N O T I C E

THIS DOCUMENT HAS BEEN REPRODUCED FROM MICROFICHE. ALTHOUGH IT IS RECOGNIZED THAT CERTAIN PORTIONS ARE ILLEGIBLE, IT IS BEING RELEASED IN THE INTEREST OF MAKING AVAILABLE AS MUCH INFORMATION AS POSSIBLE

A JET-DIFFUSER EJECTOR FOR A V/STOL FIGHTER

by

Morton Alperin and Jiunn-Jenq Wu

February 1981

(NASA-CR-166161) A JET-DIFFUSER EJECTOR FOR FOR A V/STOL FIGHTER Contractor Final Report, Sep. 1979 - Apr. 1981 (Flight Dynamics Research Corp.) 50 p HC A03/MF A01 CSCL 21E G3/07

N81-24064

Unclas 23439

Distribution of this report is provided in the interest of information exchange. Responsibility for the contents resides in the authors or organization that prepared it.

Prepared under Contract No. NAS2 10373 by
Flight Dynamics Research Corporation
Van Nuys, California

for

AMES RESEARCH CENTER
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

and

NAVAL AIR DEVELOPMENT CENTER
WARMINSTER, PENNSYLVANIA

Table of Contents

Abstract

The jet-diffuser ejector was integrated into the General Dynamics Corporation E205 fighter/attack aircraft to provide a VTOL capability for the aircraft. Some modifications of the ejector design were required to achieve the integration and stowage required for avoidance of deleterious effects on the aircraft performance during conventional flight. The ejector is designed to operate at a nozzle pressure ratio of 3 with an expected thrust augmentation of 1.95.

The necessary thrust force for transition to conventional flight was to be achieved by a unique system consisting of vector control jets and a diffuser flap. This system was intended to provide a rearward deflection of the effluent flow and a corresponding thrust force in the flight direction.

A single ejector equipped with only one vector control jet and a diffuser flap was installed close to the leading edge of the strake of a one-fifth scale, semi-span model of the aircraft, without wing, canard or tail surface. Tests of the system at a nozzle pressure ratio of 1.24 indicated a thrust augmentation of 1.92 and a thrust in the flight direction of about 12% of the total thrust under static conditions. An ejector stall occurred at a ratio of tunnel dynamic pressure to nozzle gage pressure of about 0.008. Ejector stall speed can be delayed by using a boundary layer control jet at the front inlet lip of the ejector.

List of Illustrations

Nomenclature

C_{di} inlet drag coefficient = Total pressure loss of induced flow in terms of the ideal dynamic pressure of the induced flow at the throat of the ejector (Reference 4)

F_f forward thrust

F_t total thrust

NPR nozzle pressure ratio

VEO vectored engine over (wing)

δ geometric diffuser area ratio

η_N nozzle thrust efficiency

η_{dj} jet-diffuser efficiency

κ angular setting of vector control jet (Figure 8)

θ angle of primary injection with respect to normal to the plane of symmetry (Figure 6)

ϕ thrust augmentation = ejector thrust/reference jet thrust

ϕ' thrust augmentation for tubular nozzles

Summary

A jet-diffuser ejector previously developed by Flight Dynamics Research Corporation (FDRC) under NASA/NADC sponsorship, was modified to permit integration into the strake of a supersonic fighter/attack aircraft, designed by General Dynamics and designated E205. Thrust vectoring for transition was to be accomplished by an asymmetric extension of the solid portion of the diffuser in combination with vector control jets. The overall program consisted of several tasks, as follows:

1. A reduction of the aircraft configuration, with minor modifications to provide for ejector integration, from drawings of discrete cross-sections, to analytical form for precise description of arbitrary sections by computer methods.

2. An integration of the ejector into the aircraft strake to define the location and size of the ejector system required to achieve the specified force for VTOL, at specified injected gas characteristics, and to assure feasibility of closure of the ejector cavity during conventional flight, and adequate ducting arrangements.

3. Exploratory tests to determine the influence of the ejector modifications, and interference effects on the ejector performance.

4. Analysis of ejector performance over ranges of ejector geometry, and loss factors, to provide a basis for optimal design for operation at the eventual test conditions at the NASA, Ames Laboratory.

5. Preliminary drawings and specifications of the ejectors and the semi-span aircraft model to be designed, fabricated and tested by NASA.

Integration and aircraft model design studies, indicated the desirability for a reduction of the ejector inlet depth to permit stowage of the primary and diffuser jet nozzles within the strake thickness of the aircraft design. This represented a 25% reduction of the ejector inlet depth with possible attendant loss of performance, since the ejector was originally shorter than other ejectors of comparable performance. For this reason, it was necessary to conduct an analytical investigation of realistic ejector performance and an exploratory test program to optimize the ejector configuration with emphasis on the ejector design configuration required for effective integration.

The theoretical analysis of ejector performance included the influence of compressibility, nozzle pressure ratio, ejector geometry and internal loss factors. This analysis showed good agreement with the experimental results obtained at a low pressure ratio, for those configurations in which the loss factors were accurately known. Modifications to the diffuser area ratio required for effective operation at high pressure ratios were indicated by the theoretical analysis.

Conclusions drawn from the experimental data previously acquired during the development of the primary nozzles (References 2 and 3), were utilized to determine the orientation of the primary nozzles which would provide optimal performance at a position which permitted enclosure within the strake depth of the aircraft design. The exploratory tests at FDRC provided confirmation of the selection of the location and orientation of the existing primary nozzles within the envelope dictated by the stowage considerations, the performance of the asymmetric diffuser flap and vector control jets for thrust vectoring, and interference effects between the ejector and the aircraft.

Acknowledgements

The work reported in this document is a portion of the effort performed under Contract No. NAS2 10373, sponsored by the Ames Research Center of the National Aeronautics and Space Administration and the Naval Air Development Center. The technical monitors for NASA were Mr. Dave Koenig and Mr. K. Aoyagi. Technical monitor for the NADC was Dr. Ken Green.

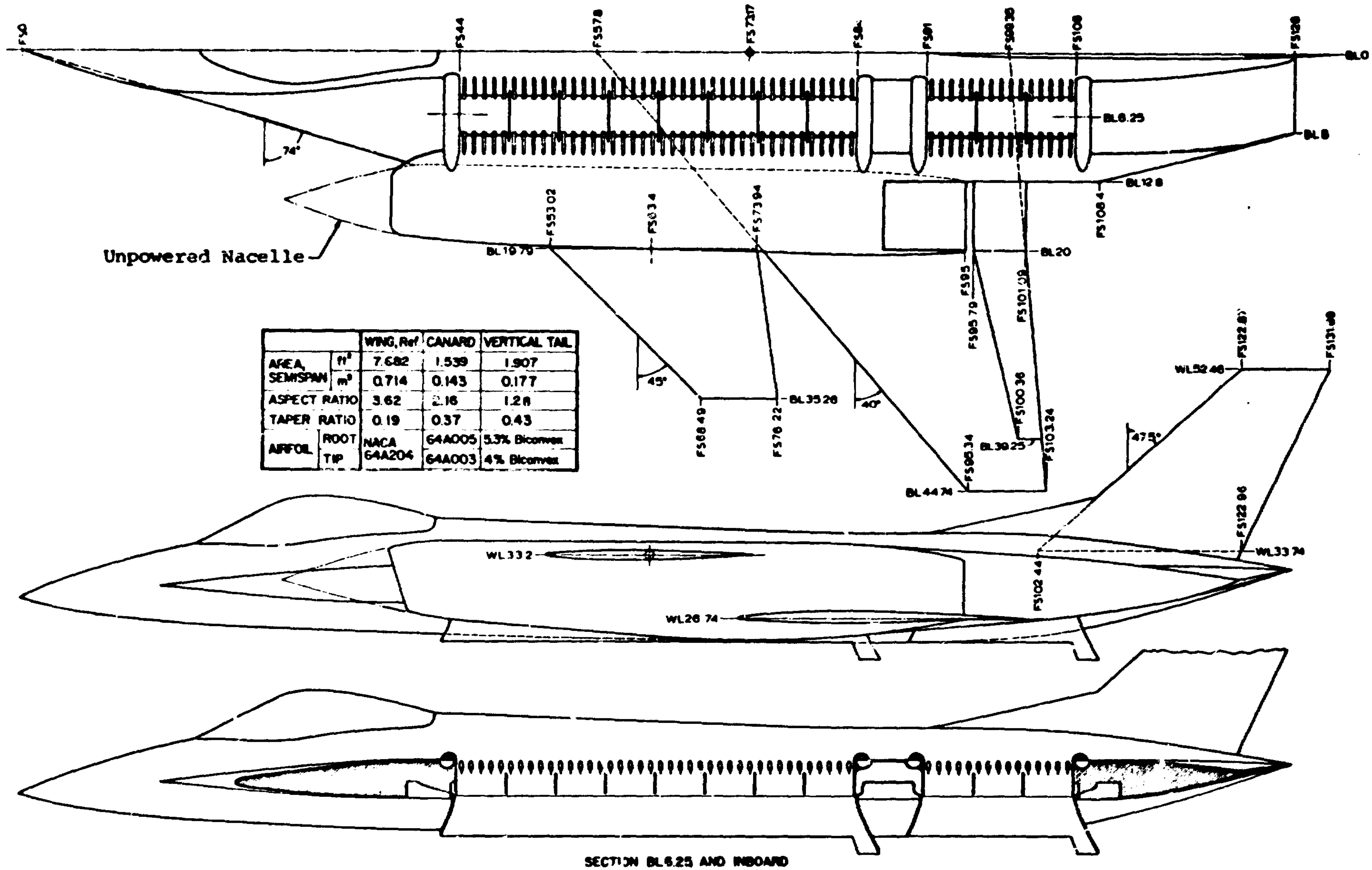
Special thanks to the Fort Worth Division of the General Dynamics Corporation for providing the detailed aircraft cross-sections on Drawing No. FW 7806025, which was of great value as a supplement to the aircraft description contained in NASA CR-152128.

Introduction

The application of ejector thrust augmentation as a means for achievement of a vertical take-off, landing and transition to conventional flight requires the use of a compact high performance ejector, if the penalties during high speed flight are to be minimized. The jet-diffuser ejector developed by FDRC under sponsorship of the Naval Air Development Center and the National Aeronautics and Space Administration, has these characteristics and in addition provides a means for thrust vectoring by a unique system consisting of an asymmetric diffuser flap design combined with thrust vector control jets.

The jet-diffuser ejector configuration as it existed prior to the present effort is described in detail on References 1, 2 and 3. Its overall depth in its thrust direction is about 2.5 times its throat width, with non-protruding primary nozzles supplied from a plenum which can be common to that which supplies the diffuser jet. In the rectangular shape, having a throat width of 10.2 cm (4 in), a length of 38.1 cm (15 in) and a diffuser area ratio of 2.78, its measured thrust augmentation is 2.02. It therefore appeared desirable to attempt to integrate this type of ejector into a supersonic aircraft, to provide a VTOL capability and to provide a portion of the required thrust for transition to conventional flight.

This document describes the overall program aimed at the achievement of this objective, and the results of the exploratory experiments, performed at the FDRC laboratory (Appendix A), aimed at a trade-off of the ejector design to provide stowable integration, thrust vectoring and optimal performance at the injected gas characteristics prescribed for the testing of the model at the NASA, Ames 7 x 10 ft. wind tunnel. The final arrangement of the aircraft/ejector system, derived as a result of this investigation is illustrated on Figure 1, and a scheme for ejector stowage is presented in Appendix B.



		WING, Ref	CANARD	VERTICAL TAIL
AREA, SEMISPAN	ft²	7.682	1.539	1.907
	m²	0.714	0.143	0.177
ASPECT RATIO		3.62	2.16	1.28
TAPER RATIO		0.19	0.37	0.43
AIRFOIL	ROOT	NACA 64A204	64A005	5.3% Biconvex
	TIP		64A003	4% Biconvex

Figure 1. V/STOL Fighter (one-fifth scale model)

Approach

Design studies were conducted to establish the general arrangement and size of the ejectors required for integration into the General Dynamics E205 aircraft design. The ejector arrangement was required to provide the specified lift force as a function of the model scale, and to assure passage of the force through the center of gravity of the aircraft, allowing space for the ducting which supplies the energized gas to the ejectors. These studies indicated a necessity for modification of the ejector configuration to provide for stowability within the strake thickness during conventional flight. A redesign of the ejector, to reduce its inlet depth, involved a relocation of the primary nozzles (No. 5) to a position which was about 2.54 cm (1.0 in) closer to its throat. This reduction of ejector depth could conceivably result in performance degradation due to inadequate mixing and entrainment, as indicated in the map of thrust augmentation described in References 2 and 3. Therefore a test program was initiated to optimize the location and orientation of the primary nozzles within the envelope dictated by the stowage considerations.

These exploratory tests were first performed with an ejector which was similar to the ejector described in References 2 and 3, with a geometric diffuser area ratio of 2.78, but having a modified inlet which included provision for installation of a vector control jet, and a means for movement of the primary nozzles. After a satisfactory primary nozzle and inlet configuration were established, the diffuser was modified to provide for later testing at high nozzle pressure ratios (NPR=3), and to provide for the diffuser asymmetry required for the production of the thrust force for transition to conventional flight. Testing of this ejector, with a geometric diffuser area ratio of about 2.3 and an asymmetric extension of one end of the diffuser was then carried out to determine the influence of the modification on the performance of the ejector.

A semi-span one-fifth scale model of the E205 aircraft, similar to that shown on Figure 1, with one ejector located at the front of the strake but without the wing, canard and vertical tail was then designed, fabricated and tested on the FDRC static test rig. Upon completion of these static tests, the system comprised of the aircraft/ejector was installed in the FDRC wind tunnel for observation of the influence of translational speeds upon the ejector stall.

Ejector Performance

Ejectors operating in a compressible fluid medium must be designed to achieve efficient ingestion and discharge of the working fluid if optimal performance is to be achieved. The theory described in Reference 4 provides the basis for determination of the flow properties throughout the ejector for any given set of operational and injected gas characteristics, provided the loss factors which influence the internal flow are accurately known. In general, the operational and injected gas characteristics to be encountered are specified, but the loss factors must be evaluated by experiments. Thus the design of high performance ejectors must be accomplished by a series of experiments with theoretical guidance, to indicate the achievement of, or the departure from the optimal configuration.

To illustrate the advantage achievable by optimal ejector design, the analysis described in Reference 4 was used to evaluate the performance and to determine the optimal geometry of the jet-diffuser ejector developed under this program. The influence of the geometric diffuser area ratio, the nozzle pressure ratio and the loss factors upon the realistically achievable thrust augmentation are described on Figures 2 and 3.

The nozzle thrust efficiency (η_N), had been evaluated experimentally at a low pressure ratio (NPR = 1.24) and is reported in Reference 2. At this low pressure ratio it was determined that the nozzle thrust efficiency is 0.96 and it is estimated that at high pressure ratios this factor will exceed 0.99 as a result of the Reynolds No. effect. The inlet drag coefficient (C_{di}) depends upon the shape of the ejector and the primary nozzle design. Previous measurements and theoretical correlations indicate that this factor has a value of 0.013 for a two-dimensional ejector. The increase of C_{di} due to skin friction at the ends of the ejector is a function of the throat aspect ratio of the ejector and is taken into account in the performance calculations presented on Figures 2 and 3. The effect of skin friction upon the performance of the diffuser jet is evaluated with the aid of conventional boundary layer theory as described in Reference 4. To include viscous effects, the influence of manufacturing and flow non-uniformities, two and three-dimensional effects and finite longitudinal dimensions, a factor (η_{dj}) called the jet-diffuser efficiency was used to represent the ratio of the effective to the geometric area ratio of the solid portion of the diffuser as described in Reference 4.

As illustrated on Figure 2, there exists an optimal diffuser area ratio for any given nozzle pressure ratio. The magnitude of this optimal diffuser area ratio, and the thrust augmentation achievable with this optimal design depend upon the other geometric ejector factors and the loss factors. Thus as shown on Figure 2, an increase of the diffuser area ratio can compensate somewhat for performance degradation due to increased losses. Conversely, diffuser area ratios in excess of the optimal value can result in large performance losses. The lowest dashed curve is drawn to indicate the correlation of theory and experiment for the test conditions utilized in the experiments. The measured thrust augmentation of 1.95, achieved during the present program, is very close to the theoretical curve using the factors derived for the ejector having a diffuser area ratio of 2.78.

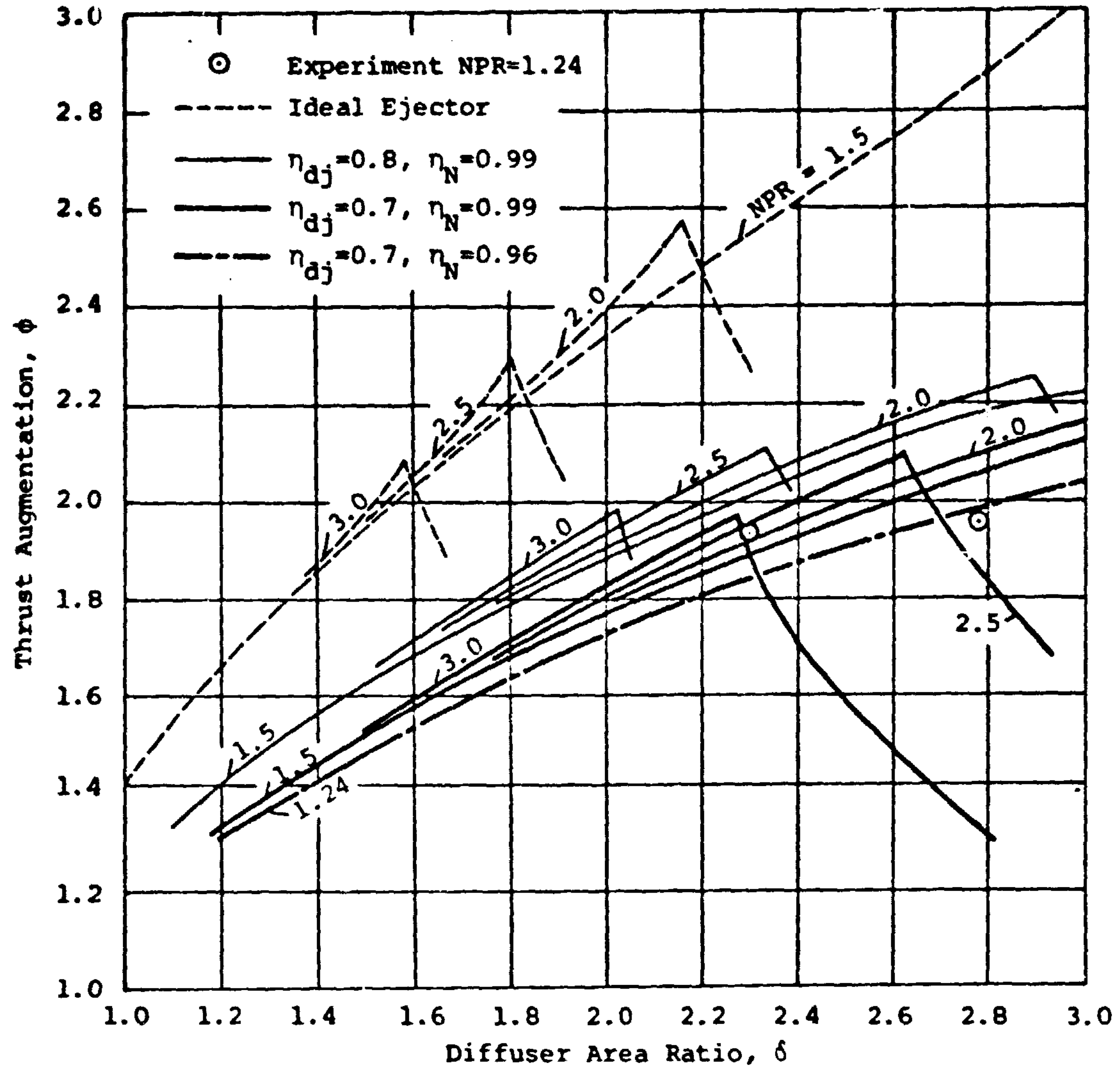
As can be observed on Figure 2, testing of this ejector at higher pressure ratios would result in operation beyond the optimal point with drastic degradation of performance. For example at a nozzle pressure ratio of 3.0, the thrust augmentation would be reduced from its optimal value of 1.95 to about 1.32, if the diffuser area ratio remained at 2.78. To provide optimal performance at a nozzle pressure ratio of 3.0, the solid diffuser area ratio must be reduced to about 2.3 if the losses at this pressure ratio are as assumed. Since the loss factors have not been evaluated at these high pressure ratios, some uncertainty exists regarding their magnitude at these conditions.

The diffuser of the ejector was cut down to a nominal area ratio of 2.3, with an asymmetric extension of one end (diffuser flap) for thrust vectoring purposes, as discussed in a later section of this document. Tests at the nozzle pressure ratio of 1.24 indicated a thrust augmentation of 1.93; a point which lies above the theoretical curve based upon the same factors which existed at the larger diffuser area ratio. This indicates an improvement of the jet-diffuser efficiency due to a decrease of the diffuser area ratio. Measurement of the loss factors were beyond the scope of the present investigation, and not considered appropriate at the low pressure ratios available in the FDRC laboratory.

To illustrate the importance of an accurate knowledge of the loss factors, for optimal design of ejectors, the thrust augmentation is plotted vs nozzle pressure ratio, for an ejector having a diffuser area ratio of 2.3, on Figure 3.

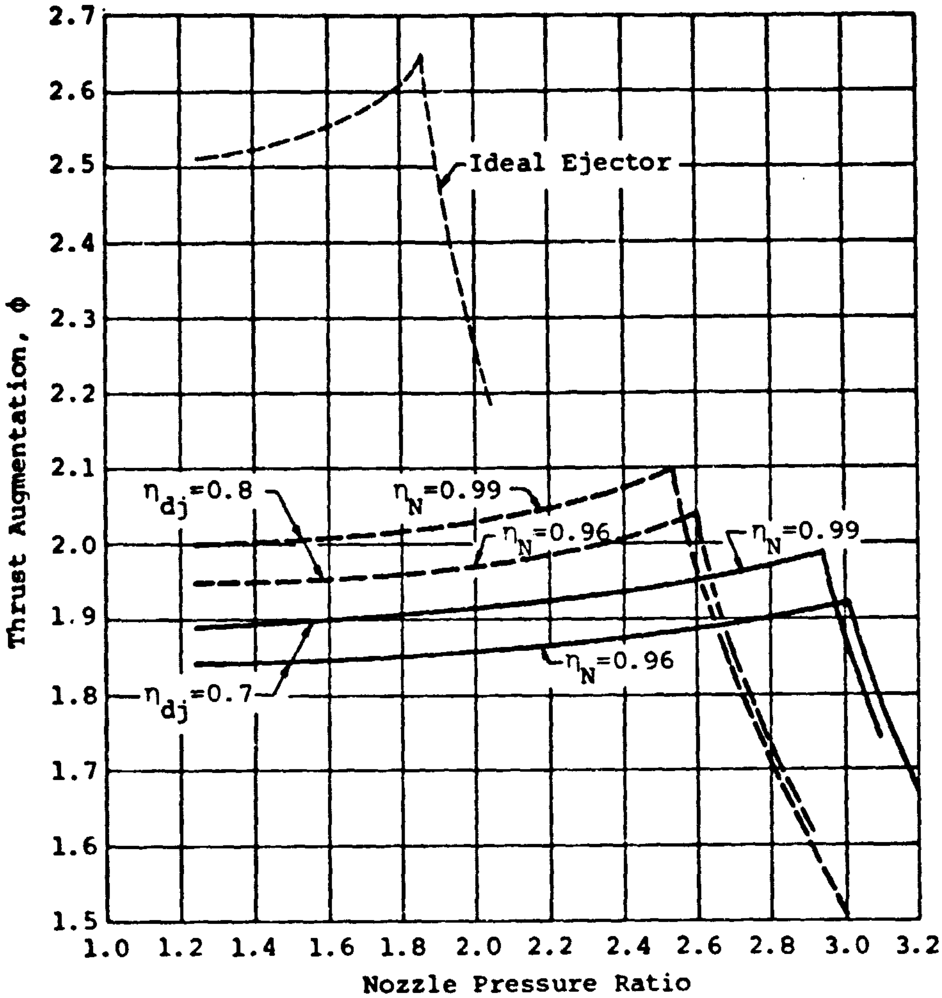
As illustrated, a change of the jet-diffuser efficiency from 0.7 to 0.8, results in a reduction of the cut-off nozzle pressure ratio from 2.95 to 2.55. Thus if the jet-diffuser efficiency is increased as a result of the reduction of the area ratio, the tests at a nozzle pressure ratio of 3.0 can result in operation beyond the cut-off point and a large departure from optimal thrust augmentation, from about 1.95 to about 1.5.

The diffuser area ratio of 2.3 was chosen under the assumption that the efficiency is 0.7, and if this factor is larger, the performance at a nozzle pressure ratio of 3.0 will be considerably degraded since it lies beyond the cut-off point shown on Figure 3. Theoretical analyses performed in-house by FDRC have indicated that, at a nozzle pressure ratio of 3, and a plenum temperature below about 1200° F, the optimal diffuser area ratio increases with increasing plenum temperatures. Thus it may be necessary to revise the diffuser area ratio or to operate the ejector at a higher temperature than the planned isentropic temperature.



Air Source: Fan Air (isentropically compressed, @ sea level)
Ejector Throat: 10.16 cm wide, 38.1 cm long (4 in wide, 15 in. long)
Inlet Area Ratio: 32.14 (=throat area/primary nozzle area)
Diffuser Jet/Primary Jet Mass Flow Ratio: 0.7

Figure 2. Jet-Diffuser Ejector Performance, as a Function of Diffuser Area Ratio



Air Source: Fan Air (isentropically compressed, @ sea level)
Ejector Throat: 10.16 cm wide, 38.1 cm long
(4 in. wide, 15 in. long)
Inlet Area Ratio: 32.14 (=throat area/primary nozzle area)
Diffuser Jet/Primary Jet Mass Flow Ratio: 0.7
Diffuser Area Ratio: 2.3

Figure 3. Jet-Diffuser Ejector Performance, as a Function of Nozzle Pressure Ratio

Aircraft/Ejector Configuration Analysis

The design of the aircraft/ejector system was based upon the use of an existing jet-diffuser ejector design, described in References 2 and 3, and a supersonic fighter/attack aircraft design described in Reference 5 and Dwg. No. FW 7806025, provided by the Fort Worth Division, of the General Dynamics Corporation.

The feasibility of integration of an ejector system which provided the required force vectors and was stowable within the strake of the aircraft, was investigated. As a basis for this study, requirements were established to assure suitability for VTOL flight conditions, to define the limitations imposed upon the ejector configuration by the aircraft design and for testing in the 7 x 10 ft. wind tunnel at NASA, Ames Research Center. These requirements included:

A. The basic aircraft design characteristics:

1. wing area = 35.67 sq m (384 sq ft)
2. fuselage length = 16.25 m (640 in)
3. wing loading = 4364 Pa (91.15 psf)
4. center of gravity at FS 365.86 (FS=0 at nose)
5. maximum strake thickness = 3% of fuselage length with stowed ejectors

B. The ejector system design characteristics:

1. thrust loading = 1.3 x wing loading = 5664 Pa (118.3 psf)
2. nozzle pressure ratio = 3.0
3. force to intersect center of gravity of aircraft
4. ejectors to be stowable within strake
5. ejectors to avoid interference with VEO flap
6. ejectors to be located between FS 233.56 and FS 537.91 (FS=0 at nose)
7. ejectors to be energized by isentropically compressed air in the 7 x 10 ft wind tunnel
8. one-half of the energized air to be supplied through a duct located between the ejectors
9. ejector cross-section to adhere to the existing jet-diffuser ejector design to avoid excessive costs of a new primary nozzle mold
10. thrust vectoring to be achieved by
    a) asymmetric extension of rear end of diffuser surface
    b) auxiliary vector control jets

Based upon the supercritical pressure ratio, the corresponding isentropic temperature to be utilized in these tests, and the loss factors derived from previous experiments on the jet-diffuser ejector, extended to apply to the ejector lengths, and to the three-dimensional effects, the thrust augmentation was evaluated using existing computer programs. The following is a discussion of the derivation of the selected design configuration which was based upon the evaluated thrust augmentation and the integration of the ejector with the aircraft contours.

It is estimated that the solid portions of the diffuser can be folded to form a surface which is 2.54 cm (1.0 in) below the throat of the ejector, when the diffuser area ratio is somewhat less than 2.3 (Appendix B). Originally, as described in References 2 and 3, the top of the primary nozzles of the existing ejector was located at 10.4 cm (4.09 in) above the throat of the ejector, and thus, avoiding complicated inlet folding, the total depth of the ejector after folding was 12.9 cm (5.09 in). Using the laboratory ejector, an aircraft scale factor of 0.265 is required to permit the stowage of that ejector into a scaled model of the E205. At a nozzle pressure ratio of 3.0 a system of two laboratory ejectors with vector control jets can deliver a thrust of about 17 lbs per inch of ejector. At an aircraft scale factor of 0.265, the total length of ejector required by the specifications would be about 238 cm (94 in). The space available in the strake, would be only about 205 cm (81 in) and is not sufficient to accomodate this ejector length. However, reduction of the inlet depth of the ejector by about 25% or 2.54 cm (1.0 in) and thickening of the strake from 3% to 3.[illegible]% of the fuselage length, with a slight relaxation of the B.6 specification to allow for the structure and duct construction between the front and rear ejector, permits the design of a 0.2 scale model of the E205 aircraft using the basic components of the existing ejector.

The airframe assembly of the 0.2 scale semi-span model is depicted in detail on Figure 4. Flexibility for variation of the positions of the airframe components relative to each other is provided.

The positions of the ejectors relative to the airframe can easily be modified in all three directions, to assure passage of the force through the center of gravity of the aircraft design.

The front and rear portions of the strake are detachable, to permit modification and replacement of these components if design changes are indicated during the wind tunnel tests.

The canard is attached to the nacelle through a rod, clamp and bracket to permit rotation for control purposes.

The model nacelle is presently conceived as being solid, and although not shown on Figure 4, a nose has been added to the detailed design to avoid a blunt leading edge, as illustrated on Figure 1, and a faired trailing edge should be designed to simulate the blunt base of the unpowered VEO-wing nozzle as discussed in Appendix B.

The general characteristics of the ejectors and the model are presented in Table 1, and are shown on Figure 1.

Table 1

Characterisics of the wind tunnel model

EJECTOR	cm (in)
Length	
front	= 101.60 (40)
rear	= 38.10 (15)
Throat width	= 10.16 (4)
Primary nozzle areas	
front	= 32.01 (4.96)
rear	= 12.00 (1.86)
Primary nozzle spacing	= 2.54 (1.0)
Diffuser jet area	
front	= 15.43 (2.39)
rear	= 7.05 (1.09)
Vector control jets area	
front (7)	= 6.10 (0.95)
rear (2)	= 1.74 (0.27)
Geometric diffuser area ratio	
front	= 2.20
rear	= 2.28
Gap between ejectors	= 17.78 (7)
Overall jet area	= 74.33 (11.52)

AIRCRAFT semi-span	m (ft)
Wing	
airfoil	NACA 64A204
area	= 0.714 (7.682)
semi-span	= 1.136 (3.728)
aspect ratio	= 3.62
taper ratio	= 0.19
Canard	
airfoil	NACA 64A005 (root) NACA 64A003 (tip)
area (exp)	= 0.143 (1.539)
span (exp)	= 0.393 (1.289)
aspect ratio	= 2.16
taper ratio	= 0.37
Fuselage length	= 3.251 (10.67)
Nacelle length	= 1.468 (4.816)
Vertical tail	
airfoil	5.3% biconvex (root) 4% biconvex (tip)
area (exp)	= 0.177 (1.907)
span (exp)	= 0.475 (1.560)
aspect ratio	= 1.28
taper ratio	= 0.43

Some consideration has been given to the closure of the ejector cavity to provide aerodynamically "clean" surfaces during conventional flight. A brief discussion and sketches illustrating one conceptual design for ejector stowage are presented in Appendix B.

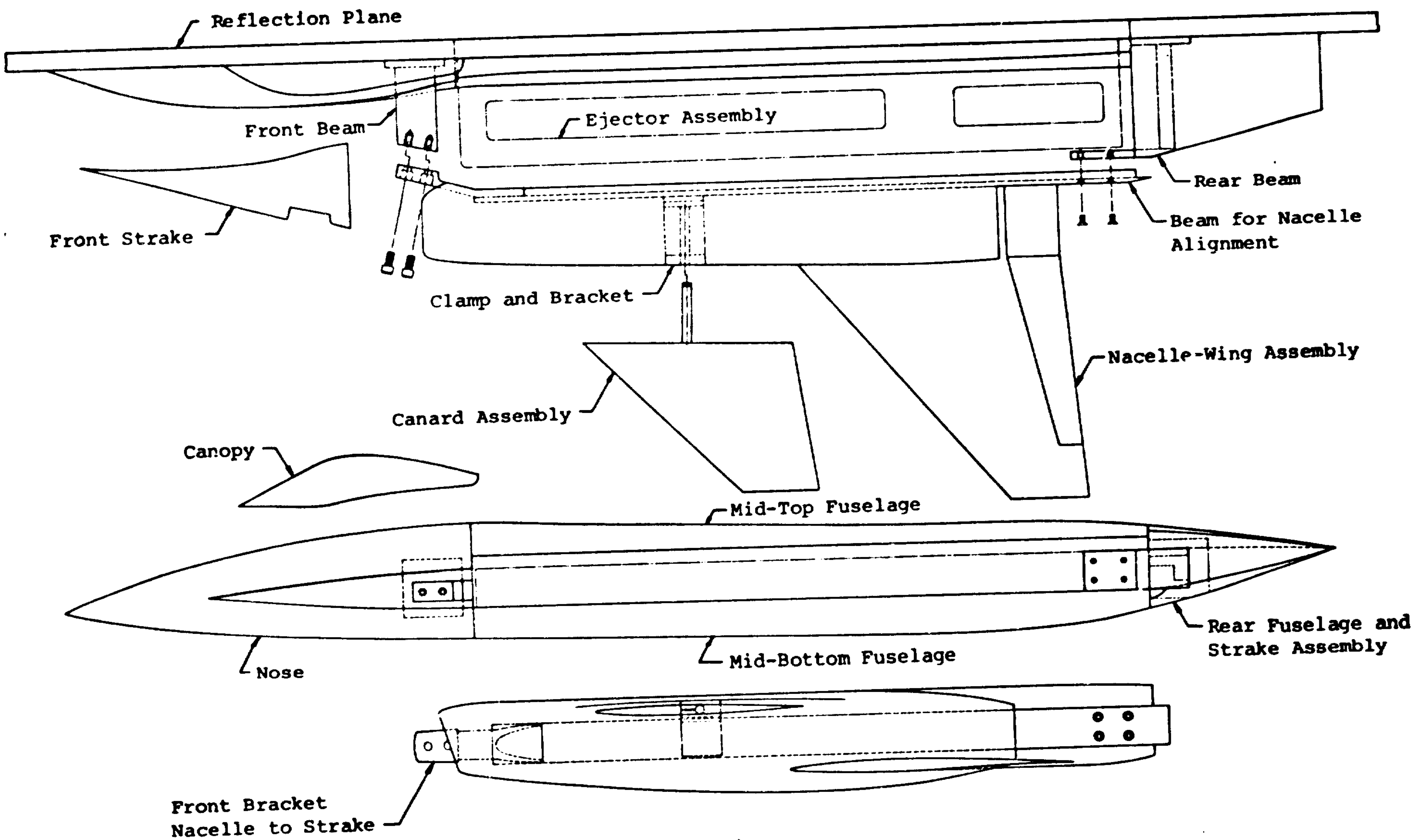


Figure 4. V/STOL Fighter (7x10 Model), Air Frame Assembly

Exploratory Test Program

The requirement for a reduction of the ejector inlet depth by 2.54 cm, to permit containment of the ejector within the strake depth, involved a design modification of the inlet of the ejector. The new inlet was designed to permit this change of primary nozzle position and to provide for installation of one vector control jet.

Testing of the modified ejector with its original diffuser, and with a modified diffuser designed to optimize performance at a nozzle pressure ratio of 3 as specified, and with the asymmetry designed to provide thrust vectoring, was performed on the FDRC static test rig and wind tunnel. All tests at FDRC were carried out at a nozzle pressure ratio of 1.[illegible]. The facilities of the FDRC Laboratory are described in Appendix A.

The approach leading to the design of Primary Nozzle No. 5 (Reference 2), was based upon a map of thrust augmentation obtained through testing of a series of adjustable, tubular nozzles, constructed of standard tubing, described in References 2 and 3. The agreement between the ejector performance using the tubular nozzles and the performance achieved with Primary Nozzle No. 5, signifies the value of this map. A compressed version of that map is presented on Figure 5, which illustrates only the optimal thrust augmentation as a function of the nozzle exit distances from the throat of the ejector. As indicated, the ejector with the final primary nozzle design, performs as described by the maps. Therefore this map served as an important guide for the present investigation.

Static Tests

Initially, tests were performed on the bare (without aircraft model) ejector, with the original symmetrical diffuser having an area ratio of 2.78, and one vector control jet in place at the approximate middle of the ejector. In this configuration, retaining the original injection angle (60 deg), the thrust augmentation was 1.85. This result could be predicted by extrapolation of the compressed maps of thrust augmentation (Figure 5). The [illegible] performance is attributed to the difference between the injection angle and the direction of the induced flow at the region of injection, since the primary and induced flows are crossing at an angle of about 11 degrees. As concluded in References 2 and 3, it is essential to avoid large crossing angles between the primary jet efflux direction and the local induced flow. This can be accomplished by setting the primary nozzle exits at larger angles.

ORIGINAL PAGE IS
OF POOR QUALITY

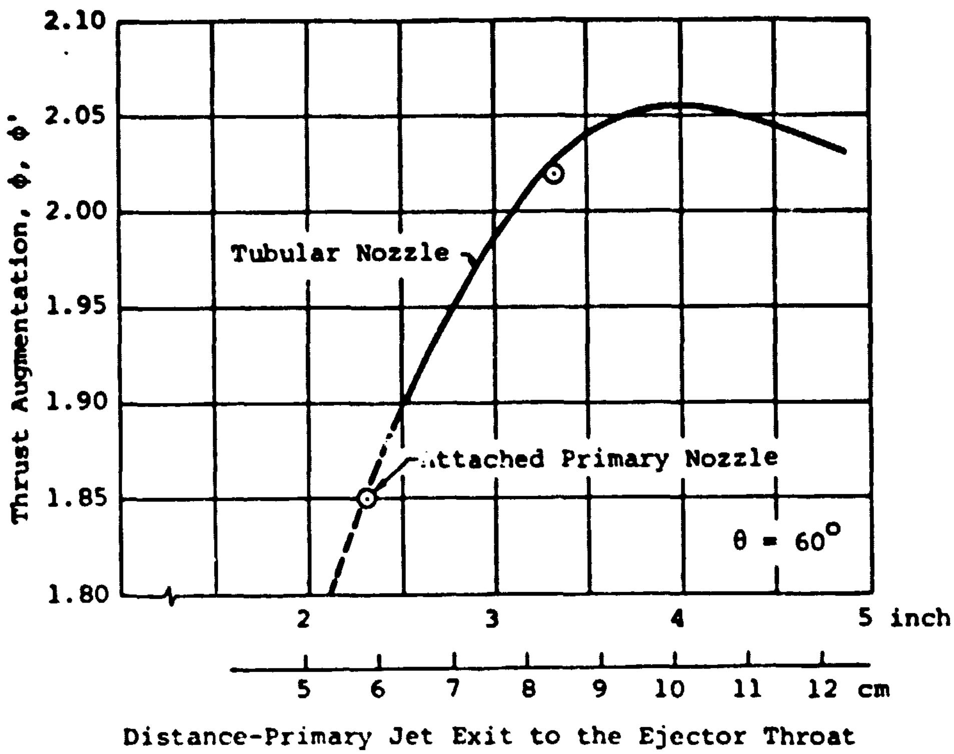
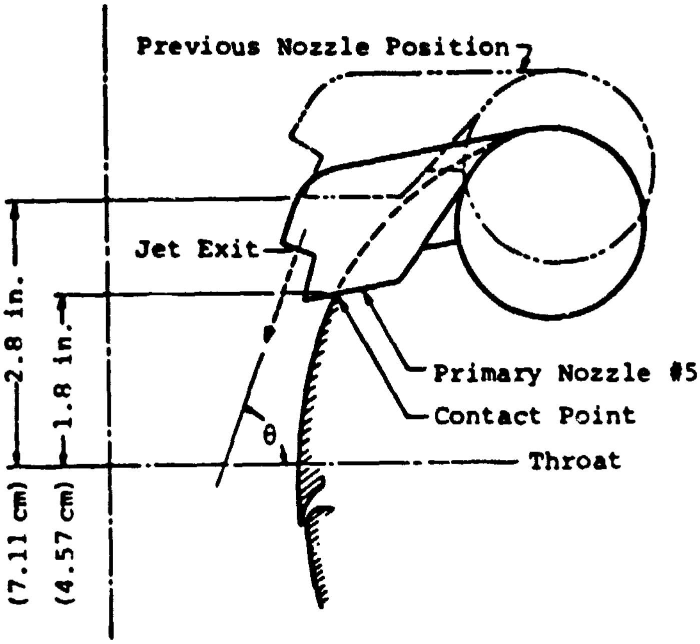


Figure 5. Influence of Primary Nozzle Location on Ejector Performance ($\theta = 60$ deg.; see Figure 6 for definition of location)

A series of tests were performed to optimize the location and orientation of the primary nozzles, in the light of the information regarding crossing primary and induced flows. Rotation and sliding of the primary nozzles about a point on the inlet surface which is 4.57 cm (1.8 in) from the throat of the ejector, produced a significant increase of thrust augmentation. As illustrated on Figure 6, the thrust augmentation increased monotonically with increasing injection angle (or decreasing crossing angle), to a value of 1.95 at an injection angle of 71.7 degrees.

The contact point of the nozzle and the inlet surface was lowered to 4.52 cm (1.779 in) to permit nozzle rotation to 12 degrees ($\theta = 72$ deg) for further reduction of the crossing angle, as illustrated on Figure 7. At this location and orientation the induced flow is at 74.7 degrees as estimated by the method described in References 2 and 3. This relocation of the primary nozzles also reduces the distance between the primary jets and the throat of the ejector from 8.44 cm (3.323 in) to 5.47 cm (2.154 in), a reduction of 35%. Since the primary nozzle was designed to operate at an injection angle of 60°, it presents an unnecessary inlet protrusion near the root of the nozzle when operating at an injection angle of 72°. The nozzle can easily be redesigned to avoid this protrusion and to achieve an inlet depth of less than 7.85 cm (3.09 in) but this is not recommended at this stage of the investigation.

Asymmetric extension of the diffuser wall provides a very effective method for production of a side force on the ejector as indicated in Reference 6. In the present application, the thrust vectoring capability must provide a longitudinal force rather than a side force as occurred in the STAMP (Small Tactical Aerial Mobility Platform) experiments. This technique for thrust vectoring can probably be effective only when the length of the ejector is not too large compared to its width, therefore some method must be found to augment the turning of the ejector flow when the ejector is long in the direction of the desired force. The structure designed for this purpose during the present investigation, is called a vector control jet. This device is similar to a jet flap airfoil with trailing edge blowing as described in Reference 7.



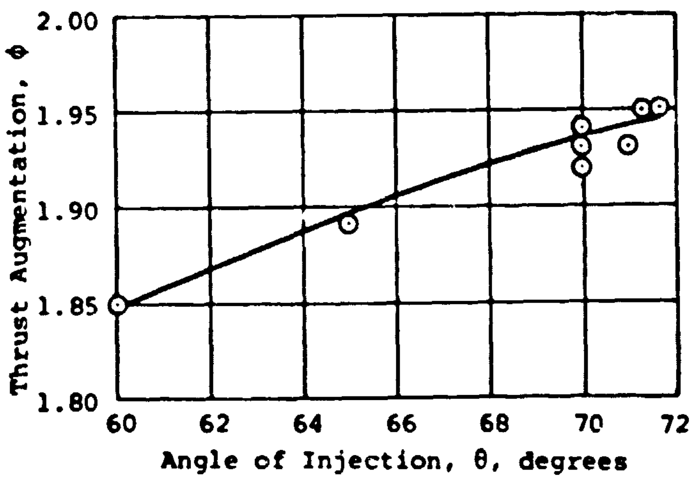


Figure 6. Typical Ejector Performance at Various Primary Jet Injection Angles

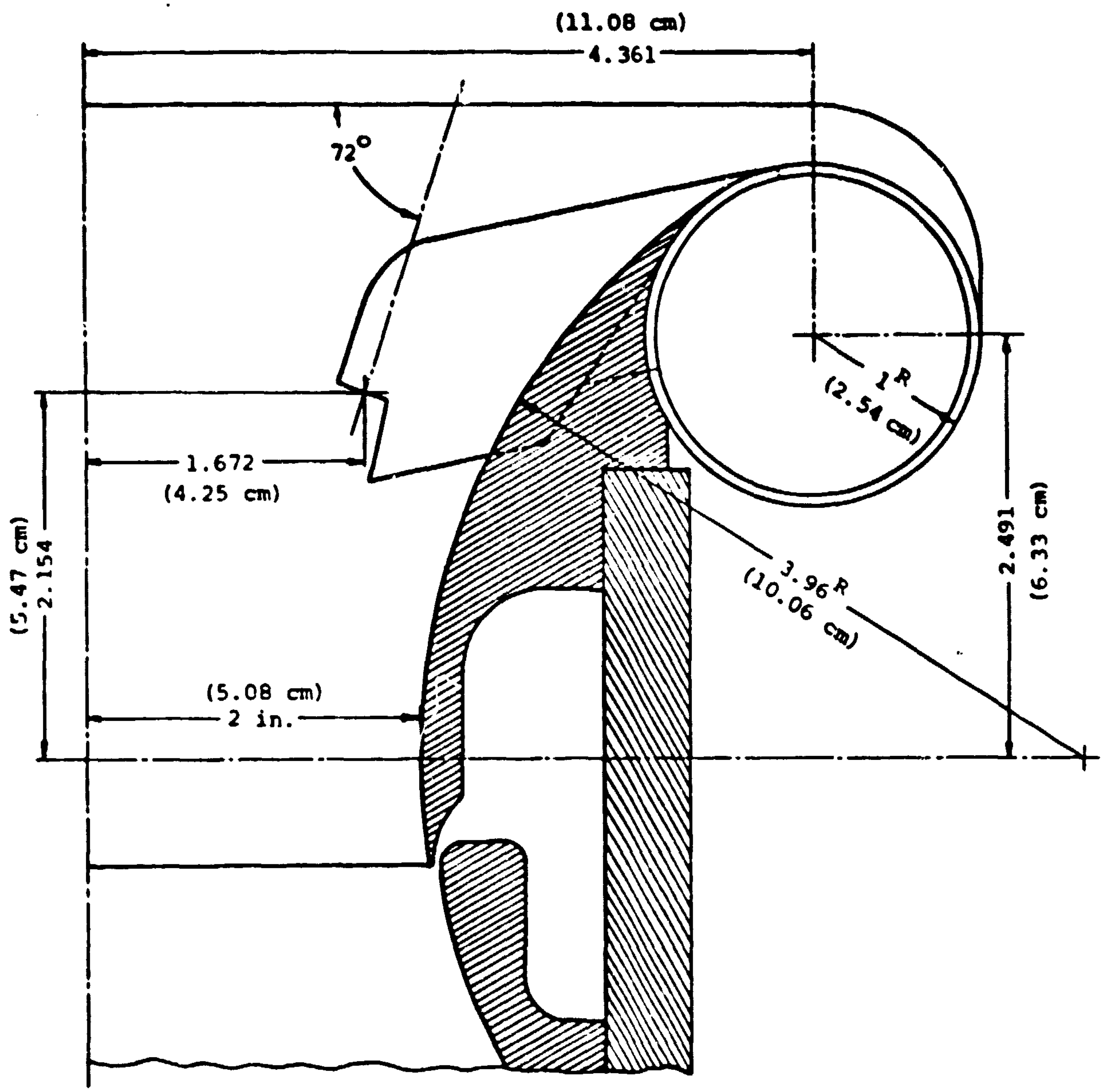


Figure 7. Inlet Arrangement for Study of Ejector/Airframe Integration

The vector control jet is a row of 44 holes of 1.59 mm (1/16th in) diameter, rotatable from -15 degrees to +45 degrees and is located at the trailing edge of a faired duct which is 6.35 cm (2.5 in) long and 3.81 mm (0.15 in) thick, as shown on the top of Figure 8 and the top photograph of Figure 9. The thin duct housing the vector control jet is a result of consideration of minimizing the interference between this duct and the primary nozzle fairings which exist in the present ejector arrangement. A thicker duct with longer chord can be designed if the spacing between the primary nozzles adjacent to the vector control jet is increased. A thicker duct can be valuable as a structural member and can serve as a common duct to provide a passage between the two sides of the ejector.

As illustrated on Figure 5, the same nozzle installed at different locations with the same orientation, produces thrust augmentations which fit into the map, with and without the vector control jet. This suggests that the presence of the vector control jet structure does not have a significant adverse effect on the performance of the ejector.

The ability of the vector control jet to provide a longitudinal force was measured in a series of experiments described on Figure 8. The thrust augmentation based upon the resultant force produced by the ejector and the ratio of the forward thrust to the total thrust were measured on the FDRC static test rig. The results shown on Figure 8, indicate a small forward force when the diffuser was symmetrical, with an area ratio of 2.78. A reduction of the geometrical area ratio of the diffuser and the addition of the diffuser flap resulted in a large improvement of the force in the thrust direction, with monotonically increasing ratio of forward thrust to total thrust, reaching a value of about 11% at a vector control jet angle of 40°.

The ejector with its modified inlet and diffuser was then installed at a forward location (FS44 to FS59) in the strake of the 0.2 scale semi-span model of the E205 aircraft, without the wing and canard, as shown on Figures 8 and 9. In this configuration, the ratio of forward thrust to total thrust reached 12% and the static performance of the ejector was determined to be slightly reduced from that of the bare ejector. This small, almost negligible decrease of performance may be attributable to the increased inlet drag due to skin friction on the reflection plane or to the asymmetric inlet shown on Figure 10, which can cause rotation of the thrust vector in the direction which is not measureable in the present set-up.

It is important to note that the ratio of forward thrust to total thrust increased, while the thrust augmentation remained constant up to control jet deflection angles as large as 30°, as shown on Figure 8.

The spacing of the vector control jets has been reduced from about 19 cm (7.5 in) in the exploratory model to 12.7 cm (5 in) in the design of the 7 x 10 foot wind tunnel model, to provide an increase of the ratio of the forward thrust to total thrust. This, in combination with the use of a nose-down pitch of the aircraft, accomplished with some assistance from the unpowered VEO-wing flaps and flaperons, to maintain zero (or small) aerodynamic lift during transition, appears to offer sufficient forward thrust to achieve transition speed of the aircraft.

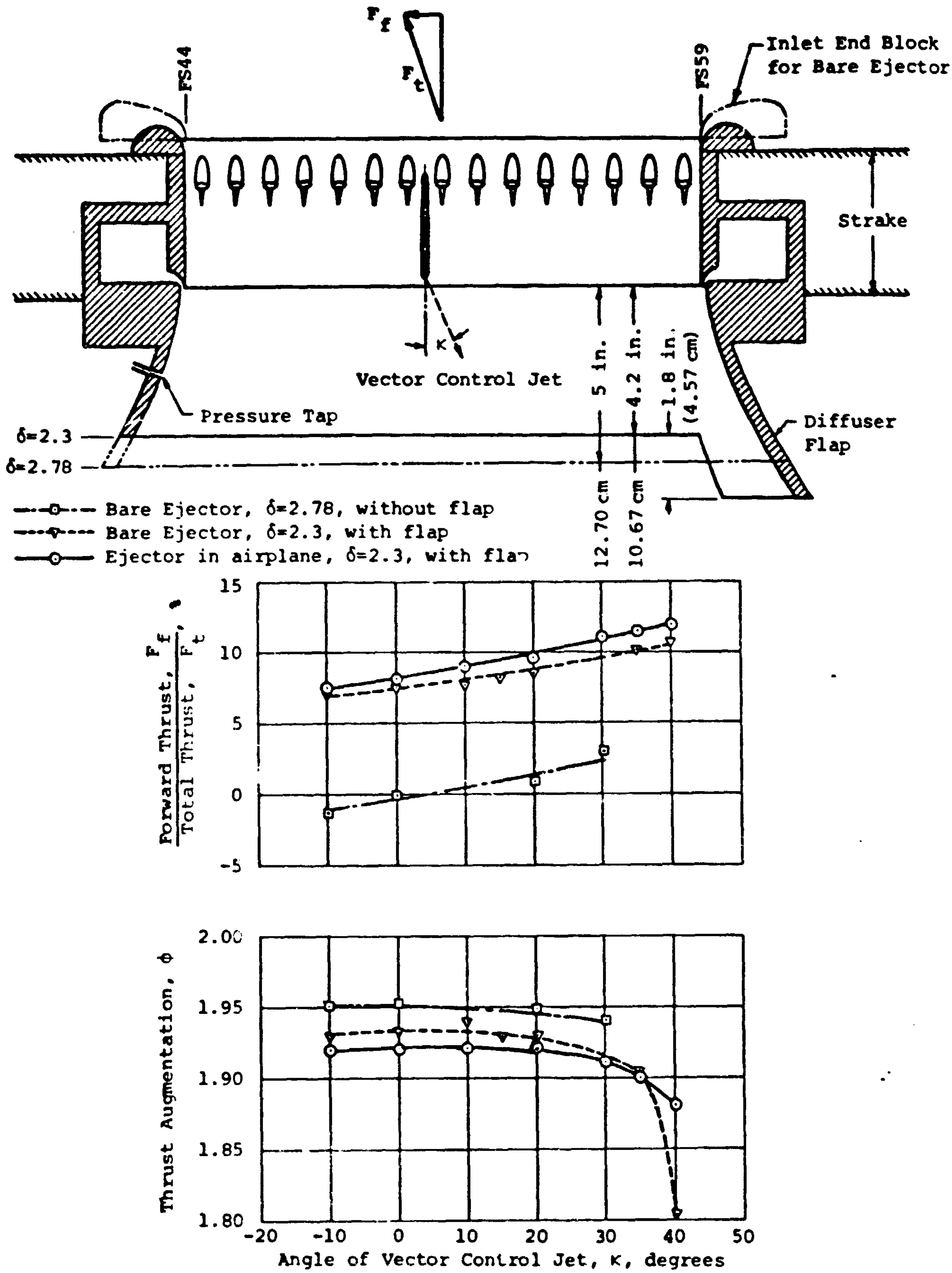
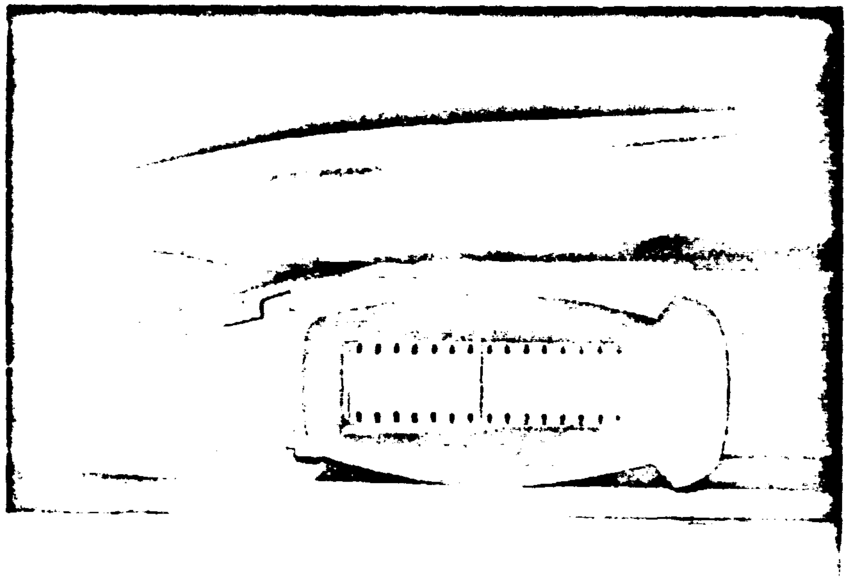


Figure 8. Performance of the Thrust Vector Control System



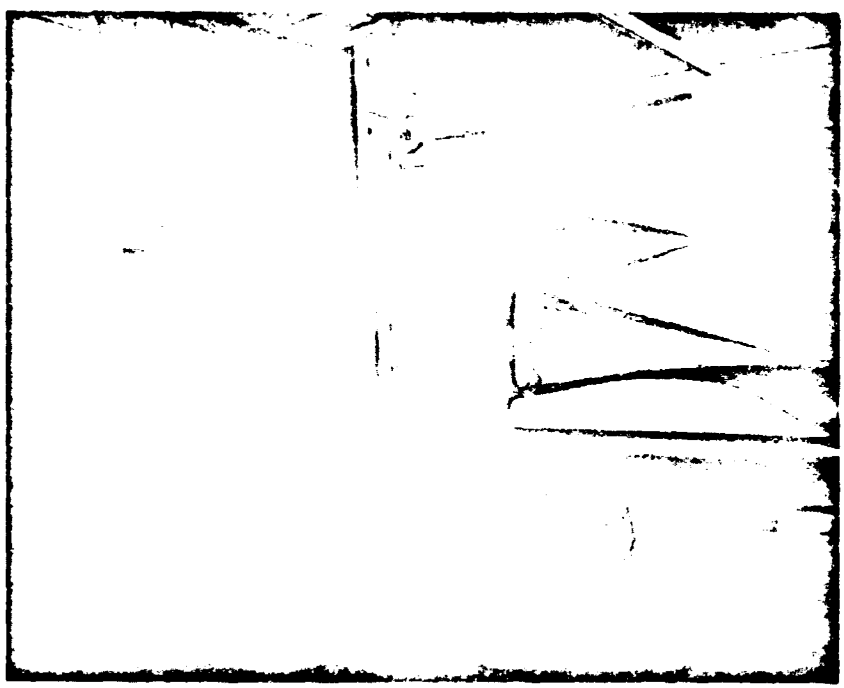


Figure 9. Photograph of Exploratory Model on FDRC Static Test Rig

ORIGINAL PAGE IS
OF POOR QUALITY

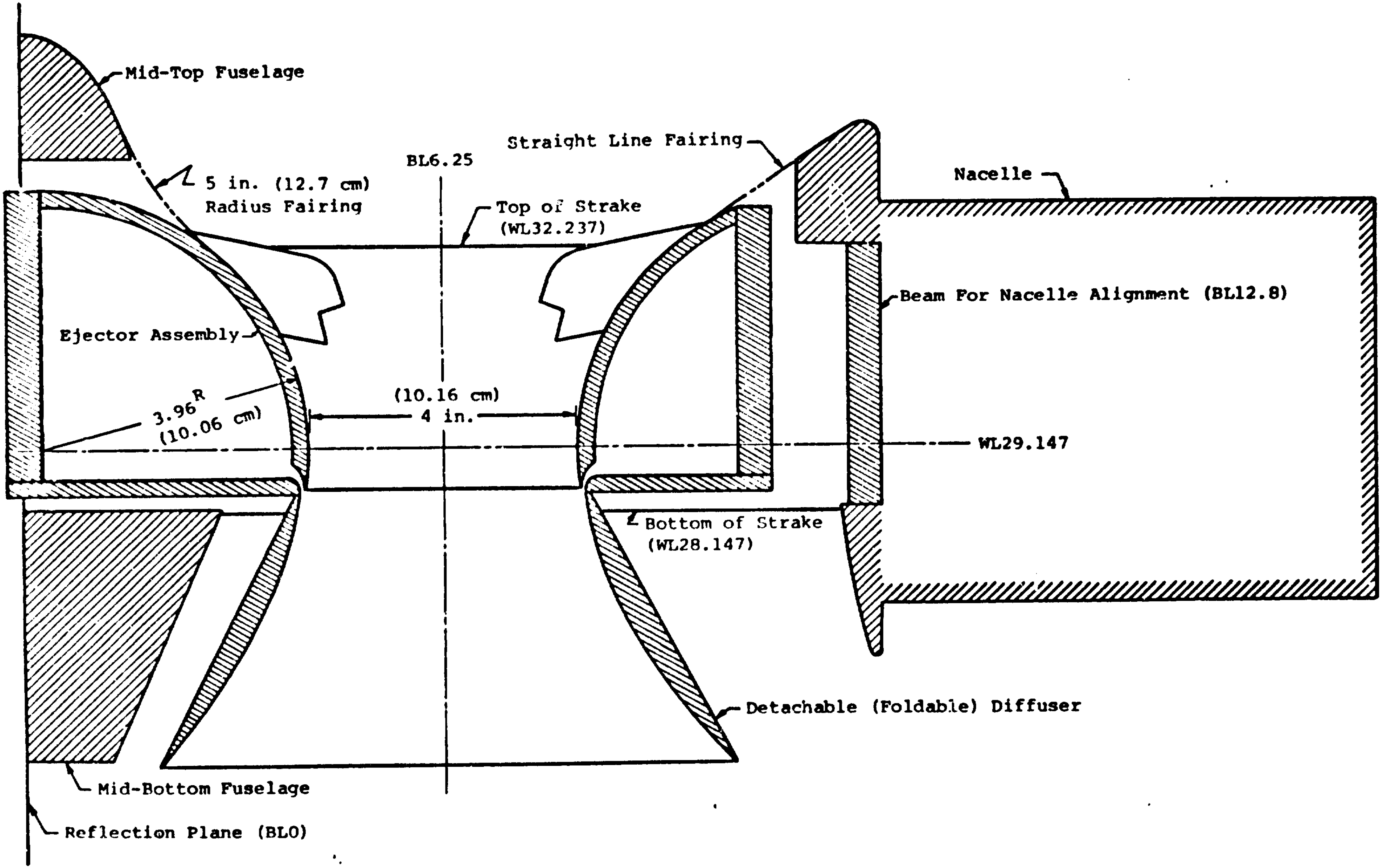


Figure 10. Typical Ejector Alignment and Fairings

Wind tunnel tests

Although it was desirable to measure the influence of translational motion upon the performance of the ejector/aircraft system, the 0.2 scale model was too large for meaningful force tests in the FDRC wind tunnel. Despite this, the model including part of the aircraft, was installed in the tunnel (Figure 11), and tests were performed to determine the influence of tunnel speed upon the stalling characteristics of the ejector.

Since force measurements were not feasible in the present configuration, the ejector stall characteristics were investigated by the use of static pressure measurements in the diffuser. Other investigators consider this to be a good indicator of ejector performance and have utilized it to determine the performance of ejectors (Reference 8).

Although we do not believe that thrust augmentation is a function of the static pressure alone, we do believe that by increasing wind tunnel speed and observing the change of static pressure in the diffuser, one can obtain a good indication of the ejector stall. A steady reading of static pressure on the diffuser wall indicates a well established ejector flow. A sudden rise of static pressure in the diffuser with increasing tunnel speed, accompanied by large fluctuations, is an indication of the on-set of ejector stall. In these tests, a pressure tap was installed at the forward end diffuser wall, at a location which was approximately 6.4 cm (2.5 in) downstream of the diffuser jet slot, at the plane of symmetry (Figure 8). These tests indicated an ejector stall at a ratio of tunnel dynamic pressure to primary nozzle gage pressure of about 0.008; the same ratio as existed during the STAMP tests (Reference 6). Extrapolation to a nozzle pressure ratio of 3.0 indicated an ejector stall at a sea level free stream dynamic pressure of about 1623 Pa (33.9 psf), or a stall speed of 185 km/hr (100 knots). Since the specified wing loading is 4364 Pa (91.15 psf), this corresponds to a required lift coefficient equal to 2.69 for the aircraft to remain wing borne without ejector assistance.

Reference 9 indicates that the required lift coefficient of 2.69 is easily achievable with the use of the powered high lift system installed in the E205 aircraft. Thus it appears that the ejector can operate without stall up to transition to aerodynamic flight speeds.

To explore phenomena associated with ejector stall in the event that a higher stall speed is desired, a blowing jet having a width of 20 cm (8 in) and a slot thickness of 0.064 cm (0.025 in) was installed at the leading edge end block of the ejector as illustrated on Figure 12. The ejector stall test indicated an increase of between 50% and 100% in the ratio of tunnel dynamic pressure to primary nozzle gage pressure. This indicates that the ejector stall is associated primarily with inlet separation and can easily be delayed by boundary layer control. Further investigation, aimed at minimizing the amount of blowing jet required to satisfy a specific requirement is recommended.

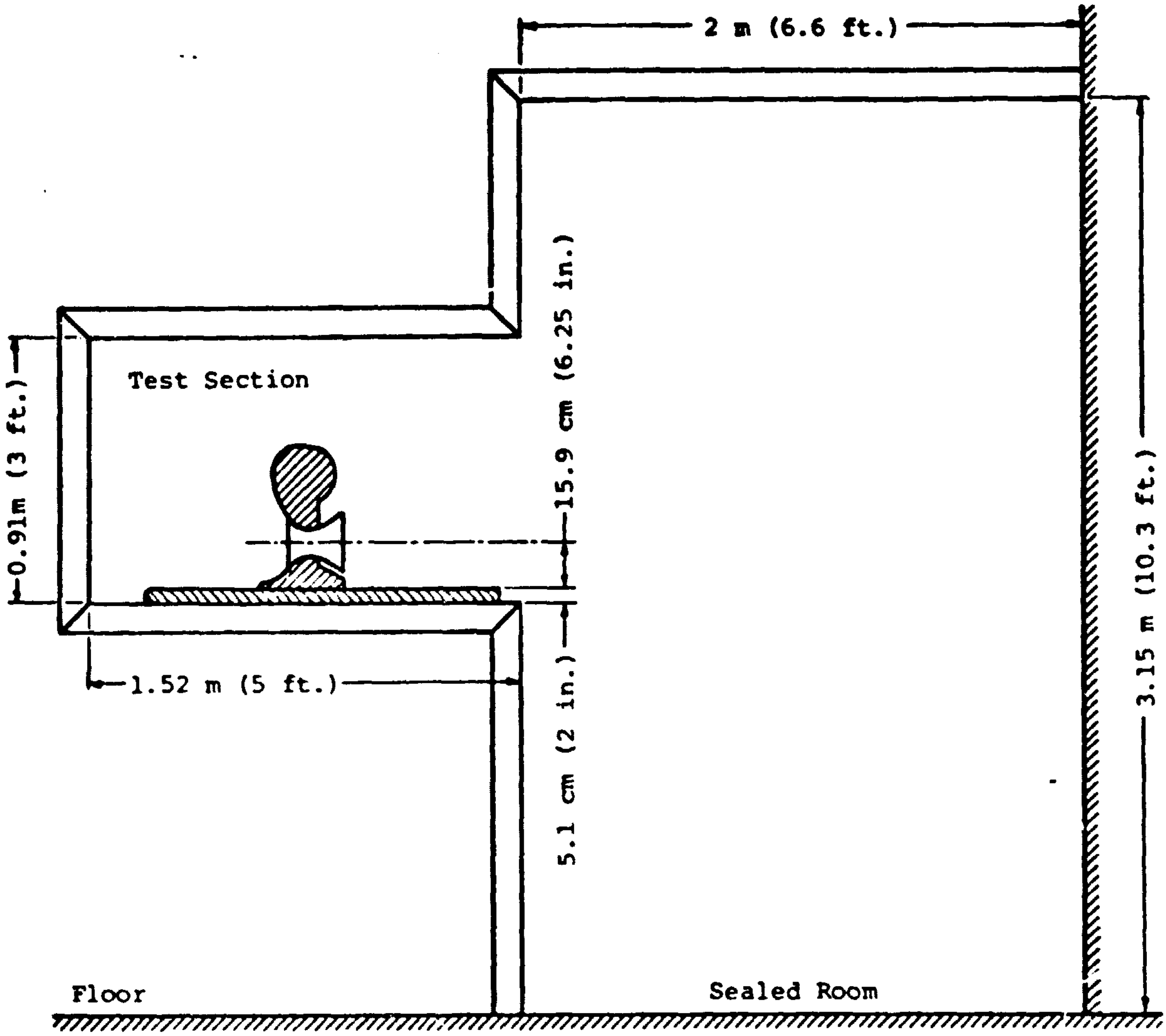


Figure 11. Typical Section of Ejector/Aircraft (FS51) Installed in the FDRC Wind Tunnel

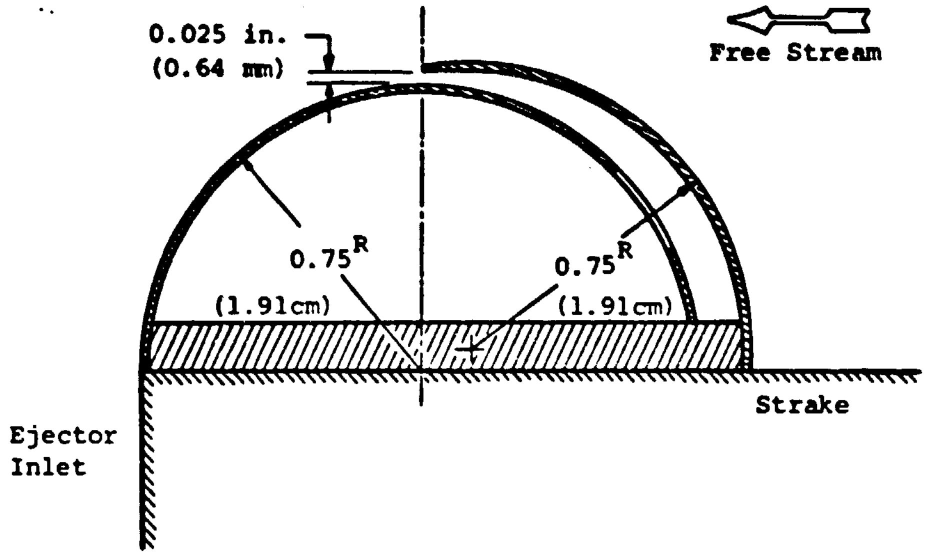


Figure 12. Boundary Layer Control - Front Inlet End Block

Conclusions, Remarks and Recommendations

This program represented a serious attempt to integrate a jet-diffuser ejector into an existing aircraft design. The jet-diffuser ejector was designed to operate at a nozzle pressure ratio of 3, with expected static thrust augmentation of 1.95. The ejector has a ratio of throat area to total jet injection area of 19, an overall depth to throat width of 2, and is foldable for stowage in the strake of the aircraft to a depth which is about equal to its throat width.

The achievement of the objective, i.e. the utilization of the ejector to provide the forces required for vertical take-off and for transition thrust, required advances in the state-of-the-art. The results of the theoretical and experimental work performed in the facilities of Flight Dynamics Research Corporation are encouraging. Extrapolation to more realistic conditions must await testing in a laboratory capable of providing conditions closer to those to be encountered in actual flight.

Ejector testing at low nozzle pressure ratios and low temperatures could only recently be extrapolated to more realistic operational conditions. The results of these extrapolations indicate acceptable performance, however the validity of these extrapolations must be determined by comparison of theory and experiment at those realistic conditions.

The achievement of thrust vectoring by diffuser asymmetry and vector control jets appears promising, but further effort is required to evaluate this concept under realistic flight conditions.

Interference effects between the aircraft surfaces and one ejector, appear minimal at the conditions of the reported tests. Further testing is required to evaluate these effects at higher speeds and pressure ratios.

The influence of hot gas injection into the ejector remains to be investigated. Such investigations should be carried out by comparison of theory and experiment to provide information necessary for future designs.

It is estimated that the present ejector/aircraft design can perform without stall from hover to transition. Higher stall speeds can be achieved with simple boundary layer control of the front inlet end block.

References

1. Alperin, M., Wu. J.J. "End wall and Corner Flow Improvements of the Rectangular Alperin Jet-Diffuser Ejector", Flight Dynamics Research Corporation, Naval Air Development Center, NADC-77050-30, May 1978

2. Alperin, M., Wu, J.J. "Jet-Diffuser Ejector - Attached Nozzle Design", Flight Dynamics Research Corporation, NASA, Ames Research Center and Naval Air Development Center NASA CR 152361, May 1980

3. Alperin, M., Wu, J.J. "Recent Development of a Jet-Diffuser Ejector", Flight Dynamics Research Corporation, AIAA-80-0231, AIAA 18th Aerospace Sciences Meeting Jan. 14-16 1980.

4. Alperin, M., Wu, J.J. "High Speed Ejectors", Flight Dynamics Research Corporation, USAF Flight Dynamics Laboratory, AFFDL-TR-79-3048, May 1979

5. Lummus, J.R., "Study of Aerodynamic Technology for VSTOL Fighter/Attack Aircraft", General Dynamics/Fort Worth Division, NASA CR 152128, May 1978

6. Alperin, M., Wu, J.J., and Smith, Ch. A. "The Alperin Jet-Diffuser Ejector (AJDE), Development, Testing, and Performance Verification Report". Flight Dynamics Research Corporation, Naval Weapons Center, NWC TP 5853, Feb. 1976

7. Lachmann,G.V. Editor, "Boundary Layer and Flow Control". Vol 1, Pergammon Press, N.Y. 1961, Pgs. 21 to 73 by Poisson - Quinton and Lepage, "Survey of French Research on the Control of Boundary Layer and Circulation"

8. Quinn, B., "Recent Developments in Large Area Ratio Thrust Augmentors", AIAA Paper No. 72-1174, AIAA/SAE 8th Joint Propulsion Specialist Conference, 1972

9. Falarski, M.D., Whitten, P.D., and Harris, M.J. "Aerodynamic Characteristics of a Large-Scale Model of a Highly Maneuverable Supersonic V/STOL Fighter: STOL Configuration", AIAA-80-0234, AIAA 18th Aerospace Sciences Meeting, Jan 14-16, 1980.

Appendix A

Test Apparatus

The laboratory equipment utilized for the investigation reported in this document consists primarily of a static test rig, a 3 x 5 ft. wind tunnel and the associated instrumentation required for measurement of the forces, pressures and temperatures utilized for determination of the performance of the ejector. Tests reported in this document were performed at a plenum pressure of 24.1 kilopascals (3.5 psig) or a pressure ratio of 1.24 in the static test rig and wind tunnel.

The FDRC static test rig is shown on Figure A-1. The basic structure consists of two components; a fixed frame assembly secured to the foundation, and a rigid assembly consisting of the air supply piping and the test article, supported by three bearing balls. This latter assembly is thus free to rotate and translate on a horizontal plane, restricted only by two flexible bellows and three load cells which provide the force and moment measurements.

Compressed air is supplied by a rotary, positive displacement blower to a large plenum chamber. Distribution of the compressed air and control of its mass flow rate and pressure is accomplished by three remotely operated valves. One valve each on the primary and diffuser jet supply lines, and a dump valve on the by-pass line. The mass flow rate in each supply line is measured with the aid of calibrated sharp edge orifices and pressure and temperature sensors.

The forces on the test article are transferred through the floating structure to the load cells, whose readings were precisely calibrated to permit evaluation of the tare forces introduced into the system by the flexible bellows and the pressurization of the system.

Pressure, temperature and force measurement by the transducers are transmitted to a digital readout at the control console.

The FDRC wind tunnel is shown on Figure A-2. It is an open circuit tunnel with a 3 x 5 ft test section, and can be operated either closed throat or half-open throat. One side of the test section opens into a sealed room, permitting access to the model during operation. Air is ingested through a large area ratio inlet bell, and exhausted through the roof of the laboratory. Power is supplied by a large blower, downstream of the diffuser. A test section velocity of 100 fps is achievable with most model installations.

Compressed air is supplied to the model from the same compressor as is utilized in the static test rig. The compressed air is introduced into the tunnel system at the downstream end of the diffuser and fed through two separate ducts containing flow metering sharp edge orifices and valves. Control of the mass flow rate and pressure is accomplished by a system of three remotely operated valves. One valve on each supply line and a dump valve on a by-pass line. The mass flow rate in each line is measured independently by the orifices and pressure and temperature sensors.

The present ejector/aircraft is too large for force measurement in the FDRC wind tunnel, as discussed in the main text of this report. Under normal test conditions, the model is suspended on a sting which is restrained by three load cells and flexible bellows on the compressed air supply ducts. The load cells and the orifices are precisely calibrated to permit evaluation of the tare forces introduced into the system by the flexible bellows and the pressure and temperature effects due to the passage of the compressed air. Load cell and pressure and temperature transducer signals are transmitted to signal conditioners and a digital readout at the control console.

A model shop with various machinery and other equipment is available for model construction and modification as required.

The laboratory also includes an IBM 5100 computer and printer, for use in data reduction and theoretical analyses.

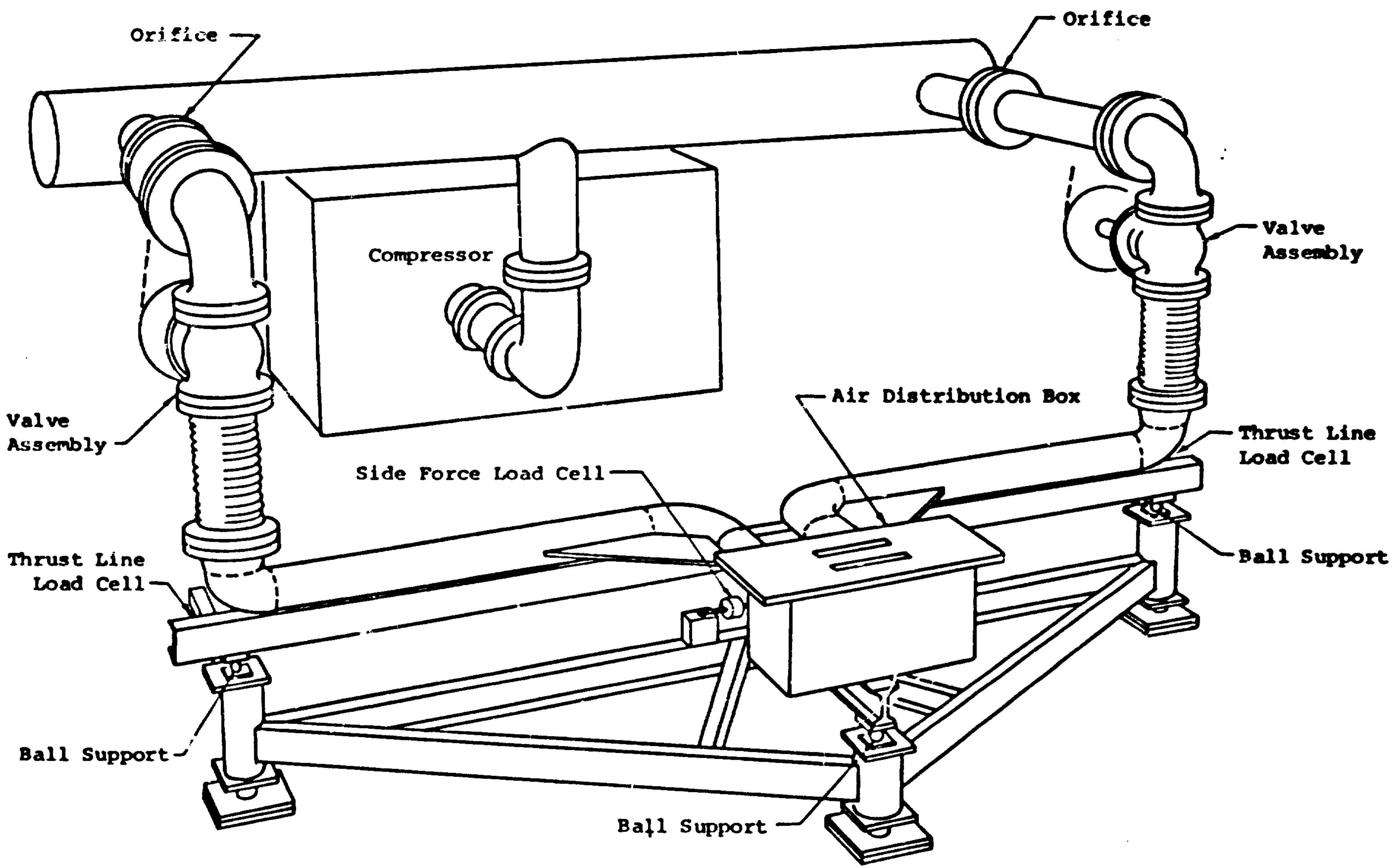


Figure A-1. FDRC Static Ejector Test Rig

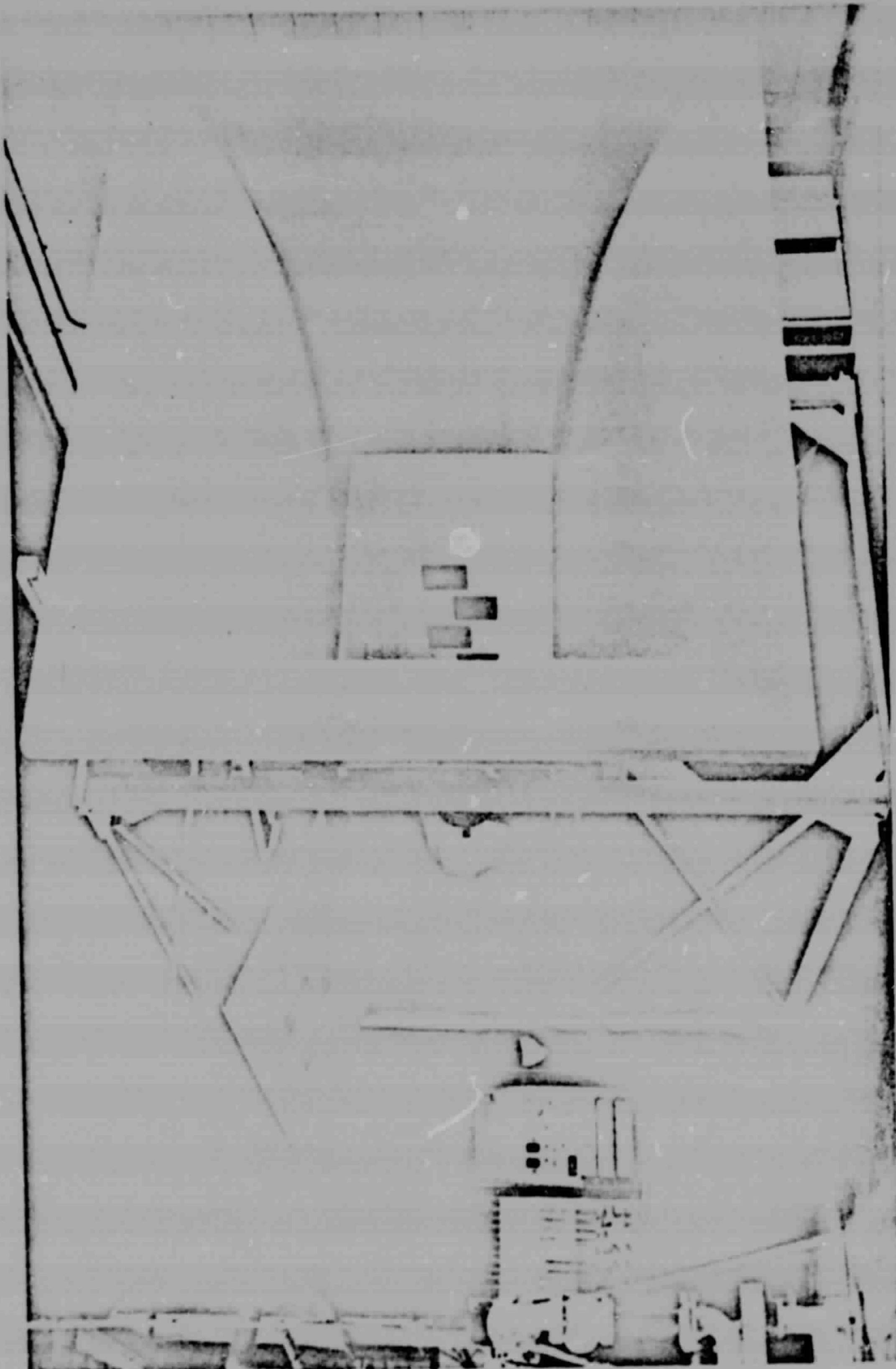


Figure A-2. FDRC Wind Tunnel

ORIGINAL PAGE IS
OF POOR QUALITY

Appendix B

Ejector Stowage and Unpowered Nacelle Considerations

Ejector Stowage

The top and bottom of the ejector must be closed during conventional flight, without alteration of the basic configuration of the E205 design. This can be accomplished in a variety of ways, however, it is essential to avoid excessive complexity and surfaces which might interfere with proper ejector performance in the deployed configuration. The following is a preliminary suggestion for the ejector stowage design which may ultimately be improved when more precise design information becomes available.

As previously indicated, the primary nozzles (No. 5), utilized in the exploratory tests and intended for use in the 7 x 10 foot wind tunnel tests, protrude above the upper surface of the strake, near the root of the nozzles, as a result of the necessity for alteration of the injection angle of the primary fluid (Figure 10). However, these nozzles can easily be redesigned to avoid their protrusion, as illustrated on Figures B-1 and B-2.

The top opening of the ejector, assuming non-protruding nozzles are utilized, can be closed by a hinged door, as illustrated on Figures B-1 and B-2. In the deployed configuration (Figure B-1), the doors are folded on the nacelle side, with a reasonably large radius of curvature at their leading edge. The radius of curvature may be somewhat increased or decreased in comparison to that shown on Figure B-1, if desired. A proper design however, must avoid the possibility of inlet separation, which would occur if the inlet doors were comprised of single, relatively thin sheets of material. The sliding element moves along countersunk tracks upstream and downstream of each ejector, thus avoiding inlet interference.

In the stowed configuration, the top surface of the strake is flat, with the hinge inside the ejector cavity, as shown on Figure B-2. Stiffeners can be incorporated on the inside surface of the top closure plates for structural rigidity. These stiffeners must be spaced to avoid interference with the primary nozzles when the doors are closed.

The bottom opening of the ejector can be sealed by use of the diffuser panels as illustrated on Figures B-1 to B-4. The sides of the diffuser shown in their deployed configuration on Figure B-1, can be stowed as illustrated on Figure B-2. The inboard panel is constructed in one piece (Figure B-3), and the outboard panel is constructed similar to "piano keys" as illustrated on Figure B-4, to avoid interference of the stowed panel with the fixed portions of the ejector in the vicinity of the diffuser jet, as shown on Figure B-2. The forward end of the front diffuser can be folded into the cavity of the strake as shown on Figure 1. The aft diffuser end of the rear ejector and the diffuser ends between the two ejectors can be folded in a similar manner, however, a "telescope" type folding scheme may be required. The diffuser flap shown on Figure 8 and the top photograph of Figure 9 has a somewhat arbitrary boundary. The "cut-off" line is a streamline which has starting coordinates corresponding to the break point of the diffuser panel, at the exit of the diffuser, for the folding scheme shown on Figures B-1 to B-4. Modification of the flap boundary may be desirable from the stowage point of view. Simplification of this diffuser folding design may be feasible if the high nozzle pressure ratio tests indicate the feasibility for using a smaller diffuser area ratio.

Half cylindrical inlet end blocks at the fore and aft ends of the ejectors can be retracted into the strake as illustrated on Figure 1.

Unpowered Nacelle

Since the nacelle of the one-fifth scale, semi-span model is to be unpowered during the planned tests in the 7 x 10 foot wind tunnel, it is suggested that the nacelle be constructed as a solid element of the model. To avoid adverse effects due to the flow about the nacelle, it is recommended that a nose cone and a simulated aft end be incorporated into the model.

The nose cone is a simple, forward extension of the leading edge of the nacelle as illustrated on Figures 1 and 9. Detailed full-scale cross-sections of the model nose cone have been submitted to NASA under separate cover.

Since the E205 aircraft design is supplied with VEO-wing nozzles, certain trailing edge bluntness is likely to exist during realistic flight conditions when the air flow is diverted to the ejectors. The suggested aft end design shown on Figure B-5, is intended to minimize the base drag or to simulate the VEO-wing nozzle cowl when the nozzle is in a closed position.

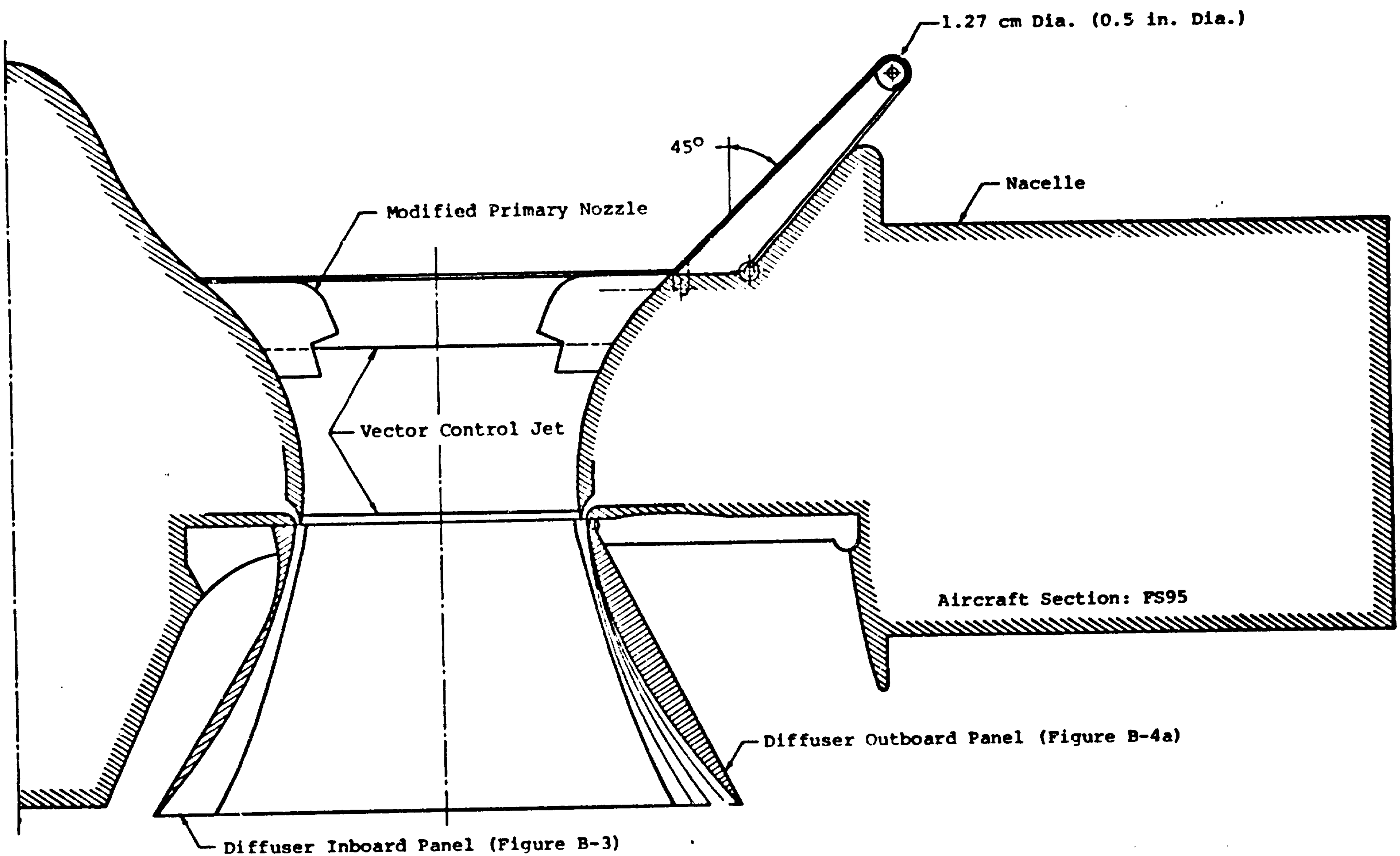


Figure B-1. Typical Section with Deployed Ejector

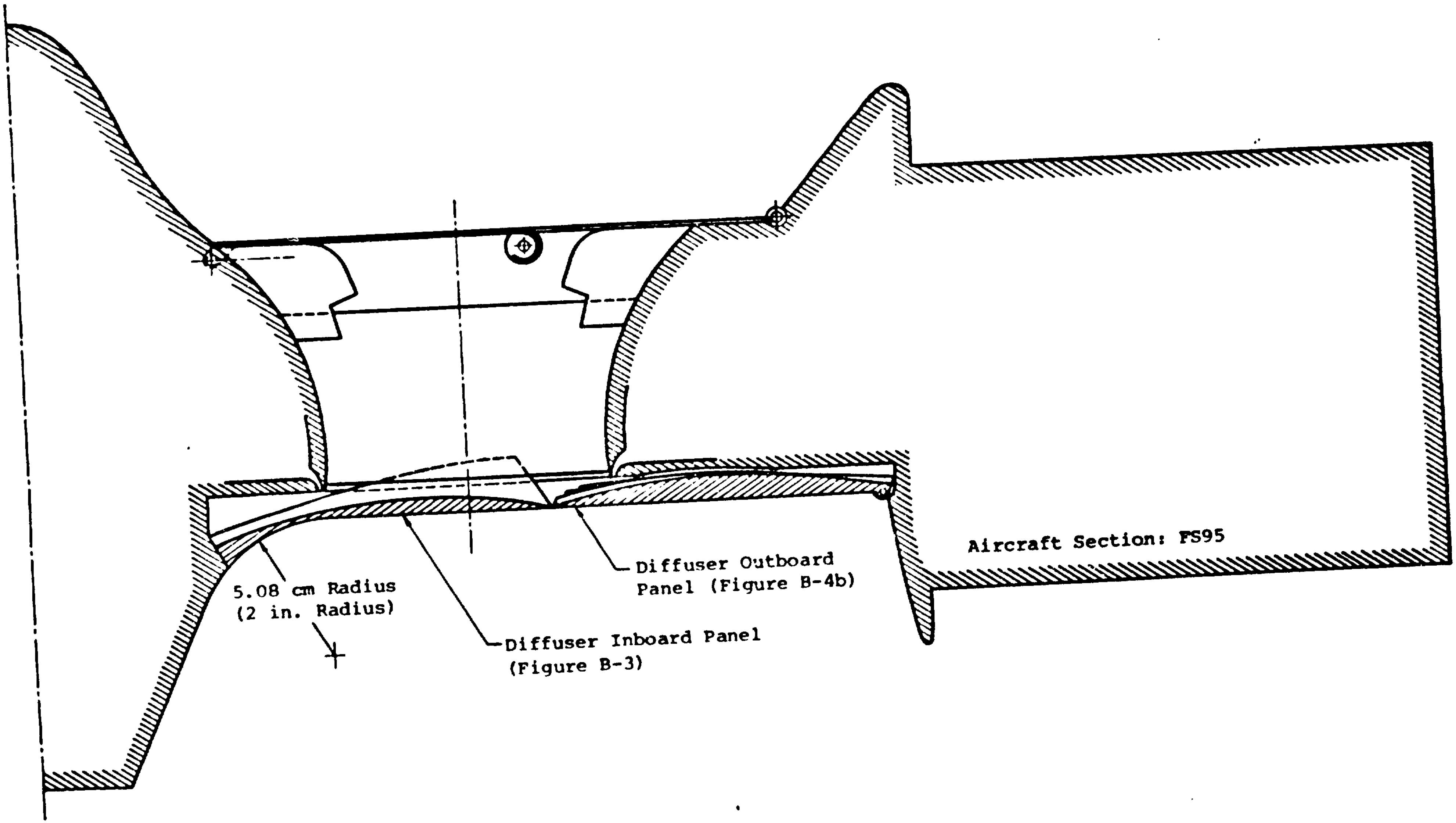


Figure B-2. Typical Section with Stowed Ejector

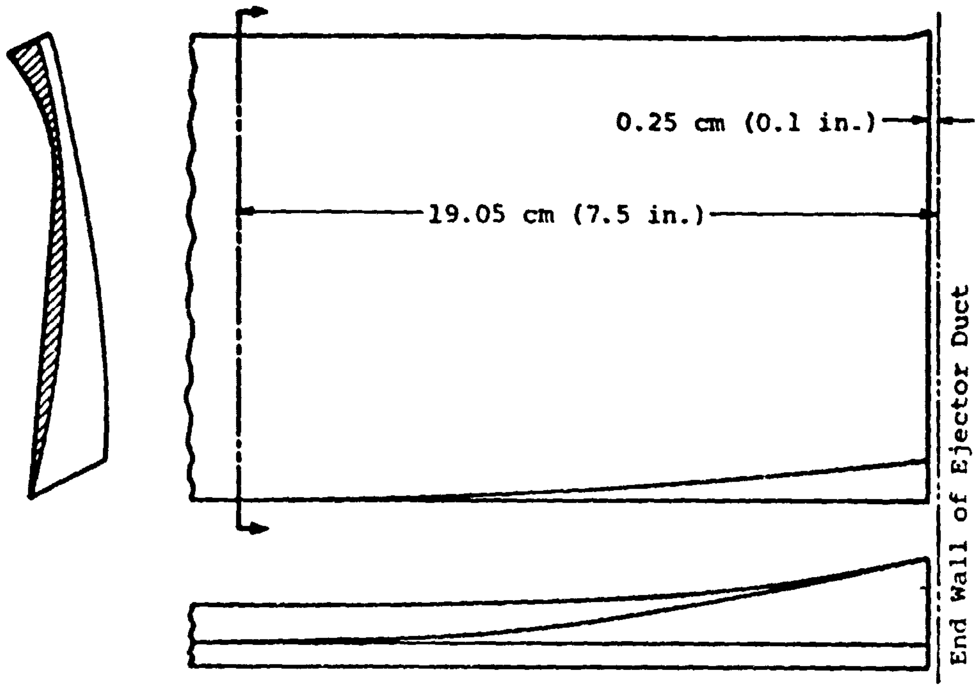
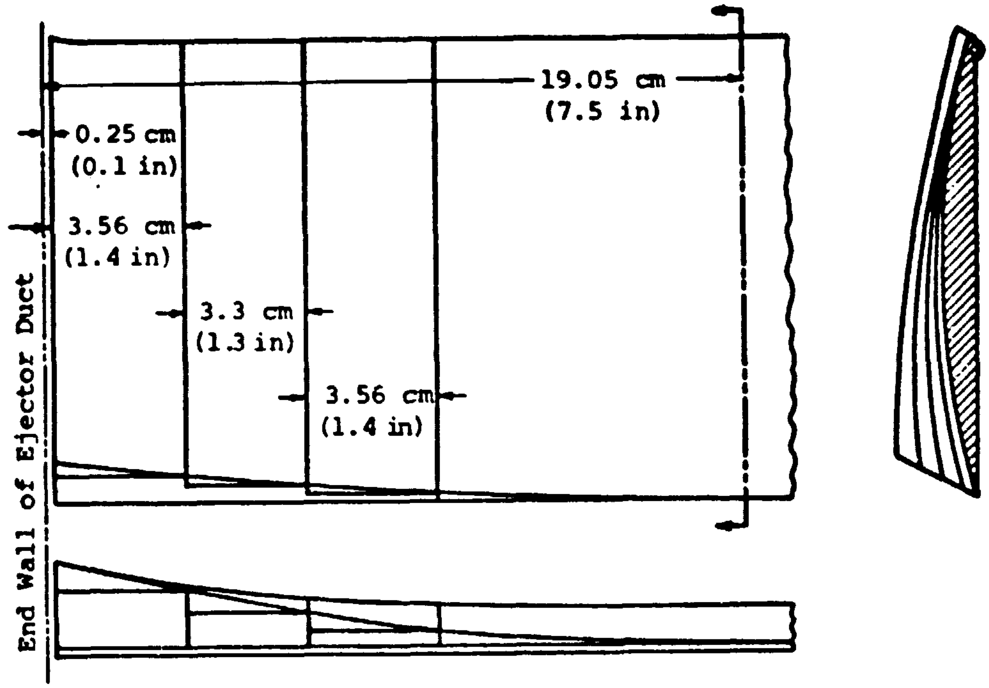
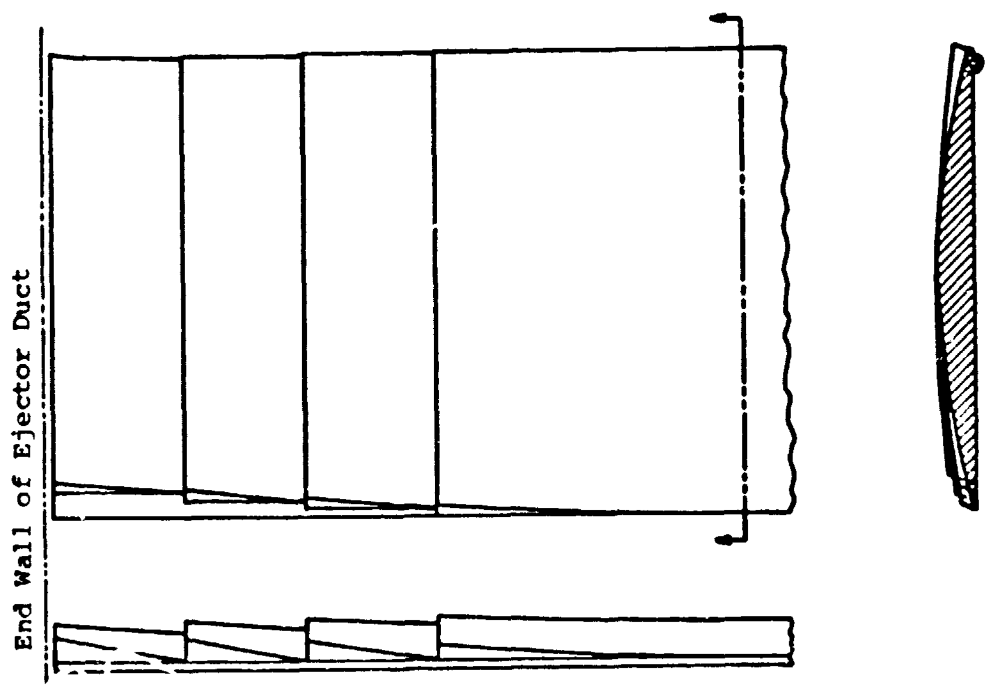


Figure B-3. Diffuser Inboard Panel



(a) Expanded Configuration



(b) Compressed Configuration

Figure B-4. Diffuser Outboard Panel