REACTION CONTROL SYSTEM AUGMENTATION FOR V/STOL AIRCRAFT

H. G. Streiff and R. E. Donham

Lockheed California Company
Burbank, California

INTRODUCTION

V/STOL control during hover and low-speed flight is provided directly or indirectly by the propulsion system. The control requirements during these flight conditions have a large influence on and, in fact, generally dictate the propulsion system size. Means of obtaining control from the propulsion system are varied and are generally dictated by configuration design and control required by emergency conditions. Reaction controls produced by bleeding air from the engine compressor, and ducting that air to extremities of the aircraft is one of those means. Advantages and problems associated with augmentation of reaction controls are the subject of this paper.

ADVANTAGES OF REACTION CONTROL AUGMENTATION

Generally, when evaluating the relative merits of ejector thrust augmentation and the net gain obtained from incorporating such advice into a particular design, the losses associated with transferring the air from the gas generator to the ejector must be included. These losses can be of the order of 15% or more. In addition, in order to minimize these losses, the ducting of the air while keeping flow losses to these levels requires the using up of large fuselage and wing volumes. In arguing the case for augmenting reaction controls, these losses need not be initially considered because the ducting and transfer losses exist whether or not the air provided to the reaction control nozzles is augmented. With the exception of the incremental increase in configuration nozzle weight caused by adding the ejector and, of course, assuming the ejector does not significantly alter the aerodynamic performance or flying qualities of the configuration, the gains achieved through augmentation of the reaction controls are real gains.

Several advantages of augmenting reaction control are presented in figure 1. The first two listed advantages appear identical, but differ in design philosophy and propulsion system selection. The first item alludes to the ability to achieve the maximum amount of control power from the amount of bleed available from a given gas generator. For example, consider an aircraft such as the AV-8 where the flying qualities are constrained by the amount of control available and the performance varies in accordance to the amount of bleed demanded by the control system. Installation of a compact ejector into a redesigned wing tip, out board of the outrigger landing gear, would significantly increase the maximum roll control available and decrease the amount of bleed required for normal roll control inputs.

The second item applies to the design of a new configuration where the propulsion system is sized according to the amount of compressor bleed required to provide adequate control for acceptable flying qualities. In this case, designing the engine to provide the control power required for minimum bleed reduces the size of the gas generator as well as the engine specific fuel consumption. The reduced propulsion system weight and SFC has a payoff in cruise performance as well as the V/STOL flight modes.

The advantages can be put in perspective by considering the impact of compressor bleed on the design of a V/STOL aircraft. Figure 2 presents the weights, inertia, and control requirements for a typical medium size four engine, four fan V/STOL transport. If reaction control is considered for the roll axis only, the amount of control force required for the one engine inoperative condition is 4,000 lb. The amount of engine bleed required to provide that amount of force and the effect of providing that bleed on engine SFC and weight is summarized in figure 3 for both augmented and unaugmented reaction controls. A relatively modest augmentation of 1.4 was assumed for the example calculations in order to show that significant improvements can be attained without having to achieve extremely large values of augmentation. It is realistic to assume that augmentation in excess of 1.4 is achievable, however a value of 1.4 produces a reduction in VTO gross weight or an increase in VTO payload of approximately 2,700 lb for a 40,000 lb aircraft.

PROBLEM AREAS

Figure 4 summarizes the problem areas that require careful consideration before the amount of compressor bleed augmentation achievable can be ascertained. The vast majority of all ejector test work accomplished to date has been performed at ambient temperatures and very low (less than 2.5) pressure ratios. The pressure ratios of compressor bleed air are of the order of 7.0 to 10.0 and the temperatures can be as high as 1200° F. Test data is required for these large pressures and temperatures. Almost all ejector test programs have been conducted under static conditions. Test data is required for ejectors operating at speed and in crossflows. In designing an ejector for augmenting reaction controls, it is desirable to get the largest amount of force out of the smallest possible ejector. The effect and limitations of large mixing sections velocities (near sonic) on ejector performance is not currently known and is important in determining the optimum ejector size. The packaging of the ejector into a convenient operational installation without adversely affecting the ejector performance or the external aerodynamics of the cruise configuration must be given careful consideration. Lastly, the operation of the ejector under failure conditions must be evaluated to insure compliance with the level 2 and 3 control requirements.

STATE OF THE ART IN EJECTOR DESIGN

The remainder of the paper presents the current status of compact ejector technology and the expected performance of known efficient designs for reaction control applications.

Figure 5 presents the ejector definitions used in the report. In all cases in this report, augmentation is defined as the gross measured force produced by the ejector divided by the amount of thrust that can be produced by an isentropic expansion of the measured primary mass flow. Figure 6 presents the thrust augmentation that can be obtained from an ideal ejector. In a practical case however, the ideal thrust can be significantly reduced by the losses listed in figure 7. Assuming flow separation in the ejector can be minimized, either through BLC jets or generous turning radii, and applying reasonable loss coefficients to each of the listed losses, the curves of figure 6 are reduced to the augmentation values presented in figure 8. Augmentation values of these magnitudes have, in fact, been experimentally achieved by several investigators. Compact ejector designs that have achieved augmentation ratios on the order of 2.0 are presented in figure 9. The one problem with these results is that they have been attained at static conditions, ambient temperatures, and pressure ratios less than 2.5. Figure 9 also contains the results obtained from tests of an axisymmetric ejector at ambient temperature and pressure ratio 10.0. These tests have achieved augmentation ratios as high as 1.45, however, the apparatus had a relatively long mixing and diffuser length and would be very difficult to package.

Results of augmentation ratio as a function of pressure ratio for an axisymmetric ejector are presented in figure 10. These data indicate that if the ratio of mixing section area (A_m) to primary (A_p) is low, there is a large decrease in augmentation as pressure ratio is increased. As A_m/A_p is increased, the augmentation becomes constant with pressure ratio. This indicates that with the proper ejector sizing the pressure ratio effect can be minimized. Figure 11 is a compilation of test results obtained for many single- and multiple-nozzle ejector designs. In this figure, it is seen that the axisymmetric results of the preceding figures fit in the single source band quite nicely while the compact ejector results of figure 9 fit into the multiple-source band. Since an axisymmetric ejector can be designed to remain relatively constant with pressure ratio, it is reasonable to assume that the multiple-source configurations can also be designed to give good performance at high pressure ratios.

A theoretical prediction of the effect of temperature on thrust augmentation is shown in figure 12. These results do not agree with the experimental results of Quinn.[1] In this work, Quinn measured the mass entrainment in an

---

[1] Quinn, Brian: Ejector Performance at High Temperatures and Pressures. J. Aircraft, vol. 13, no. 12, Dec. 1976.

axisymmetric ejector at high temperature and pressure ratios. He found very little change in entrainment with temperature and concludes that "theoretical analyses argue only from thermodynamics and ignore the dynamic role played by the heart of the ejector process, turbulent mixing. Present theories fail to identify which effect of heating the primary stream, higher impact losses or increased mixing, will dominate the performance of compact ejectors." Compact ejectors with enhanced mixing have not been tested at temperatures of the magnitude of compressor bleed air. It appears that a controversy exists as to just how significant temperature is to thrust augmentation and will only be resolved from a comprehensive test program of an efficient compact ejector.

With the exception of significantly increased friction losses caused by the sonic velocities, the gross effects of choking the flow in the mixing section of an ejector are not currently known. Intuitively, it is assumed that choking should be avoided and the mixing section velocity should be Mach 0.7 or less. With this as a constraint and the primary thrust known, the curves of figure 8 can be reworked to provide lines of constant mixing section velocity as a function of gross thrust, mixing section area, and diffusion ratio. These data are shown in figure 13. From these curves, it is seen that the mixing section for an ejector with a thrust augmentation of 1.4 (gross thrust of 4000 lb) would have to have a mixing area on the order of 600 in.^2 for a mixed velocity of $M \leq 0.7$.

Figure 14 shows the thrust augmentation received from several ejector configurations tested at WPAFB-ARL. This data shows that extremely good augmentation can be obtained using the ARL hypermixing nozzles in a compact ejector. The configuration C ejector geometry with aspect ratio 8 hypermixing nozzles was selected for the design of a V/STOL reaction control augmentor. A typical configuration that is capable of providing the required 4000 lb force for roll control of the figure 2 V/STOL aircraft is shown as a wing tip configuration in figure 15.

CONCLUSIONS

From the preceding discussion the following conclusions have been made:

- Significant benefits are to be gained in the following through augmentation of reaction control
    - Reduced cruise SFC
    - Increased payload capability or reduced VTO G.W.
    - Increased engine life because of reduced bleed requirements
    - Maximum control force obtainable from specified available bleed

- Small increase in thrust augmentation produces a relatively large improvement in VTO G.W.
- Augmentation limitations encountered at large PR and TR do not appear insurmountable but require systematic evaluation
- A practical compact ejector of the ARL hypermixing nozzle type can be incorporated into a wing tip and will have minor influence on the aircraft's overall aerodynamic characteristics

- MAXIMUM CONTROL POWER FROM AVAILABLE BLEED
- SATISFACTORY CONTROL POWER FOR MINIMUM BLEED AIR
- MINIMIZE CRUISE SFC'S WHILE PROVIDING ADEQUATE BLEED
- MINIMIZE ENGINE WEIGHT REQUIRED BY VTOL, STOL, AND CRUISE FLIGHT CONDITIONS
- VTO GROSS WEIGHT ENHANCEMENT BY ENGINE WEIGHT REDUCTION AND CRUISE SFC IMPROVEMENT
- REDUCE ENGINE ABUSE AND PROLONG ENGINE LIFE
- FAIL SAFE/OPERABLE CONTROL

Figure 1.- Advantages of augmented reaction controls.

INERTIA

I_X = 57,000 SLUG FT^2
I_Y = 73,000 SLUG FT^2
I_Z = 116,000 SLUG FT^2
WT = 40,000 LB

CONTROL REQUIREMENT FROM MIL SPEC 83300

N_Z 1.05 (1.03)
35 KT. WIND (CRITICAL WINDS)
ADVERSE C.G.
SIMULTANEOUS CONTROL:
.5 (.3) RAD/SEC^2 ROLL
.25 (.2) RAD/SEC^2 PITCH
.2 (.15) RAD/SEC^2 YAW

NOTE: ( ) = LEVEL 2

CONSIDERING REACTION CONTROL USED FOR ROLL AXIS ONLY

CRITICAL CONDITION IS ONE ENGINE INOPERATIVE, LEVEL 2 REQUIREMENTS

CRITICAL CONDITION REQUIRES ROLL CONTROL FORCE OF 4000 LB

Figure 2.- Control required for a typical ASW V/STOL transport.

	% BLEED	% CRUISE SFC	% ENGINE WEIGHT
UNAUGMENTED	22.0	11.0	20.0
1.4 AUGMENTATION	15.7	7.0	12.5

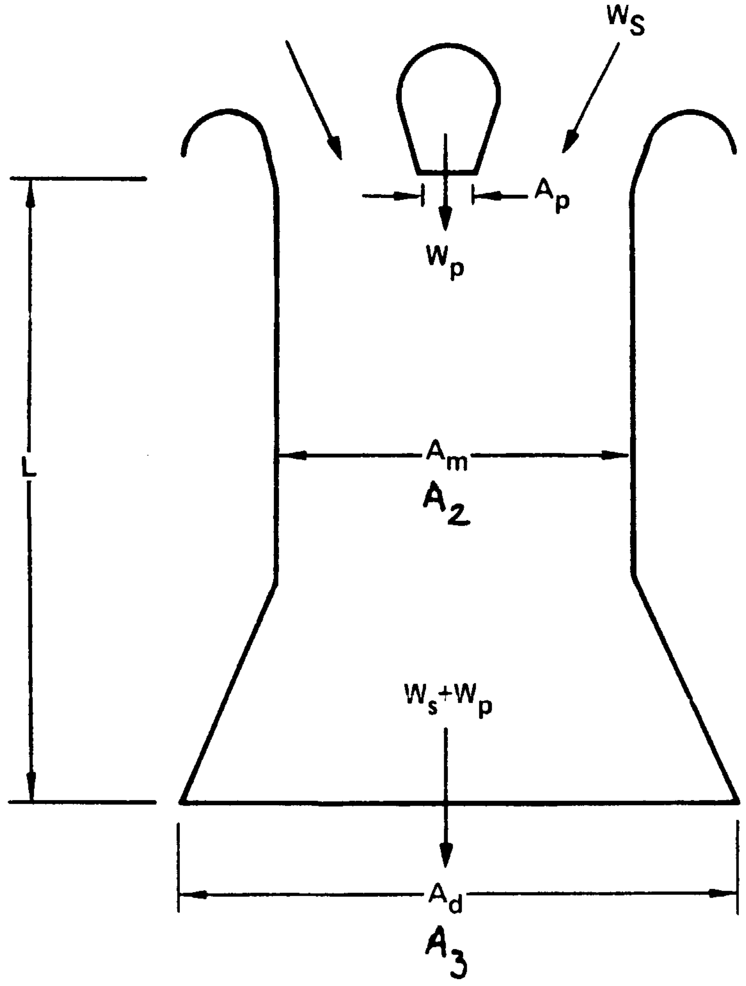
	ENG WT (4 ENG)	ΔWT	Δ% SFC	ΔGR. WT
UNAUGMENTED	5424			
1.4 AUGMENTATION	5017	–407	4	2700*

* 3.7 LBS AIRCRAFT WEIGHT PER 1 LB ENGINE WEIGHT
300 LBS AIRCRAFT WEIGHT PER 1% SFC

Figure 3.- Reaction control roll axis only effect of augmentation on G. W. typical ASW V/STOL transport.

- EJECTOR PERFORMANCE AT HIGH PRESSURE RATIOS
- HIGH TEMPERATURE CHARACTERISTICS
- CROSSFLOW PERFORMANCE
- SONIC OR NEAR SONIC FLOW IN EJECTOR MIXING SECTION
- PACKAGING INTO A PRACTICAL OPERATIONAL INSTALLATION
- SATISFACTORY FAILURE MODES AND EFFECTS CHARACTERISTIC

Figure 4.- Areas requiring detailed evaluation.



GEOMETRIC VARIABLES:

- MIXING SECTION AREA RATIO A_m/A_p
- DIFFUSER AREA RATIO $(A_m/A_d)^{-1}$
- LENGTH RATIO L/dm

AUGMENTATION RATIO

$$\phi = \frac{F_{GROSS}}{F_{ISENTROPIC\ PRIMARY}}$$

Figure 5.- Ejector definition.

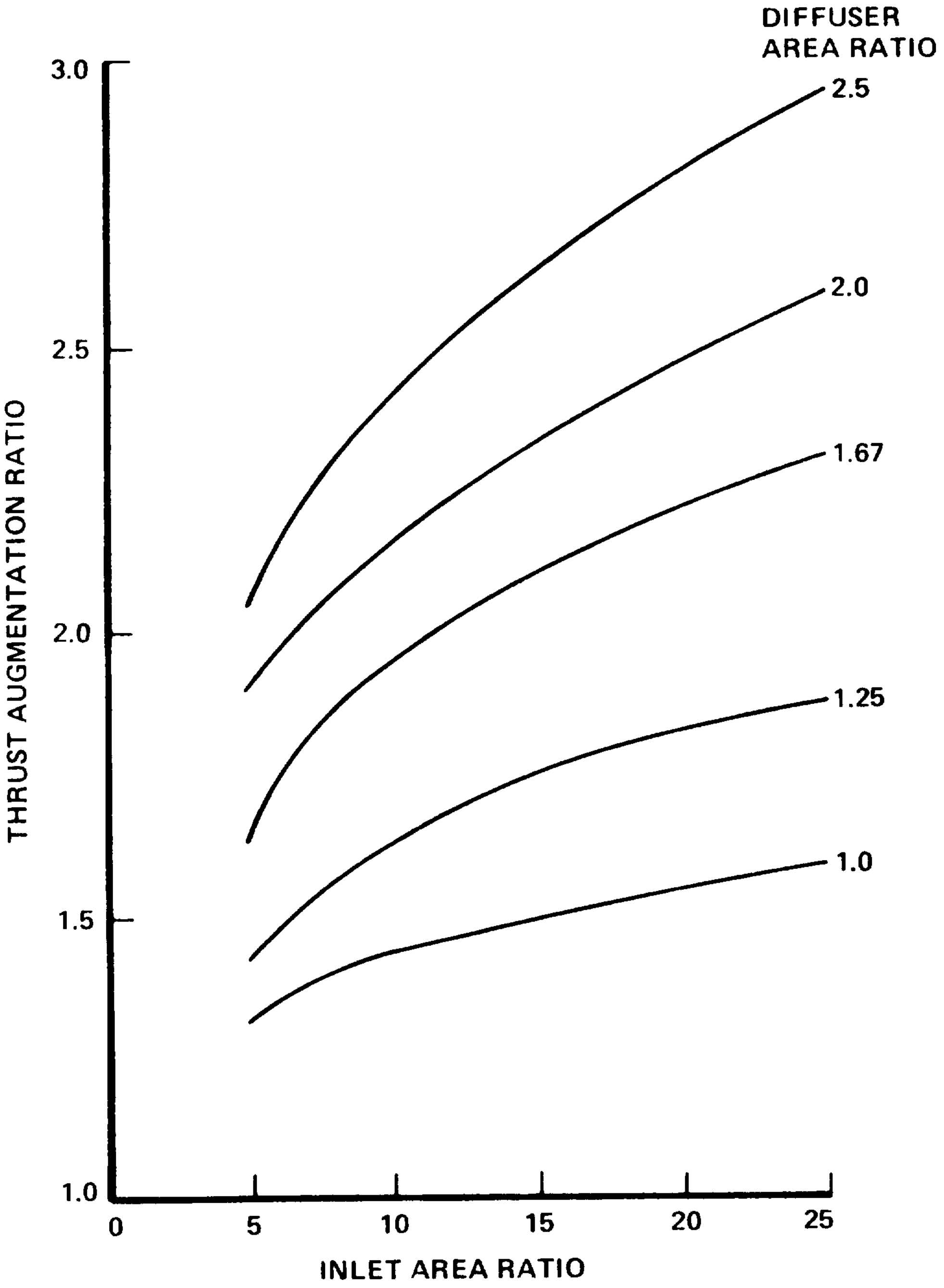


Figure 6.- Thrust augmentation of an ideal ejector.

- INLET TOTAL PRESSURE LOSS
- WALL FRICTION LOSS
- DIFFUSER LOSS
- MIXING LOSS

Figure 7.- Ejector performance losses.

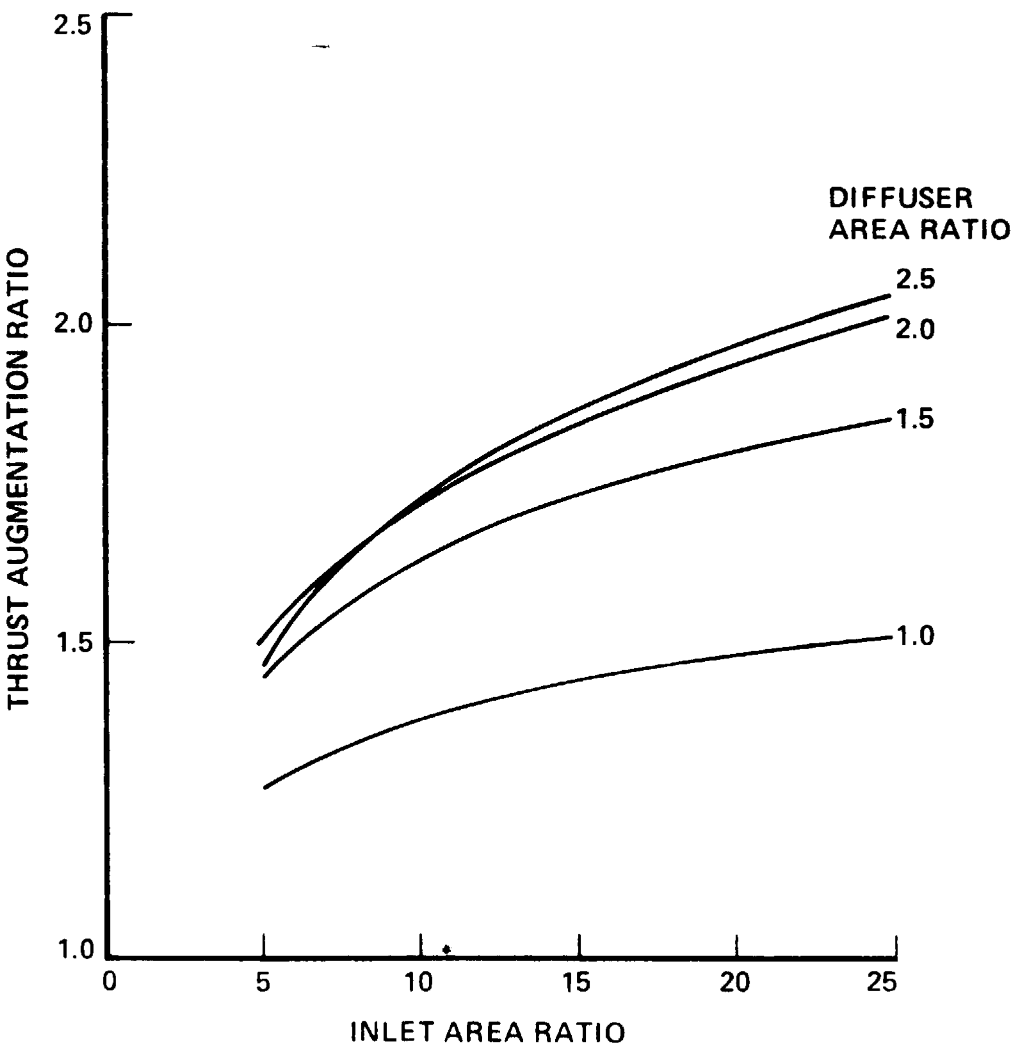


Figure 8.- Thrust augmentation with losses.

HIGH PERFORMANCE COMPACT EJECTORS	
ARL HYPERMIXING NOZZLES STRAIGHT DIFFUSER	2.0
LTV TAILORED CONTOUR EJECTOR	1.87
ALPERIN JET DIFFUSER EJECTOR	2.09
ALL TESTED AT RELATIVELY LOW PR (PR < 2.5) AND AMBIENT TEMPERATURES	
NSRDC AXISYMETRIC EJECTOR TESTS	
MIXER ALONE	1.25
SINGLE VENTED DIFFUSER	1.35
STAGED VENTED DIFFUSER	1.45
TESTED TO PR OF 10 AT AMBIENT TEMPERATURE	

Figure 9.- Summary of ejector performance.

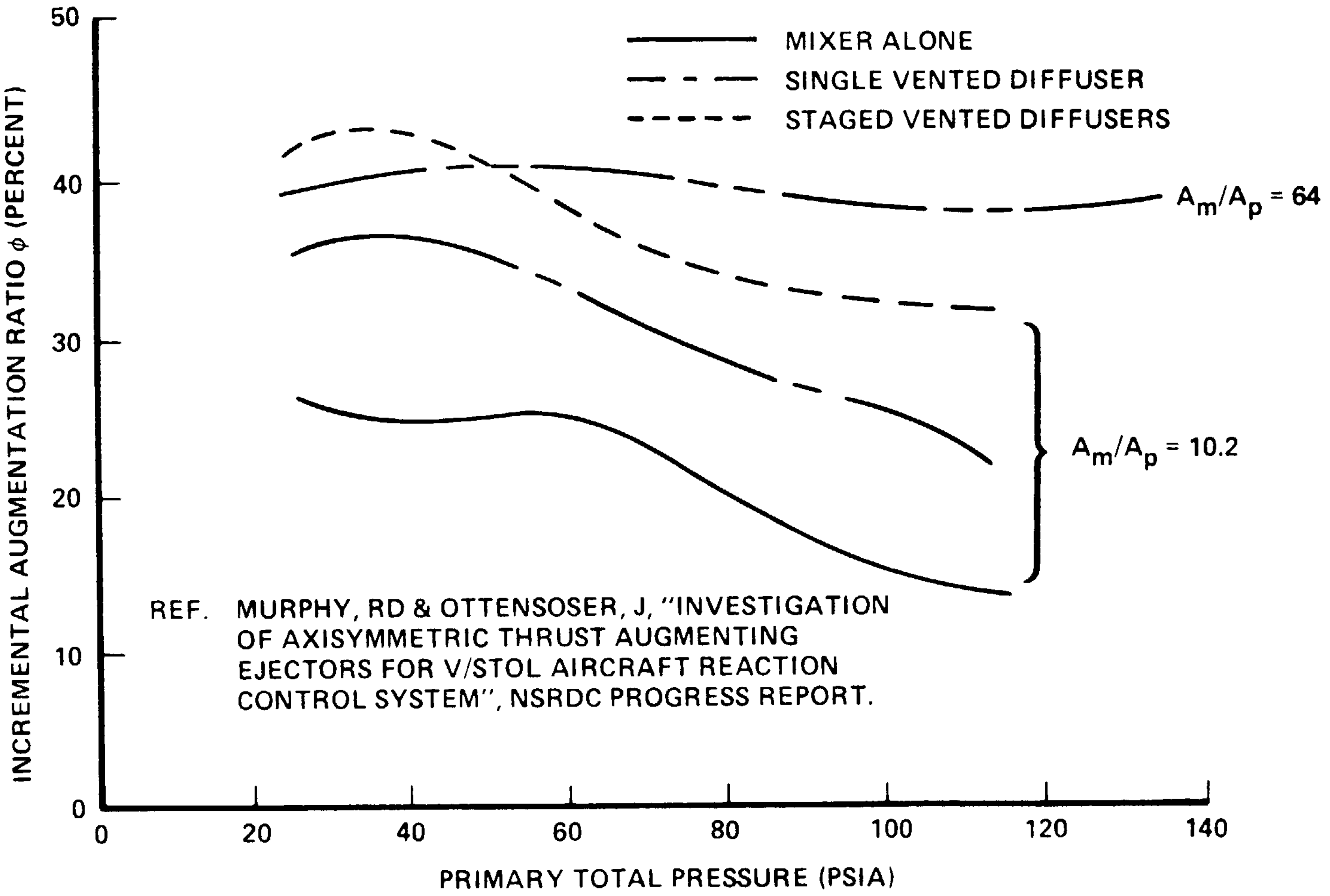
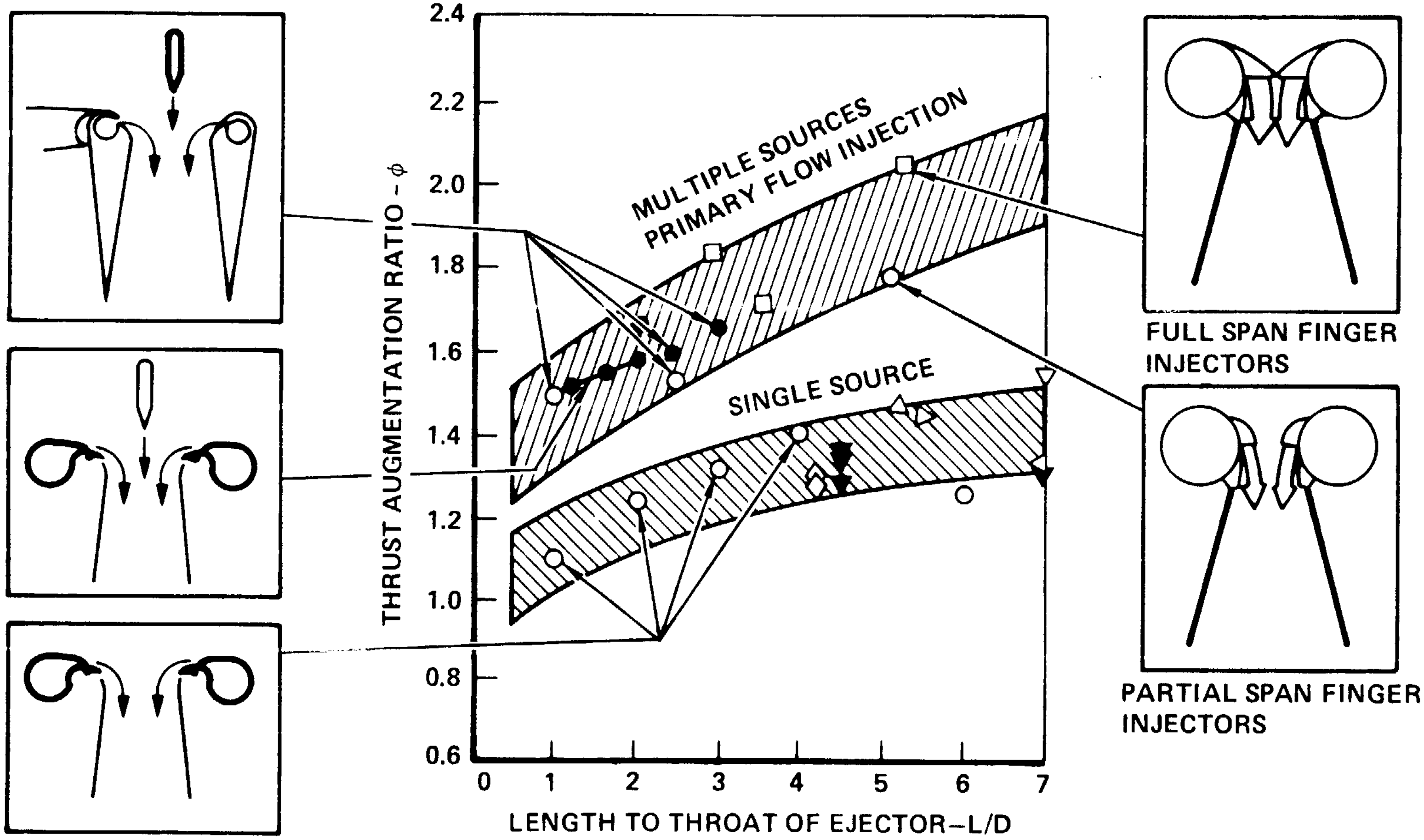


Figure 10.- Effect of primary pressure ratio on thrust augmentation.



REFERENCE:
COMPOUND EJECTOR THRUST AUGMENTOR
DEVELOPMENT BY L.W. THRONDSON
ASME REPORT 73-GT-67

Figure 11.- Summary of ejector thrust augmentation experimentally achieved.

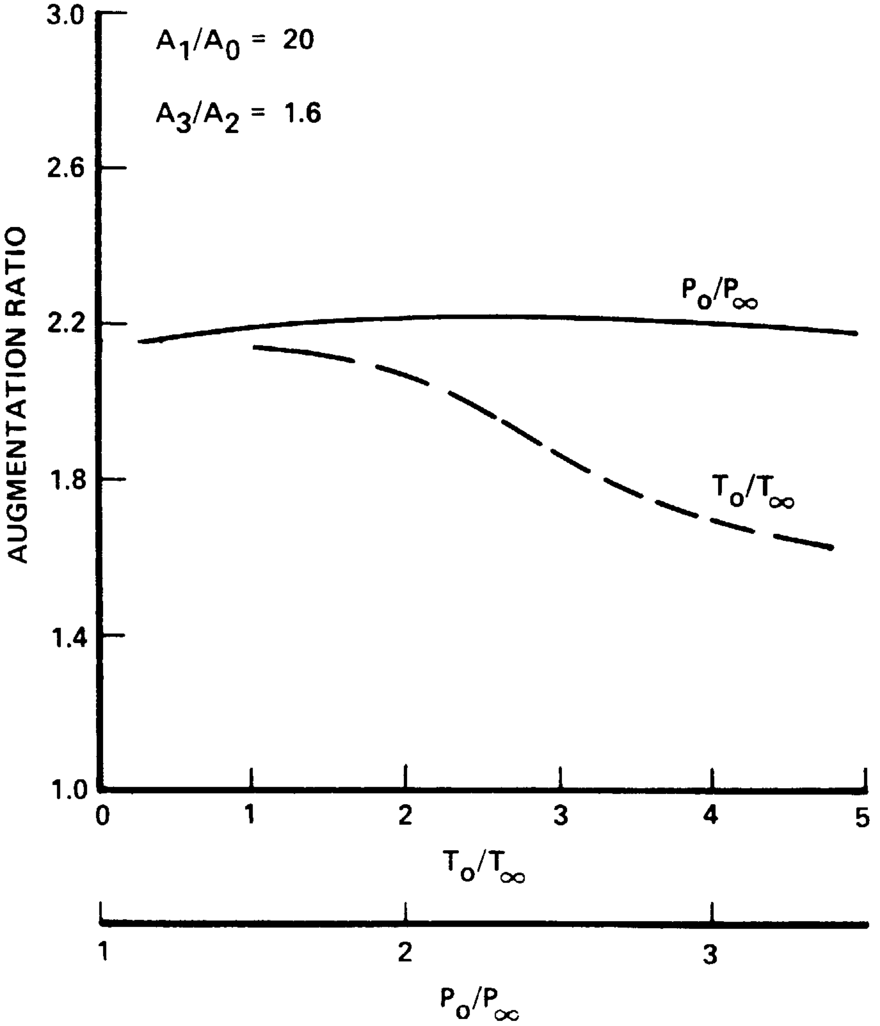


Figure 12.- Primary temperature and pressure ratio (theory).

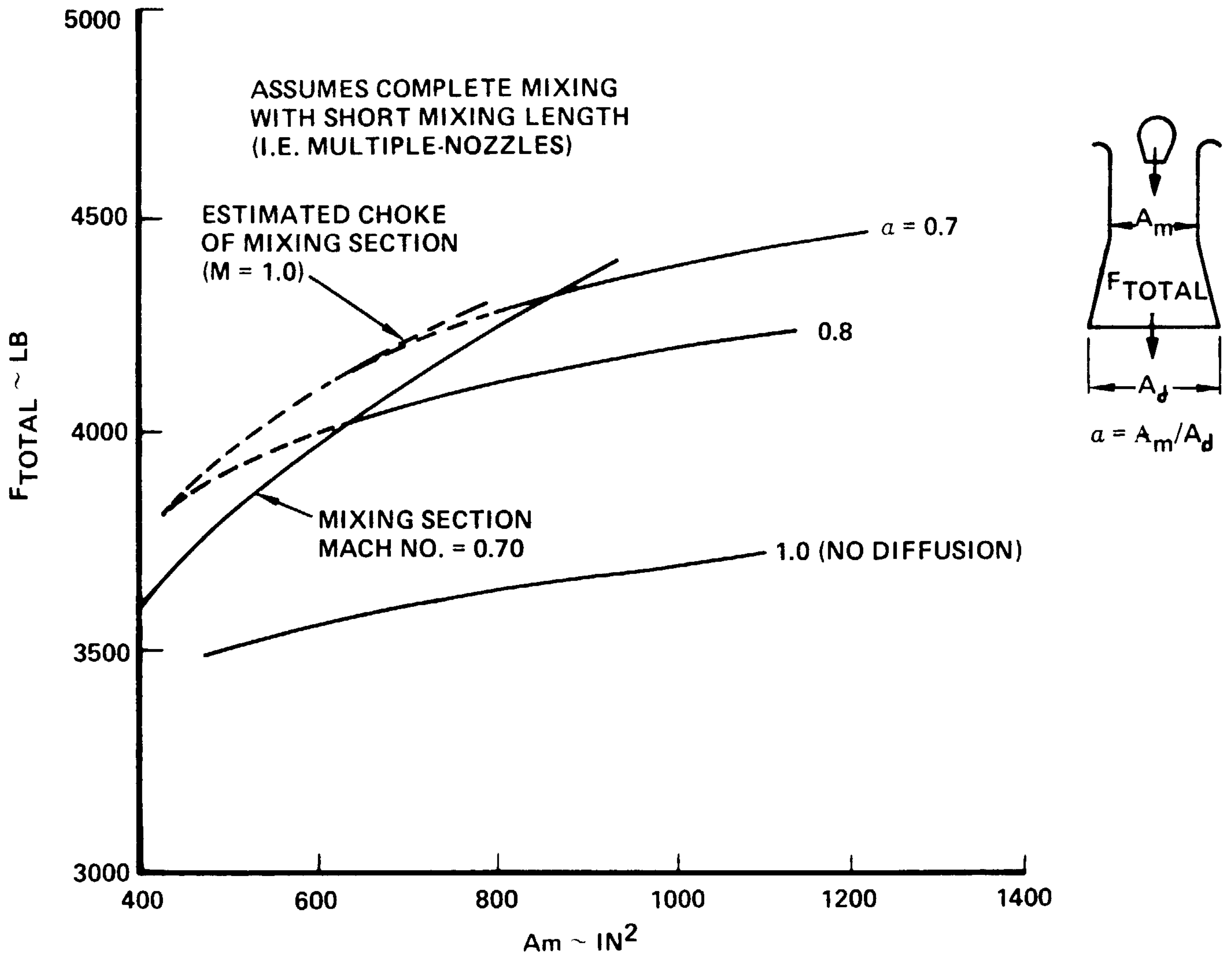
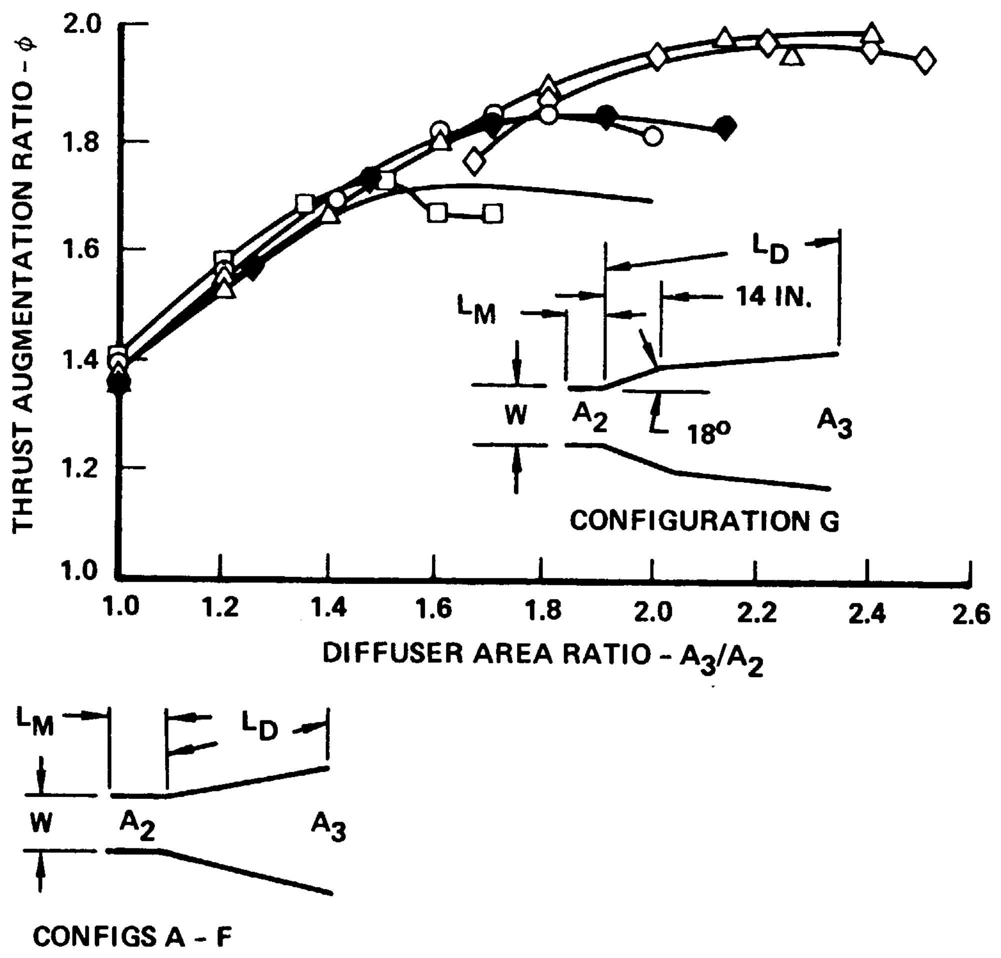


Figure 13.- Preliminary estimated augmentor performance.



CONFIG	L_M	L_D	W	L_M/W	L_D/W
A ○	13	32.25	10	1.3	3.225
B □	13	15.25	10	1.3 1	1.525
C ●	5	23.0	10	0.5	2.30
D X	16	34.0	10	1.6	3.40
F △	5	45.0	10	0.5	4.50
G ◇	5	45.0	10	0.5	4.50

*QUINN, B. "COMPACT EJECTOR THRUST AUGMENTATION"
JOURNAL OF AERONAUTICS VOL 10 NO. 8 AUGUST 1973

Figure 14.- Thrust augmentation of several ARL hypermixing configurations.*

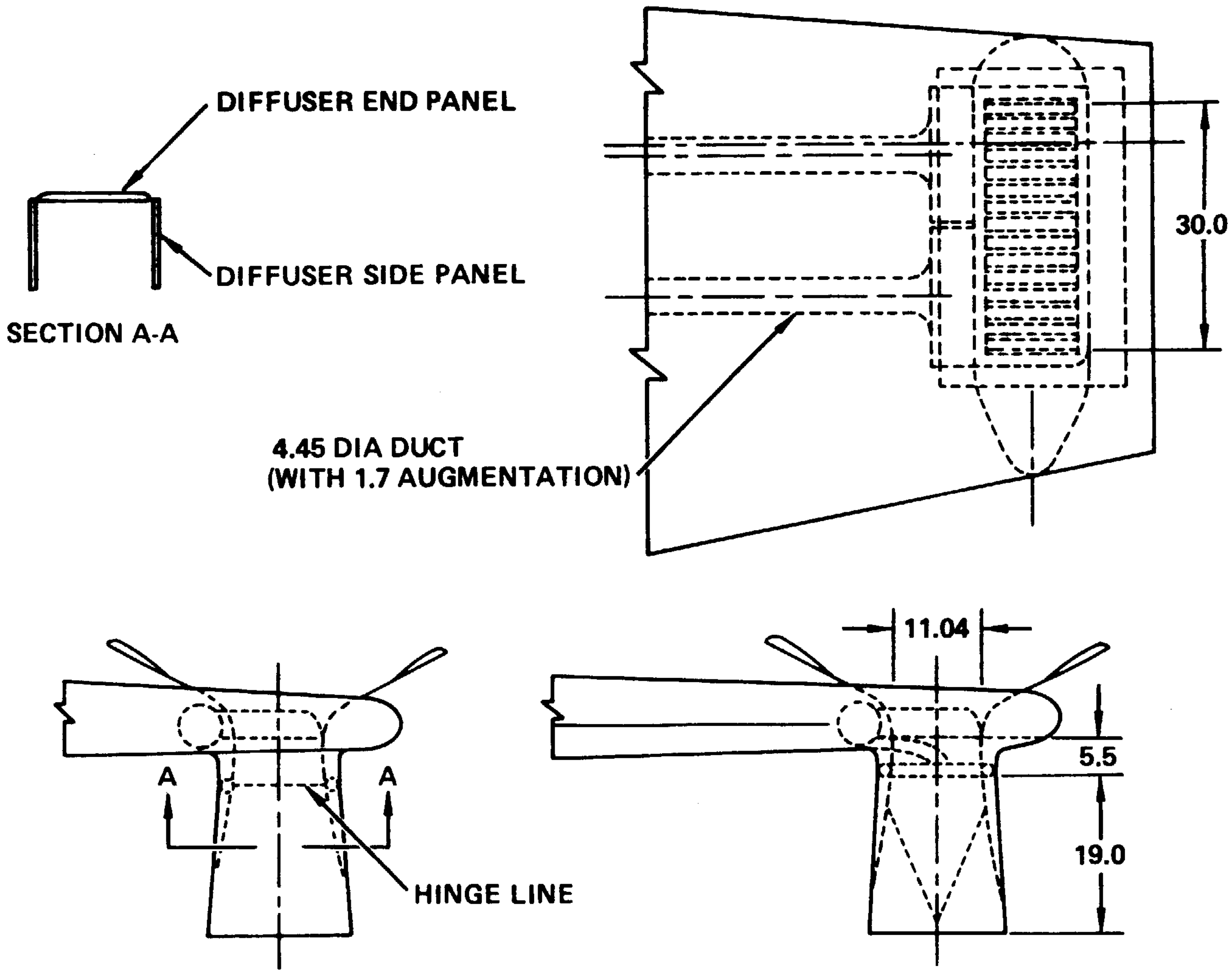


Figure 15.- Wing tip reaction control hypermixing ejector.