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RESEARCH MEMORANDUM

EXHAUST NOZZLES FOR SUPERSONIC FLIGHT WITH TURBOJET ENGINES

By Thomas B. Shillito, Donald P. Hearth, and Edgar M. Cortright, Jr.

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

WASHINGTON

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SUMMARY

Performance levels currently obtainable with various nozzle types were reviewed. Particular attention was devoted to special problems associated with plug and ejector nozzles.

It is shown that the excellent off-design thrust characteristics measured with plug nozzles in quiescent air may not materialize in some flight installations due to jet-stream interaction effects. Preliminary attempts to cool a plug with compressor bleed air have been generally successful.

Experiments indicate that variable ejectors will require divergent shrouds to remain efficient at Mach numbers much above 1.8. The secondary air flow for the ejector may be efficiently provided by either fixed auxiliary inlets or a bypass from the main engine air inlet. In the latter case, the bypass can serve to help match the inlet to the engine.

INTRODUCTION

During the early history of the turbojet engine, the exhaust-nozzle-design problems were relatively simple. A properly sized, convergent, conical restriction installed on the end of the tailpipe gave good performance without requiring in-flight size adjustment. Afterburners introduced the complication of variable exit area. A convergent nozzle was still adequate for good performance, however, at all flight conditions attainable by the initial afterburner-equipped airplanes. Supersonic flight speeds create additional complications, because a variable-area exit restriction is still required and nozzles with the design-point performance characteristics of converging-diverging nozzles are desirable. A simple converging nozzle will not give the required efficiencies at high flight speeds.

Some nozzles that have been considered for high-speed flight are the variable convergent-divergent nozzle, the plug nozzle, and the variable-shroud ejector nozzle (fig. 1), all of which are assumed to have variable throats. The divergent shroud, which is indicated for the ejector nozzle, is required for efficient operation above a Mach number of 2.

Of the three nozzles, the one with the greatest mechanical complication would appear to be the variable convergent-divergent nozzle because the hinge point providing exit-area variation must be translated radially as the throat area is varied. (An iris-type construction is assumed.) Only one mechanical variable, throat area, is required for the plug nozzle. Although hinge points are required in the ejector for varying both throat area and exit area, they are mechanically isolated from each other. These different degrees of mechanical complexity are factors which have to be weighed against the obtainable in-flight performance for the nozzles.

Various aspects of these nozzles have been investigated at the NACA Lewis laboratory in the past few years. The more important and some of the most recent results obtained in these investigations are discussed in this report.

RESULTS AND DISCUSSION

Tests in quiescent air (refs. 1 to 5) indicate that any of the three nozzles discussed can be designed to give good efficiency at a given pressure ratio. This is shown in figure 2, where net thrust ratio is given as a function of flight Mach number. The net thrust ratio is defined as the ratio of the net thrust of the nozzle or ejector system to the net thrust ideally available from the engine exhaust. For the examples shown in figure 2, the nozzle pressure ratio varied from about 2.0 at takeoff to about 25.0 at a Mach number of 3.0, according to a preselected flight schedule. The break in the curves at a Mach number of 0.8 is caused by a change from nonafterburning to afterburning operation of the engine.

The top curve is the locus of design-point performance obtained experimentally for the variable convergent-divergent nozzle, the plug nozzle, and the variable-shroud ejector nozzle. These three nozzles gave essentially the same performance over the entire range of conditions considered. Even at a Mach number of 3.0, about 95 percent of the ideal net thrust can be obtained with any one of the nozzles. For the convergent nozzle, shown by the bottom curve, less than 70 percent of the ideal net thrust is available. The middle curve is a locus of design-point performance for conventional ejectors. A conventional ejector nozzle is one with either a convergent or cylindrical shroud similar to the types reported in references 6 to 8. This curve for conventional ejectors shows the best performance that can be obtained with nondivergent ejectors and illustrates the value of shroud divergence at high operating pressure ratios (high Mach numbers).

In the following sections, the performance characteristics and some of the special design requirements of the plug nozzle and the variable-shroud ejector nozzle are examined.

Plug Nozzle

Operating characteristics. - Quiescent-air tests indicate excellent off-design characteristics for the fixed-plug nozzle. External flow can, however, have adverse effects on the off-design performance of plug nozzles. A brief review of the operating principles of plug nozzles will help to explain the occurrence of these adverse effects of external flow.

In figure 3, the flow conditions and expansion processes for plug nozzles operating in quiescent air and with external flow are illustrated. Operation at a design-point pressure ratio H_j/p_0 (where H_j is nozzle total pressure and p_0 is ambient pressure) of 14.0 (flight Mach number, 2.5) and at an off-design pressure ratio of 4.0 (flight Mach number, 0.9) is illustrated. When the nozzle is operating at the design pressure ratio in quiescent air (fig. 3(a)), the jet executes a turn outward at the edge of the flap and leaves the nozzle in an axial direction. The expansion fan from the edge of the flap causes the pressure to decrease along the plug surface and to reach ambient pressure at the plug tip.

With external flow, the local pressures in the vicinity of the flap may drop below ambient pressure in some installations because the external flow expands around the corner formed by the flap and the afterbody. At the design pressure ratio (fig. 3(c)), these low pressures cause drag on the flap. The low pressures in the region of the flap do not alter the internal performance of the nozzle at the design pressure ratio from that obtained in quiescent air because any local overexpansions in the jet do not occur on the plug surface. Some slight improvement over quiescent-air thrust might even occur, if the shock caused by interference between the jet and the external flow is strong enough to move onto the surface.

When the nozzle is operating at a low pressure ratio in quiescent air (fig. 3(b)), expansion of the jet from the flap lip proceeds only until the plug surface pressure reaches ambient pressure; downstream of this point the flow recompresses. With external flow, however, the low pressures in the region of flap, in addition to causing flap drag, make the jet overexpand, lowering the plug pressures and causing an internal thrust loss. The over-all effects can be very serious since, even at subsonic flight Mach numbers (fig. 3(d)), local supersonic Mach numbers with accompanying large decreases in pressure can exist in the region of the flap.

Some examples of the magnitude of stream effects on plug-nozzle performance are shown in figure 4, where net thrust ratio is shown as a function of flight Mach number for an afterburning plug-nozzle geometry. The uppermost curve is based on data obtained in quiescent air and is shown for reference. In addition, data are shown for the performance of plug nozzles installed in three different afterbodies at high subsonic speeds. The indicated nozzle performances include flap and plug pressure forces, but neglect forces on afterbody surfaces ahead of the flap hinge line. Flap drag is considered zero where base pressure equals ambient static pressure. The data are not corrected for wind-tunnel-wall interference; such a correction would make the stream effects slightly more adverse than indicated.

At the design point having a Mach number of 2.5, flap drags of from 2.5 to 4.0 percentage points are estimated to occur. Much larger stream effects can occur in the cruise range of a Mach number of 0.9, however. For example, the data show that the nacelle-type installation with a cylindrical afterbody and a discontinuity at the flap (configuration A, fig. 4) exhibits thrust more than 12 percent lower than indicated by quiescent-air tests. Of the over-all reduction of 12 percent, about 6 percent was due to flap drag and 6 percent was due to reduced plug pressures. These data were obtained in the facility of reference 9.

When the nozzle hinge line was preceded by a boattail or rounded fairing (configurations B and C, fig. 4), the flap base pressures were much nearer ambient, and the flap drag and plug overexpansion losses were thus reduced. The resulting performance was correspondingly nearer quiescent-air levels. It may even be possible in some installations, to realize higher off-design nozzle thrust than quiescent-air tests would indicate. This situation might occur if nozzle installations behind highly boattailed bodies resulted in base pressures above ambient and plug pressures higher than measured in still air.

Several additional possibilities of reducing the sensitivity of plug nozzles to stream effects appear worthy of investigation at this time. These include reduction of the flap angle either through the use of partial internal expansion or by merely reducing the angle from the theoretical value. Limited experience has shown that at least a 10° reduction is possible without changing the plug contour. In addition, variable fairings and boundary-layer control at the hinge line appear of interest at cruising speeds.

Any final evaluation of nozzle off-design performance must consider the performance of the nozzle-afterbody combination including boattail drag. At high subsonic and transonic speeds in particular, the boattail pressure drag is influenced by the nozzle type and it could be misleading, when comparing nozzles, to only consider plug and flap pressures, as was done in figure 4.

Cooling. - The plug and supporting struts of a plug nozzle require a special cooling system. Experiments conducted on a full-scale nozzle have shown that about 2 percent of the engine air flow is required to cool the plug-nozzle surface and supporting struts at an afterburner-outlet temperature of 2800° F. A photograph of this nozzle in operation on a 32-inch afterburner is shown in figure 5. In this photograph, the flow is from left to right. The plug was film-cooled by air flowing parallel to the plug surface from nine circumferential slots. Some of these slots can be seen in the photograph.

The light and dark patterns shown in figure 5 are typical for an afterburning run and show that the surface temperature had a more or less regular pattern of hot and cool zones. This is believed to be caused primarily by nonuniformities in the afterburner-outlet temperature. The cooling-air requirements for the nozzle were established by setting a limit of 1800° F for the hot zones of the plug surface to ensure structural soundness for the nozzle.

The cooling-air-flow requirements are shown in figure 6 as a function of exhaust-gas temperature. At an exhaust-gas temperature of 2800° F, 2 percent of the engine air flow was required to cool the plug surface and limit the hottest zones of the plug surface to 1800° F. The data for the curve shown on figure 6 were obtained at an afterburner pressure of about 4000 pounds per square foot. At the surface temperature of 1800° F the nozzle operated satisfactorily and, except for some surface rippling, maintained its structural integrity. The full-scale plug nozzle was operated for a total of 12 hours with afterburning.

Ejector Nozzle

The ejector nozzle also has a number of important problems associated with its use. Figure 2 shows that a divergent-shroud ejector is required for good performance at high Mach numbers. This is shown again in figure 7, where net thrust ratio is given as a function of flight Mach number for a fixed-shroud divergent ejector with a design Mach number of 2.0 and for a fixed-shroud conventional ejector. At Mach numbers greater than 2.0, the divergent-shroud ejector gave much better performance than the conventional ejector. This improvement is especially significant, since the curve for the conventional ejector is near the locus of maximum performance obtained with this type of ejector nozzle.

The fixed divergent shroud does, however, compromise the performance at low Mach numbers where low over-all pressure ratios exist. Losses in performance result from overexpansion in a manner similar to that occurring in a convergent-divergent nozzle. These losses could obviously be eliminated by use of a variable shroud, which would reduce the physical expansion ratio at low pressure ratios. In fact, test results show that the performance of a given variable-shroud ejector configuration will follow the dashed curve closely, which indicates the locus of maximums for ejectors.

The curves shown in figure 7 for both the conventional and divergent ejectors are based upon quiescent-air tests. Their geometries are such that they may be susceptible to the effects of external flow (refs. 10 and 11) and their performance at low Mach numbers would probably not be as good as shown. A variable shroud would therefore appear to be doubly desirable at low Mach numbers, so that the shroud-exit diameter could be reduced to the point where external flow would not adversely affect the internal performance. However, reducing the shroud exit diameter increases the flap angle and tends to produce high-drag afterbody geometries. Therefore, when control can be exercised in the design of variable-shroud ejectors, steep flap angles should be avoided.

The effect of flap angle on the ratio of flap drag to net thrust is shown in figure 8. The curve shown in figure 8 is for a nacelle-type installation with a cylindrical afterbody (solid lines in inset sketch) operating at a Mach number of 0.9 without afterburning (ref. 9). The drag increases rapidly with increasing flap angle. Effective net thrust losses from 12 to 14 percent result at flap angles greater than 40°.

As with the plug nozzle, the severity of adverse stream effects depends on the type of body in which the ejector is installed. Boattailing ahead of the flaps, which would be characteristic of a fuselage engine installation and which is indicated by the dashed lines in the sketch in figure 8, has been found to eliminate the drag losses on the flap in the cases tested at high subsonic speeds. The datum point shown was obtained with a flap angle of 45° preceded by an 8° boattail. As was pointed out in the discussion of the plug nozzle, more gentle turning at the flap-forebody junction may also reduce external drag, even if the flap is preceded by a cylindrical body. Also, as with the plug nozzle, attainment of ambient static pressure on the flap and, thus, realization of quiescent-air nozzle performance is not necessarily the best than can be done. In the boattail body studied, for example, use of lowered flap angles could probably result in flap pressures above ambient and in flap thrust as defined in this figure (see ref. 9). The advantages of reduced flap angle are expected to be less than in the nacelle configuration, however. Further experimentation is required to resolve this problem for various nozzle installations.

Up to this point, little consideration has been given to the source of the ejector secondary-air flow. One source of this flow is auxiliary inlets mounted on the airframe upstream of the exit. An explanation of this system and the matching problems involved is given in reference 12. Such an over-all system is reported in reference 13. Representative auxiliary-inlet performance (refs. 13 and 14) was used in preparing the following curves.

If the auxiliary inlet were located in the free stream, relatively high pressure recovery would be available. The resulting high secondary pressure would allow the ejectors to handle large amounts of secondary-air flow. However, for most ejectors at higher flight speeds, the net thrust reaches a maximum at a secondary weight flow less than the maximum possible if the free-stream inlet were operated close to its maximum pressure recovery. Because of this (fig. 9), location of the inlet in the boundary layer results in slightly higher net thrust, although the pressure-recovery capabilities of the inlet have been reduced.

The gains made possible with divergent ejectors by location of the auxiliary inlets in the boundary layer are small, less than 1 percent at a Mach number of 3.0. For conventional ejector nozzles the gains are greater, since the net thrust performance of those ejectors is more sensitive to changes in secondary flow.

When an auxiliary inlet is being designed for an ejector, the question arises as to whether it must be variable or whether a fixed inlet of the proper size can be designed to provide good performance over an entire flight plan. In figure 10 the net thrust performance is shown for the following three fixed inlets: a large inlet that gives good performance at low Mach numbers, but poor performance at intermediate Mach numbers; a small inlet that gives good performance at high Mach numbers, but is poor for cruising conditions; and a so-called compromise size that gives moderate to good performance over the entire Mach number range. Also shown in figure 10 is the performance of a variable inlet capable of supplying the optimum ejector flow at all flight conditions. The large fixed-size inlet suffers from subcritical additive drag at intermediate Mach numbers, whereas the small inlet throttles the secondary flow at low Mach numbers so that internal performance losses result. An inlet between these two extreme sizes results in a compromise design which compares favorably with the performance of a variable auxiliary inlet.

The effects shown in figure 10 are typical of other ejector-nozzle types and of other locations of the auxiliary inlet. It appears, therefore, that a fixed auxiliary inlet can efficiently supply the secondary air flows for ejector exhaust nozzles. Careful consideration of the inlet size is required, however.

Another source of the ejector secondary air flow is the main inlet. For this system, the main inlet may be fixed and all excess air flow delivered by the inlet, but not required by the engine, would then be bypassed around the engine to the ejector. This would result in critical inlet performance over the entire flight plan without the complication of a variable inlet. Elimination of the auxiliary inlet for the ejector would also result.

The performance of an ejector-bypass arrangement is shown in figure 11. The net thrust ratio is shown as a function of the flight Mach number for the integral ejector-bypass system and for the more complicated system equipped with variable main-inlet bypass and a separate auxiliary inlet for the ejector. The ejector-bypass system gives a net thrust ratio comparable to that for the more complicated ejector-auxiliary-inlet configuration. At the lower speeds, the flow to the ejector in the ejector-bypass arrangement has to be throttled to avoid supercritical operation of the main inlet; small performance losses result. At high speeds, the performance of the ejector-bypass system is superior because of the high bypass drags that occur in the separate system.

For these calculations, the excess main-inlet air flow could be handled by ejectors having good thrust performance. The engine air-flow characteristics were such that the match was good over the entire speed range. For an engine whose air-flow requirements were more sensitive to flight Mach number, the match is not quite as good. However, this system still appears to be comparable to the auxiliary inlet system.

CONCLUDING REMARKS

Some of the problems facing the designer of exhaust nozzles for turbojet engines operating up to Mach number of 3.0 have been discussed. If mechanical complexity were not a consideration, the variable convergent-divergent nozzle would appear the most desirable type of exhaust system. However, because of its mechanical complexity, two other types of nozzles, the ejector and the plug, are currently under consideration.

Data show that the ejector nozzle will deliver high thrust up to at least a Mach number of 3.0 if the shroud is variable and will, when necessary, become divergent. Care should be exercised, however, in providing low flap angles at cruising speeds, since high-flap drags can result for some airplane installations, particularly the nacelle type. It seems that the ejector secondary air flow may be efficiently provided by either a fixed auxiliary inlet or the main engine inlet.

The excellent performance characteristics indicated by quiescent-air tests for the mechanically simple plug nozzle may not, for some installations, occur with external flow. As with the ejector, installation of the nozzle behind a boattail or reduction of nozzle flap angle tends to reduce adverse stream effects.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, March 23, 1956

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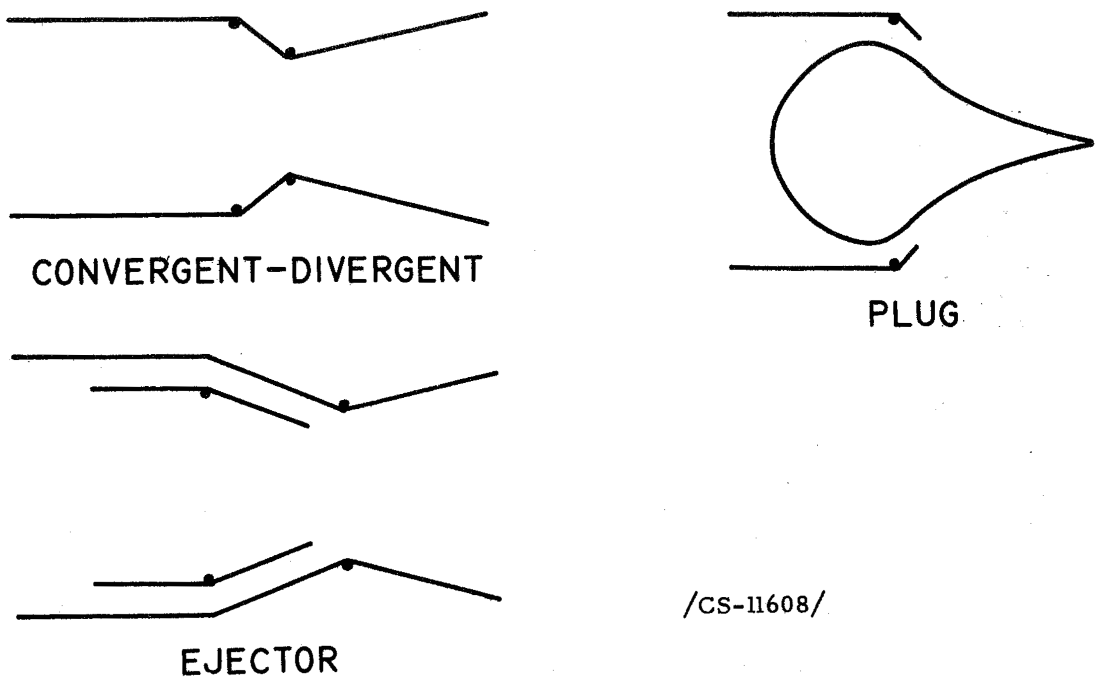

Figure 1. - Nozzle types.

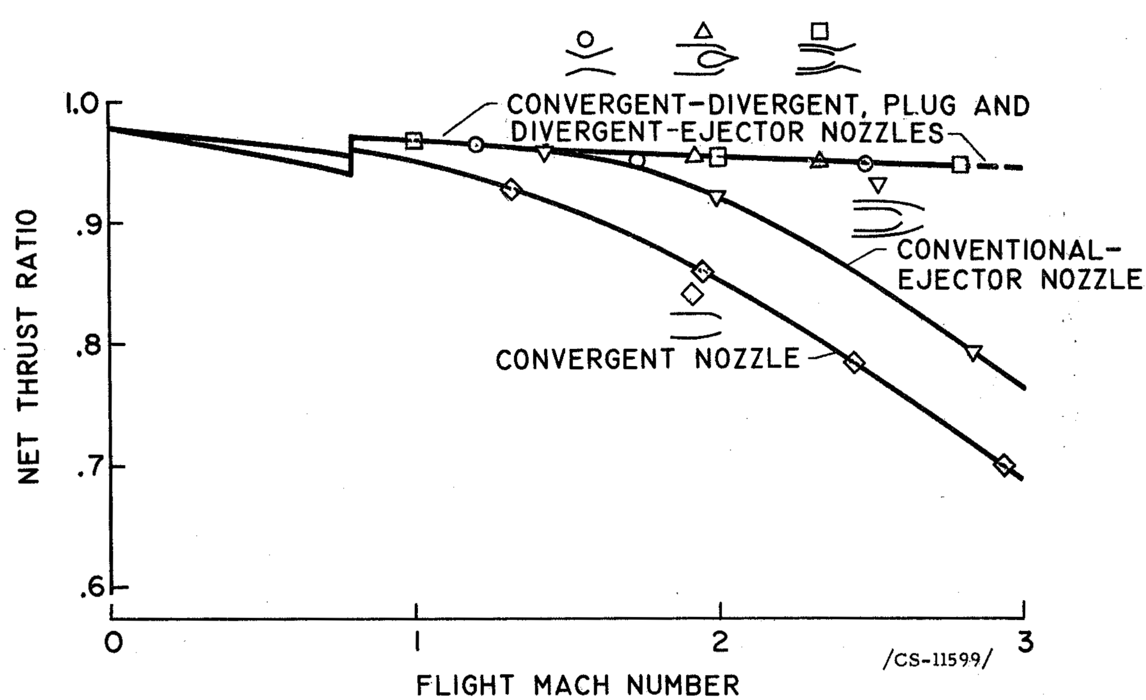

Figure 2. - Design-point nozzle performance; quiescent air.

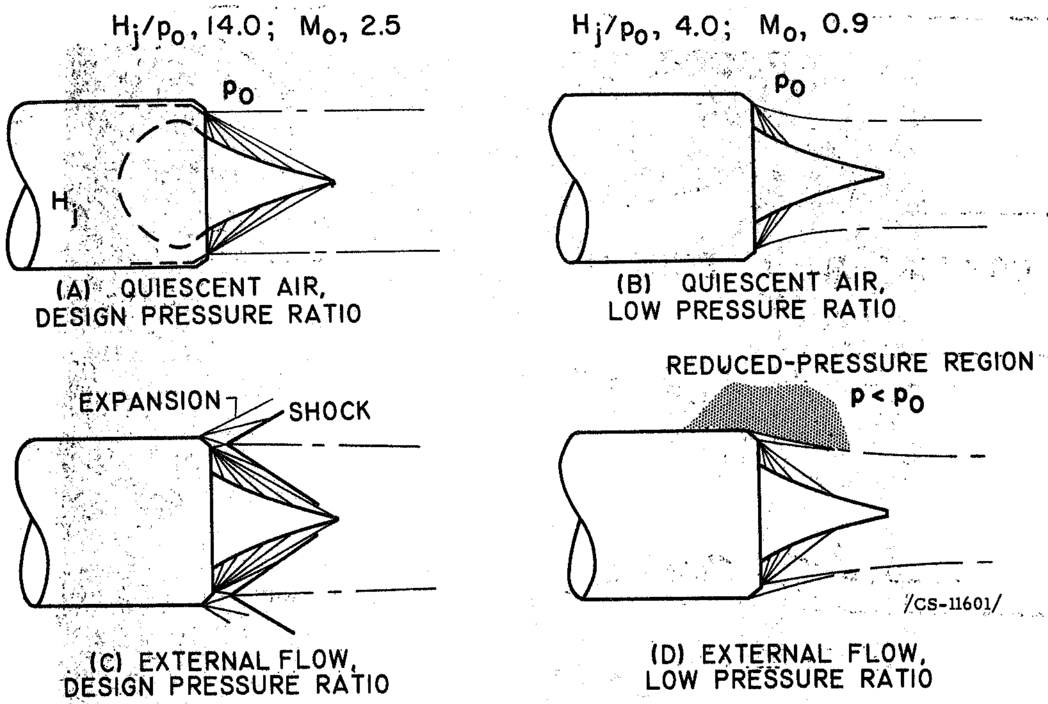

Figure 3. - Plug-nozzle operating principles.

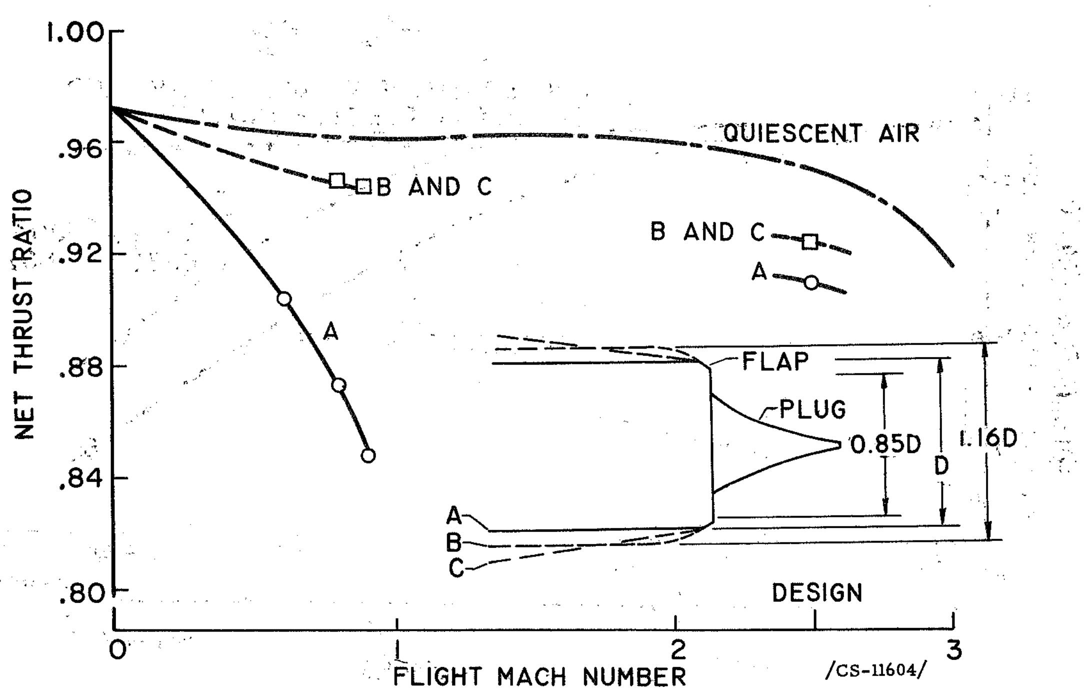

Figure 4. - Effect of external flow on plug-nozzle performance. Afterburner on.

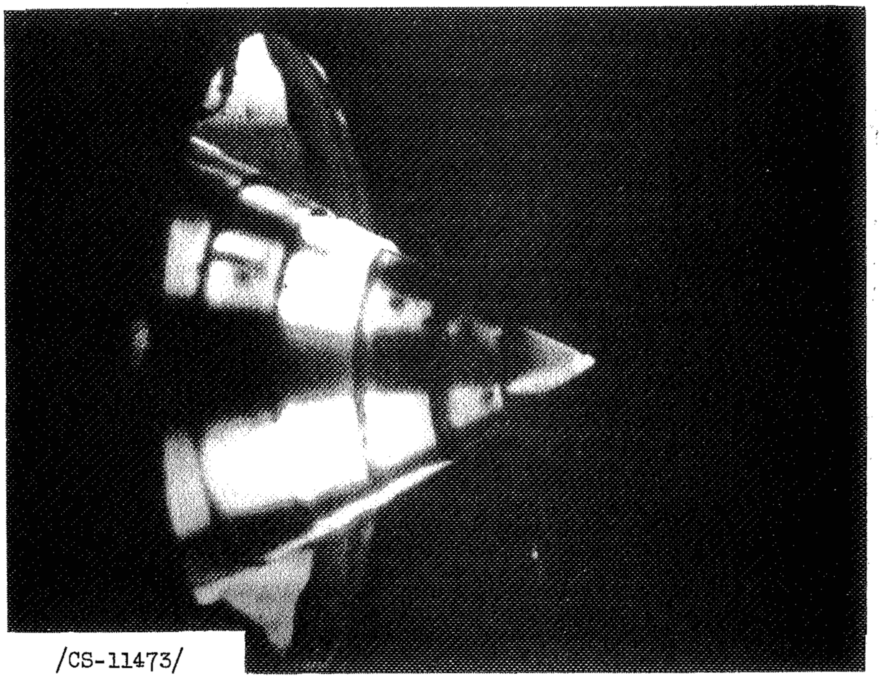

Figure 5. - Full-scale plug nozzle.

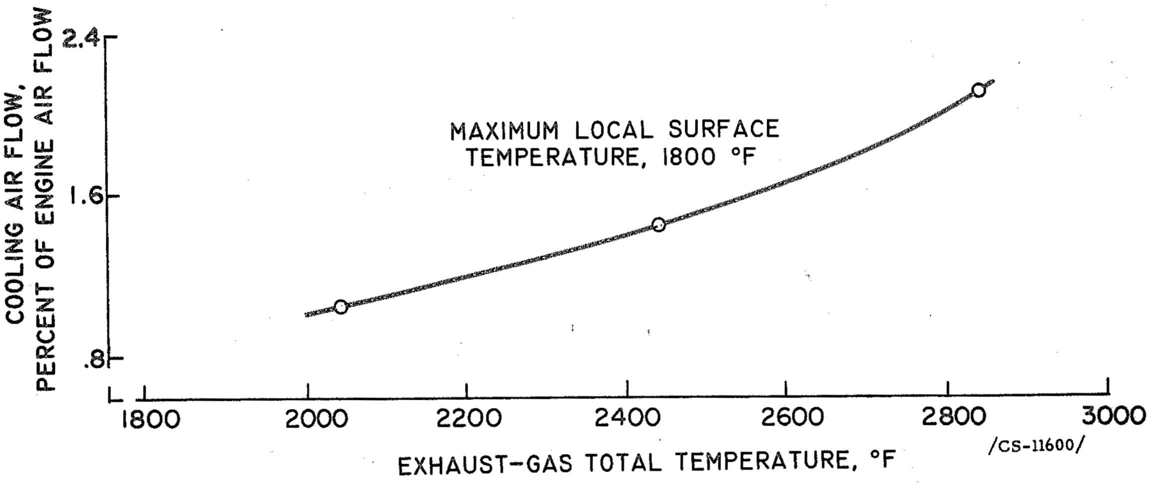

Figure 6. - Plug-nozzle cooling requirements.

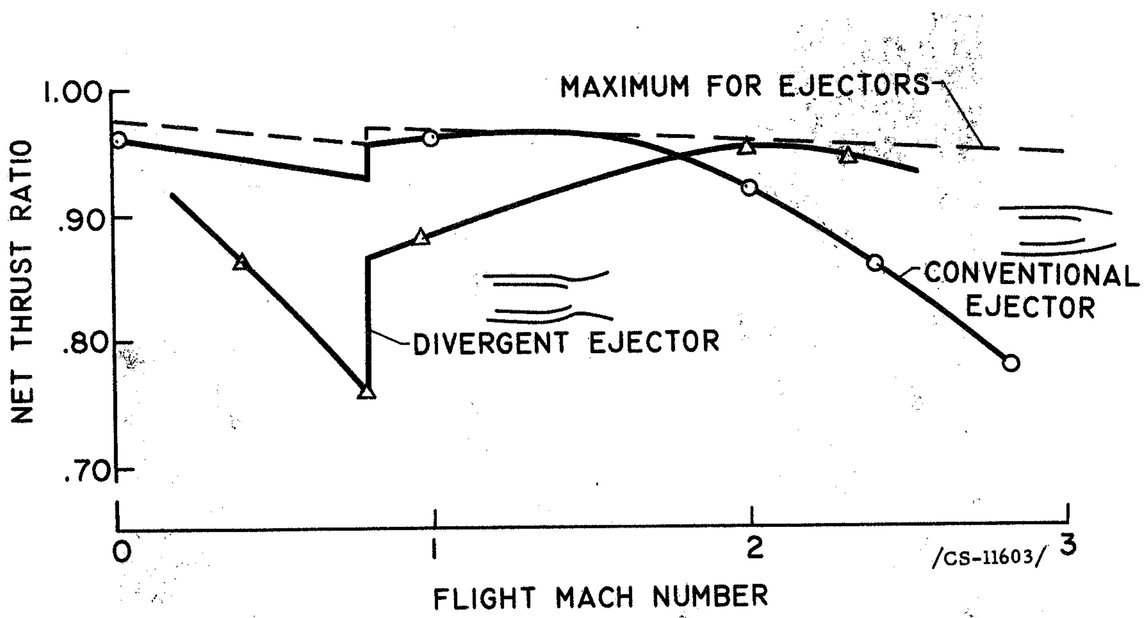

Figure 7. - Fixed-shroud ejector performance.

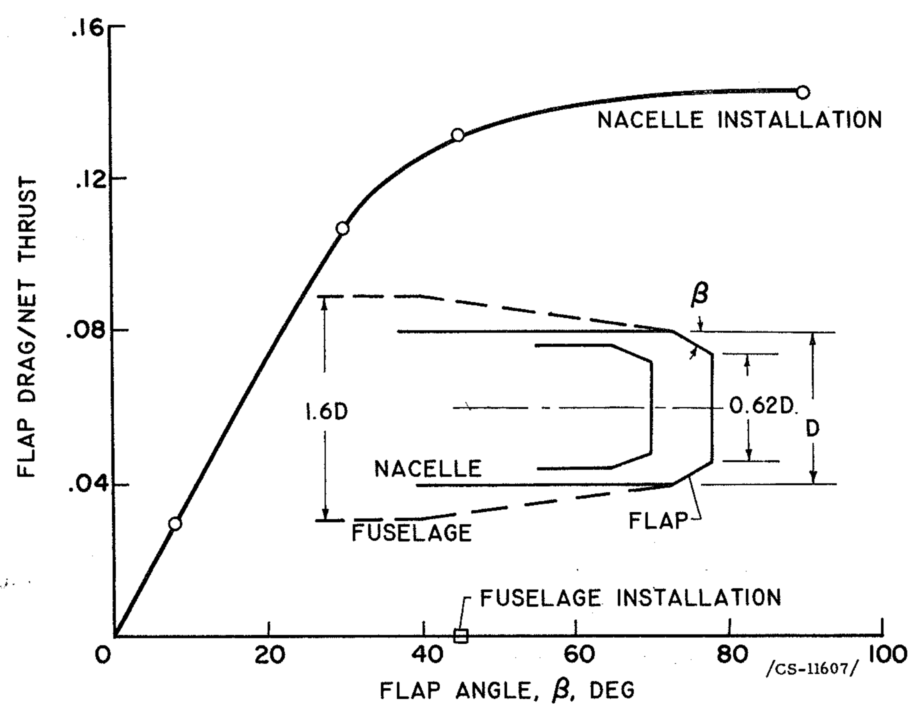

Figure 8. - Ejector-shroud flap drag. Flight Mach number, 0.9; no afterburner.

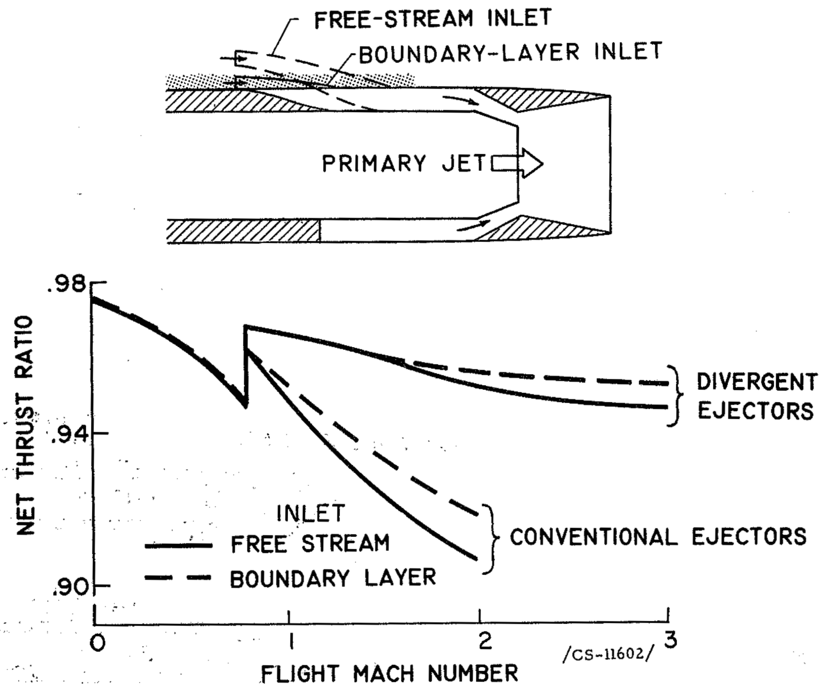

Figure 9. - Effect of auxiliary-inlet position.

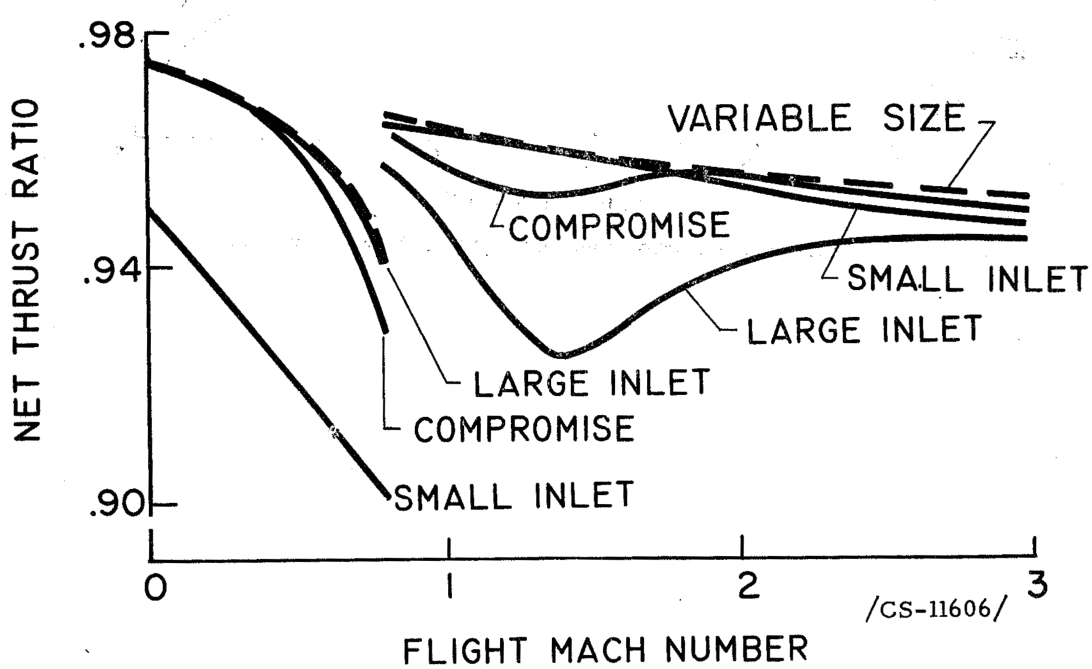

Figure 10. - Effect of auxiliary-inlet size for boundary-layer inlet and divergent ejectors.

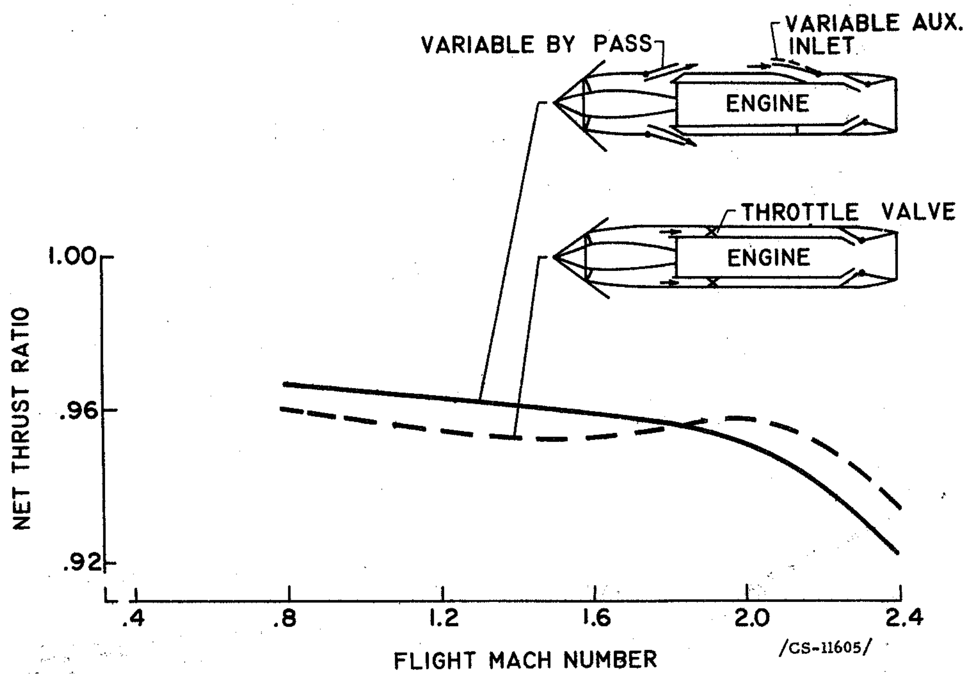

Figure 11. - Performance of ejector-bypass system.

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Bodies - Shape Variables 1.3.2

Bodies, Ducted - Tail Shape 1.3.4.2

Nozzles 1.4.2.2

Exits 1.4.3

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Abstract

Good internal performance over a wide range of flight conditions can be obtained with either a plug nozzle or a variable ejector nozzle that can provide a divergent shroud at high pressure ratios. For both the ejector and the plug nozzle, external flow can sometimes cause serious drag losses and, for some plug-nozzle installations, external flow can cause serious internal performance losses. Plug-nozzle cooling and design of the secondary-air-flow systems for ejectors were also considered.