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INCREASING THE STABLE OPERATING RANGE OF A MACH 2.5 INLET

by Bobby W. Sanders and Glenn A. Mitchell
Lewis Research Center
Cleveland, Ohio

TECHNICAL PAPER proposed for presentation at
Sixth Propulsion Joint Specialist Conference sponsored by
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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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Abstract

The results of an experimental investigation to increase the stable operating range of a supersonic mixed-compression inlet are presented. Large stability margins were obtained with inlet throat bleed systems utilizing controlled bleed plenum pressure. These throat bypass systems removed airflow through either distributed normal holes, distributed educated slots, or a single forward-facing slot. Control of the bleed plenum pressure was provided by variable choked exits, vortex valves, or self-acting mechanical valves. Stability limits were determined for steady-state operation and transient internal airflow disturbances. Mechanical valve instability was encountered at some discrete inlet operating conditions.

Introduction

To minimize inlet cowl drag for sustained flight at speeds above Mach 2.0, it becomes essential that some portion of the supersonic area contraction be accomplished internally. Although an inlet of this type, which utilizes a mixture of external and internal compression affords efficient diffusion, it also has an undesirable transient characteristic known as unstart. The conventional inlet of this type must operate with the terminal shock near the throat for peak performance, but if this shock inadvertently moves ahead of the throat it is abruptly expelled ahead of the cowling. This unstart causes a sharp reduction in mass flow and pressure recovery and a large increase in drag. It is desirable that an inlet provide a margin in corrected weight flow below the optimum value for peak performance without incurring unstart. This margin is usually defined as the stable subcritical range. An inlet may be designed to have a limited stable subcritical range that is provided by the capacity of the performance bleed system to spill increased airflow as the terminal shock moves ahead of the throat. With bleed exit areas that are fixed, this range may not be adequate to absorb many of the transient disturbances that are encountered by a supersonic propulsion system. Stability margins greater than the stable subcritical range may be obtained for these inlets by operating supercritically with a resultant loss in performance.

If greater stable subcritical range is to be provided by throat bleed alone in order to avoid this performance loss, then the throat bleed system must also function as a throat bypass in order to provide large increases in bleed as the inlet operation proceeds from supercritical to minimum stable conditions. Ref. 1 shows that these large increases in bleed can be obtained without prohibitive amounts of bleed during normal operation if the bleed exit area can be controlled to maintain nearly constant pressure in the bleed plenum. This exit area variation might either be done with an active control that senses shock position and regulates the exit area, or it may be possible to devise high-speed valves that are automatically regulated by pressure changes that occur when the terminal shock changes position.

The objective of a recent test program in the Lewis 10- by 10-Foot Supersonic Wind Tunnel was to evaluate the effectiveness of several different types of such stability bleed systems. The experimental investigation was conducted with a Mach 2.5 mixed-compression inlet having 40 percent of the supersonic area contraction occurring internally. Throat bypass airflow was removed through the cowling with either porous bleed of distributed normal holes, distributed educated slots, or a large forward-facing slot. These bleed areas were designed to remove approximately 20 percent of the inlet capture airflow during minimum stable operation.

Choked exit throttling plugs, self-acting mechanical valves, and vortex valves were utilized to provide the required bleed plenum pressure control. The valves were intended to increase stability during steady-state conditions as well as to provide fast-acting variable exit controls that are necessary to absorb transient disturbances and prevent the expulsion of the terminal shock.

Inlet stability limits were determined for steady state and transient internal airflow disturbances. These data were obtained at a free-stream Mach number of 2.50 and Reynolds number, based on cowl lip diameter, of 3.88×10^6.

Apparatus and Procedure

The inlet used in this investigation was an axisymmetric, mixed-compression configuration with 40 percent of the design supersonic area contraction occurring internally. It was designed for a free-stream Mach number of 2.50 with a translating centerbody to accomplish starting and off-design operation. This inlet was sized to match the airflow requirements of the J85-GE-13 engine and has a capture diameter of 18.63 in. (47.32 cm). Photographs of the inlet model mounted in the Lewis 10- by 10-Foot Supersonic Wind Tunnel are presented in Fig. 1. Major variations were made in the cowl bleed ducting during the investigation. Therefore, a relatively bulky cowling was used to accommodate model changes and hence was not representative of flight-type cowling.

Some of the basic inlet details are presented in Fig. 2. Initial supersonic compression was accomplished by a two-cone surface. The cowl lip shock was cancelled at its impingement point on the centerbody by a turn in the surface. The inlet throat Mach number before

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the terminal shock was 1.30. Bleeds were located in the throat region on both the cowl and centerbody. Sufficient bleed was removed through the centerbody bleed region to assure high inlet performance. This bleed was ducted through two of the three available hollow centerbody support struts to two coldpipes. The stability bleed entered the cowl bleed ducting through the bleed region shown in Fig. 2. Bleed was ducted back to a location where either the automatic mechanical or vortex valves could be mounted to control the backpressure. Downstream of the valves the bleed airflow was collected into two coldpipes, one on either side of the model. Remote actuated plugs controlled the bleed airflows and the main airflow (fig. 1(b)). The cowl bleed plugs were open and unchoked when the automatic valves were in use. The subsonic portion of the inlet diffuser incorporated two remotely controlled bypass systems: a high response overboard system, and a low-speed valve for engine and nozzle cooling (fig. 2). Centerbody vortex generators were used.

Throat bleed details for each of the three basic configurations are shown in Figs. 3 to 5. The forward cowl performance bleed, illustrated in Fig. 3, was used only with the forward-facing slot and was exhausted overboard. While several variations in the design of the large slot, porous, and educated slot bleeds were tested, only one of each type is presented in these figures. Variations of the porous and educated bleed were accomplished by sealing portions of the open bleed areas. Slot configurations were changed by utilizing different downstream lip shapes.

Stability bleed valve details are presented in Figs. 6 and 7. A photograph of the self-acting mechanical valves installed in the inlet cowl is shown in Fig. 6(a) and details of its mechanical design appear in Fig. 6(b). It was essentially a free piston which was positioned by differential pressures. Control of the internal reference pressure in the valve chamber determines the pressure at which the valve opens. As the terminal shock moves over the bleed region, the bleed pressure increases and exceeds the reference pressure pushing the valve face off the seat and allowing bleed flow to occur. In the case of the vortex valves (fig. 7), the tangential control flow creates a vortex that blocks the bleed flow at the lower bleed pressures associated with supercritical inlet operation. However, the higher bleed pressures obtained during subcritical operation break down the vortex which allows bleed flow to exit through the center sidewall holes.

The inlet stability limits were determined for steady state and transient internal airflow disturbances. The ability of the inlet stability system to absorb transients was determined by pulsing the overboard bypass doors at the engine face and determining the reduction in bypass flow area that the inlet would tolerate without an unstart. Dynamic transients with single sine wave pulses representing frequencies up to 40 Hz were used. The door area change was related to door airflow from steady-state data and this incremental airflow was used as a measure of inlet disturbance tolerance. The dynamic characteristics for self-acting mechanical valves, for vortex valves, and for fixed choked exits downstream of small and large bleed plenums were obtained.

Results and Discussion

Throat bleed flow characteristics and inlet performance for the distributed porous configuration are presented in Fig. 8. The series of dashed line curves faired through the open symbols in Fig. 8(a) represent the bleed performance obtained for different fixed bleed exit areas. Each of the dashed curves were generated by reducing the compressor face airflow from a supercritical value and causing the terminal shock to move forward until unstart occurred. By utilizing this mode of operation, the locii of minimum and maximum throat bypass bleed airflows were obtained. The minimum airflows corresponded to supercritical operation and the maximum airflows were obtained at minimum stable operation.

A maximum throat bypass mass-flow ratio of about 0.25 was obtained (fig. 8(a)). However, the fixed exit area required to obtain the maximum bleed rate also provided prohibitive amounts of supercritical bleed (approximately 10 percent of the inlet capture airflow). If the bleed exit area was reduced to maintain an acceptable supercritical bleed level, the amount of bleed obtained at minimum stable was also greatly reduced. Similar results were reported in Ref. 1. An examination of Fig. 8(a) shows that large changes in mass-flow ratio could be obtained if a constant bleed recovery is maintained as the inlet proceeds from supercritical to minimum stable conditions. For example, if a constant bleed recovery of 0.32 was maintained by the variable plugs, a large increase in throat bypass mass-flow ratio from 0.02 to 0.25 would be obtained.

Steady-state data for the self-acting mechanical valves and vortex valves are represented by the filled symbols in Fig. 8(a). As discussed previously, these valves open automatically in response to an increase in the bleed plenum pressure. The valves were set to begin operation at their initial condition indicated by the flagged symbols. These initial inlet conditions are at about 90 percent pressure recovery and have a bleed mass-flow ratio of about 0.02 through the stability bleed system for performance boundary layer removal. This bleed was obtained by locating small auxiliary fixed exits in parallel with the bleed control valves. Thus, at this initial condition of valve operation, no airflow passed through the valves. The valve operating curves shown in Fig. 8(a) were generated by closing the main duct choked plug.

The mechanical valves provided an increase in subcritical operating range of 0.20 in mass-flow ratio as a result of maintaining a near constant plenum pressure from supercritical to minimum stable conditions. Between bleed mass-flow ratios of 0.04 and 0.08 during steady state operation these valves were observed to oscillate at a frequency of about 40 Hz, which was higher than the valve natural frequency of 12 Hz. No adverse effects on inlet performance were noted. (Subsequent bench tests of these valves have indicated that extremely small amounts of damping could eliminate this instability.)

The vortex valves did not provide an increase in bleed airflow equivalent to that obtained with the mechanical valves since the geometric flow area through the valve in its open mode of operation could not be made as large. However, they did provide an increase greater than that obtained with the comparable fixed-exit area. For example, a fixed-exit area with a bleed mass-flow ratio of 0.02 during supercritical operation can only provide a subcritical operating range of 0.01 in mass-flow ratio. The vortex valves provided a subcritical operating range of 0.05 mass-flow ratio.

The stable subcritical range for an inlet is defined as the percentage change in engine corrected airflow between any given operating condition and the minimum stable condition. While the stable subcritical range for the system tested was primarily obtained by increases in throat bypass airflow, an increase in inlet total pressure between an inlet-engine match condition and the unstart limit also provides a considerable portion of the actual stability range. Inlet performance data for the porous configuration are presented in Fig. 8(b). These data indicate that pressure recovery increases over 0.04 can be realized between an initial operating condition at a pressure recovery of 0.90 and the minimum stable point. For this porous configuration the inlet stable subcritical range was 5.4 percent with the small fixed exit, 10.6 percent with the vortex valve bleed control, and 26.0 percent with the self-acting mechanical valves.

Performance data for the forward-facing slot bleed are shown in Fig. 9. This slot had a blunted rear lip which was flush with the cowl surface. Recessed (educated) rear lips and sharp lips were also investigated but were found to be about equal or inferior to the configuration presented herein. These data indicate that significantly higher bleed recoveries can be achieved with the slot bleed configuration (fig. 9(a)) than were obtained with the porous bleed concept of Fig. 8(a). High bleed recoveries are desirable because they increase the weight flow capacity of the stability system and reduce the payload penalties that are associated with the overboard exhaust of low energy airflows. A maximum bleed mass-flow ratio of 0.188 was recorded. Again it is obvious as for the porous configuration that constant bleed plenum pressure control can provide a large increase in stability mass-flow range. Only one data point is presented for steady state operation of the mechanical valves. These data were obtained with the valve closed and the auxiliary exit holes allowing the amount of bleed shown to exhaust directly overboard. No other steady state data were obtained because the valve face oscillated rather severely at about 40 Hz for all valve openings. This problem is currently under study. The vortex valves showed no instability with the large slot and were successfully tested. Vortex valves obtained a slightly larger increase in bleed mass-flow ratio with the slot than with the porous configuration.

The inlet performance for the slot configuration (fig. 9(b)) indicate that the increase in inlet recovery from an initial condition of 0.90 to inlet unstart was smaller than that obtained with the porous configuration.

Data obtained for the educated slots are presented in Fig. 10. This configuration, like the porous and large slot bleeds, provided a large stability range if a near constant plenum pressure was maintained from supercritical to minimum stable conditions. When educating bleed, the desire is to reduce the flow coefficient relative to bleed geometries normal to the surface (i.e., normal holes) for supersonic external flow without seriously reducing the flow coefficient with external subsonic flow. Due to the geometry requirements of educating bleed, the porosity of the educated bleed is less than that of the normal hole porous bleed. Therefore, the educated bleed had to extend farther forward on the cowl to obtain a flow area equal to that of the normal porous configuration. A comparison of the flow characteristics of the distributed educated slots and the porous normal hole configuration is valid with supersonic external flow since the open area for both bleeds were equal and the Mach number was about constant over the bleed region. Comparing the rapid decrease of the initial portion of the minimum bleed curve (fig. 10(a)) with the porous bleed performance (fig. 8(a)) indicates that the supersonic characteristics of educated bleed were obtained. However, the more forward extent of the educated bleed limited the maximum flow and pressures in the bleed plenum due to bleed recirculation problems. Therefore the minimum stable curves of Figs. 8 and 10 are not directly comparable. Comparison of the minimum stable curve of Fig. 8 with the minimum stable curve for a porous normal hole configuration of similar forward extent (not presented herein) showed similar characteristics as those presented here for the educated bleed. Therefore the potentially high capacity of the educated bleed to accept subsonic flow could not be achieved since the inlet unstarted prematurely because of these recirculation problems. Fig. 10(b) shows that the subcritical pressure recovery rise was similar to that of the porous bleed.

The ability of the inlet utilizing the porous and large slot stability bleed systems to absorb internal airflow transients was investigated. Disturbances were obtained with initial inlet conditions of 0.90 total-pressure recovery with about two counts of bleed through the stability system. The disturbances were created by moving the overboard bypass doors which were located near the compressor face. The single sine wave pulse used to reduce the door opening is shown in Fig. 11(a). The bypass door flow was calibrated at steady-state conditions in terms of corrected weight flow. At each frequency, the maximum door amplitude that the inlet would tolerate without unstarting was determined and converted by means of the steady-state calibration to a corrected weight flow. This corrected weight flow was referenced to the total diffuser exit corrected weight flow at the initial conditions to obtain a transient stability index. The bypass flow could not be as accurately determined as the plug flow, particularly under dynamic conditions. Therefore the stability index is a qualitative parameter and doesn't fully agree with the previous steady-state curves which were obtained by variation of the more accurately measured main plug flow.

The transient stability index obtained with the porous and large slot bleed configurations is presented in Fig. 11 as a function of frequency. For these data, the inlet was attached to a coldpipe plug system which added 9.2 ft^3 to the 4.8 ft^3 of the inlet diffuser and bypass system. Data are presented for the self-acting mechanical valves and the vortex valves mounted in the bleed system; and for a fixed bleed exit allowing a bleed mass-flow ratio of 0.02 at the initial operating condition. The fixed exit area configuration was tested with both a large and small bleed plenum volume. The small plenum volume was the same as that with the stability valves. A large bleed plenum might be obtained in an actual aircraft by using empty fuel tanks or internal nacelle volume.

As shown in Fig. 11 the smallest transient stability index was obtained when the fixed exit was placed at the valve attachment station to give a small bleed plenum volume. A change in the entrance conditions to this small plenum volume as represented by a change from the porous bleed (fig. 11(a)) to the slot bleed (fig. 11(b)) seemed to have no effect upon this stability index. The ability of this system to absorb transients increased from a stability index of about 7 at 1 Hz to 35 at 40 Hz. This increase in tolerance with frequency represents the ability of the inlet diffuser and coldpipe volume to absorb the transient.

The use of vortex valves, rather than the fixed exit with small volume, improved the stability index 5 to 12 percentage points over the frequency range tested for the porous configuration (fig. 11(a)). When a large volume plenum was used ahead of the fixed exit the stability index was about equal (within the measurement accuracy) to the small-volume, fixed-exit value at the low pulse frequency of 1 Hz. But the stability index increased almost linearly with frequency and at 30 Hz exceeded the door amplitude limit of 40 percentage points used with the large slot configuration (fig. 11(b)). With the porous bleed configuration even larger increases were obtained. For instance, at 30 Hz, the dynamic stability index reached the larger door amplitude limit of 54 points used with this configuration. Therefore, at 30 Hz, replacing the small bleed plenum with a large plenum increased the stability index by 18 points for the bleed slot and 28 for the porous bleed configuration. This ability of the large plenum volume to absorb transient pulses results from the increase in fill time of the large volume relative to that of the small plenum.

The stability index which was obtained by the mechanical valves at 1 Hz was 34 points for the porous configuration and 20 with the large slot. These values were the largest measured for any configuration. But the dynamic stability did not increase as rapidly with frequency as with other bleed controls because the valves had a natural frequency of about 12 Hz. As a result, at 30 Hz the mechanical valves had stability ranges somewhat below those obtained with the large bleed plenum. However, for the porous configuration, replacing the fixed exit on the small bleed plenum with mechanical valves improved the stability index 28 points at 30 Hz. The mechanical valves were the only stability bleed control system yielding large improvements in stability index over the small-volume, fixed-exit values for the complete dynamic range. For the large slot configuration, these improvements were about 13 to 17 points over the range from 1 to 30 Hz. For the porous configuration, the dynamic stability range of the small bleed plenum was improved with valve installation by 30 to 17 points over the range from 1 to 40 Hz.

Concluding Remarks

An experimental program was conducted to evaluate the effectiveness of various types of inlet throat bleed (or bypass) and throat bleed exit controls in providing an increased inlet stable operating range. The following results were obtained:

1. With an inlet operating at a high performance condition, a large stable operating range can be provided by maintaining a near constant plenum pressure on an inlet throat bypass bleed system.
2. Each of the types of bleed tested (normal porous, educated slots, and forward-facing slot) provided a large stability range.
3. For the porous bleed configuration, the inlet steady-state stable operating range (airflow reduction from peak performance to unstart) was 26.0 percent with the self-acting mechanical valves, 10.6 percent with the vortex valves, and 5.4 percent with a small comparable fixed-bleed exit area.
4. For the bleed configurations investigated the forward-facing slot bleed provided the highest bleed recovery.
5. The ability of the inlet utilizing a small bleed plenum with a fixed-exit area to absorb transients increased from a stable subcritical range of 7 percent at 1 Hz to 35 percent at 40 Hz. This increase in tolerance with frequency represents the ability of the inlet diffuser and coldpipe to absorb a transient.
6. Replacing the fixed exit on the small bleed plenum with vortex valves increased the transient stability margin about 5 to 10 percent of engine airflow over the frequency range from 1 to 40 Hz.
7. Replacing the fixed exit on the small plenum with the mechanical valves provided a large transient stability (above 34 percent of the engine airflow for the porous configuration) over the frequency range investigated.
8. A large bleed plenum with a fixed exit provided the largest transient stability at the higher frequencies (a transient stability of 54 percent of engine airflow at 30 Hz for the porous bleed). No improvements over the small plenum volume with a fixed-exit area control was obtained at a frequency of 1 Hz. Such a large bleed plenum might be provided by empty fuel tanks or available nacelle volume.

The stable operating range of the bleed systems investigated may possibly be improved by combining the performance of these systems with the performance of other inlet airflow control hardware. For example, the configuration with vortex valves at the bleed exit would provide a large stable operating range over the complete frequency spectrum if combined with a closed loop controlled high response overboard bypass system (cf, ref. 2). If a large plenum volume with a fixed exit is combined with an overboard bypass, only a moderate bypass frequency response to improve the lower frequency capability would be required to obtain a large capacity over the entire frequency range. Since the mechanical valves have a large transient stability capability at all frequencies, this configuration would only need a relatively slow overboard bypass system that is normally used to match inlet-engine airflow requirements.

Symbols

f frequency

M Mach number

m mass flow rate

P total pressure, lb/ft^2 (N/m^2)

SI stability index, $SI = \left\{1 - \left[\left.\frac{W\sqrt{\theta}}{\delta}\right|_{mins} \Big/ \frac{W\sqrt{\theta}}{\delta}\right]_2\right\}100$

T total temperature, ^{o}R (K)

α angle of attack, degrees

δ $P/2116\ lb/ft^2$ or $P/10.131 \times 10^4\ N/m^2$

θ $T/518.7^{o}$ R or T/288 K

Subscripts:

BY overboard bypass

b bleed

mins minimum stable inlet operation

th inlet throat

0 free-stream conditions

2 compressor face station

References

1. Sanders, Bobby W.; and Cubbison, Robert W.: Effect of Bleed-System Back Pressure and Porous Area on the Performance of an Axisymmetric Mixed-Compression Inlet at Mach 2.50. NASA TM X-1710, 1968.

2. Crosby, Michael J.; Neiner, George H.; and Cole, Gary L.: Restart and High Response Terminal Shock Control for an Axisymmetric Mixed-Compression Inlet With 60-Percent Internal Contraction. NASA TM X-1792, 1969.

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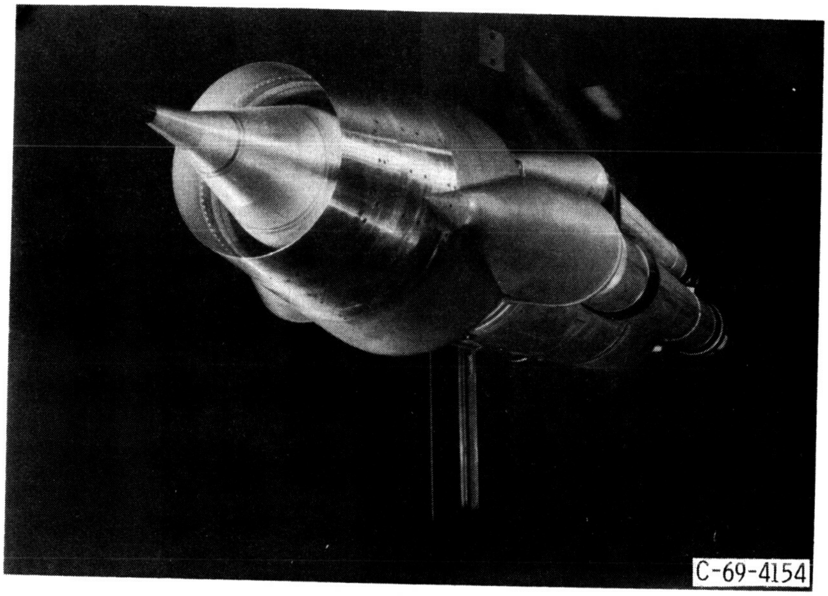
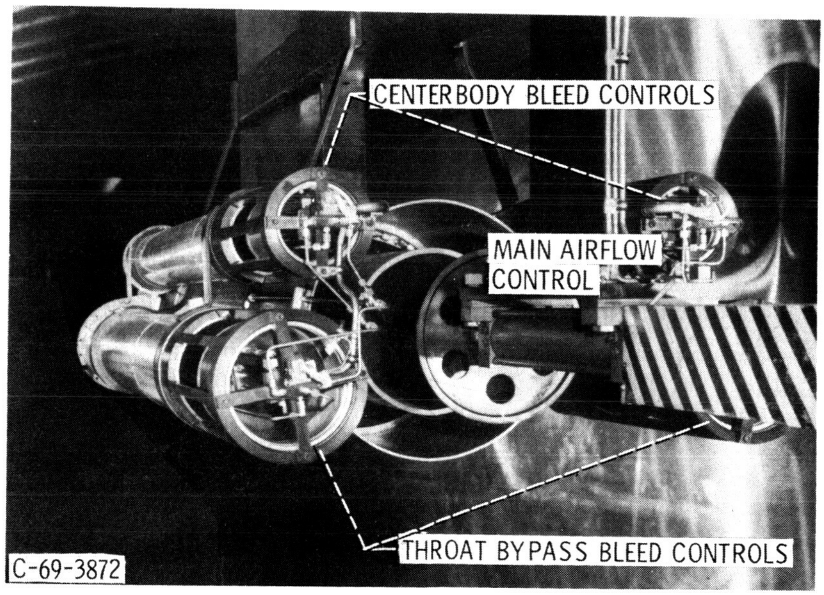


(a) Front view.



(b) Model installation showing choked exit mass flow throttling controls.

Figure 1. - Model installed in the 10- by 10-Foot Supersonic Wind Tunnel.

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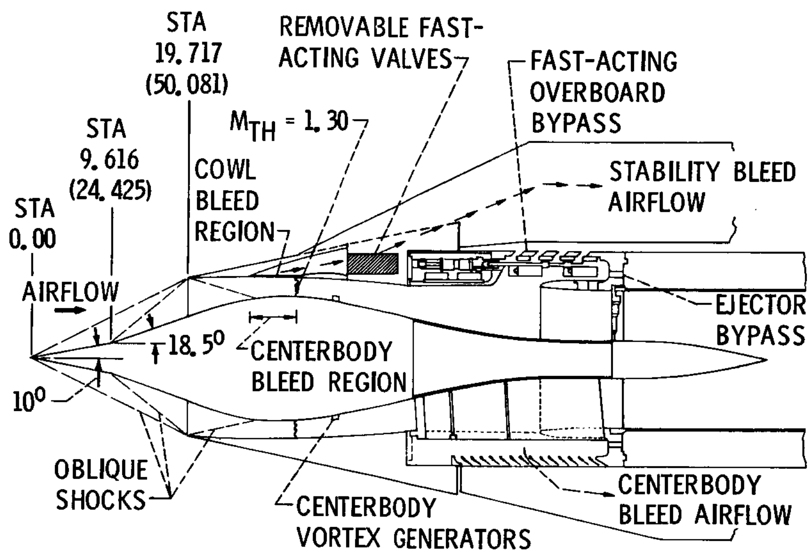

Figure 2. - Inlet details

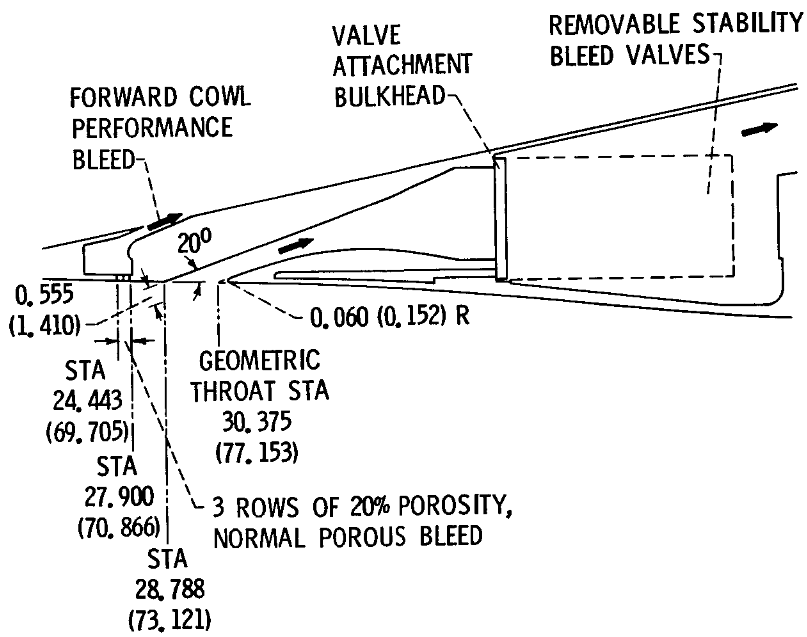

Figure 3. - Sketch of model cowl which includes a forward facing slot throat bypass, dimensions are in inches (cm).

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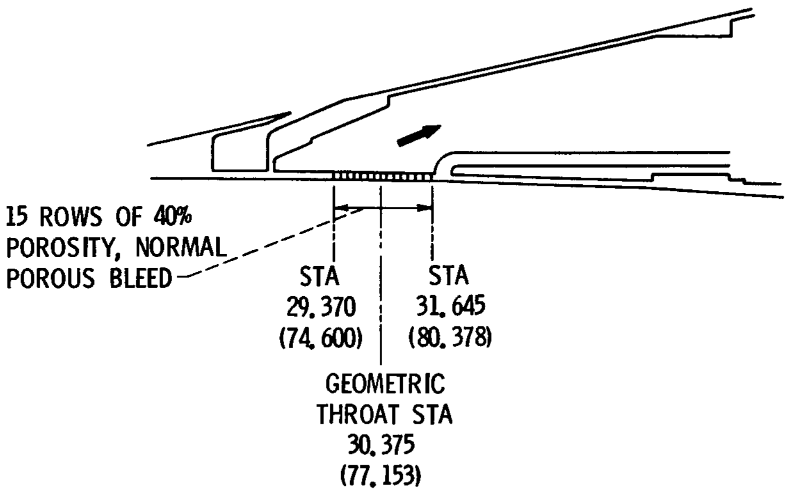

Figure 4. - Distributed porous throat bypass bleed system, dimensions are in inches (cm).

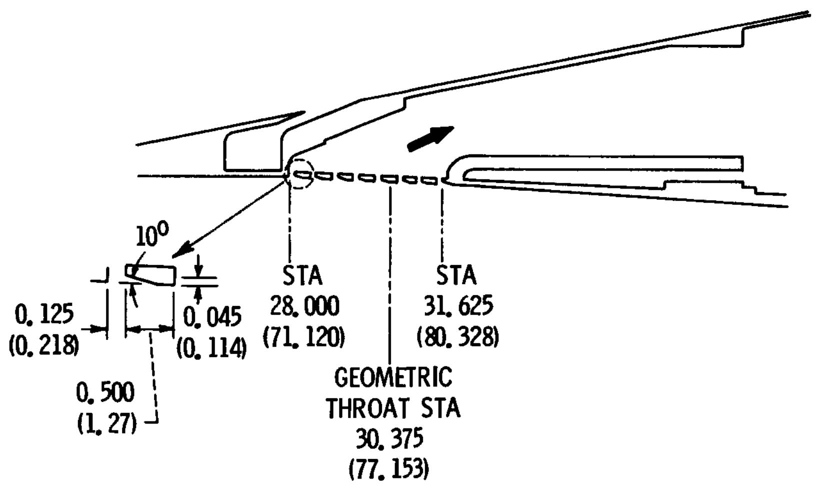

Figure 5. - Distributed educated throat bypass, dimensions are in inches (cm).

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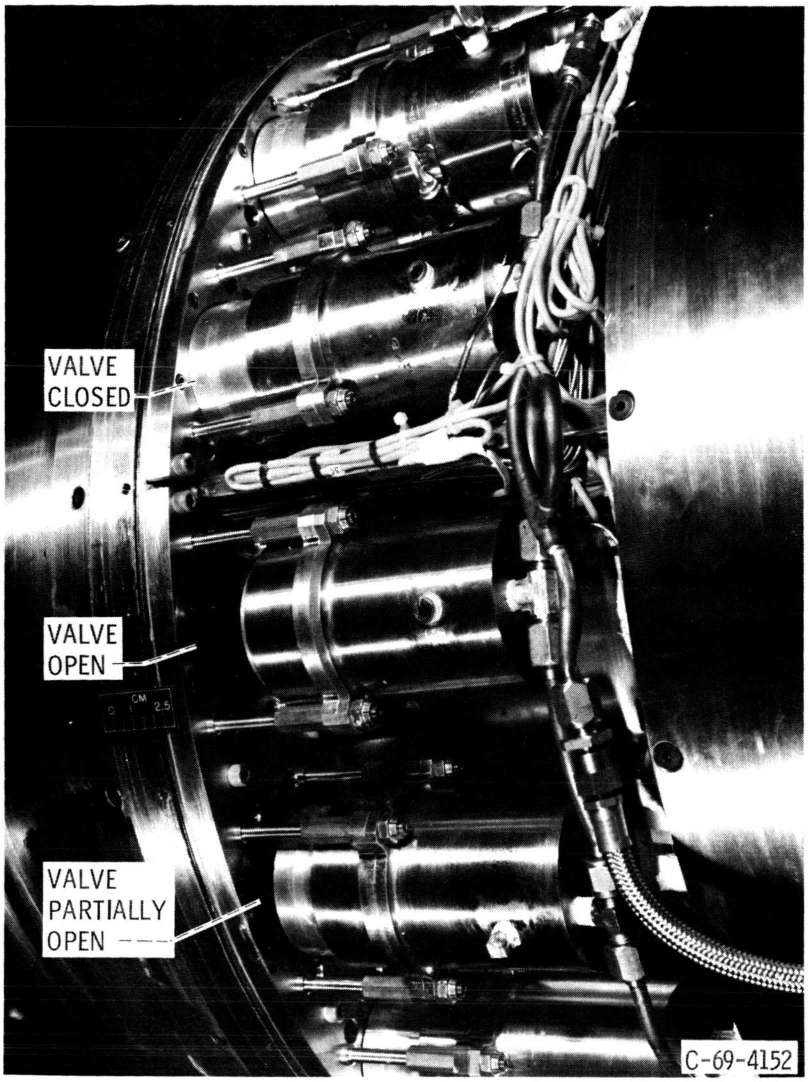
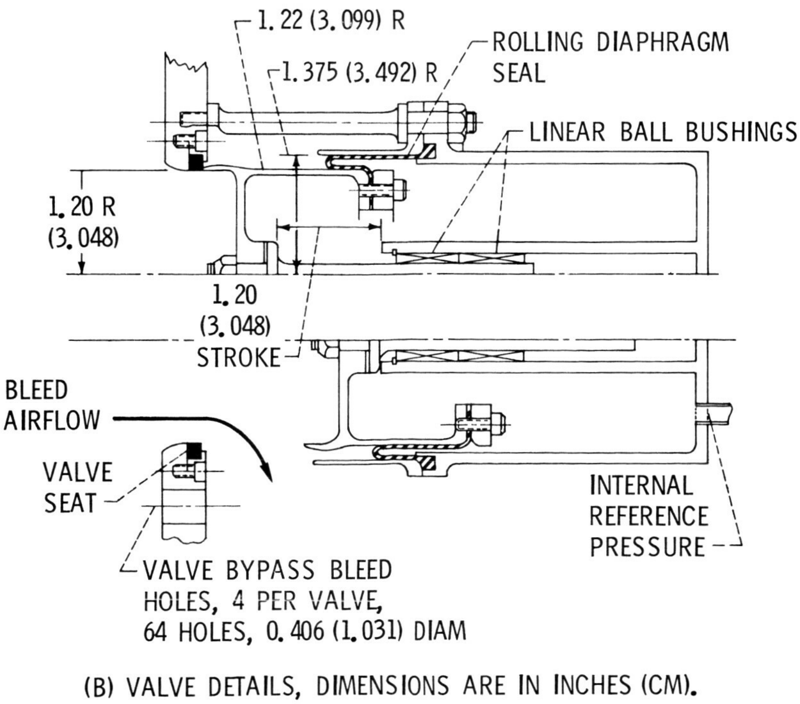


(A) VALVE INSTALLATION, SEVERAL VALVE POSITIONS SHOWN.



(B) VALVE DETAILS, DIMENSIONS ARE IN INCHES (CM).

Figure 6. - Self-acting mechanical valve.

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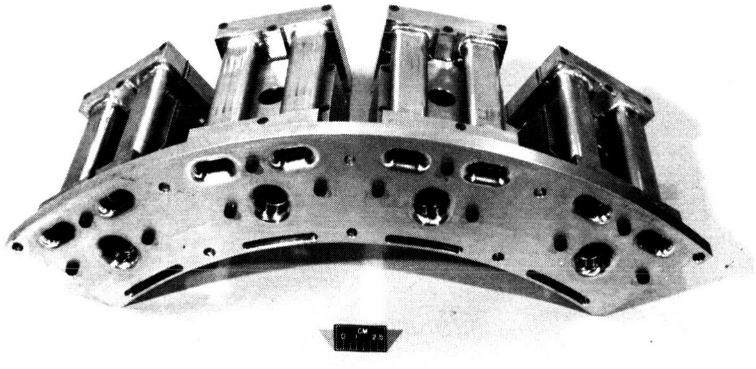

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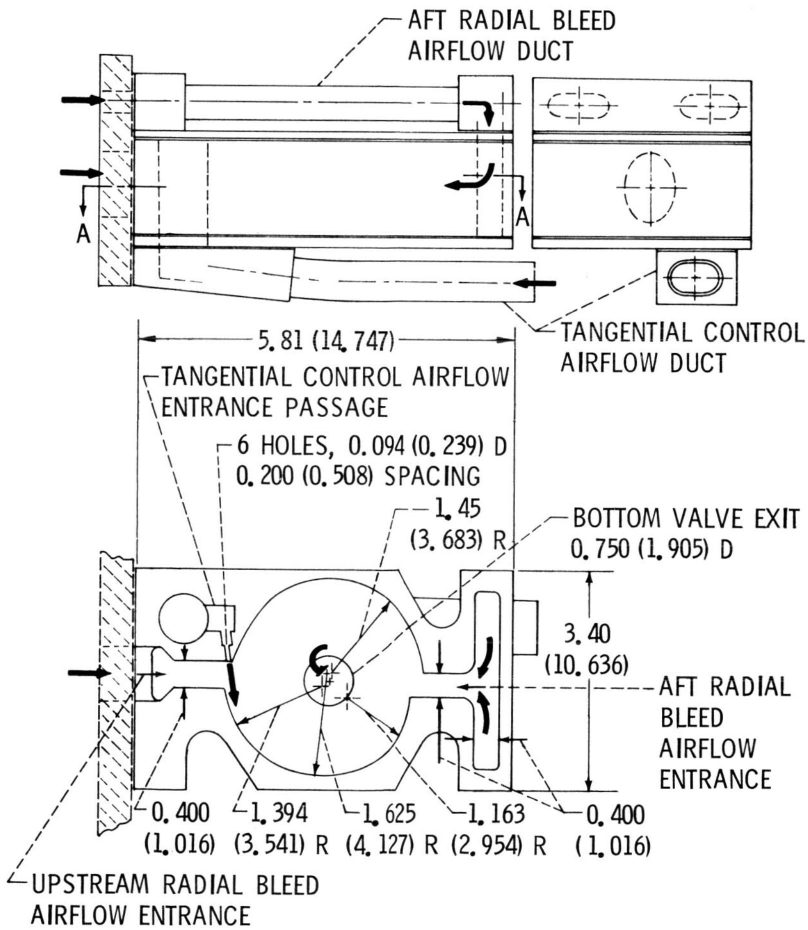
(A) VORTEX VALVES AND MOUNTING PLATE.



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(B) VALVE DETAILS, DIMENSIONS ARE IN INCHES (CM).

Figure 7. - Vortex valve.

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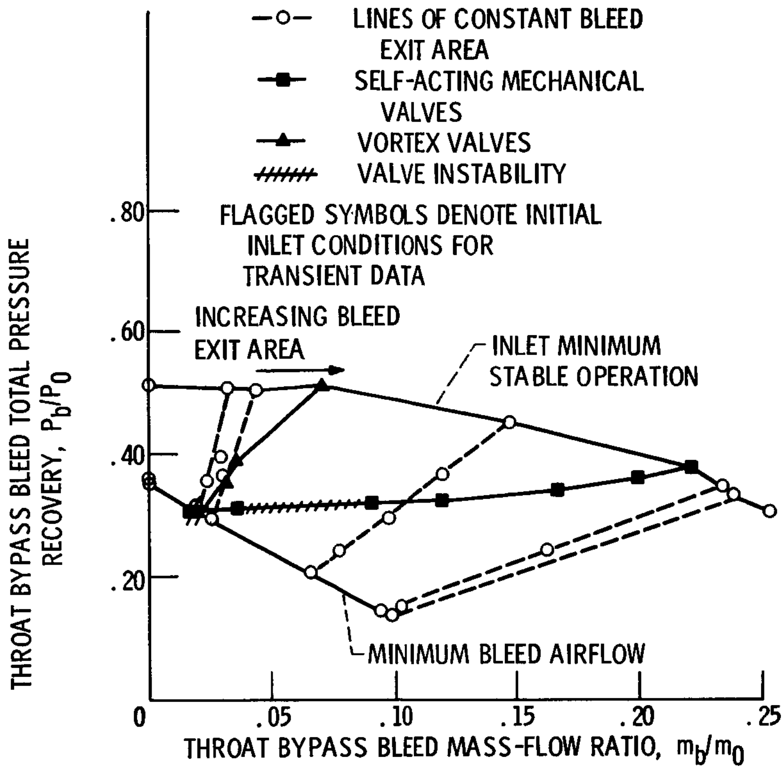
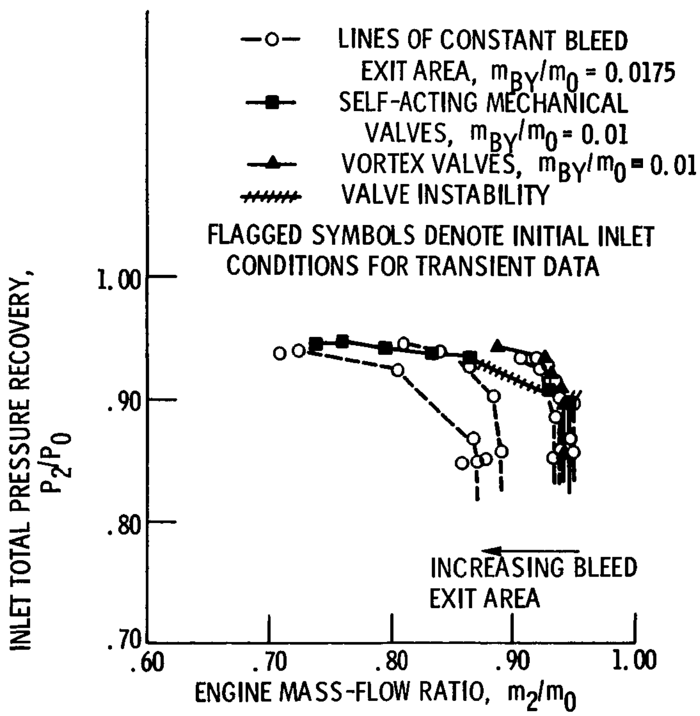


(A) THROAT BYPASS PERFORMANCE.



(B) INLET PERFORMANCE.

Figure 8. - Performance of the distributed porous configuration, $M_0 = 2.50$, $\alpha = 0^\circ$.

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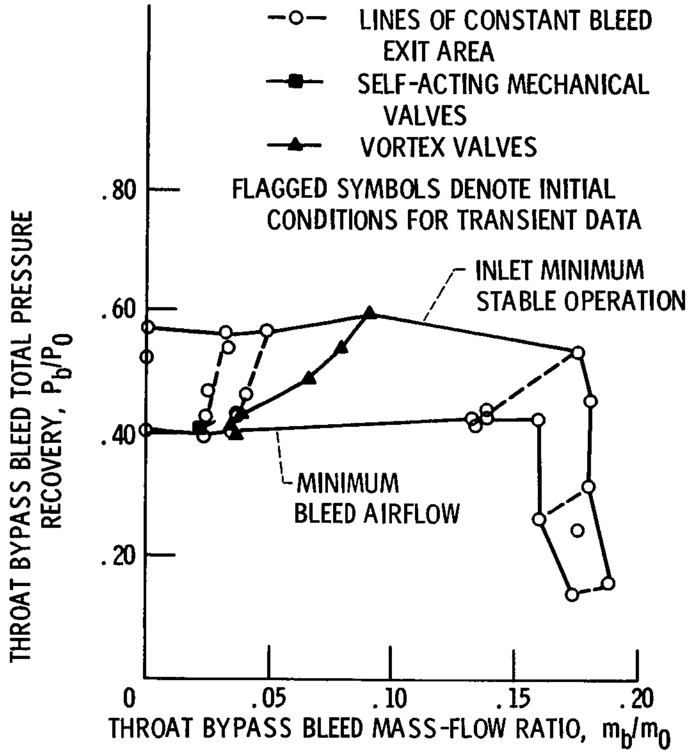
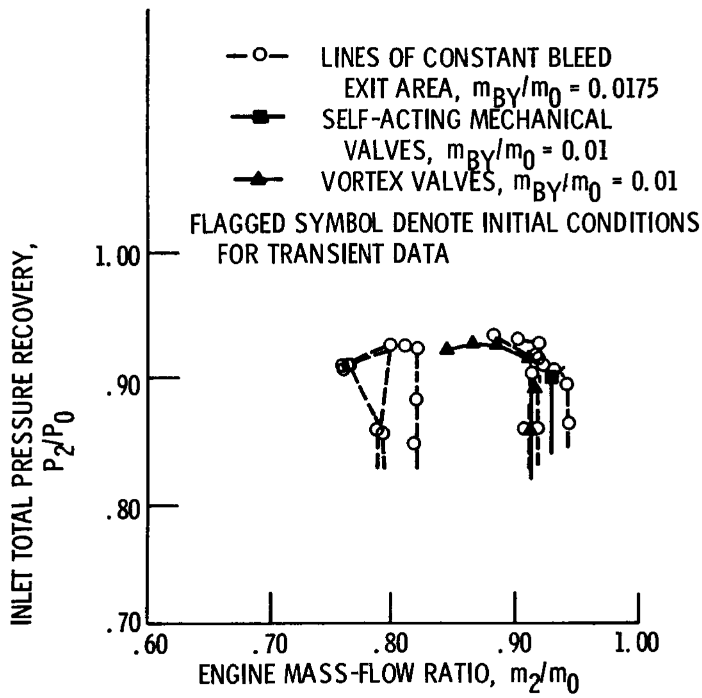


(A) THROAT BYPASS PERFORMANCE.



(B) INLET PERFORMANCE.

Figure 9. - Performance of the forward facing slot configuration, $M_0 = 2.50$, $\alpha = 0°$.

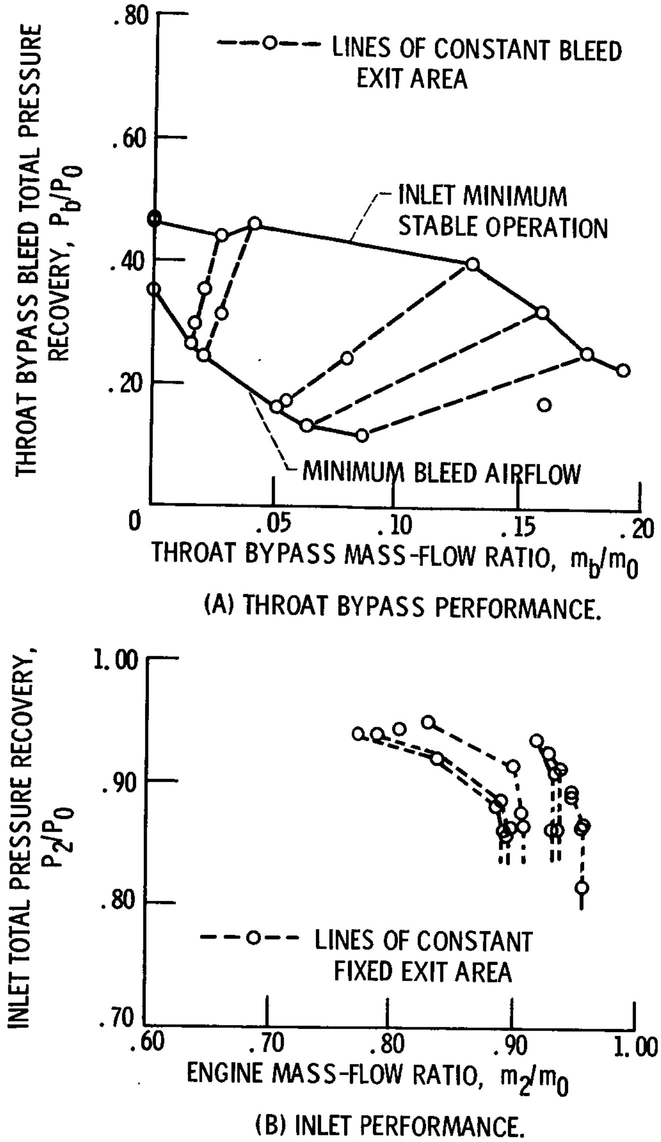


Figure 10. - Performance of the distributed educated bleed configuration, $M_0 = 2.50$, $\alpha = 0^{\circ}$, $m_{BY}/m_0 = 0.01$.

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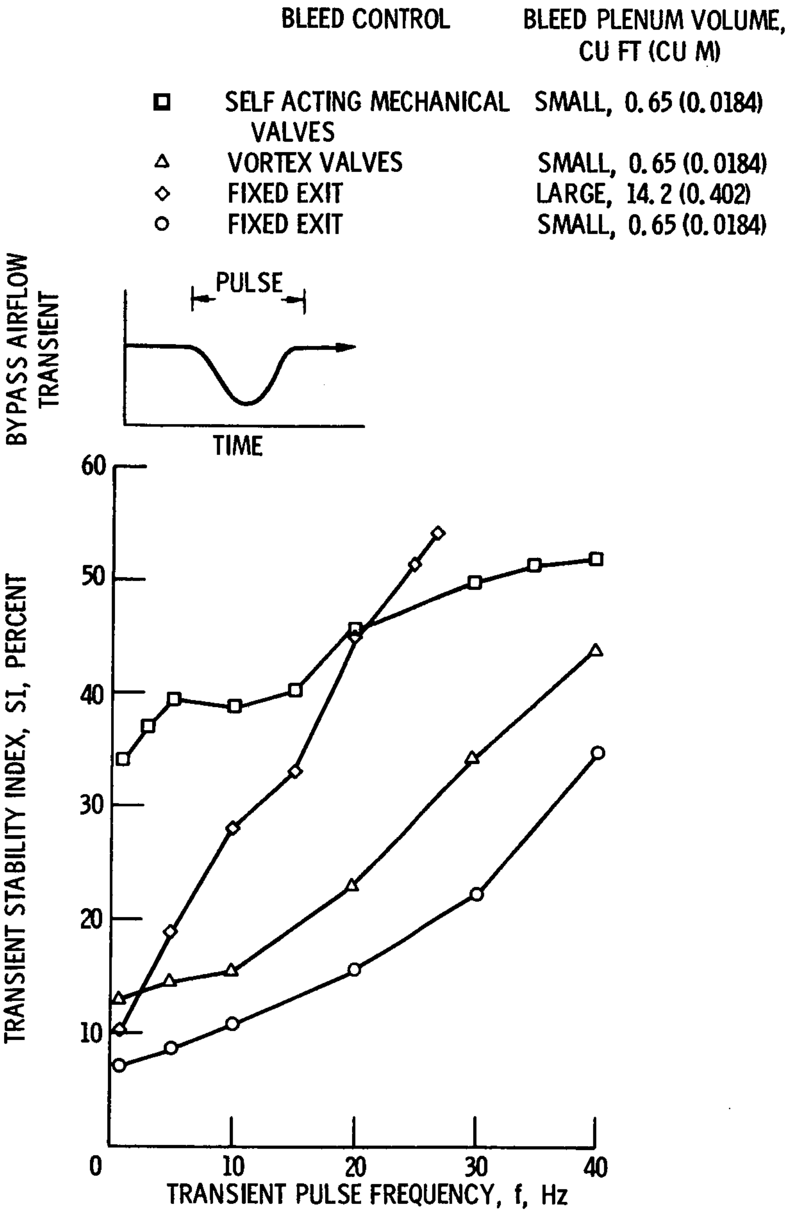
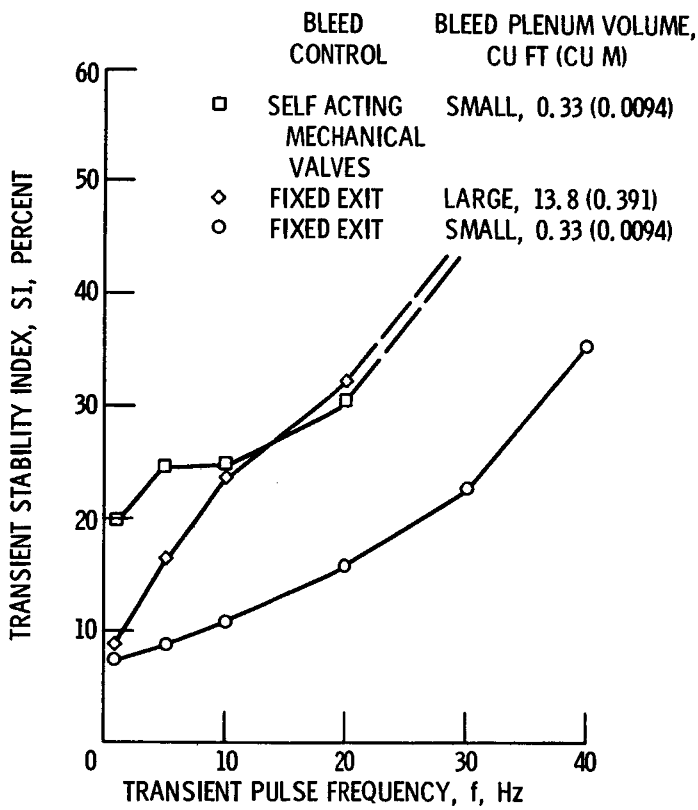


(A) DISTRIBUTED POROUS CONFIGURATION.

Figure 11. - Unstart limits of the inlet system utilizing stability bleed when subjected to transient disturbances, $M_0 = 2.50$, $\alpha = 0^0$.



(B) LARGE SLOT BLEED CONFIGURATION.

Figure 11. - Concluded.