ADVANCES IN EJECTOR TECHNOLOGY - A TRIBUTE TO HANS VON OHAIN'S VISION

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Hans Von Ohain has made many significant contributions in the aeropropulsion area. His invention of the first turbojet engine is well known. The impact of that invention is all too well illustrated by the enormous commercial and military aircraft development that has happened since that time when the first jet powered aircraft was successfully flown in Germany in August 1939. Since the time of his arrival in the United States, Hans Von Ohain has contributed significantly to other technology programs. The development of ejector technology in the Air Force illustrates vividly Hans' farsightedness and leadership. Hans' magnetic personality, very striking characteristics of humility and humanity and absolute devotion to science and technology as well as to the well-being of his co-workers make him a unique person. I express my deep affection and high regard to what Hans Von Ohain means to me by dedicating this article to him.

A great deal of fundamental investigations and applied research has been performed in the area of ejectors as jet pumps over a period of several decades. However, it is only recently that ejectors are recognized as thrust augmentors since the early work of Von Karman (Ref. 1). Subsequently, U. S. Air Force undertook a project of developing the ejector technology for thrust augmentation purposes. A great deal of fundamental and applied work (see the References section) was performed in the course of the last fifteen to twenty years, and a considerable amount of the results has been published.

Initially, a systematic fundamental study was undertaken at the Aerospace Research Laboratories (ARL) at WPAFB under the direction of Hans Von Ohain. Subsequently, an applied study was initiated in the early 1970's at the Air Force Flight Dynamics Laboratory, and the specific task of completing the design of an ejector thrust augmented V/STOL aircraft was completed.

The basic studies at ARL conducted over a period of about ten years yielded several significant results (Ref. 2-14). Extensive in-house studies at ARL and several contracted studies provided considerable information on ejector characteristics and on the design aspects of practical ejector for aircraft applications.

Following are some of the significant and fundamental developments in thrust augmenting ejectors that resulted from ARL's studies (Ref. 6).

1. Development of hypermixing nozzles for mixing enhancement was achieved. This provided a basis for designing a more compact ejector (Refs. 4, 5, 7-10).

2. Demonstration that mixing and diffusion of flows could be done simultaneously with performance advantage was accomplished. Previously, it was believed that performance advantage would result if diffusion is preceded by the accomplishment of complete mixing.

3. An incompressible ejector analysis which will parametrically evaluate an ejector performance was performed (Ref. 5).

4. Thrust augmentation of the order of two in an ejector of inlet area ratio 23 was successfully achieved experimentally (Ref. 8).

5. Good thrust augmentation for V/STOL purposes was also realized by using full-scale multichannel ejectors (Ref. 12). Bypass air from a turbofan engine was diverted by suitable valving into the ejectors installed in a wing. Test data confirmed that an aircraft-installed ejector would perform satisfactorily.

6. It was demonstrated that diffusion normal to the plane of the velocity profile always leads to improved mixing in contrast to diffusion in the plane of the velocity profile (Refs. 7, 13).

7. An ejector-wing model (6 ft model) was designed, fabricated and tested (under an ARL sponsored study which was performed by the Bell Aerospace Company in a wind tunnel (Ref. 14). The tests showed that the resulting favorable supercirculation effects due to the ejector flow would enable transitioning from hover to cruise condition even when the lift due to the thrust component is drastically reduced. This supercirculation effect resulting from an ejector wing in flight points out the inherent shortcoming of an ejector incorporated in the fuselage of an aircraft (as was done in the case of the Hummingbird).

8. Further compactness of the ejector was realized by the utilization of a device that combines efficient boundary-layer energization with a configured diffusion device, that is, trapped vortex cavity (Ref. 15). This work was performed under contract by the Advanced Technology Center, Inc. of the Vought Corporation, Dallas, Texas.

A few of ARL's publications and others which describe the fundamental ejector developments are indicated in the bibliography which also includes the reports resulting from other AF projects on thrust augmenting ejectors.

Air Force Flight Dynamics Laboratory of WPAFB undertook some exploratory study in the ejector area in the late 1960's. A more systematic design study of a V/STOL demonstrator aircraft was initiated in the early 1970's.

Initial exploratory studies supported under AFFDL contract led to the development of the so-called Jet Flap Diffuser Ejector (JFDE). Although jet flap diffuser concept had been proposed earlier in France, no systematic effort was undertaken then to develop an effective configuration. Hans Von Ohain's suggestion regarding the orientation of the primary jet injection relative to the inlet geometry proved successful, and the subsequent tests performed on the jet diffuser ejector at the Flight Dynamics Research Corporation in California showed that relatively high thrust augmentation could be realized in a compact ejector.

In support of the design study of a V/STOL demonstrator vehicle trailing-edge ejectors on wings were fabricated and tested (Refs. 16, 17). One of the wind-tunnel models (Ref. 16) was fabricated and tested in the 7- by 10-ft low speed tunnel at NASA-Ames. This wind-tunnel model was a constant chord two-dimensional 30-in. span and 44.5-in. chord (with the flaps up) model. The tests assessed the lift off and low speed transition phases of flight. The results of the tests showed that in an aircraft configuration, with sufficient BLC provided, a trailing-edge ejector system could provide predicted levels of thrust augmentation. Some insight was also gained about optimal flap settings for transitioning the aircraft from hover to cruise condition.

Preliminary design of an ejector thrust augmented aircraft required a theoretical methodology which could evaluate the performance of the ejectors subject to a wide range of variation in the thermodynamic parameters of the injected and entrained fluids. A compressible ejector flow analysis was developed by assuming that the primary and the secondary streams mixed in a constant area duct (Ref. 18). The schematic of the single-stage ejector is shown in Figure 1. The analysis was performed in steps as shown below:

1. Pressures were prescribed incrementally at station 1, and the other flow quantities were determined from the thermo fluid dynamic relations.

With choked primary flow, the static pressure of the secondary flow was allowed to take on values less than the primary static pressure. The computations were cut off just before the secondary Mach number reached unity.

The analysis was extended to include the ejector flight velocities in the performance calculations. While in flight, the static pressure at station 1 was allowed to take on values greater than the ambient air static pressure, but less than the ambient stagnation pressure. It was noted in some instances from the results that the ejector performance reached optimum levels whenever the entrained air was compressed as it entered the injection station 1. This characteristic requires some further examination.

2. The momentum balance equation in the constant area mixing duct also included the total ejector flow losses evaluated empirically from the test results of ARL.

The velocity of the mixed flow at station 2 was provided by a quadratic equation - one solution corresponding to mixed subsonic flow, and the other corresponding to mixed supersonic flow. Only the subsonic solution was considered, and the supersonic solution was ignored.

3. Diffuser flow was evaluated isentropically. However, any diffuser loss that arises has been accounted for empirically in the momentum equation.

4. Considerations to the thermodynamic constraints (i.e., no entropy decrement as the flow moves forward) were given in the computations.

Typical results of the calculations are shown in Figure 2. It is worth noting that the net thrust augmentation reaches a peak value around 2 for the diffuser area ratio and then begins to drop. This indicates that the flow in the diffuser is separating from the walls. Further, the net thrust augmentation decreases as the primary air stagnation temperature is increased. In fact, the performance degradation with increasing primary stagnation temperature was consistently demonstrated by the computed data for all cases of inlet area ratio, temperature conditions and pressure ratio. It should, however, be noted that experiments have also shown that the effect of temperature is minimal on an incompletely mixed flow (Ref. 12). Regarding the pressure ratio effect on the ejector performance, the situation is quite complicated. The pressure ratio effect seems to depend on the inlet area ratio, the primary stagnation temperature and the static pressure at the injection plane (i.e., the diffuser area ratio).

The effect of ejector forward velocity on the thrust augmentation ratio is quite conceivable. As the forward velocity increases, the net thrust augmentation decreases due to ram drag. The results shown in Figure 3 illustrate typically the ejector performance in flight. However, as will be shown later, an ejector with a different operating thermodynamic condition in the shroud would provide a different performance characteristic (Ref. 20). This will be discussed subsequently in some detail.

The sensitivity of ejector performance to inlet conditions is illustrated in Figure 4. In fact, an operating ejector in an aircraft may well require a variable inlet geometry for yielding optimal performance. Inlet design is a significant factor in optimal ejector designs, for it is the effect of the pressure forces acting on the inlet that determines the thrust magnitude. However, the performance may become sensitive to other ejector components also, for example, at higher forward velocities. Sensitivity of the ejector components as well as of the ejector itself will have to be carefully evaluated, especially when the ejector is installed in an airplane.

It is worth making reference to the performance calculation of a two-stage ejector. A schematic of a two-stage ejector being considered is shown in Figure 5. The performance calculations are illustrated in Figure 6. It is seen that with smaller inlet area ratios in the two staging process, augmentations which correspond to those of high inlet area ratios in single-stage ejector can be achieved. The potential usefulness of staging may also be realized if a staged ejector becomes necessary due to the packaging problems in an airframe.

Based on the data obtained from the analysis, preliminary design study of a V/STOL demonstrator vehicle was conducted (Ref. 21). An RPV vehicle having a canard wing arrangement with a trailing-edge ejector, balanced by a forward fuselage ejector was designed (Figure 7). The injection area ratio of the ejectors was an optimum 13.5 which was designed to produce a thrust augmentation ratio of 1.66 or a VTOL gross weight of 896 lb. The design configuration was powered by the Williams F107-WR-100 engine which in turn fed the fuselage and wing trailing-edge ejectors. At the maximum VTOL weight, the vehicle was designed with fuel capacity of 205 lb, and with full control capability. Further, it had hover acceleration margin of 1.02, radius of 100 n. mi. and loiter time of 100 min. Internal ducting characteristics were evaluated based on the pressure losses due to the internal aerodynamics (Ref. 22). A digital computer program for calculating the internal gas ducting system weight of the ejector thrust augmented vehicle was developed for the vehicle sizing determination (Ref. 23). This program is capable of generating a large and consistent amount of trade-off data for achieving an optimum vehicle.

Aside from the design studies performed at AFFDL, some theoretical studies on augmentors and augmentor wings were also performed. Particularly, Hasinger's investigations (Refs. 24-27) were noteworthy. Although the objective of the investigations is to design a jet pump which would yield the lowest possible primary plenum pressure to achieve a given pressure ratio (of the ejector exhaust stagnation pressure to the secondary stagnation pressure) at a given mass flow ratio (of the primary mass flux to the entrained mass flux), the analysis which deals with both subsonic as well as supersonic mixed flow cases is capable of yielding information that will be relevant to thrust augmenting ejector designs as well. The analysis also indicates the inlet flow conditions which determine whether the mixed flow is coming subsonically or supersonically at the exit of the mixing duct.

High lift characteristics of an ejector-flapped wing was theoretically evaluated by Woolard (Ref. 28) for a two-dimensional wing section with a point sink located aft of the wing chord for simulating the ejector intake flow. The work also treated the matching problem of the airfoil external flow with the ejector internal flow and derived the overall ejector-flapped wing section aerodynamic performance. Comparisons of the lift characteristics of an ejector-flapped wing with those of a jet augmented flapped wing show the superior performance of the former at low forward speeds. Significant items in the analytical approach and evaluation of the results are presented in the author's paper presented elsewhere, (Ref. 30).

A three-dimensional calculation method for determining the aerodynamic characteristics of arbitrary ejector-jet-flapped wings was developed under AFFDL contract by the McDonald-Douglas Aircraft Company. The computer program which is user oriented is capable of generating the aerodynamic coefficients including the ground effect of arbitrary wing-ejector configurations. The analysis program is based on the linear theory, and compressible ejector flow program is coupled with the wing aerodynamic program of Douglas.

A trailing-edge ejector installed on a wing was fabricated and tested in the AFFDL subsonic tunnel whose test section measures one square meter (Ref. 29). The wing-tunnel model was provided with an upper door at the inlet which in cruise flight condition would fold down as the ejector flaps would fold up to provide the conventional cruise wing. The upper door which captured the external flow and directed the flow into the ejector shroud was designed to be set at different angles relative to the wing plane. It was possible also to set the ejector flaps at desired angles. The semispan wing ejector model was one fourth the scale of the wing ejector designed for the AFFDL V/STOL demonstrator vehicle. Lift, drag, and pitching-moment data were taken over a range of upper door setting angles, the ejector flap angles and at several angles of attack as the wind-tunnel airspeed was varied from 20 to 60 ft/sec. The test result showed, for example, that the wing stall angle was substantially larger compared to the unpowered (or the unaugmented) case. Flow visualization tests were also performed utilizing helium bubbles. These tests showed the separated flow region on the exterior side of the aft flap of the ejector for certain configuration positions. The tests demonstrated again the favorable lift characteristics that would result in the ejector augmented case.

Recent theoretical calculations of ejector performance have shown that under certain conditions, it appears to be possible to achieve relatively high thrust augmentation values in forward flight (Ref. 20). Based on the results obtained from a simple, incompressible evaluation of the ejector performance (Fig. 8), it became clear that proper aerothermodynamic matching of the ejector flows (also including the ejector geometric characteristics) would play a significant role in optimal ejector designs. An effort on a more systematic evaluation of ejector performance was undertaken under AFFDL contract by the Flight Dynamics Research Corporation, Van Nuys, California. The investigations utilized one-dimensional compressible flow equations much the same way as was done in Reference 18, and these equations, without accounting for ejector losses, were solved by incrementally assigning values to the inlet flow Mach number M_1 of the entrained stream at the injection plane. In reference 18, the solution process was explicitly started by assigning values incrementally to the static pressure at the injection plane.

Loss effects were not analytically accounted for in the initial studies primarily because all the realistic losses could be estimated only after the geometric and other related flow parameters were fixed based on the objectives of the specific ejector mission roles. However, the analysis that would account for the incomplete mixing effects as well as the skin-friction effects was performed in a general sense.

The calculations in Reference 20 were performed by imposing the thermodynamic constraint that the entropy did not decrease as the flow progressed in the ejector toward the exit. This ensured that only physically acceptable solutions were utilized in the ejector performance calculations. The present investigations considered mixed supersonic flow conditions also, unlike those reported in Reference 18. The ejector performance was evaluated based on both the first solution (corresponding to the subsonic mixed flow) and the second solution (corresponding to the supersonic mixed flow).

The results of the calculations are shown in Figures 9-16. The results shown in Figure 9 pertain to the same ejector as indicated in Figure 10. The plus and minus signs in parentheses indicate that the results correspond to supersonic and subsonic mixed flows respectively at the end of the mixing duct. Propulsive efficiency, if defined in the classical manner where the reference jet energy is purely mechanical, can exceed one in certain thermodynamic situations because the thermal energy of the primary jet can also contribute along with the jet kinetic energy to the useful work produced by the system. However, if the reference jet energy is the total jet energy (including mechanical and thermal components), then the propulsive efficiency will be less than unity.

The data in the Figures 9-16 indicate that ejectors, based on the so-called second solution, exhibit a great deal of potential usefulness as thrust augmentors. It is necessary to pursue further the design aspects of such practical ejectors. A great deal of parametric analysis as well as design optimization studies will be required before new ejector configurations can be defined. However, the possibility of deriving new ejector concepts for thrust augmentation purposes is clearly indicated by the recent Air Force studies.

NOTE:
(i) Figure 8 was taken from a communication sent to AFFDL by FDRC in 1976.

(ii) Progress Reports as well as the final report submitted by FDRC and published as AFFDL-TR-79-3048 contributed to Figures 9-16.

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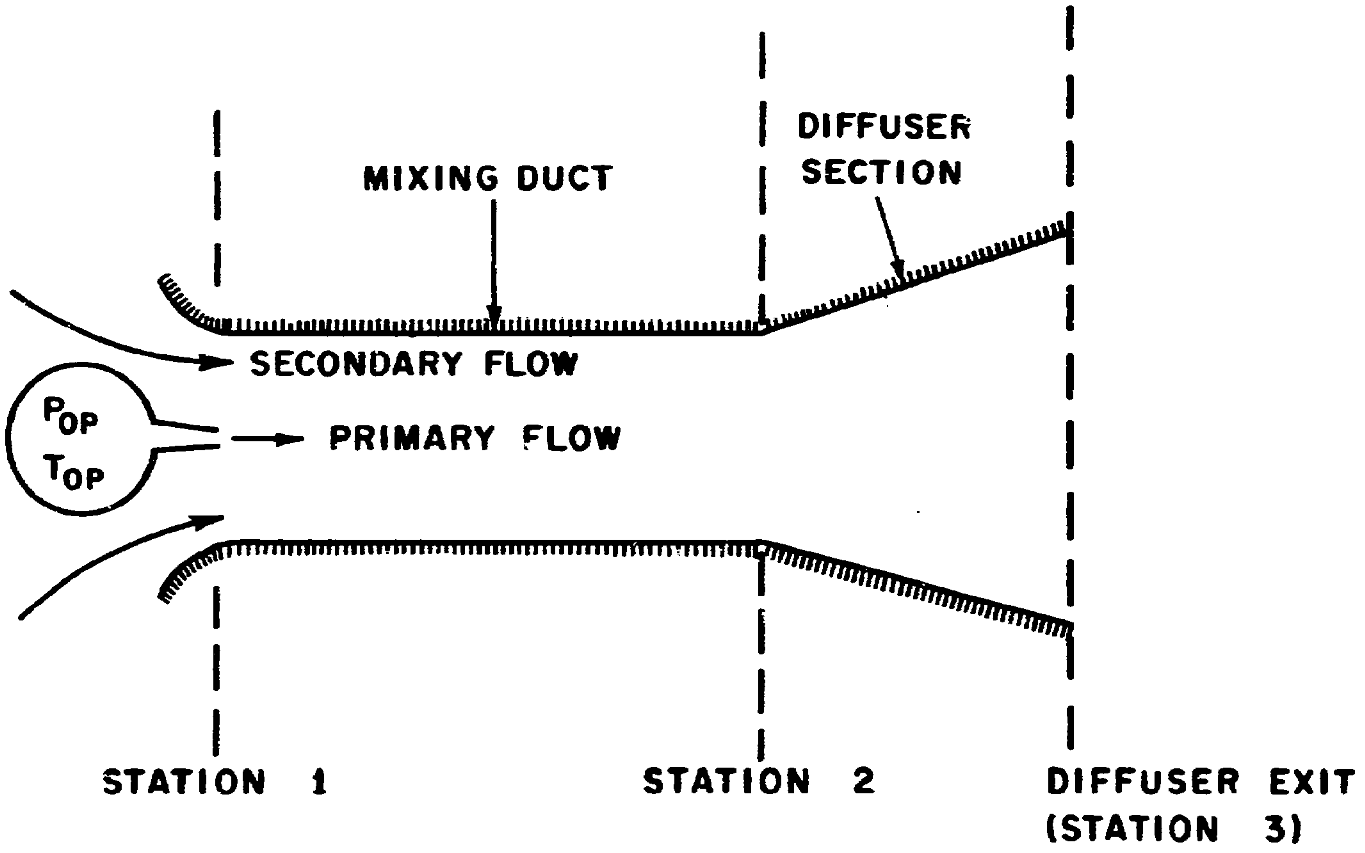


Figure 1.- Schematic of a single-stage ejector.

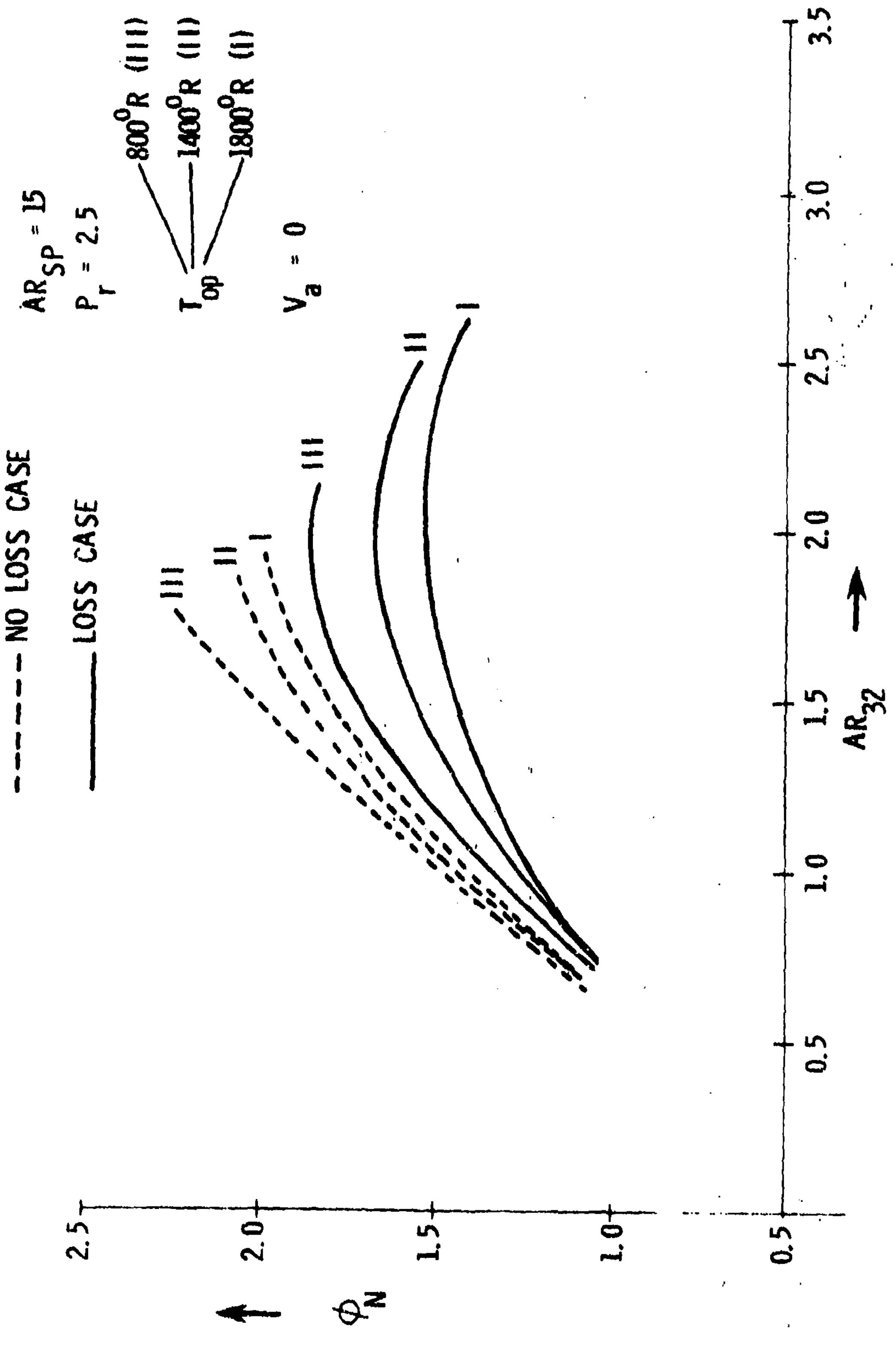


Figure 2.- Thrust augmentation ratio vs diffuser area ratio.

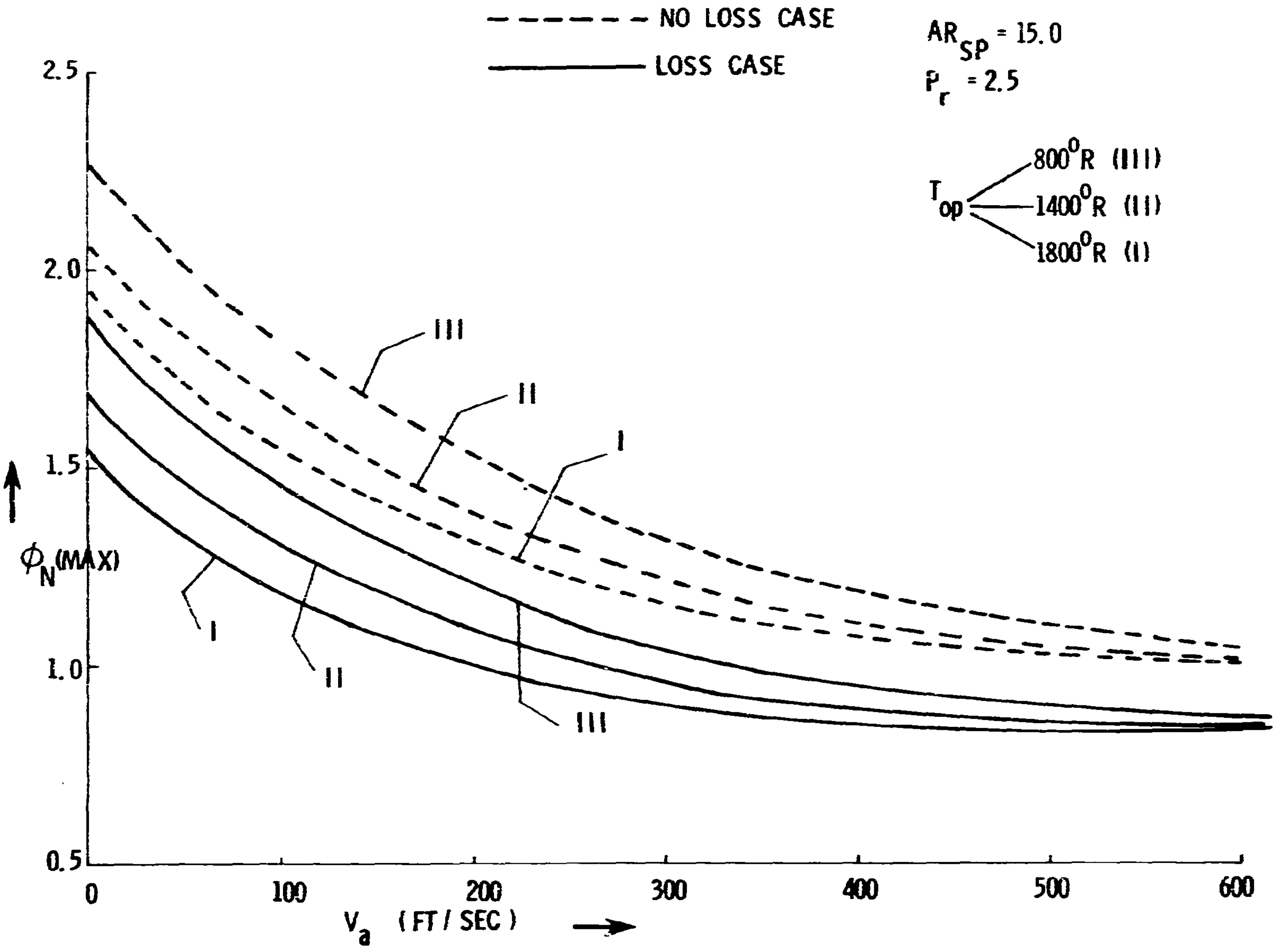


Figure 3.- Distribution of ϕ_N(max) vs V_a(forward velocity).

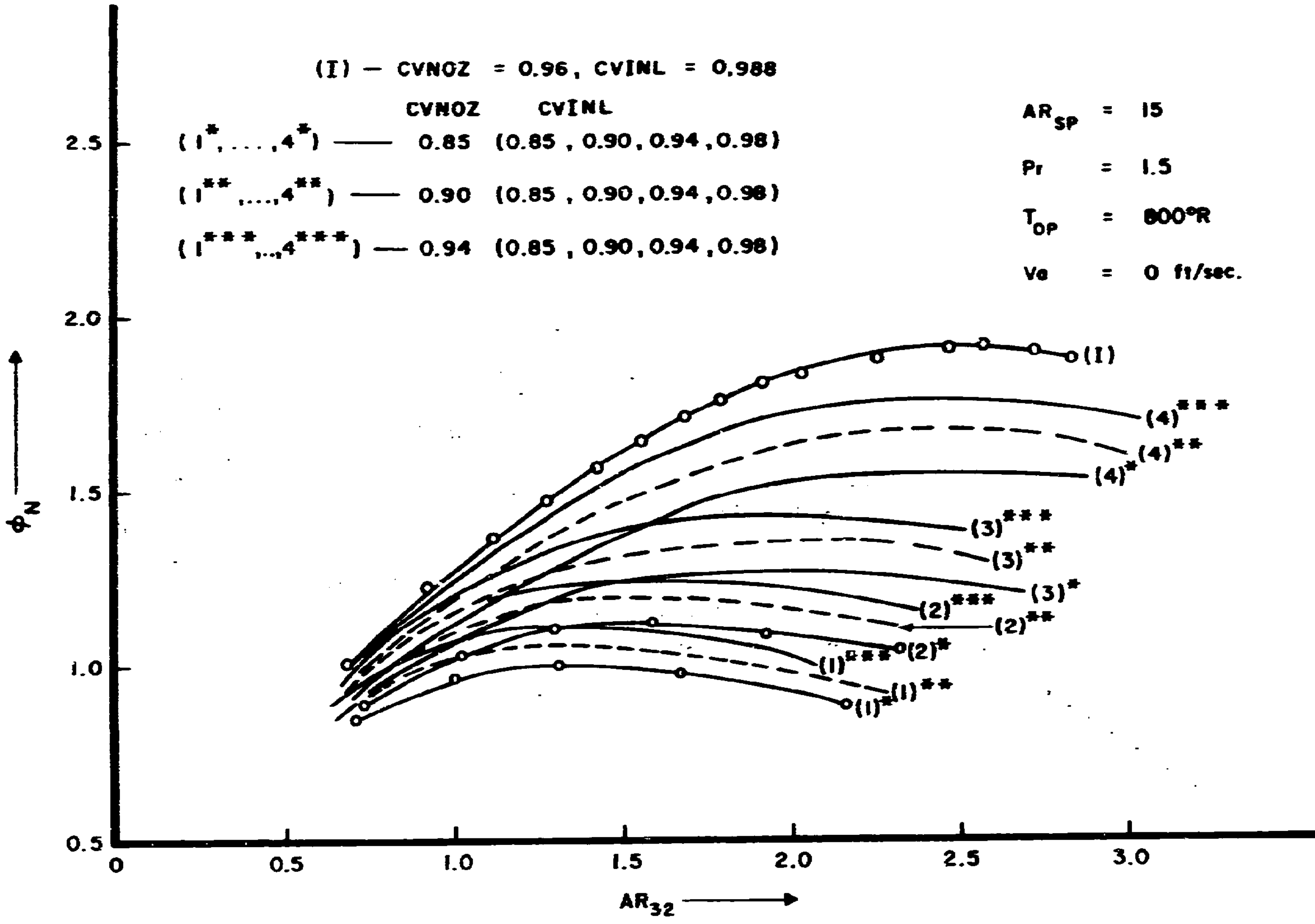


Figure 4.- Thrust augmentation characteristics for several nozzle and inlet losses.

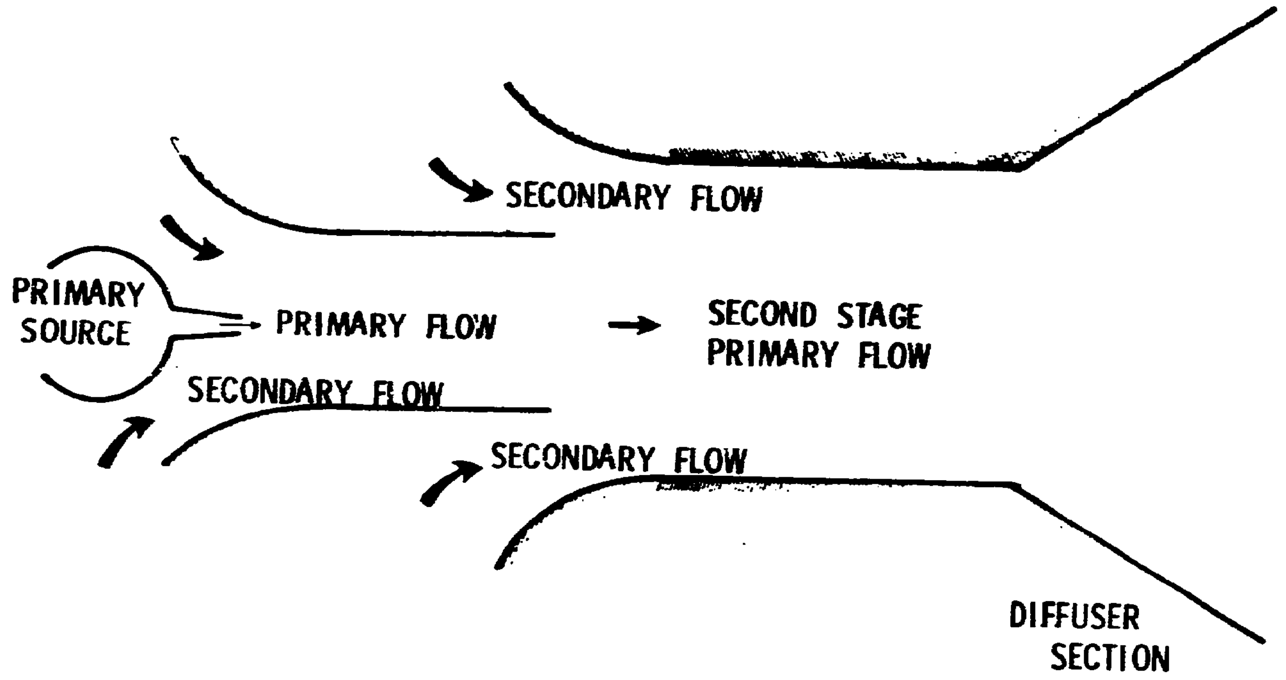


Figure 5.- Schematic of a two-stage ejector.

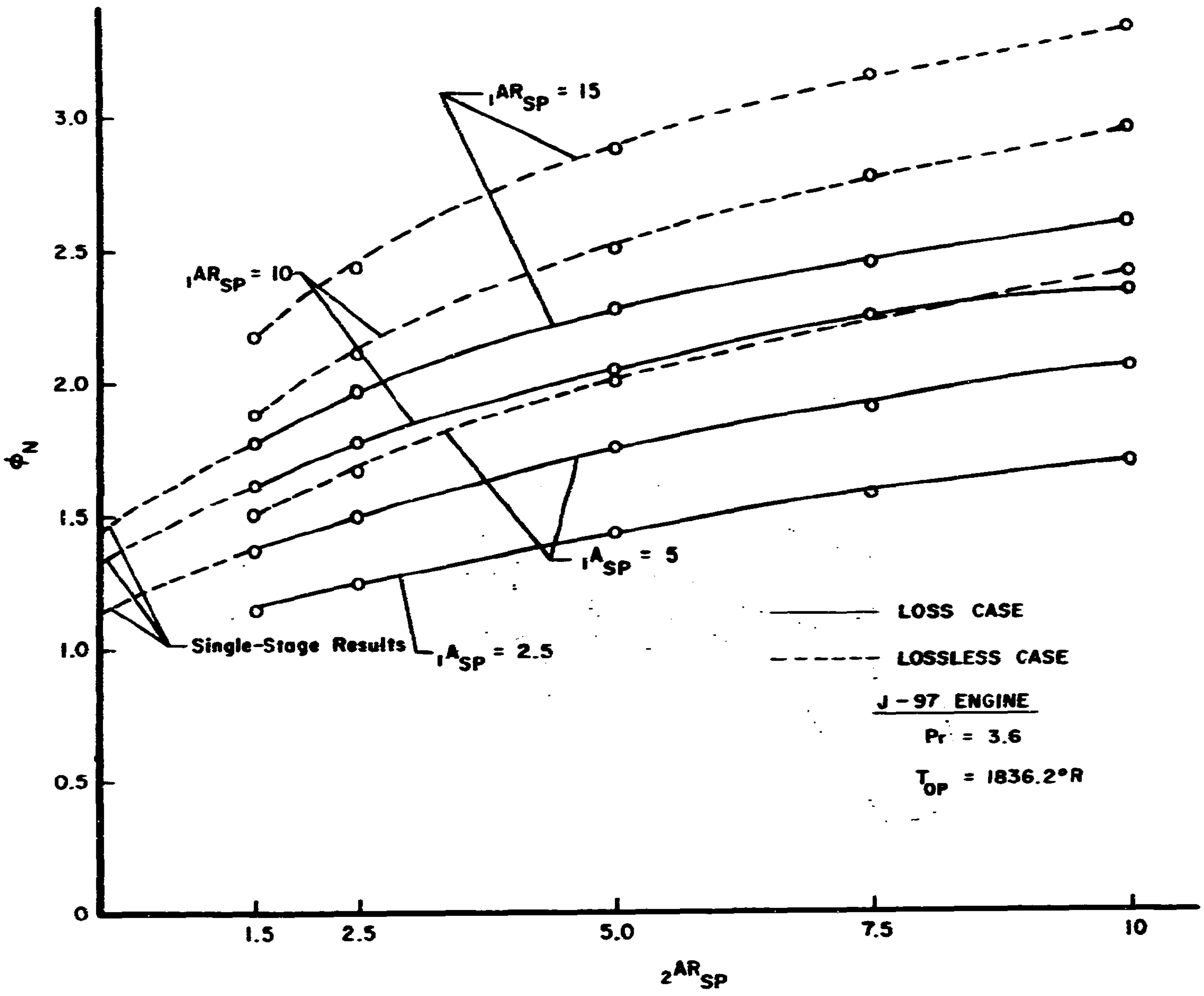
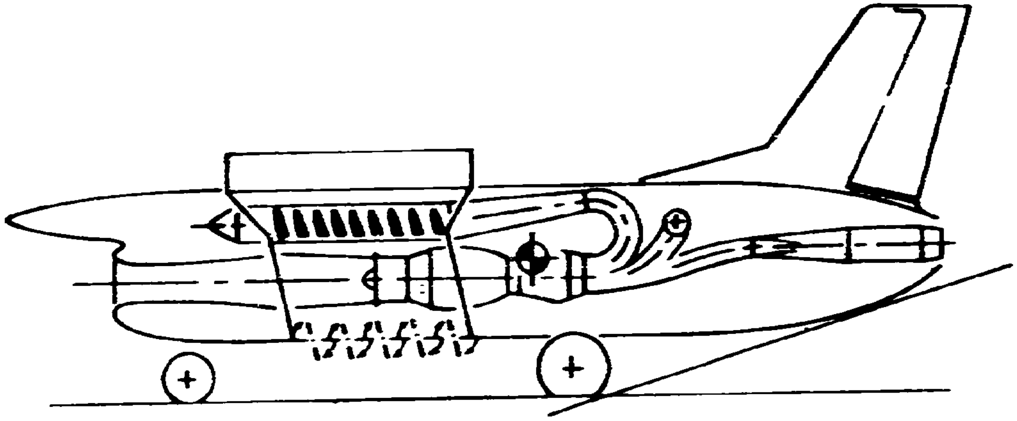


Figure 6.- Thrust augmentations in two-stage ejector flows.



F107-WR-100 DEMO ENGINE	GAS DUCTING SYSTEM	EJECTOR STATIC PERFORMANCE
● 600 LBT CLASS	6.25% PRESSURE LOSS	OPTIMUM IAR = 13.5
121 LB WEIGHT	210 LB WEIGHT	OPTIMUM Φ = 1.66

Figure 7.- Propulsion system.

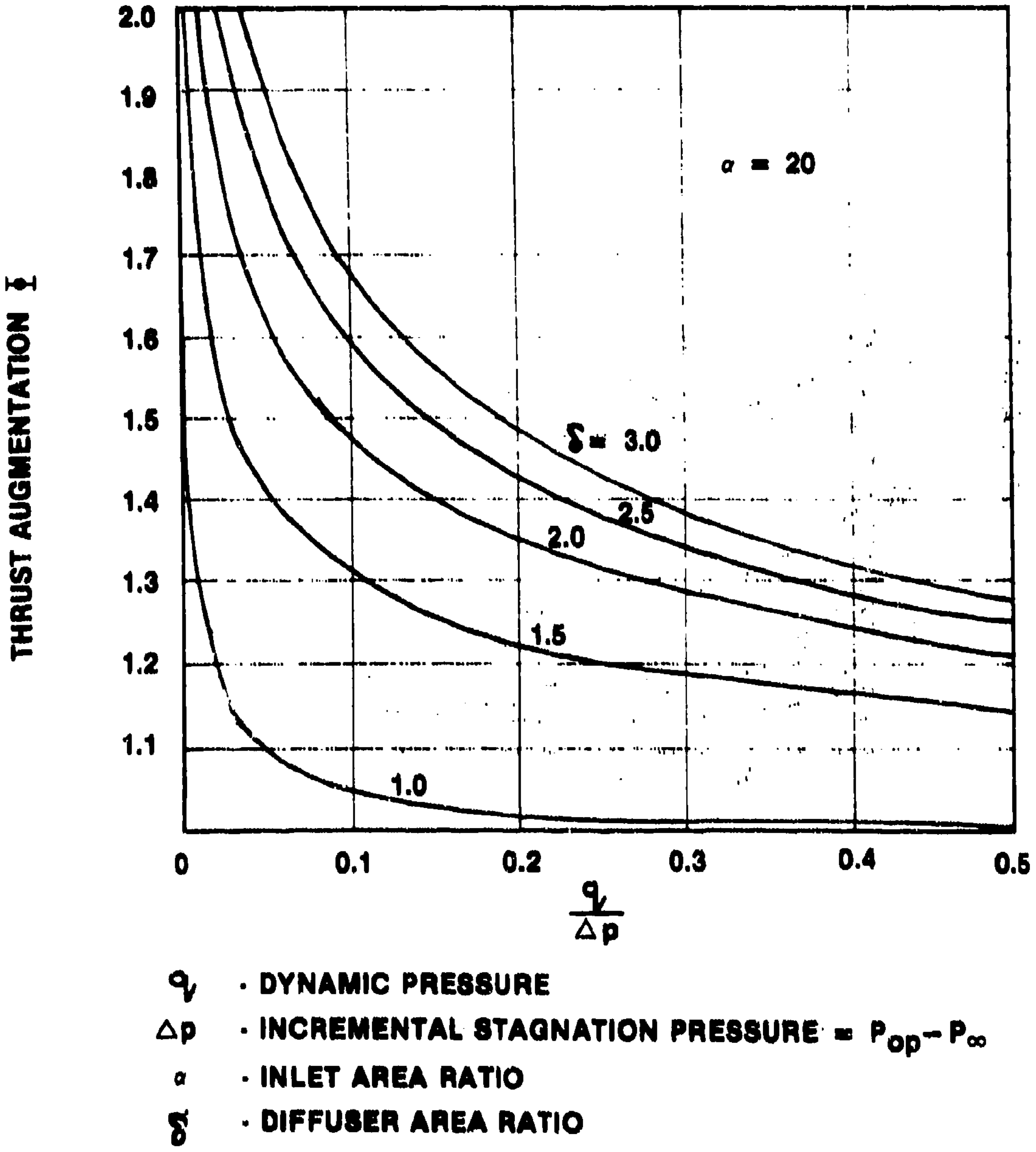


Figure 8.- Variation of thrust augmentation with q/Δp.

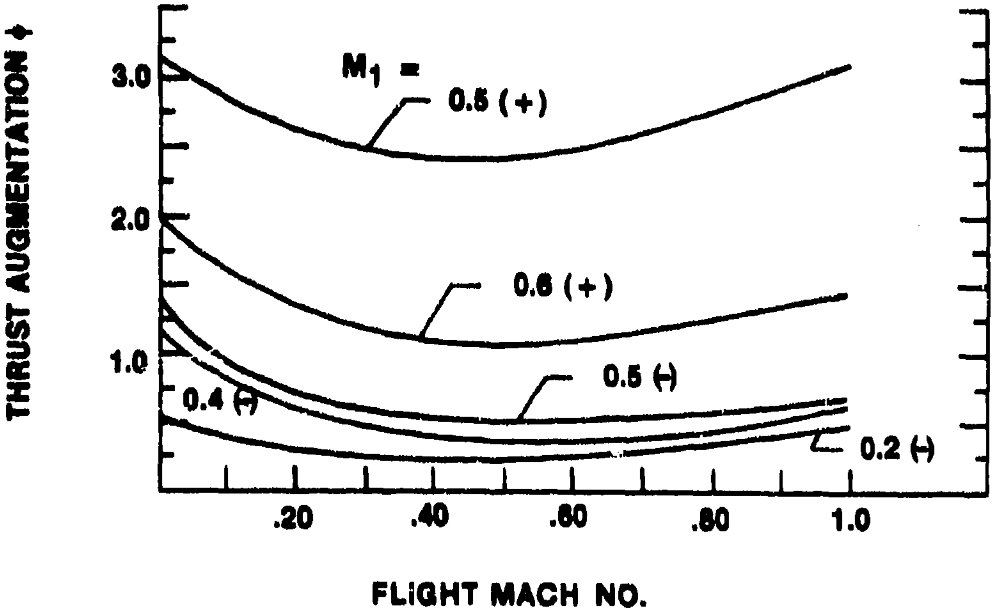


Figure 9.- Variation of thrust augmentation flight Mach number.

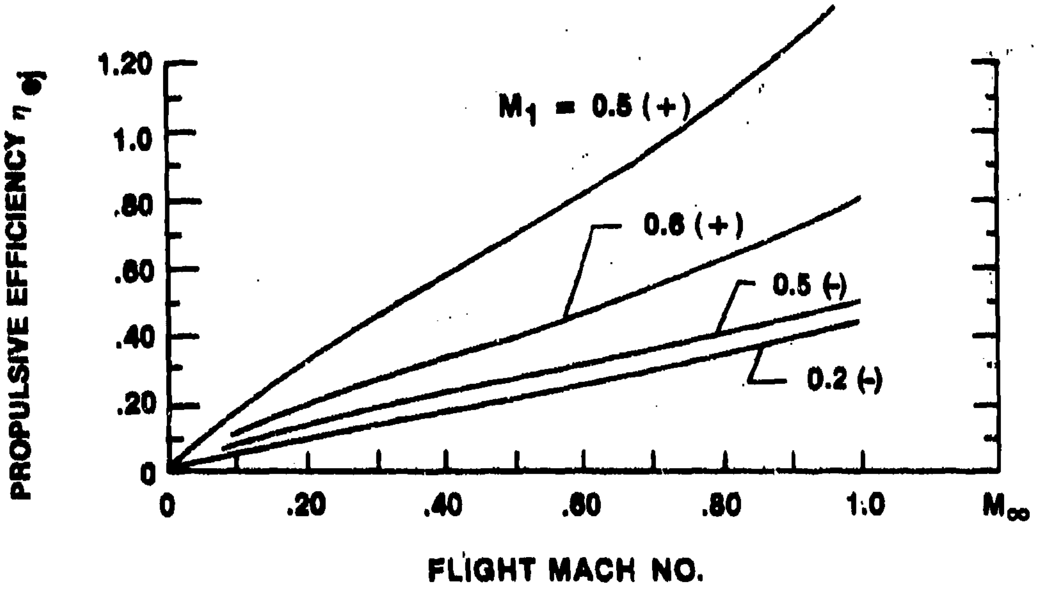


Figure 10.- Solid diffuser ejector performance; $\alpha_\infty = 20$, $\Delta T/T_\infty = 5.0$, $\Delta P/p_\infty = 3.0$, $C_{di} = C_F = C_\mu = 0$.

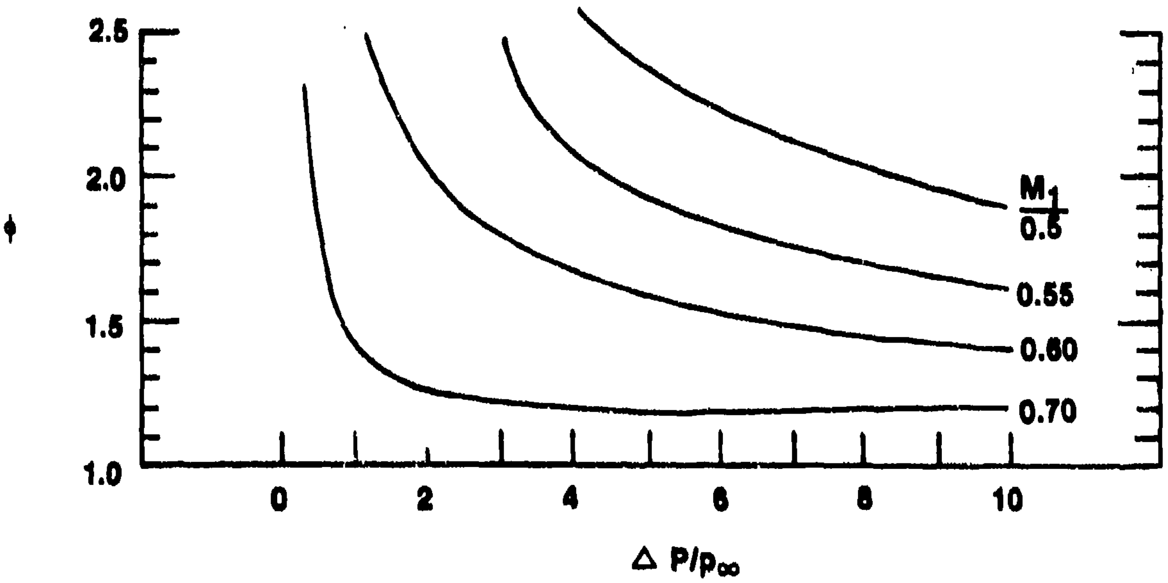


Figure 11.- Ideal high-speed ejector; $M_\infty = 0.5$, $\alpha_\infty = 20$, $\Delta T/T_\infty = 3.0$; second solution.

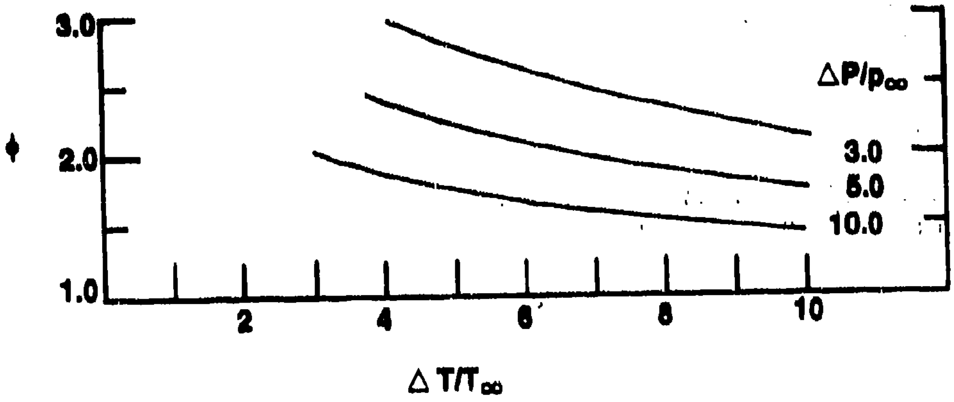


Figure 12.- Ideal high-speed ejector; $M_\infty = 0.8$, $\alpha_\infty = 20$, $M_1 = 0.5$; second solution.

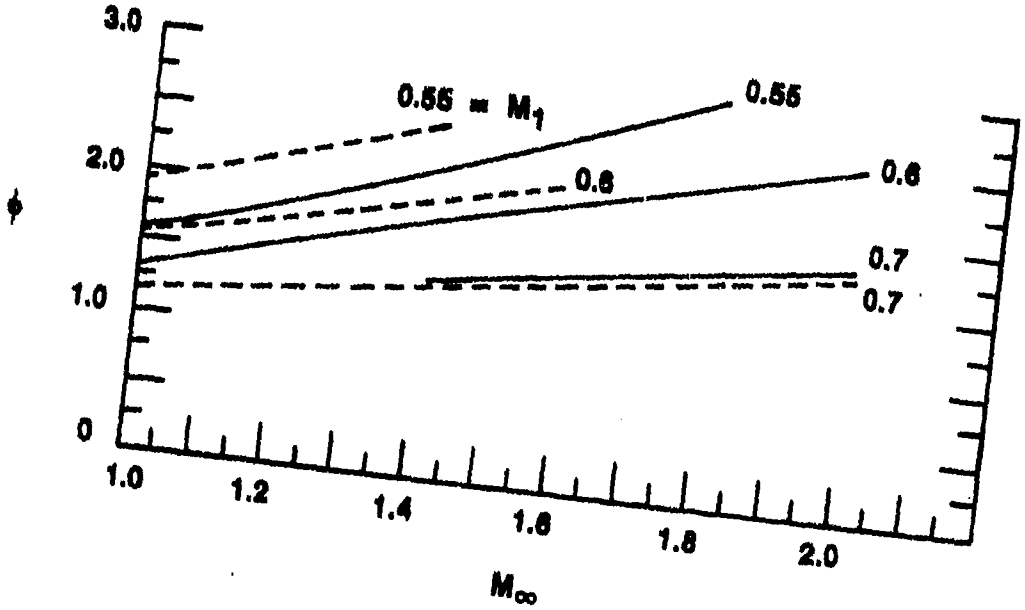


Figure 13.- Supersonic ejector performance; $\alpha_\infty = 20$, $P/p_\infty = 5.0$, $\frac{\Delta T}{T_\infty} = \begin{cases} \text{———— } 10.0 \\ \text{- - - - } 5.0 \end{cases}$; second solution.

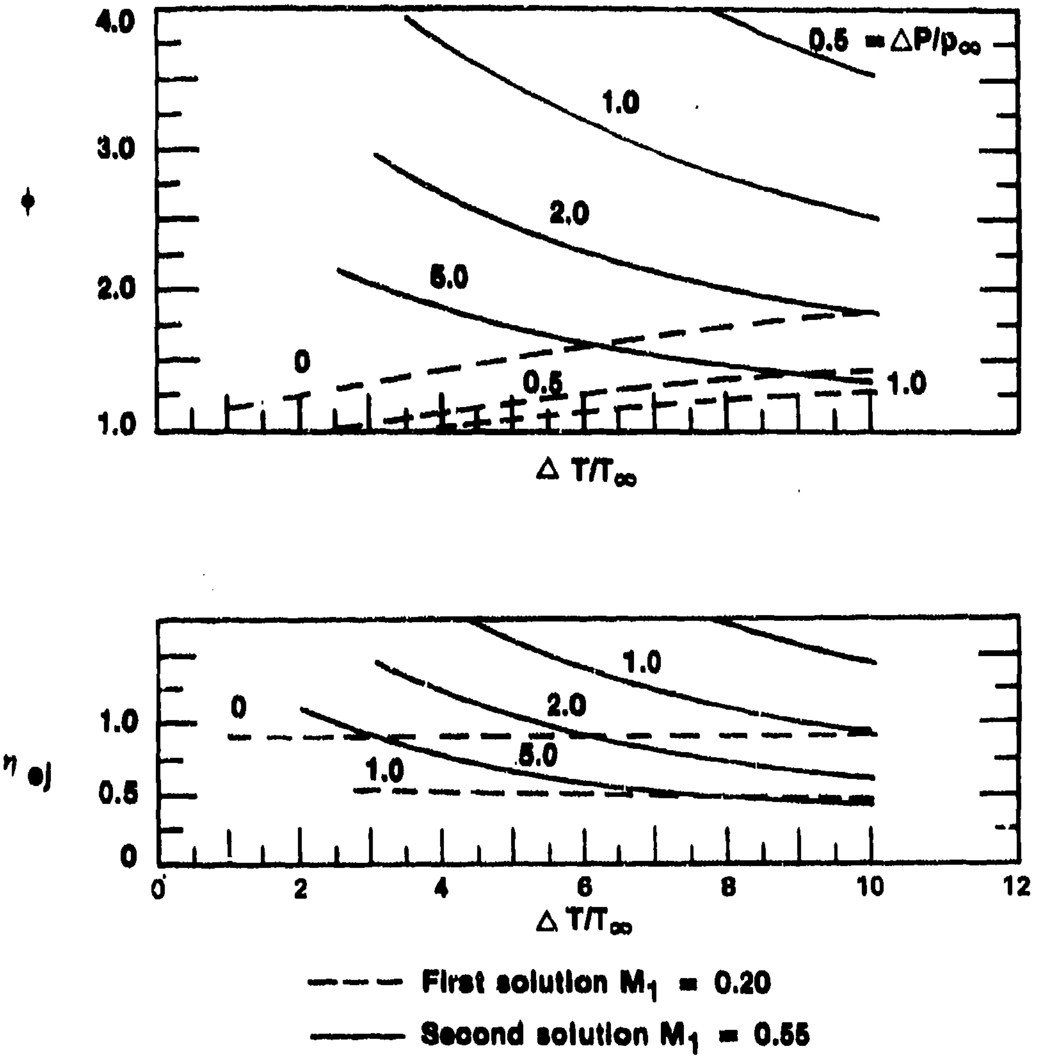


Figure 14.- Ideal high-speed ejector; $M_\infty = 0.8$, $\alpha_\infty = 20$, $s_\infty/a_\infty = 0$.

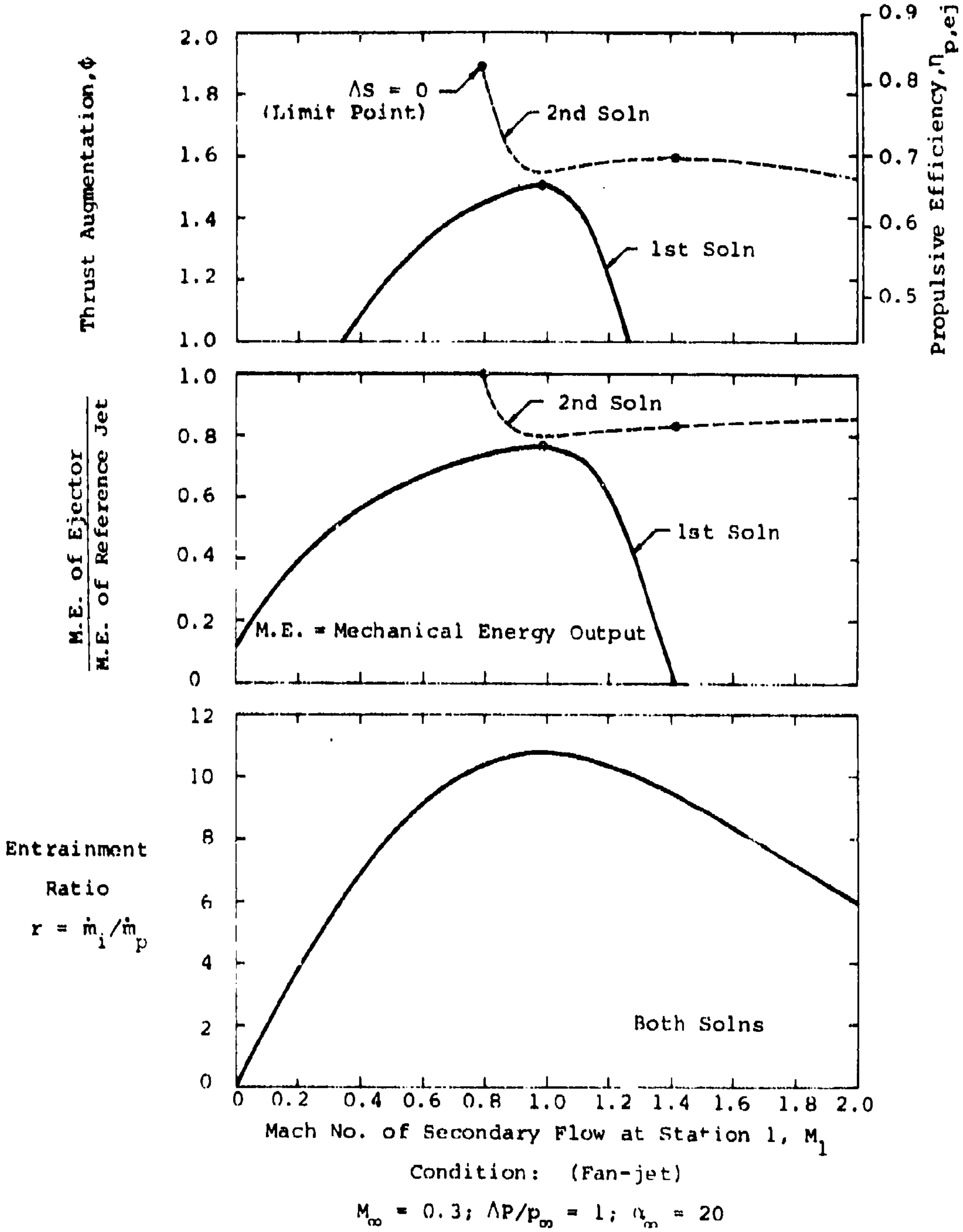
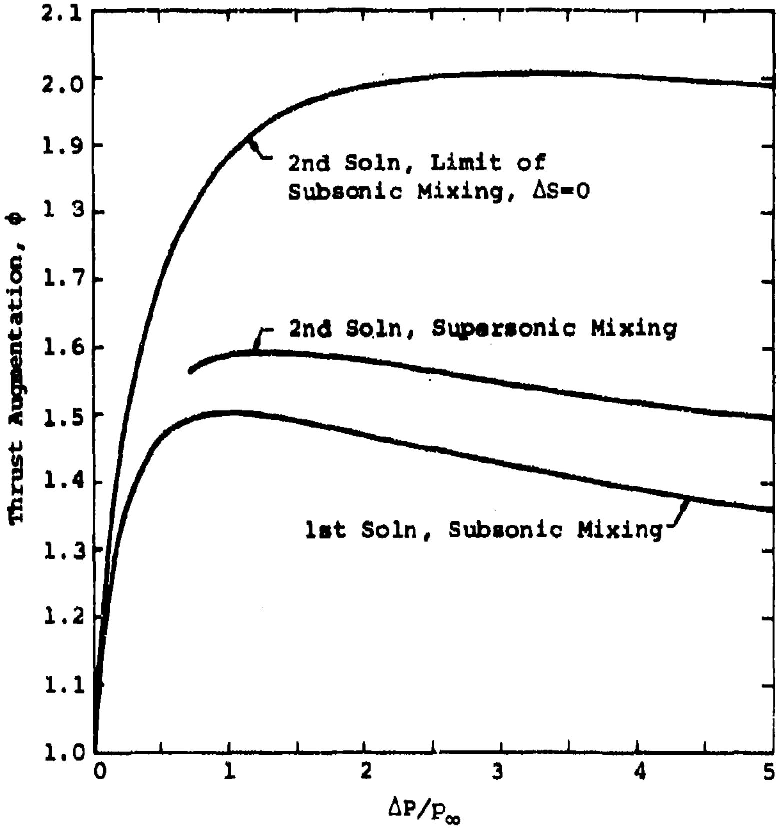


Figure 15.- Ejector in low-speed flight.



Condition: (Fan-jet)

$M_\infty = 0.3$; $\alpha_\infty = 20$

Figure 16.-Influence of pressure on low-speed ejector performance.