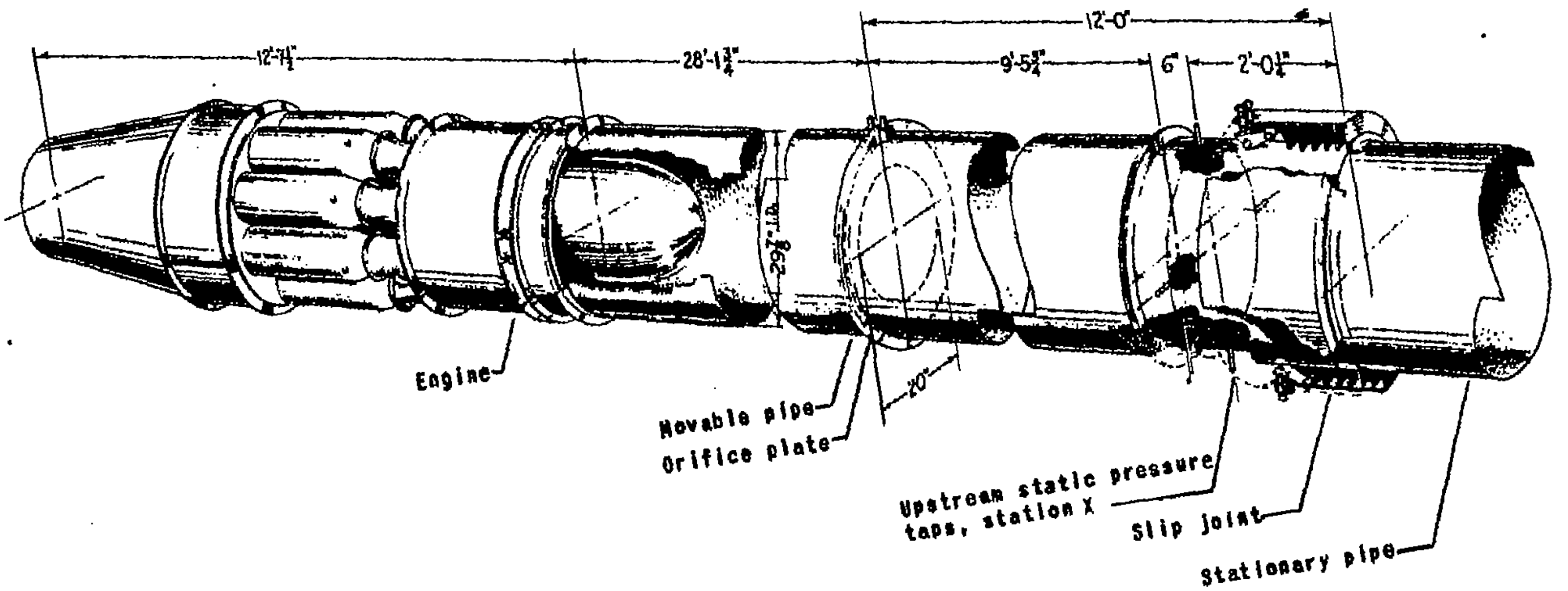
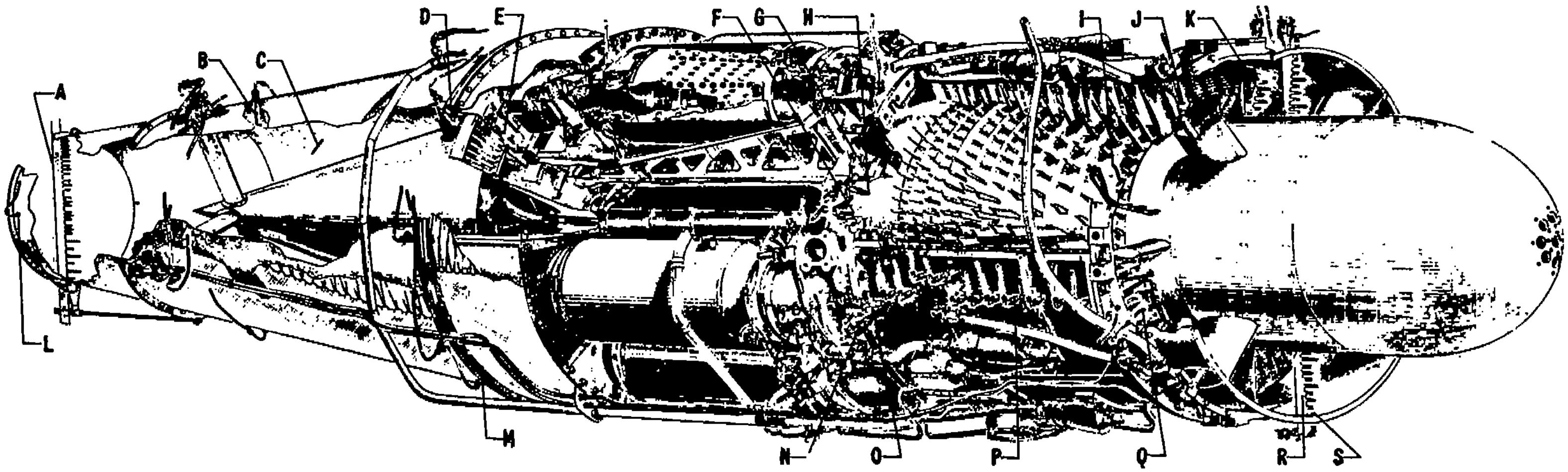


Figure 2. - Installation of closed duct from tunnel make-up air system to engine inlet for supplying air at ram pressures.



A Tail-pipe-discharge total and static-pressure and temperature survey (NACA)
B Tail-pipe total-pressure tube
C Tail-pipe thermocouple
D Turbine-outlet thermocouple
E Turbine-inlet total-pressure tube
F Compressor-outlet total-pressure tube
G Compressor-outlet static-pressure wall orifice (NACA)
H Compressor-outlet total-pressure and temperature survey (NACA)
I Compressor-inlet static-pressure wall orifice
J Compressor-inlet thermocouple
K Compressor-inlet total- and static-pressure survey (NACA)
L Tail-pipe-discharge static-pressure wall orifice (NACA)
M Turbine-outlet static-pressure wall orifice
N Compressor-outlet thermocouple
O Compressor-outlet static-pressure survey (NACA)
P Compressor-interstage static-pressure wall orifices
Q Compressor-inlet total-pressure tube
R Cowl-inlet total- and static-pressure and temperature survey (NACA)
S Cowl-inlet static-pressure wall orifice (NACA)

(NACA) Instrumentation installed by NACA for altitude-wind-tunnel tests. All other instrumentation standard.

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Figure 3. - Instrumentation of 4000-pound-thrust axial-flow turbojet engine for altitude-wind-tunnel investigations.

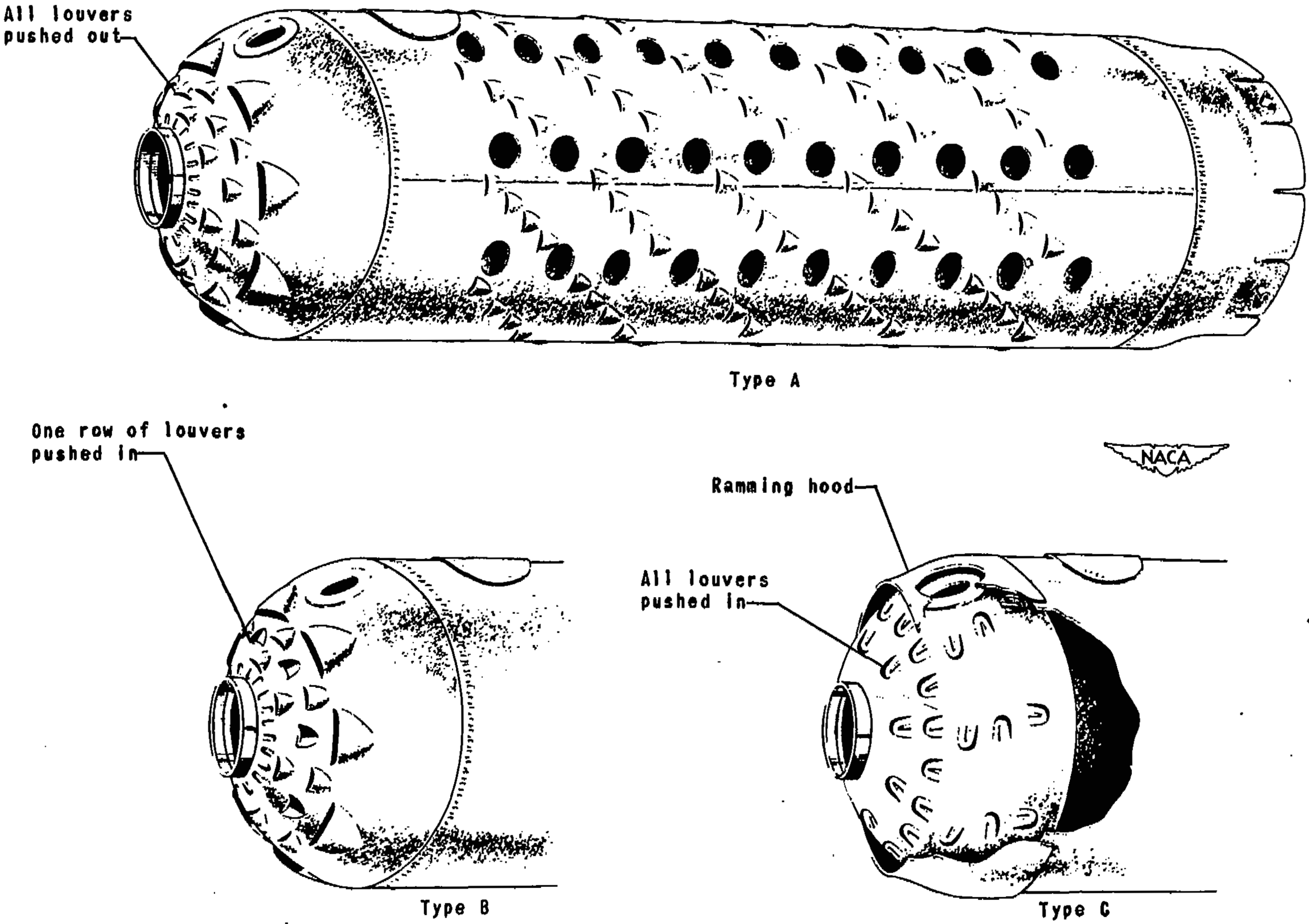

Figure 4. - Comparison of the three types of combustion chamber used on 4000-pound-thrust axial-flow turbojet engine during the altitude-wind-tunnel investigation illustrating the manner in which air was introduced into the primary burning zone of each.

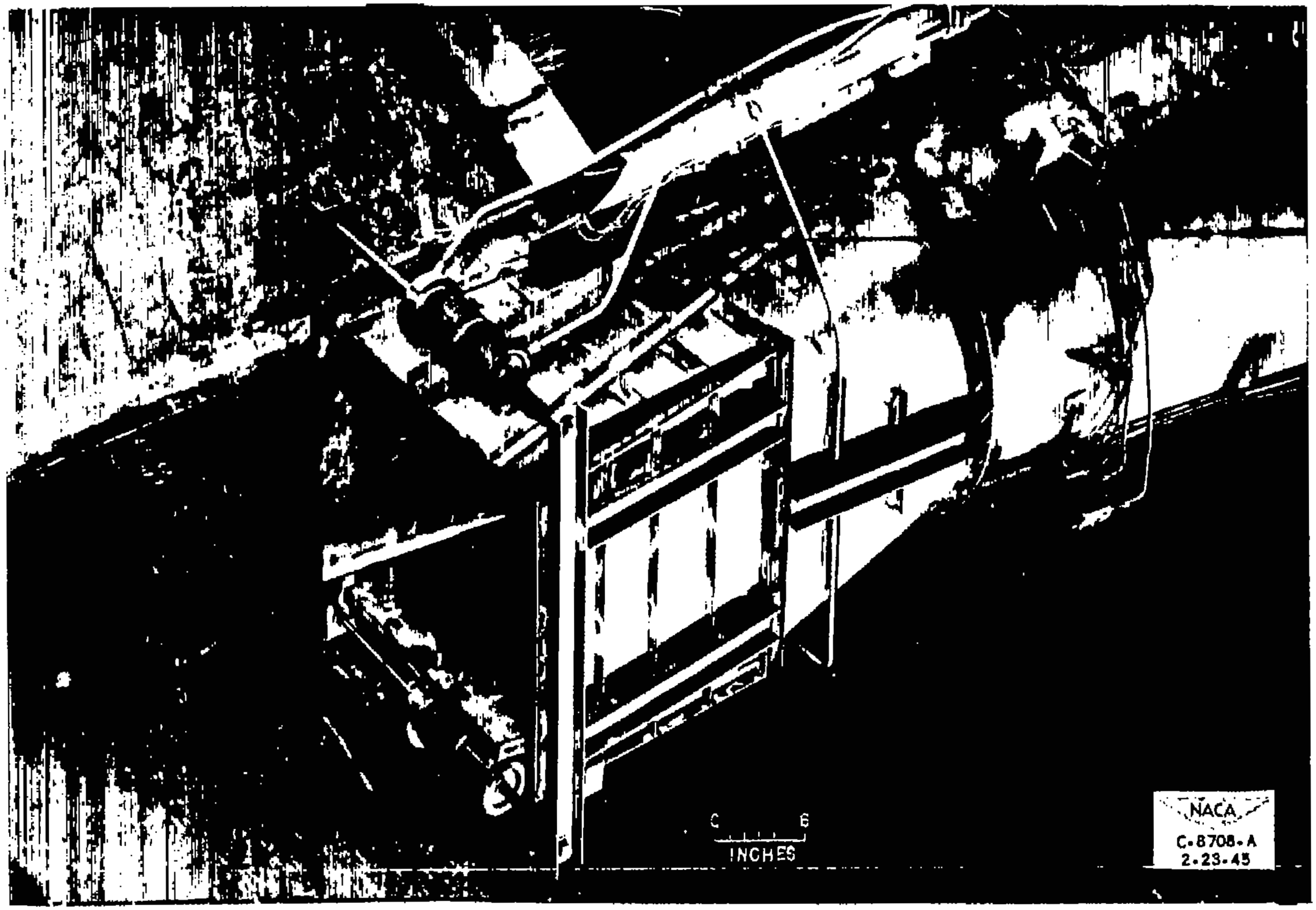

Figure 5. - Installation of the variable-area jet nozzle on 4000-pound-thrust axial-flow turbojet engine.

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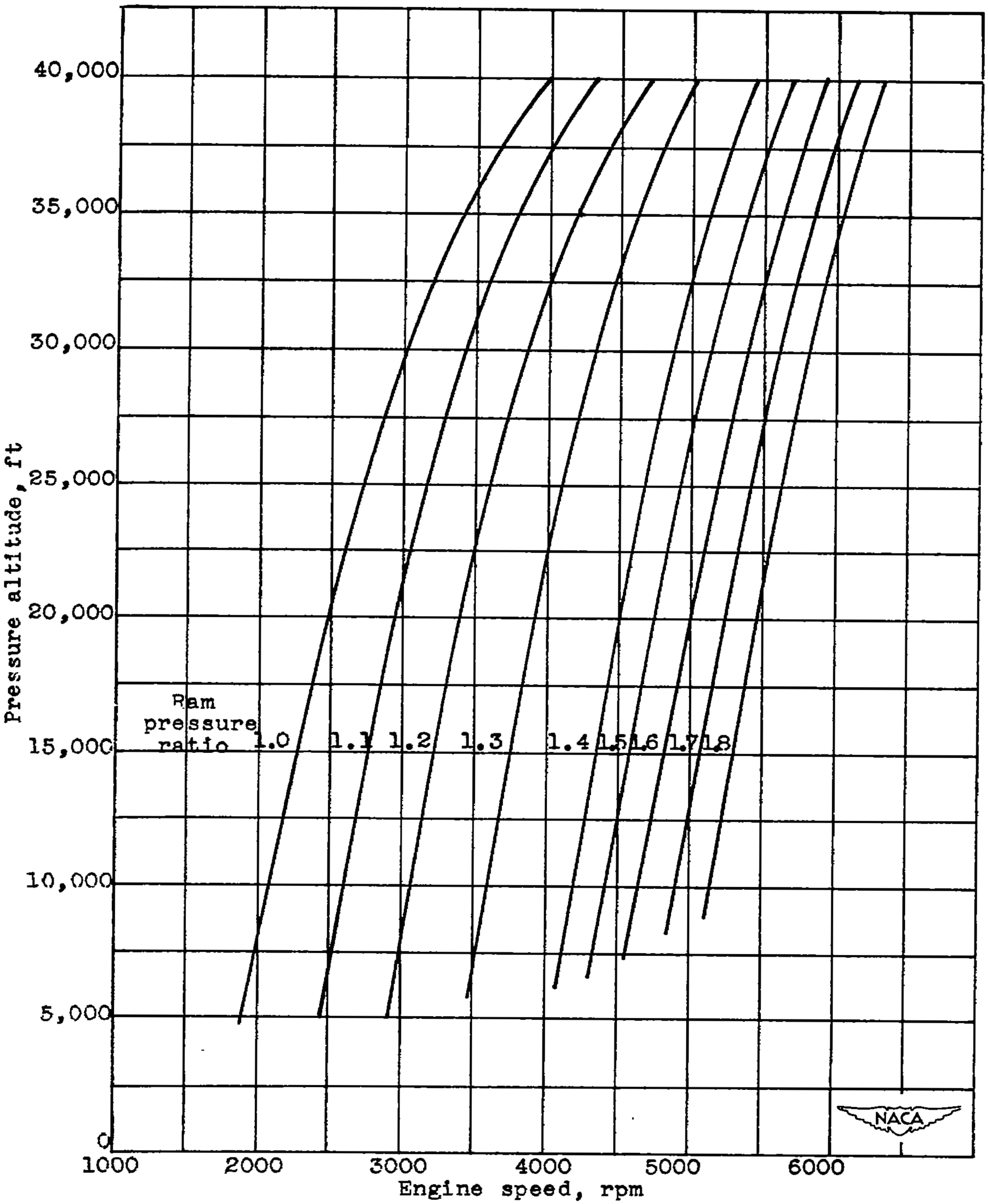

Figure 6.- Variation of minimum operating speeds with pressure altitude and ram pressure ratio with low-flow compressor, configurations 1 to 5.

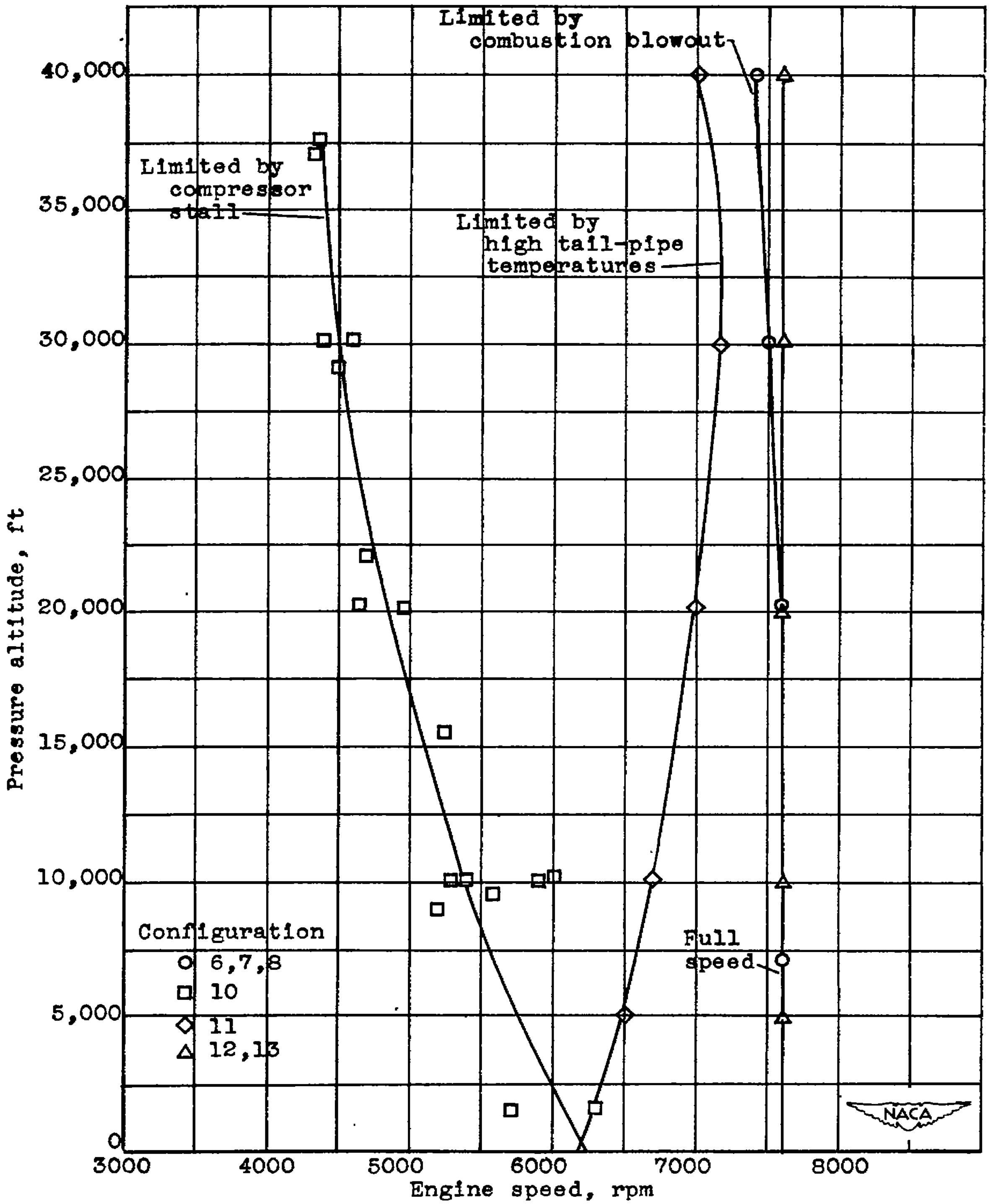

Figure 7.- Effect of pressure altitude on maximum engine speed with high-flow compressor installed on configurations 6, 7, 8, 10, 11, 12, and 13.

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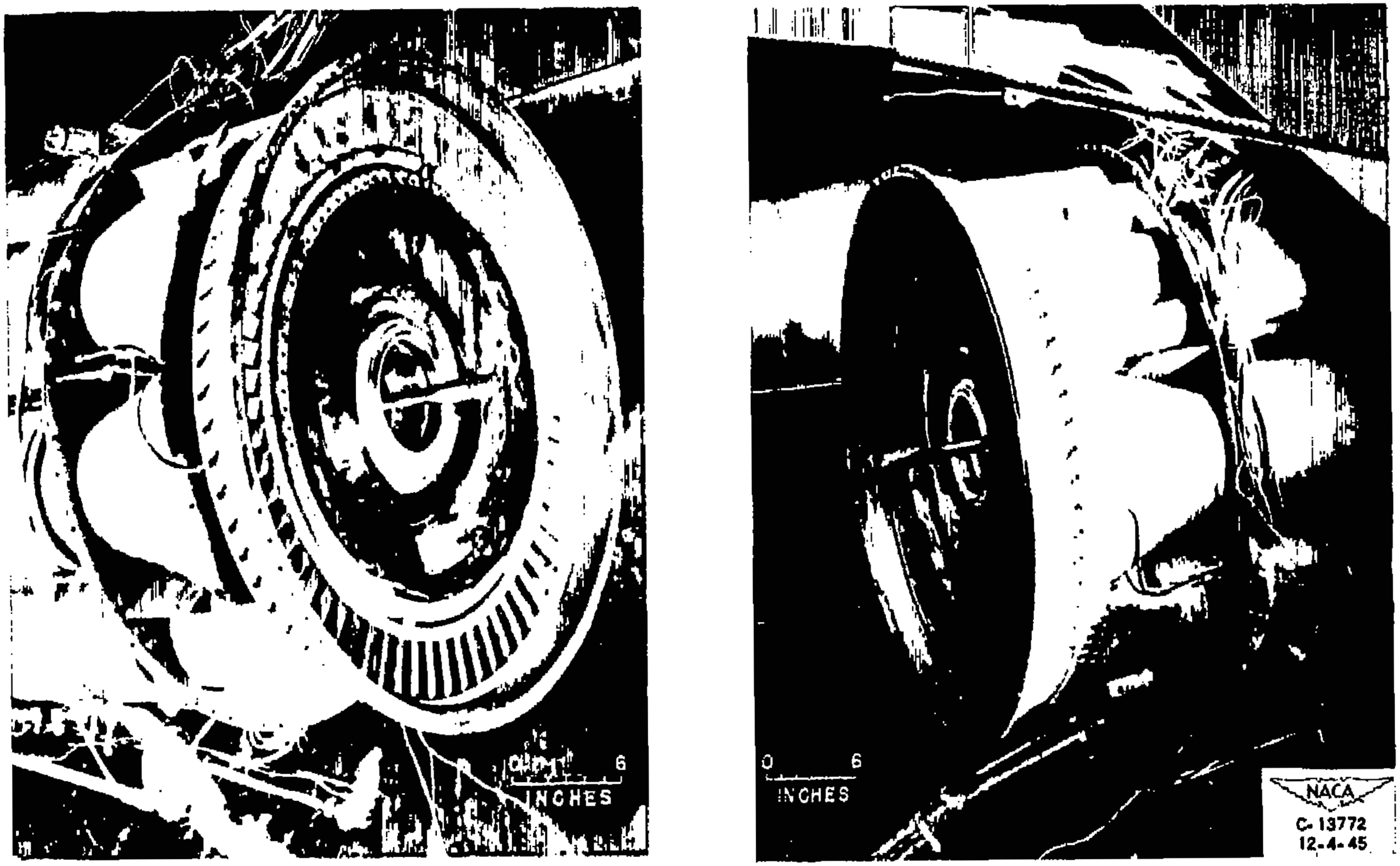

(a) Sections broken away.

(b) Section collapsed.

Figure 8. - Transition sections broken away from turbine nozzle and collapsed after operating engine 36 minutes with configuration 9.

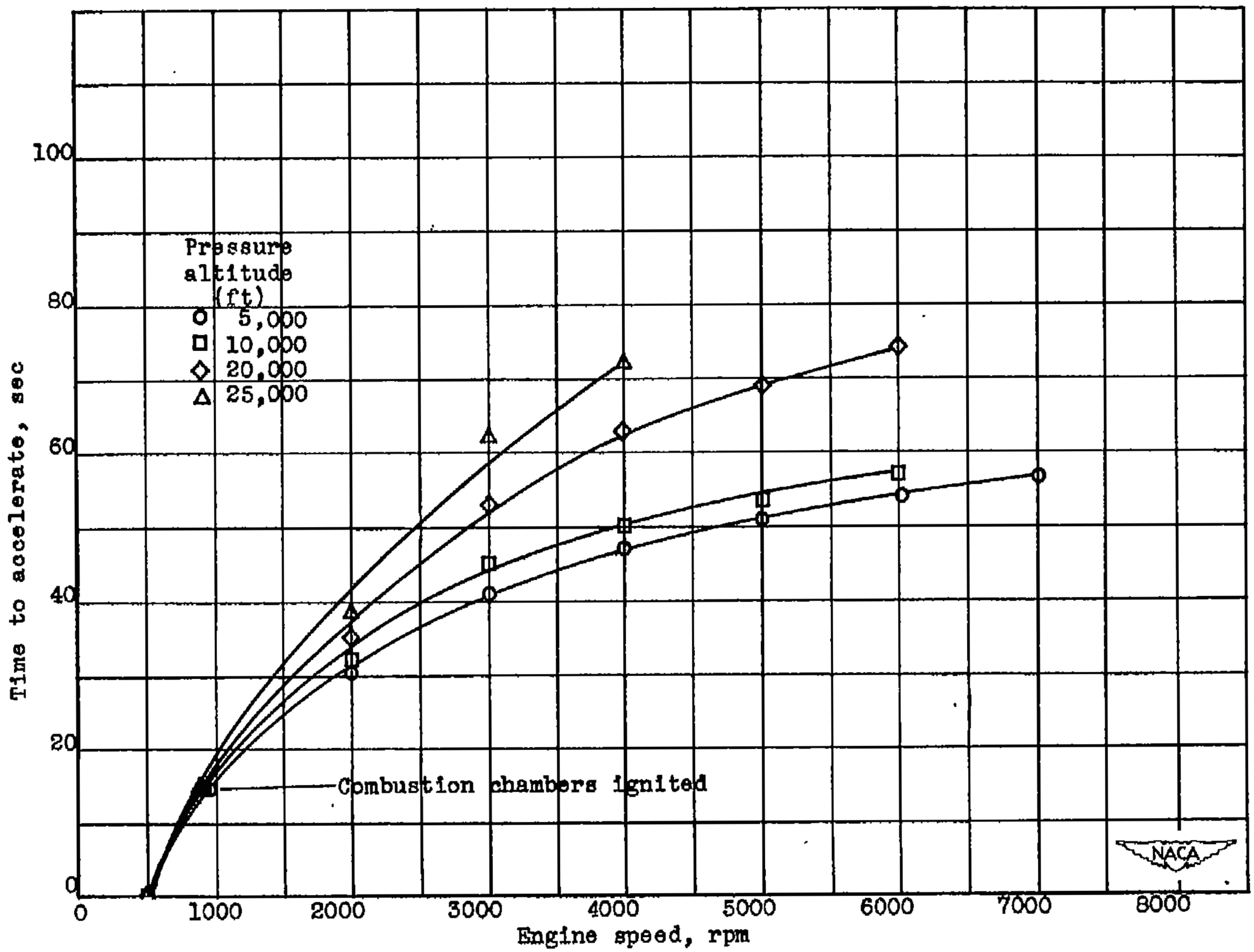

Figure 9.- Effect of pressure altitude on time required to start and accelerate with low-flow compressor, configurations 1 and 5.

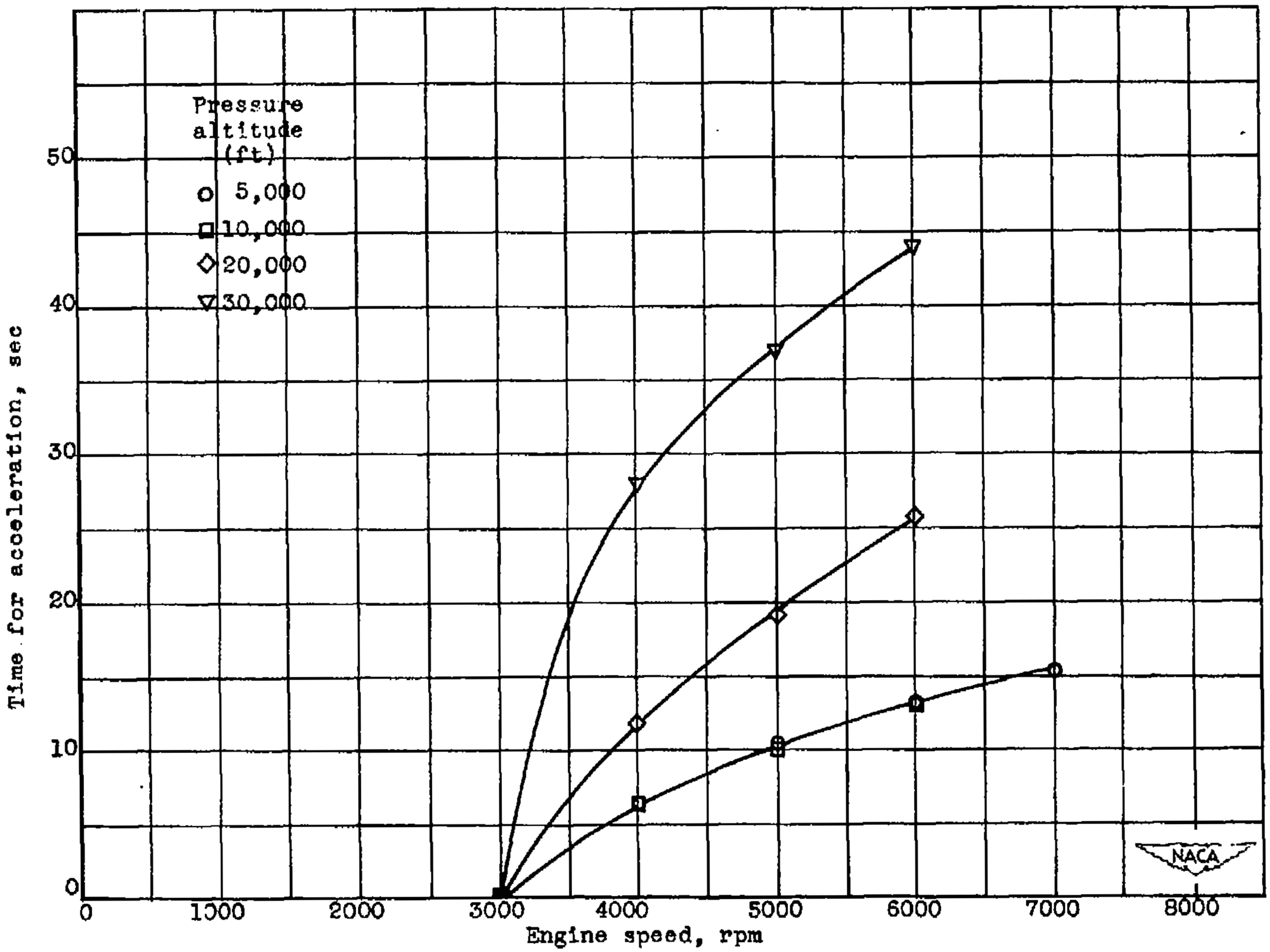

Figure 10.- Effect of pressure altitude on time required to accelerate from an idling speed of 3000 rpm with low-flow compressor, configurations 1 and 5.

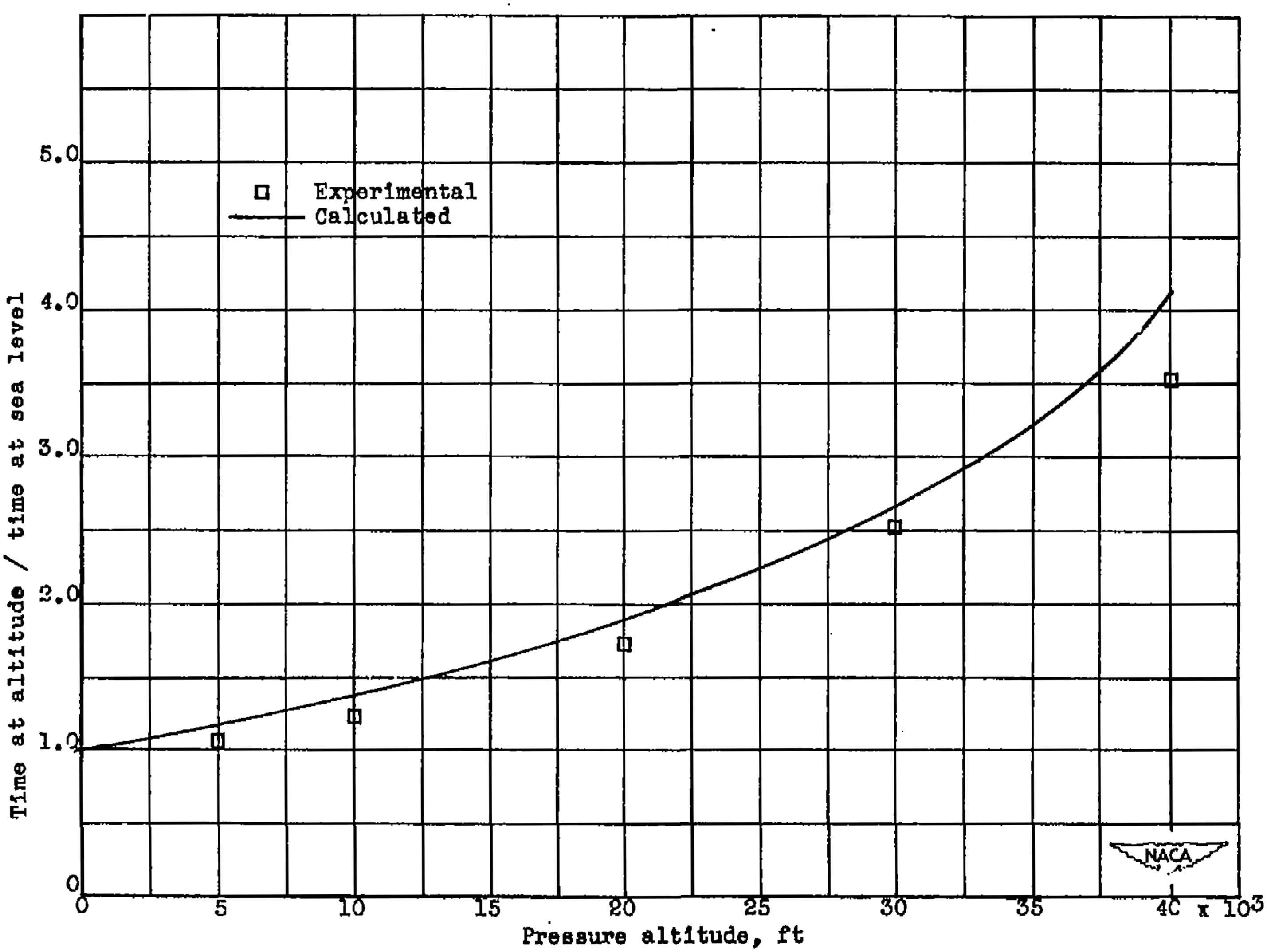

Figure 11.- Experimental and calculated data showing effect of altitude on the ratio of time required to accelerate at altitude to time required to accelerate at sea level with configurations 1 and 5.

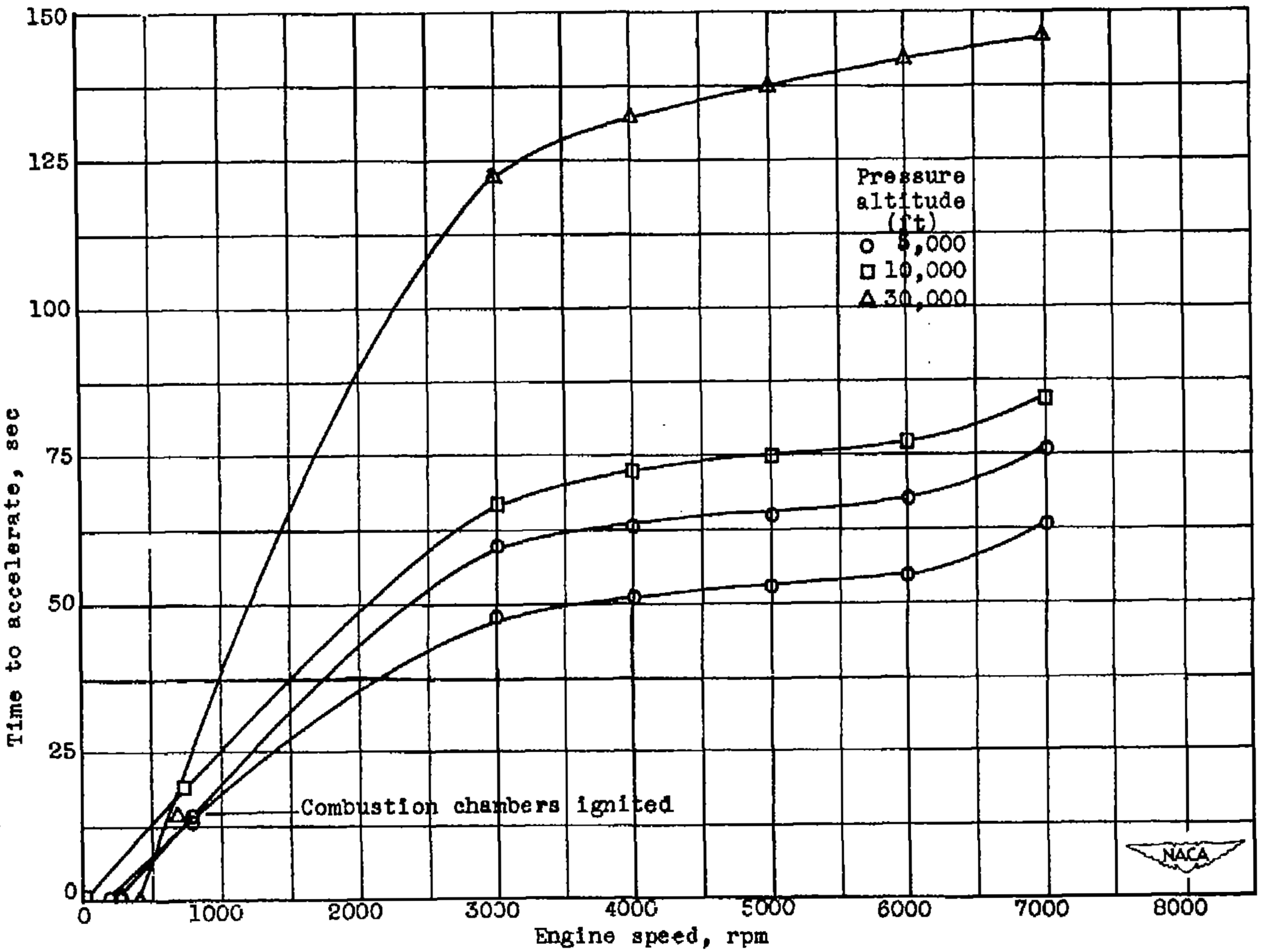

Figure 12.- Effect of pressure altitude on the time required to start and accelerate with high-flow compressor, configuration 13.

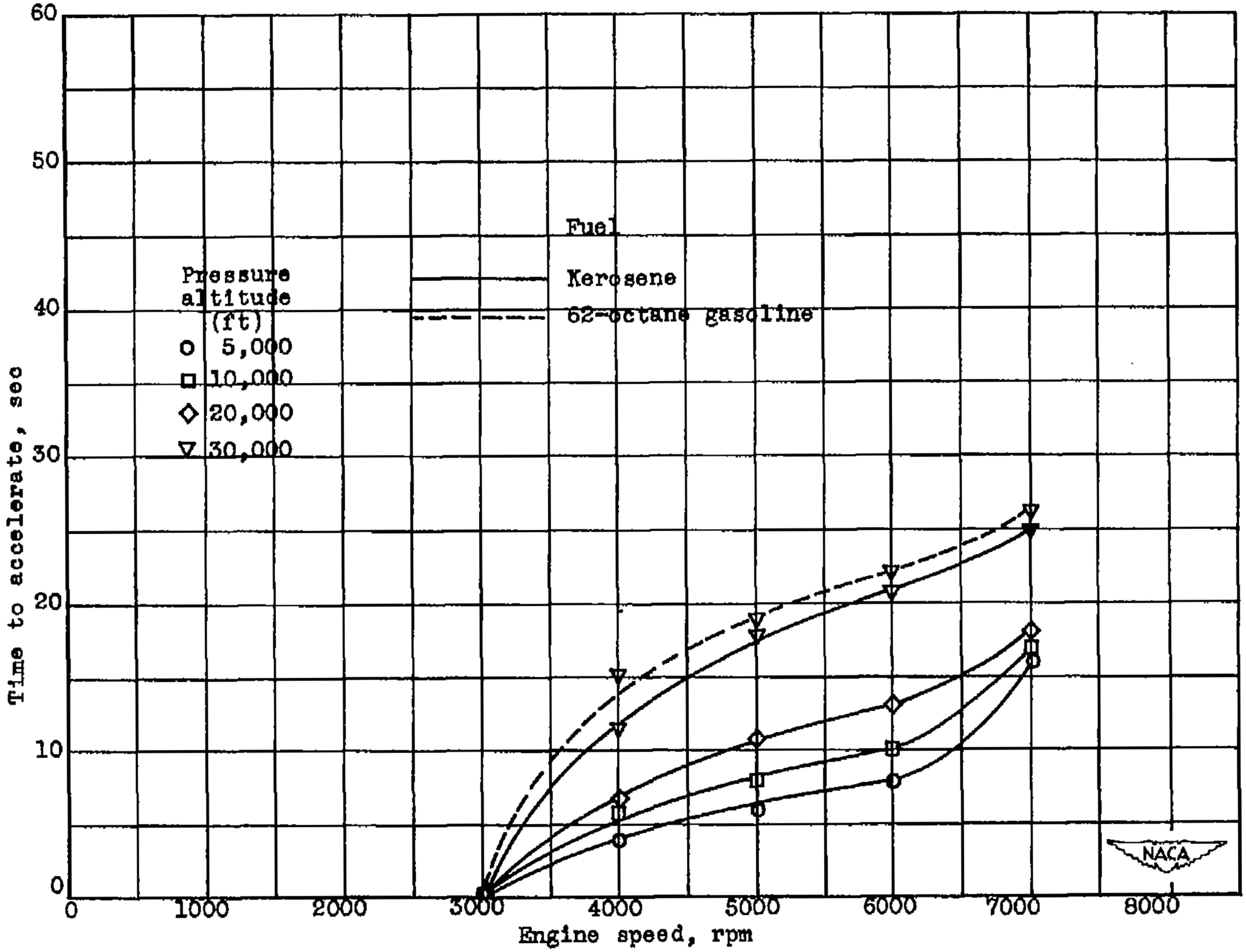

Figure 13.- Effect of pressure altitude on the time required to accelerate from an idling speed of 3000 rpm with high-flow compressor, configuration 13.

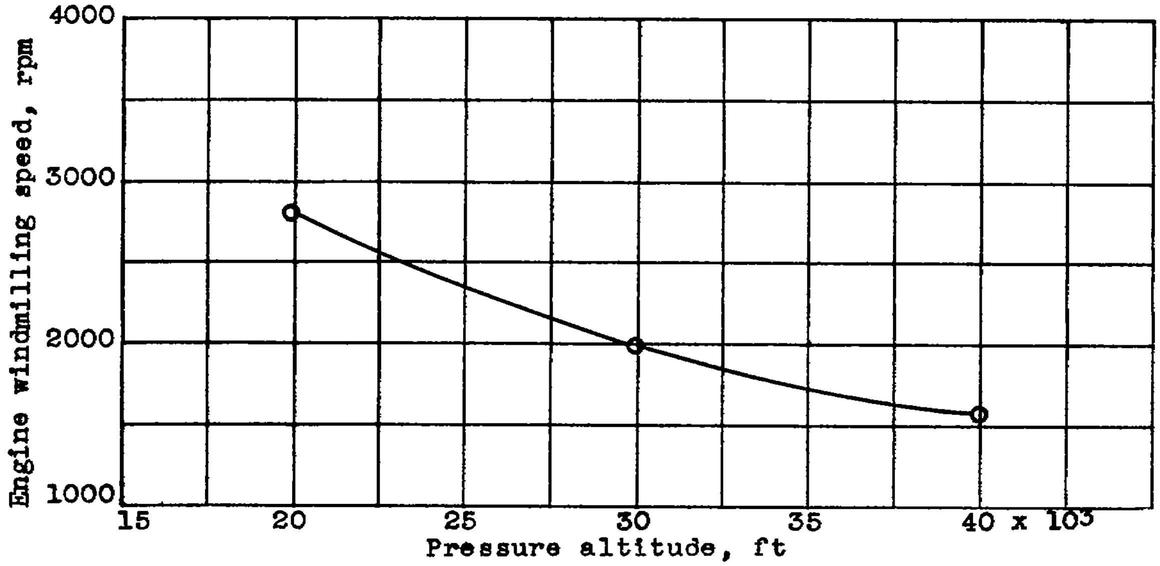

Figure 14. - Variation with altitude of maximum engine windmilling speed at which engine could be started.

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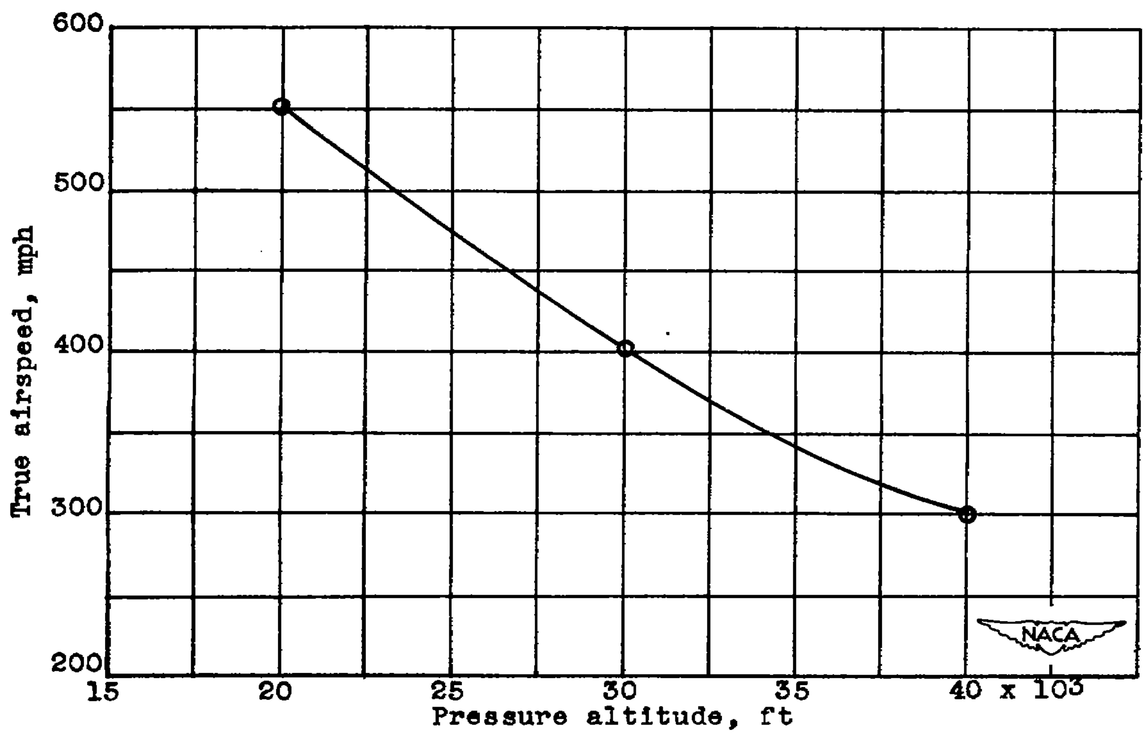

Figure 15. - Variation with altitude of maximum true airspeed at which engine could be started.

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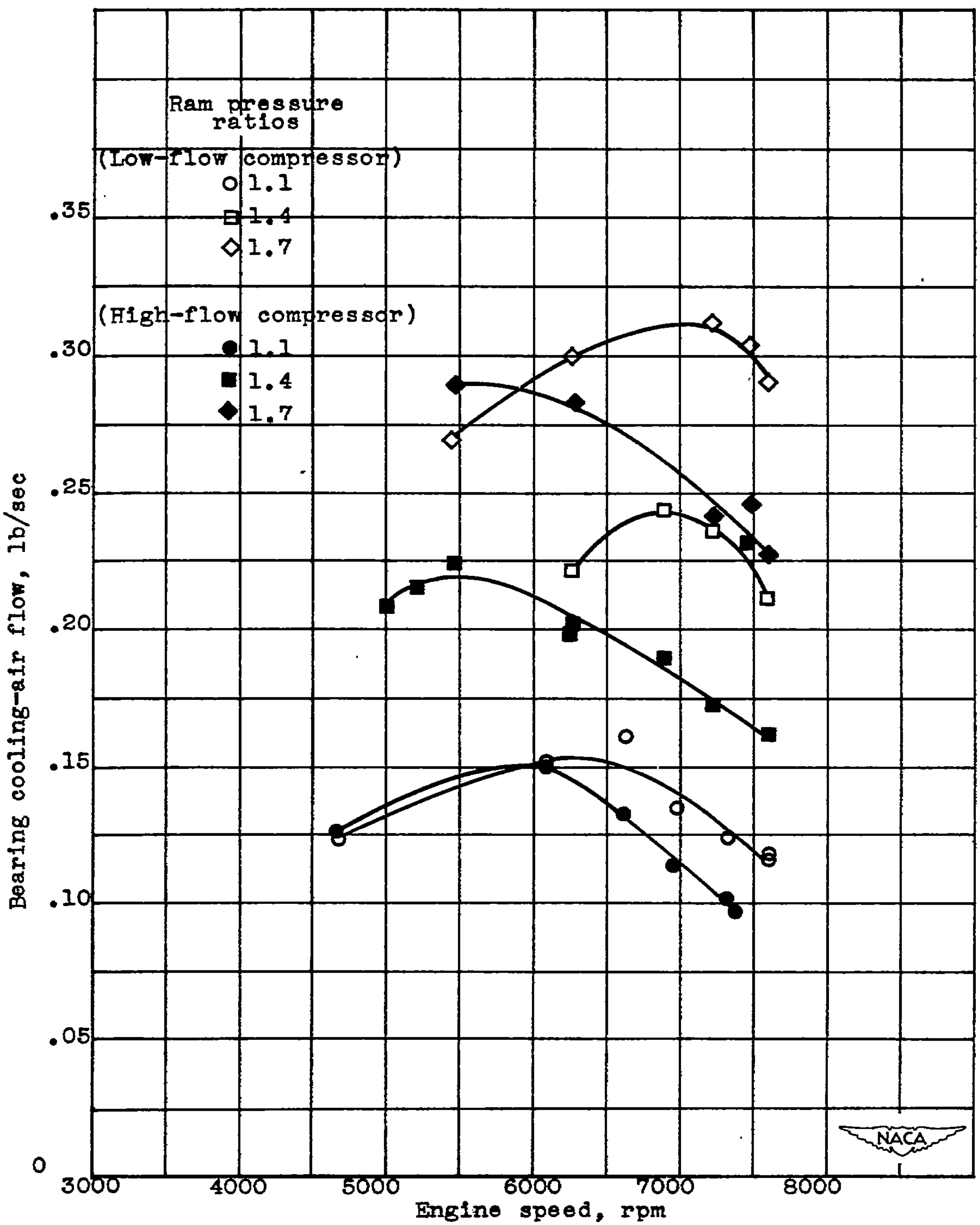

Figure 16.- Comparison of bearing cooling-air flow with low-flow and high-flow compressors at a pressure altitude of 30,000 feet.

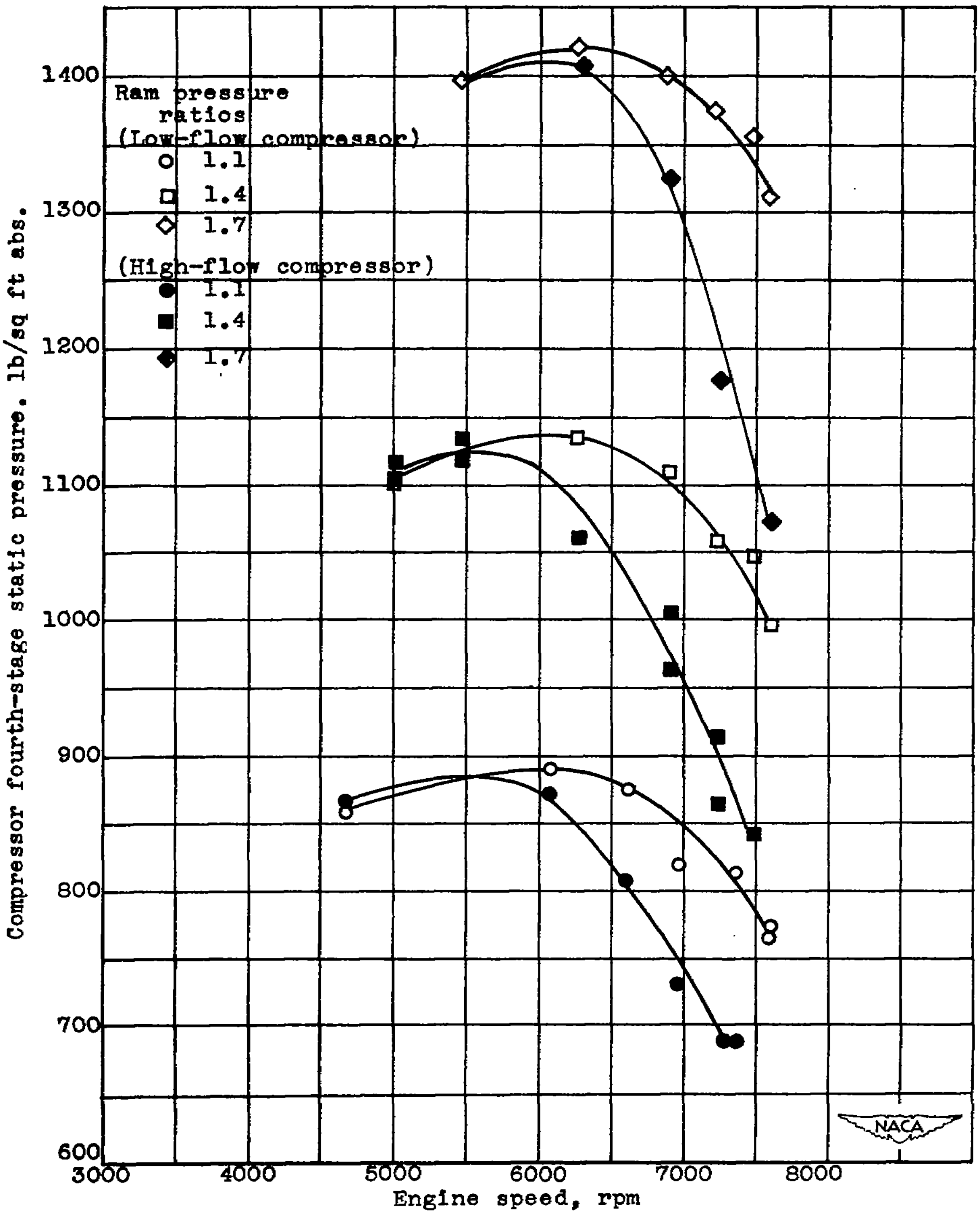

Figure 17.- Comparison of compressor fourth-stage static pressure with low-flow and high-flow compressors at a pressure altitude of 30,000 feet.

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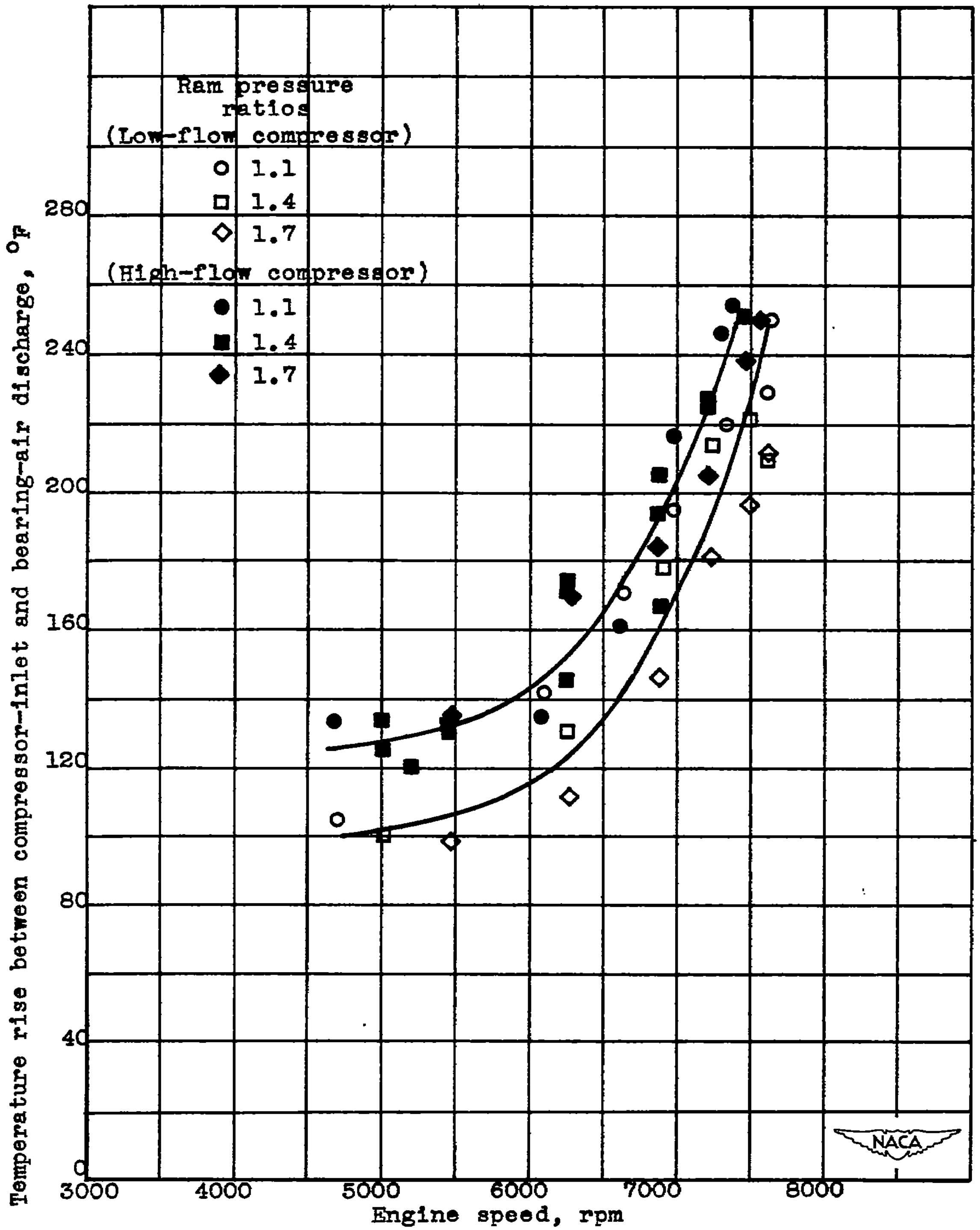

Figure 18.- Comparison of temperature rise between the compressor inlet and bearing-air discharge with low-flow and high-flow compressors at a pressure altitude of 30,000 feet.

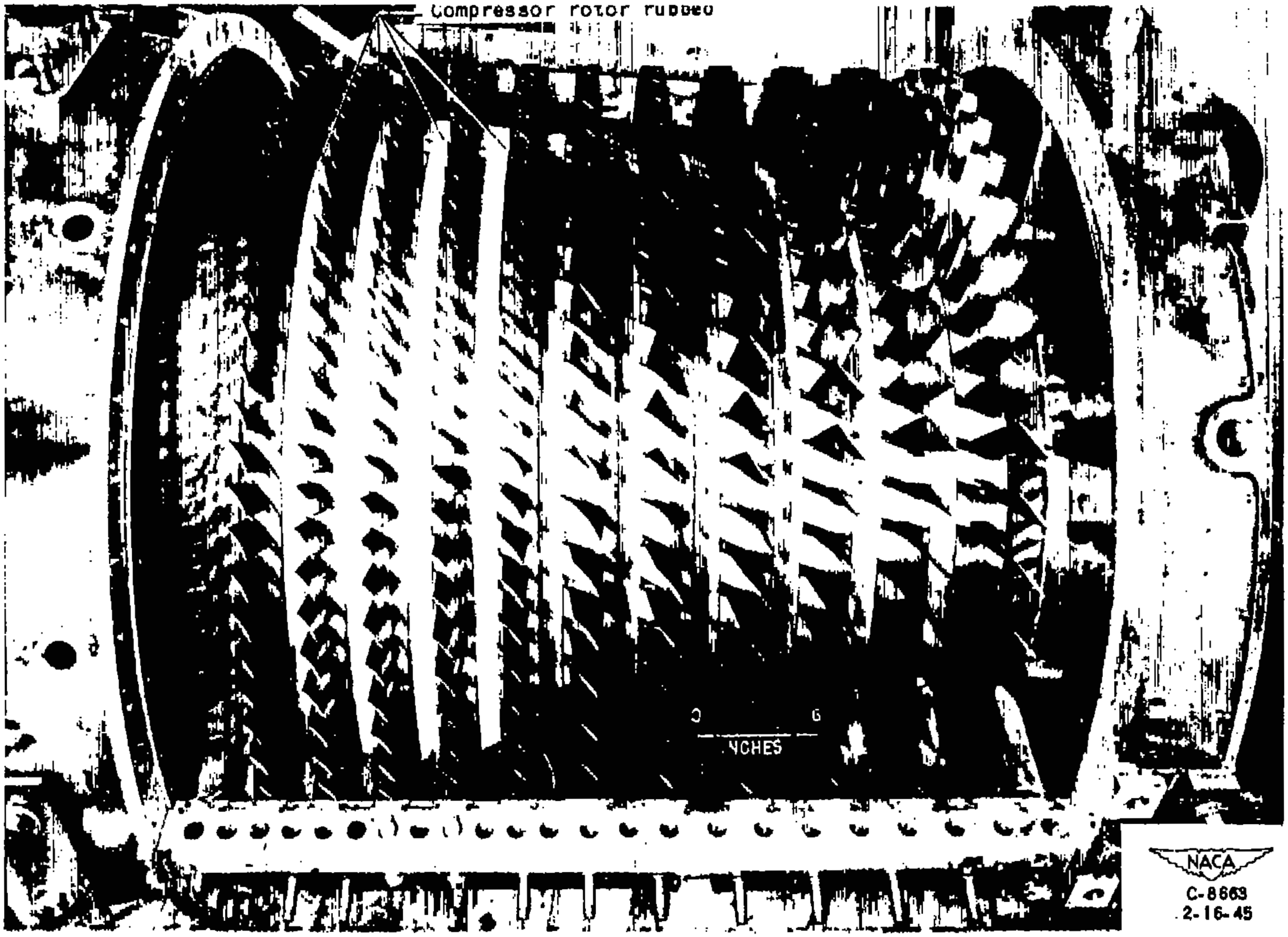

Figure 19. - View of the compressor rotor after the mid-bearing failure showing the area where the stator blades rubbed the rotor.

532

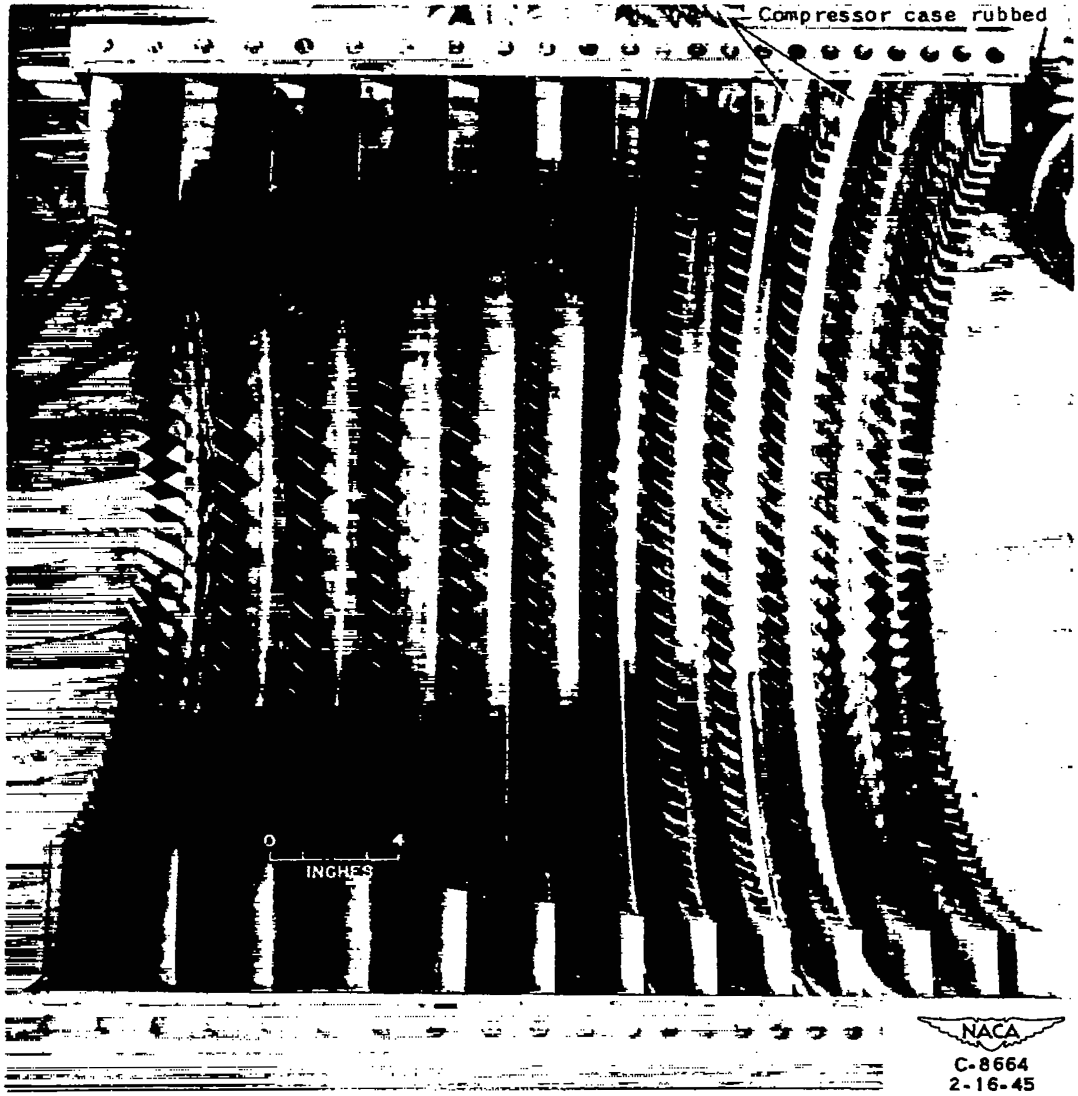

Figure 20. - View of the compressor case after the mid-bearing failure showing the areas where the rotor blades rubbed the casing.

532

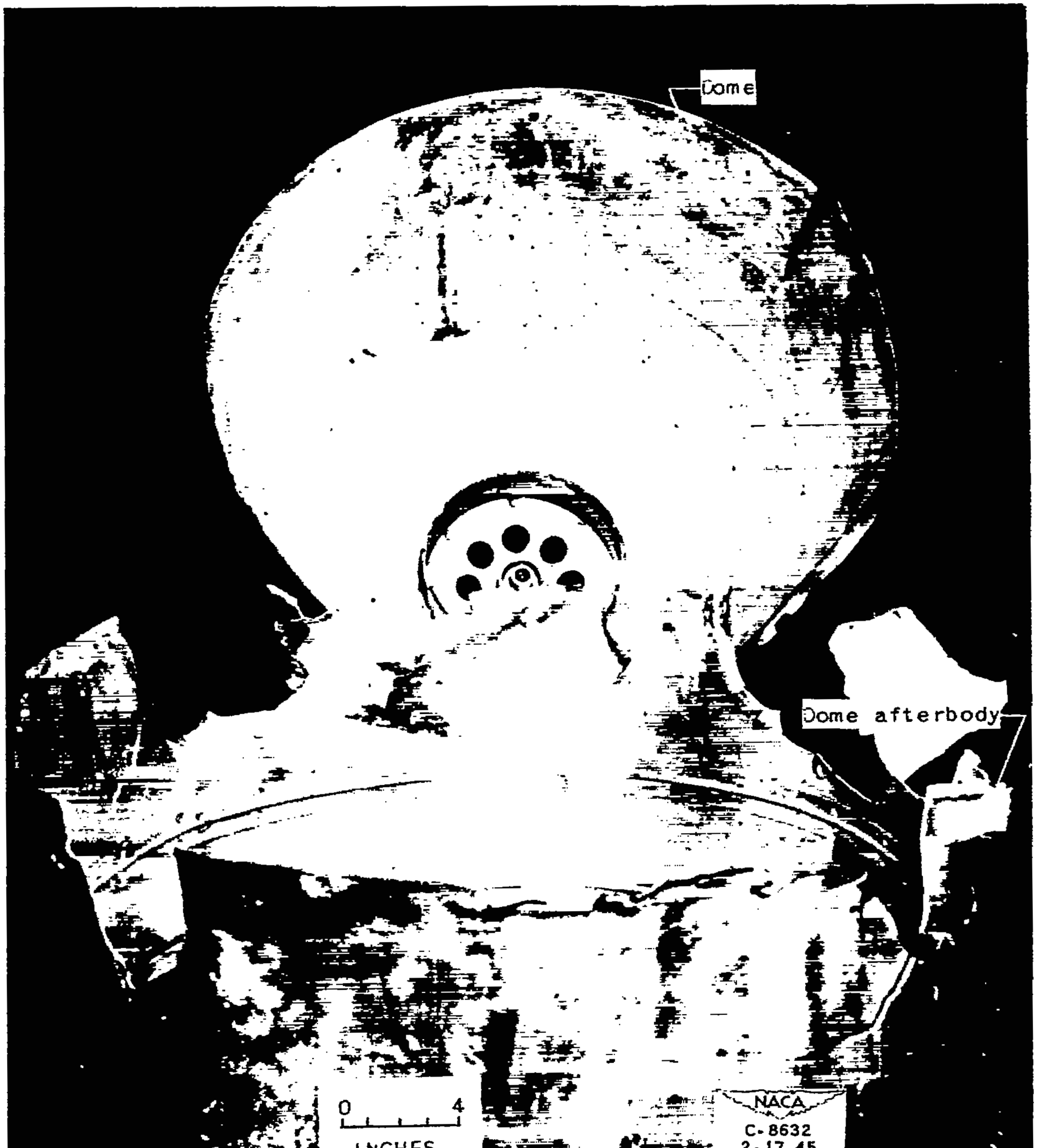

Figure 21. - View showing damage to accessory dome and afterbody.