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# A PRELIMINARY DESIGN ANALYSIS OF A MULTI-CHANNEL EJECTOR THRUST AUGMENTATION CONCEPT SITH OVAL OR RECTANGULAR AIR SUPPLY DUCTS

D. C. Wright, et al

Bell Aerospace Company
Buffalo, New York

May 1972

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*BELL AEROSPACE COMPANY*
*BUFFALO, NEW YORK*

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This design study has been based on the use of the present Lycoming PLF1A-2 engine and includes investigations into the feasibility of eliminating the bleed air from the plenum and its effects in regard to engine performance.

The analytical evaluations have been included to determine the advantages and disadvantages in the areas of weight and structural penalties for the central air supply duct configurations developed. The approach taken was that the duct configurations selected could be suitably adapted to a Research Test Vehicle employing the ARL thrust augmentation concept.

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AEROSPACE RESEARCH LABORATORIES
OFFICE OF AEROSPACE RESEARCH
UNITED STATES AIR FORCE
WRIGHT-PATTERSON AIR FORCE BASE, OHIO

## FOREWORD

This report was prepared by the Bell Aerospace Company, Buffalo, New York, and covers the work performed under USAF Contract No. F33615-71-C-1802. The contract was administered by the Aerospace Research Laboratories, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio. Dr. Brian P. Quinn served as Technical Program Manager.

The work reported herein was accomplished during the time period of August 1971 to December 1971.

The authors and contributing personnel of Bell Aerospace Company were Messrs. Donald C. Wright, Technical Director; J. G. Allen, Design, W. N. Meholick, Structural Analysis; C. Tilyou, Weight Analysis; and G. R. Salter and R. Ashby Propulsion Analysis.

This report was submitted by Bell Aerospace Company in February 1972. The contractor's report number is 2445-953001.

This technical report has been reviewed and is approved.

## ABSTRACT

This report represents the results of a minimum preliminary design and analysis to determine the feasibility of achieving improved mixing efficiency with area ratios ($A_2$ to $A_0$) near 27 for the multi-channel ejector thrust augmentation concept. This is to be accomplished by replacing the existing cylindrical air supply ducts presently being used on an existing four channel ejector wing model in Building 71B, G Bay, at WPAFB, Dayton, Ohio, with oval or rectangular ducts incorporating an improved ejector nozzle design.

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LIST OF SYMBOLS FROM SECTION C

| | | |
|---|---|---|
| $\eta_z$ | = | Vertical load factor |
| b/t | = | Unsupported plate width over plate thickness |
| $F_{T_U}$ | = | Ultimate tensile stress allowable |
| $F_{T_y}$ | = | Yield tensile stress allowable |
| $F_{S_U}$ | = | Shear stress allowable |
| $F_{b_{ru}}$ | = | Bearing stress allowable |
| $\tau_{cr}$ | = | Shear buckling stress |
| $\sigma_{cr}$ | = | Compressive buckling stress |
| $\bar{\sigma}_F$ | = | Post-buckling compressive stress |
| M.S. | = | Margin of safety |
| $\tau$ | = | Shear stress |
| $I_{xx}$ | = | Moment of inertia about x-x |
| $A_e$ | = | Effective area |
| $f_{b_t}$ | = | Bending stress - tension |
| $f_{b_c}$ | = | Bending stress - compression |

LIST OF SYMBOLS FROM SECTION C
(Cont'd)

| | | |
|---|---|---|
| $\sigma_L$ | = | Axial stress in longitudinal direction |
| $\sigma_C$ | = | Bending stress in circumferential direction |
| $Q_y$ | = | Static moment about y-y axis |
| $I_{yy}$ | = | Moment of inertia about y-y axis |
| E | = | Young's modulus |
| G | = | Shear Modulus |
| $E_c$ | = | Core compression modulus |
| $G_c$ | = | Core shear modulus |
| $F_c$ | = | Core compressive stress allowable |
| q | = | Running shear flow |
| $R_a$ | = | Ariel stress |
| $R_s$ | = | Shear stress ratio |
| $\sigma_1, \sigma_2$ | = | Principal stresses |

# I INTRODUCTION

New concepts of thrust augmentation, applicable to V/STOL technology, have been the subject of analytical and experimental research by the Air Force Aerospace Research Laboratories over the past several years. These new concepts are based upon the ejector principle of thrust augmentation, utilizing the bypass air of relatively high bypass ratio turbofan engines. Substantially higher thrust augmentation levels then in previous ejector tests have been achieved by improvements in mixing efficiency and by improved ejector nozzle design arrangements.

The objectives of this minimum preliminary design analysis were:

(1) To determine the feasibility of achieving area ratios ($A_2/A_0$) near 27 using nozzle effective areas in the multi-channel ejector system, recently developed by the Aerospace Research Laboratory, by replacing the existing cylindrical air supply ducts on the full scale wing model with oval or rectangular ducts.

(2) Using the present PLF1A-2 Lycoming engine, investigate the possibility of eliminating the bleed air from the existing plenum and its effects on engine performance.

(3) Discuss the disadvantages in the areas of weight and structural penalties of the air supply duct configuration.

In conducting this design study on the feasibility of replacing the existing cylindrical air supply ducts on the full scale wing model, using the latest ARL multi-channel ejector system, it appeared desirable to approach the evaluation from the following standpoints:

(1) Prepare a preliminary design of a suitable flight configuration of the latest ARL multi-channel ejector system.

(2) Prepare a preliminary design study to simulate the flight configuration with an inexpensive modification to the ARL full scale wing model.

(3) Prepare a preliminary design study to duplicate the flight configuration on the ARL full scale wing model.

To insure that the duct configuration selected could be suitably adapted to an aircraft employing the ARL thrust augmentation concept an investigation was made into the structural attachment of the multi-channel ejector wing with the proposed fuselage structure of the Research Test Vehicle (RTV) outlined in Reference 1.

## II DESIGN DESCRIPTION

### A. WING CROSS SECTIONAL GEOMETRY

In order that all air supply duct configurations could be evaluated on a common ground certain basic criteria were established prior to the layout phase as shown in Figure 1. These include an area ratio ($A_2/A_0$)near 27, a constant mixing area between 10 and 11 inches where practical, a diffuser area ratio ranging from 1:1 to 2.2:1 between the constant mixing area and the exit area of the diffuser and nozzles recently developed under ARL's nozzle research program as shown in References 2, 3 and 4.

Cross sectional layouts were prepared for a four channel ejector system, using the basic criteria noted above, five configurations used a modified 15% airfoil section as shown in Reference 5 and two used a 12% airfoil section.

#### 1. Cross Section Geometry - Elliptical Ducts, Figure 2

This configuration utilizes nozzles and nozzle panels with chordwise locations of the ejector equipment identical to that shown in Reference 6, with the nozzle exit locations shifted vertically to accommodate the 15% modified airfoil wing section. The upper leading edge surface has also been modified to accept the Reference 4 nozzle and inlet door No. 1.

Air supply duct No. 1 remains a cylindrical tube with the same diameter as the full scale wing model shown in Reference 6. Ducts 2, 3 and 4 are true ellipses to provide sufficient duct area and accommodate the multiple diffuser doors within the wing contour. Duct No. 5 is a round tube but of smaller diameter than the flap tube on the full scale wing model to provide space for the multiple diffuser doors. The four inlet doors are similar to those provided with the ARL full scale wing model. Inlet fairings on the top surface of air supply ducts 2, 3 and 4 support the first three inlet doors and form the $44^{\circ}$ ramp to the constant mixing area. Fairings fore and aft of the air supply ducts maintain the constant mixing area and provide supports for the diffuser doors. Due to the integration of the ARL multi-channel ejector system into this wing profile, the constant mixing area lengths in bays 1 and 4 has been reduced from the desired 10 to 11 inches to 9.5 and 6.5 respectively. Duct areas in this configuration are adequate in all cases except duct #4 which is approximately 16 square inches undersized.

#### 2. Cross Section Geometry - 12% Wing Section, Figure 3

Wing cross sections outlined on this drawing adapt the present ARL multi-channel ejector system to a 12% airfoil. Nozzles and nozzle pannels are fitted to irregular shaped sheetmetal air supply

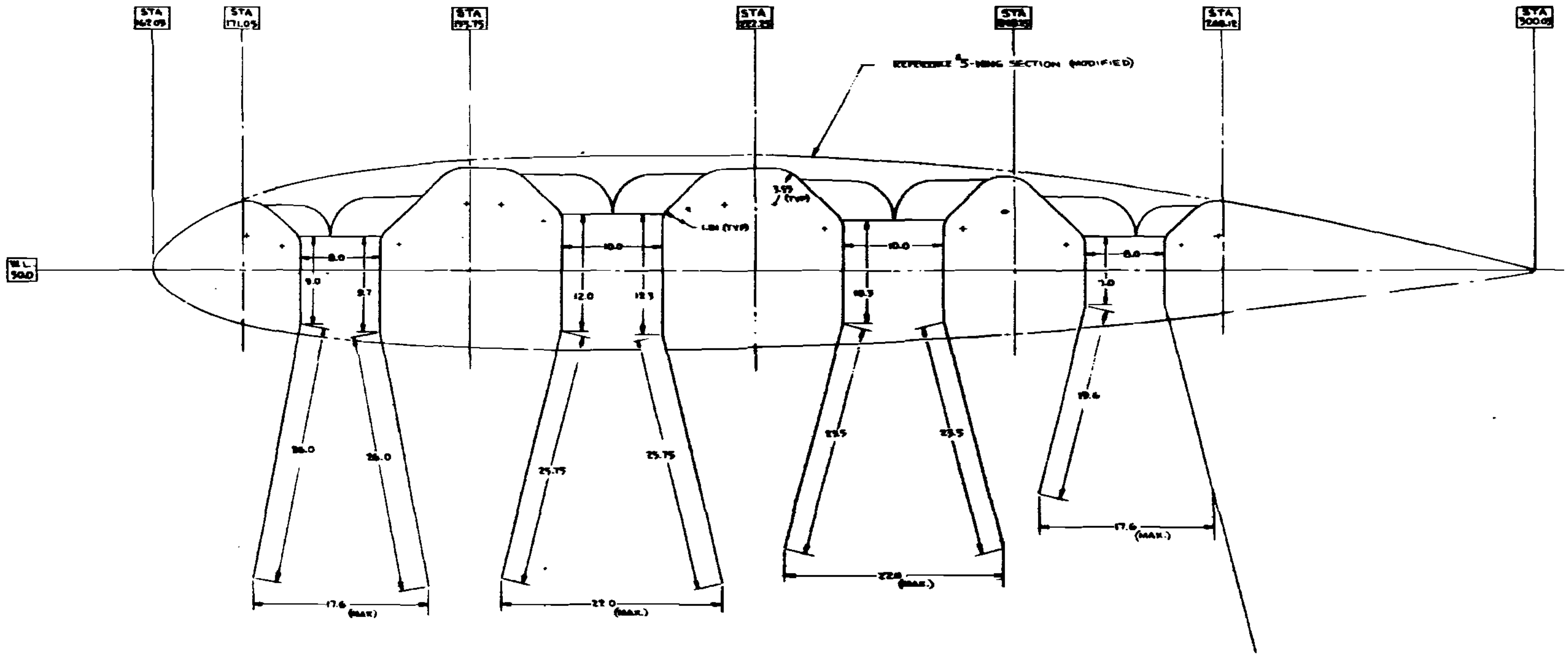



Figure 1. Basic Geometry, Full-Scale Wing Model. ARL Multichannel Ejector System

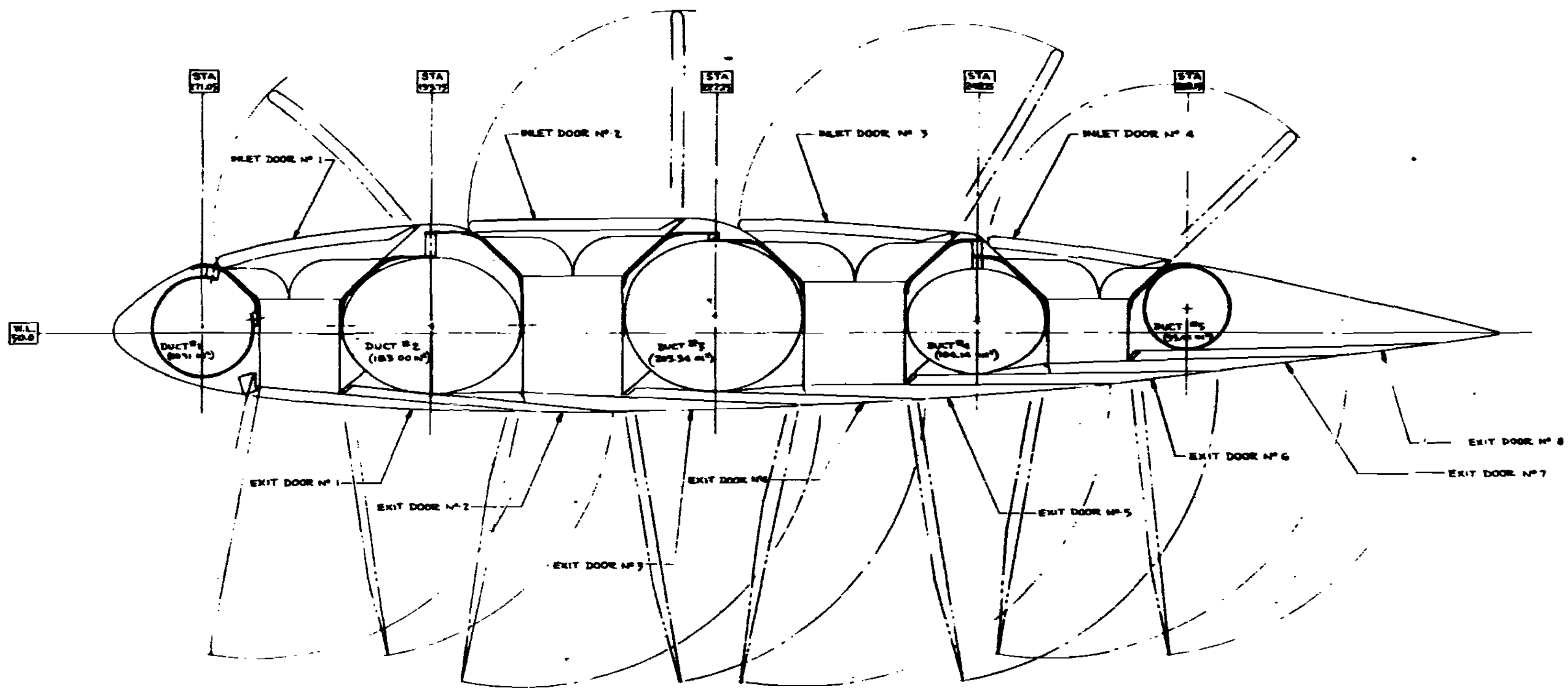



Figure 2. Cross Section Geometry, Elliptical Ducts. ARL Multichannel Ejector System

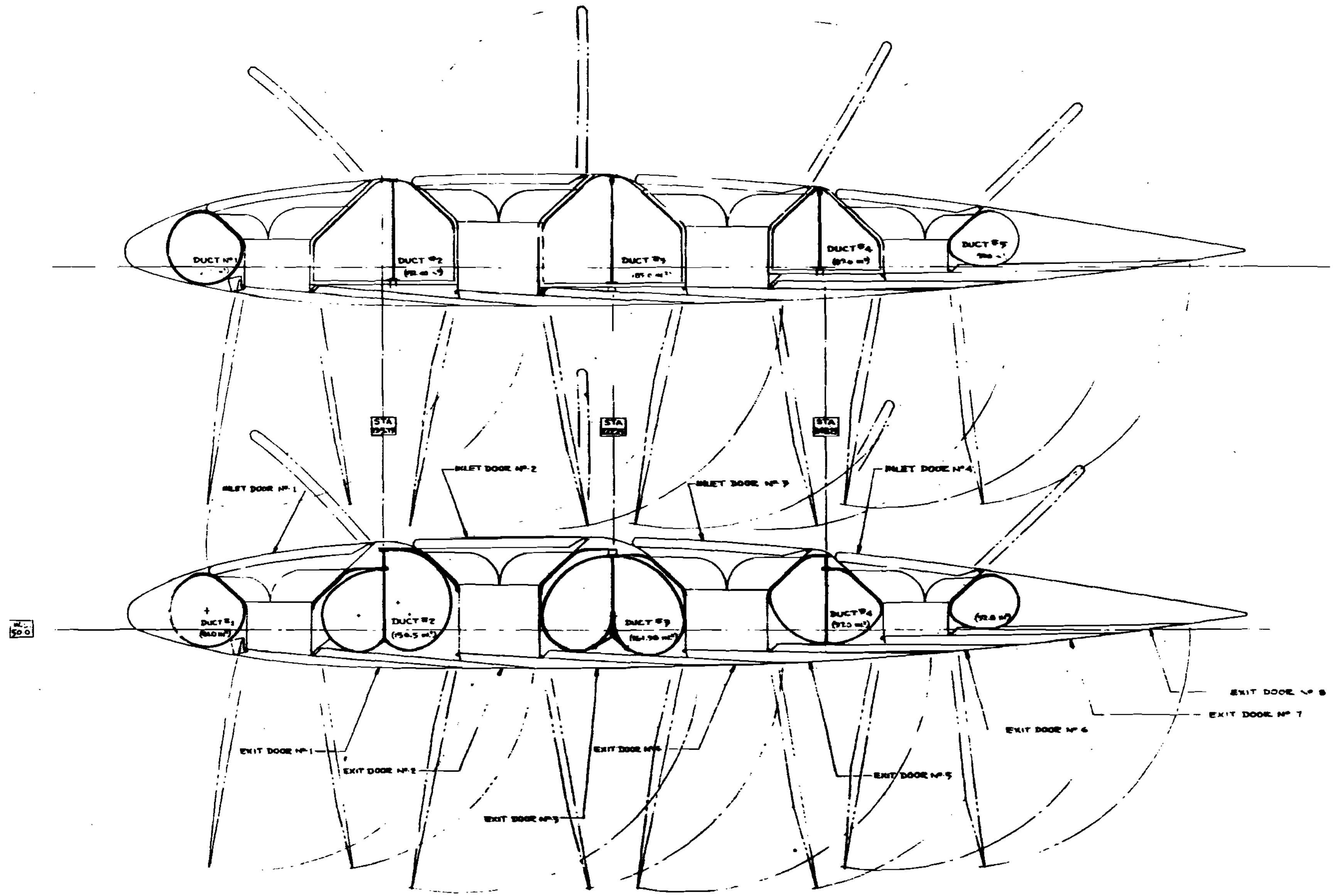



Figure 3. Cross Section Geometry, Multichannel Ejector System. ARL Full Scale Wing Model 12%

ducts as shown in the lower section. In the upper section the nozzles are shown mounted directly on the inside surface of the 44° ramp surface of the aluminum cored air supply ducts. In each configuration the air supply areas are critically small, especially in duct #4, and the constant mixing lengths in all ejector bays is extremely short. As a result of these unsatisfactory aerodynamic conditions further consideration for adapting the present multi-channel ejector system into a 12% airfoil wing was abandoned.

3. Cross Section Geometry - Sandwich Ducts, Figure 4

This cross sectional layout employs the use of an aluminum sandwich structure for air supply ducts 2, 3 and 4 which provide a maximum cross sectional area, straight sides to form the constant mixing area, and ramp angles of 44° for nozzle mounting with inlet and diffuser doors contained within the 15% airfoil section. Circular duct sections, similar to the other configurations are used for air supply ducts #1 and 5. Nozzle exit planes have been adjusted slightly to suit the upper surface of the wing contour. Constant mixing area lengths of 10 to 11 inches have been maintained in bays 2 and 3 but a reduction to 9.5 and 6.5 inches occurs in bays 1 and 4.

4. Cross Section Geometry - Sheet Metal Ducts, Figure 5

The ejector geometry of this configuration is identical to that shown in Figure 2. Nozzles and nozzle panels are mounted on irregular sheet metal ducts. Ducts 1 and 5 are identical to those shown in Figure 2. Ducts 2, 3 and 4 consist of a light sheet metal pressure vessel attached to spanwise beams which are the prime wing load carrying members. Inlet fairings on the upper surface of the ducts support the four inlet doors. Superstructure on the sides and lower sides provide the constant mixing area and supports for the eight diffuser doors. Air supply duct areas in this configuration are sufficient for nozzle demands, however, nozzle exit planes have been adjusted slightly to satisfy the upper wing contour and therefore effect the lengths of the constant mixing areas slightly.

5. Cross Section Geometry - Sandwich Ducts Modified, Figure 6

As in previous configurations air supply ducts 1 and 5 remain as cylindrical ducts but ducts 2, 3 and 4 have been reshaped to provide maximum area and to simplify the fabrication of the sandwich duct, however, the diffuser door hinge support in this configuration would be much larger. The 44° inlet ramp to the constant mixing area has been replaced by a large radius and would require a modification to the present large alternating and slot nozzles. Since this configuration varies slightly from the basic criteria

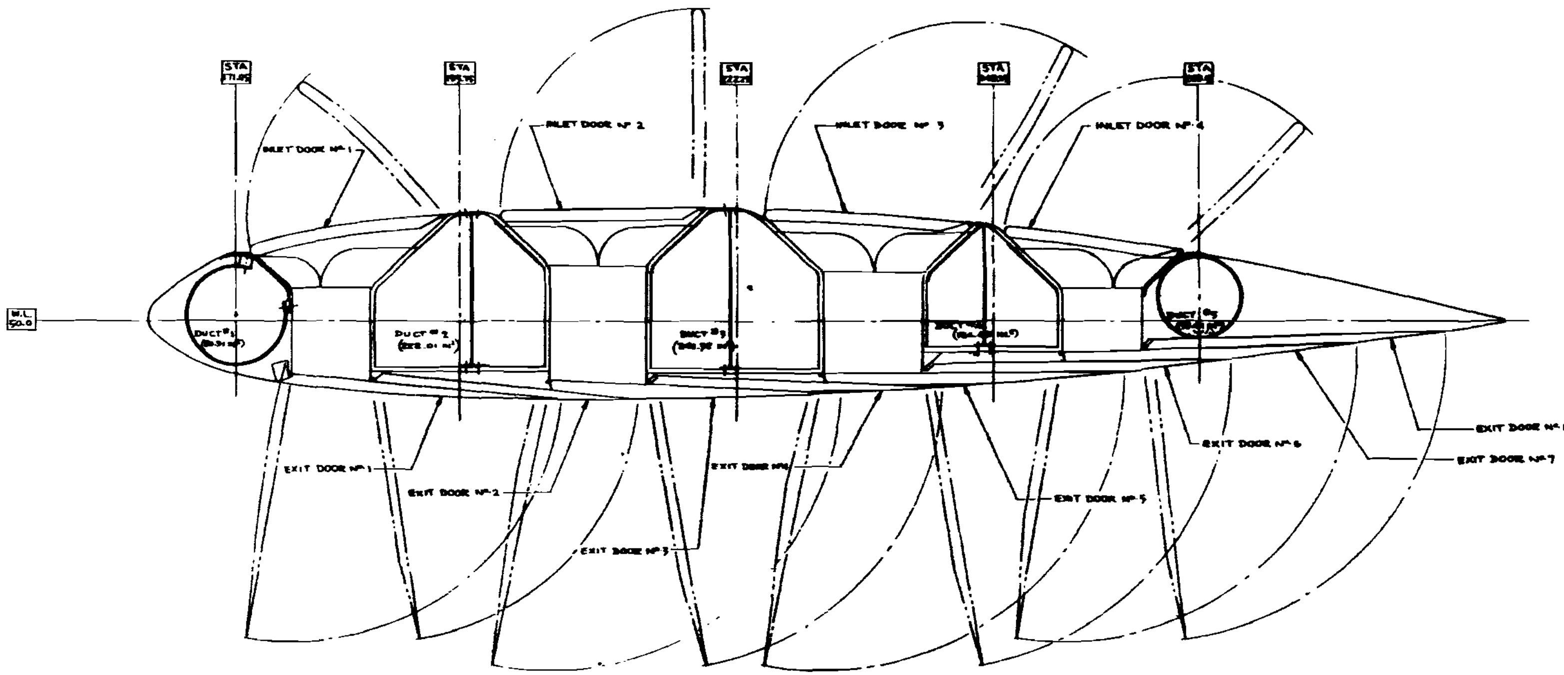



Figure 4. Cross Section Geometry, Sandwich Ducts. ARL Multichannel Ejector System

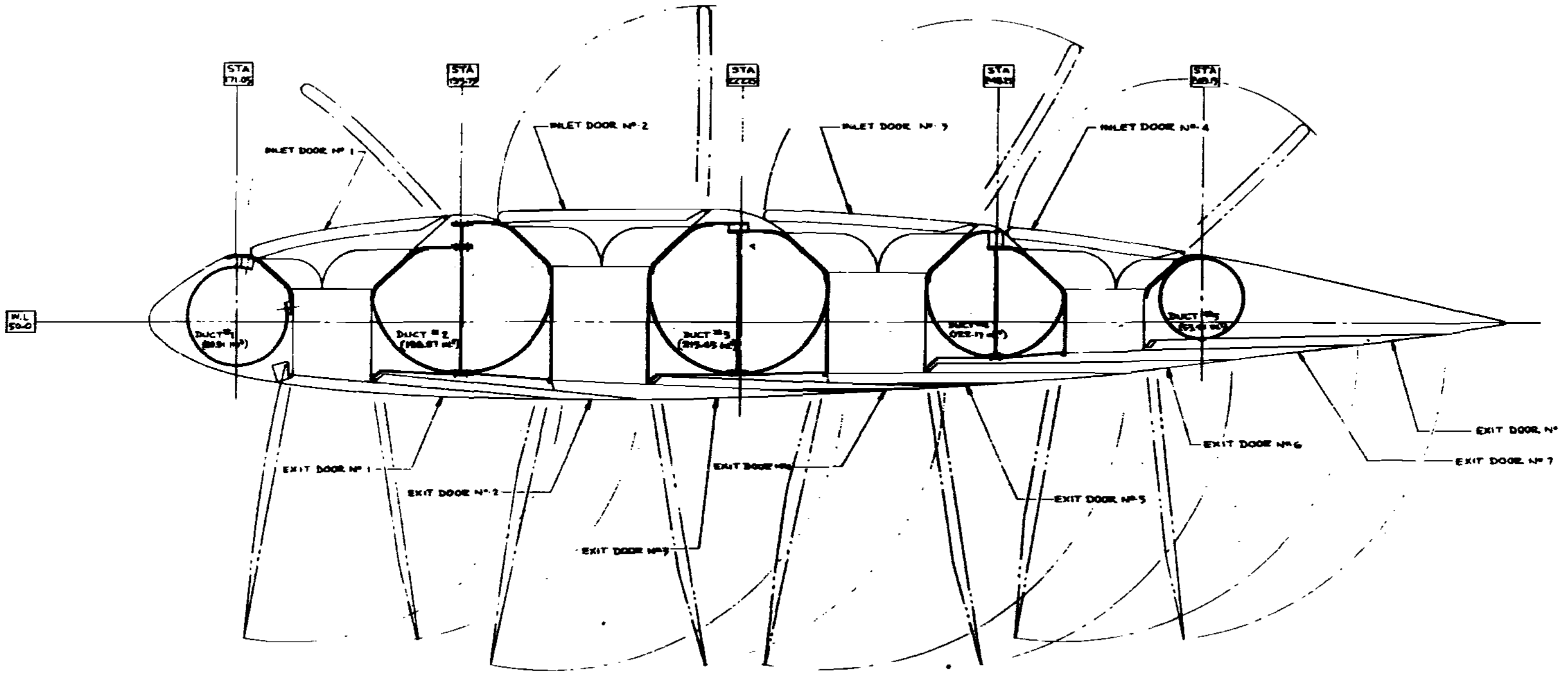



Figure 5. Cross Section Geometry, Sheet Metal Ducts. ARL Multichannel Ejector System

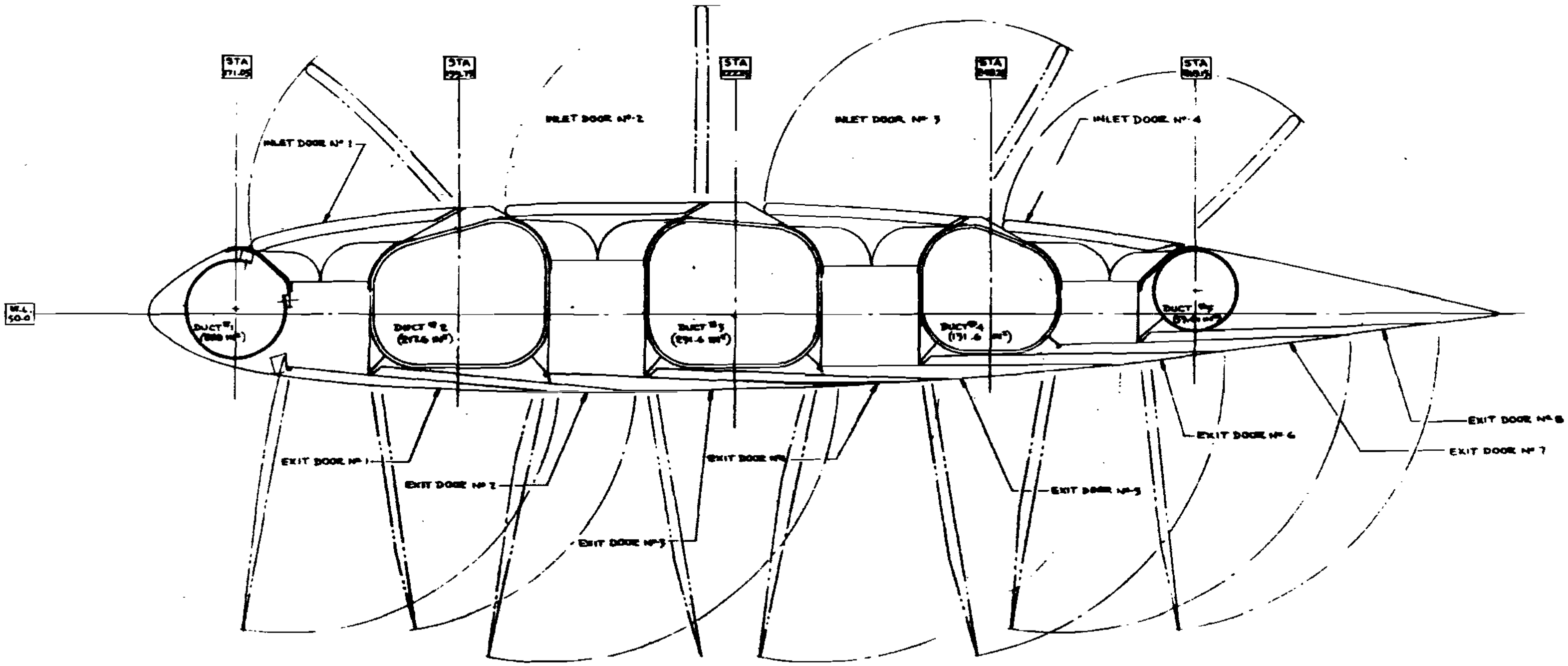



Figure 6. Cross Section Geometry, Sandwich Ducts Modified, ARL Multichannel Ejector System

established in the latest ARL multi-channel ejector system it was eliminated from further consideration.

## B. DETAIL DESIGN

The five wing cross sectional layouts discussed above were investigated from an overall geometric arrangement, both from an aerodynamic and structural standpoint, and two of the most promising candidates were selected for a more detailed evaluation.

Since this detailed evaluation of the selected configurations would ultimately be adapted to an aircraft employing the ARL multi-channel ejector system, it appeared desirable at this time to use the Research Test Vehicle (RTV) as the basis for this study.

In the RTV configuration the horizontal stabilizer is located on the aft outboard section of the boom and the loads applied to the wing tip are such that duct #4 is the most highly loaded. In addition with the airflow in duct #4 at a higher velocity than in the other ducts and since total pressure loss and nozzle performance are very sensitive to the airstream velocity, particular attention has been given to the internal aerodynamics of duct #4. Because of these aerodynamic and structural considerations, detail investigations were directed primarily to the configuration of duct #4.

### 1. Duct No. 4 - Sandwich/Sheet Metal, Figure 7

In this configuration the current ARL alternating type and slot nozzles are mounted on separate panels which are in turn attached to a combination sandwich and sheet metal air supply duct. Due to the contour of the upper wing surface, an irregular shaped duct structure results as well as a slightly different nozzle exit plane in order to accommodate the two identical nozzle panels. Although sufficient area is available in this configuration to obviate the need for the turning vanes on the inboard end of the duct, it, however, does not provide structural continuity in the duct section, and therefore was eliminated for further consideration.

### 2. Duct No. 4 - Sandwich - Continuous, Figure 8

In this configuration the air supply duct is made from a continuous sandwich layup. Current ARL alternating type and slot nozzles are used; however, the top edge of the aft primary nozzle must be modified to suit the duct surface. Nozzles and panels are mounted on the inside surface of the duct and nozzle replacement from a service standpoint becomes very difficult. Special hinges and hinge support structure are required for the attachment of inlet and diffuser doors. Sufficient area is provided in this configuration to eliminate the turning vanes located at the inboard end of the air supply duct.

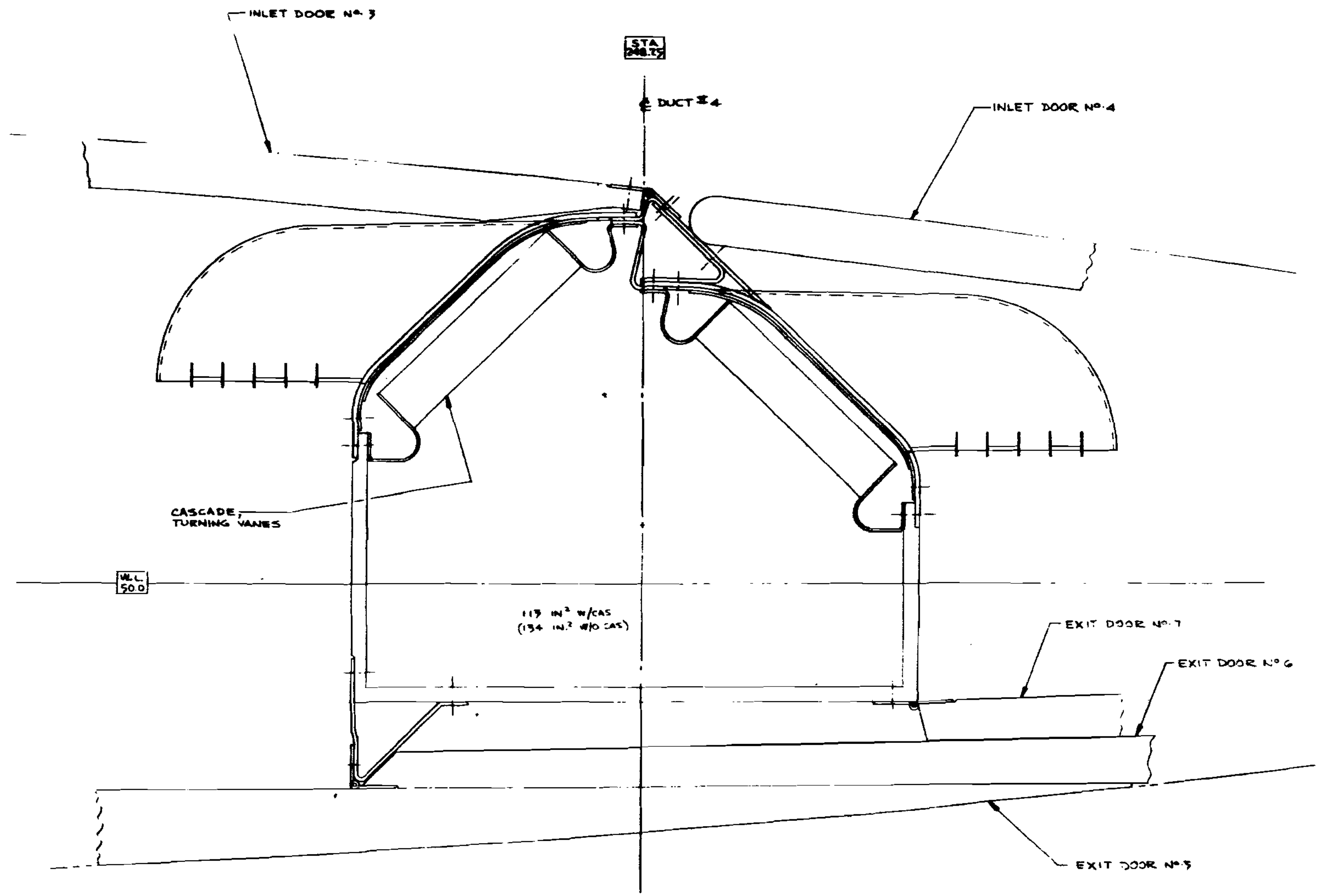



Figure 7. Duct No. 4-Sandwich/Sheet Metal. ARL Multichannel Ejector System

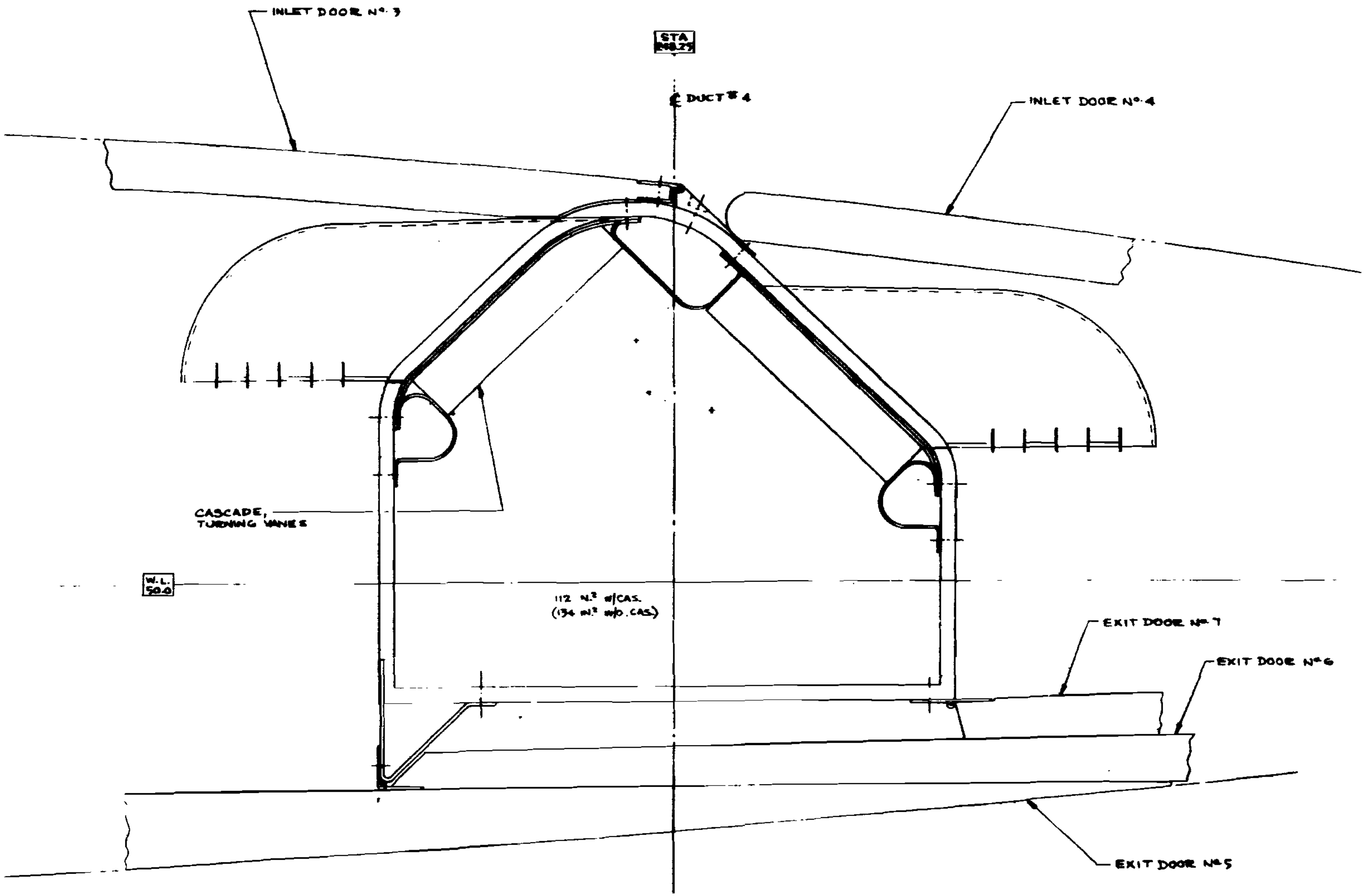



Figure 8. Sandwich-Continuous. ARL Multichannel Ejector System

3. Duct No. 4 - Sheet Metal, Figure 9

An all sheet metal fabricated air supply duct is shown in this configuration. A spanwise beam bisects the pressure structure to accommodate the wing loads. Current ARL nozzles are mounted on panels which in turn are attached to the duct assembly, however, both the nozzle and panel on the upper end of the aft nozzle assembly must be modified to satisfy the structural continuity of the duct. Additional structure is required to form the constant mixing area as well as providing hinge supports for the diffuser doors. A hinge has been integrated in the top beam cap to accommodate the inlet door attachment. Fore and aft channel sections have been added at 1/3 and 2/3 span locations to reduce the size of the section supporting the lower edge of the nozzle panels.

4. Duct No. 4 - Sandwich-Split, Figure 10

A split sandwich duct is shown in this configuration so that identical nozzles and nozzle panels may be utilized. Several undesirable features are inherent in this arrangement, and include the eccentric structural attachment of the duct assembly in the area of the inlet doors, the nozzle and nozzle panel attachment to the inside surface of the duct which makes nozzle replacement difficult, and the modifications to the upper wing contour to accommodate the inlet door hinge. For these reasons the configuration was eliminated from further consideration.

5. Duct No. 4 - Integral Nozzles, Figure 11

One piece nozzles interconnecting adjacent air supply ducts are shown in this arrangement. These nozzles could be cast in approximately 1-foot spanwise increments and attached to the sandwich duct structure. Additional structure would be required to provide supports for both the inlet and diffuser door assemblies. This configuration results in a highly indeterminate structure since the nozzles act as ribs tending to transfer applied wing loads in the chordwise direction. Consequently the nozzles will be highly loaded due to the resulting high chordwise bending moments. In addition differential bending of each duct assembly due to tip torsion will add to the chordwise bending moments. Providng strength for chordwise bending is difficult since each nozzle panel assembly is attached to a relatively thin duct wall which has low bending capability. Normally the duct wall size is based on providing strength in the hoop direction due to internal pressure loads and providing stiffness to preclude beam general instability. For this reason this configuration was eliminated from further consideration.

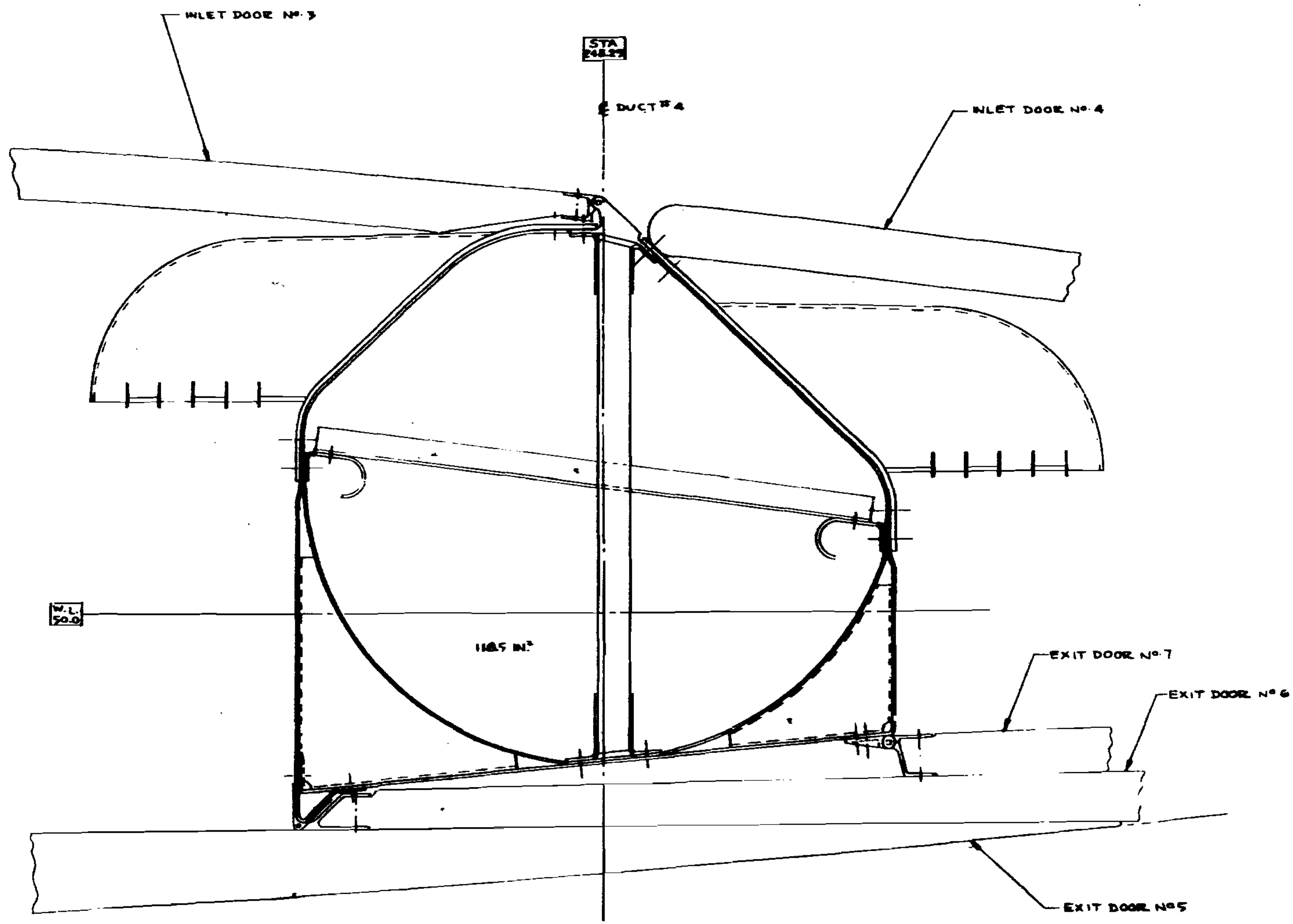



Figure 9. Duct No. 4-Sheet Metal. ARL Multichannel Ejector System

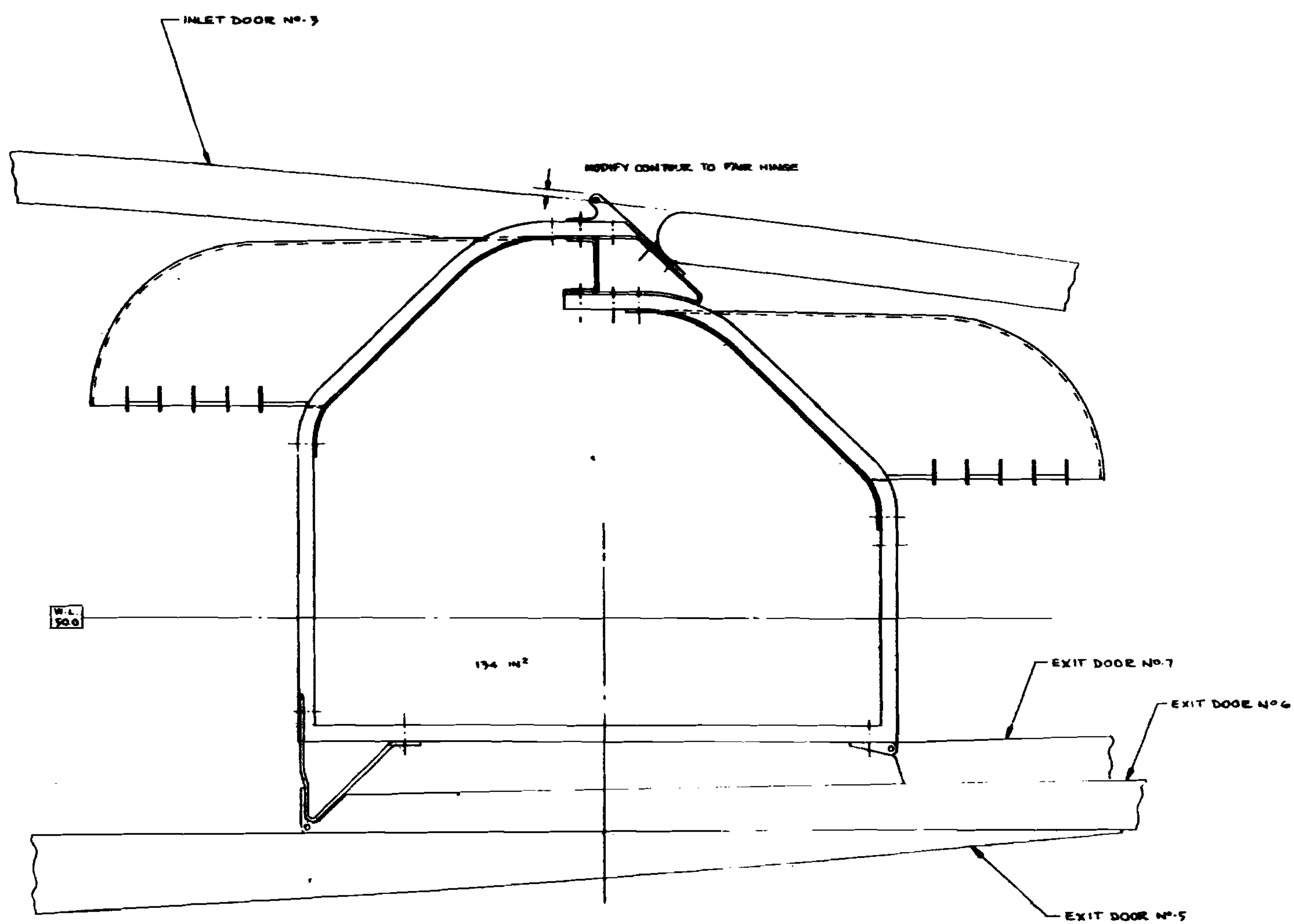



Figure 10. Duct No. 4-Sandwich Split. ARL Multichannel Ejector System

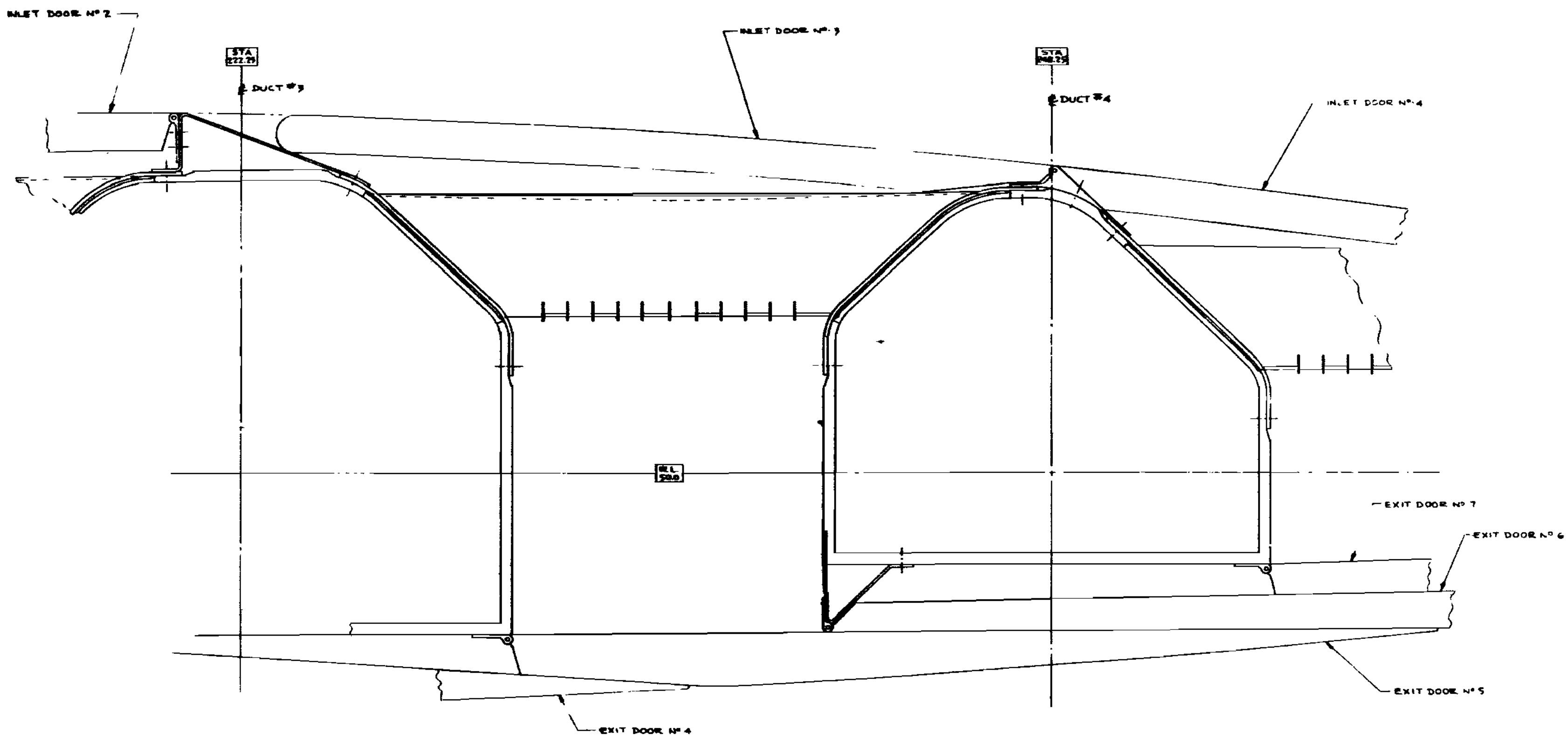



Figure 11. Duct No. 4-Integral Nozzles. ARL Multichannel Ejector System

6. Duct No. 4 - Sandwich/2 Panel, Figure 12

This arrangement of the air supply duct utilizes a sandwich construction of varied thickness to permit the external mounting of the nozzle panels. Structural continuity of the duct is maintained in this configuration as well as ease of fabrication and nozzle replacement. Sufficient internal area of the duct is available to preclude the use of the turning vanes located in the inboard end of the duct. The use of two different nozzles and nozzle panels are required due to the unsymetrical top surface of the air supply duct to accommodate adjacent inlet doors.

## C. TRADE-OFF AND SELECTION OF FINAL CONFIGURATION

A trade-off study was conducted on these six configurations of duct #4 which defined nozzle attachment, air supply duct design, and attachments for both the inlet and diffuser doors. Elements considered in this study included the dimensional requirements of Figure 1, aerodynamic and structural criteria, weight and performance penalties, number and complication of detail parts, ease of assembly and nozzle replacement, and overall multi-channel system maintainability. The summary of this study indicated that the arrangement which satisfied most requirements was as shown in Figure 13.

In this arrangement a continuous alumimum core sandwich construction is utilized for the air supply duct. A reduction in wall thickness is included in the upper portion of the duct to provide for the flush external mounting of the nozzle panels in the constant mixing area. Extruded aluminum hinges, which can be bonded or mechanically attached to the duct sides and bottom have been provided for support of the diffuser doors. The extruded aluminum hinge located on the top surface of the duct, used for the inlet door and a base for the upper nozzle panel attachment can be either bonded or mechanically attached to the duct structure. A structural plastic has been utilized for the slot nozzle, however, aluminum alloy has been selected for the primary nozzles because the mechanical properties are guaranteed per MIL Handbook 5A. Other candidate materials such as glass reinforced plastics generally have a large spread in mechanical properties which are dependent, in part, on the fabrication process. Guaranteed properties provide more reliability since the nozzles are the primary lifting devices for an aircraft using the ARL multi-channel ejector system.

## D. DUCT APPLICATIONS TO RTV

Although the duct configuration shown in Figure 13 incorporates the current ARL features of the multi-channel ejector system in a simple and lightweight structure, the feasibility of its use as a primary wing structure depends largely on the manner in which it can be attached structurally to the fuselage and boom sections. Figure 14

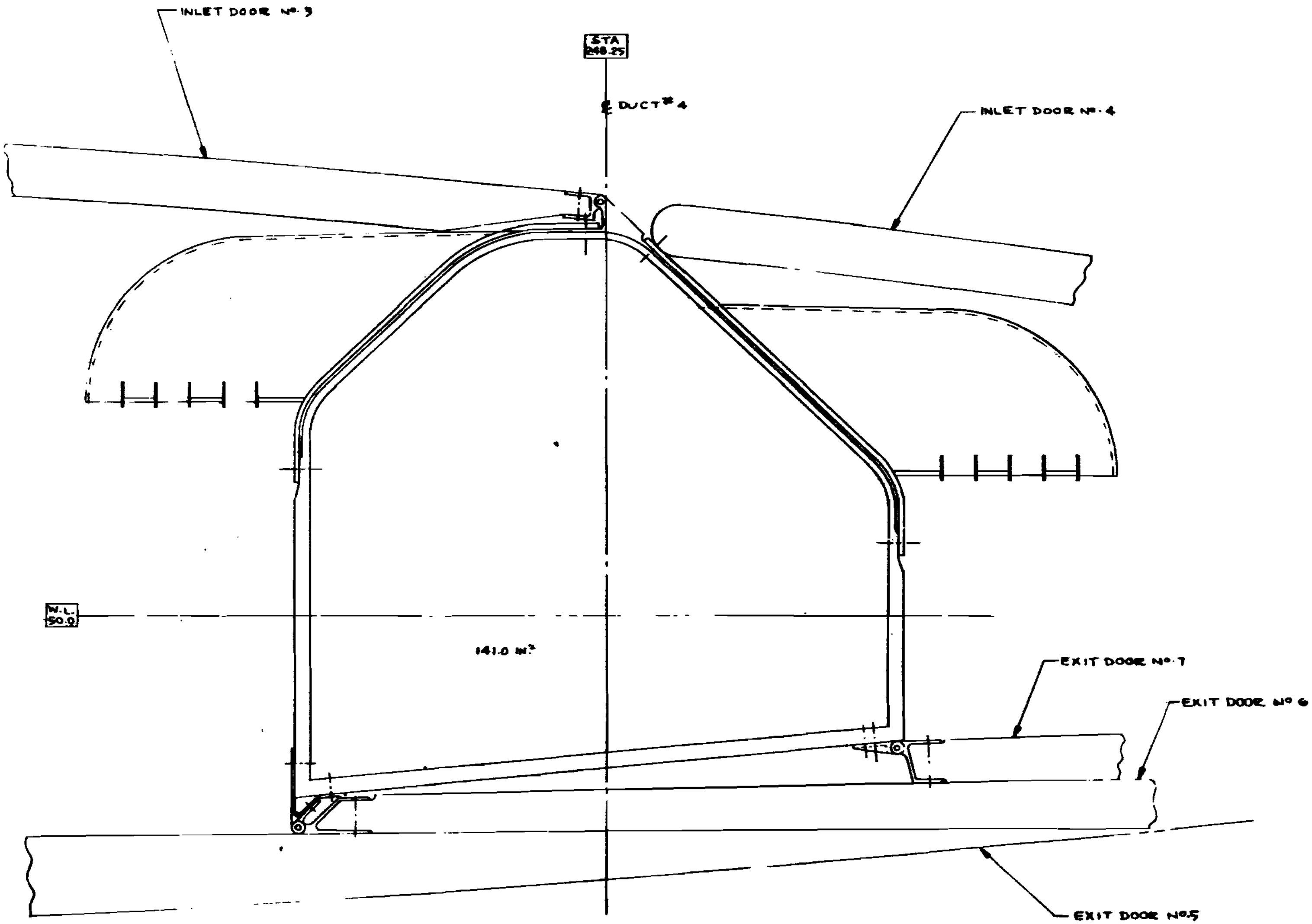



Figure 12. Duct No. 4-Sandwich/2 Panel. ARL Multichannel Ejector System

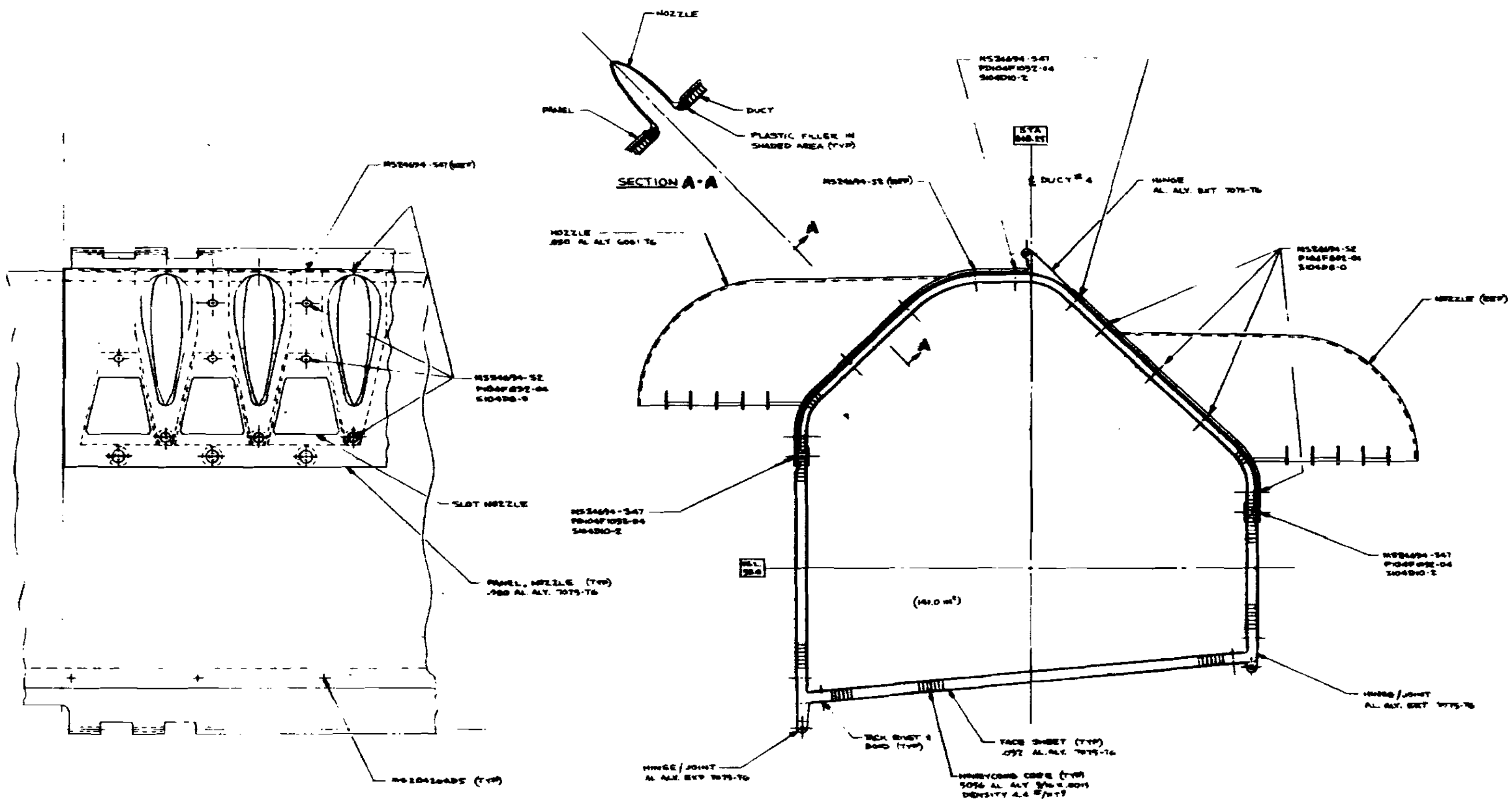



Figure 13. Duct No. 4-RTV Wing. ARL Multichannel Ejector System

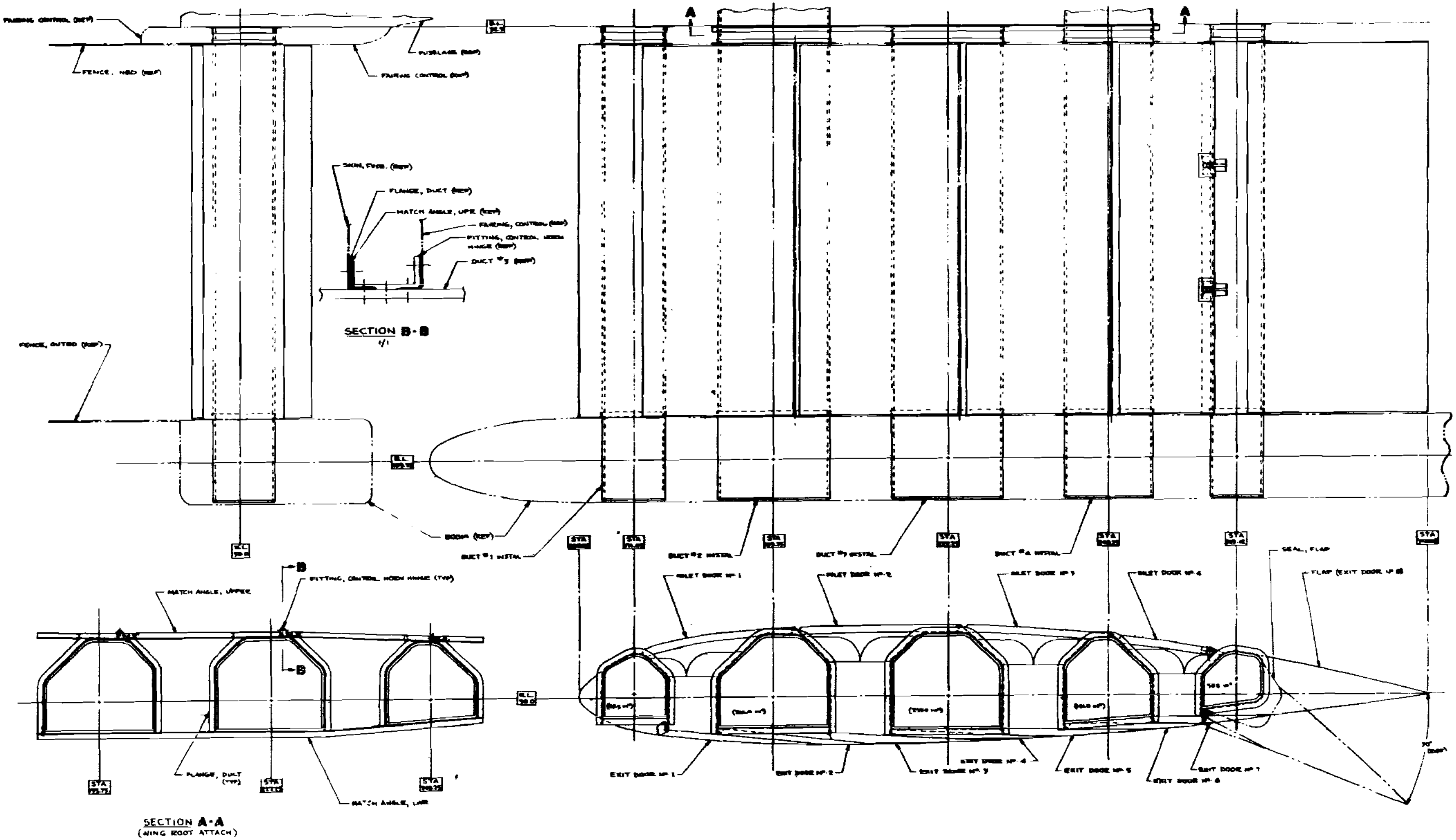



Figure 14. Wing Assembly, RTV ARL Multichannel Ejector System

defines a flight type wing assembly utilizing the revised duct geometry as applied to the Research Test Vehicle (RTV). It differs from the other cross sectional geometries in that a trailing edge flap has been incorporated. Diffuser doors have been shortened approximately 8 inches to insure adequate ground clearance and to permit the flap to operate independent of the diffuser doors as well as acting as diffuser door #8 when in the VTOL mode. Shortening the diffuser doors does, however, increase the diffuser angle if the ratio of 1:1 to 2.2:1 is maintained. In this configuration duct #5 is fixed and the flap hinge is supported on a superstructure at the lower forward edge of the duct. Inlet door #4 is hinged at the wing root and tip to fittings in the fuselage and boom. Midspan stand-off hinges are attached to duct #5 to provide a gap between the trailing edge of the door and the duct. The wing root attachment for all ducts is similar to that for duct #4 shown in Figure 15. In this attachment the duct is extended inside the fuselage for approximately 7 inches to eliminate the need for additional splice members. In addition, a match angle is provided to attach the duct to the fuselage frames and longerons.

## E. ARL FULL SCALE WING MODIFICATIONS

### 1. Modification No. 1

Figure 16 depicts a minimum modification to the ARL full scale wing model to simulate a flight type configuration except for the capability of closing the diffuser doors to maintain the lower wing contours. In this modification the nozzle exit planes in ejector bays #1 and 4 are lowered to accommodate the addition of the inlet doors and to maintain the upper wing contour. Ejector bays #2 and 3 remain intact except for the addition of several hinges to support the inlet doors. The inlet doors provided with the original installation of the full scale wing model may be used with only a small rework for suitable hinges and hinge supports.

Larger cutouts are required in air supply ducts #4 and 5 to accommodate the repositioned nozzle exit plane. This repositioning requires a new nozzle and nozzle panel for the aft location in duct #4 and the relocation of the existing nozzle and nozzle panel in duct #5. Existing cutouts may be used for air supply ducts #1 and 2, however, the lowering of the nozzle exit plane requires a new nozzle and nozzle panel for the forward side of duct #6 and the relocation of the existing nozzle and nozzle panel in duct #1.

New end plates for the reworked spars in ejector bays 1 and 4 would be required as well as a seal in the plenum and boom to satisfy the altered cutouts in air supply ducts 4 and 5.

One method for the elimination of the existing plenum exhaust vents is shown in this modification. Excess airflow, now being

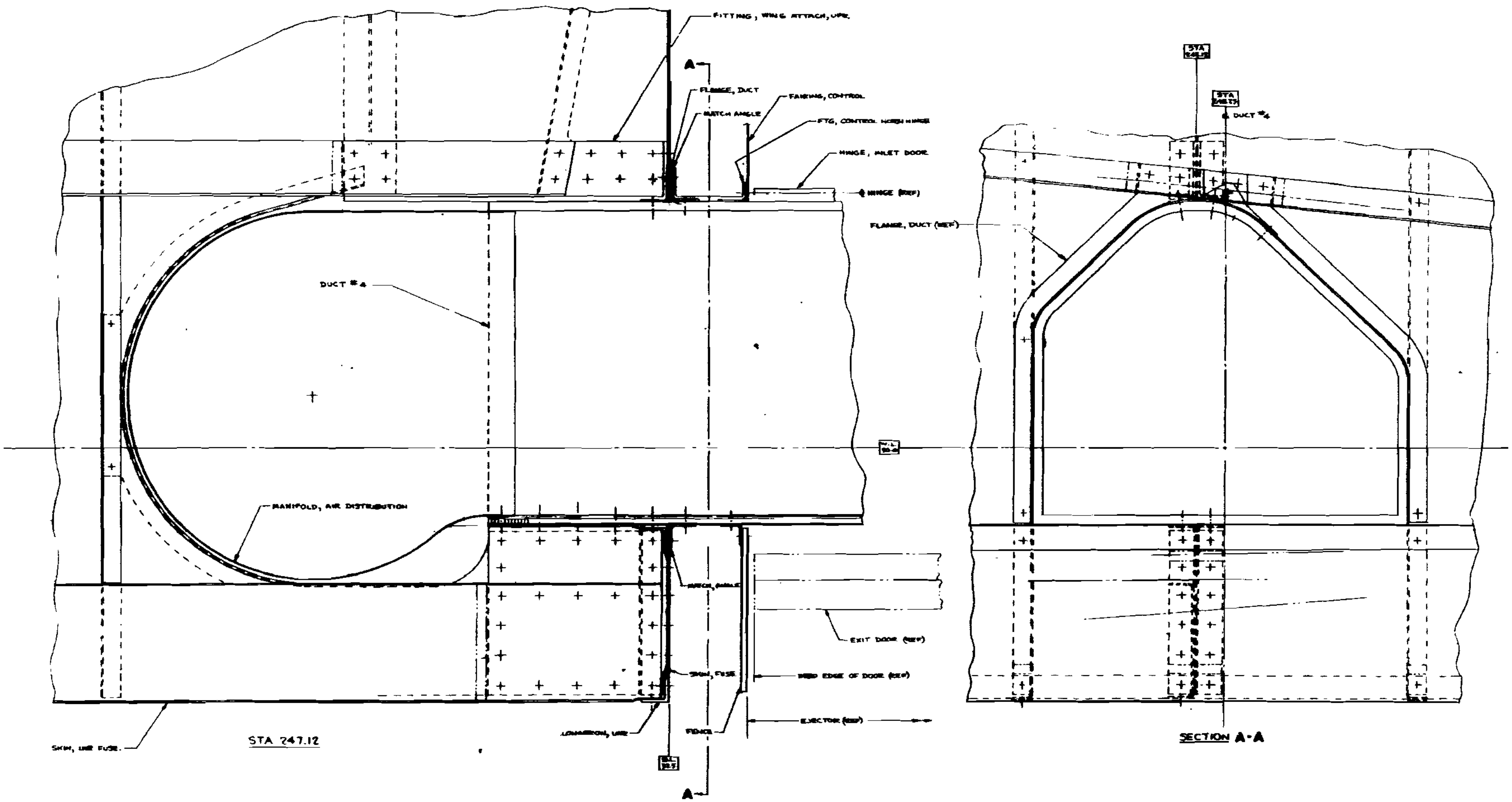



Figure 15. Interface, Wing and Fuse. (RTV) Sta. 247.12/Duct No. 4. ARL Multichannel Ejector System

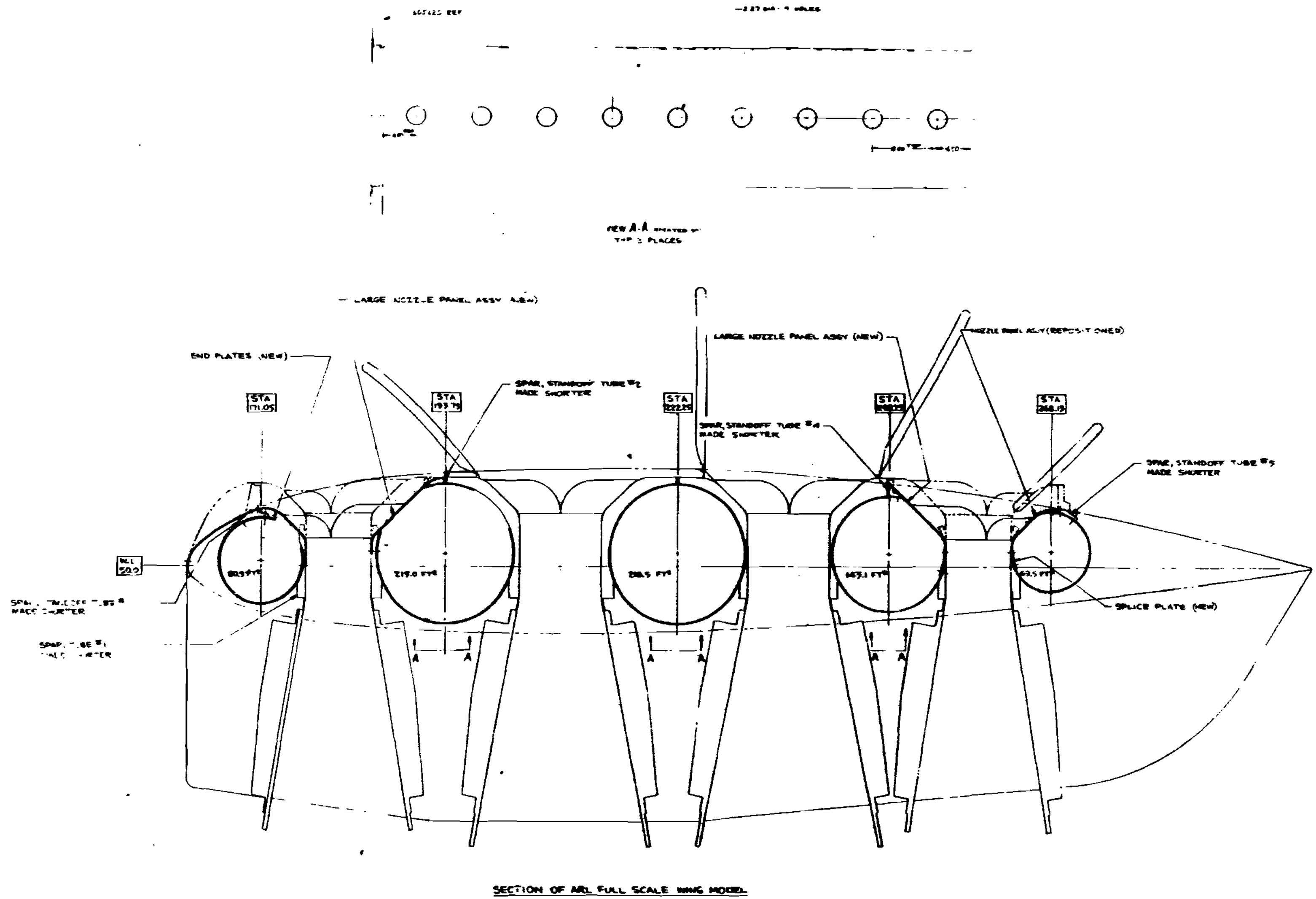



**Figure 16. Modification, ARL Full-Scale Wing Model - Simulated RTV/ARL Multichannel Ejector System. Modification No. 1**

passed through the existing exhaust vents would be passed through the wing air supply ducts and vented through 9 square edged circular holes, each 2.27 inches in diameter and located in ducts 2, 3 and 4, as shown in View A-A of Figure 16.

2. Modification No. 2

A more extensive modification of the existing full scale wing model is shown on Figures 17 and 18. The internal as well as the external airflow geometry is duplicated to provide a flight type configuration.

For this modification, it will be necessary to remove the full scale model from the test stand and disassemble into its major subassemblies. The existing circular air supply ducts would be removed and replaced with the revised shaped ducts fabricated from either .31 inch thick 6061-T6 or .25 thick 7075-T6 aluminum alloy. The circular cutouts in the one side of the plenum and boom assemblies would either be modified to accept the revised duct shapes as shown on Figures 17 and 18 or replaced with new structure.

New diffuser doors would be required if it is desirable to close them within the existing lower wing contour. However, the present inlet doors may be reworked as necessary to suit the new duct structure.

New nozzles and nozzle panels would be required for ejector bay 3 and the forward side of ejector bay 4. All other nozzles and nozzle panels may be reused with minor modifications.

The plenum exhaust vents could be eliminated by providing vent holes in the air supply ducts #2, 3 and 4 as described above under Modification No. 1.

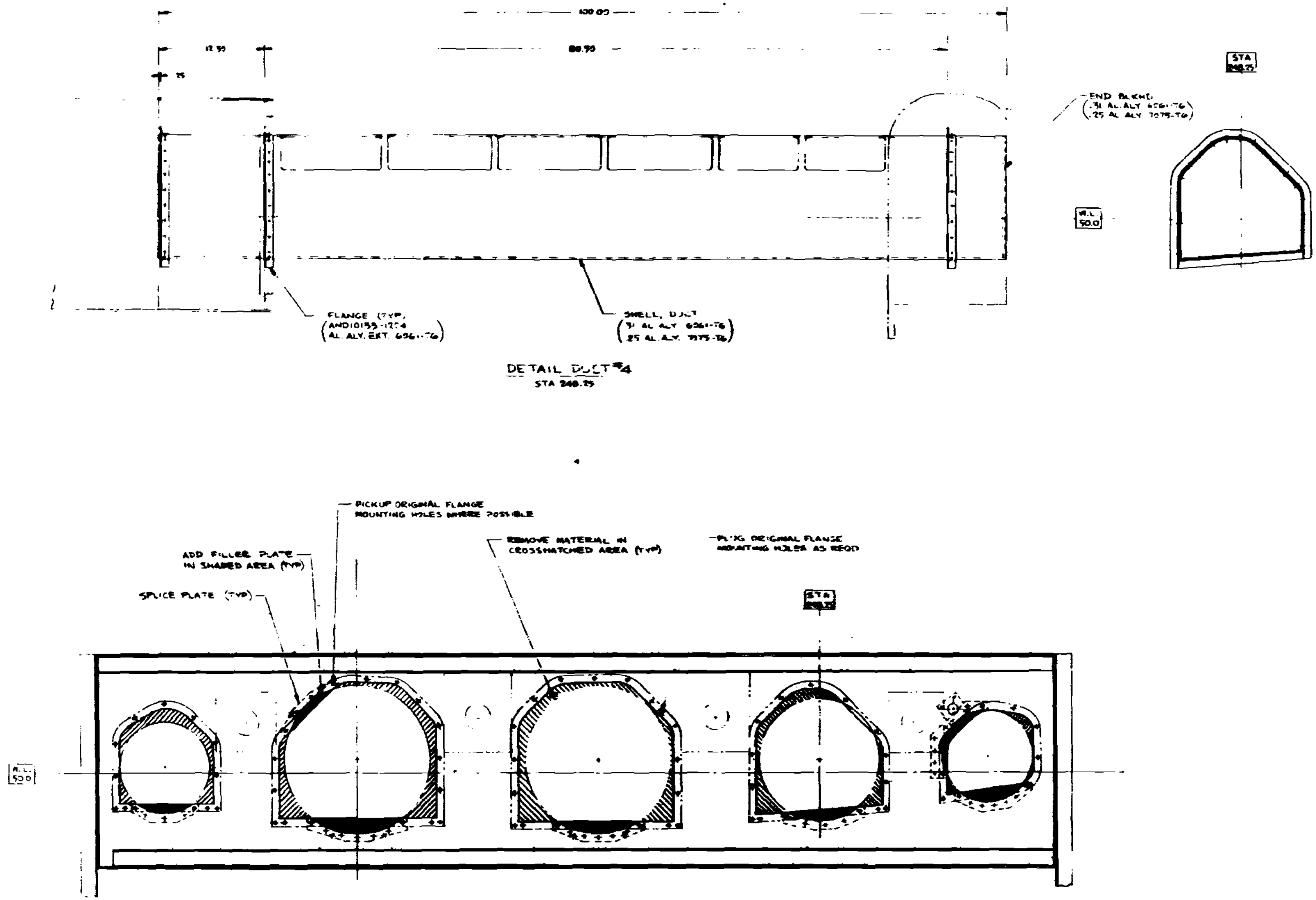



Figure 17. Plenum Box Modification. ARL Multichannel Ejector System. ARL Full Scale Wing Model Modification No. 2

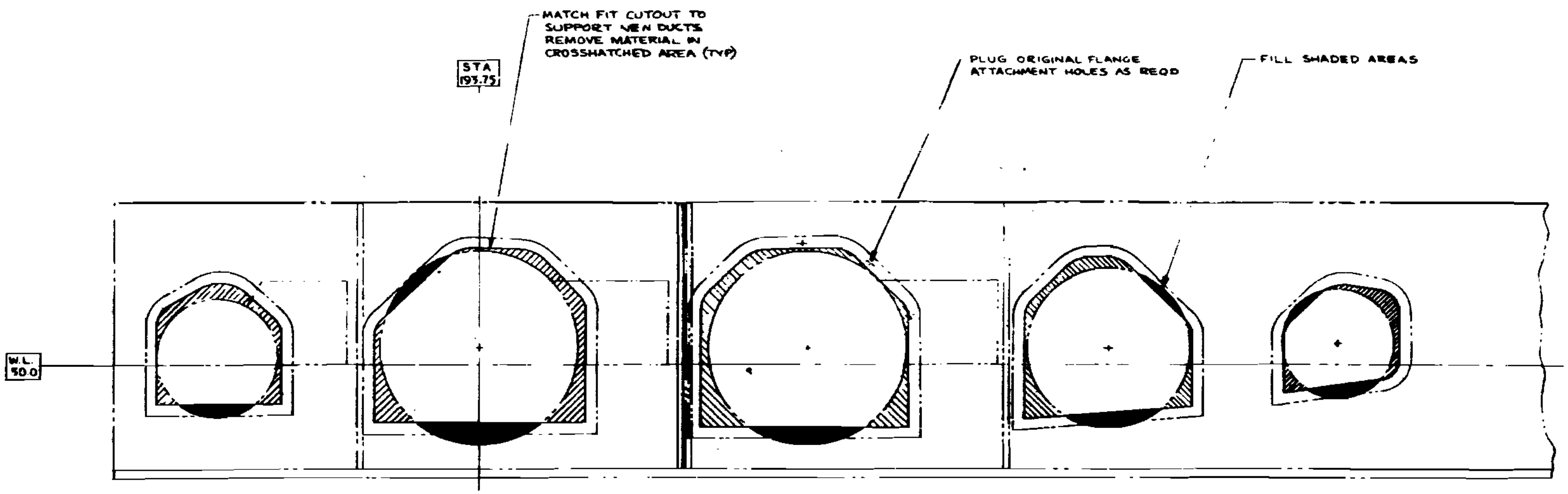



Figure 18. Boom Modification. ARL Multichannel Ejector System. ARL Full Scale Wing Model Modification No. 2

# III STRUCTURES

## A. GENERAL

The results of a structural analysis of a built-up section and sandwich section duct design concept are summarized in this section. Each incorporates the ejector geometry and latest design for the nozzle panel assemblies shown in Reference 6 and being used on the full scale multi-channel ejector wing model in Building 71B, G Bay, at WPAFB, Dayton, Ohio. This wing model is representative of an ejector wing proposed for use on a Research Test Vehicle (RTV) as proposed in Reference 1.

The analyses presented are based on a structural design criteria and critical loads at the root of duct #4 established for the (RTV). A weight comparison between the built-up and sandwich ducts is calculated on a unit pound per foot basis. Total wing weights are compared in Section D.

## B. STRUCTURAL EVALUATION

Each design concept has been evaluated on the basis that the structure be flightworthy and designed with readily available proven aircraft grade materials. High strength 2024 and 7075 aluminum alloys are used predominately throughout the various designs with titanium and steel usage restricted to areas where strength is required for concentrated loads within a limited space allowance.

The evaluations of the cross sectional geometry shown in Figures 2 through 6 designs revealed severe lack of structural continuity in carrying duct pressurization loads. This is evident along the upper contour in Figures 2, 3 and 5 where the forward and aft nozzle panel assemblies are mismatched vertically at the duct centerline. The sandwich duct designs shown in Figures 4 and 6 provide reasonably good continuity; however, the upper and lower door hinge points are placed some distance away from the ducts which will incur slight weight penalties due to large hinges that will be required. As discussed in Section II, these designs are deficient on the basis of various aerodynamic and propulsion considerations.

To eliminate the lack of structural continuity from the vertical mismatch at the upper contour, the Figure 7 design was prepared using a sandwich lower section and a complicated system of formed sheet metal parts for the upper section. The load paths in the upper section of this design require bending of thin formed sheet sections, thus unnecessary weight penalties will result. A continuous sandwich duct as shown in the Figure 8 design is the best approach with modifications to achieve the lightest door hinge weight and satisfactory nozzle panel installation. In sheet metal or a built-up design concept, the Figure 9 design is best structurally since it provides the necessary continuity for resisting the pressurization loads as well as the beam loads.

The split sandwich concept shown in the Figure 10 design will have a weight penalty because of the method of carrying hoop bending loads due to duct pressure at the top. Each sandwich duct section is shown to be spliced with formed sheet metal parts.

The integral nozzle concept shown in the Figure 11 design is adequately described to include structural considerations in Section II.

Modification to the Figure 8 continuous sandwich duct design is shown in the Figure 12 sandwich design. The final configuration will ultimately evolve when detailed design and analysis efforts and final nozzle panel geometry and installation procedures are completed, such as shown in the Figure 13 design.

The design concepts presented basically fall into two types involving formed sheet metal parts on a built-up section or the use of sandwich panels. Each type carries duct pressurization and beam loads in a slightly different manner; therefore, the weight differences are greatest between these two types. The designs shown in Figures 8 and 9 evolved sufficiently early in the design phase to permit a detailed stress analysis and the calculation of the unit spanwise pounds per foot weight variation. The results of the structural sizing of these two duct designs is summarized in this section.

The feasibility of the sandwich duct design use as a primary wing structure is shown in Figures 14 and 15. The attachment of the ducts at the wing root to the fuselage and at the wing tip to the tail boom is seen to be more efficient than previously arranged for circular ducts. This is because the straight sides of the ducts line up with the stiffening frames of the fuselage and tail boom for the shear tie and the flatter geometry of the sandwich permits simple fittings for the bending moment attachment. The torsional attachment is combined with the shear and is made with a match angle that follows the outer contour of the duct.

## C. DUCT SIZING

### 1. Structural Design Criteria and Loads

The RTV configuration employing the multi-channel ejector wing concept described in Reference 7 is designed primarily to the requirements of the Specification series MIL-A-8860 through MIL-A-8871. The requirements of MIL-S-8698 for helicopters is used as appropriate. The basic flight design gross weight is established at 10,450 pounds.

The aircraft is capable of hovering flight, transition from hovering to conventional forward flight and back, and of landing or taking off in either vertical or conventional flight modes. During transition the ejector exit doors are deflected to obtain thrust; consequently, for this study it was assumed that a 3.0 g symmetrical maneuvering vertical design load factor was acting along with the duct pressurization loads.

The pressurization loads are as follows:

Limit Pressure = 6.5 psi

Yield Pressure = 1.33 x 6.50 = 8.63 psi (Ref. 7)

Ultimate Pressure - 2.00 x 6.50 = 13.00 psi

The beam loads are based on the sizes stipulated for Duct #4 in Reference 7. Duct #4, at the root, was described as a 17.0 inch diameter O.D. circular sandwich panel duct. Overall wall thickness of the duct is .375 inches and the face sheets are 0.020 inches thick made of 7075-T6 aluminum alloy. The ultimate load capabilities of this duct section are as follows:

-Spanwise bending moment = $M_A$ = 432,000 in.-lbs. producing compression on the upper surface.

-Vertical shear - $V_a$ = 10,000 lbs. acting up

-Torsion = $T_A$ = 350,000 in.-lbs. applied in a clockwise direction looking inboard.

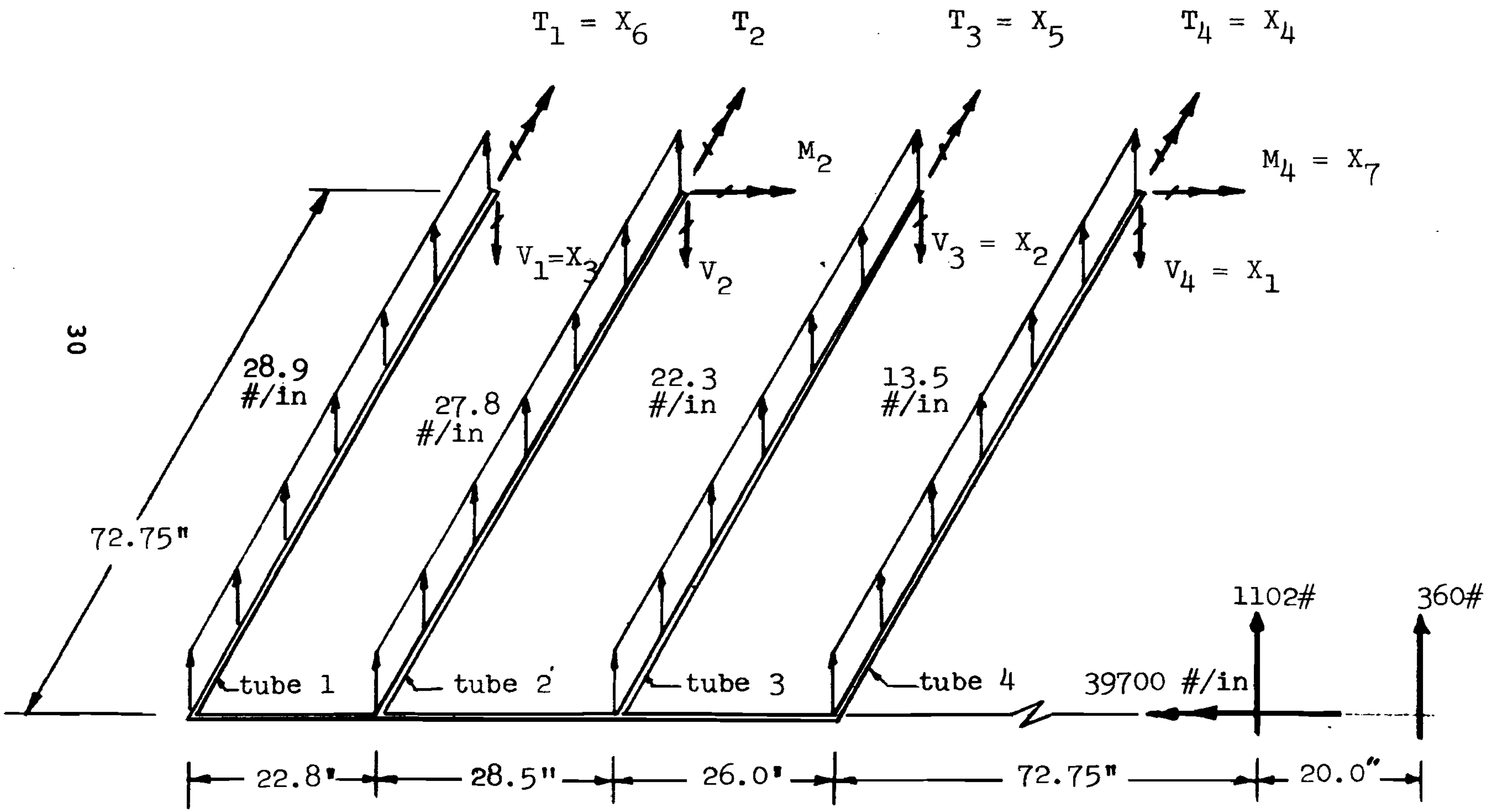
For this design study, it is assumed that the beam loads summarized above are applied during an $\eta_g$ = 3.0 g abrupt pitch maneuver and that they combine with the pressurization loads.

To justify the beam load magnitudes for this flight condition, the internal loads distribution were obtained from a strain energy solution for the root reactions due to the tail and wing loads applied. The location and magnitude of the loads applied and the positive root reaction load directions are shown on Figure 19. Ten root reaction loads exist, 3 which can be calculated from static load balance and 7 which can be obtained from deflection equations.

A computer program was written for use on Bell's remote access terminals (RAX) to solve for the 7 redundants using the principle of virtual work. The principle states that the sum of the bending and torsional energy is zero due to the "dummy" unit load applied in the direction of each redundant. The reactions are summarized in Table I. Ultimate loads are equal to a limit to ultimate factor of 1.50 times the limit loads shown. These loads are seen to be less than the beam load capabilities existing for duct #4, thus justifying

FIGURE 19 APPLIED EXTERNAL LIMIT LOADS AND ROOT REACTIONS NOMENCLATURE

RTV WING



the adequacy of the conservative initial beam loads assumption.

TABLE I - LIMIT ROOT REACTION LOADS - RTV WING

| DUCT | M (in.-lb.) | V (lb.) | T (in.-lb.) |
|---|---|---|---|
| 1 | 0 | $X_3$ = 522 | $X_6$ = 3910 |
| 2 | -163800 | 3298 | 9070 |
| 3 | 0 | $X_2$ = 117 | $X_5$ = 12370 |
| 4 | $X_7$ = 213800 | $X_1$ = 3870 | $X_4$ = 18040 |

2. Analysis of Built-Up Section Duct

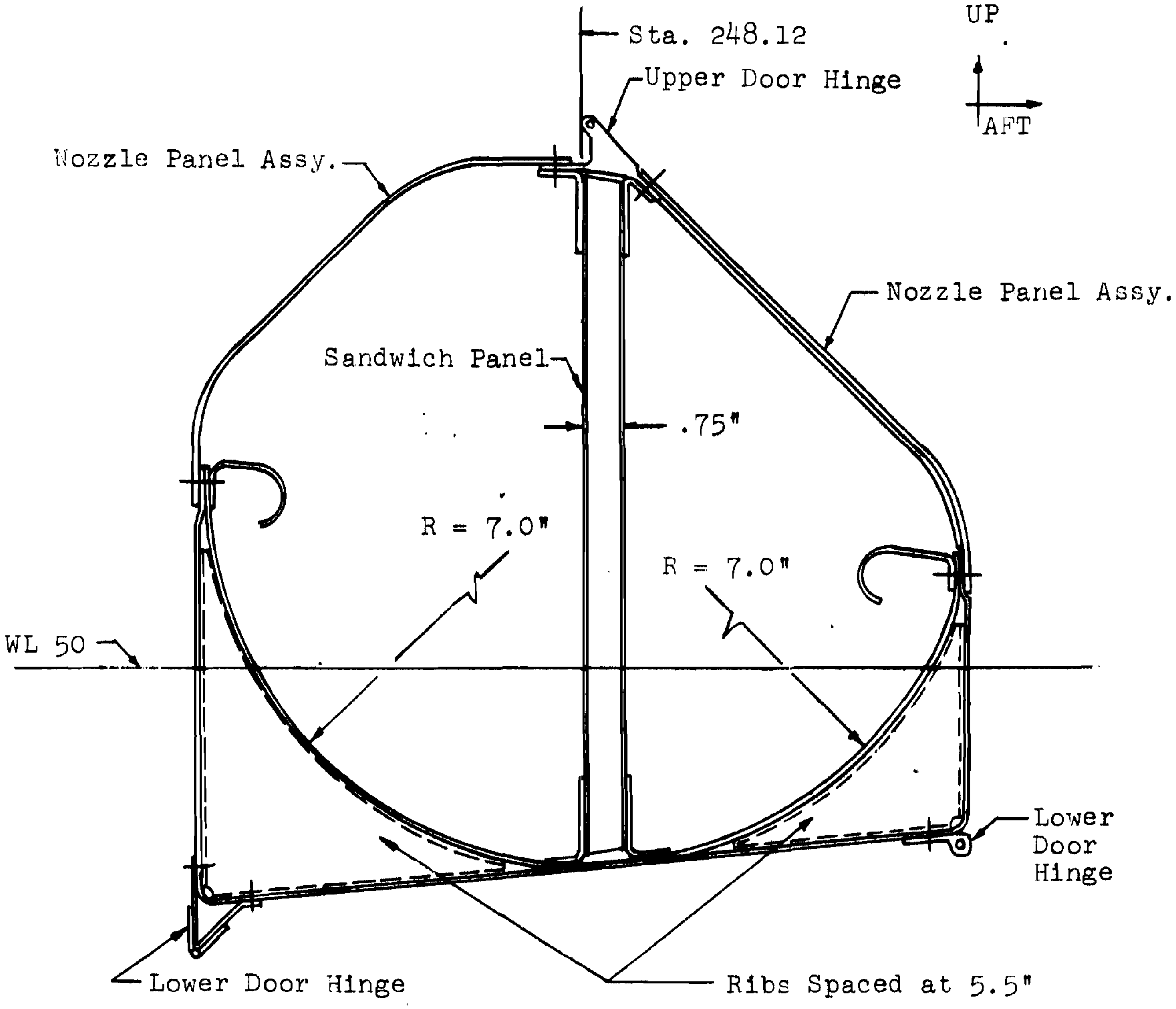
The general arrangement is shown at 1/3 scale on Figure 20. The structural elements are a center sandwich web beam with angle capstrips, forward and aft nozzle panel assemblies, spanwise reinforcing channels at the lower edge of each nozzle panel, circular duct and a large stiffened sheet that establishes the ejector area size. The lower door hinges are attached at each of the forward and aft corners of this stiffened sheet while the upper door hinge is part of the capstrip of the center sandwich web beam. The spanwise reinforcing channels are tied together across the center sandwich web beam to reduce deflection and weight. Material used is 7075-T6 aluminum alloy.

The pressures acting in the duct are distributed internally as shown in Figure 21. Pressures on the ducts are carried as hoop membrane loads and on the panel assemblies as plate bending loads. The center beam and side channels are loaded by the end reactions of the ducts and panel assemblies. The side channels are beams in the spanwise direction with supports extending across the duct through holes in the center beam. Two supports break the side channels into 3 beam segments of equal span. Providing 3 equal span beam segments decreases appreciably the side channel size which might increase airflow interference.

The distribution of internal loads due to shear, bending moment and torsion loadings is dependent on the loading magnitudes. For low values, the entire cross section is effective in reacting the loadings applied up to loads where initial buckling in compression occurs on the flat elements with a high b/t. At higher loadings where compressive buckling is present, the section strength

FIGURE 20. GENERAL ARRANGEMENT - BUILT-UP SECTION DUCT

Scale 1/3



is maintained with stable effective areas of the sandwich panel face sheets and upper door hinge. The internal loads distributed does not vary very much for bending that produces compression on the upper surface because of the thick nozzle panel assembly plate thickness. However, for bending that produces compression on the lower surface, the internal loads distribution does depend on loading magnitude for the reasons stated above. A summary of the compressive and shear buckling allowables for each structural element is shown in Table II.

TABLE II - SUMMARY OF COMPRESSIVE & SHEAR ALLOWABLES FOR EACH STRUCTURAL ELEMENT

7075-T6 Aluminum Alloy Material (Bare)

$F_{tu}$ = 76,000 psi

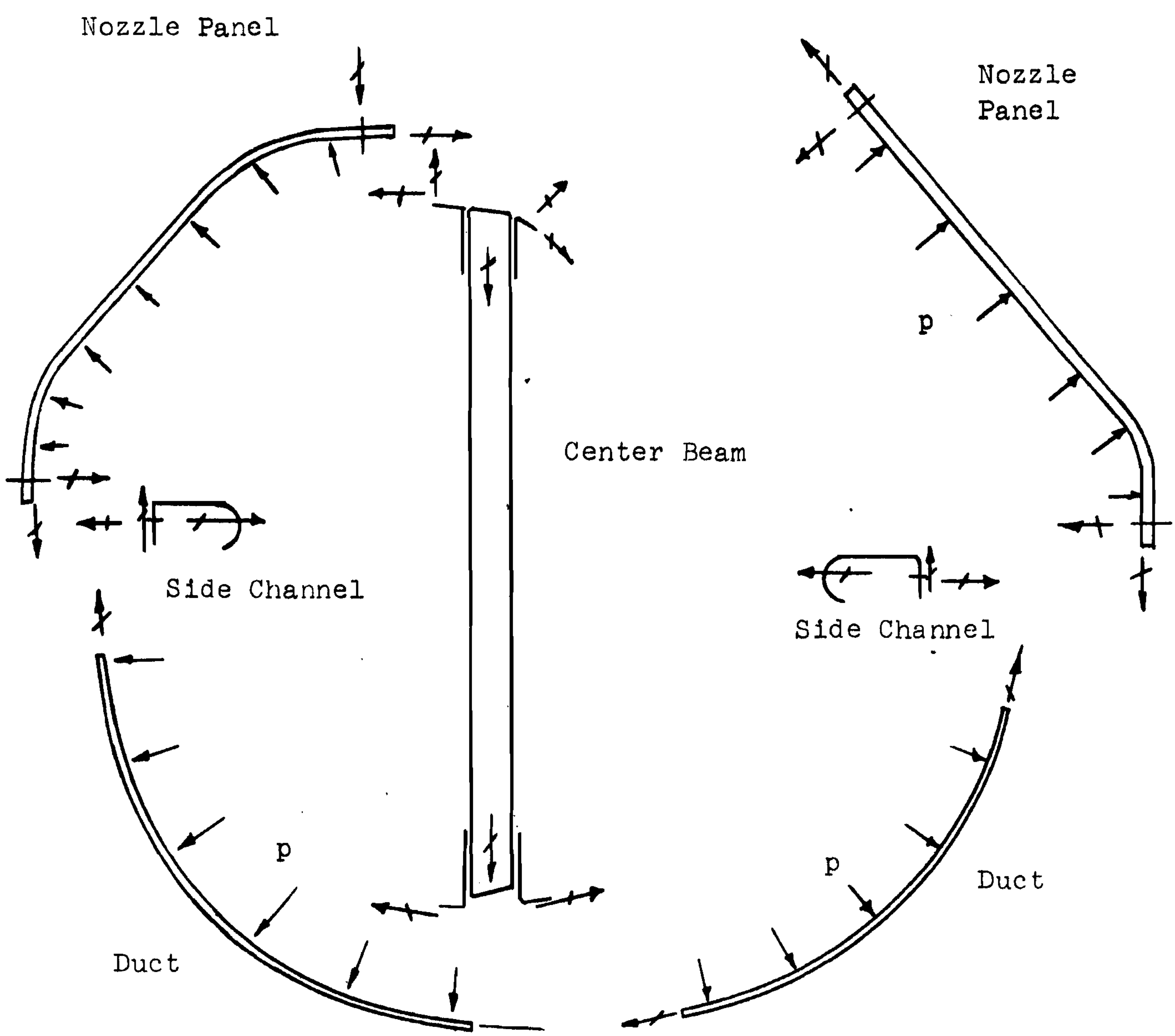
$F_{ty}$ = Fcg - 69,000 psi (Ref. 11)

$F_{su}$ = 46,000 psi

$F_{b_{ru}}$ = 144,000 psi

| Structural Elements | t (in) | b,r (in) | a,l (in) | Ref 12 $\tau_{CR}$ (psi) | Ref. 12 $\sigma_{CR}$ (psi) | Ref 12 $\bar{\sigma}_F$ (psi) |
|---|---|---|---|---|---|---|
| Lower Fwd. Flat | .050 | 5.50 | 5.50 | 7300 | 3000 | 11600 |
| | .063 | 5.50 | \| | 11500 | 4780 | 18600 |
| | .050 | 2.75 | \| | 29200 | 12000 | 46000 |
| | .063 | 2.75 | 5.50 | 46000 | 19200 | 69000 |
| Lower Aft Flat | .050 | 5.00 | 5.50 | 8000 | 3600 | 12800 |
| | .063 | 5.00 | \| | 13000 | 5720 | 20300 |
| | .050 | 2.50 | \| | 32000 | 14400 | 51200 |
| | .063 | 2.50 | 5.50 | 46000 | 22900 | 65000 |
| Circular Ducts | .050 | 7.0 | 5.50 | 19600 | 20300 | |
| Panel Assy's. | .205 | - | - | 46000 | 65000 | 65000 |

FIGURE 21. DISTRIBUTION OF INTERNAL LOADS DUE TO PRESSURE BUILT-UP SECTION DUCT



A bending and shear analysis was made using the method described on Pages 490-900 of Reference 8. The vertical shear load was assumed applied at the shear center. The bending stresses are summarized in Figure 22. A 2-cell box beam idealization was made to determine shear flows as shown in Figure 23. The calculated total shear flows due to vertical shear plus torsion are shown in Figure 24. The margines of safety in shear are calculated as follows:

| | | Allowable Shear Stresses $\sim\tau_{CR}$ | | |
|---|---|---|---|---|
| Shear Stresses $-\tau$ | | Without Stiffeners | With Stiffeners | M.S. |
| *841.5/.050 = | 16,800 psi | 7300 | 29200 | + .74 |
| *745.5/.050 = | 14,900 psi | 7300 | 29200 | + .96 |
| 796.5/.050 = | 15,900 psi | 19600 | 19600 | + .23 |
| *662.7/.050 = | 13,200 psi | 7300 | 29200 | +1.21 |

*Require Stiffeners.

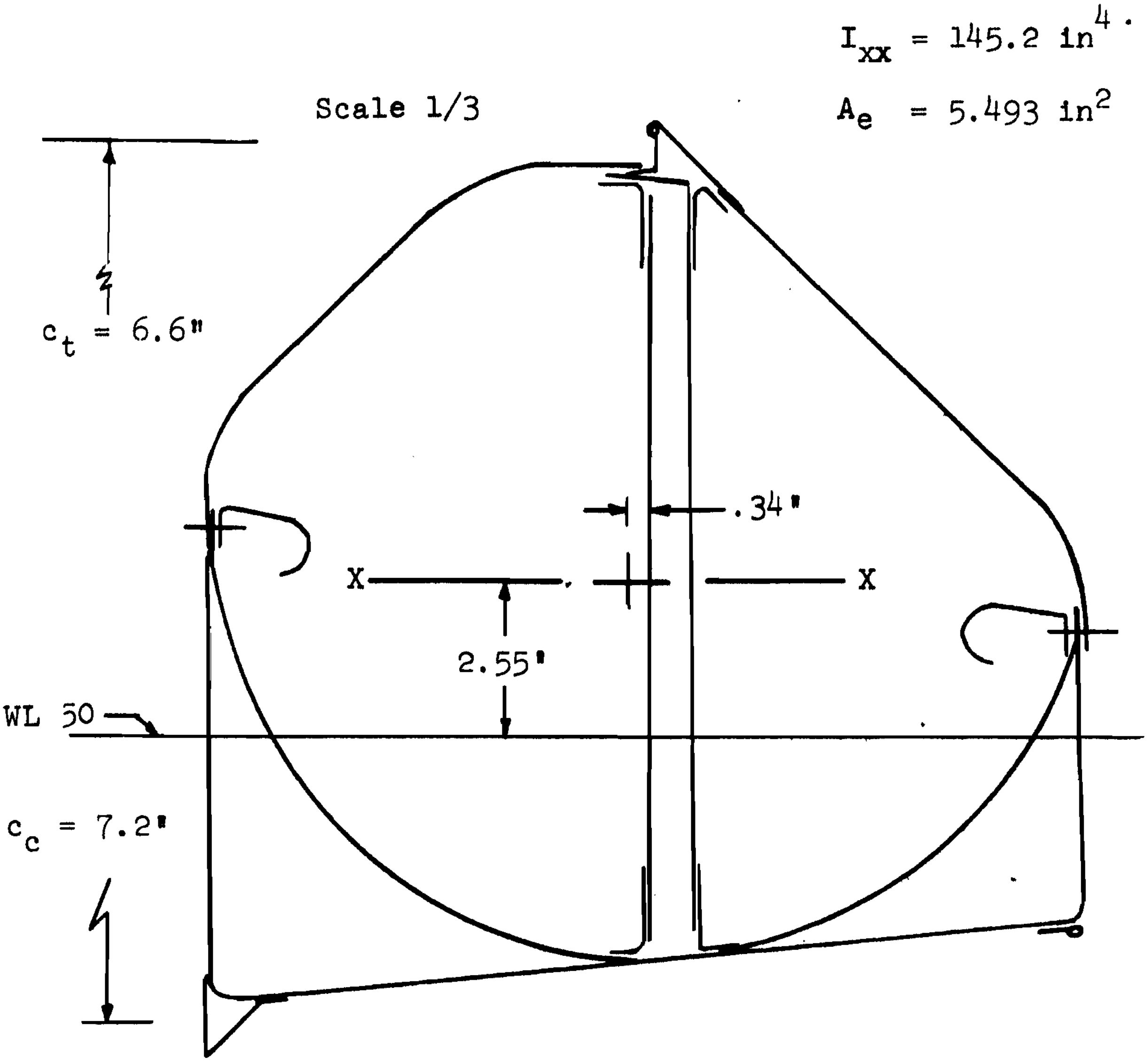
3. Analysis of Sandwich Section Duct

The general arrangement is shown at 1/3 scale on Figure 25. The structural elements are the sandwich duct that outlines the ejector, hinges for the upper and lower doors, and nozzles that fit in cutouts in the duct. The sandwich panel consists of .313 inch deep core (3/16 - 5056-.0015) and .032 in skins (7076-T6) giving a total depth of 3/8 inches.

For analysis purposes, the structure is idealized as a system of 55 finite elements as shown in Figure 26. Also shown is the duct section properties for resisting beam loads.

The buckling allowables for the panel are given in Table III. The allowables are determined by the methods outlined in Section C12.5 of Reference 9. The circumferential shear, axial load, and moment distributions for an internal ultimate pressure of 13 psi are given in Figure 27. Element 31, located under the upper door hinge, is the point of maximum stress. The margin of safety for combined biaxial and shear stresses at element 31 is calculated as follows:

FIGURE 22 <u>BENDING CHECK OF THE BUILT-UP DUCT SECTION</u>

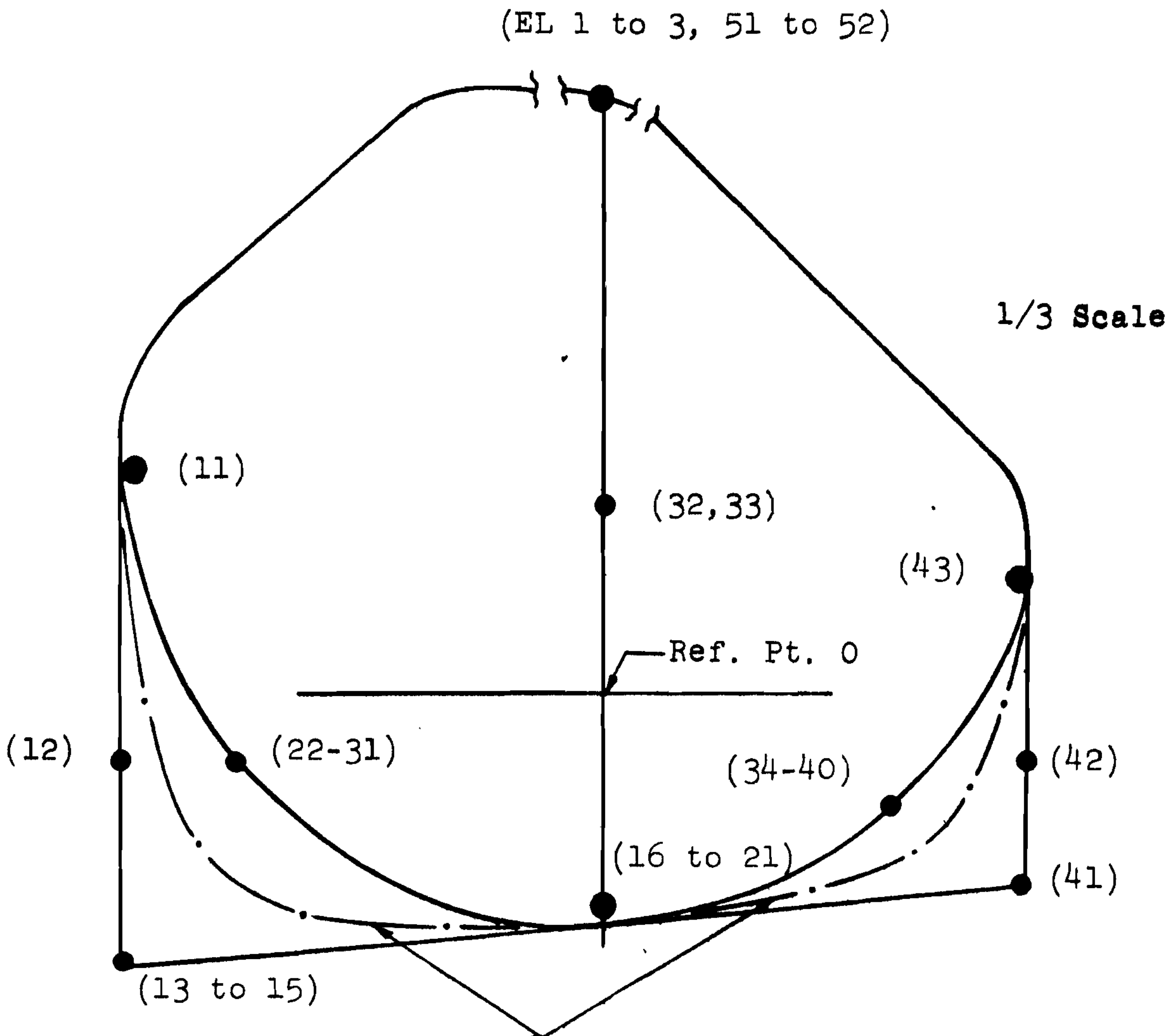



$M = 432000$ in-lb Ultimate

$f_{bt} = \dfrac{7.2}{145.2}(432000) = +21300$ psi at lower fwd hinge

$f_{bc} = \dfrac{6.6}{145.2}(432000) = -19500$ psi at upper hinge

FIGURE 23 SECTION IDEALIZED FOR SHEAR FLOW ANALYSIS BUILT-UP SECTION DUCT

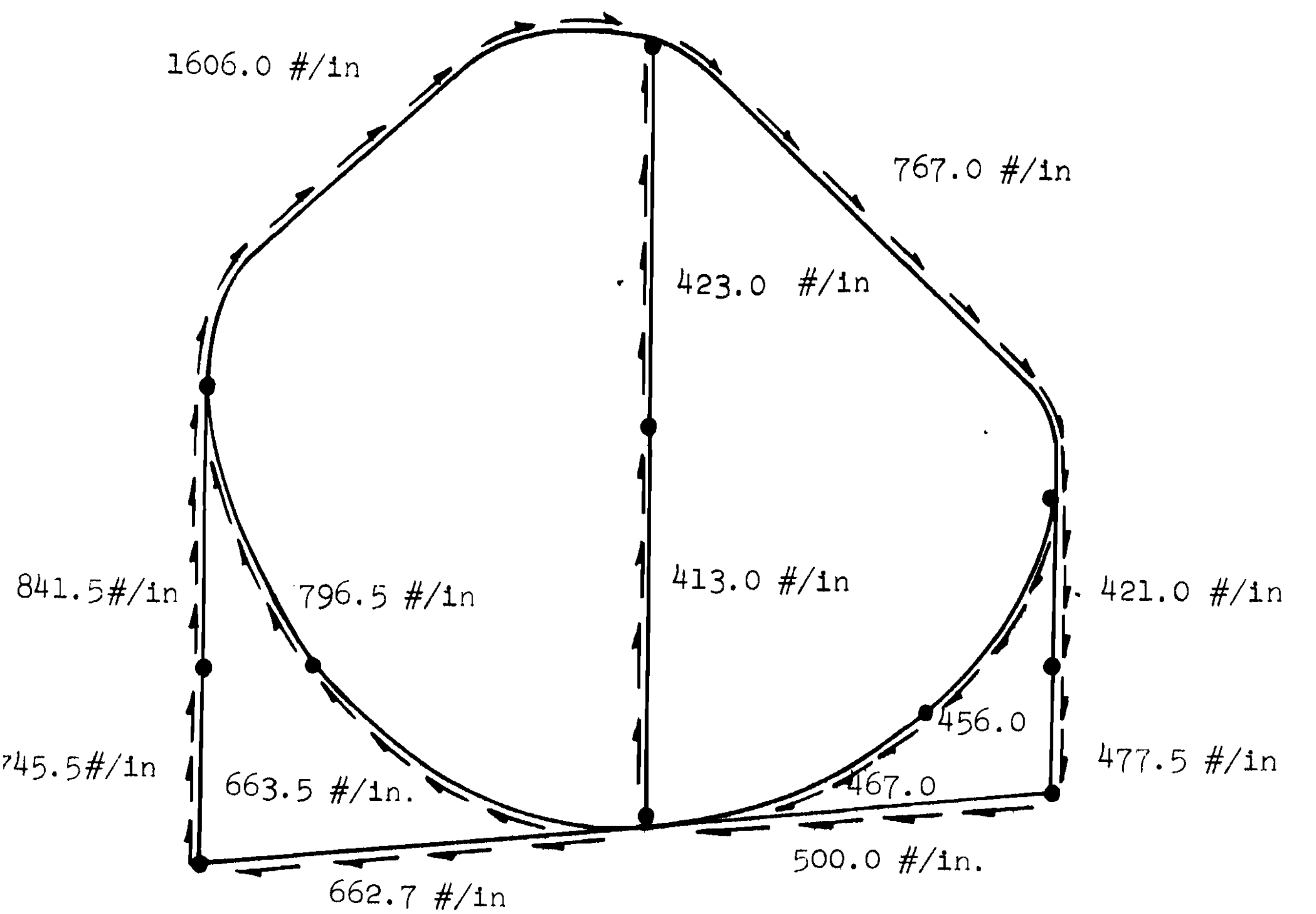



The duct and straight sections are assumed to produce a common line to define the cell.

FIGURE 24

INTERNAL SHEAR FLOW DISTRIBUTION BUILT-UP SECTION DUCT

Total Shear Flows V = 10000 lb. + T = 350,000 in-lb. Ultimate



The ultimate axial stress in the longitudinal direction = $\sigma_L$

$$\sigma_L = \frac{M_{yy}}{I_{yy}} X = -46{,}600 \text{ psi (Ult.)}$$

From Figure 27, the ultimate loads in the circumferential direction are P = 95.6 lb./in. and M = 45.5 in.-lb./in.

$$\sigma_c = P/A \pm M/Z = \begin{array}{l} 5630 \text{ psi (Ult.)} \\ -2650 \text{ psi (Ult.)} \end{array}$$

TABLE III SUMMARY OF COMPRESSIVE & SHEAR ALLOWABLES FOR SANDWICH PANEL

| 7075-T6 FACES (Reference 11) | 3/16 - 5056 - .0015 CORE (Reference 10) |
|---|---|
| $F_{TU}$ = 76000 PSI | $F_C$ = 490 PSI (min.) |
| $F_{TY}$ = 65000 PSI | $F_{SU}$ = 340 PSI ("L" direction) |
| $F_{CY}$ = 67000 PSI | $F_{SU}$ = 198 PSI ("W" direction) |
| $F_{SU}$ = 46000 PSI | E = 310,000 PSI |
| E = $10.3 \times 10^6$ PSI | G = 68,000 PSI ("L" direction) |
| G = $3.9 \times 10^6$ PSI | G = 27,500 PSI ("W" direction) |

| | Material Allowables | |
|---|---|---|
| Criteria | $F_{CW}$ or $F_{CI}$ (PSI) | $F_{SW}$ or $F_{SI}$ (PSI) |
| Core Wrinkling | 67000 | 38700 |
| Intracell Buckling | 67000 | 46000 |

FIGURE 25

GENERAL ARRANGEMENT - SANDWICH PANEL DUCT

Scale: 1/3

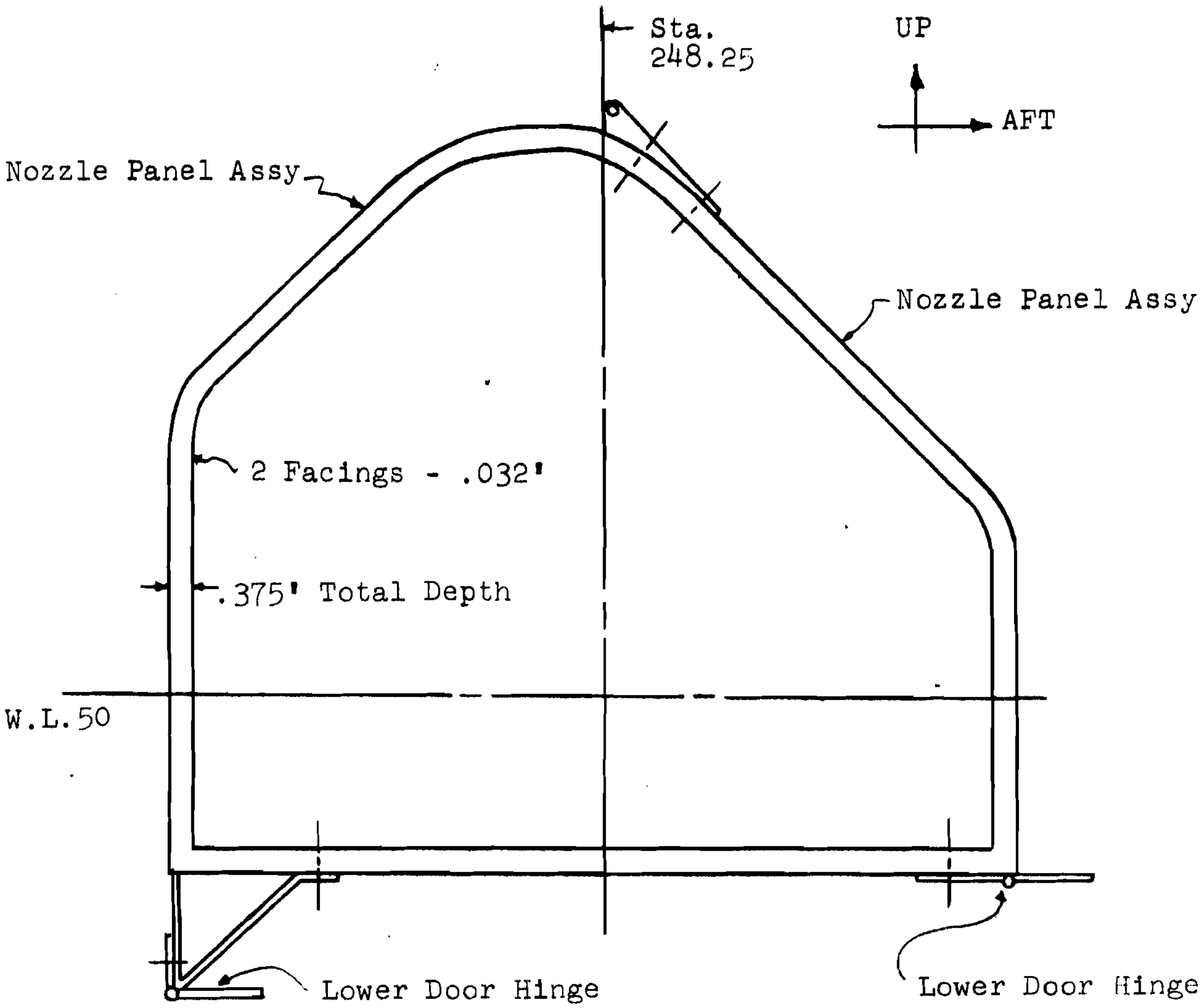


FIGURE 26

STRUCTURAL IDEALIZATION - SANDWICH PANEL DUCT

Configuration: Sandwich panel with .032 Facings & total depth of 3/8 inch

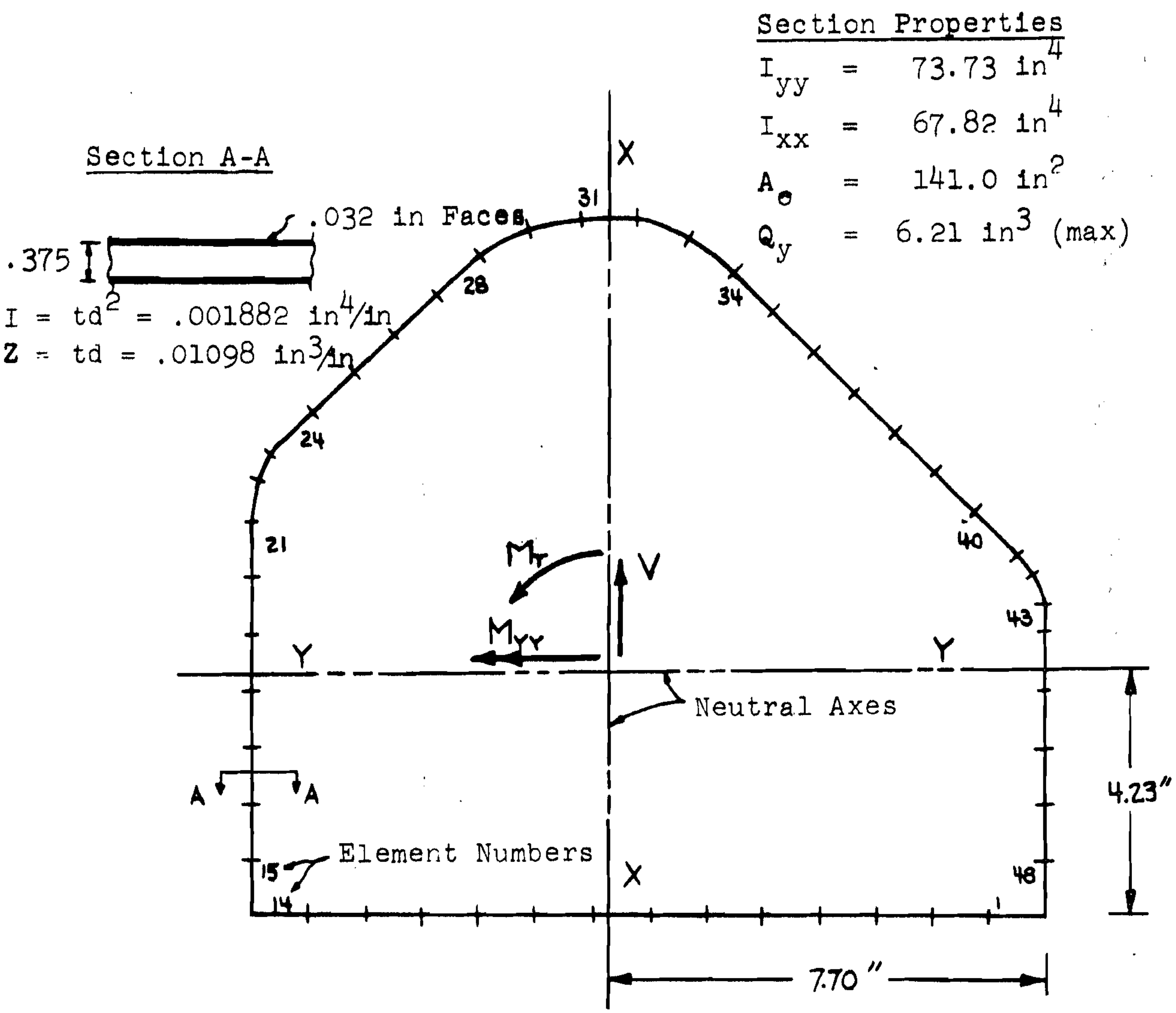
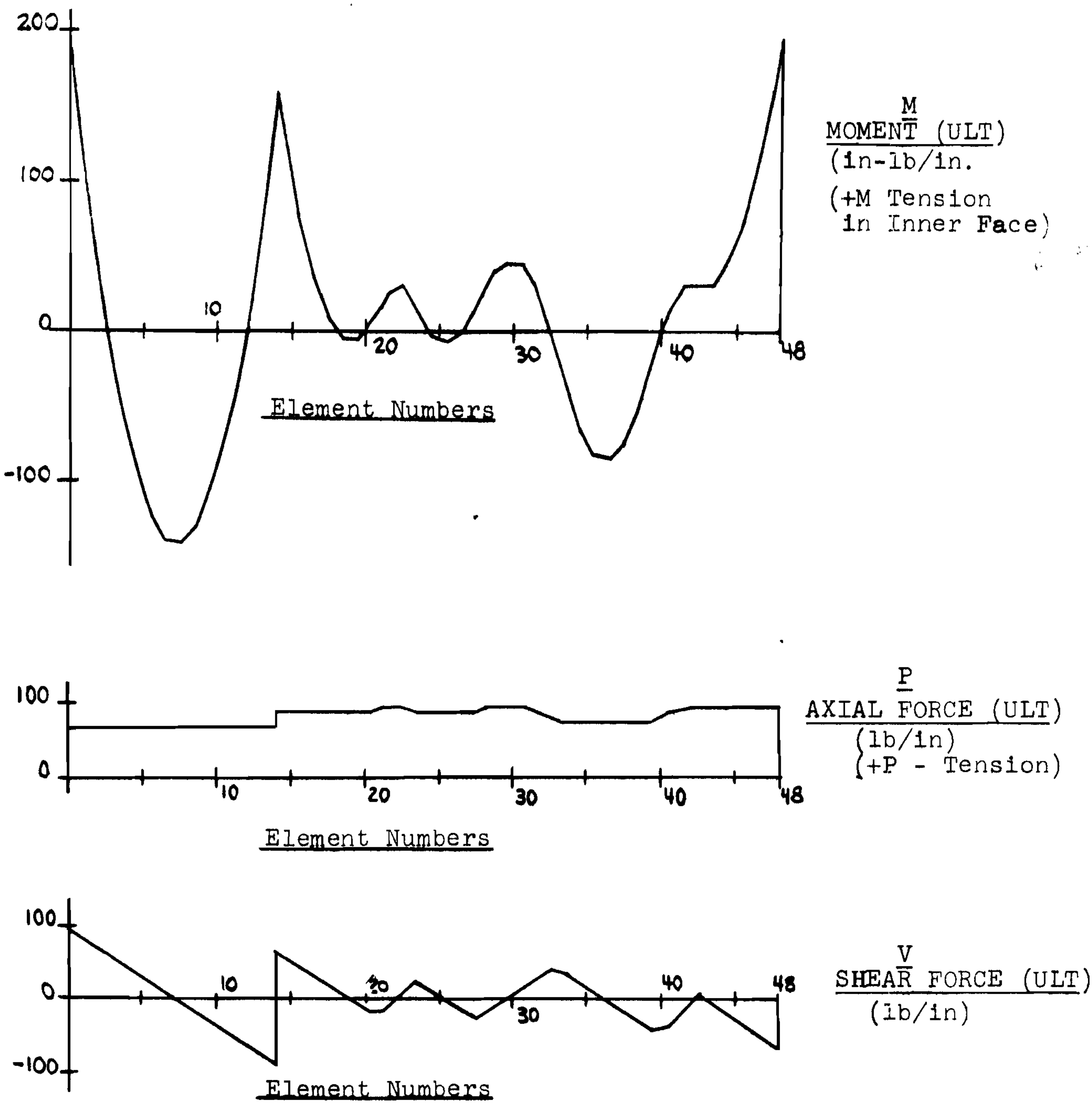


FIGURE 27

CIRCUMFERENTIAL AXIAL FORCE, SHEAR FORCE, & MOMENT DIAGRAMS FOR ULTIMATE INTERNAL PRESSURE OF 13 PSI - SANDWICH PANEL DUCT




Note: See Figure 26 for location of nodes on the sandwich duct.

NOTE: The contribution of the shear force, 10,000 pound (ult.), to the shear flow is zero at element 31. So the shear flow = $q = M_T/2A_0$ = 1240 lb./in. (ult.)

The ultimate shear stress $= \tau$

$$\tau = q/2t = 19{,}400 \text{ psi (ult.)}$$

BIAXIAL & SHEAR CHECK - Wrinkling Criteria

$$\gamma = \sigma_c/\sigma_L = -.120 \qquad F_{CW_x} = F_{cy}/\gamma_i = 62{,}900 \text{ psi}$$

$$\gamma_i = (1-\gamma+\gamma^2)^{1/2} = 1.065 \qquad F_{SW} = F_{cy}/\sqrt{3} = 38{,}700 \text{ psi}$$

$$R_a = \sigma_L/F_{CW_x} = .742$$

$$R_S = \tau/F_{SW} = .501$$

$$\text{M.S.} = \frac{2}{R_a + (R_a^2 + 4R_S^2)^{1/2}} - 1 = +0.01$$

PRINCIPAL STRESSES (Ult.)

$$\sigma_{1,2} = \left[\frac{\sigma_L + \sigma_c}{2} \pm \left(\frac{\sigma_L - \sigma_c}{2}\right)^2 + \tau^2\right]^{1/2}$$

$\sigma_1$ = 12,000 psi

$\sigma_2$ = 54,000 psi

$\tau(\text{max})$ = 32,500 psi

BIAXIAL CHECK

$\gamma = .222 \quad \gamma_i = 1.128 \quad F_{CW_X} = 59{,}400$ psi

$$\text{M.S.} = \frac{F_{CWX}}{\sigma_2} - 1 = +0.10$$

SHEAR CHECK

$\tau_{(\text{max})}$ = 32,500 psi $\qquad F_{SW} = F_{cy}/\sqrt{3}$ = 38,700 psi

$$\text{M.S.} = \frac{F_{SW}}{\tau(\text{max})} - 1 = \underline{\underline{+0.10}}$$

STRENGTH CHECK - TRANVERSE SHEAR

From Figure 27, the maximum tranverse shear force is 87.2 lb/in. (ult.) and located at junction of elements 1 and 48. The honeycomb core (3/4-5056-.0015) has an ultimate shear allowable = 340 psi. See Reference 10.

Core depth - .375-2(.032) = .311 in.

$$\tau = V/_{d} = 240 \text{ psi.}$$

$$\text{M.S.} - \frac{F_{SU}}{\tau} - 1 = \underline{\underline{+0.21}}$$

D. WEIGHT ANALYSES AND SUMMARY

A weight comparison on a unit pounds per foot of span basis between the built-up and sandwich section type ducts is shown in Table IV. Included is the contribution of each structural element to the total unit weight.

TABLE IV - WEIGHT COMPARISON OF BUILT-UP SECTION DUCT AND SANDWICH PANEL DUCT

| CONFIGURATION : BUILT-UP SECTION DUCT | |
|---|---|
| ITEMS | WEIGHT (Lb./Ft. of Span) |
| Skins, Door Hinges Joint Connections | 9.74 |
| Added "Z" Stiffeners | .48 |
| Sandwich Core | .39 |
| Ribs | .30 |
| Total | 10.91 |

| CONFIGURATION : SANDWICH PANEL DUCT | |
|---|---|
| ITEMS | WEIGHT (Lb./Ft. of Span |
| Panel Skins & Core | 4.31 |
| Door Hinges | 1.92 |
| Nozzle Retaining Flange Plate | 1.61 |
| Total | 7.84 |

Results of the duct sections described in Section II and in Section III of this report are applied in a weight analysis on the RTV vehicle weight and balance for the configuration shown in Reference 1. The RTV gross weight is 6622 pounds and includes 1190 pounds of fuel. The c.g. location at takeoff is at 25.9% MAC. These data are based on the wing structural design employed in the Reference 1 configuration with a wing weight breakdown as follows:

TABLE V - WING WEIGHT BREAKDOWN - REFERENCE 1 CONFIGURATION

| | |
|---|---|
| Duct #1 | 62.0 Lbs. |
| " #2 | 104.0 " |
| " #3 | 99.0 " |
| " #4 | 90.0 " |
| " #5 | 36.0 " |
| Flaps | 36.0 " |
| L.E. Door | 27.2 " |
| Exit Door #1 | 32.0 " |
| " " #2 | 44.6 " |
| " " #3 | 42.2 " |
| " " #4 | 33.4 " |
| Inlet Door #1 | 32.0 " |
| " " #2 | 33.2 " |
| " " #3 | 33.0 " |
| " " #4 | 33.7 " |
| Straps, Wing/Fuse Attach. | 6.0 " |
| Match Angles | 6.0 " |
| Wing Root | 77.0 " |
| Wing Root Fence | 43.6 " |
| Misc. Allowance | 43.1 " |
| Total Wing Weight | 914.0 Lbs. |

These data are based on drawing analyses and stress analysis supporting the design concepts. The ducts were round and the exit doors were of the journal bearing type.

In Table IV, weight comparisons of two different duct design concepts are shown. Sections of these concepts are shown in Figures 20 and 25. The data is representative of some of the components required in the total duct assembly, neglecting, for example, items such as tip bulkhead and angles and eliminating the lower door bearings now that double exit doors are used. The comparable items in the Reference 1 wing have a weight per foot of 5.308 for duct #4, as follows:

TABLE VI - DUCT #4 WEIGHT/FOOT - REFERENCE 1 CONFIGURATION

| | | |
|---|---|---|
| Sandwich Assembly | | 3.15 |
| Nozzle and Retainer | | .662 |
| Hat Assembly - Upper | | .579 |
| Bearings | | .856 |
| Filler | | .061 |
| | Weight/Foot | 5.308 |

Comparisons with the data in Table IV show that the new concepts are heavier, the built-up section duct components weighing 10.91 pounds/foot and the sandwich panel duct weighing 7.84 pounds/foot. The change to double exit doors is also expected to add weight due to reduction of the enclosed cross-sectional area of each door which is detrimental from a stiffness point of view, and also the door control mechanisms become more complex. Weight changes associated with double exit doors are not incorporated in these analyses except for inclusion of the hinges in the new design.

The weight of the components in duct #4 are compared in Table VII.

TABLE VII - DUCT #4 WEIGHT COMPARISON

| ITEM | REFERENCE 1 WEIGHT | BUILT-UP SECTION WEIGHT | SANDWICH PANEL DUCT WEIGHT |
|---|---|---|---|
| Sandwich | 21.30 | 55.10 | 29.2 |
| Tip Bulkhead | 0.88 | 0.88 | 0.88 |
| Tip Bulkhead Angle | 0.50 | 0.55 | 0.55 |
| Bearings | 5.80 | - | - |
| Nozzles | 2.00 | 2.00 | 2.00 |
| Nozzle Doublers | 2.49 | - | 10.90 |
| Flanges | 1.66 | 1.66 | 1.66 |
| Doorstop | 2.53 | 2.53 | 2.53 |
| Hat Assembly | 3.92 | - | - |
| Root Doublers | 2.51 | 2.51 | 2.51 |
| Filler | 0.41 | - | - |
| Attachments | 1.00 | 1.00 | 1.00 |
| "Z" Stiffeners | - | 3.25 | - |
| Door Hinges | - | 13.00 | 13.00 |
| Ribs | - | 2.04 | - |
| TOTAL/SIDE | 45.00 | 84.52 | 64.23 |

On the basis of this comparison, the weight changes on ducts #1, 2 and #3 are estimated to also cause increases so that the new wing weight would be 309 pounds heavier with the built-up section concept of Figure 20, and 151.4 pounds heavier with the sandwich panel duct of Figure 25.

Accordingly, assuming that the vertical thrust available for takeoff is unchanged from that used in the referenced configuration, then the fuel load would be reduced to 881 pounds and 1039 pounds respectively. However, until test results verifying the thrust values and further design efforts, especially with regard to the double lower doors and their control system are completed, these weight changes to the RTV are valid only for trend purposes.

# IV. AERODYNAMIC AND PROPULSION

## A. PRIMARY EJECTOR NOZZLE EFFECTIVE AREA ESTIMATION

There are four nozzle types used in the multi-channel ejector. They are the large alternating exit nozzles shown in Reference 3, the small alternating exit nozzles shown in Reference 4, and the slot nozzles shown in Reference 2, and the end bay nozzles designed and fabricated by AEROSPACE RESEARCH LABORATORIES and located at the ends of each ejector bay. The total nozzle effective area, $A_0$, of these nozzles has been estimated to be as follows:

134.1 Square inches - Large alternating nozzles

24.6 Square inches - Small alternating nozzles

34.4 Square inches - Slot nozzles

14.4 Square inches - ARL end bay nozzles

207.5 Square inches - $A_0$, total primary nozzle effective area

There are 276 large alternating nozzles used in the ejector. There are 12 panels, 72 inches in length, each of which contain 23 of these nozzles. The effective exit area of each nozzle has been determined to be 0.486 square inches. This value was established by tests conducted by ARL. The geometric exit area of these nozzles, based on the skewed exit plane, is 0.692 square inches. The resulting area coefficient (effective to geometric) is 0.702.

There are 92 small alternating nozzles. These nozzles are similar to the large nozzles, but are somewhat smaller in size. The geometric exit area of each nozzle is 0.380 square inches as measured in the skewed exit plane. Since these nozzles are geometrically similar to the large alternating nozzles the large nozzle area coefficient of 0.702 is multiplied by the small nozzle geometric area to provide an estimated effective exit area of 0.267 square inches per nozzle.

There are 384 slot nozzles. The geometric exit area of each of these nozzles is 0.0915 square inches. The effective exit area is estimated by applying an area coefficient of 0.98 as suggested by ARL and results in an effective exit area of 0.0897 square inches.

There are 16 ARL end bay nozzles, each having an effective exit area of 0.9 square inches. The value for the effective area of these nozzles was provided by ARL.

There are then a total of 768 nozzles which are predicated to pass the same airflow as an ideal nozzle having an exit area of 207.5 square inches.

## B. AUGMENTATION RATIO AND PRIMARY NOZZLE VELOCITY RATIO ESTIMATION

The wing augmentation ratio ($\phi$) is a function of the ejector geometry. Before an estimate of the value of the augmentation ratio can be made, it is necessary to determine the various ejector areas and area ratios in addition to the previously determined value of the primary nozzle effective area ($A_0$).

The total mixing section area ($A_2$) is 5184 square inches. This was determined as follows:

$$A_2 = \underbrace{(36)}_{\text{SUM OF SECTION WIDTHS}} \; \underbrace{(72)}_{\text{SECTION LENGTHS}} \; \underbrace{(2)}_{\text{NO. SIDES}} = 5184 \text{ inches}^2$$

NO. SIDES

SECTION LENGTHS

SUM OF SECTION WIDTHS (8 + 10 + 10 + 8 = 36 inches)

The area ratio $A_2/A_0$ is generally referred to as the area ratio of the ejector and is the ratio of the mixing section geometric area to the primary nozzle effective area. The effective area used to form this ratio is slightly different from value of $A_0$ determined in the previous section, however. The value of $A_0$ used to form the ejector area ratio ($A_2/A_0$) does not include the end bay nozzle area as the purpose of these end nozzles is simply to eliminate any end wall effects which would tend to cause the end primary nozzles to operate differently from the nozzles in the interior of the span. The ejector area ratio is therefore,

$$A_2/A_0 = 5184 / (207.5 - 14.4) = 26.85$$

and the primary to secondary inlet area ratio ($A_1/A_0$) is

$$A_1/A_0 = 26 \quad \text{Approximately}$$

The diffusor area ratio ($A_3/A_2$) used in the analysis was 1.7 as suggested by ARL. This led to the overall ejector area ratio ($A_3/A_0$) shown below.

$$A_3/A_0 = (A_3/A_2)(A_2/A_0) = (1.7)(26.85) = 45.6$$

An ejector having this area ratio would be predicted to have a nominal augmentation ratio of 1.89 based on the information provided in Figure 28.

When an unchoked primary nozzle is operating in an ejector the nozzle exit static pressure drops below ambient and the exit velocity increases above that computed for the nozzle when discharging to ambient conditions. The increase in discharge velocity was computed using the BAC incompressible ejector performance computer program, STATEJ.

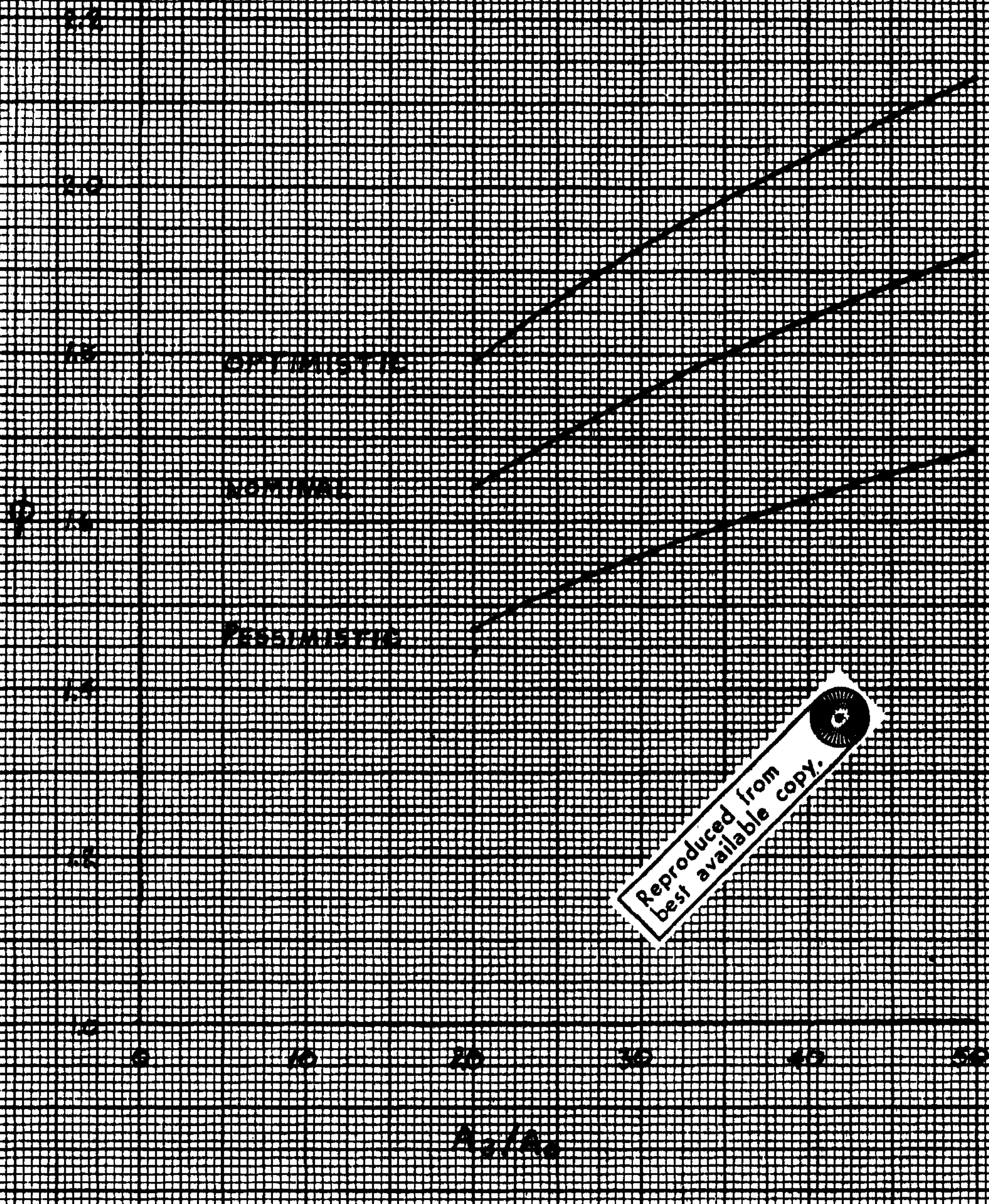





FIGURE NO. 28

ESTIMATE OF THRUST AUGMENTATION STATE-OF-THE-ART
(FOR EJECTORS IN AN EJECTOR WING CONFIGURATION)

(DATA PROVIDED BY ARL)

The input to the program included the following:

$A_1/A_0 = 26$

$\eta_D = 0.855$ DIFFUSER EFFICIENCY $= (p_3 - p_2)/1/2\,\rho\,(V_2^2 - V_3^2)$

$\eta_i = 0.980$ INLET EFFICIENCY $= (P_0 - P_1)/1/2\,\rho\,V_1^2)$

$\zeta = 0.020$ MIXING LOSS COEFF. $= (p_1 - p_2)/(1/2\rho V_2^2)$

$A_3/A_2 = 1.7$

The velocity ratio $(V_0/V_0')$ computed was 1.05. This means the primary nozzle velocity is 5% higher when operating in the ejector than when operating with an ambient back pressure. This program also computes an augmentation ratio. The value computed was 1.896 which agrees well with the value of 1.89 read from Figure 28. This indicates that a realistic selection of $\eta_D$ $\eta_i$, and $\zeta$ was used in the STATEJ program input.

C. AIR SUPPLY SYSTEM ANALYSIS

The augmentor wing primary nozzles are supplied by the bypass air from an AVCO Lycoming PLF1A-2 turbofan engine. This engine provides more air than can be passed through the primary ejector nozzles. The excess air is passed through 4 symmetrically located exhaust vents as shown in Reference 13. These vents are mounted on the rear surface of the plenum box and will direct the excess fan airflow upward and downward to insure that no net force is sensed by the thrust load cell. Three sets of 4 identical exhaust nozzles are provided for the exhaust vents. One set of nozzles is sized to enable the engine to operate on its normal operating line. This is shown by the broken line in Figure 29. With this set of nozzles, the engine may be operated up to a total pressure ratio of approximately 1.35 before reaching the engine temperature limit. As can be seen in Figure 29, there is a fairly large margin between the normal operating line and the surge line. The second set of nozzles is sized to reduce this margin by setting the operating line closer to the surge line. The maximum pressure ratio at which the engine bypass fan may be operated is thereby increased to 1.43. Although there is expected to be an ample margin between the working line produced by the second set of nozzles and the surge line, a third set of exhaust vent nozzles having an intermediate exit area is provided.

Before the exhaust vent nozzle exit areas could be determined it was necessary to,

a. pick the desired design point operating conditions

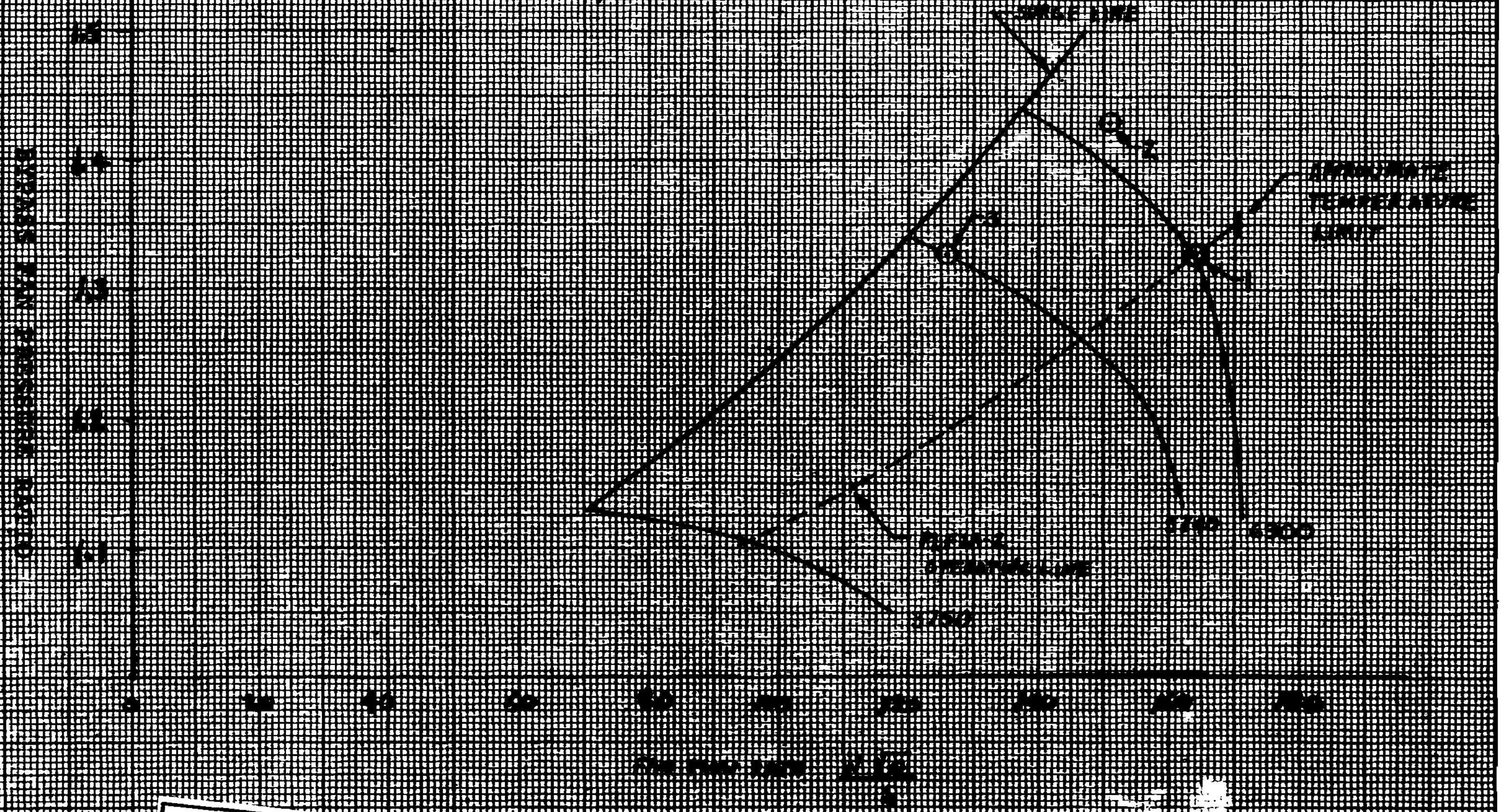





FIGURE No. 29

b. estimate the amount of air to be passed through the exhaust vents

c. design an exhaust vent capable of passing the required airflow

d. estimate the total pressure losses in the exhaust vent

1. Design Point 1

The first design point selected corresponds to the highest pressure ratio run (#33), made by ARL on 7-8-69. The fan performance data from this test was provided by ARL and is summarized below.

| | | | |
|---|---|---|---|
| PR | = | 1.328 | Total Pressure Ratio |
| $W_T$ | = | 164 #/Sec. | Bypass Airflow |
| $\eta_p$ | = | 0.91 | Polytropic Efficiency |
| N | = | 6300 RPM | Speed |

This operating conditions is represented by Point 1 on Figure 29 and allows for some margin between the selected operating point and the temperature limit. The total pressure rise across the fan is 4.82 PSI. The pressure losses from the fan exit plane to the primary nozzle exit plane has been estimated to be 10% of the fan total pressure rise or 0.48 PSI. Most of this loss is assumed to occur as the fan air enters the plenum box. The total pressure at the primary nozzles is 19.04 PSIA. The corresponding nozzle flow conditions were computed based on this total pressure, an effective nozzle exit area of 207.5 square inches, and a nozzle exit velocity ratio of 1.05. The nozzle flow conditions are summarized below.

| | | | |
|---|---|---|---|
| $P_{T0}$ | = | 19.04 PSIA | Exit Total Pressure |
| $T_{T0}$ | = | $102^{\circ}$ F | Exit Total Temperature |
| $M_0$ | = | 0.654 | Exit Mach Number |
| $V_0$ | = | 729 FPS | Exit Velocity |
| $\dot{W}_0$ | = | 78.1 #/Sec. | Total Airflow (All nozzles) |

The excess air ($\dot{W}_B$) which must be removed from the plenum through the exhaust vents is simply the difference between the total fan flow ($\dot{W}_T$) and the air flow through the primary nozzles ($\dot{W}_0$). At Design Point 1,

$$\dot{W}_B = 164.0 - 78.1 = 85.9 \text{ \#/Sec.}$$

This design point results in the maximum value of excess airflow to be removed from the plenum, and was the condition for which the exhaust vent ducts were designed.

The exhaust ducts are each required to remove approximately 21.5 pounds of air per second from the plenum, turn the air through 90°, and deliver the air to the exhaust nozzles with a minimum of pressure loss and turbulence.

The vent duct shape was chosed to be rectangular, primarily to facilitate the simple construction of a vaned, mitered 90° turn. The duct inside dimensions are 13.00 inches by 6.75 inches. The duct was divided into 5 sections for the purpose of design and analysis. These sections are defined as follows. (See Figure 30)

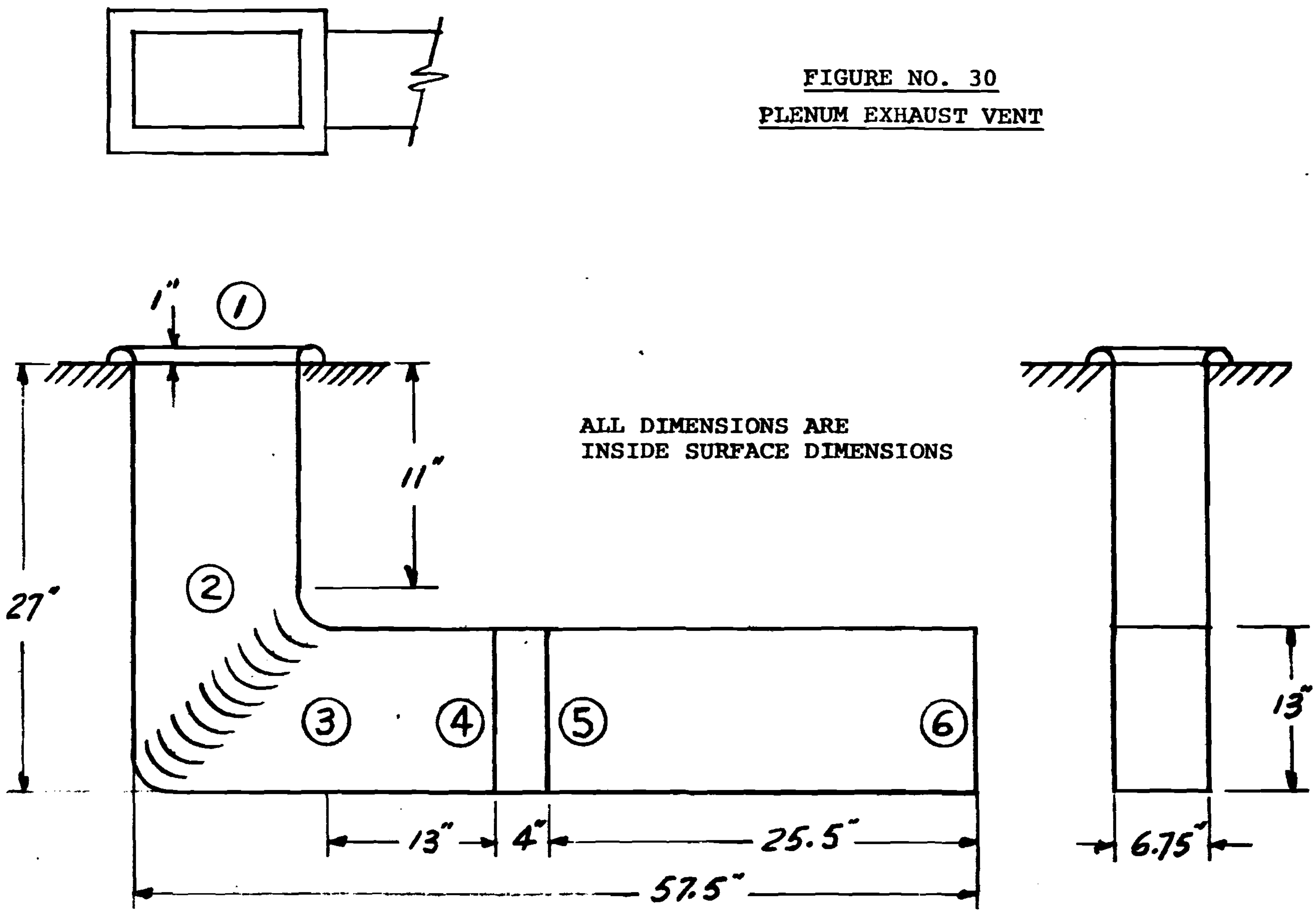
| STA | SECTION |
|---|---|
| 1 - 2 | INLET |
| 2 - 3 | 90° BEND |
| 3 - 4 | BEND TO STRAIGHTENER |
| 4 - 5 | FLOW STRAIGHTENER |
| 5 - 6 | STRAIGHTENER TO NOZZLE |

The inlet of the exhaust vent duct is considered to be the rounded inlet lip and the first 11 inches of the rectangular duct. The inlet rounding and straight duct section is provided to insure uniform flow conditions at the 90° turn. The Mach number of the flow in the rectangular inlet section is 0.362. The pressure loss coefficient ($\Delta P_{T1-2}/q_2$) is estimated to be 0.10 based on the work reported in Reference 14. The total pressure loss is estimated to be 0.16 PSI.

The mitered and vaned 90° turn is designed to turn the flow yet introduce a minimum of pressure loss and turbulence. There are 10 equally spaced circular arc, sheet metal vanes in the duct. Each vane as well as the duct corners has a 3 inch radius. The vaned corner was designed according to the methods described in References 14 and 15. The vanes are 90° of arc in length and are set at zero angle of attack to the airstream. The pressure loss coefficient is estimated to be 0.25 with a corresponding total

FIGURE NO. 30

PLENUM EXHAUST VENT



pressure loss of 0.40 psi at the Design Point operating conditions.

A section is provided between the vaned corner and the flow straightener. This section will allow any abnormal velocity distributions, other than vortex or helical which might be preserved by a flow straightener, to normalize. The loss in this section is predicted to be due to friction between the airstream and duct walls. The basis for the loss estimate is the assumption of a friction loss factor (f) of 0.01 which is the value for a smooth pipe at Reynolds number $2 \times 10^6$. The pressure loss coefficient for a 13 inch length of pipe is estimated to be 0.015 with a corresponding total pressure loss of 0.03 PSI.

The flow straightener is a 4 inch length of hexel honeycomb having a .75 inch mesh size. The flow coefficient for a straightener of this type has been suggested to be 0.20 by Pope (Reference 16). The total pressure loss through the straightener is 0.33 PSI.

A section of approximately three hydraulic diameters separates the flow straightener and the vent nozzle inlet. A total pressure loss of 0.05 PSI is estimated for this section.

A summary of the Design Point 1 pressure loss analysis is shown below.

| Station | Mach No. | Total Pressure PSIA | Loss Coeff. | Dynamic Press. PSI |
|---|---|---|---|---|
| 1 | 0 | 19.04 | | |
| 2 | 0.362 | 18.88 | 0.10 | 1.60 |
| 3 | 0.372 | 18.48 | 0.25 | 1.60 |
| 4 | 0.372 | 18.45 | 0.02 | 1.63 |
| 5 | 0.380 | 18.12 | 0.20 | 1.63 |
| 6 | 0.382 | 18.07 | 0.03 | 1.66 |

$$\Delta P_{T_{1-6}} = 0.97$$

$$q_1 = 1.60$$

$$\frac{\Delta P_{T_{1-6}}}{q_1} = 0.606 = K_L$$

The nozzle inlet conditions are summarized below.

| | | | |
|---|---|---|---|
| AIRFLOW | = | 21.5 | Pounds/Sec. |
| MACH NUMBER | = | 0.382 | |
| TOTAL PRESSURE | = | 18.07 | PSIA |
| STATIC PRESSURE | = | 16.31 | PSIA |
| TOTAL TEMPERATURE | = | $102.0^{\circ}$ | F. |
| STATIC TEMPERATURE | = | $86.0^{\circ}$ | F. |

Assuming an ambient pressure of 14.7, the exit area of an ideal nozzle passing the required airflow would be 62.0 square inches. A two-dimensional nozzle having a total angle of convergence of $25^{\circ}$ was chosen for this application. The nozzle construction is shown in Reference 17. The discharge coefficient assumed for a nozzle of this type is 0.92 which is slightly better than the commonly accepted value of 0.91 for a conical nozzle of the same convergence angle. The assumption of this discharge coefficient leads to a required vent nozzle exit area of 67.5 square inches.

2. Design Point 2

Design Point 2 is shown in Figure 29. The fan performance expected at this design point is listed below.

| | | | |
|---|---|---|---|
| PR | = | 1.430 | |
| $W_T$ | = | 151 | #/Sec. |
| $\eta_p$ | = | 0.88 | |
| N | = | 6600 | RPM |

This design point is expected to be readily attainable by the PLF1A-2 engine being within the predicted surge, turbine temperature and RPM limits. A 10% weight flow margin between the design point and the surge line is expected.

The total pressure at the fan aft face will be 21.0 PSIA. Applying the 10% loss, discussed in the Design Point 1 Section, the airstream total pressure is decreased to 20.39 PSIA at the primary ejector nozzle inlets. The nozzle flow conditions are shown below.

$$P_{T0} = 20.39 \text{ PSIA}$$

$$T_{T0} = 116^{o} \text{ R}$$

$$M_0 = 0.738$$

$$V_0 = 824 \text{ FPS}$$

$$\dot{W}_0 = 87.6 \text{ \#/Sec.}$$

The excess airflow ($\hat{W}_B$) which must be expelled through the exhaust vent ducts is therefore;

$$\dot{W}_B = 63.4 \text{ \#/Sec.}$$

The flow through the vent ducts is controlled by the Design Point 2, nozzle. The loss coefficient in the vent duct system is expected to be nearly identical with the value computed for Design Point 1. The duct geometry is identical and the duct mach number is only reduced to 0.24. Applying the previously derived loss coefficient ($K_L$) gives the Design Point 2 vent duct total pressure loss.

$$P_{T_{1-6}} = (K_L) \text{ (Inlet Dynamic Pressure)} = (0.606)\ (0.80) = 0.48 \text{ PSI}$$

The nozzle inlet conditions are therefore,

| | | |
|---|---|---|
| AIRFLOW = 63.4/4 | = 15.84 | #/Sec. |
| MACH NO. | = 0.246 | |
| TOTAL PRESSURE | = 19.91 | PSIA |
| STATIC PRESSURE | = 19.09 | PSIA |
| TOTAL TEMPERATURE | = 116.0° | F. |
| STATIC TEMPERATURE | = 109.0° | F. |

The Design Point 2 nozzle is a two-dimensional nozzle, having the same convergence angle as the Design Point 1 nozzle. Applying the assumed discharge coefficient of 0.92 to the Design Point 2 nozzle leads to a required exit area of 43.9 square inches.

A summary of the exhaust vent nozzle sizes shown in Reference 17 are listed below:

| Nozzle | Exit Height | Exit Width | Exit Area |
|---|---|---|---|
| Design Point 1 | 9.48 | 7.12 | 67.50 |
| Intermediate | 7.82 | 7.12 | 55.68 |
| Design Point 2 | 6.16 | 7.12 | 43.86 |

## D. INVESTIGATION OF METHODS OF ELIMINATING THE EXHAUST VENT DUCTS

At Design Point 1 there is an excess airflow of 85.9 #/sec. above the amount which may be passed through the ejector wing primary nozzles. This air is removed from the system through the exhaust vent ducts. If the exhaust vent ducts were removed, the engine operating line would fall to the left of the surge line shown in Figure 29 and the engine would surge at all throttle settings.

A possible method of eliminating the exhaust vent ducts would be to set the engine operating line nearer to the fan surge line to minimize the excess airflow and then to pass the remaining excess air through an increased exhaust area in the wing.

As an example, suppose the system were designed to run at the Design Point 1 pressure ratio (1.328) but much nearer the fan surge line. Point 3 on Figure 29 represents such a condition. The excess airflow would be reduced from 85.9 #/sec. at point 1 to 47.9 #/sec. at point 3. If the wing span is not changed and the primary nozzle effective area is increased by 61% the exhaust ducts may be eliminated. This change would reduce the ejector area ratio ($A_2/A_0$) from 26.89 to 16.7 with a corresponding decrease in the wing augmentation ratio (Ø) from 1.89 to 1.73. This would require a redesign or spacing change in the primary nozzles.

Another means of providing the required area without changing the primary nozzle design or basic ejector area ratio would be to increase the wing span. A 61% increase in wing area, however, would lead to an 88 inch increase in model width.

A third method for passing the excess airflow through the wing ducts requires bleed holes to be provided in the bottom of the ducts 2, 3 and 4. The wing span and primary nozzle-to-mixing-section area ratio is not altered by this method. Each 72 inch duct span would require 9 square edged circular holes, each 2.[illegible]7 inches in diameter and 8 inches on center as shown in Figure 16. The air would pass between the wing diffuser doors. This airflow would create a thrust of approximately 1,000 pounds which would have to be determined more exactly and handled as a tare force when determining the wing augmentation ratio. Care must be taken to determine if the flow between the diffuser doors will alter the basic augmentor performance either favorably or unfavorably by altering the pressure field on any portion of the wing or diffuser surface.