15. SUMMARY OF RESEARCH ON JET-EXIT INSTALLATIONS

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SUMMARY

A review is made of recent NASA research on performance of propulsive exhaust nozzles and jet-airframe interference. The importance of off-design performance and nozzle-installation effects is emphasized. Extensive reference is made to papers describing specific research.

INTRODUCTION

As early as a decade ago, the NACA had made comprehensive studies of aircraft jet-engine exhaust-nozzle performance for nozzles of conventional type such as convergent-divergent ejectors and isentropic spike nozzles. Although the performance penalties associated with off-design operation and jet-airframe interference were recognized problems, primary attention had been directed toward achievement of maximum performance at specified design operating conditions. Representative papers on early research on exhaust nozzles are cited in references 1 to 4.

More recently, development of the variable-sweep concept for aircraft wings and increasing interest in tactical fighter and supersonic transport aircraft have revived general interest in aircraft propulsion, especially in the off-design performance of exhaust nozzles, and in the mutual influence between the propulsion system and the airframe. Research on aircraft propulsion stemming from these interests has produced a sizable volume of information, some of which has not received wide distribution. It is the purpose of this paper to present a brief résumé of recent NASA research on exhaust nozzles and jet effects.

SYMBOLS

D	drag of external airstream on nozzle components, plus ram drag of nozzle secondary flow
F	nozzle gross thrust
F_i	ideal gross thrust of exhaust gases, isentropically expanded to ambient static pressure
L/D	lift-drag ratio

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M free-stream Mach number

ΔR increment in range

θ discharge angle

DISCUSSION

Performance Sensitivity to Critical Parameters

Figure 1 illustrates the importance of exhaust-nozzle performance in relation to other factors which determine overall aircraft performance. The chart is based on a 3500-nautical-mile mission for a 450 000-pound supersonic transport aircraft cruising at a Mach number of 2.7. Increment in range is shown as a function of percentage change in a specified parameter. The parameters considered are: inlet pressure recovery, propulsion package weight, airframe lift-drag ratio, and nozzle gross thrust coefficient. For example, a 1-percent improvement in nozzle gross thrust coefficient will increase the range by 100 nautical miles, in this case by about 3 percent. It is obvious also that nozzle performance has much more influence on aircraft range than the other factors considered. (See ref. 5.)

Supersonic Transport Fuel Usage

Fuel usage for a typical supersonic transport mission is shown in figure 2. Inasmuch as one-half of the fuel is used in cruise at $M = 2.7$, the highest possible nozzle performance must be achieved at that design condition. Note, however, that 35 percent of the fuel (and perhaps the 15-percent reserve fuel) is used in the off-design conditions of take-off, climb, acceleration, letdown, and loiter, so that high performance of the nozzle in off-design operation is also of prime importance and should be achieved without compromising cruise performance.

The expression "off-design" is used herein to indicate values of airspeed and nozzle pressure ratio considerably different from those for which the nozzle design is optimized. For supersonic transport nozzles, "off-design" frequently implies operation at subsonic and transonic speeds. In this sense, much of the exhaust-nozzle research at Langley has been directed toward study of off-design performance.

Partial Scope of Research on Isolated Nozzles

Figure 3 indicates the scope of some recently completed and current NASA research on isolated exhaust nozzles. The principal types of propulsive nozzles, classified broadly as "open" and "plug," are indicated in this figure along with special features having general application. Any of these nozzles which can provide for efficient expansion of the exhaust gases at high pressure ratio can be designed to give good performance at a specified design condition. The merit of any particular nozzle type, however, frequently depends upon its ability to operate efficiently at conditions other than design. This quality usually requires variable geometry. Research on terminal fairings for exhaust nozzles is treated in references 6 to 11. In this paper, no attempt is made to summarize the research on noise suppressors (see refs. 12 to 16) or on thrust reversers (see refs. 17 to 27).

Research Models

Figures 4 and 5 present composite photographs of jet-exit research models investigated in the Langley 16-foot transonic tunnel. Each model incorporated a hydrogen-peroxide gas generator to produce a hot jet properly scaled to simulate the engine exhaust. (See refs. 28 to 30.) Each investigation pertained to the effects of jet operation on afterbody pressures and drag, on aircraft stability and control, and, in some cases, on temperature of airframe components washed by the jet. Description of work conducted with these models is presented in the references as follows: F-11F, references 11, 21, 31, and 32; F-101, references 33 to 35; A-2F(A-6), references 36 and 37; wing-nacelle jet, reference 38; isolated nacelle, reference 39; and clustered jet exits, reference 40. The nozzle types indicated in figure 3 are representative of many configurations which have been investigated on test rigs similar to the isolated nacelle shown in figure 5.

Convergent-Divergent Ejector Nozzles

In the field of aircraft propulsion, the convergent-divergent ejector nozzle is sometimes regarded as a standard by which other nozzles may be evaluated. In figure 6, the thrust efficiency of a convergent-divergent nozzle is presented as a function of flight Mach number. Thrust efficiency is defined as the ratio of nozzle gross thrust minus external drag to ideal thrust. (The drag term also includes the ram drag of secondary air.) The shaded region in this figure represents the band of efficiency within which convergent-divergent nozzles for the supersonic transport can be designed to operate. (See ref. 41.) At design conditions near a Mach number of 3.0, the nozzle afterbody can be made cylindrical, in which case there is no pressure drag, skin friction drag is small, and thrust-minus-drag performance is near ideal. To achieve high performance over a wide range of speeds, the nozzle must incorporate variable geometry as indicated in the sketches and have the ability to vary expansion ratio from a value of unity at low speeds to about 4.0 at a Mach number of 3.0. At off-design conditions, however, especially at subsonic cruise or loiter and for transonic acceleration, the boattail angle (and, therefore, drag) is large, and thrust-minus-drag performance is reduced accordingly. Even though the variable-geometry convergent-divergent ejector nozzle will operate with high efficiency over a wide range of speeds, this type of nozzle, in general, is mechanically complex and heavy. Results of research on miscellaneous convergent-divergent and ejector nozzles are presented in references 2, 3, 39, and 41 to 61. Boattail and afterbody drag pertinent to variable-geometry convergent-divergent nozzles is discussed in references 62 to 70.

Blow-In-Door Ejector Nozzle

Features of the blow-in-door exhaust nozzle system, which makes use of base ventilation to improve off-design performance, are illustrated in figure 7. The name is derived from the free-floating flaps, or blow-in doors, which are located just upstream of the ejector shroud. At subsonic and transonic speeds where the jet total-pressure ratio is low, the doors are forced inward by the higher external pressure. External air flows into the ejector and reduces the overexpansion of the primary exhaust. At higher Mach numbers, the higher pressure inside the shroud forces the doors to a closed position and the system functions as a convergent-divergent ejector. Because these doors or auxiliary inlets are upstream of the nozzle exit, it might be expected that this type of nozzle would be sensitive to installation effects or to unsymmetical external flow.

The solid-line curve in figure 7 presents subsonic and transonic data obtained with an isolated nozzle operating in axisymmetric external flow (ram drag of secondary air not included in performance parameter). The dashed-line curve shows performance of a nozzle of the same design when installed as a twin cluster in an aircraft configuration and operating in the aircraft flow field. A comparison of nozzle performance for the isolated and installed cases shows that the performance for the installed nozzles is lower than that for the isolated nozzle by about 2 percent. A small part of this loss was internal and was caused by lower pressures in the secondary air passage which forms an internal base. Most of the loss, however, is due to increased external drag. The severe drop in performance at transonic speeds for both the isolated and installed nozzles is due to rapid increase in drag on the doors and shrouds in this speed range. At higher Mach numbers, the doors close; the performance improves and has been shown to fall within the shaded band. The curves showing performance at subsonic and transonic speeds are data for a specific engine operating at specified values of pressure ratio. The shaded band showing supersonic performance is intended to indicate general capability of the blow-in-door type of nozzle. Performance of several blow-in-door nozzle designs is presented in references 71 to 73, and data pertinent to auxiliary inlets for supplying nozzle secondary air flow are given in reference 74.

Plug Nozzle With Terminal Fairings

Typical performance for an isentropic plug nozzle with and without terminal fairings is presented in figure 8. An isentropic plug nozzle can generally be designed to give good performance at any specified operating condition. For example, the nozzle without terminal fairings shown in the upper left-hand side of figure 8 was designed for a pressure ratio of 10 corresponding to operation of a turbojet at Mach 1.8. At speeds near this value the performance of this nozzle is good, as shown by the solid-line curve. Because the basic design of an isentropic plug nozzle requires rather abrupt curvature of the outer lip, lip drag is high, especially at transonic speeds, and performance is correspondingly low. At speeds above the design value, the nozzle is underexpanded and performance suffers.

One approach toward improving the off-design operation is through the use of terminal fairings as illustrated in the upper right-hand side of figure 8. The terminal fairings are streamlined bodies which fair into the rearward-facing surface of the nozzle outer lip and effectively reduce afterbody boattail angle. These fairings reduce lip drag, permit venting of the base at low speed, and provide additional expansion surface for the jet at high speeds. The performance of the $M = 1.8$ design nozzle with the terminal fairings is shown by the dashed line. Subsonic and transonic performance is improved through reduction of lip drag; peak performance is at about the same level, but design speed and pressure ratio have been increased because the effective expansion ratio has been increased. The performance of plug and other type nozzles with and without terminal fairings is presented in references 6 to 11, and 75 to 82.

Long-Cone Plug Nozzle

The long-cone plug nozzle, illustrated in the sketches in figure 9, attacks the problem of lip drag by removing most of the lip. The essential elements of the nozzle are a more or less cylindrical shroud surrounding a relatively long straight conical plug. The upper left-hand sketch in the figure shows the nozzle in the off-design or subsonic configuration. The shroud lip has a very shallow boattail angle and terminates near the maximum diameter of the plug. Subsonic performance of the nozzle with full length plug as shown by the solid line is excellent. The plug length can be reduced by one-half (short-dash line) with only a small penalty. Further reduction in plug length results in rather drastic losses. The performance of this subsonic configuration is generally poor at speeds greater than a Mach number of 1.0 because of reduced pressure on the plug (ref. 83).

For transonic and supersonic operation, this type of plug nozzle must incorporate a translating shroud as indicated in the upper right-hand sketch so that the configuration becomes an annular convergent-divergent nozzle. With translation of the shroud scheduled to provide expansion ratio appropriate to Mach number and pressure ratio, the performance at supersonic speeds is competitive with that of a convergent-divergent nozzle. Although good performance can be obtained over a wide range of Mach number, the cone plug nozzle poses a mechanical design problem when variation of nozzle throat area is required, as for afterburning.

Concave-Plug Nozzle

Figure 10 presents typical performance of a concave-plug nozzle. This nozzle design concept represents an extreme approach to weight reduction in a plug-type nozzle, in that most of the plug is eliminated. The central plug base is contoured to promote a vortex-ring type of recirculating flow. This recirculating flow acts as a gas plug which is pressurized by the converging flow of the annular jet. Pressure acting on the concave-plug base increases with discharge angle θ and with increasing total pressure of the jet.

In the lower part of figure 10, performance is shown for two schedules of jet total-pressure ratio. The higher values correspond to the operating pressure-ratio schedule for a turbojet engine, the lower values are for a turbofan. When used with a turbojet engine, the concave-plug nozzle is at least competitive with other type nozzles. Performance is generally poor at transonic speeds and low pressure ratio, the loss being associated with partial entrainment of the recirculating base flow by the annular jet which results in reduced base pressure. Performance can be improved by the use of terminal fairings. The performance of various concave-plug nozzles is presented in references 8 and 84 to 87.

Clustered Jet Exits

In multiengine airplane configurations, it may be advantageous sometimes to install the engines in one package rather than place individual pods along the fuselage or on the wings. One of the models used to study afterbody drag and jet interference effects of clustered jet exits is shown in figures 5 and 11. This model represents a side-by-side cluster of four engines having convergent-divergent nozzles with 5° boattail angle. In figure 11 some of the results obtained with this model are compared with those from an isolated nozzle. The solid-line curve shows performance for the inline clustered jets, the short-dash curve is for the staggered jets, and the long-short-dash curve is for an isolated nozzle. The external drag of the in-line clustered jet afterbody was found to be about double that of four isolated nacelle nozzles throughout the Mach number range of the tests. This increase in external drag reduced performance by as much as 3 percent. Staggering the two inboard engines had a slight beneficial effect at supersonic speeds because of the favorable interference from the outboard jet exhaust on the boattail of the inboard nozzles. In making a choice between the use of clustered or isolated engines, the rather considerable increase in afterbody drag for the clustered engines would have to be weighed against the possible advantages of this arrangement. Data pertinent to clustered jet-exit arrangements are presented in references 40 and 88 to 93. Related information on jet-airframe interference is given in references 94 to 102.

CONCLUDING REMARKS

A brief review of some of the recent NASA research on exhaust nozzles and jet effects has been presented. In summary, there are several points to be emphasized. Although isolated nacelle investigations are valuable in studies of the effects on nozzle performance of the external flow field and of parametric changes, the ultimate evaluation of exhaust-nozzle performance should be made with nozzles incorporated in the aircraft configuration. Furthermore, in the selection of an exhaust system, performance at off-design operating conditions as well as at design cruise must be considered. Compromises between these performance characteristics and both exhaust system weight and complexity of operation must be evaluated in order to optimize airplane performance.

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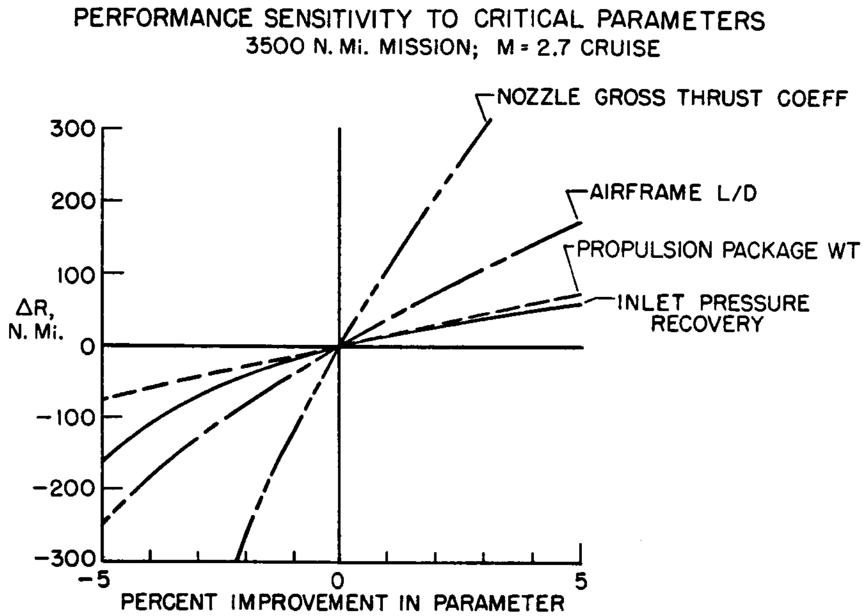
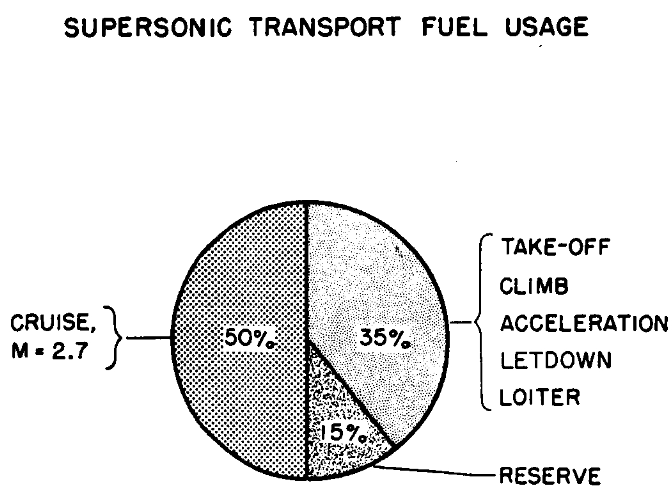


Figure 1



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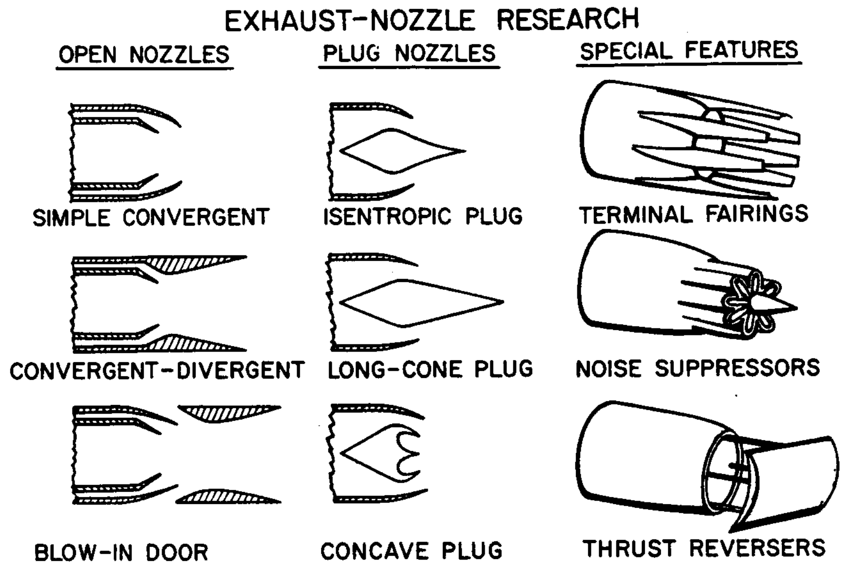

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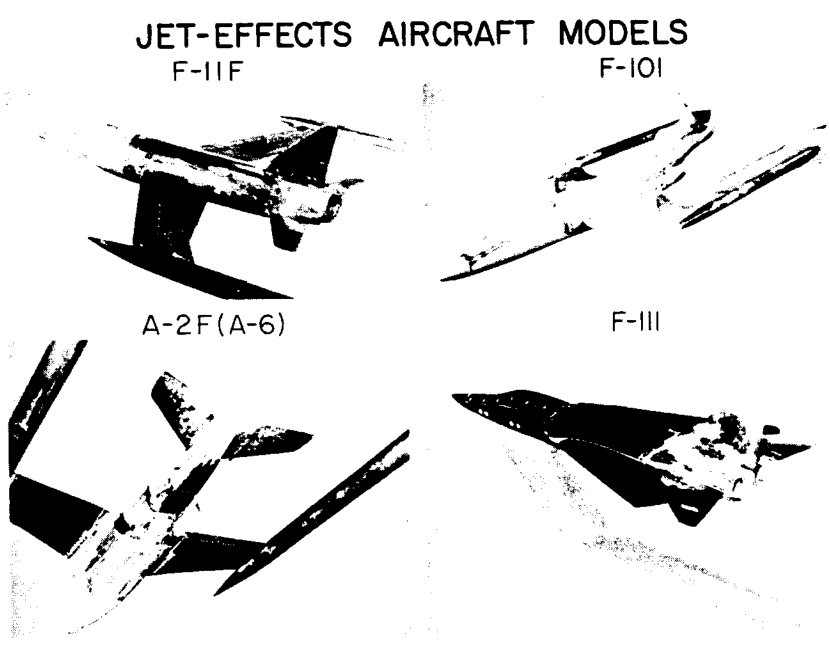


Figure 4

L-2680-4

V/STOL AND RESEARCH MODELS

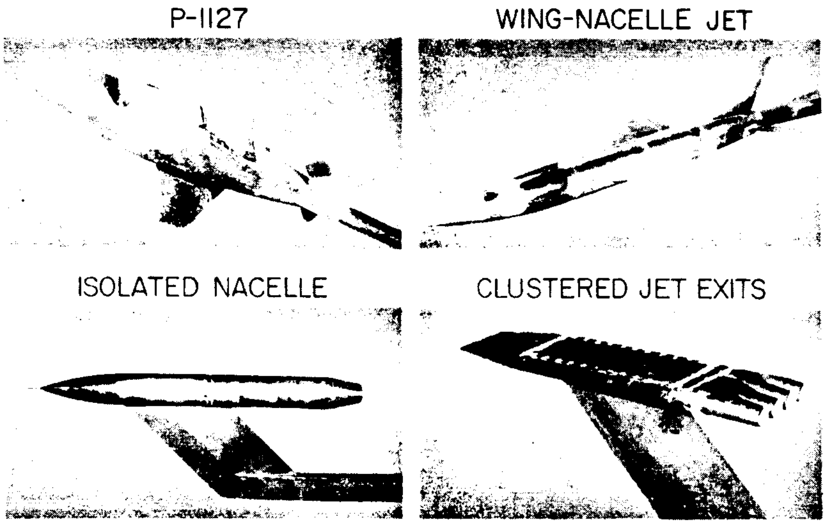
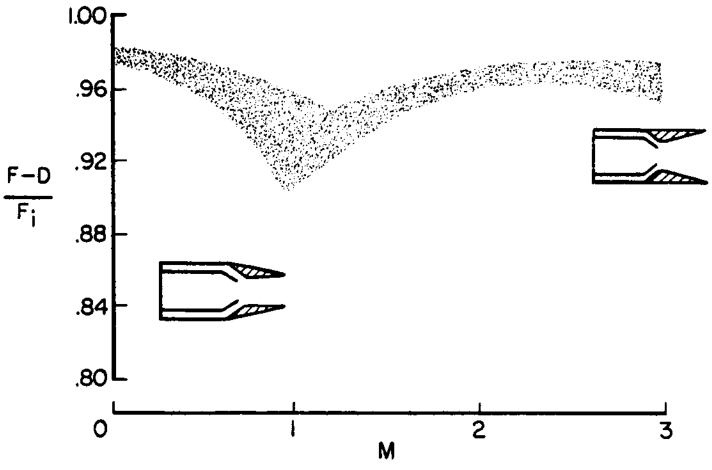


Figure 5

L-2680-5

PERFORMANCE OF CONVERGENT-DIVERGENT EJECTOR NOZZLES



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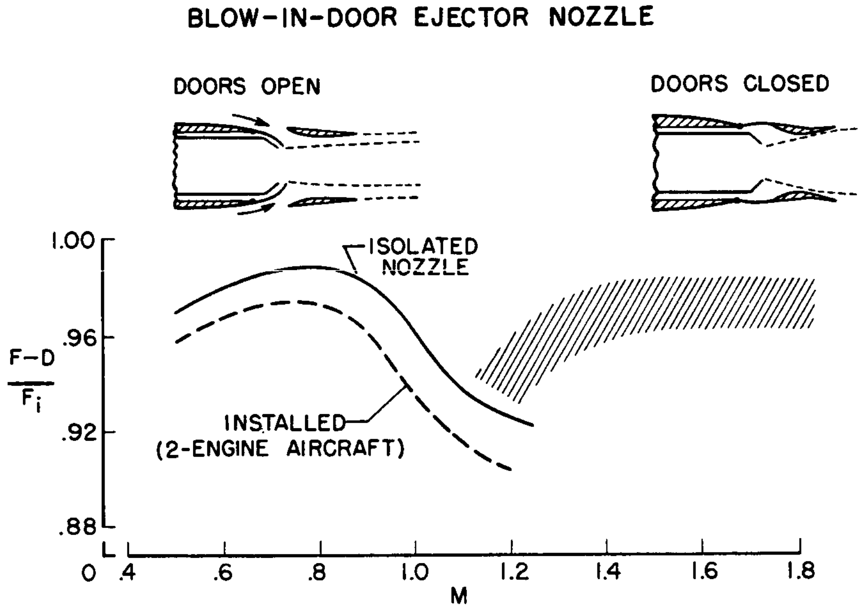

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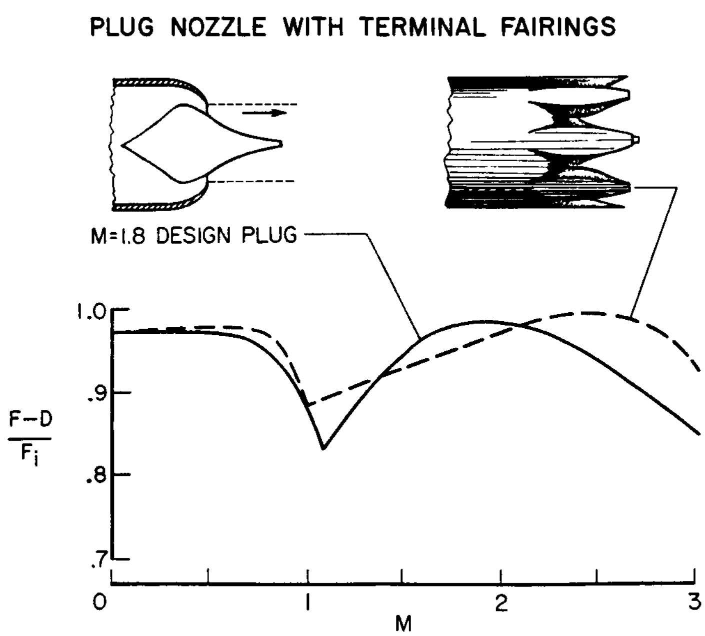

Figure 8

LONG-CONE PLUG NOZZLE

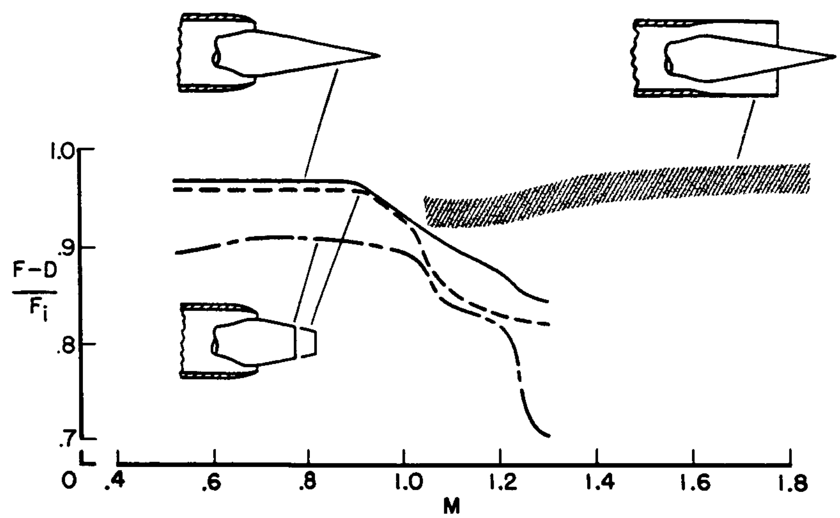

Figure 9

CONCAVE-PLUG NOZZLE

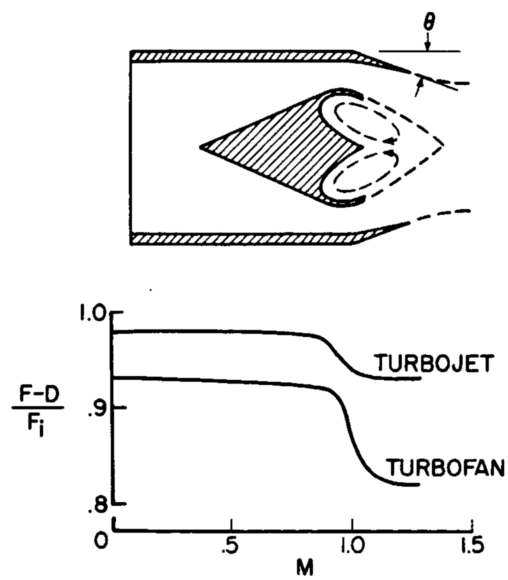

Figure 10

CLUSTERED JET EXITS

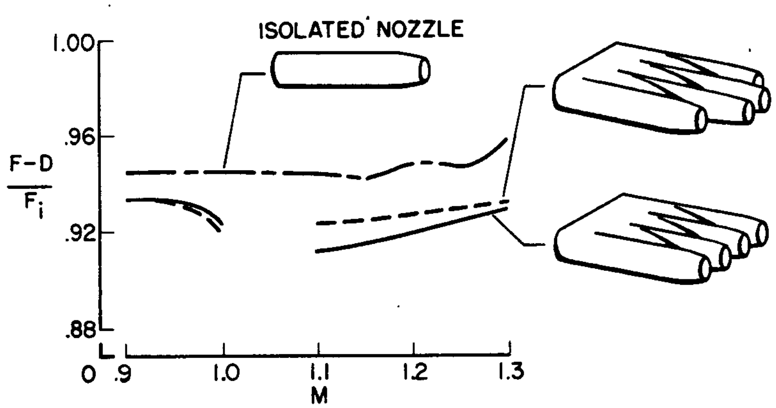

Figure 11