RESEARCH MEMORANDUM

EFFECTS OF COMPRESSOR INTERSTAGE BLEED AND ADJUSTABLE INLET GUIDE VANES ON COMPRESSOR STALL CHARACTERISTICS OF A HIGH-PRESSURE-RATIO TURBOJET ENGINE AT ALTITUDE

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NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS

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SUMMARY

The stall characteristics of the J71-A2(X-29) turbojet engine were determined in an altitude test chamber at the Lewis laboratory. The engine is equipped with two-position inlet guide vanes and interstage bleeds. The stall limits of the normal high-speed configuration of bleeds closed, inlet guide vanes open, and the normal low-speed configuration of bleeds open, inlet guide vanes closed were obtained over a range of altitudes from 15,000 to 50,000 feet at 0.4 Mach number and over a range of corrected speeds from 2000 to 6000 rpm. In addition, the effects of opening the bleeds and closing the inlet guide vanes independently were determined.

When the normal high-speed configuration of bleeds closed, inlet guide vanes open was operated in the low-speed range, the stall-limit line intersected the operating line at 4067 and 4630 rpm. Operation with the high-speed configuration was impossible between these speeds. The normal low-speed configuration of bleeds open, inlet guide vanes closed provided the greatest improvement in stall margin in the critical speed range from 3250 to 5000 rpm. Opening the bleeds (with inlet guide vanes open) tended to eliminate the knee in the stall-limit line; while closing the inlet guide vanes (with bleeds closed) shifted the knee to a lower speed. Increasing altitude reduced the stall margins of each variable-geometry configuration investigated.

INTRODUCTION

The need for turbojet engines with high thrust, low specific fuel consumption, and low frontal area has led to the use of high-pressure-ratio, axial-flow compressors. These compressors have good performance near design speed; however, as speed is reduced the compressor stages become mismatched. The mismatching problem tends to become more serious as the number of compressor stages is increased to attain the desired high pressure ratio. As indicated in reference 1, mismatching causes the inlet stages to operate in a low-efficiency, high-angle-of-attack region at low speeds. This deterioration in the performance of the inlet stages may result in a knee in the compressor stall line such that when the compressor is used in an engine, serious part-speed acceleration problems may occur. The steady-state operating line may be very close to the stall-limit line in this low-speed range, making acceleration difficult and slow; or the steady-state line may actually intersect the stall line, making acceleration impossible. 3770

References 1 and 2 indicate several solutions to the part-speed problems through the use of variable-geometry components that do not compromise design-speed performance. These include adjustable compressor inlet guide vanes and stators, compressor interstage or exit bleed, adjustable turbine stators, and two-spool engine designs. The engine reported herein utilized two of these variable-geometry components, two-position inlet guide vanes and compressor interstage bleed. During high-speed operation, the bleeds are closed and inlet guide vanes open. During part- and low-speed operation, the bleeds are open and inlet guide vanes closed. The stall characteristics of these two compressor configurations were determined in an altitude test chamber at the NACA Lewis laboratory. In addition, the effects of opening the bleeds and closing the inlet guide vanes individually were determined.

Data were obtained to show the compressor pressure ratio and engine-fuel-flow stall margins of the design-speed configuration and the effects of inlet guide vanes and interstage bleed, individually and combined, on these margins. The data cover a range of engine speeds from 2000 to 6175 rpm (approximately 32 to 100 percent of rated speed) and a range of altitudes from 15,000 to 50,000 feet at 0.4 Mach number.

APPARATUS

Engine

The J71-A2(X-29) turbojet engine (fig. 1) has a bifurcated inlet, a 16-stage axial-flow compressor with eighth-stage bleeds and two-position inlet guide vanes, a cannular-type combustor with ten circular inner liners, a three-stage turbine, an afterburner, and an ejector-type exhaust nozzle with both primary and secondary nozzles of the continuously variable iris-type. The ejector was removed for this investigation. The engine has a static sea-level military thrust rating of 10,000 pounds (nonafterburning) at a rotor speed of 6175 rpm and an exhaust-gas temperature of 1240° F indicated by the manufacturer's thermocouples.

Compressor

The 16-stage axial-flow compressor has a constant tip diameter of $33\frac{1}{2}$ inches with an inlet hub-tip radius ratio of 0.55 and exit hub-tip radius ratio of 0.90. At static sea-level rated conditions (bleeds closed, inlet guide vanes open), the compressor air flow is approximately 165 pounds per second; the pressure ratio, $8\frac{1}{2}$; and the efficiency, 81 percent.

The 43 two-position inlet guide vanes rotate through an angle of 20°. The open position (reference angle, zero) corresponds to an angle of 14° with the engine axis (measured near the blade root); while the closed position (reference angle, 20°) corresponds to an angle of 34° with the engine axis. The interstage bleed system is divided into four units located symmetrically about the engine axis. Each unit consists of a groove in the compressor case over the eighth-stage rotor, a 3-inch-diameter port, a butterfly-type valve, and suitable ducting. Each groove covers about 80° of the circumference and gradually increases in depth from the ends to the middle. The port, located at the middle of the groove, is the flow restriction when the valves are open. The corrected air flow through the bleed system is about 8 pounds per second in the intermediate speed range from 2500 to 5000 rpm.

The manufacturer's control system changes the bleed and inlet-guide-vane positions simultaneously at an engine speed of 5300 rpm (86 percent speed). Above 5300 rpm, the bleeds are closed and guide vanes open; below 5300 rpm, the bleeds are open and guide vanes closed. For this investigation, the control system was modified so that bleed and guide-vane positions could be regulated independently. In order to evaluate the effects of bleeds and inlet guide vanes, individually and combined, the positions were fixed as indicated in the following table:

Configuration designation (a)	Bleed position	Inlet-guide-vane position
A (B-C, V-O)	Closed	Open, 0°
B (B-O, V-O)	Open	Open, 0°
C (B-C, V-C)	Closed	Closed, 20°
D (B-O, V-C)	Open	Closed, 20°

[a]B, bleeds; V, vanes; C, closed; O, open.

Configurations A (B-C, V-O) and D (B-O, V-C) correspond to the manufacturer's normal schedule for speeds above and below 5300 actual rpm, respectively.

Installation

The altitude test chamber in which the engine was installed is 10 feet in diameter and 60 feet long and is divided into two compartments. Air, at pressures and temperatures simulating the desired flight condition, was supplied to the front compartment and ducted into the engine through a bellmouth and a venturi used to measure the steady-state air flow. The rear compartment, which contained the engine and thrust measuring platform, was maintained at the desired ambient exhaust pressure. An automatic bypass valve in the bulkhead maintained constant compressor-inlet total pressure during transient operation. A bypass-type regulator (ref. 3) was used in place of the normal engine fuel control to provide the step increases in fuel flow (see Procedure). Figure 2 is a photograph of the engine installed in the test chamber.

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Instrumentation

Instrumentation for measuring steady-state pressures and temperature was installed at various stations throughout the engine, as shown in figure 1(a). The table presented in figure 1(a) indicates the number and types of steady-state measurements obtained at each station. The pressures were recorded on manometers and photographed; the temperatures were recorded on self-balancing potentiometers. The steady-state fuel flow was measured by calibrated rotameters.

Table I shows the instrumentation and parameters measured during transient operation. The low-speed oscillograph instrumentation for recording transient pressures and engine speed had a flat frequency response to about 15 cycles per second and responded to frequencies of about 75 cycles per second with some attenuation. The fuel-flow instrumentation had a greater time lag, which did not affect its usage for measuring fuel-step magnitudes. The exhaust-gas temperature was measured with an uncompensated thermocouple that had a time lag dependent upon operating conditions. The high-speed oscillograph instrumentation used only to determine rotating stall frequencies responded to frequencies of about 200 cycles per second.

Procedure

The inlet pressure and temperature and ambient exhaust pressure were set to simulate the desired flight condition. The steady-state data were recorded at a given engine speed. Then successive fuel steps of increasing magnitude (each initiated from the same steady-state point) were put into the engine until the compressor-stall

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pressure ratio and the fuel flow at stall were determined. The following table summarizes the conditions at which the data were obtained:

Altitude, ft	Mach number	Engine-inlet temperature, °F	Configuration	Engine speed range, $N/\sqrt{\theta_1}$, rpm	Exhaust-nozzle position
15,000	0.4	50	A (B-C, V-O)	[a]4500 - 5000	Open
15,000	.4		D (B-O, V-C)	[a]3750 - 4750	Open
35,000	0.4	-30	A (B-C, V-O)	4700 - 6000	Rated
35,000	.4		A (B-C, V-O)	2000 - 6000	Open
35,000	.4		B (B-O, V-O)	2000 - 6000	Open
35,000	.4		C (B-C, V-C)	2000 - 6000	Open
35,000	.4		D (B-O, V-C)	2000 - 6000	Open
50,000	0.4	-30	A (B-C, V-O)	5200 - 6000	Open
50,000	.4		D (B-O, V-C)	4700 - 6500	Open

[a]Upper limit due to fuel-system flow limit.

The transient pressure ratio and fuel flow were determined from the oscillograph traces taken during transient operation. A limited amount of high-speed oscillograph traces were obtained during steady-state and transient operation to indicate the existence of rotating stall.

The fuel used throughout this investigation was MIL-F-5624A, grade JP-4, with a lower heating value of 18,700 Btu per pound and a hydrogen-carbon ratio of 0.17. The symbols used in this report are given in the appendix.

RESULTS AND DISCUSSION

In order to facilitate an understanding of the data to be presented, the effects of fuel steps on engine operation will be discussed briefly, typical oscillograph traces will be presented, and several terms will be defined. Ideally, a step increase in fuel flow instantaneously raises the turbine-inlet temperature, causing the compressor operating point to move from the steady-state value toward stall along a constant-speed line. The combination of the new compressor operating point, new turbine operating point, and fixed exhaust-nozzle area results in an excess torque which increases the rotor speed. However, if the fuel step is too large, the compressor will be forced into stall. The term stall is used to indicate the breakdown of normal air flow through the compressor due to flow separation from the compressor blades. This stall, as will be shown by the data, resulted in either a single-zone rotating stall or engine surge.

Figure 2 is a typical oscillograph trace of a successful acceleration. Trace 5, although measured with a time lag, shows the magnitude of the fuel step; and trace 1 (fuel manifold pressure) shows that the fuel change occurred almost instantaneously. The compressor discharge pressure (trace 3) and exhaust-gas temperature (trace 4) increased, indicating the changing component operating points. Trace 6 shows the resultant speed increase.

When, at high speeds, fuel steps large enough to cause compressor stall were put into the engine, the compressor stall caused engine surge and combustor blow-out (hereinafter called surge blow-out). Typical oscillograph traces showing a surge blow-out are presented in figure 3. When the fuel step was initiated (fig. 3(a)) the compressor-discharge pressure, exhaust-gas temperature and engine speed began to increase as in figure 2; however, the compressor-discharge pressure was forced too high and surge blow-out occurred. The surge is indicated by the large fluctuations in inlet pressure, and the ensuing blow-out by the drop in compressor-discharge pressure, exhaust-gas temperature, and engine speed. The total and static pressures through the compressor were recorded on the high-speed oscillograph traces in figure 3(b). (Note the difference in chart speeds between figs. 3(a) and (b).) These traces show random fluctuations at steady-state operation, the pressure increase during the fuel step, and pressure drop after surge and blow-out.

At low speeds, compressor stall resulted in a severe single-zone rotating stall. Figure 4 presents typical oscillograph traces of this stall. Here also the speed began to increase following a fuel step, until the single-zone rotating stall was encountered (fig. 4(a)). The single-zone rotating stall is indicated by a reduction in compressor-discharge pressure, the high frequency fluctuations in compressor-inlet and discharge pressures, an increase in exhaust-gas temperature, and a very slight decrease in engine speed. Reducing the fuel flow to the steady-state value did not eliminate the rotating stall. The duration of the high-speed oscillograph trace (fig. 4(b)) is indicated on figure 4(a). The high-speed traces clearly show the frequency of the pressure variations of the single-zone rotating stall. (These traces also show a four-zone rotating stall, which is the type of rotating stall most often encountered along the steady-state operating line and will be discussed later.) Recovery from the single-zone rotating stall was erratic. One or more of the following procedures was necessary: reducing fuel flow to the steady-state value or lower, opening the bleeds, closing the inlet guide vanes, or in extreme cases even shutting off the fuel flow and relighting the engine.

Compressor Performance at Steady State and Stall

During normal engine operation, the manufacturer's control system changes the bleed and guide-vane positions simultaneously at an engine

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speed of 5300 rpm. The bleeds are closed and guide vanes open above 5300 rpm, while below 5300 rpm, the bleeds are open and guide vanes closed. Thus as the compressor-inlet total temperature varies with altitude and flight Mach number, the corrected speed for the change-over will vary. For example, increasing flight Mach number from 0.8 to 1.5 in the tropopause will increase the inlet total temperature from 443° to 570° R and result in a reduction in the change-over corrected speed from 5737 to 5057 rpm (93 to 83 percent of rated).

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The data to be presented showing the effects of the variable-compressor geometry were obtained at a simulated flight condition of 35,000 feet altitude, 0.4 Mach number, and -30° F inlet total temperature. All comparisons will be made at these conditions unless otherwise specified. Also for convenience of discussion, the data, which were obtained over a corrected speed range from 2000 to 6000 rpm, were arbitrarily divided into high- and low-speed ranges above and below 5000 rpm, respectively. This arbitrary division is used throughout the remainder of the report.

Design-speed configuration. - The compressor pressure ratio at steady state and stall for the design-speed configuration A (B-C, V-O) is presented in figure 5 as a function of corrected engine speed for both rated and open exhaust-nozzle areas. The stall points are shown at the speed at which stall occurred, as determined from the oscillograph traces. In the high-speed region (above 5000 rpm) steady-state operation was stall free with either open or rated exhaust-nozzle area, and the margin between the stall limit and operating line increased rapidly as speed was increased. In addition, the compressor-stall pressure ratio was independent of the exhaust-nozzle size, as would be expected, and every time stall was encountered, surge blow-out occurred. Stall data at corrected speeds higher than 6200 rpm could not be obtained because of the danger of overspeeding the engine, but steady-state data were obtained with rated exhaust-nozzle area up to a corrected speed of 6750 rpm with no compressor stall being encountered.

In the low-speed region (below 5000 rpm) the knee in the compressor-stall limit line intersected the open exhaust-nozzle steady-state operating line at 4075 and 4630 rpm. When the stall limit was approached by decreasing engine speed, surge blow-out occurred at 4630 rpm. When the stall limit was approached by increasing engine speed, the severe single-zone rotating stall encountered at 4075 rpm and the resultant excessive exhaust-gas temperature limited operation. At speeds below 4075 rpm, steady-state operation was possible, but the margin between the steady-state and stall limit was small. Steady-state four-zone rotating stall existed between 3430 and 3825 rpm; below these speeds, pressure fluctuations were observed in the compressor but no definite stall pattern existed. Fuel steps in this low-speed region caused single-zone rotating stall either at the stall pressure ratio or after acceleration to 4075 rpm.

The shape and relation of the stall line to the steady-state operating line is indicative of the stage mismatching at low speeds and good matching at high speeds, as discussed in reference 1. With this compressor configuration, engine acceleration from low to high speeds was impossible because of the intersection of the stall and steady-state lines.

Effect of interstage bleed. - Compressor interstage bleed, as was previously mentioned, may be used to improve part-speed performance (ref. 2). The selection of the bleed location and amount of air bleed is a complex problem and depends upon the specific compressor characteristics. Generally, in the low-speed range, the inlet stages stall because the compressor-exit stages are choked. Interstage bleed increases the weight flow through the inlet stages, which reduces the angles of attack of the blades in these inlet stages and improves the performance. In the high-speed region where the inlet stages are choked, interstage bleed can only cause a reduction in performance.

The steady-state (open exhaust nozzle) and stall pressure ratios for configuration B (B-O, V-O) are shown in figure 6 along with the steady-state and stall lines for configuration A (B-C, V-O) from figure 6 so that the effects of bleed may be noted. In the high-speed region, steady-state operation was stall free, and surge blow-out was encountered at the stall pressure ratio.

In the low-speed region (below 5000 rpm) continuous operation along the steady-state operating line was possible. However, four-zone rotating stall existed between 2725 and 3415 rpm along the steady-state operating line. At the stall pressure ratio in this low-speed region, single-zone rotating stall was encountered. The effect of interstage bleed on the margin between steady-state operation and the stall limit was not appreciable except in the region of the knee in the stall line. The severity of the knee was reduced; that is, a substantial margin between the steady-state and stall lines resulted. At high speeds, both steady-state and stall pressure ratios were reduced; while at low speeds, they were increased slightly.

Effect of inlet guide vanes. - The use of adjustable inlet guide vanes, as mentioned in the INTRODUCTION, is another method of improving compressor part-speed performance (ref. 1). In the low-speed region where the inlet stages are normally stalled, closing the inlet guide vanes increases the turning of the air so that the angle of attack on the first rotor is reduced. This tends to unstall the blades and improve the performance of the inlet stage. Ordinarily guide-vane adjustment alters the operating point of the first stage but has little effect on the remaining stages. Reference 1 indicates that closing inlet guide vanes tends to reduce the speed at which the knee in the stall line occurs but not necessarily its severity. In the high-speed region,

region, closing the inlet guide vanes again lowers the angle of attack of the inlet stage, which is now operating near or at its design point. This results in a loss of performance in most cases.

The steady-state (open exhaust nozzle) and stall compressor pressure ratio for configuration C (B-C, V-C) are shown in figure 7. The steady-state and stall lines for the design-speed configuration A are included for comparison. In the high-speed region, steady-state operation was stall free, and surge blow-out occurred at the stall pressure ratio. Both the steady-state and stall pressure ratios were reduced as anticipated. In the low-speed region (below 5000 rpm) continuous operation along the steady-state line was possible although operation was marginal at 3900 rpm. Closing the inlet guide vanes shifted the knee in the stall line to a lower speed, but did not change its severity appreciably. Four-zone steady-state rotating stall was encountered between 3475 and 3875 rpm, about the same speeds as with vanes open. In this low-speed range, single-zone rotating stall again occurred at the stall pressure ratio.

<u>Combined effects</u>. - The combined effects of opening the bleeds and closing the inlet guide vanes, configuration D (B-O, V-C), on the steady-state (open exhaust nozzle) and stall pressure ratios are presented in figure 8. For comparison, the steady-state and stall lines for configuration A (B-C, V-O) are included. In the high-speed region (above 5000 rpm) steady-state operation was stall free, and at the stall pressure ratio, surge blow-out was still encountered. The stall and steady-state pressure ratios for configuration D were reduced more at high engine speeds than by either opening the bleeds or closing the inlet guide vanes individually.

In the low-speed region, continuous operation along the steady-state line was possible and no steady-state rotating stall was observed. At the stall pressure ratio, single-zone rotating stall occurred up to a speed of 3500 rpm, and surge blow-out occurred at higher speeds. The combined effects of the bleeds and inlet guide vanes essentially eliminated the knee in the stall line. A substantial margin between the steady-state operating line and the stall line resulted at corrected engine speeds above 3000 rpm. As was mentioned previously, this configuration is scheduled in the manufacturer's control system at actual speeds below 5300 rpm. Thus at the specified flight condition (inlet temperature, -30° F) the engine would operate with bleeds open and inlet guide vanes closed up to a corrected speed of 5825 rpm.

<u>Comparison of configurations</u>. - The effects of opening the bleeds and closing the inlet guide vanes, individually and combined, on the compressor steady-state and stall limit lines are compared in figure 9, which gives the variation of pressure-ratio acceleration margin with engine speed. The pressure-ratio acceleration margin is defined as the

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difference between the stall-limit pressure ratio and the steady-state pressure ratio divided by the steady-state pressure ratio. This margin is an approximate index of the acceleration potential of the engine. However, the margins obtained with different engine configurations are not always directly comparable because of changes in the steady-state operating lines. In the critical part-speed range between 3000 and 5000 rpm, opening the bleeds and closing the inlet guide vanes (combined effect-configuration D) gave the greatest increase in acceleration margin. At a corrected engine speed of 4500 rpm, this margin corresponded to an acceleration rate of about 500 rpm per second at an altitude of 35,000 feet and flight Mach number of 0.4. Above 5000 rpm, closing the inlet guide vanes with bleeds closed (configuration C) gave the greatest acceleration margin. Below 3000 rpm, all configurations had about the same margin.

Additional insight into the effects of the bleeds and inlet guide vanes may be gained by examining their effects on the steady-state (open exhaust nozzle) compressor efficiency and air flow as shown in figure 10. In the high-speed region where the inlet stages choke, opening the bleeds had little effect on inlet air flow, and the compressor efficiency was lowered. (The method used to calculate compressor efficiency is defined in the appendix.) In the low-speed region where the exit stages choke and the inlet stages tend to stall, opening the bleeds increased the inlet air flow thus rematching the inlet and exit stages, causing the compressor efficiency to increase. (The amount of bleed air at different engine speeds is shown in fig. 10.) Closing the inlet guide vanes in the high-speed region reduced the inlet air flow because the inlet flow area was decreased and also reduced the compressor efficiency. In the low-speed region, closing the inlet guide vanes had little effect on the inlet air flow because the compressor exit stages were choked. However, the compressor efficiency was increased, indicating the favorable rematching of the compressor stages.

As was previously mentioned, the manufacturer schedules the control to operate on an actual engine-speed basis (5300 rpm) and not a corrected engine-speed basis. Thus, at an inlet temperature -30° F, the bleeds close and inlet guide vanes open at a corrected engine speed of 5825 rpm. In contrast to the manner that the control operates, the steady-state and stall lines of a compressor are primarily a function of the corrected engine speed (figs. 5 to 9). Therefore, once the critical region in the knee of the stall line has been passed by and reasonable acceleration rates obtained, it would be advantageous to actuate the variable-geometry configurations to their normal high-speed configuration. This manner of operation would be most satisfactory if done on a corrected speed basis because it would allow operation at the peak component and over-all performance level possible at any given corrected speed.

Effect of altitude. - The effects of altitude on the steady-state and stall limit pressure ratios of two configurations, A (B-C, V-O) and D (B-O, V-C), were determined and are presented in figure 11. Increasing altitude from 15,000 to 50,000 feet had little effect on the steady-state pressure ratio for configuration A (fig. 11(a)) but the stall-limit pressure ratio was reduced. For configuration D (fig. 11(b)) increasing altitude had little effect on the stall-limit pressure ratio, but the steady-state pressure ratio was increased. The net result for each configuration was a reduction of stall margin with increasing altitude as shown in figure 12. The maximum speed for which stall-limit data were obtained at 15,000 feet was low because of the flow limit of the fuel system.

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Fuel Flow at Steady State and Stall

In order for the engine reported herein to accomplish a successful acceleration, the scheduled fuel flow must not cause compressor stall that would result in a single-zone rotating stall or surge blow-out. Data are therefore presented to show the limiting fuel flow over a range of engine speeds that would just avoid this compressor stall.

Comparison of configurations. - The fuel flow at steady state and at stall for the four compressor configurations (A, B, C, and D) is presented in figure 13. The data were obtained by making step increases in fuel flow from a given steady-state operating point until the stall value was determined. In the region of the stall line, the solid symbols indicate the points for which stall occurred, while the open symbols indicate the no-stall points. All transient fuel-flow values are shown at the speed at which the fuel step was initiated.

The trends of the fuel-flow curves are similar to those of the respective compressor-pressure-ratio curves of figures 5 to 8. A direct comparison of the configurations is made in figure 14, which shows the variations in the fuel-flow stall margins with engine speed. The fuel-flow stall margin is defined as the difference between the stall-limit fuel flow and the steady-state fuel flow divided by the steady-state fuel flow. The fuel-flow stall margins clearly show the adverse effects of the knees in the stall-limit lines and the improvements effected by the variable-geometry components.

Effects of altitude. - The effects of altitude on the steady-state and stall-limit fuel flows of configurations A and D are presented in figure 15. Increasing altitude from 15,000 to 50,000 feet affected the fuel flows in a similar manner as the pressure ratios of figure 11 causing a reduction in the fuel flow stall margins as shown in figure 16.

CONCLUDING REMARKS

The effects of the compressor interstage bleed and two-position inlet guide vanes, individually and combined, were investigated to determine their effectiveness in alleviating the part-speed stall margin of the J71-A2(X-29) turbojet engine.

Opening the bleeds with guide vanes open tended to eliminate the severe knee in the stall line and made steady-state operation (with open exhaust nozzle) possible through the entire speed range. In the low-speed range, opening the bleeds increased the compressor efficiency and raised both the steady-state operating line and stall line but in such a manner so as to improve the acceleration margin. Closing the inlet guide vanes with bleeds closed caused the knee in the stall line to shift to a lower speed although the severity of the knee was not changed greatly. Steady-state operation with open exhaust nozzle was marginal between 3800 and 4000 rpm. In the low-speed range below the knee in the stall line, closing the inlet guide vanes increased the compressor efficiency and slightly raised both the steady-state operating line and stall line but did not improve the acceleration margin to any degree. The combined effect of opening the bleeds and closing the inlet guide vanes (the manufacturer's normal low-speed configuration) provided the largest improvements in the stall margins in the critical speed range between 3250 and 5000 rpm (53 to 81 percent of rated speed).

Increasing altitude slightly reduced both pressure ratio and fuel-flow stall margins of each variable-geometry configuration investigated.

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National Advisory Committee for Aeronautics
Cleveland, Ohio, August 1, 1955

APPENDIX - SYMBOLS

The following symbols are used in this report:

H stagnation enthalpy, Btu/lb

N rotative speed, rpm

P total pressure, lb/sq ft

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T total temperature, $^{\circ}R$

W_a air flow, lb/sec

W_f fuel flow, lb/hr

δ ratio of total pressure to NACA standard sea-level pressure, P/2116

η_c compressor efficiency

θ ratio of total temperature to NACA standard sea-level temperature, T/519

Subscripts:

b bleed (eighth stage)

Numbered subscripts refer to instrumentation stations within the engine (fig. 1).

Equation for obtaining compressor efficiency:

$$\eta_c = \frac{(W_{a,1} - W_{a,b})(H_{3,isentropic} - H_1)}{W_{a,1}(H_3 - H_1) - W_{a,b}(H_3 - H_b)}$$

(Eq. (A11) of ref. 2.)

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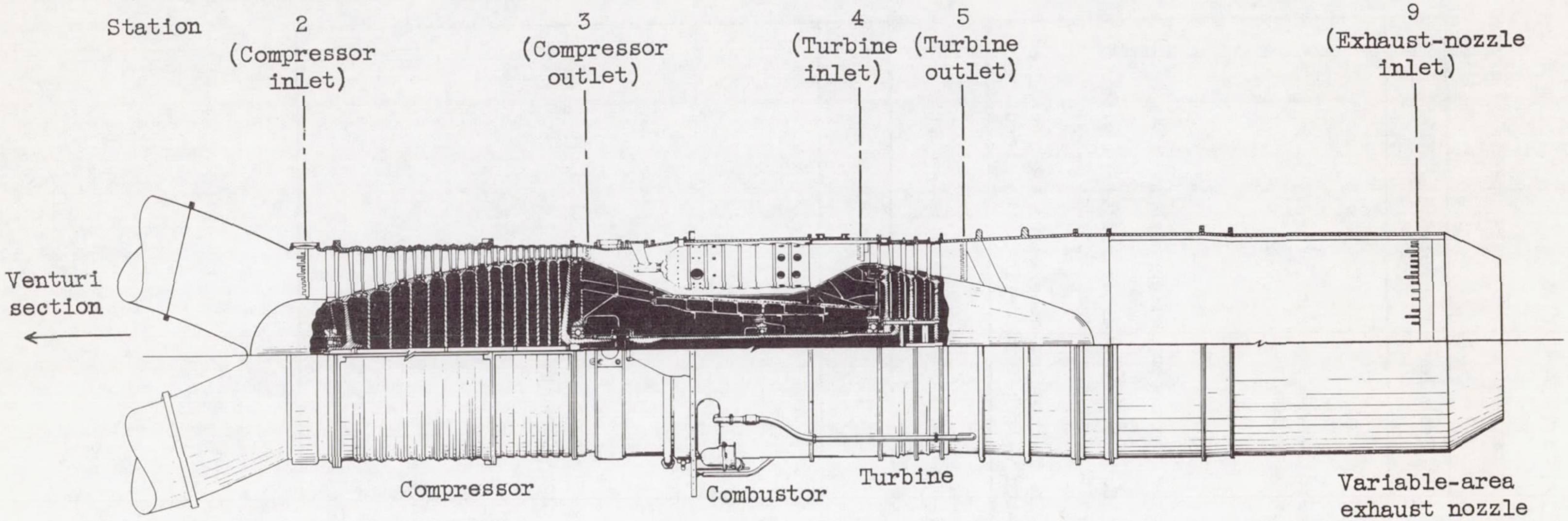
TABLE I. - TRANSIENT INSTRUMENTATION

(a) Six-channel oscillograph (low speed); maximum linear chart speed, 50 mm/sec.

Channel number	Parameter	Engine station	Transient instrumentation
1	Fuel manifold pressure	-	
2	Total pressure	2	Aneroid-type pressure sensor, with strain-gage element. (channels 1 to 3)
3	Total pressure	3	
4	Total temperature	5	Single thermocouple; uncompensated.
5	Fuel flow	-	a-c Output of flowmeter rectified with voltage proportional to fuel flow.
6	Engine speed	-	Engine tachometer-generator; a-c rectified with voltage proportional to speed.

(b) Eight-channel oscillograph (high speed); maximum linear chart speed, approx. 50 in/sec.

Channel number	Parameter	Engine station	Transient instrumentation
1	Total pressure	2	
2	Total pressure	2	
3	Total pressure	3rd stage	
4	Static pressure	3rd stage	
5	Static pressure	3rd stage	Aneroid-type pressure sensor, with strain-gage element. (channels 1 to 8)
6	Static pressure	3rd stage	
7	Static pressure	7th stage	
8	Static pressure	13th stage	



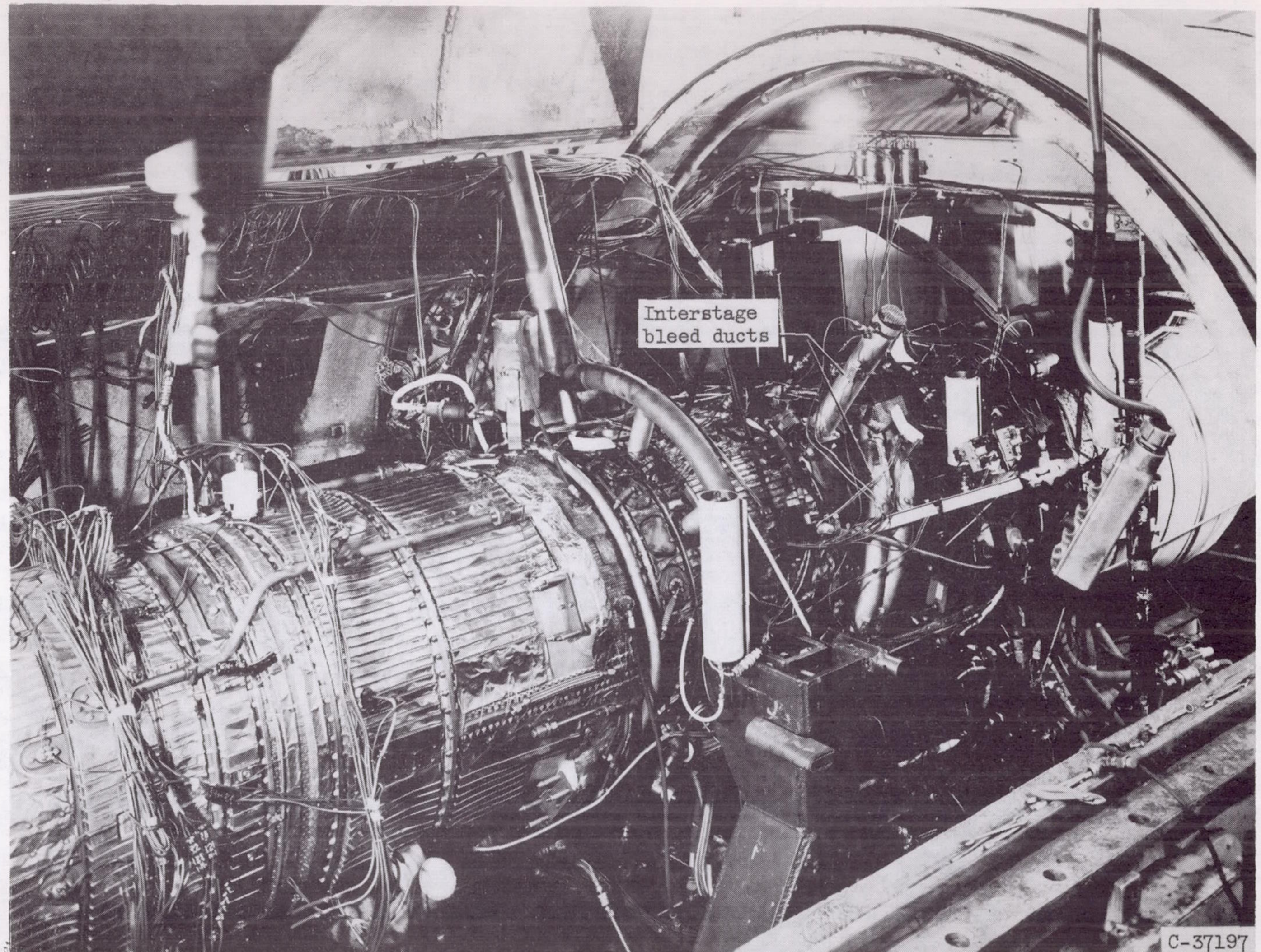
Station	Total-pressure taps	Static-pressure taps	Thermocouples
1	12	7	6
2	12	4	-
3	8	2	8
4	9	-	9
5	25	-	37[a]
9	14	-	14

[a]12 Engine manufacturer and 25 NACA thermocouples.

CD-4106

(a) Steady-state instrumentation stations.

Figure 1. - J71-A2(X-29) turbojet engine.



(b) Installed in altitude test chamber.

Figure 1. - Concluded. J71-A2(X-29) turbojet engine.

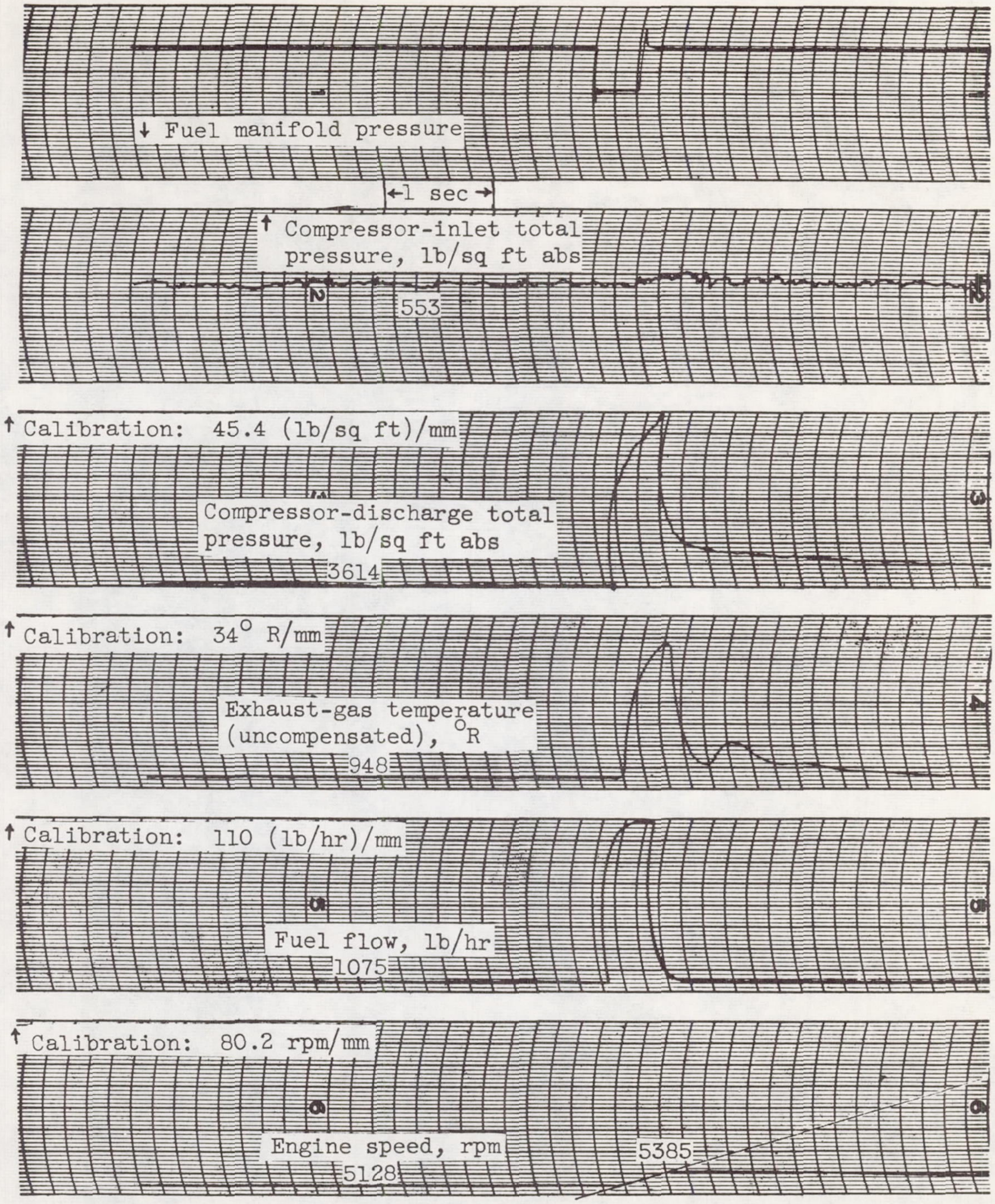
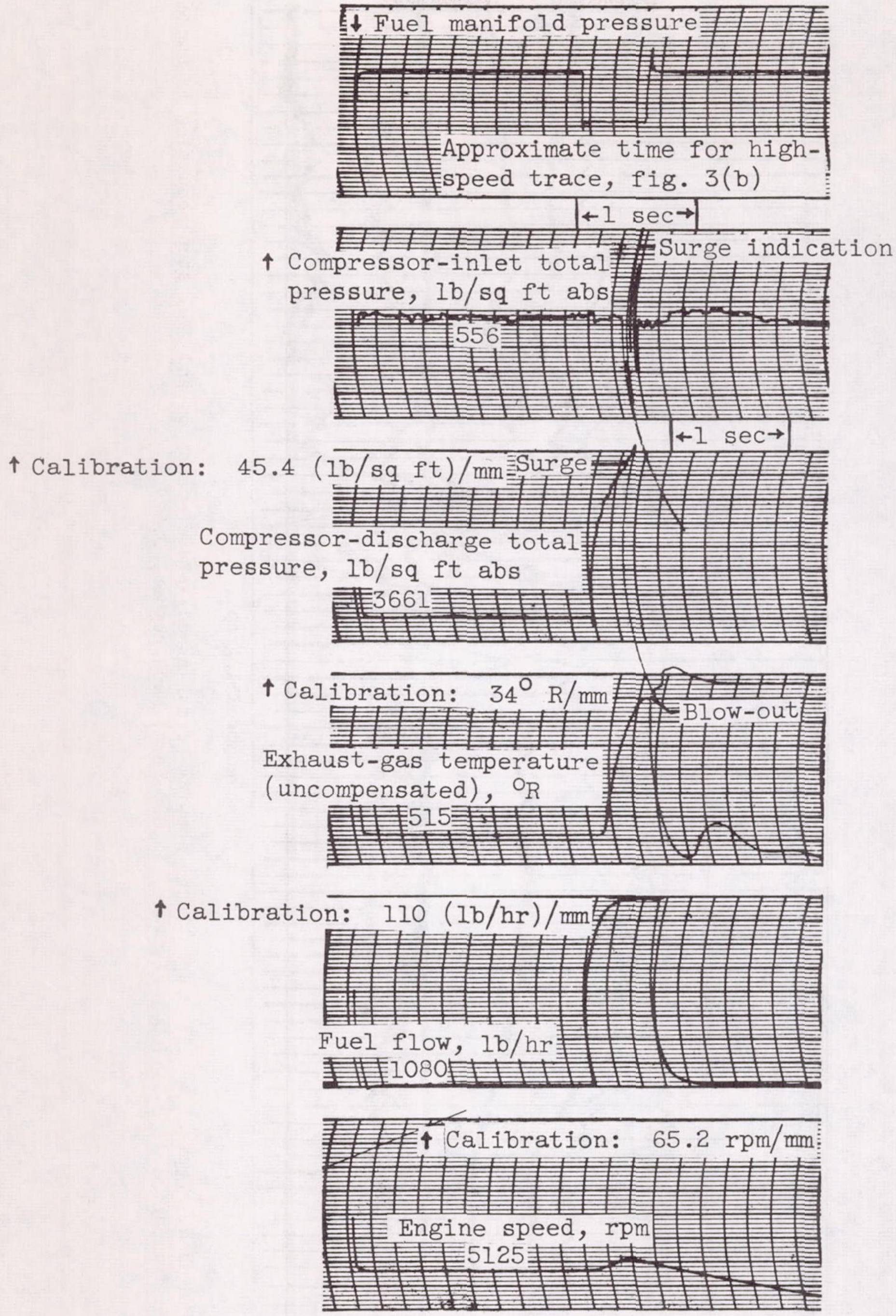
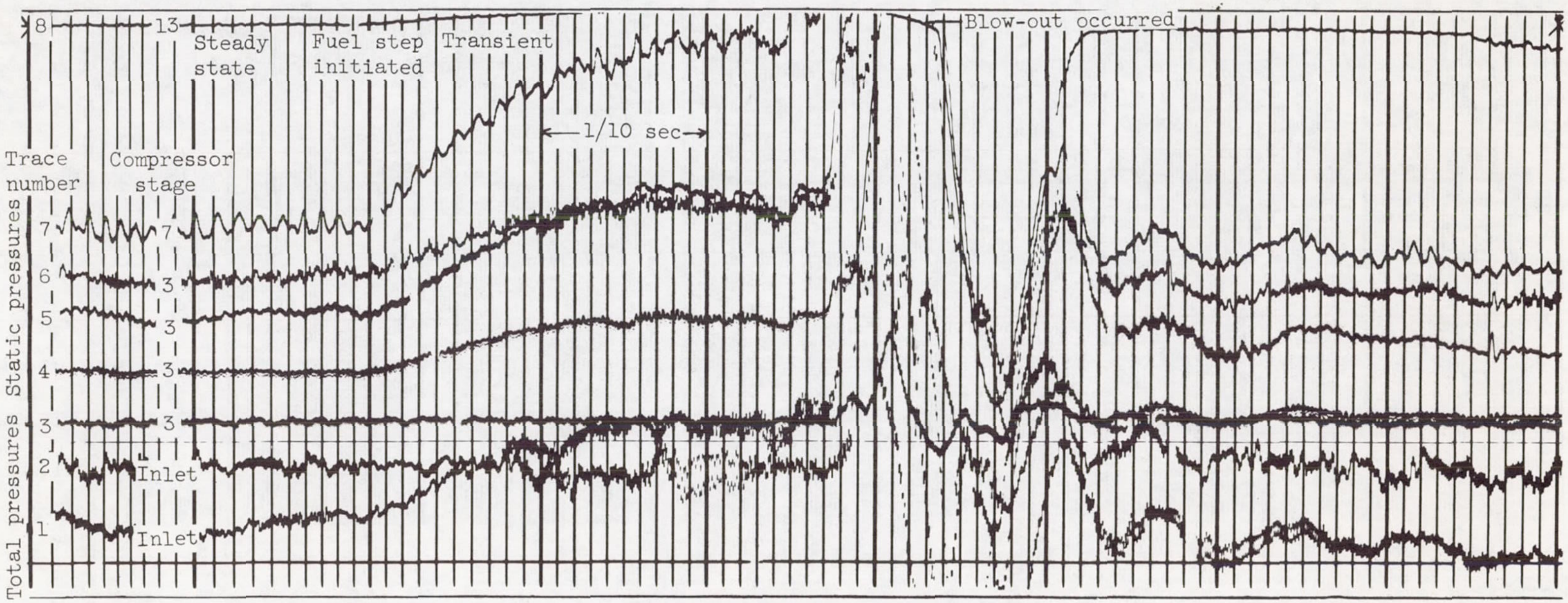


Figure 2. - Typical low-speed oscillograph traces showing successful acceleration. Configuration A (B-C, V-0); altitude, 35,000 feet; Mach number, 0.4.



(a) Low-speed oscillograph.

Figure 3. - Typical oscillograph traces showing normal steady-state operation and fuel step resulting in surge blow-out. Configuration A (B-C, V-0); altitude, 35,000 feet; Mach number, 0.4.



(b) High-speed oscillograph.

Figure 3. - Concluded. Typical oscillograph traces showing normal steady-state operation and fuel step resulting in surge blow-out. Configuration A (B-C, V-0); altitude, 35,000 feet; Mach number, 0.4.

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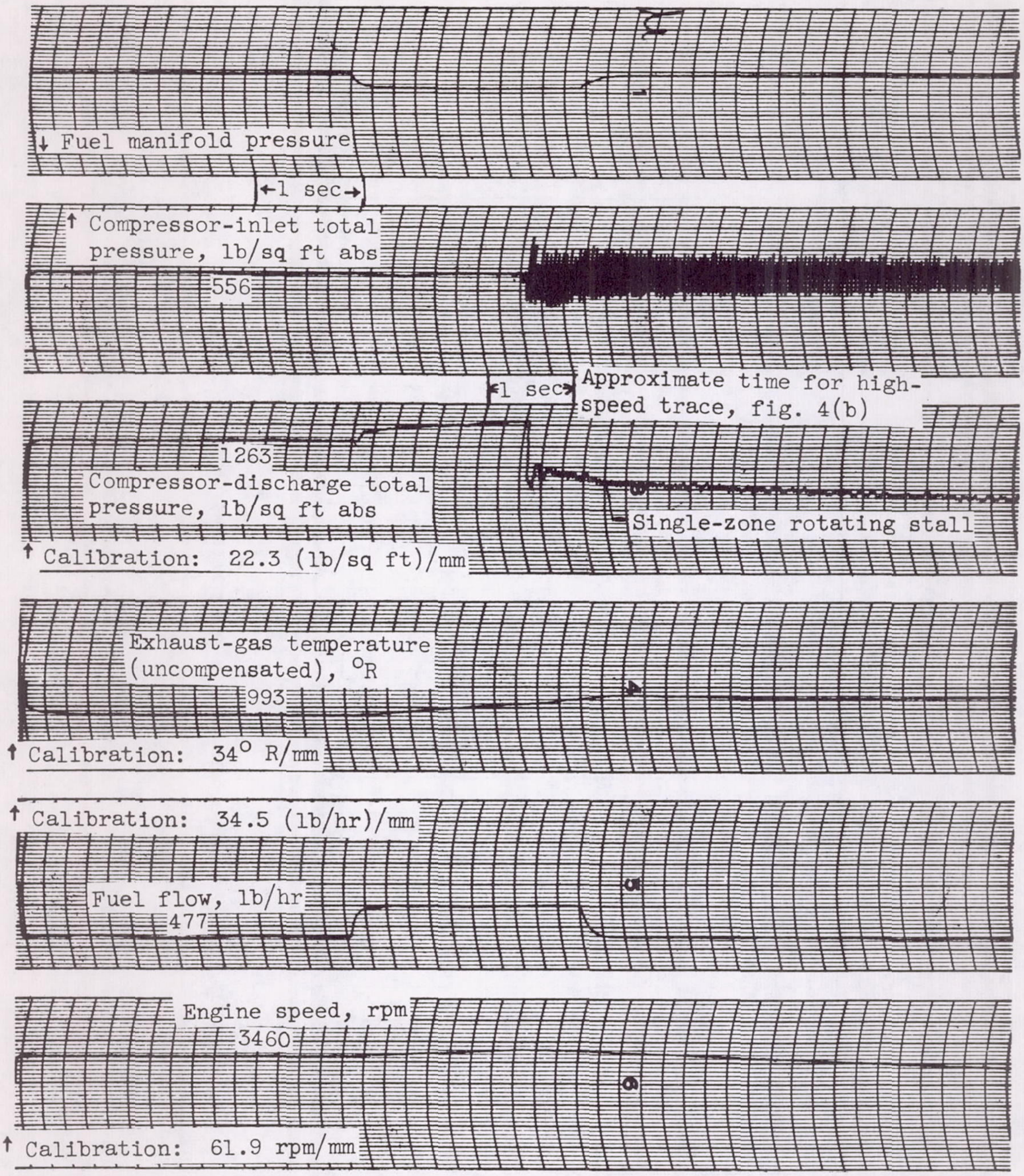
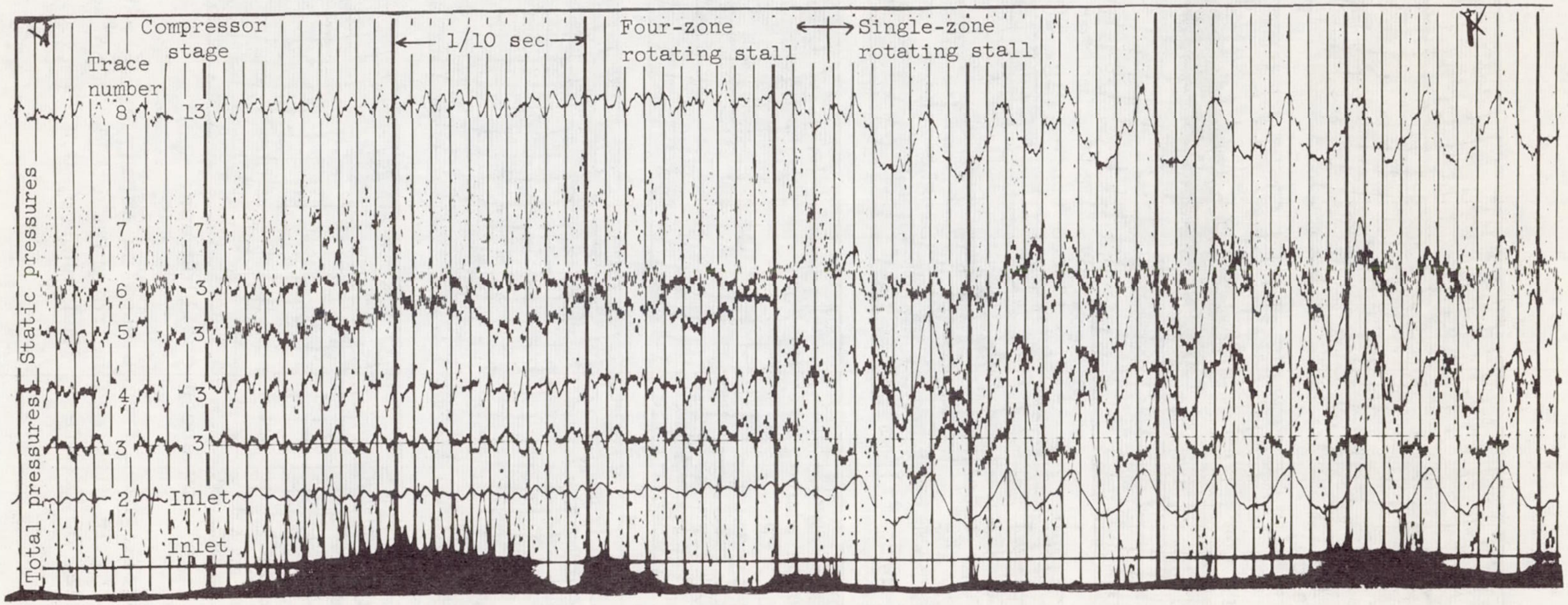


(a) Low-speed oscillograph.

Figure 4. - Typical oscillograph traces showing steady-state rotating stall and fuel step resulting in single-zone rotating stall. Configuration A (B-C, V-0); altitude, 35,000 feet; Mach number, 0.4.



(b) High-speed oscillograph.

Figure 4. - Concluded. Typical oscillograph traces showing steady-state rotating stall and fuel step resulting in single-zone rotating stall. Configuration A (B-C, V-0); altitude, 35,000 feet; Mach number 0.4.

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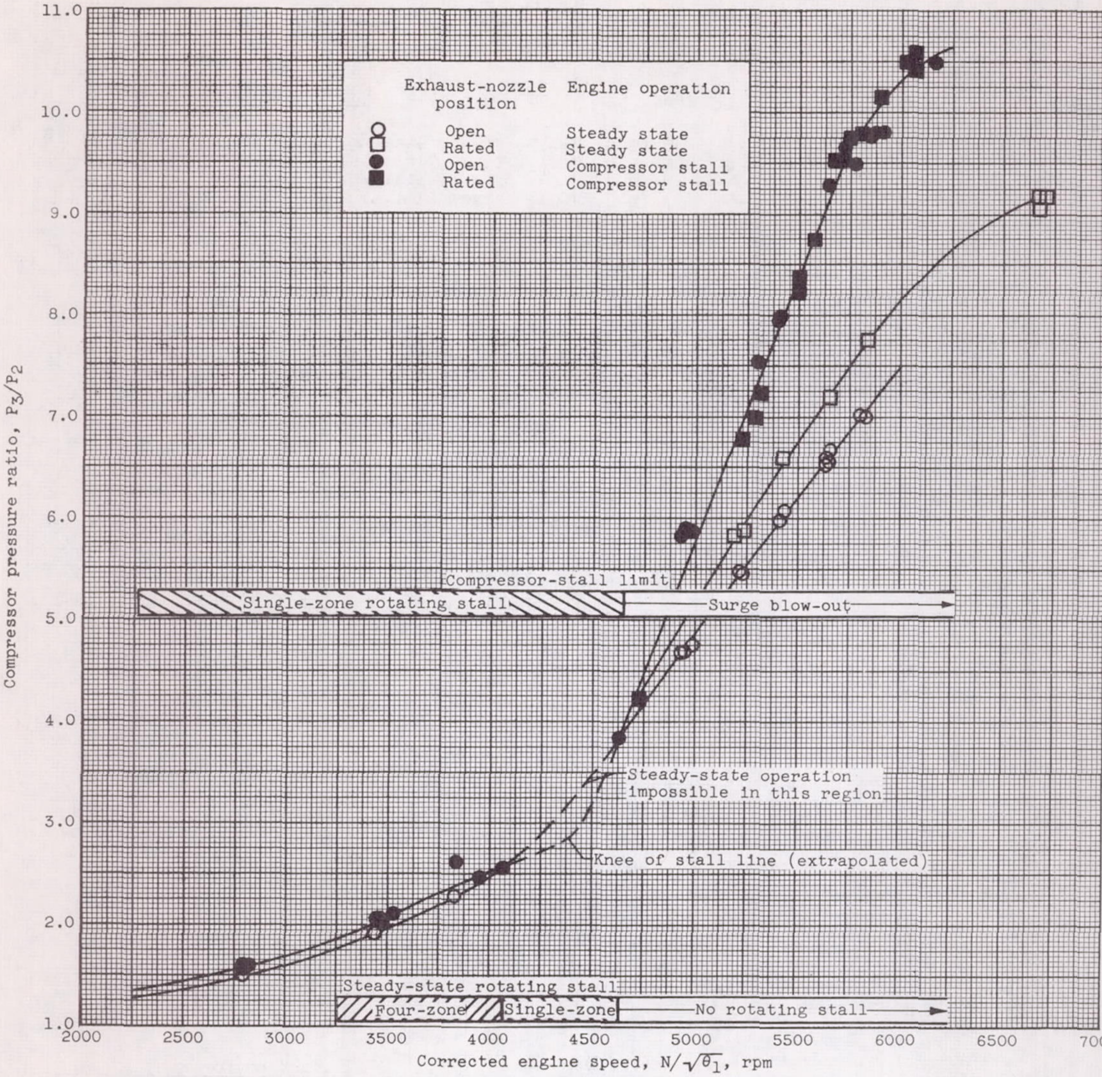

Figure 5. - Steady-state and stall-limit pressure ratios for configuration A (B-C, V-0). Altitude, 35,000 feet; Mach number, 0.4; inlet temperature, -30° F.

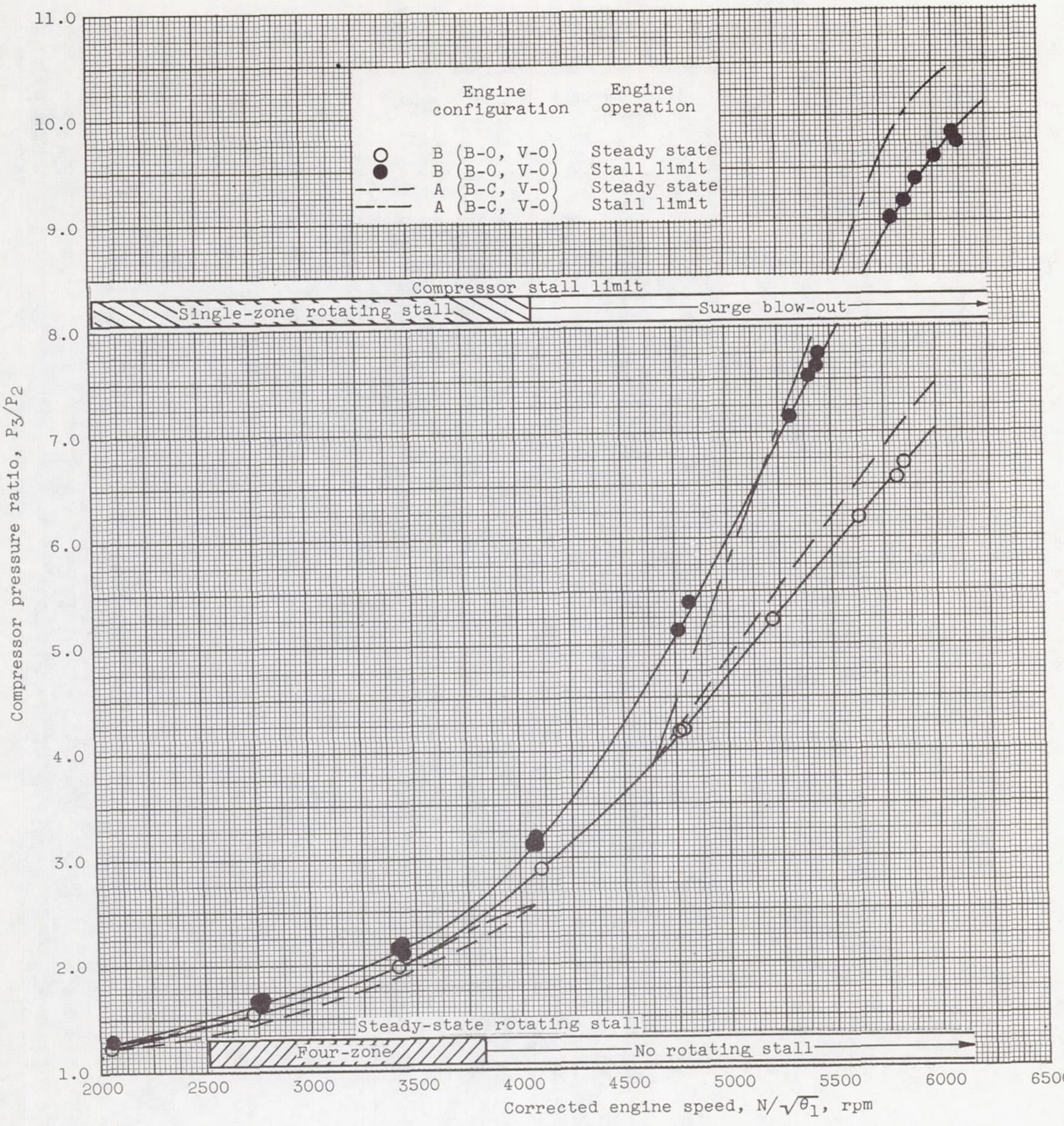

Figure 6. - Effects of opening bleeds on steady-state and stall limit pressure ratios. Inlet guide vanes, open; exhaust nozzle, open; altitude, 35,000 feet; Mach number, 0.4; inlet temperature, -30° F.

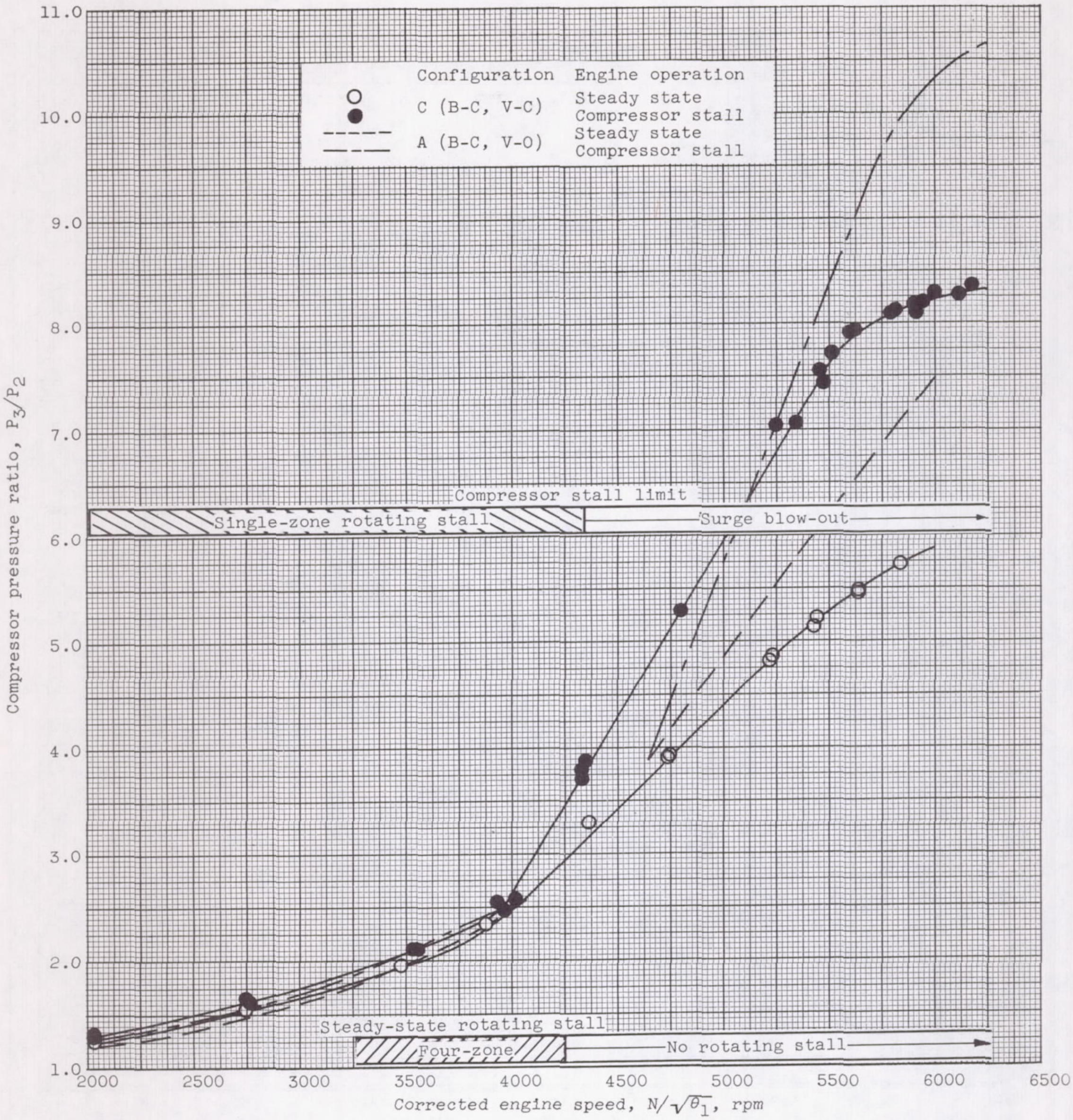

Figure 7. - Effects of closing inlet guide vanes on steady-state and stall-limit pressure ratios. Bleeds, closed; exhaust nozzle, open; altitude, 35,000 feet; Mach number, 0.4; inlet temperature, -30° F.

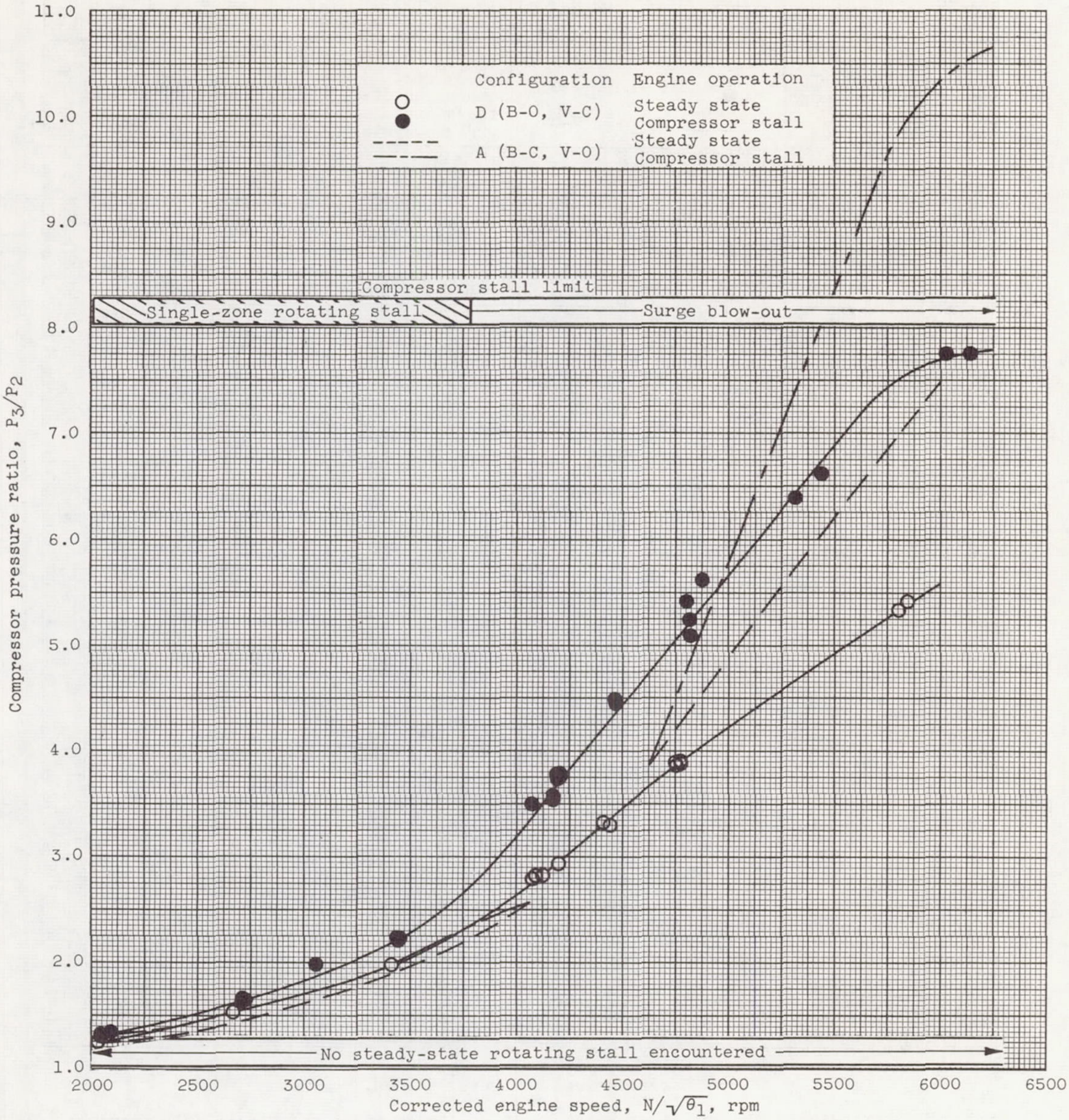

Figure 8. - Combined effects of opening bleeds and closing inlet guide vanes on steady-state and stall-limit pressure ratios. Exhaust nozzle, open; altitude, 35,000 feet; Mach number, 0.4; inlet temperature, -30° F.

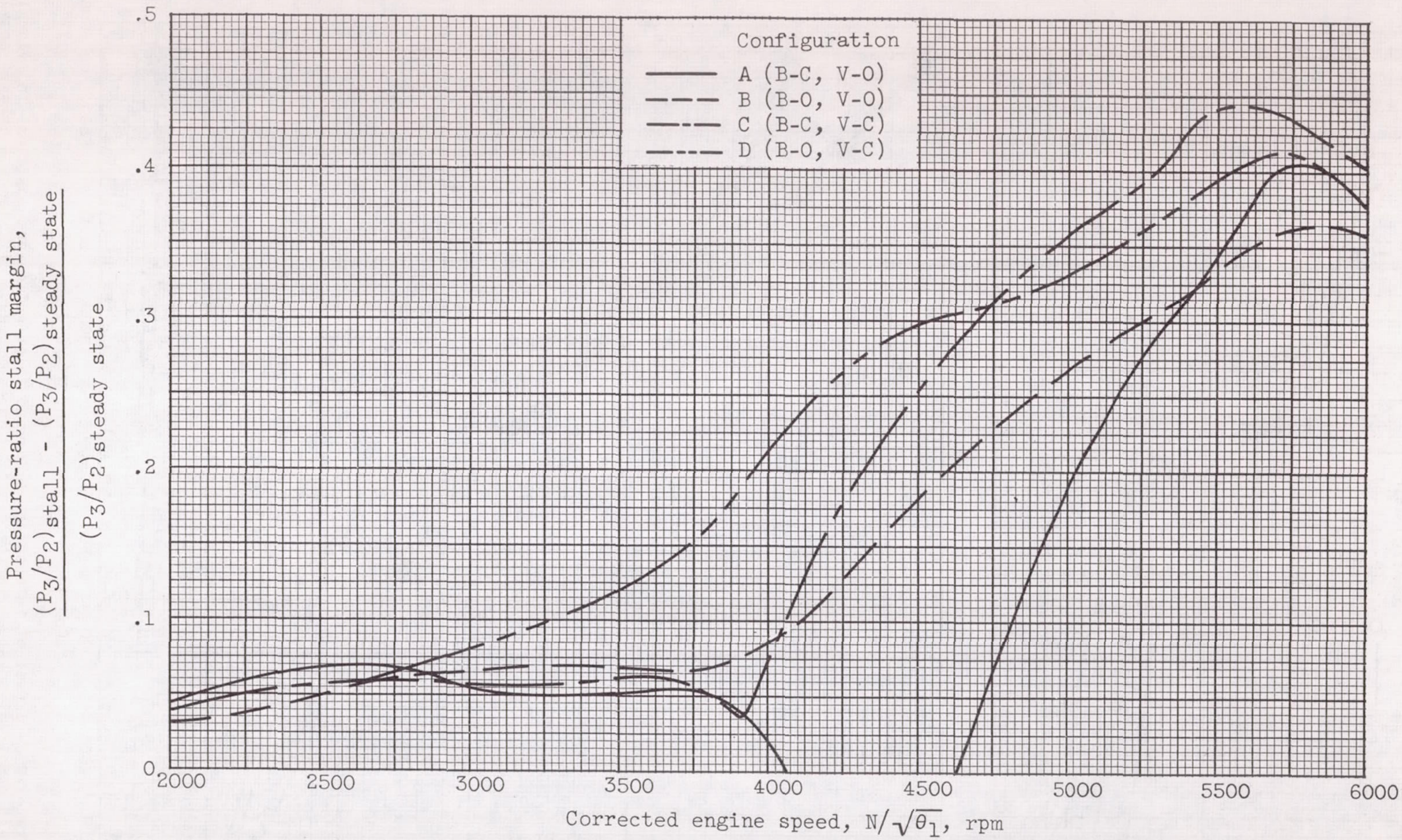

Figure 9. - Effect of interstage bleeds and inlet guide vanes individually and combined on compressor-pressure-ratio stall margin. Exhaust nozzle open; altitude, 35,000 feet; Mach number, 0.4.

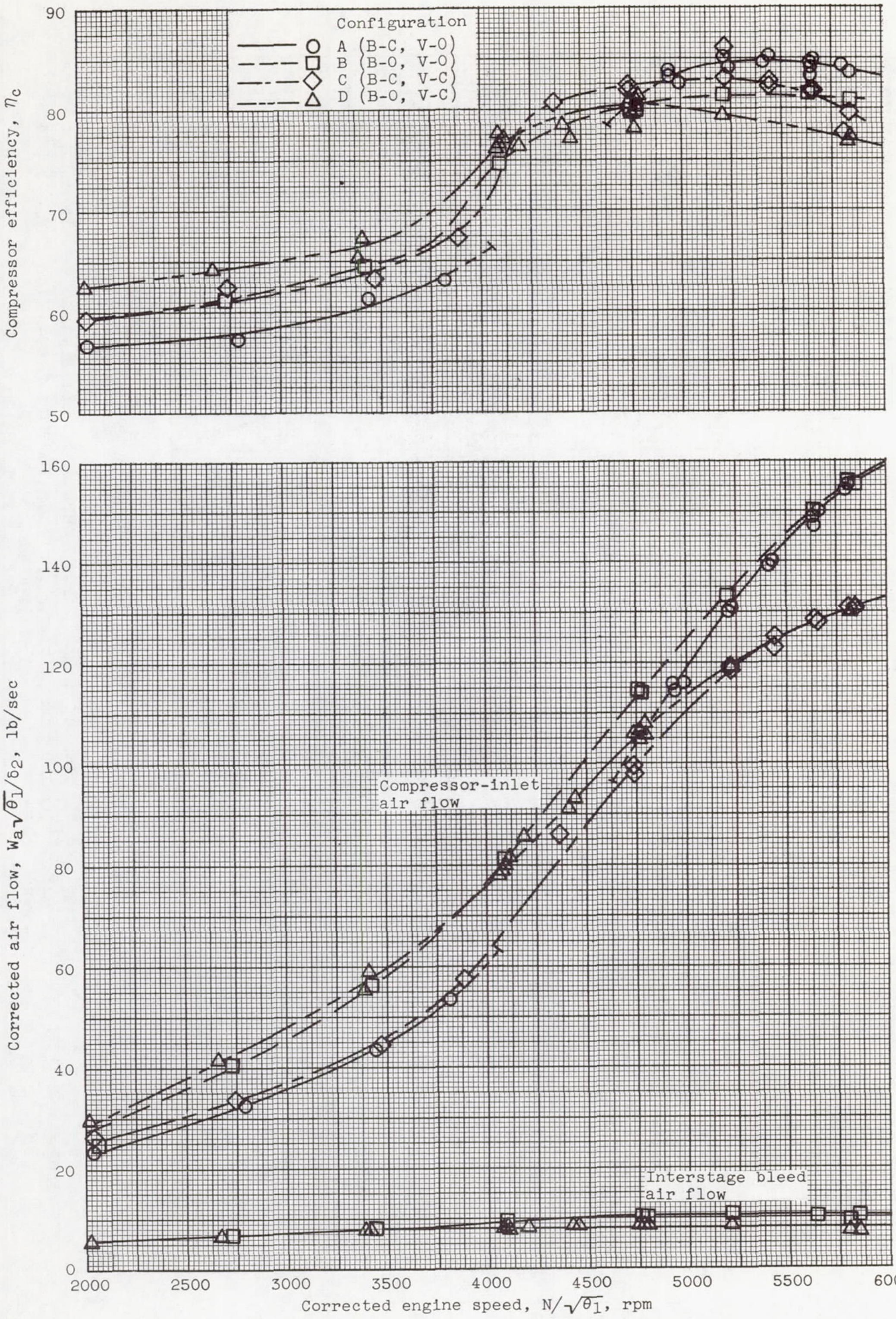

Figure 10. - Effect of interstage bleeds and inlet-guide-vane position, individually and combined, on steady-state air flow and compressor efficiency. Exhaust nozzle open; altitude, 35,000 feet; Mach number, 0.4; inlet temperature, -30° F.

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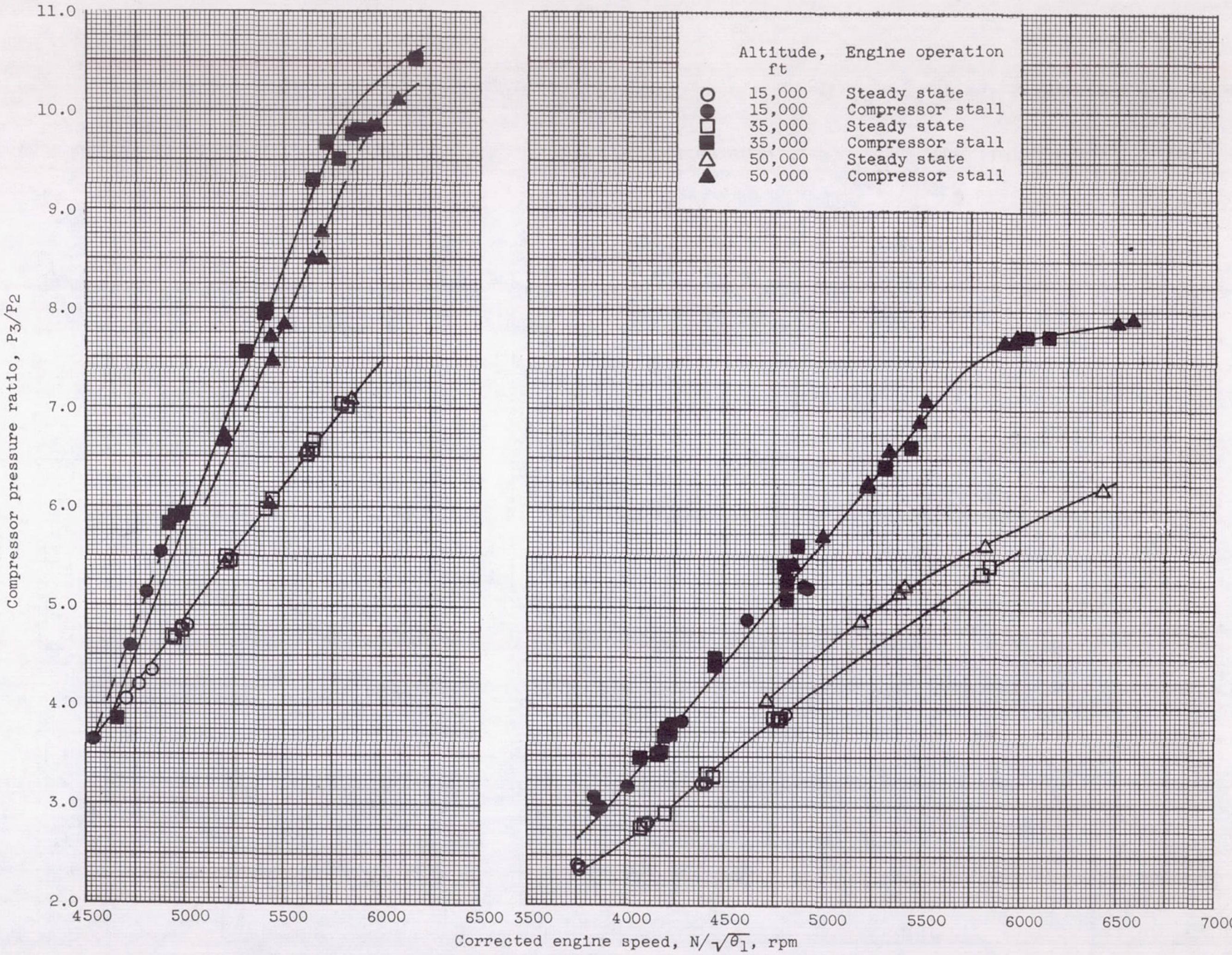
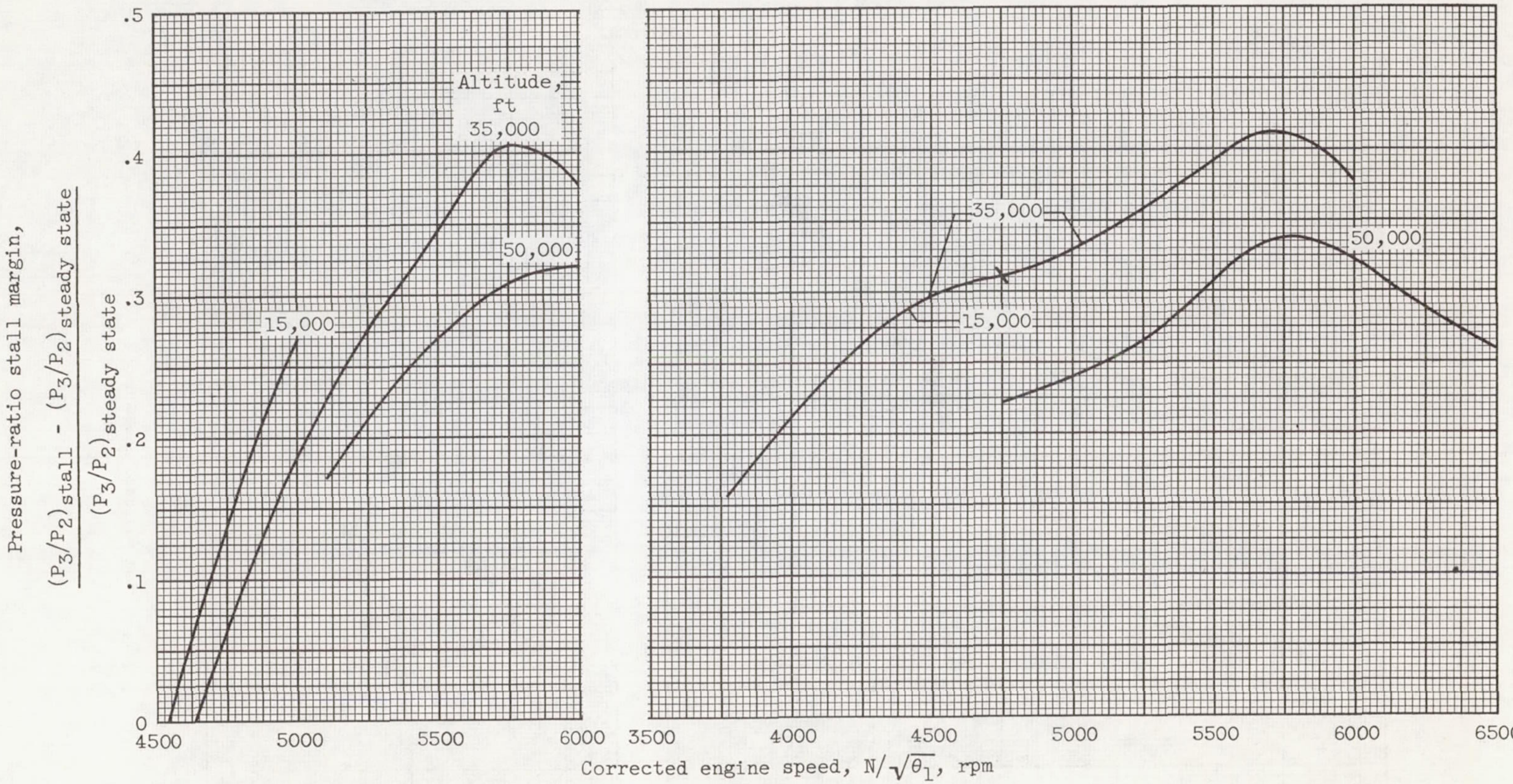


(a) Configuration A (B-C, V-O).

(b) Configuration D (B-O, V-C).

Figure 11. - Effect of altitude on steady-state and stall-limit pressure ratios for configurations A and D. Exhaust nozzle, open; Mach number, 0.4.



(a) Configuration A (B-C, V-O)(normal high-speed configuration).

(b) Configuration D (B-O, V-C)(normal low-speed configuration).

Figure 12. - Effect of altitude on compressor-pressure-ratio stall margins for configurations A and D. Exhaust nozzle open; Mach number, 0.4.

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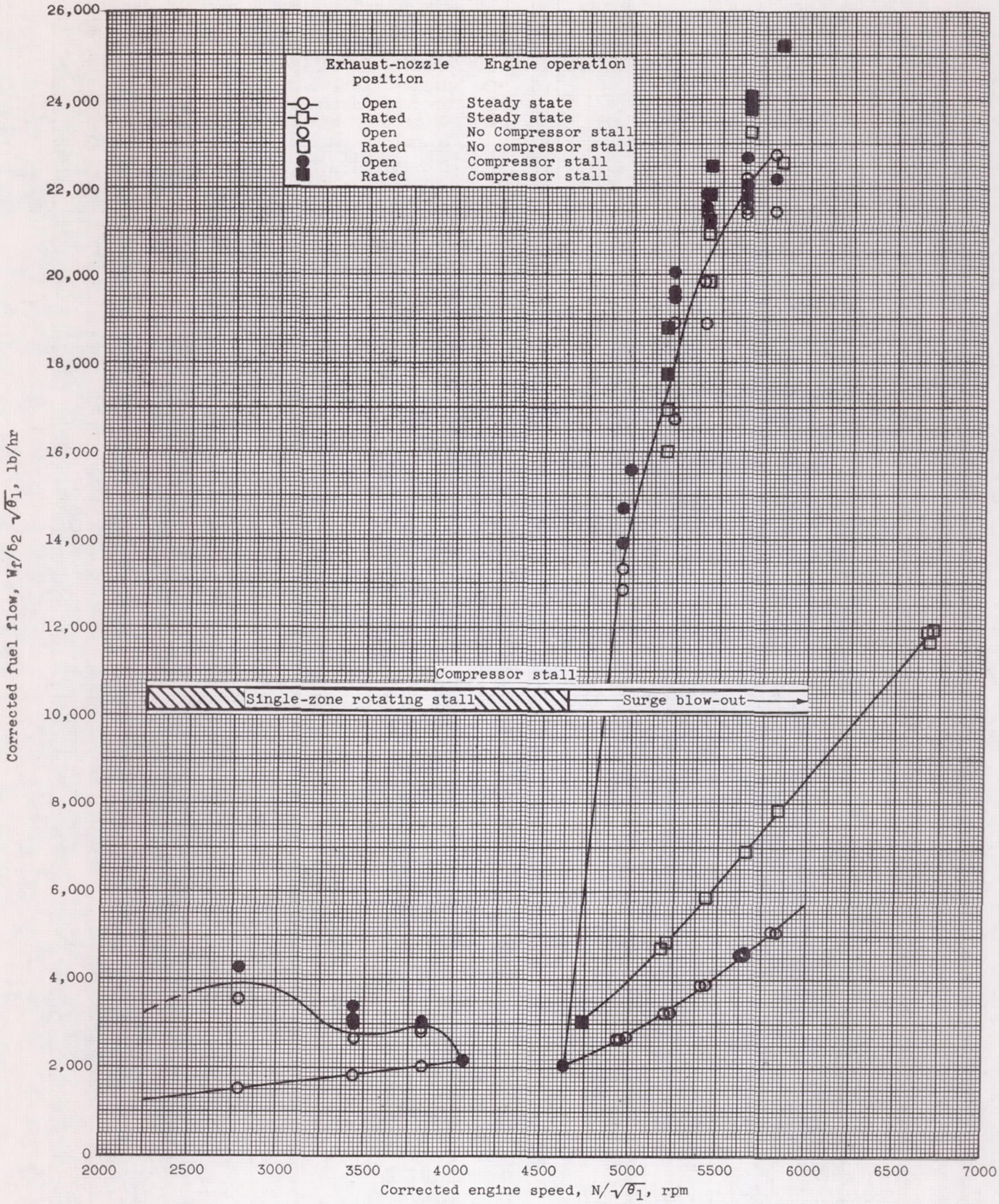

(a) Configuration A (B-C, V-O).

Figure 13. - Steady-state and transient fuel flows. Altitude, 35,000 feet; Mach number, 0.4; inlet temperature, -30° F.

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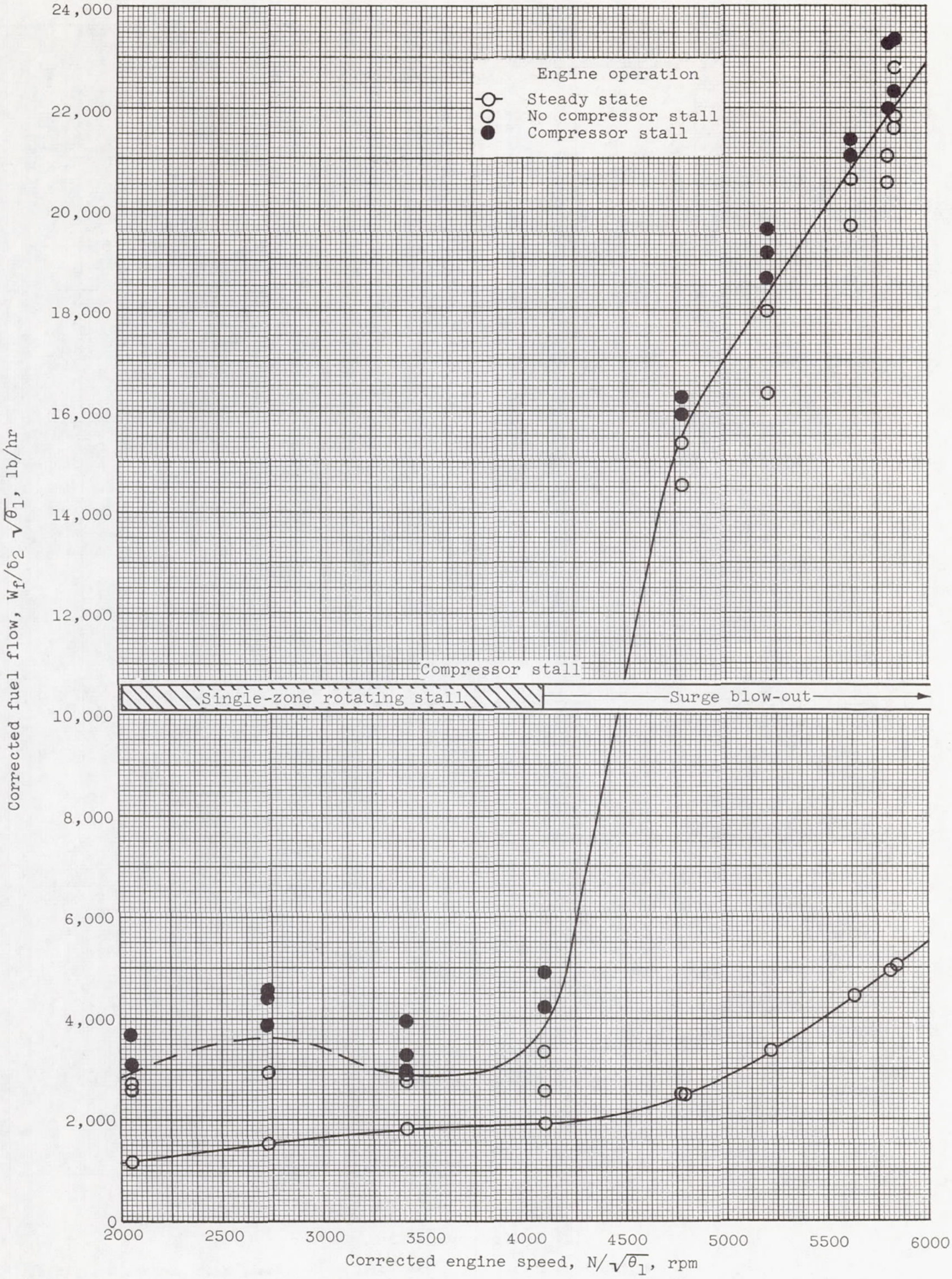
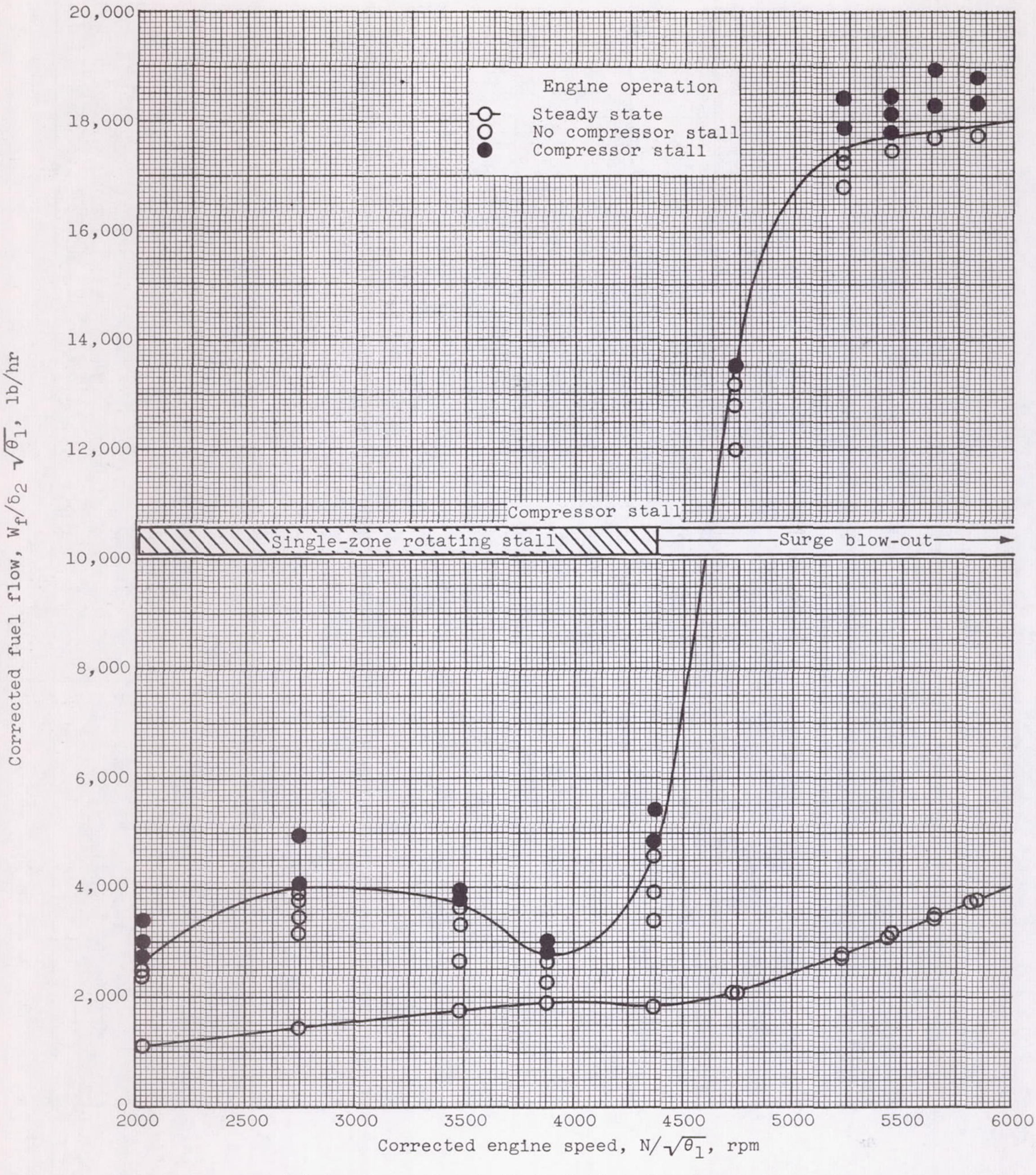


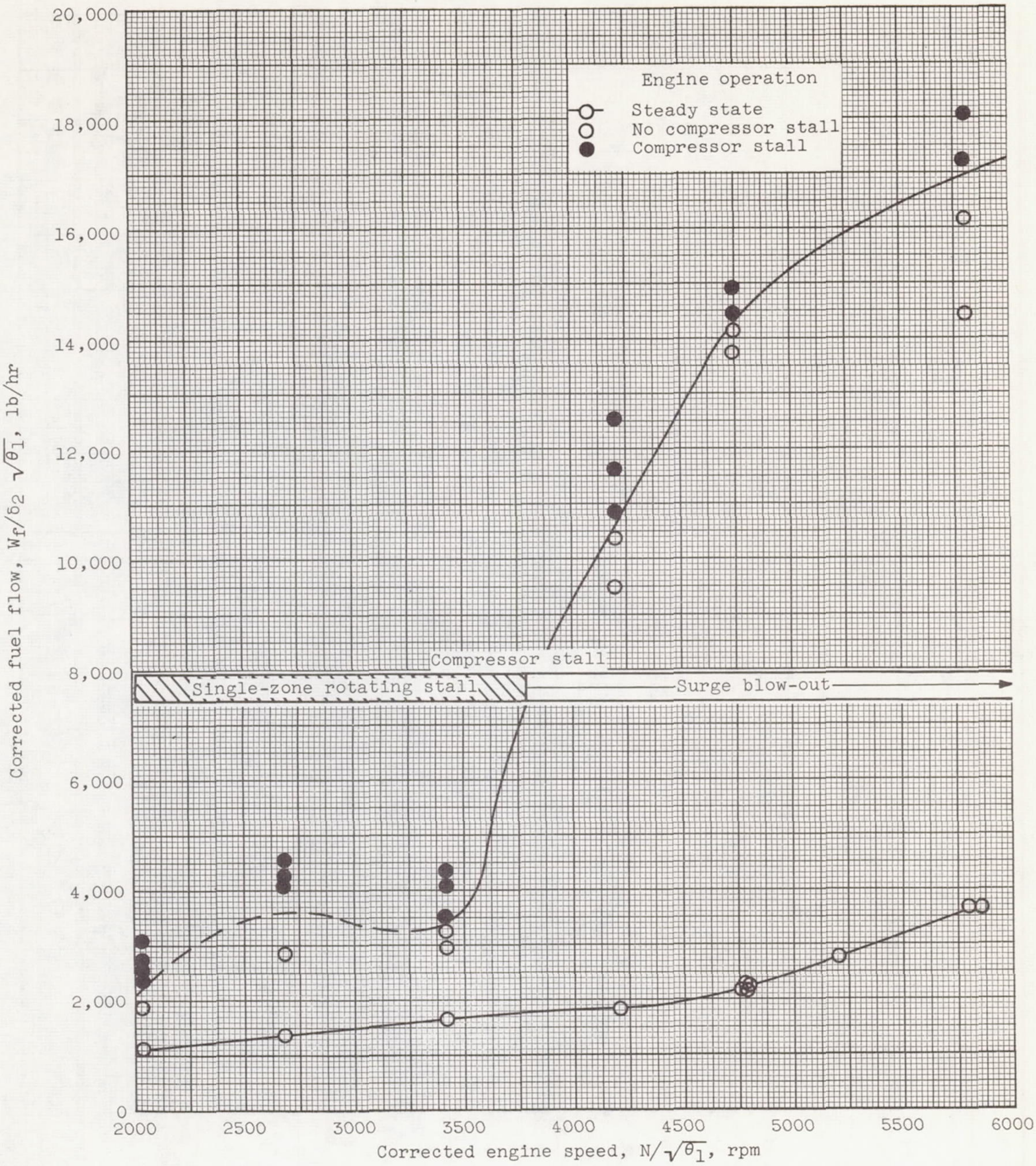
(b) Configuration B (B-0, V-0); exhaust nozzle, open.

Figure 13. - Continued. Steady-state and transient fuel flows. Altitude, 35,000 feet; Mach number, 0.4; inlet temperature, -30° F.



(c) Configuration C (B-C, V-C); exhaust nozzle, open.

Figure 13. - Continued. Steady-state and transient fuel flows. Altitude, 35,000 feet; Mach number, 0.4; inlet temperature, -30° F.



(d) Configuration D (B-0, V-C); exhaust nozzle, open.

Figure 13. - Concluded. Steady-state and transient fuel flows. Altitude, 35,000 feet; Mach number, 0.4; inlet temperature, -30° F.

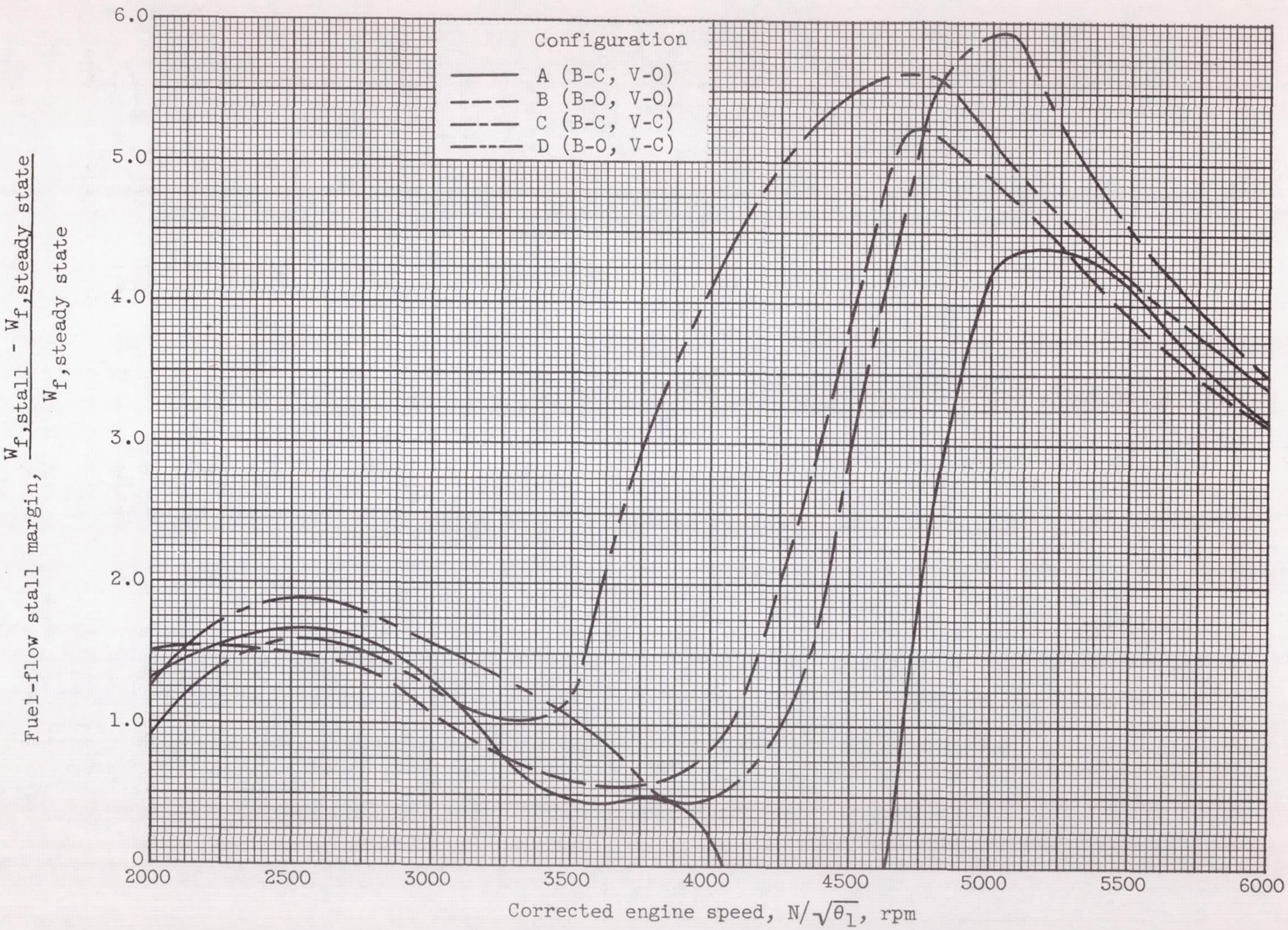
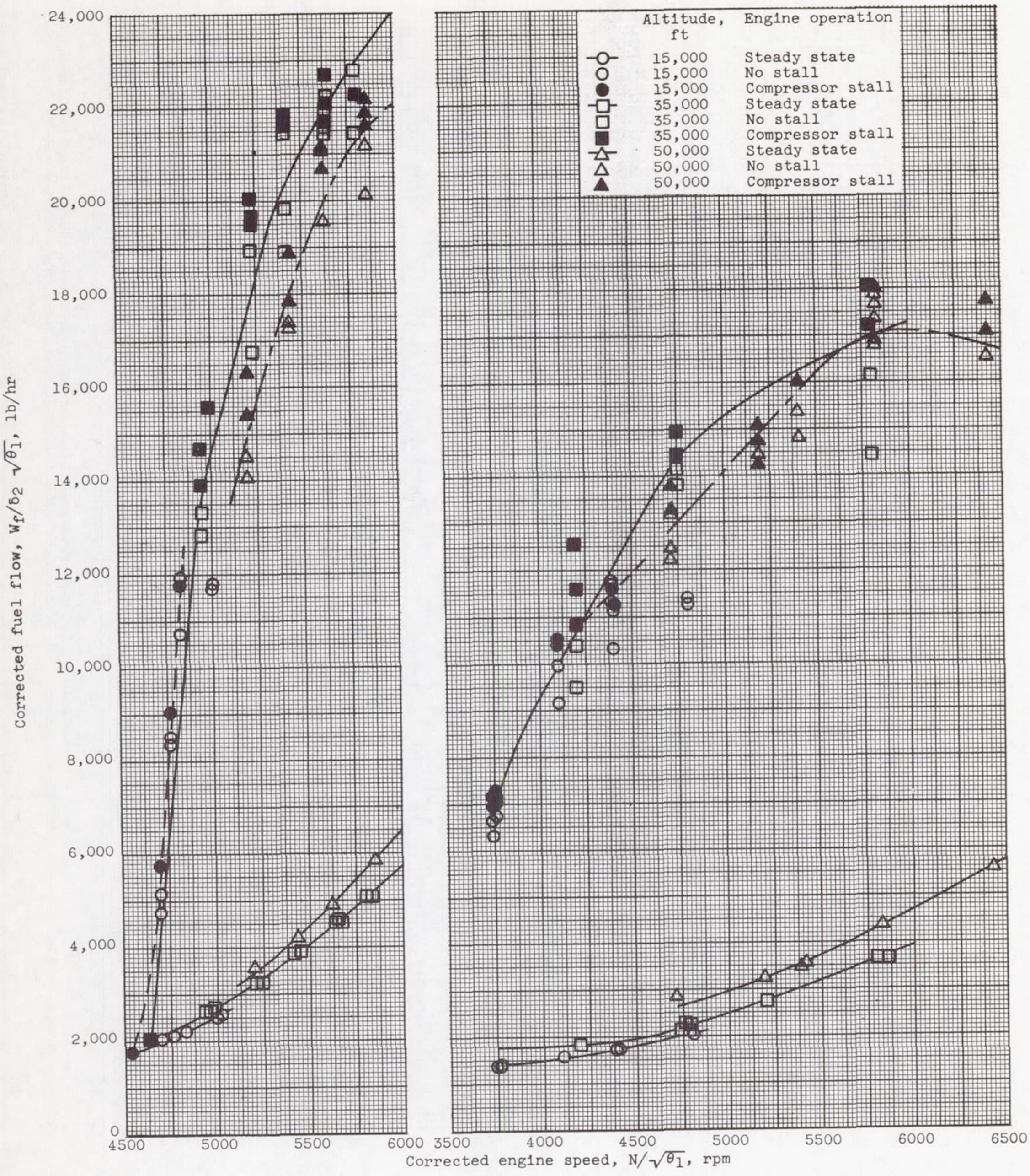


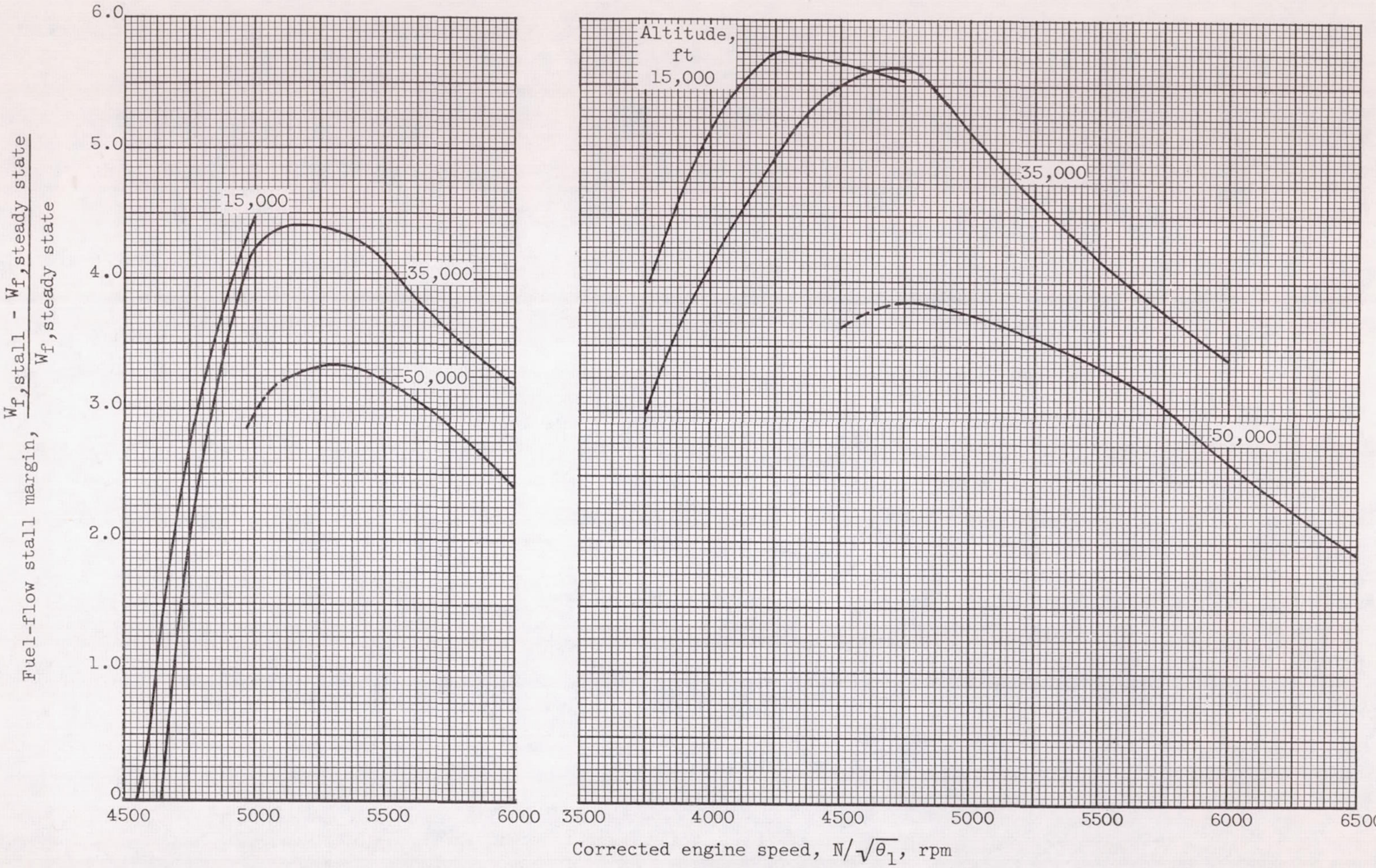
Figure 14. - Effect of interstage bleeds and inlet guide vanes, individually and combined, on fuel-flow stall margin. Exhaust nozzle open; altitude, 35,000 feet; Mach number, 0.4.



(a) Configuration A (B-C, V-O) (normal high-speed configuration).

(b) Configuration D (B-O, V-C) (normal low-speed configuration).

Figure 15. - Effect of altitude on steady-state and transient fuel flows for configurations A and D. Exhaust nozzle, open; Mach number, 0.4.



(a) Configuration A (B-C, V-O)(normal high-speed configuration).

(b) Configuration D (B-O, V-C)(normal low-speed configuration).

Figure 16. - Effect of altitude on fuel-flow stall margins for configurations A and D. Exhaust nozzle open; Mach number, 0.4.