Test Results of a VTOL Propulsion Concept Utilizing a Turbofan Powered Augmentor

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Several questions relevant to the feasibility of achieving successful VTOL flight with thrust augmenting ejector wings are answered by the present experimental study. Tests were performed with a large-scale turbofan powered augmentor that embodied many of the problems encountered in the design of real flight hardware. The apparatus consisted of four separate and parallel ejector channels in each of two wings. Results were compared with data from other laboratory experiments using a single channel ejector of similar geometry. Over-all performance levels of the large multichannel apparatus correlated well with the single-channel results. Minor interactions between the four ejector channels on each wing had no significant effect on the over-all level of thrust augmentation. However, the distribution of thrust was affected and should be considered in future aircraft system designs. Operating as an air pump, the turbofan engine was maintained in its safe operating regime throughout all test configurations.

Nomenclature

A = area
BLC = boundary-layer control
MCE = multichannel ejector
P = static pressure
P_t = total pressure
SCE = single-channel ejector
T = temperature
V = velocity
η = nozzle thrust efficiency
ξ = inlet loss coefficient
Φ = static thrust augmentation ratio

Subscripts

a = ambient
CYL = refers to cylinder plenum condition
IP = inlet probe
LC = load cell
0,1,2,3 = primary, entrained or inlet, diffuser entrance, diffuser exit, respectively

Introduction

Background

TODAY, aircraft designs that embody thrust augmenting ejectors to achieve VTOL flight continue to approach the point of reality as laboratory tests approach theoretical performance levels. Static tests at moderate inlet area ratios have demonstrated that properly designed ejectors can more than double the isentropic thrust available to the primary nozzle. This has been achieved within the severely limiting ejector length constraints imposed by aircraft installation requirements.

The open literature contains relatively few descriptions of ejector experiments in wind tunnels. However, all unanimously agree that lift, as well as thrust, is augmented by "ejector wings." This is especially true of VTOL concepts in which the ejectors consume a major fraction of the wing area. Such an augmented propulsive-lift system, though very attractive, is fraught with several design problems. One of the most difficult consists of transmitting engine power to the ejector. It is in this area that ducting losses can steal almost as much from the available thrust as the ejector can add. The ejector wing concept that inspired this work reduces duct losses by locating the augmentors near the air supply and by utilizing the relatively thick wing roots to accommodate large duct cross sections.

VTOL Concept

Figure 1 artistically describes a multiple-channel, ejector-in-wing concept. During takeoff and landing the cruise turbofan engines serve as air pumps for the ejector's primary flow system. By-pass air from the turbofan engine is diverted by suitable valving to the hollow tubes extending outboard in the wings. These tubes also serve as pressure plenums for the ejectors' primary nozzles.

In takeoff mode, the portions of the wing surface that conceal the ejectors open to form guide vanes on top of the wing and diffusers below. Through the action of confined turbulent mixing, the ejectors entrain air from above the wing, augmenting the thrust of the fan air in the process, and positioning the resultant thrust vector in a vertical direction. Following liftoff, the guide vanes and diffusers are slowly canted forward and backward, respectively, producing an inclination of the thrust vector and a gradual transition from vertical to forward flight. The forward velocity interacts immediately[1,2] and favorably with the efflux of the ejector to produce a strong circulation around the wing. This is the seed of the lift augmentation mentioned above. The aerodynamic lift and drag characteristics of the ejector wing provide a broad VTOL transition corridor and, equally important, a STOL capability under overload conditions. At a predetermined flight speed the fan air is redirected to the fan nozzles and the wing is closed to present a clean profile for efficient cruise. It is important to note that engines used to power ejector wings are sized to the demands of cruise flight and not to the demands of VTOL. Interested readers may find more complete discussions of ejector wing concepts and applications in Refs. 3–5.

Present Test Objective

One of the first steps in determining the feasibility of the concept was to demonstrate high levels of thrust aug-

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Index category: VTOL Powerplant Design and Installation.

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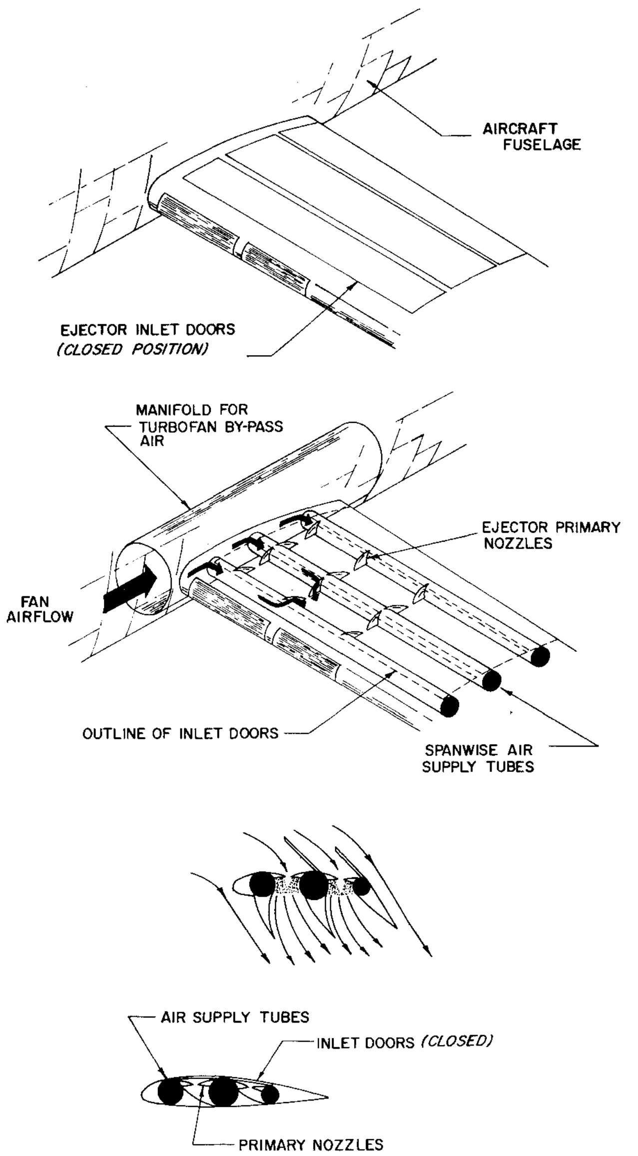


Fig. 1 Artist's conception of ejector wing VTOL system: a) view of upper surface from leading edge. b) Simplified detail of wing and fuselage interior showing primary air ducting. c) Ejectors operating during transition from VTOL to conventional flight. d) Cross section through ejector wing, cruise configuration.

mentation with an ejector that was sufficiently compact for wing integration. This was accomplished in a previous investigation and disclosure[6] in which the performance of a single-channel ejector was reported. However, several questions remained. Was the turbofan engine cycle compatible with the variety of back pressures offered by an ejector with a variable diffuser geometry? Would interference between adjacent ejector channels prove seriously degrading to performance? Also, was it valid to utilize the static performance results of a single-channel ejector to predict the static performance of a similar but multiple channel ejector?

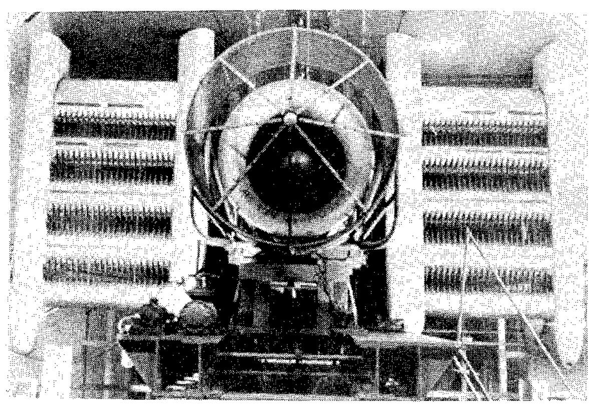
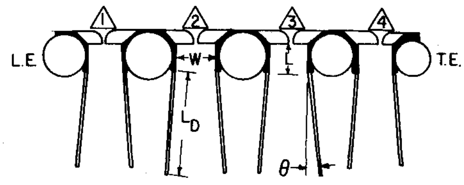


Fig. 2 Multichannel ejector. Frontal view of engine and upper surface of wing with inlet doors removed.



CHANNEL NO	1	2	3	4
W L L_D	8" 10" 28"	10" 10" 30"	10" 10" 30"	8" 10" 28"
DIFFUSER AREA RATIOS (A_3/A_2)	1.0 1.2 1.4 1.7 2.0	1.0 1.2 1.4 1.7 2.0	1.0 1.2 1.4 1.7 2.0	1.0 1.2 1.4 1.7 2.0
DIFFUSER HALF ANGLES (θ)	1.6° 3.3° 5.7° 8.2° 0°	1.9° 3.8° 6.7° 9.6° 0°	1.9° 3.8 6.7° 9.6° 0°	1.6° 3.3° 5.7° 8.2° 0°

Fig. 3 Ejector dimensions and available diffuser positions (ejector schematic not to scale).

The present study represents an extension of previous tests and answers these questions by examining the static performance of an engine powered large-scale multiple-channel ejector. While facility restrictions prevented the study of some ejector topics, the present experiments do examine static augmentation, energy distribution among the several ejector channels, interference between channels, and duct losses.

Description of Experimental Set-Up

Test Site

The experiment was located in a former propellor test cell which measures 45 ft × 45 ft × 122 ft in height, width, and length. Doors and honeycomb at each end of the cell permit the free passage of air during testing. The ejector wing was located 48 ft from the inlet end at a point where the wall contour reduces to a circular section 41.5 ft in diameter. Instrumentation leads, fuel lines, oil lines, etc. were led to an adjacent control room which housed test operators and electronic monitoring equipment.

Multichannel Ejector

The ejector was an approximately full scale, "boiler-point," version of an ejector wing designed[7] for a research test vehicle in 1968. A photograph of the ejector wing apparatus mounted in place on the test stand, is presented in Fig. 2. The wing span measured 24.67 ft. The chord was 11.5 ft. An Avco Lycoming PLF1A-2 high bypass ratio turbofan engine‡ provided the primary air for the ejector system. Upon leaving the fan, the bypass air was slightly diffused before entering a manifold which directed it toward the four ejector channels on each wing. These had a rectangular planform 6 ft long and extended from the root to nearly the tip of each semispan. On each wing the two central channels had 10 in. mixing duct widths while the

‡The PLF1A-2 was an advanced development demonstrator built in the early 1960's. By-pass ratio 5.0, fan pressure ratio 1.4, 4320 lb sea-level thrust.

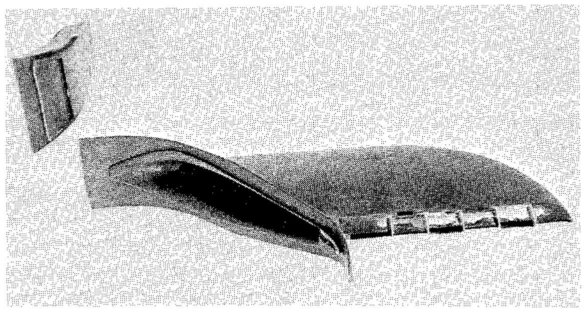


Fig. 4 Three-quarter view of hypermixing nozzle and BLC nozzle.

leading and trailing edge ejectors had 8 in. mixing duct widths. The length of the constant area mixing duct in the flow direction was 10 in. for all channels. The chart presented as Fig. 3 summarizes the geometric dimensions of the ejectors and also indicates the available diffuser settings.

Hypermixing nozzles identical to those used in the earlier experiments[6] served to inject the fan air into the mixing ducts. The hypermixing primary nozzles and slot-type BLC nozzles used to control inlet losses are shown in ¾ view in Fig. 4. Both were injection molded using a Nyafil material and were positioned as described in the previous reference.

The inboard and outboard endwalls of each ejector channel were equipped with small nozzles to energize the endwall boundary layer. Such treatment has been found necessary[6] to avoid premature diffuser stall in rectangular ejectors. With the 46 hypermixing primary nozzles, 48 BLC nozzles, and 2 endwall nozzles in each ejector channel, an over-all design inlet area ratio, A_1/A_0 of 23.4 was achieved. Figure 5 contains data relevant to the determination of this area ratio.

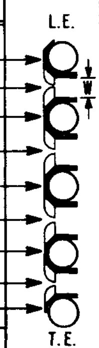
Sizing the engine to the ejector necessitated our venting about half of the available cold fan air flow in order to maintain the turbofan in its normal operating regime. This was accomplished by installing four calibrated venting nozzles on the rearward face of the manifold chamber. To prevent their thrust from being sensed by the load cell, two vent nozzles discharged upward and two downward in a plane normal to the thrust axis of the test bed. The mass flow characteristics of each vent nozzle were determined from calibration tests in a separate facility.

Instrumentation

The turbofan engine was instrumented with pressure, temperature, and frequency sensors by the manufacturer for suitable monitoring of engine parameters. Additionally, the ejector wing was fitted with pressure and temperature probes at appropriate locations for measuring the necessary ejector performance parameters. Notably, the inlet to each of the eight ejectors was equipped with two hook-type static pressure probes that measured the pressure of the entrained air stream at the plane of primary flow injection. In a later section, it will be shown how this measure of static pressure was used to indicate the level of static thrust augmentation.

Pressures were read on three 48-channel Scanivalve transducer systems. The transducers were Statham PL 131TC gage type with an accuracy guaranteed to within ± 0.1% of full scale by the manufacturer. Temperatures were measured with either iron-constantan or chromel-alumel thermocouples and a Pace-Wiancko-Whitacre reference junction.

The entire ejector wing and engine assembly was mounted to the test stand through a one degree-of-freedom thrust bed. A 5000 lb load cell recorded the total gross thrust of the entire ejector with engine apparatus.



CHANNEL NO.	SUPPLY TUBE NO.	TUBE FLOW AREA (IN²)	W (IN)	A (IN²)	DESIGN A_0 PRIMARY	DESIGN A_0 BLC	DESIGN A_0 ENDWALL	A_1/A_0 $\left[=\frac{A_2}{A_0}-1\right]$
	1	80.9						
1			8	576	18.1	4.39	1.53	23.0
	2	220.4						
2			10	720	23.0	4.39	1.77	23.7
	3	220.4						
3			10	720	23.0	4.39	1.77	23.7
	4	148.5						
4			8	576	18.1	4.39	1.53	23.0
	5	70.9						
COMPOSITE 4 CHANNELS		741.1	----	2592	82.2	17.56	6.60	23.4

Fig. 5 Inlet area ratio determination (ejector schematic not to scale).

System Calibration

The pressure measurement equipment was thoroughly calibrated on a periodic basis. The individual Scanivalve transducers were incrementally loaded through a separate air supply and the response monitored by a digital voltmeter with a sensitivity of 1 μv. The calibration pressure was read on a 30 in. mercury manometer with a high precision cathatometer, accurate to within 0.001 cm. Prior to each test, the Scanivalve transducers were rechecked for correct zero and full-scale readings.

Measurement of Static Augmentation

In the design of the multichannel ejector wing of Fig. 2, existing facility constraints dictated a one degree-of-freedom approach to measuring thrust augmentation. Therefore the turbofan was oriented so that its thrust vector was in the lift direction, paralleling the thrust of the augmentors. Only the static thrust associated with vertical takeoff was to be measured. In this configuration, inlet doors would be aligned with local entrainment streamlines above the wing to avoid ejector inlet losses. For simplicity, the doors were eliminated in the present static experiments.

Several independent measures of thrust augmentation were considered, including: a) suitable correction of gross load cell thrust in order to isolate the thrust of the augmentors alone, b) survey and integration of ejector exhaust total pressure, and c) measurement of ejector entrainment velocity. Because of the complexity of the MCE-turbofan configuration, an accurate correction of the load cell reading to account for nonejector thrust and drag components was found to be impossible.

The second approach was abandoned when it was found that an averaging total pressure rake could not measure the correct pressure profile within 20%.

The third approach is sensitive only to the internal efficiency of the ejector and had proven to be very satisfactory in previous experiments.[6] It was therefore adopted for the present study. This method of determining thrust augmentation requires the measurement of static pressure in the ejector inlet at the plane of primary injection. The value of augmentation so determined will be referenced as Φ_{IP}, denoting its measurement by means of the inlet probes described previously. The technique requires knowledge of the isentropic velocity ratio V_1/V_0.

The entrained air velocity V_1 was computed by assuming an isentropic expansion from ambient pressure and temperature, P_a and T_a, to the measured static inlet pressure P_1. A similar computation for the primary air velocity V_0 followed from taking stagnation conditions as those in each ejector cylinder, P_{tcyl} and T_{tcyl} and expanding

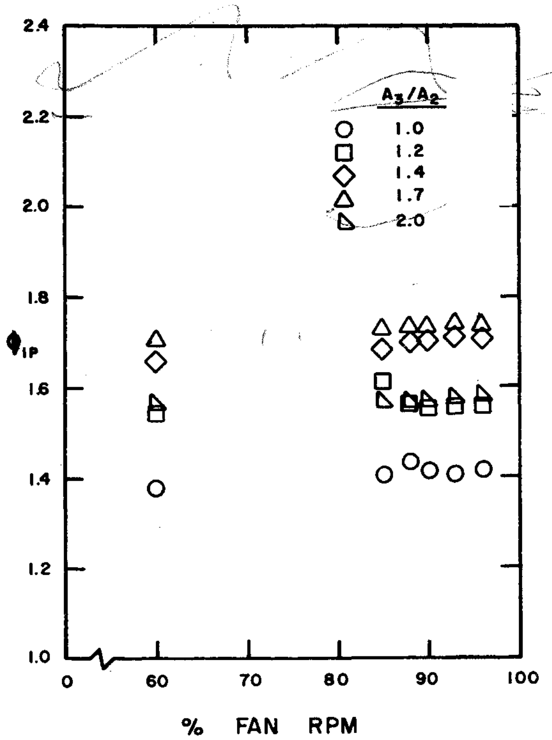


Fig. 6 Effect of fan speed on static augmentation ratio.

isentropically to P_1. In this manner the thrust augmentation ratio Φ_{IP} could be determined by the following expression:

$$\Phi_{IP} = (A_0/A_3)[1 + (A_1V_1/A_0V_0)]^2[\eta^{-2} - (1 + \xi)(V_1/V_0)^2]^{-1/2}$$

where η and ξ are the nozzle thrust efficiency and the inlet loss coefficient, respectively. In separate and independent tests designed for the specific purposes, we found $\eta = 96\%$ and $\xi = 2.5\%$. Extensive testing of ejectors with the identical inlet and nozzles has verified the reliability of these values and has generated confidence in the adequacy of Φ_{IP} as a measure of static thrust augmentation so long as two conditions are satisfied. The first requires a uniform distribution of the inlet pressure P_1 and was verified by selective probing of the inlet. The second requires

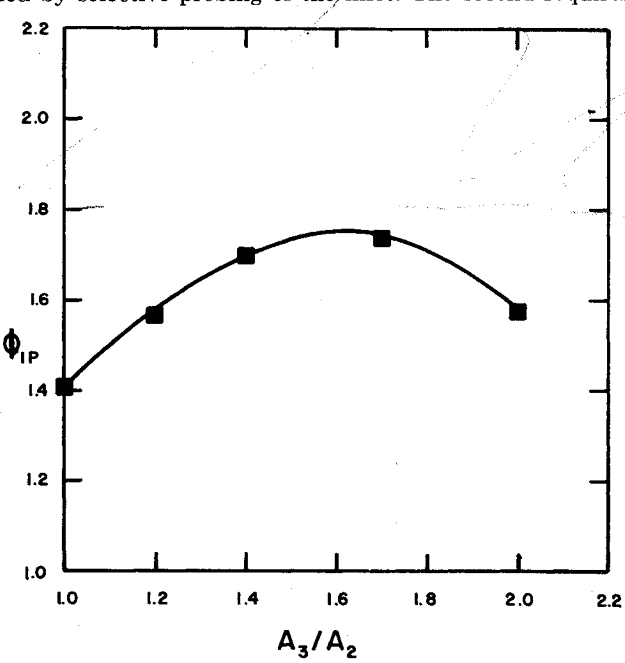


Fig. 7 Effect of diffuser area ratio on static augmentation ratio.

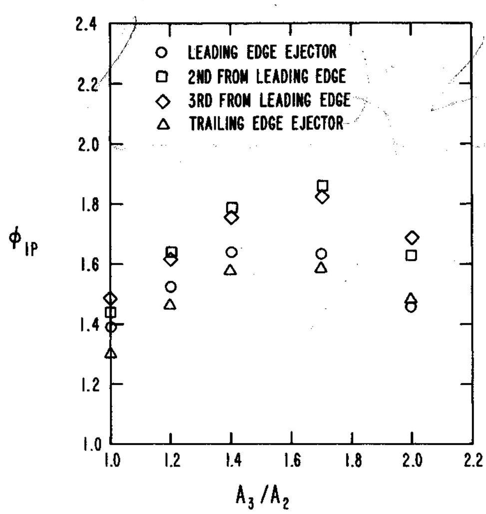


Fig. 8 Chordwise distribution of augmentation level.

a uniform velocity at the diffuser exit. In reality this never occurs, but so long as the exhaust flow skewness is held to reasonable levels the effect is small and the formula under predicts. Φ_{IP} ceases to be a meaningful measure of thrust augmentation when the diffuser enters into a stall regime. This condition is easily recognized in the data and will be discussed below.

Experimental Results

Multichannel Ejector

Data was obtained over a range of diffuser area ratios at selected engine fan speeds from 60% to 96% of rated maximum. This range corresponds to primary pressure ratios from 1.09 to 1.26. Figure 6 fails to indicate any systematic dependence of Φ on pressure ratio over the range of pressures encountered in the present tests. Accordingly, the values of Φ stated in the following discussion are actually the average of values obtained at different fan speeds.

Figure 7 contains a summary of the multichannel ejector performance results. This is a plot of static thrust augmentation, Φ_{IP}, as a function of diffuser area ratio, A_3/A_2. For this particular ejector configuration, maximum augmentation occurs at a diffuser area ratio around 1.7.

The chordwise distribution of thrust augmentation, Φ_{IP}, can be seen in Fig. 8. Each curve represents the static performance of an individual channel indicated by the symbolic code. It is evident that the central two ejectors perform better than the end two by a substantial margin at all diffuser area ratios. Using yarn tufts, we observed that the physically larger central ejectors on each wing tended to starve the leading and trailing edge ejectors of entrained air. While the stagnation streamlines were more or less symmetrically disposed on the inlets to the central ejectors, the flows entrained into the leading and trailing edge ejectors were obviously asymmetrical. The tufts clearly established that air flowing through the outermost inlets originated far forward and aft of the wing and curled sharply around the two end cylinders before passing into their respective inlets. We believe the asymmetrical inlet flow was responsible for the degraded performance of the forward and aft ejectors.

The total pressure loss in the supply ducting was continuously monitored. As mentioned above, the fan air flow passage consisted of a mild diffuser leading to a large manifold that turned the air ninety degrees and directed it into the wing ducts. Under maximum mass flow conditions a 2.6% loss in total pressure was experienced between the high pressure side of the fan and the ends of the wing ducts.

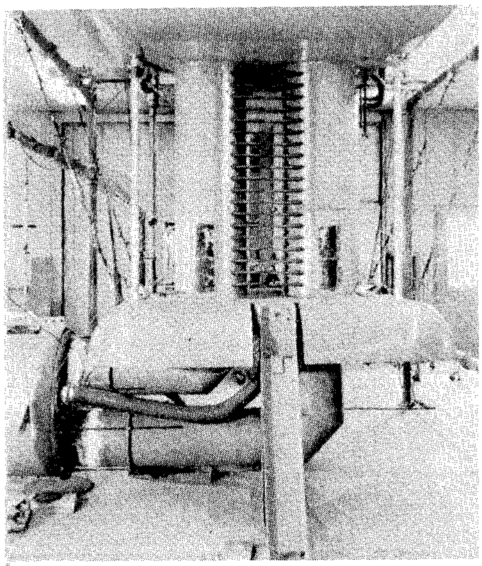


Fig. 9 Single-channel ejector test rig.

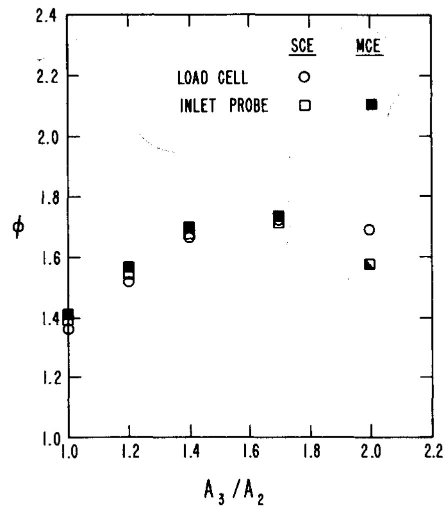


Fig. 11 Correlation of MCE and SCE augmentation results.

Correlation with Single-Channel Ejector Results

For correlation purposes, tests were conducted on the single-channel ejector (SCE) apparatus discussed in Ref. 6 with a configuration duplicating the central ejectors of the MCE tests. A photograph of the experiment is shown in Fig. 9. The length of the ejector was 60 in. between end-walls whereas this dimension was 72 in. for the MCE tests. This was the only geometric difference. Air was supplied to the primary nozzles by a supersonic mass augmentor, which in turn was driven by a high pressure "bottle farm" air supply. Pressure ratios run in the MCE experiments were duplicated in the SCE test.

Being a much simpler experimental model than the multichannel ejector, the SCE thrust was easily measured with a load cell. Thus, in this test both load cell and inlet pressure probe values of thrust augmentation were obtained. As shown in Fig. 10 both Φ_{IP} and Φ_{LC} were essentially the same as long as the diffuser efflux remained uniform. The necessity of this condition in calculating Φ_{IP} was discussed earlier. Figure 11 indicates the degree of correlation between the two separate tests. The agreement between Φ_{IP} of the MCE tests and Φ_{IP} and Φ_{LC} of the SCE tests is apparent.

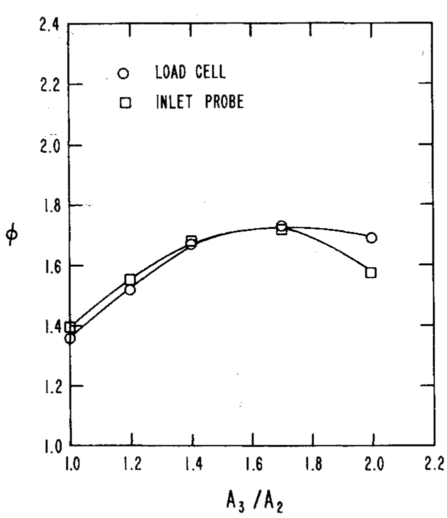


Fig. 10 Effect of diffuser area ratio on augmentation ratio in the SCE.

Conclusions

The experiments discussed above provided answers to the questions posed in an earlier section. No problems developed in using turbofan bypass air to supply the primary nozzles of the ejectors. At all engine speeds tested, the fan remained within the manufacturer's safe operating regime regardless of the ejectors' diffuser area ratio. In other words, fan and ejector cycles were compatible.

The performance of an ejector is definitely affected by the presence of other ejectors in close proximity. This point must be considered in the design of aircraft ejector wing systems. Interactions appear to be peculiar to the configuration and may be favorable or unfavorable. We observed both. On the whole, however, gains balanced losses and little difference could be seen in the net performance of our multiple-channel ejector and our single channel ejector of like geometry. This observation was especially noteworthy because it suggests that tests with a single-channel laboratory apparatus will differ very little in net performance from considerably more expensive, complex and time consuming tests with a multiple-channel ejector.

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