17. STATIC-TEST RESULTS FROM EXHAUST NOZZLES WITH NOVEL FEATURES FOR SUPERSONIC-AIRCRAFT APPLICATIONS

By Fred W. Steffen and Donald L. Bresnahan
NASA Lewis Research Center

SUMMARY

The effects of some geometric variations on the static internal performance and pumping characteristics of plug, auxiliary-inlet ejector, and variable-flap ejector nozzles are presented. The data were obtained in the nozzle static-test facility at the Lewis Research Center. It was concluded that, even though all the exit types can, in principle, provide satisfactory performance over a wide range of nozzle pressure ratios, all the exit types are mechanically complex. The effects of some mechanical simplifications on performance are shown. It was also concluded that ejector nozzles can generally obtain the amount of secondary air anticipated for adequate film cooling from ram air whereas some plug-nozzle film-cooling schemes may require engine-cycle air.

INTRODUCTION

Many types of exits have been proposed for supersonic-aircraft applications. An infinite number of modifications can be made to each of the basic types in an attempt to optimize the performance, pumping, and stability characteristics over the wide range of conditions presented by the supersonic-airplane environment. During the past several years, three types of exits - namely, the plug nozzle, the auxiliary-inlet ejector nozzle, and the variable-flap ejector nozzle - have been tested in the nozzle static-test facility at the Lewis Research Center. These three types of exits are shown in figure 1. In this paper, the effects of a few geometric variables on the internal performance and pumping characteristics of these nozzles are presented.

Internal static performance does not, of course, include external flow effects. At transonic flight conditions, where exits are boattailed and internal flows may be overexpanded, the overall installed performance obtained with external flow would be expected to differ from the internal static performance. However, at takeoff conditions, where external flow velocities are low, and at supersonic cruise conditions, where boattail angles are reduced to zero and internal flows are fully expanded, the internal performance obtained at static conditions would closely approximate the overall installed performance.

SYMBOLS

F	measured gross thrust
F_i	ideal gross thrust
p_o	ambient static pressure
p_t	total pressure
T_t	total temperature
w	weight-flow rate
w_t	tertiary weight-flow rate

Subscripts:

p	primary flow
s	secondary flow

FACILITY

The static-test facility used to obtain nozzle data is shown in figure 2. Its principal components include a mounting pipe suspended from flexure rods within a vacuum tank, a pair of vented labyrinth seals to separate the high pressure of the supply air from the low pressure in the vacuum tank, and a load cell to measure axial force on the mounting pipe and experimental nozzle. Secondary air enters the system through a flexible hose with zero axial momentum. Both primary air and secondary air are at room temperature. The nozzle gross thrust is determined from an algebraic summation of primary-flow inlet momentum, pressure-area forces, and load cell force.

The systematic error in the performance coefficients measured in the facility is essentially determined by the systematic error incurred in calibrating the facility flow measuring station with a nozzle made to ASME (American Society of Mechanical Engineers) specifications. The flow coefficient of the calibrating nozzle is known with an accuracy of ±1/2 percent. Therefore, systematic error in the flow measurement, which directly affects nozzle efficiency, is ±1/2 percent. It is clear that for some supersonic aircraft, where nozzle performance should be known to within 0.1 percent, a more accurate flow calibration method is desirable.

The random error incurred in obtaining an individual value of a performance coefficient (one data point) is about ±1/2 percent. This relatively low value is achieved by minimizing friction forces in the suspension system and making multiple pressure measurements. Further reductions in random error can be obtained by averaging measured flow coefficients and exit momenta (taken at operating conditions where these would be expected to remain constant) and computing performance coefficients based on the average value of these parameters. In this manner, the random error can be reduced to infinitesimally small values and small changes in performance can be detected. Data presented have been averaged and each point represents an average of at least five data points.

PLUG NOZZLE

An exit type which has long been considered for supersonic aircraft is the plug nozzle. A mechanically variable plug nozzle and its internal performance are shown in figure 3. The internal performance is represented by the thrust coefficient which is defined as the ratio of the measured gross thrust to the ideal gross thrust. The basic unshrouded plug nozzle concept provides for a free jet boundary so that the jet can adjust to ambient conditions. An unshrouded plug nozzle design approach is to tilt the throat plane so that, at design pressure ratio, an expansion around the shroud exit will result in axial jet flow. At a subsonic cruise pressure ratio of 6, for example, a throat tilt angle of 22° would be required. With external flow, the large boattail angle and plug angle associated with the 22° tilt angle will cause high boattail drag and overexpansion on the plug surface. In the unshrouded configuration shown in figure 3, a throat tilt angle of 7° and a plug surface angle of 15° are used with the intention of minimizing external flow effects at transonic Mach numbers. For acceleration to supersonic cruise, the plug is collapsed to permit operation of the afterburner (as opposed to other designs which may use a translating plug) and a divergent shroud is fully extended. The divergent shroud has an internal shroud angle of 9°. When cruise conditions are reached, the afterburner is shut down and the plug is expanded to its original position. The divergent shroud, which has a cylindrical exterior and therefore presents no boattail pressure drag, is left in the extended position.

As shown in figure 3, the performance of the takeoff and subsonic cruise configuration decreases with increasing pressure ratio, indicating that regions of local overexpansion on the plug surface are increasing in this pressure-ratio range. At a pressure ratio of 6, the afterburner (A/B) is assumed to be turned on. If only the plug were collapsed, the performance shown by the dashed curve would be obtained. Extension of the divergent shroud enables the acceleration performance shown by the solid curve to be realized. At cruise conditions, afterburner off, expansion occurs along the divergent shroud and plug surface and a high level of cruise performance results. With mechanical variation then, the internal performance of a plug nozzle, as indicated in figure 3, can be maintained at an acceptably high level over a wide range of flight conditions. It should be noted, however, that external flow effects will reduce the performance from that shown at transonic flight conditions.

The effects of some geometric variations on the supersonic cruise performance of the supersonic cruise configuration are shown in figure 4. In figure 4(a), increasing the shroud angle from 5° to 12° decreases the cruise performance by about 1.4 points. In figure 4(b), the effect of plug angle on cruise performance is shown to be very small for plug angles between 10° and

15°. Figure 4(c) shows the effect of reducing plug length by plug truncation. The supersonic cruise performance is decreased a negligible amount as the plug length, measured downstream from the nozzle throat, is decreased from 100 percent to 50 percent but is decreased significantly as the plug length is further decreased. The effects of some of these same geometric variations on the takeoff performance of the takeoff configuration are shown in figure 5. In figure 5(a), the effect of changing the plug angle from 10° to 15° is shown to affect the performance of the takeoff configuration only slightly. Truncation of the plug of the takeoff configuration to about 27 percent of its full length is shown, in figure 5(b), to decrease the performance from $1\frac{1}{2}$ to 3 points, depending on nozzle pressure ratio.

The plug nozzle just shown was designed for a pressure-ratio range from 3.2 to 26.0. Plug nozzles intended for smaller pressure-ratio ranges can be somewhat simplified. A plug nozzle designed for a pressure-ratio range from 2.0 to 12.5 and its performance are presented in figure 6. Although this nozzle design retains the collapsing plug feature for throat area control, the shroud does not translate but contracts for area-ratio variation. This nozzle has small amounts of secondary air introduced through a plug slot for simulated plug cooling flow. The performance of this and succeeding nozzles which have secondary flow is defined as the ratio of the measured gross thrust to the ideal gross thrust of both the primary and secondary flows.

The divergent shroud was considered to be either actuated or freely floating. Floating positions were considered to be limited by stops to an inward angle of 10.5° and an outward angle of 3°. To obtain the performance shown in figure 6, several models with different fixed divergent-shroud positions were run at each pressure ratio. The best performance obtained at each pressure ratio is shown by the solid line. The solid line, therefore, represents the performance that could be obtained if the shroud were held by actuators at optimum expansion conditions. The internal-pressure distribution data obtained during these tests, together with an assumed uniform external pressure, made it possible to calculate the floating position that the shroud would assume at each pressure ratio. The performance of the fixed models with shroud positions set at the calculated floating positions is shown by the dashed line. The dashed line, therefore, represents the reduced performance that would be obtained if the floating-shroud concept is used. Additional calculations showed that, with external flow, typical boattail pressure distributions (as opposed to a uniform static pressure) would not significantly change the floating positions. The reduced boattail pressure would affect the expansion along the plug surface, however, and the performance would be further reduced. It appears, therefore, that the elimination of divergent-shroud actuators from this particular nozzle design would result in some reduction in performance at transonic pressure ratios.

The plug surface in a plug nozzle must be cooled, possibly by film cooling. In figure 7, the measured film-cooling pressure requirements of a particular plug nozzle model are presented as a function of plug flap angle. In the upper part of the figure, the cooling slot arrangement used to obtain these data is also shown. There are two circumferential slots, one at the nozzle throat and another at about 40 percent of the full plug length. It can be seen that to obtain 6-percent corrected secondary flow (an amount which might be required with the afterburner on) at low flap angles (which would exist at these conditions), a secondary total pressure greater than the primary total pressure would be required. Even the minimum secondary-to-primary total-pressure ratio shown in this figure is as high as 0.31. Ram air would not reach this level below a flight Mach number of 1.2. Therefore, this particular plug film-cooling scheme would require air from the engine cycle below this Mach number.

AUXILIARY-INLET EJECTOR

A second type of exit that has been considered is the auxiliary-inlet ejector. The auxiliary-inlet-ejector concept is shown in figure 8. At supersonic cruise flight conditions, an auxiliary-inlet ejector operates as a standard ejector nozzle, with a small amount of secondary air being introduced for cooling. To optimize performance at these conditions, the leading-edge section of the divergent shroud is hinged so that only a small gap exists between the primary and secondary nozzles. At transonic flight conditions, the primary nozzle is mechanically opened for afterburner operation and the leading-edge section of the shroud is mechanically retracted to increase the amount of secondary flow. At subsonic flight conditions, with the afterburner off, internal and external pressure forces are expected to be such that doors on the outside of the nacelle will open and trailing-edge flaps will close, without any need for mechanical actuation. The large amount of tertiary flow which enters the auxiliary inlet is intended to prevent overexpansion of the primary nozzle stream. The last sketch in figure 8 shows the incorporation of a retractable multiple-chute noise suppressor, similar in shape to that used on subsonic engines, into the auxiliary-inlet-ejector design. It was found that chutes of this type, which in this case were probably immersed in supersonic flow, seriously reduced the takeoff performance.

The auxiliary-inlet-ejector design could be somewhat simplified if the mechanically actuated leading-edge section of the divergent shroud could be removed and replaced with a fairing fixed in the retracted position. The effects of removing this section on the cruise performance of a particular configuration are shown in figure 9. Removing the leading-edge section reduced the thrust coefficient by 0.4 of a point while the secondary-to-primary total-pressure ratio required to provide 2-percent cooling flow was essentially unchanged. A thrust coefficient decrement of 0.4 of a point at supersonic cruise conditions may be important for some applications.

VARIABLE-FLAP EJECTOR

A third type of exit is the variable-flap ejector. A schematic view of a variable-flap ejector is shown in figure 10. Fixed models of variable-flap-ejector components are shown in figure 11. The primary nozzle is considered to be actuated whereas the divergent shroud can be actuated or freely floating. Each flap in the divergent shroud is a link in a four-bar linkage. The forward pivot point in the linkage is attached to the primary nozzle so that the leading edge of the divergent shroud can follow the movements of the primary nozzle. Each flap of the divergent shroud may have several slots to promote detachment and stability of the primary jet at low area ratios and low pressure ratios. These slots can be seen in the divergent-shroud model shown in figure 11(a). Some models of this ejector had star-shaped primary nozzles. A model of a star-shaped primary nozzle is shown in figure 11(b). The star-shape design permits the leaves to fold upon one another for primary-nozzle area variation. The performance of a variable-flap ejector with a star-shaped primary nozzle and slotted flaps is shown in figure 12. Both the cruise and takeoff thrust coefficients are acceptably high. The available and required secondary-to-primary total-pressure ratios are also shown in this figure. The available secondary pressure is considered to be the total pressure available at the engine face. At supersonic cruise, the secondary-to-primary total-pressure ratio required for 2-percent corrected secondary cooling flow was well below the available amount. To obtain the takeoff thrust coefficient shown in this figure, almost all the secondary-to-primary total-pressure ratio available must be used. This result suggests that the secondary flow for takeoff, which amounts to about 4 percent of the primary flow, would have to be taken aboard through inlets located close to the ejector to minimize duct losses.

CONCLUSIONS

The effects of some geometric variables on the internal performance of plug nozzles, auxiliary-inlet ejectors, and variable-flap ejectors have been presented. It is concluded that:

1. All the exit types discussed can, in principle, meet the performance requirements of supersonic aircraft.

2. All the exit types are mechanically complex.

3. The ejector nozzles can generally obtain the amount of secondary air anticipated for adequate film cooling from ram air whereas some plug-nozzle film-cooling schemes may require engine-cycle air.

EXITS

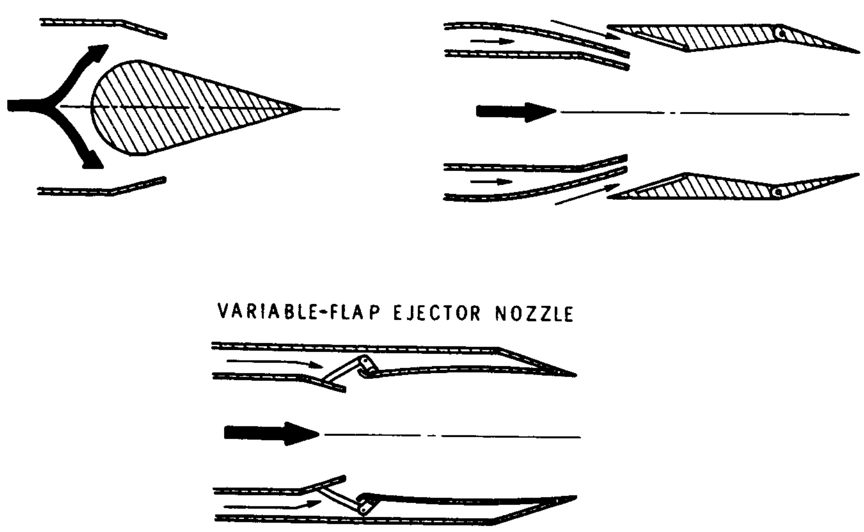

Figure 1

NOZZLE STATIC-TEST FACILITY

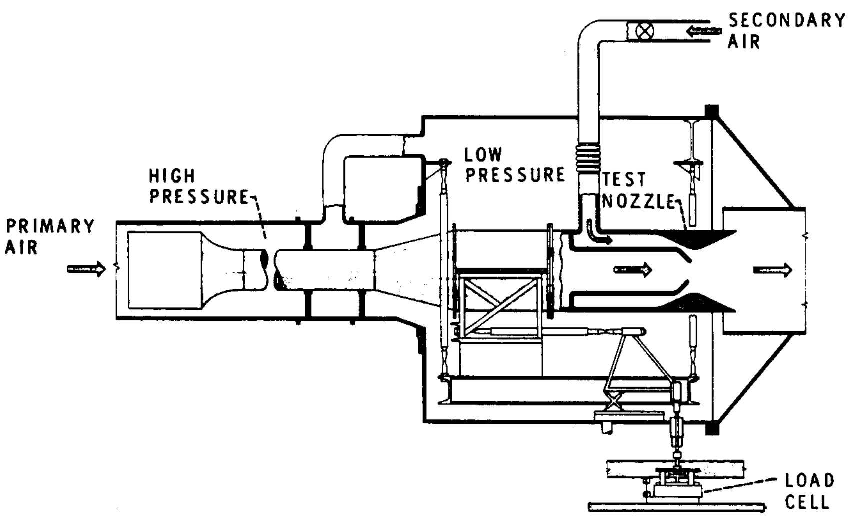

Figure 2

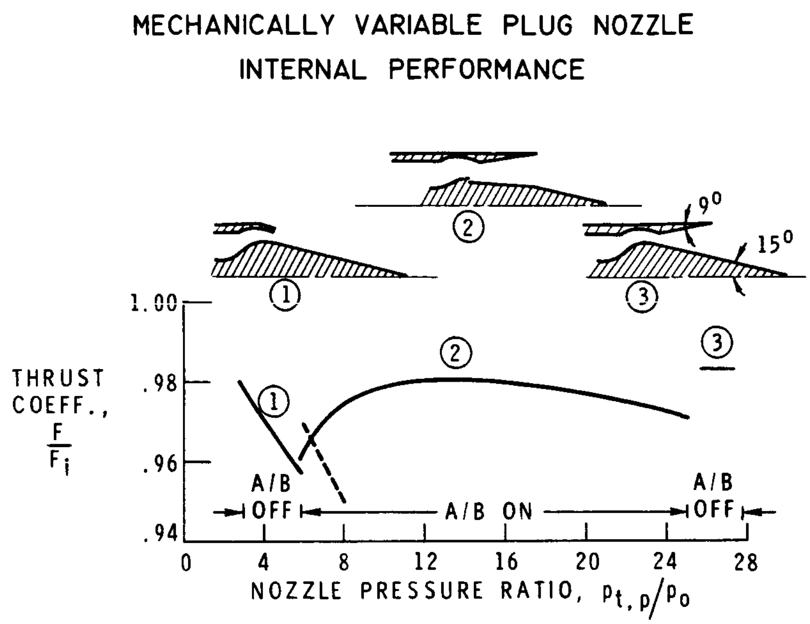

Figure 3

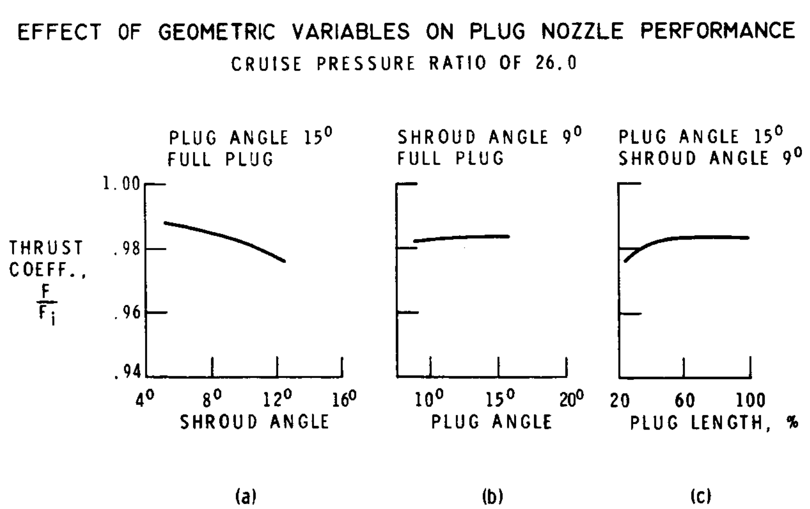

Figure 4

EFFECT OF GEOMETRIC VARIABLES ON PLUG NOZZLE PERFORMANCE

TAKEOFF PRESSURE RATIOS

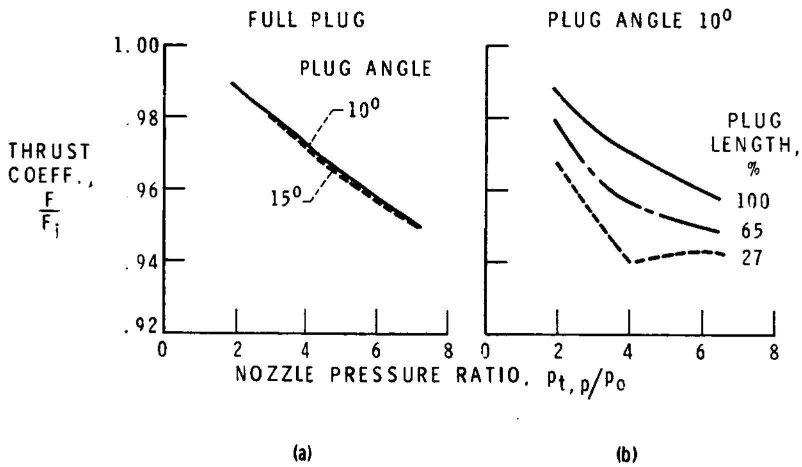

Figure 5

FLOATING SHROUD VARIABLE PLUG NOZZLE PERFORMANCE

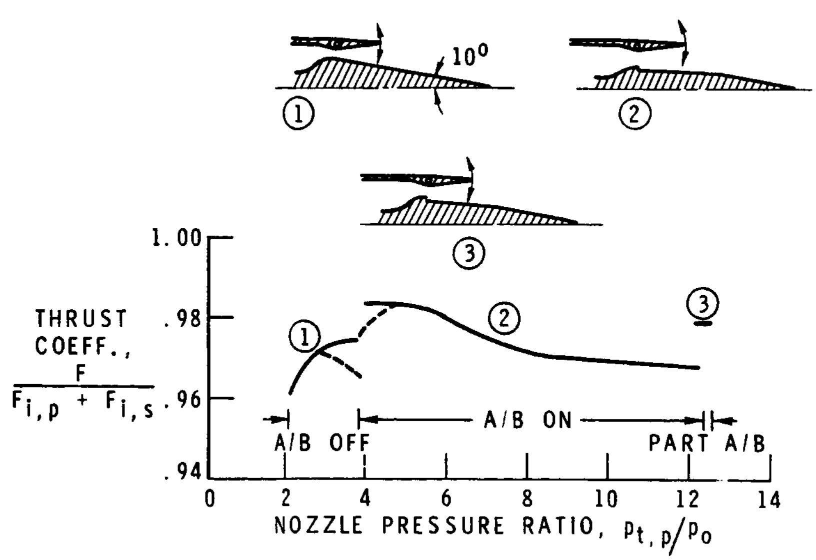

Figure 6

PRESSURE REQUIREMENTS FOR PLUG FILM COOLING

$p_{t,p}/p_o > 3.0$

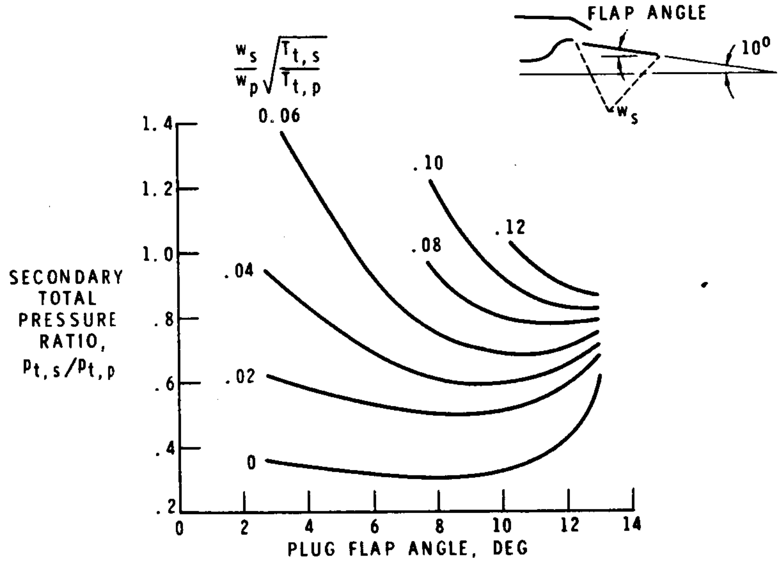

Figure 7

SCHEMATIC VIEW OF AUXILIARY-INLET EJECTOR

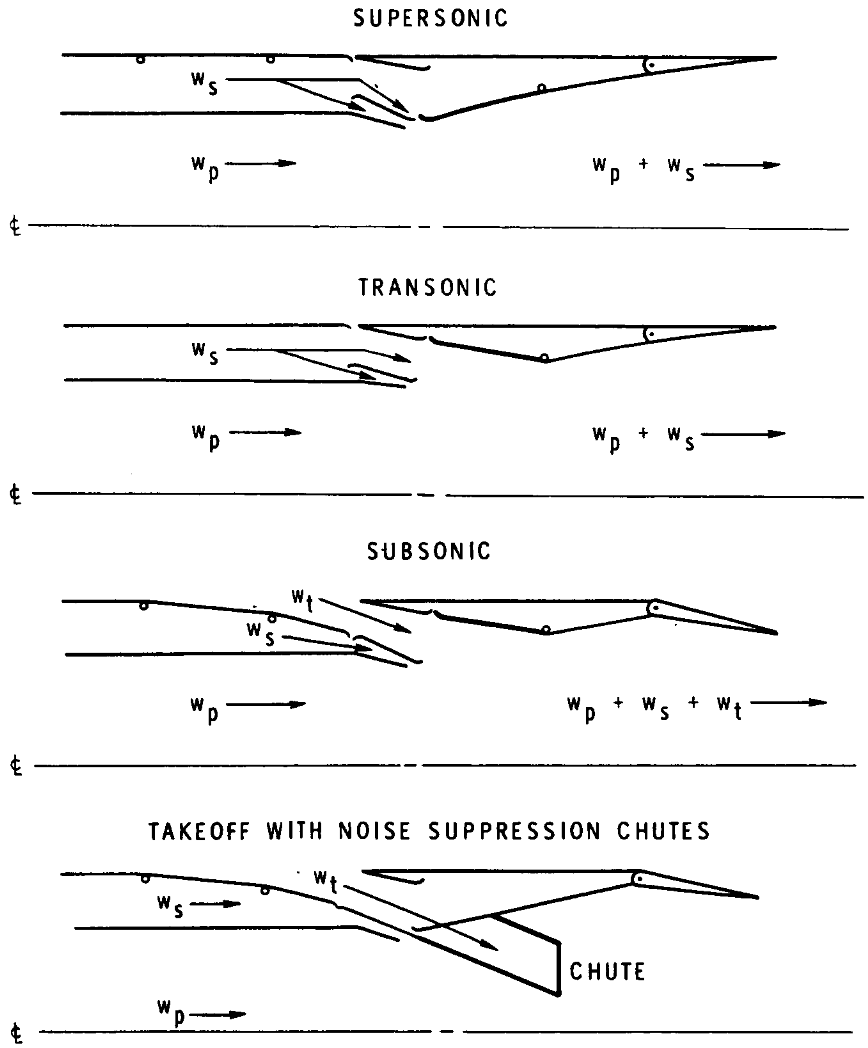

Figure 8

CRUISE PERFORMANCE AND PUMPING CHARACTERISTICS OF AN AUXILIARY-INLET EJECTOR

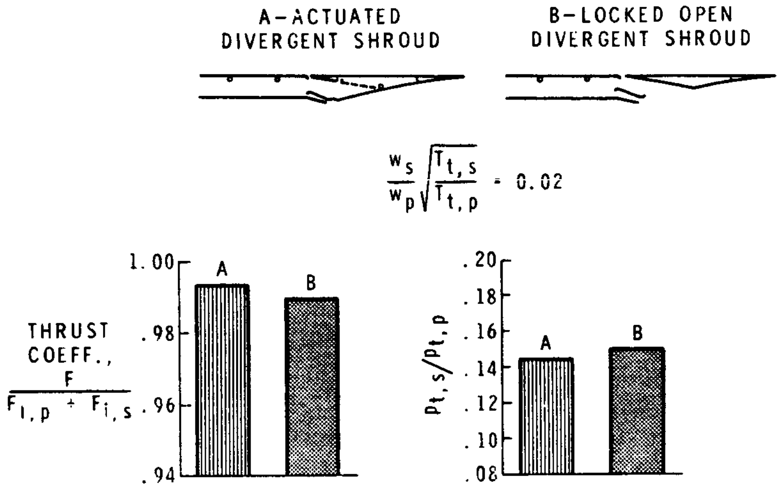

Figure 9

SCHEMATIC VIEW OF VARIABLE-FLAP EJECTOR

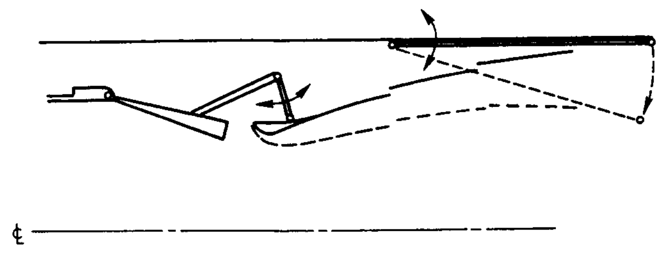

Figure 10

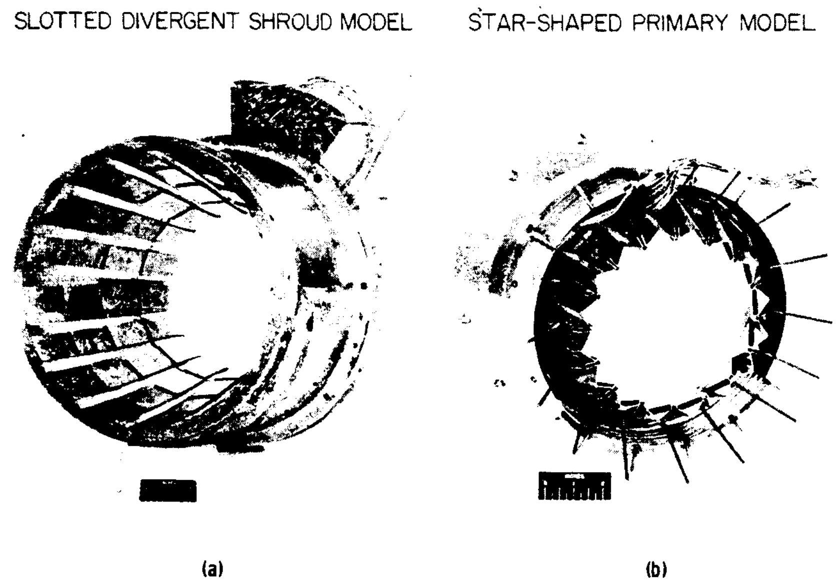

Figure 11

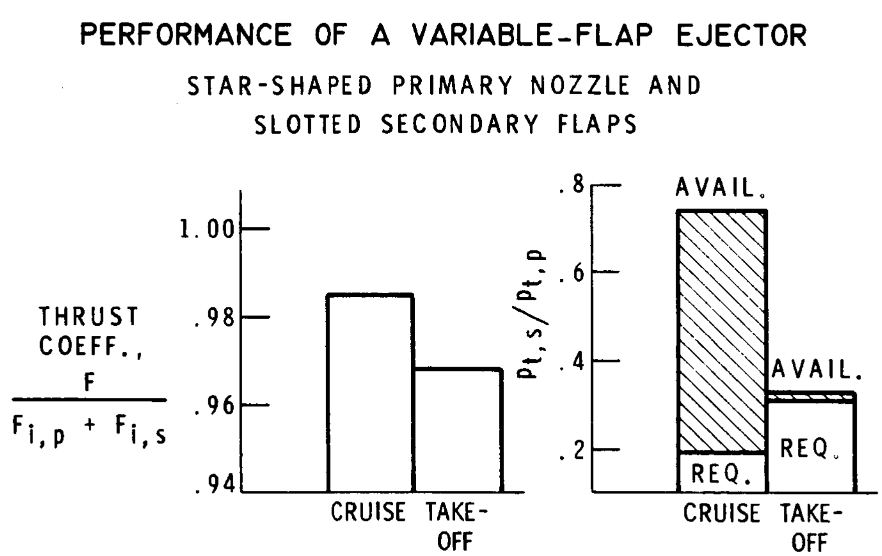

Figure 12