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STUDY FOR

CONCEPTUAL DESIGN OF VEO, VTOL EXHAUST NOZZLE

by W. C. Bittrick

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16. Abstract

Design requirements were established for a VEO-Wing V/STOL exhaust nozzle with a 2-dimensional shape and having the capability for upper surface blowing, spanwise blowing, and 90° turning of the exhaust flow for VTOL. A preliminary design of the nozzle was prepared that identified the actuation scheme, key dimensions, the flowpath, and the recommended materials. The airplane characteristics resulting from integrating the study nozzle were established. A detailed description of the design effort by General Electric is contained in the Appendix.

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1.0 INTRODUCTION

The objective of this program is to develop the design of an integrated, asymmetric two-dimensional nozzle that includes upper surface blowing capability, spanwise blowing capability, and 90° turning of the exhaust flow for VTOL capability, to be used on a VEO-wing airplane configuration.

The task was accomplished by first establishing the design requirements, the baseline vehicle configuration, the combat mission, and the engine cycle. This information was submitted to the General Electric company, who performed the conceptual design and preliminary design efforts under subcontract to General Dynamics. (General Electric's efforts are reported in Appendix A.) Finally, the baseline airplane was resized and new performance characteristics were generated using the nozzle design, weights, and internal performance characteristics resulting from General Electric's conceptual design efforts.

2.0 SYSTEM REQUIREMENTS

The baseline airplane is the VEO-Wing R-104 configuration shown in Figure 2.1. This V/STOL fighter configuration was generated by General Dynamics under contract to NASA Ames and is described in detail in NASA CR-152128.

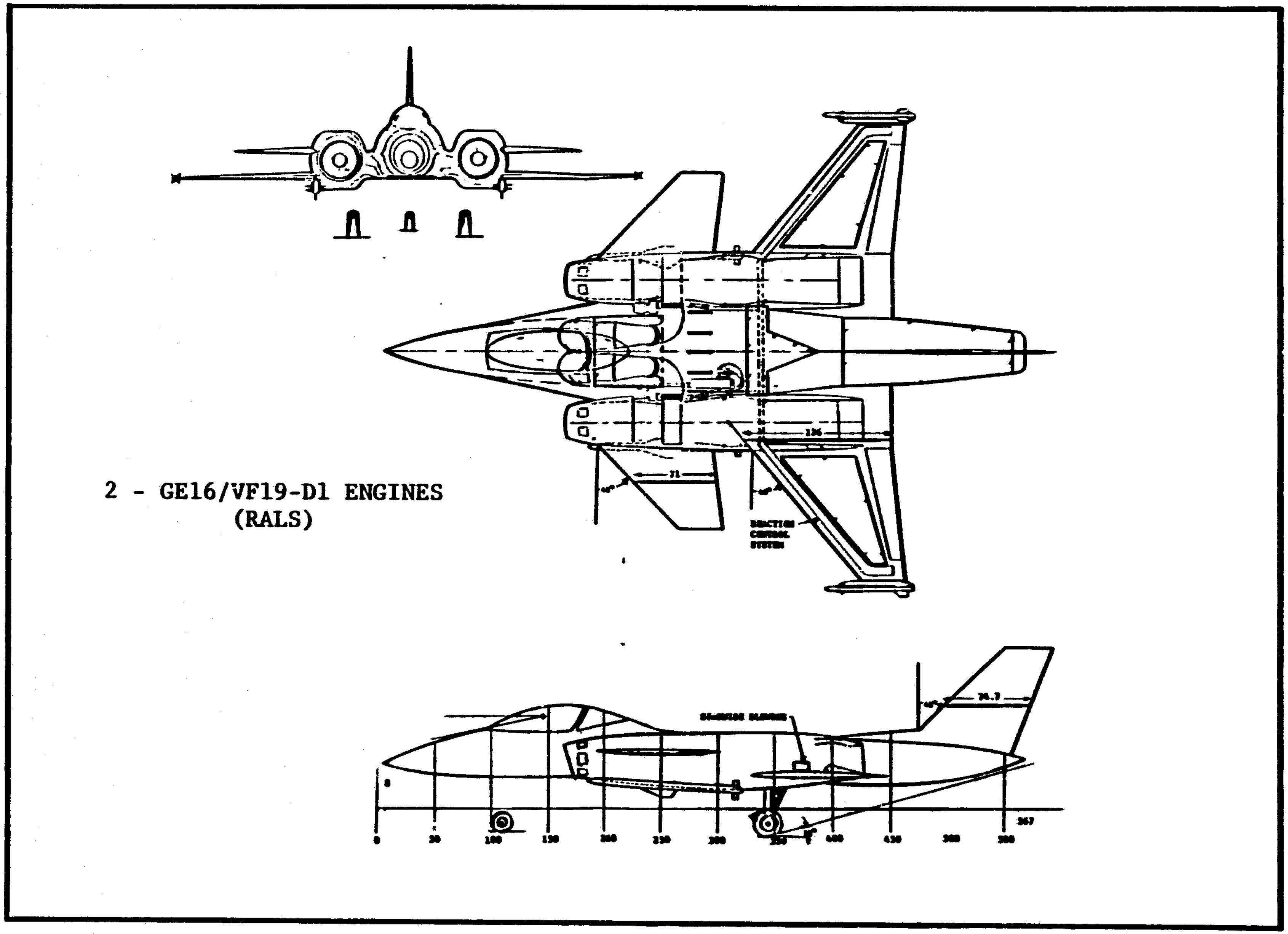

Figure 2.1(a) VEO-Wing Configuration R104, 3-View

WING

AREA	300 SQ FT
ASPECT RATIO	3.6
TAPER RATIO	.20
ROOT RATIO	182.56 IN
TIP CHORD	136.51 IN
b/2	197.18 IN
AIRFOIL - NACA 64A204	

CANARD

EXPOSED AREA	66 SQ FT
ASPECT AREA	2.16
TAPER AREA	37
ROOT CHORD	96.46 IN
TIP CHORD	36.06 IN
b/2	71.69 IN
AIRFOIL ROOT-64A005 TIP-64A003	

VERTICAL TAIL

AREA	43 SQ FT
ASPECT RATIO	1.25
TAPER RATIO	.43
ROOT CHORD (THEO)	98.5 IN
TIP CHORD	42.34 IN
b	88.0 IN
AIRFOIL ROOT 53% TIP 4% BICONVEX	

PROPULSION (2) GE 16/VVCE5 STUDY-D ENGINES
WITH REMOTE AUG. LIFT SYSTEM
(ENGINE SCALE - 1.04)
A. PER ENG - 656 IN^2

Figure 2.1(b) VEO-Wing Configuration R104, Configuration Data

2.1 Mission Definition

The baseline airplane was sized using the deck-launched-intercept (DLl) mission shown in Figure 2.2. The DL1 mission was retained for this study.

2.2 Engine Cycle Selection

The baseline airplane performance was generated using the GE16VF19-D1 variable cycle Remote Augmentor Lift System (RALS) engine. This engine cycle was retained for the resized airplane analysis, but General Electric used the GE16VF19-D5 RALS engine for their nozzle design effort. These two engines have identical up-and-away performance; they differ only in the thrust split between the RALS and the main exhaust nozzle during VTOL operation. Different engines were used as a matter of economics, with no compromise to the program (GE had the -D5 engine in computerized form but not the -D1 engine; GD had the -D1 engine in computerized form but not the -D5 engine; the GE design work was done using only the up-and-away mode, and the GD airplane analysis was done using only the up-and-away mode).

2.3 Design Requirements

The exhaust system design requirements fall into two categories: (1) General, as defined in Table 2.1 and (2) Installation related, as defined in Table 2.2 and Figure 2.3. Table 2.3 lists the operating flight conditions where exhaust system performance is critical.

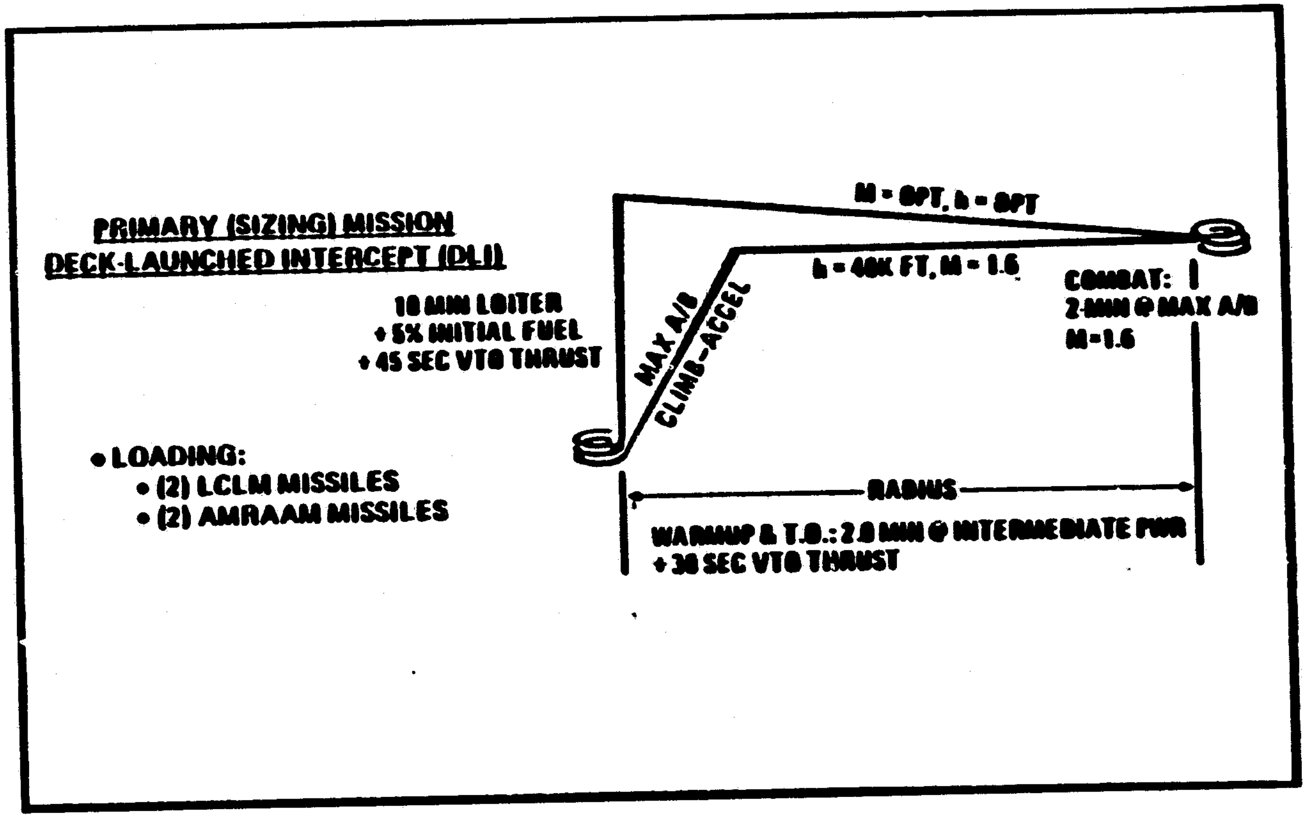

Figure 2.2 Deck-Launched Intercept Mission

TABLE 2.1 EXHAUST NOZZLE DESIGN REQUIREMENTS, GENERAL

- 2-D ASYMMETRIC SHAPE
- VTO DEFLECTOR - $90^{\circ} \pm 15^{\circ}$
- THRUST VECTOR CONTROL - $\pm 30^{\circ}$, (FOR CONVENTIONAL FLIGHT)
- VARIABLE A8 CONSISTENT WITH SELECTED ENGINE CYCLE
- SPANWISE BLOWING CAPABILITY - 30% EXHAUST FLOW AT MAXIMUM DRY POWER
- THRUST VECTOR CONTROL ACTUATION RATE = 60°/SEC

TABLE 2.2 EXHAUST NOZZLE DESIGN REQUIREMENTS, INSTALLATION RELATED

- LOW ASPECT RATIO 2-D NOZZLE
- ON/OFF SPANWISE BLOWING
- TRAILING EDGE FLAP CHORD LENGTH = 15% WING CHORD
- JET VECTOR ANGLE AND FLAP ANGLE MUST BE EQUAL WHILE VECTORING
- WHEN NOT VECTORING, FLAP MUST HAVE CAPABILITY OF FUNCTIONING AS CONVENTIONAL WING FLAP
- NOZZLE SIDEWALLS MUST TERMINATE FORWARD OF FLAP HINGELINE
- SPANWISE BLOWING PORT IS TO BE LOCATED AT 25% CHORD
- SPANWISE BLOWING VECTOR ANGLE = 40° AFT (RELATIVE TO STATION PLANE)

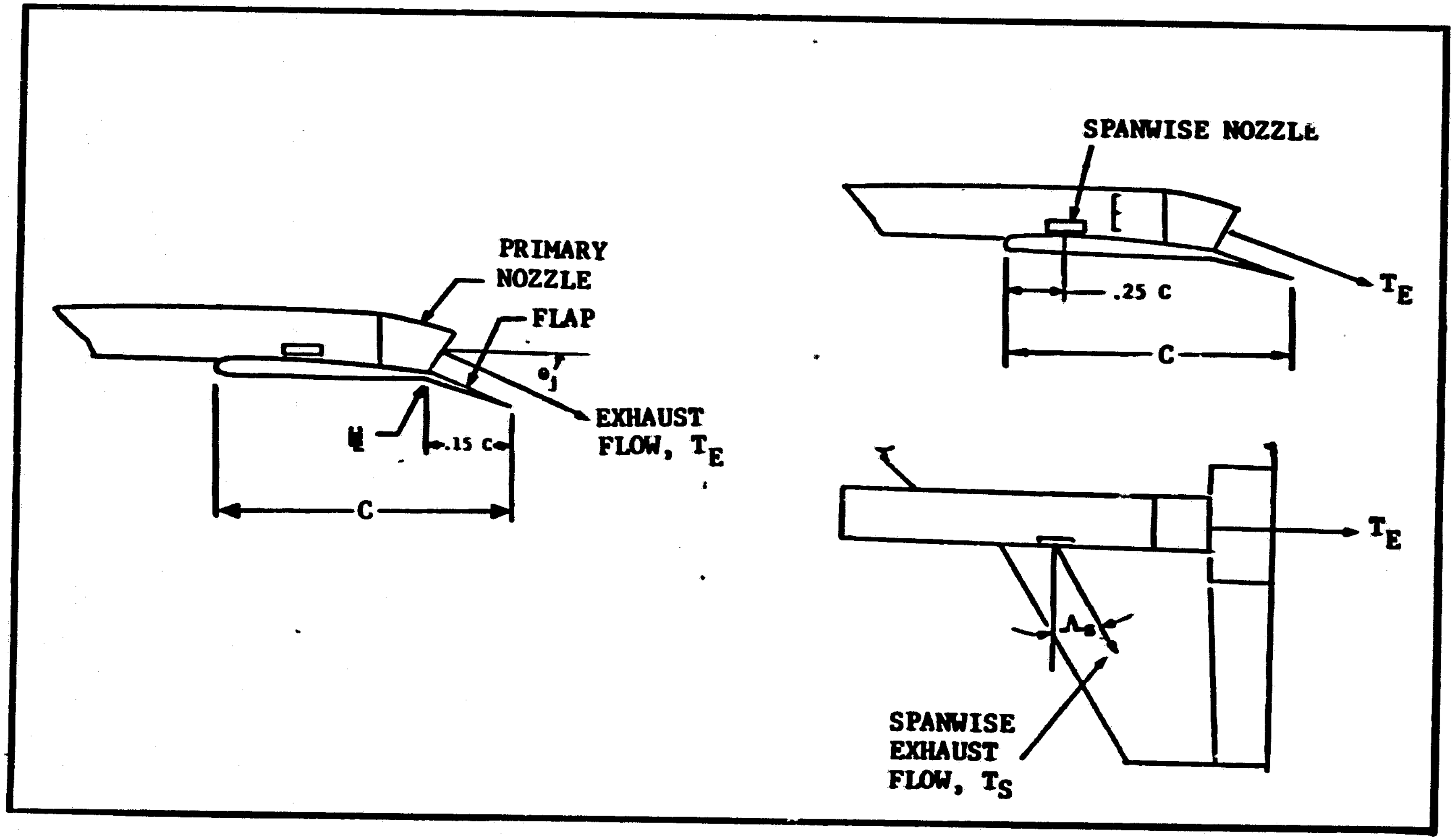

Figure 2.3 Exhaust Nozzle Design Requirements, Installation Related

TABLE 2.3 EXHAUST NOZZLE DESIGN REQUIREMENTS, KEY OPERATING POINTS

APPLICATION/SPEED	JET VECTOR ANGLE, θ_j (deg)	POWER SETTING	SPANWISE BLOWING	SPANWISE VECTOR Λ_s (deg)
• VERTICAL T.O. & LANDING	90	ALL	NO	-
• STOL T.O. $0 \rightarrow 200$ KTS	± 30	MAX A/B	YES	40
• STOL LANDING 100 KTS	± 30	$\geq$ MIL	YES	40
• MANEUVER $.3 \leq M \leq .6$	± 20	MAX A/B	YES	40
$.6 < M \leq .95$	± 15	MAX A/B	NO	-
• CRUISE $M \approx .9$	5^o	MIL	NO	-
• SUPERSONIC DASH $.95 \leq M \leq 2.0$	0	MAX A/B	NO	-

3.0 EXHAUST SYSTEM DESIGN

The design tasks were accomplished by the General Electric Company using the system requirements (Section 2.0) provided by General Dynamics. General Electric's work consisted of a conceptual design phase, followed by a preliminary design of the selected conceptual design. A complete report of the work performed by General Electric is included as Appendix A of this report.

3.1 Conceptual Design

The conceptual design phase yielded a total of eight integrated VEO-Wing VTOL exhaust systems, summarized in Table 3.1. Performance characteristics for these eight concepts are summarized in Table 3.2. Those designs with variable A9 control yield slightly better performance than with a fixed A9/A8 flap. Since variable A9 control can be designed into any of the eight concepts, all concepts can yield the same performance.

Concept No. 8 was revised as shown in Figure 3.1. This revised version met all of General Dynamics' requirements at the lowest system weight and, therefore, was selected for preliminary design.

3.2 Preliminary Design

The preliminary design of revised concept No. 8 resulted in a layout drawing presenting the aerodynamic flow path, general actuation arrangement, key dimensions, and recommended materials. Complete

TABLE 3.1 VEO NOZZLE CONCEPTS MECHANICAL SUMMARY

	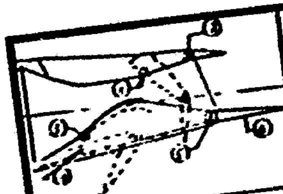	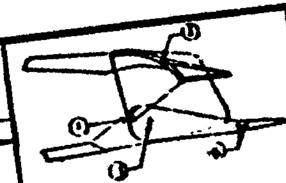	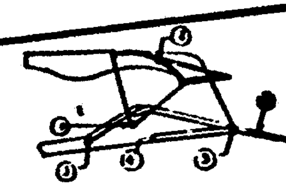
TYPE NOZZLE	CLAMSHELL/SINGLE RAMP DESIGN CONCEPT -#1	CLAMSHELL/TANDEM RAMP DESIGN CONCEPT - #2	CLAMSHELL/TRANSLATING RAMP DESIGN CONCEPT - #3
DRAWING NUMBER	4013237-603	4013237-397	4013237-650
ACTUATION SYSTEMS	TYPE: MOM OR FORCE	TYPE: MOM OR FORCE	TYPE: MOM OR FORCE
A8 ①	HYD. CYL. 30,000 LBS.	POWER HINGE 65,500 In-LBS.	HYD. CYL. 12,500 LBS.
A8/VECTORING ②	POWER HINGE 130,000 In-LBS.	HYD. CYL. 12,500 LBS.	HYD. CYL 12,500 LBS.
VECTORING ③	POWER HINGE 280,000 In-LBS.	POWER HINGE 285,000 In-LBS.	POWER HINGE 63,000 In-LBS.
VECTORING ④	SCREW JACK 10,000 LBS.	----------	SCREW JACK 10,000 LBS.
VECTORING ⑤	POWER HINGE 100,000 In-LBS.	----------	POWER HINGE 100,000 IN-LBS.
NO. ACT. SYSTEMS	5	4	5
ACTUATION WEIGHT	163 LBS.	90 LBS.	107 LBS.
TOTAL WEIGHT	781	680	853
COMPLEXITY	HIGH	MEDIUM	HIGH
COOLED SURFACE AREA	7780 In.^{2}	7260 In.^{2}	8350 In.^{2}
% COOLING FLOW	17.6	18.5	18.9
LEAKAGE AREA	3.98 In.^{2}	2.26 In.^{2}	5.4 In.^{2}
AFT FLAP ⑥	ENGINE MOUNTED	ENGINE MOUNTED	ENGINE MOUNTED
A.F. STRUCTURAL INTERFERENCE	SEVERE	SEVERE	SEVERE

TABLE 3.1 VEO NOZZLE CONCEPTS MECHANICAL SUMMARY
(Continued)

	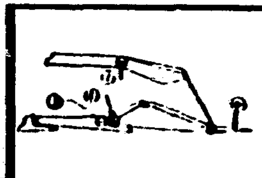	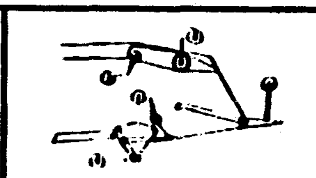	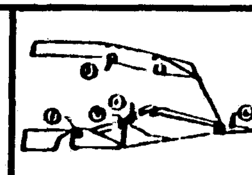	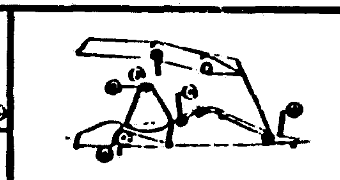	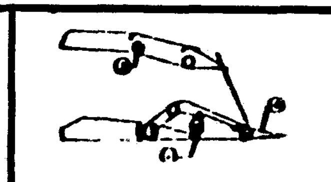
TYPE NOZZLE	ROTATING VENTRAL FLAP DESIGN CONCEPT - #4	ROTATING VENTRAL DEFLECTOR DESIGN CONCEPT - #5	DESIGN CONCEPT - #6	DESIGN CONCEPT - #7	DESIGN CONCEPT - #8
DRAWING NUMBER	4013266-166	4013266-167	4013266-168	4013266-169	4013266-170
ACTUATION SYSTEMS	TYPE: NUM OR FORCE	TYPE: NUM OR FORCE	TYPE: NUM OR FORCE	TYPE: NUM OR FORCE	TYPE: NUM OR FORCE
AB (1)	HYD. CYL., 30,000 LBS	HYD. CYL., 30,000 LBS.	HYD. CYL., 30,000 LBS.	HYD. CYL., 30,000 LBS.	HYD. CYL. 30,000 LBS.
AB/VECTORING (2)	HYD. CYL., 30,000 LBS.	HYD ROTARY ACT. 65,000 In-LBS.	----------	----------	----------
VECTORING (3)	HYD. CYL., 20,000 LBS.	HYD. CYL., 30,000 LBS.	HYD. CYL., 40,000 LBS.	HYD. CYL., 30,000 LBS.	HYD. CYL., 30,000 LBS.
VECTORING (4)	----------	HYD. CYL., 20,000 LBS.	HYD. CYL., 20,000 LBS.	HYD. CYL., 20,000 LBS	----------
VECTORING (5)	----------	----------	HYD. CYL., 20,000 LBS.	HYD. CYL., 30,000 LBS.	----------
NO. ACT. SYSTEMS	4/3/3	4/3	5/4	5/4	3/3
ACTUATION WEIGHT	93/83/64 LBS	91/81 LBS.	88/78 LBS.	88/78 LBS.	58/48 LBS.
TOTAL WEIGHT	630/620/610	656/646	637/627	677/667	508/500
COMPLEXITY	MEDIUM/LOW	MEDIUM	MEDIUM	MEDIUM	MEDIUM
COOLED SURFACE AREA	6610 In.^{2}	7400 In.^{2}	7200 In.^{2}	7800	7800
% COOLING FLOW	15.0	16.8	16.3	17.0	17.0
LEAKAGE AREA	3.08 In.^{2}	3.61 In.^{2}	4.30 In.^{2}	3.91 In.^{2}	3.80 In.^{2}
AFT FLAP 6	WING MOUNTED	WING MOUNTED	WING MOUNTED	WING MOUNTED	WING MOUNTED
A.F. STRUCTURAL INTERFERENCE	MINOR	MINOR	MINOR	MINOR	MINOR

TABLE 3.2 VEO-VTOL EXHAUST SYSTEM CONCEPTS NOZZLE PERFORMANCE, CFG DERATED FOR LEAKAGE, COOLING LOSSES

	VTOL		STOL				
CONCEPT	TAKEOFF	LANDING	TAKEOFF	APPROACH	DASH	COMBAT	CRUISEBACK
#1	.94	.94	.95	.96	.96	.97	.96
#2	.94	.94	.95	.96	.96	.96	.96
#3	.93	.93	.94	.94	.95	.96	.95
#4	.94	.94	.94	.96	.96	.96	.96
#5	.94	.94	.95	.95	.96	.96	.96
#6	.94	.93	.95	.92	.96	.96	.96
#7	.94	.93	.95	.92	.96	.96	.96
#8	.94	.94	.95	.93	.96	.96	.96

CONCLUSION: EQUIVALENT PERFORMANCE FOR ALL CONDITIONS FOR DESIGNED CONCEPT EXCEPT AT STOL APPROACH WHERE FIXED SECONDARY FLAP SCHEDULE (#6, #7, #8) PRODUCES OVEREXPANSION LOSS

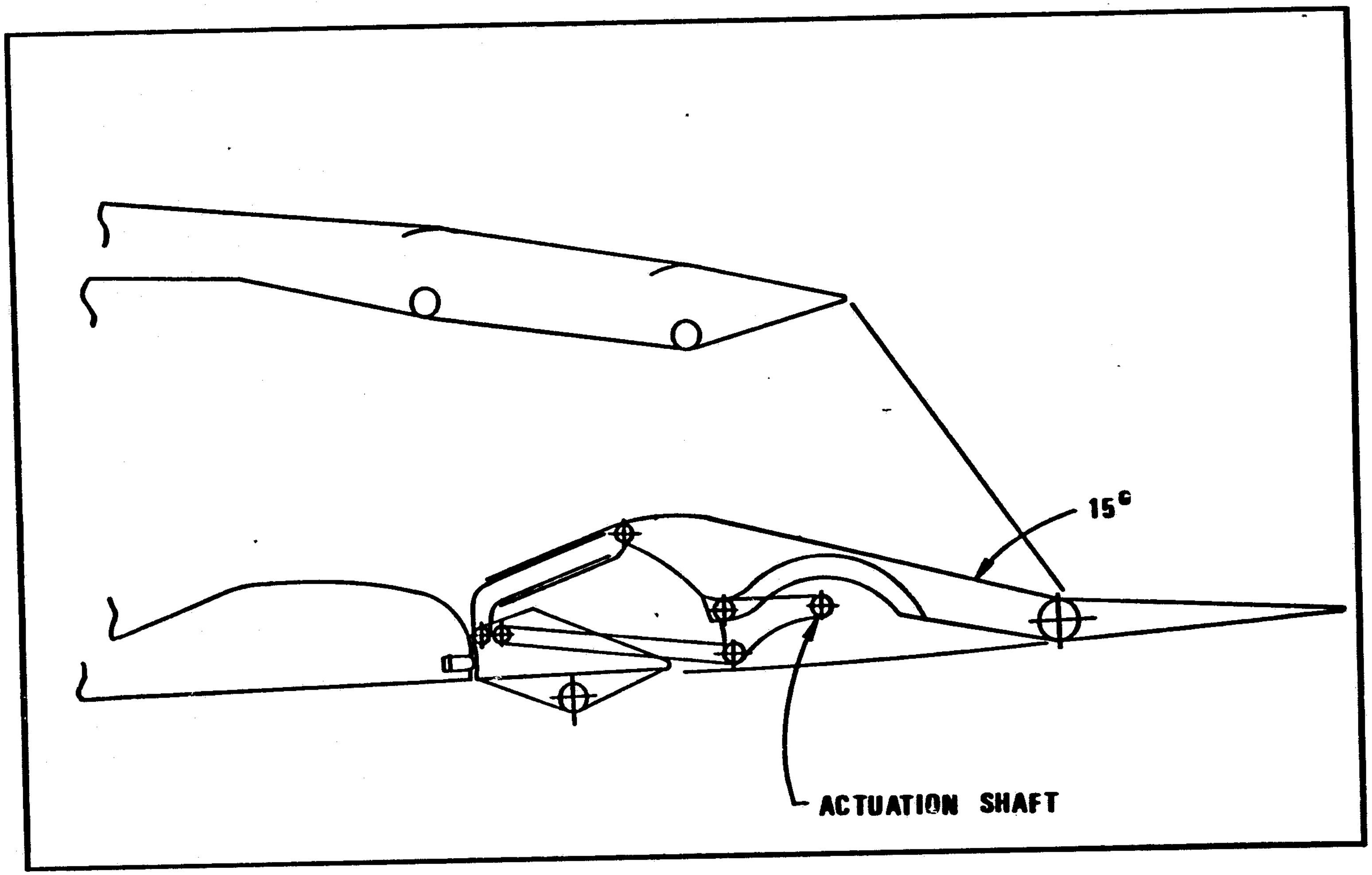

Figure 3.1(a) VEO Exhaust System No. 8, CRUISE

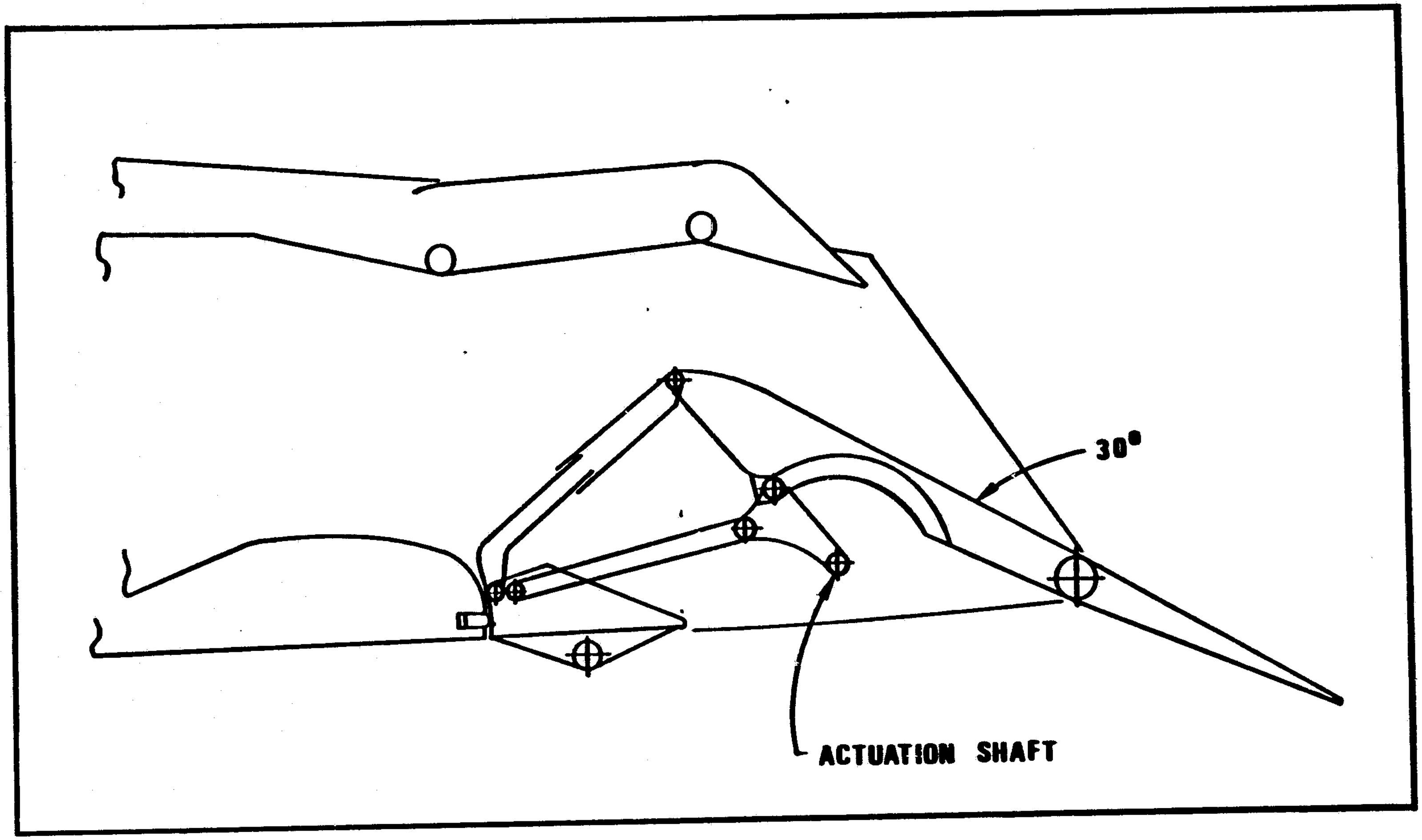

Figure 3.1(b) VEO Exhaust System No. 8, STOL

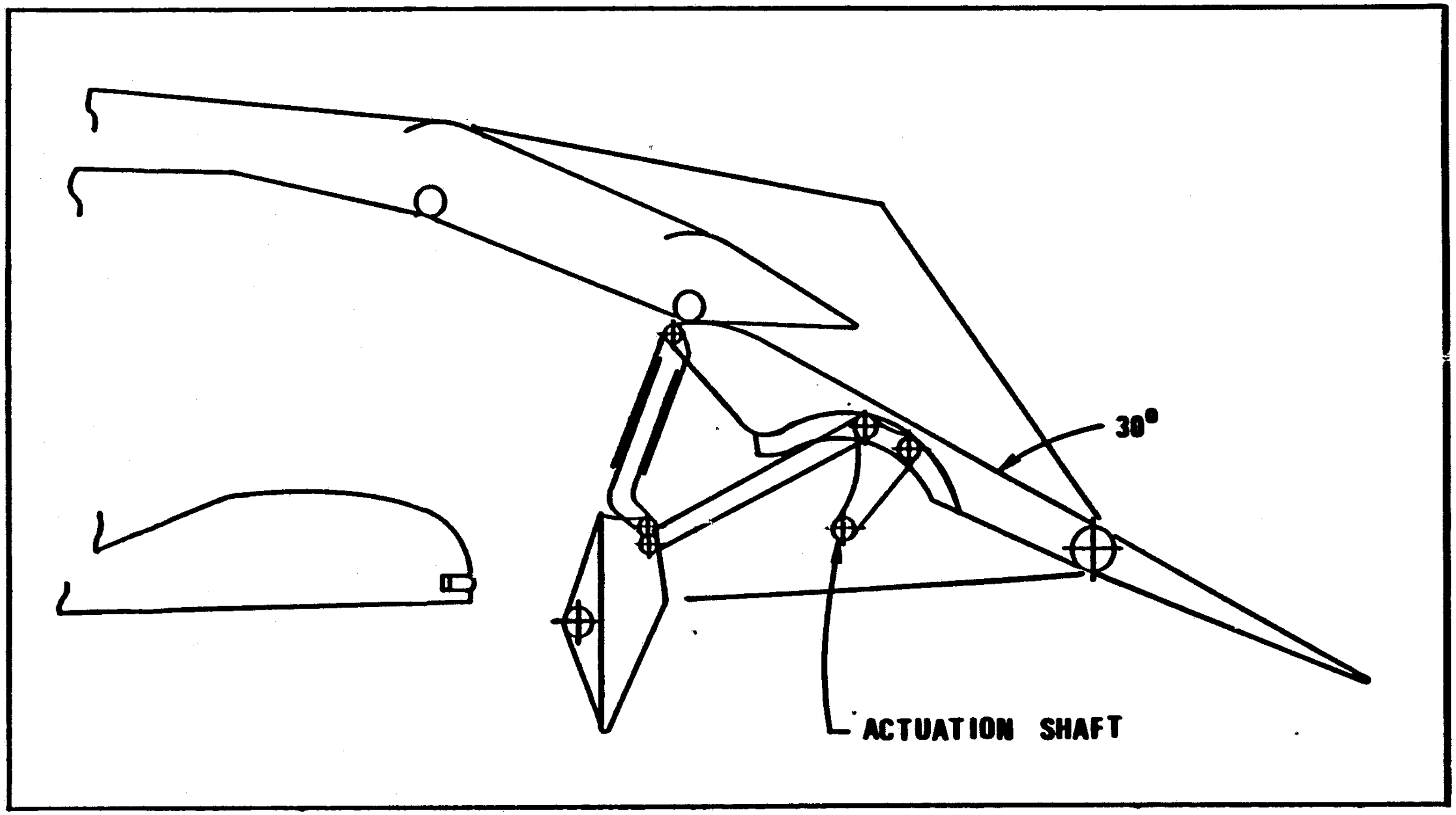

Figure 3.1(c) VEO Exhaust System No. 8, VTOL

mechanical design details including cooling system, weight, and performance are reported in Section 6.0 of Appendix A of this document.

4.0 AIRPLANE CHARACTERISTICS

The baseline R-104 VEO-Wing V/STOL configuration was sized using weight and internal performance of an ADEN nozzle, without spanwise blowing capability. Table 4.1 shows baseline airplane characteristics for reference. Table 4.2 shows airplane characteristics derived using exhaust system characteristics for design concept No. 8, resulting from this program.

5.0 CONCLUSIONS AND RECOMMENDATIONS

A. An exhaust nozzle, meeting all of the requirements specified for a VEO-Wing, V/STOL Fighter Aircraft, can be designed.

B. Since all of the design concepts yielded the same performance values, revised concept No. 8 was selected because it met all of the design requirements at the lowest weight.

C. Upgrading the R-104 airplane characteristics using the revised concept No. 8 nozzle results in an airplane with 2.5% higher take-off gross weight, with performance characteristics reduced by about the same amount.

D. Conclusions and recommendations regarding the nozzle design efforts are presented in Section 7.0 of Appendix A of this document.

TABLE 4.1 BASELINE AIRPLANE CHARACTERISTICS

		MEETS MISSION & HOVER
TOGW	lb(kg)	32700(14830)
WING AREA	$ft^2(m^2)$	300(27.87)
ENGINE SCALE (2 ENGINES)		2.08
MISSION RADIUS (DLI)	n. mi(Km)	150(277.8)
FUEL REQUIRED	lb(kg)	11702(5307)
FUEL FRACTION		.358
P_S (M.9/10kft/1g)	fps(mps)	1144(348.7)
N_z (M.6/10kft/P_S=0)	gs	5.48
ACCEL TIME (M.8-1.6/35kft)	sec	64

TABLE 4.2 REVISED AIRPLANE CHARACTERISTICS

		MEETS MISSION & HOVER
TOGW	lb(kg)	33524(15203)
WING AREA	$ft^2(m^2)$	300(27.87)
ENGINE SCALE (2 ENGINES)		2.135
MISSION RADIUS (DLI)	n. mi(Km)	150(277.8)
FUEL REQUIRED	lb(kg)	12200(5533)
FUEL FRACTION		.364
P_S (M.9/10kft/1g)	fps(mps)	1111(338.7)
N_z (M.6/10kft/P_S=0)	gs	5.35
ACCEL TIME (M.8-1.6/35kft)	sec	67

APPENDIX A

THE CONCEPTUAL DESIGN OF A VEO-VTOL EXHAUST NOZZLE

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J. Holowach

FINAL REPORT

FOR:

GENERAL DYNAMICS
FORT WORTH DIVISION
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THE CONCEPTUAL DESIGN OF A VEO–VTOL EXHAUST NOZZLE

FINAL REPORT

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1.0 PROGRAM SUMMARY

Conceptual studies were conducted to identify exhaust systems satisfying the complex VTOL, lift enhancement and cruise requirements of an advanced fighter aircraft. The preliminary design of one selected concept was developed in more detail including consideration of structures, kinematics, cooling and performance.

The resulting design is a two dimensional exhaust system featuring a two dimensional single ramp flowpath for cruise and STOL as well as an internally vectored flowpath for VTOL. A dual cowl flap provides A_8 and A_9 control and serves as a blocker during VTOL.

The nozzle is integrated with the aircraft's wing flap which is independently variable to provide partial jet vectoring up to ± 30 degrees. In addition, the system has an engine flow diverting system which is capable of supplying up to 30% of the engine flow to a wing spanwise blowing nozzle. In summary, the design satisfies all requirements for a VEO-VTOL exhaust system.

2.0 INTRODUCTION

The Vectored Engine Over-Wing (VEO) concept is a unique application of powered lift enhancement that has been under investigation by General Dynamics. This concept incorporates upper surface blowing, spanwise blowing, and vectored thrust. The basic approach utilizes a two-dimensional single expansion ramp exhaust nozzle that can provide for VTOL performance through 90° thrust vectoring. Scale model testing by General Dynamics has demonstrated significant performance benefits for the VEO concept, and the concept is now dependent on the development of an engine exhaust system design and installation that will function in a manner similar to that observed in the model tests. NASA is interested in developing such a nozzle design applicable to V/STOL aircraft. The first step requires the identification of the most promising nozzle concept and carrying it through the preliminary design stage to define a mechanically realistic VEO-VTOL exhaust system. This is the objective of the present program and the succeeding sections outline the procedures which were used to arrive at the required design. The formulation of a set of design requirements is given in Section 3.0. This is followed by the description in Section 4.0 of eight (8) candidate concepts. Section 5.0 presents a comparative evaluation and selection of the best concept. The report concludes with a preliminary design definition of the selected concept in Section 6.0.

3.0 DESIGN REQUIREMENTS

To provide a realistic basis for the conceptual designs, a set of requirements were assembled taking into account the needs of a supersonic fighter mission, an advanced engine and aircraft as well as VEO-VTOL system considerations.

3.1 Mission

A demanding mission was specified by General Dynamics for this program and consists of vertical takeoff and landing (VTOL), subsonic maneuver points, a supersonic dash leg out and subsonic cruiseback. A short takeoff and landing (STOL) capability was also specified as shown in Table 1. In addition the propulsion system was required to provide flow to auxiliary systems for aircraft pitch control or wing lift enhancement as described below.

3.2 Engine and Aircraft

The General Electric GE16VF19-D5 Variable Cycle Engine (VCE) was selected to satisfy all the mission requirements. As shown in Figure 1, this is a versatile propulsion system in which large amounts of bypass flow may be diverted into a Remote Augmentor Lift System (RALS) to provide pitch control and maintain aircraft stability during VTOL operation. This is accomplished by opening ports into the bleed manifold with a translating shroud and shutting off the bypass flow entering the rear nozzle with the variable aft VABI system.

Optionally, the same hardware is used to direct bypass flow into the spanwise blowing plenum and nozzle for wing lift enhancement. For this purpose, bypass flow would be shut off to the RALS system (with the forward translating shroud) and to the rear nozzle (with the aft VABI) and admitted into the spanwise blowing plenum and nozzle through valved ports, see Figure 2. The ADEN and STOL nozzles shown in Figures 1 and 2 were replaced by the conceptual nozzles designed for this program.

Nozzle integration guidelines were established by assuming the propulsion system is installed in the General Dynamics R-104 VEO-WING aircraft, Figure 3.

SUMMARY OF VEO NOZZLE OPERATING REQUIREMENTS

APPLICATION/SPEED	JET VECTOR ANGLE, δ_j (Deg)	POWER SETTING	SPANWISE BLOWING	SPANWISE VECTOR Λ_s (Deg)
o VERTICAL T.O. & LANDING	90 ± 15	ALL	NO	-
o STOL T.O. 0 ⟶ 200 KTS	± 30	MAX A/B	YES	40
o STOL LANDING 100 KTS	± 30	$\geq$ MIL	YES	40
o MANEUVER				
$.3 \leq M \leq .6$	± 20	MAX A/B	YES	40
$.6 < M \leq .95$	± 15	MAX A/B	NO	-
o CRUISE $M \approx .9$	$\leq 5^{\circ}$	MIL	NO	-
o SUPERSONIC DASH $.95 \leq M \leq 2.0$	0	MAX A/B	NO	-

TABLE 1

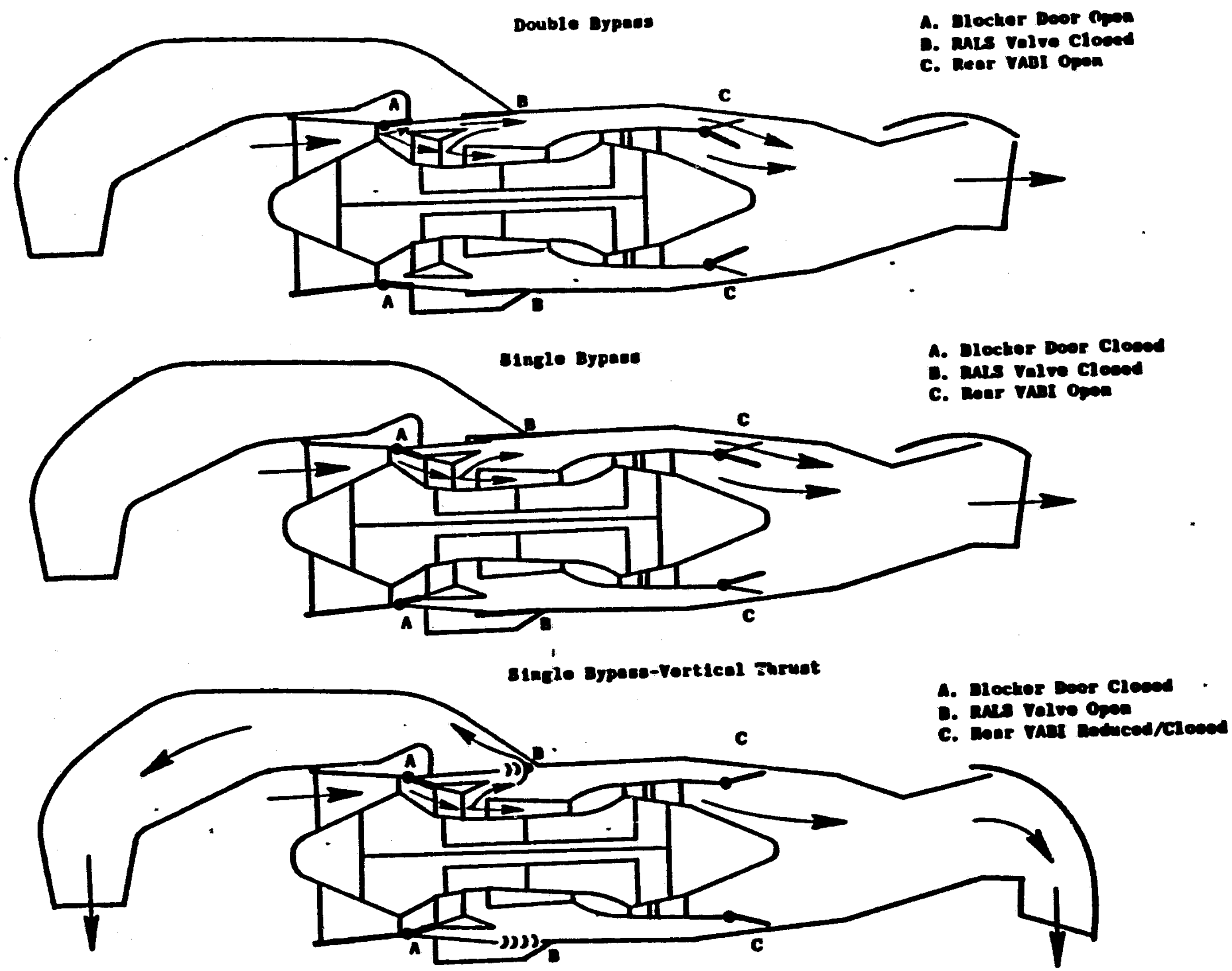


Figure 1. RALS/VCE Operational Modes.

INTEGRATED SPANWISE BLOWING SYSTEM

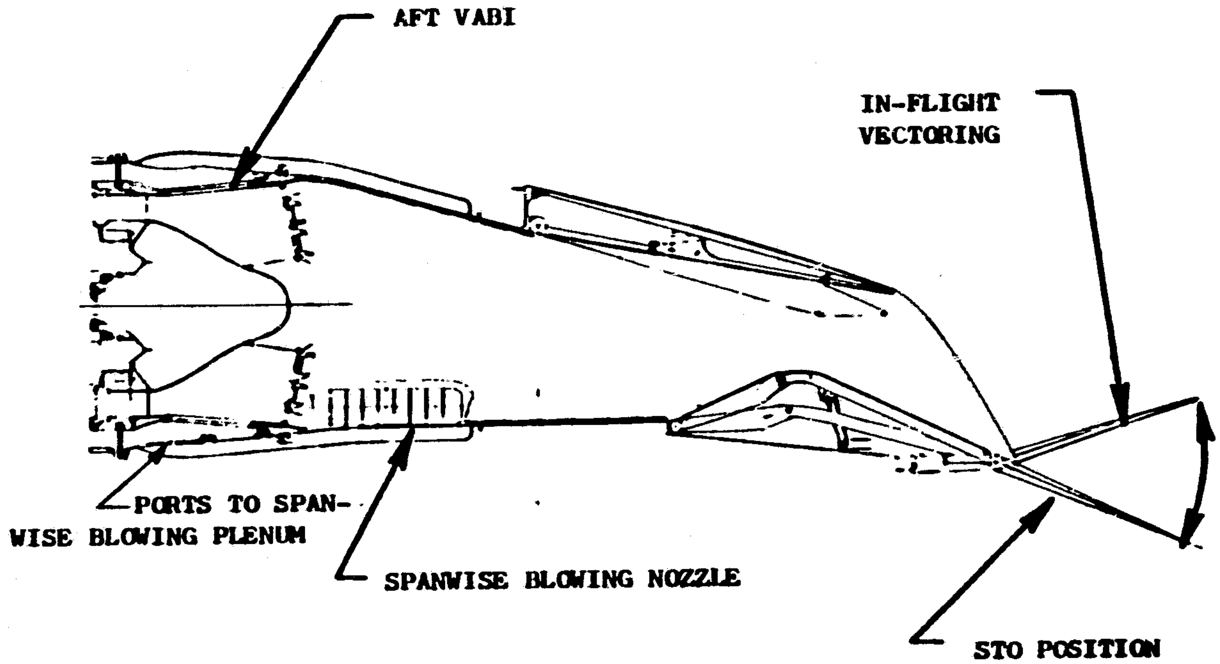


FIGURE 2

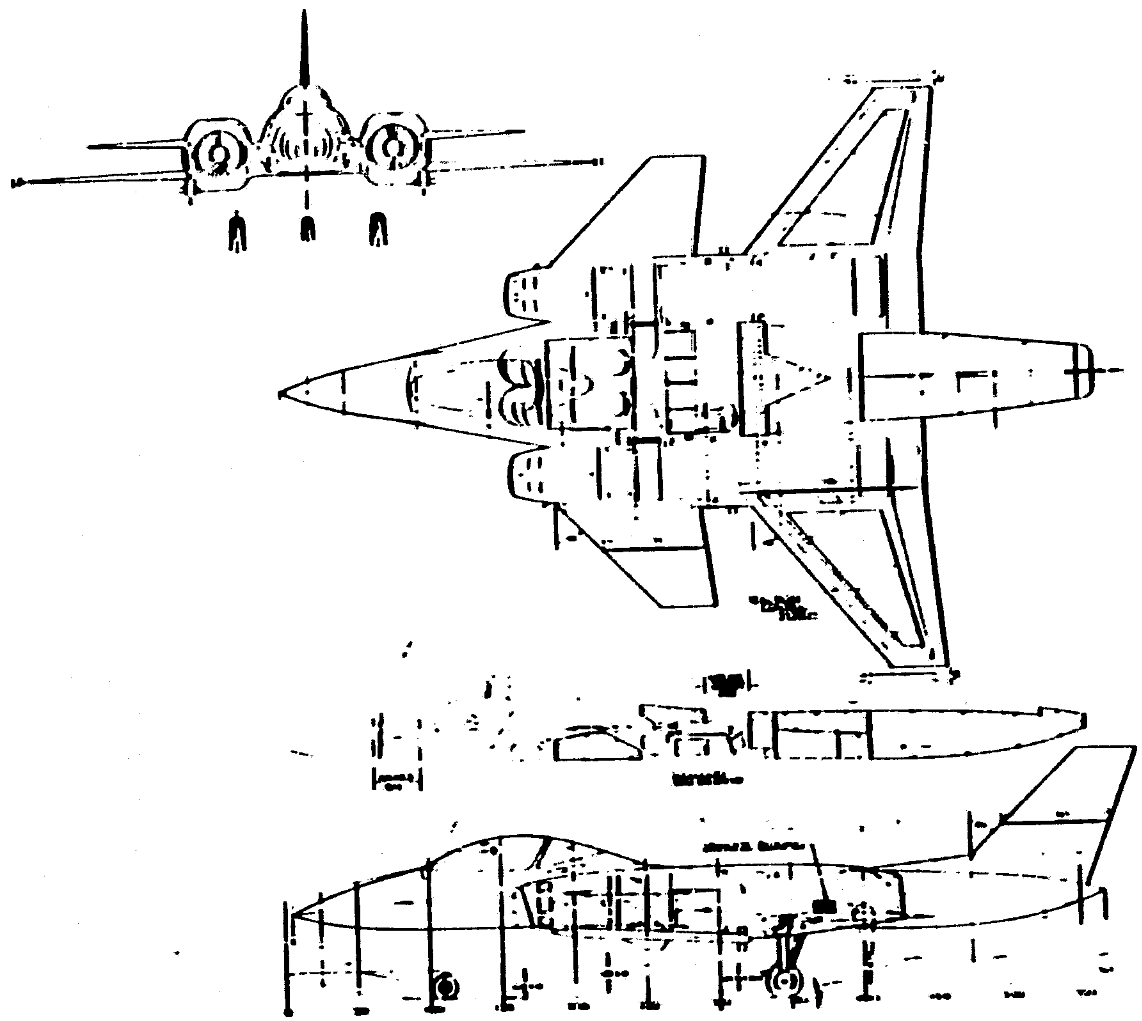


Figure 3. VEO-WING AIRPLANE CONFIGURATION R-104

The main region of interest for design purposes of this program is the NACELLE/WING area which is more clearly defined in Figure 4. The location of the spanwise blowing nozzle and wing flap size were specified in terms of wing chord (C). In addition, the jet span at the nozzle exit was determined from the naçelle on the R-104 aircraft and found to be 38.5 in. This dimension was applied to all conceptual designs.

To conform with the selected GE16/VF19-D5 engine, the transition section flowpath in the R-104 aircraft was modified to the one shown in Figure 4. This modification as well as cycle area requirements permitted further advantageous modifications in nacelle lines. The upper original line was modified to provide a more gentle nacelle boattail to mate with nozzle hardware. The bottom line was terminated earlier exposing more wing surface and thus eliminating the amount of nacelle structure that must be moved for the VTOL configured nozzle.

3.3 Nozzle

The engine and aircraft considerations were all translated into a set of key nozzle design requirements summarized in Table 2. High performance was to be maintained both internally as well as externally for all operating points. Two principle vector requirements were to be satisfied. The wing flap would be used to provide vectoring up to $\pm$ 30 degrees for STOL and inflight maneuvering. For VTOL, the vector angle must be continuously varied up to 105^{o} and trimmable $\pm$ 15 degrees at a nominal takeoff angle of 90 degrees. The VEO-VTOL nozzle was to be installed ahead of the wing flap hinge for lift enhancement. The spanwise blowing system is well upstream of the VEO nozzle and would be treated as a separate system. The remaining requirements are all aimed at evolving simple and low weight concepts. Engine cycle data was combined with aircraft and nozzle operating requirements to define the specific nozzle conceptual design requirements summarized in Table 3.

ENGINE/NOZZLE INSTALLATION

GD R-104 A/C NACELLE

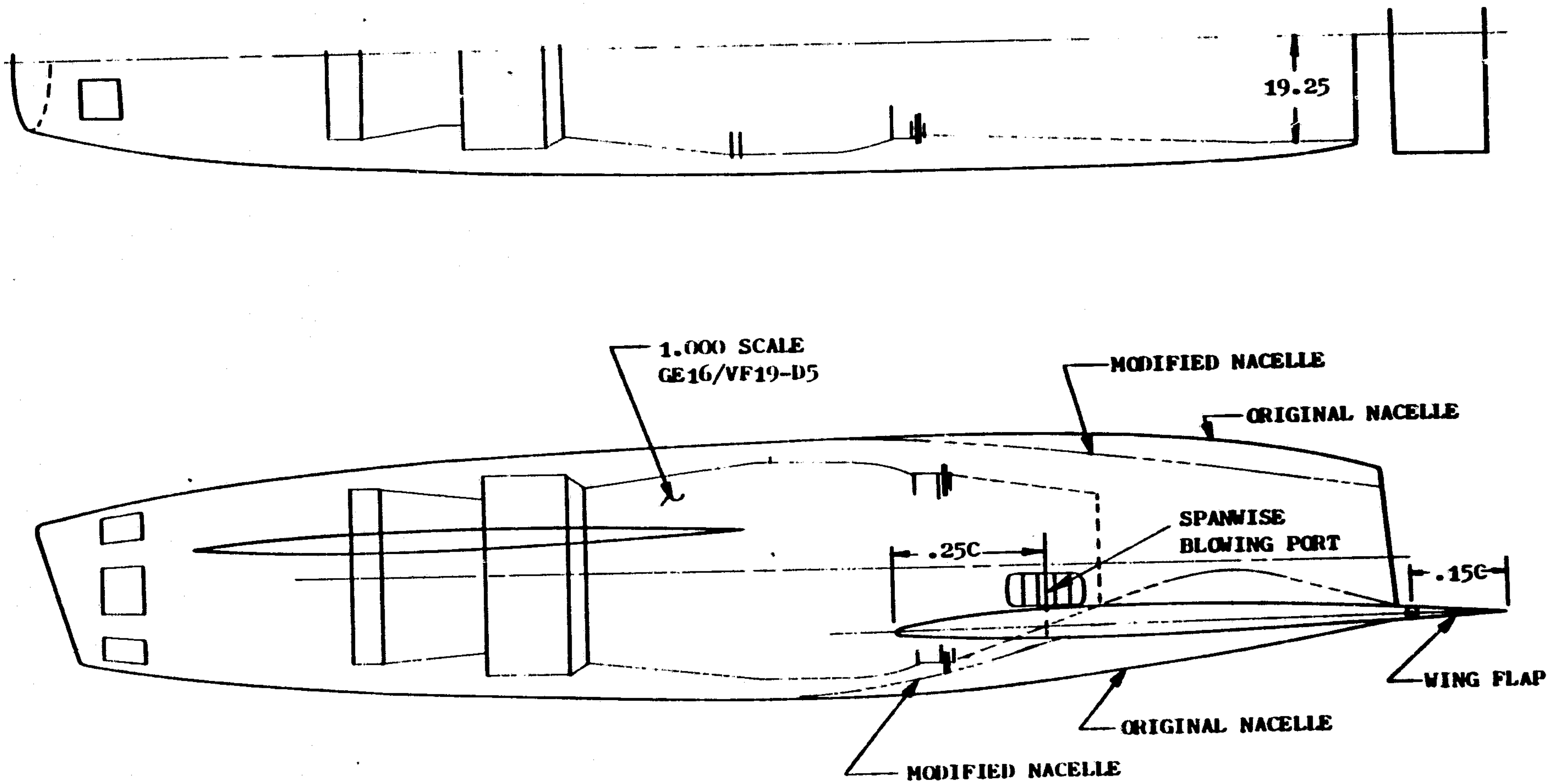


FIGURE 4

KEY DESIGN REQUIREMENTS

- MAINTAIN HIGH AERO PERFORMANCE IN ALL MODES
- KEEP NOZZLE BOATTAIL ANGLES REASONABLE
- 2 VECTOR MODES
  - STOL & INFLIGHT MANUEVER $\pm 30^0$ WITH AFT FLAP
  - VTOL $90^0 \pm 15^0$ (CONTINUOUS TO 105^0 DESIRED)
- MAINTAIN LOCATION OF NOZZLE EXIT AHEAD OF WING FLAP HINGELINE
- SPANWISE BLOWING WITH UP TO 30% OF ENGINE FLOW
- MINIMIZE NUMBER OF ACTUATION SYSTEMS
- AVOID MAJOR WING STRUCTURE <u>OR</u> MOVING STRUCTURAL PANELS
- LOW WEIGHT

TABLE 2

GD VEO-VTOL EXHAUST SYSTEMS

DESIGN REQUIREMENTS SUMMARY

GE 16/VF19 STUDY D5 ENGINE

NOZZLE JET SPAN -- 38.5 In.

FLIGHT CONDITIONS	ALTITUDE (FT.)	MACH NO.	δ_j (DEG)	POWER SETTING	$\frac{PT8}{Po}$	CYCLE Ae8	NOZZLE Ae8	CD8	H8	H9	$\frac{H9}{H8}$	REMARKS
VTOL	0	0	90	A/B	2.58	312	312	.95	8.5	8.5	1.0	W/RALS
VTOL	0	0	90	A/B	2.61	243	243	.95	6.6	6.6	1.0	W/RALS
STO	0	0	30	A/B	2.64	565	396	.98	10.5	11.2	1.07	W/30% SpanBlow
SLA	0	0	30	MIL	3.59	293	205	.97	5.5	6.6	1.20	
DASH	40K	1.6	0	A/B	12.10	437	437	.98	11.6	27.4	2.36*	
COMBAT	40K	1.6	0	A/B	11.77	469	469	.97	12.6	29.2	2.32*	
CRUISEBACK	40K	.9 .8	5	MIL	3.44	347	347	.97	9.3	11.0	1.18	

* External H9/H8 (all others internal)

TABLE 3

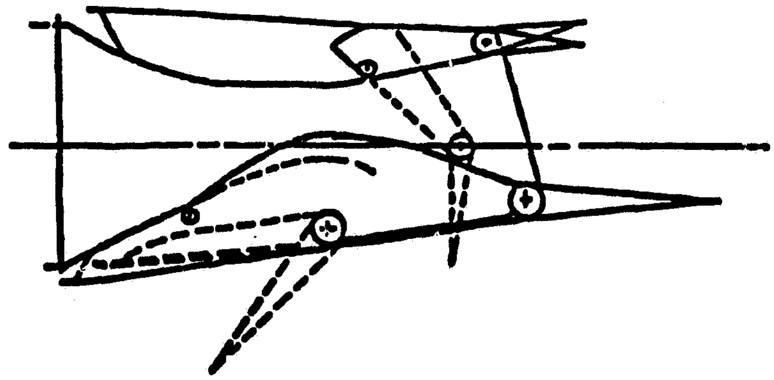
4.0 CONCEPTUAL DESIGN OF CANDIDATE NOZZLES

A series of conceptual designs were evolved to meet study requirements. These may be categorized as existing or new concepts, differing primarily in area control method and VTOL flowpath.

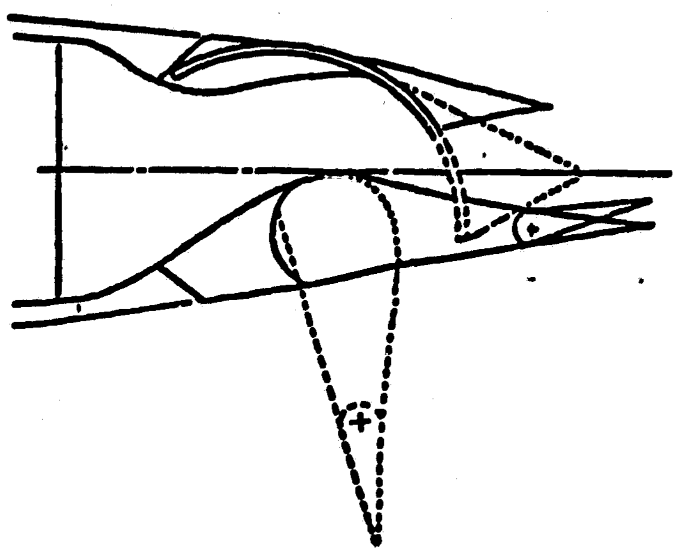
4.1 Previous Designs

Prior to this program General Electric conducted definition studies for a exhaust system. Figure 5 illustrates iterations through which the studies proceeded to meet VEO requirements. These initial designs all have shortcomings relative to VEO nozzles which require a specific relationship between the exhaust jet and wing trailing edge flap and must be installed on top of the wing forward of the trailing edge flap hinge point. As examples of undesirable nozzle features all these concepts require translation or rotation of nozzle components taking up over 1/2 of a wing section. This effectively eliminates any wing through-structure and requires complicated spar sections around the engine to support the wing and engine as well as large nozzle vectoring loads. The relatively high boattail angles associated with the rotating clamshell method for controlling flow area and vector angle are also unacceptable due to high drag and reduced thrust minus drag performance. Nevertheless, these concepts were included to evaluate a large range of candidate geometries and provide reference values for figures of merit.

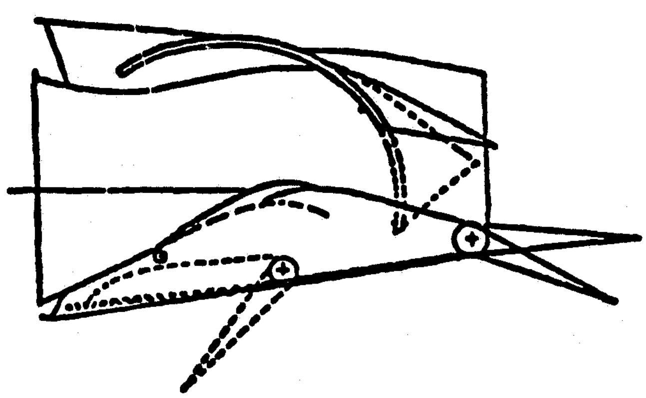
AVAILABLE VEO-VTOL DESIGNS



Concept #1



Concept #2



Concept #3

FIGURE 5

4.2 New Designs

The new concepts are all based on diverting engine flow through a ventral port in the wing for VTOL and using a pivotable cowl flap for area control during cruise and in-flight vectoring. The objective in using this approach is to:

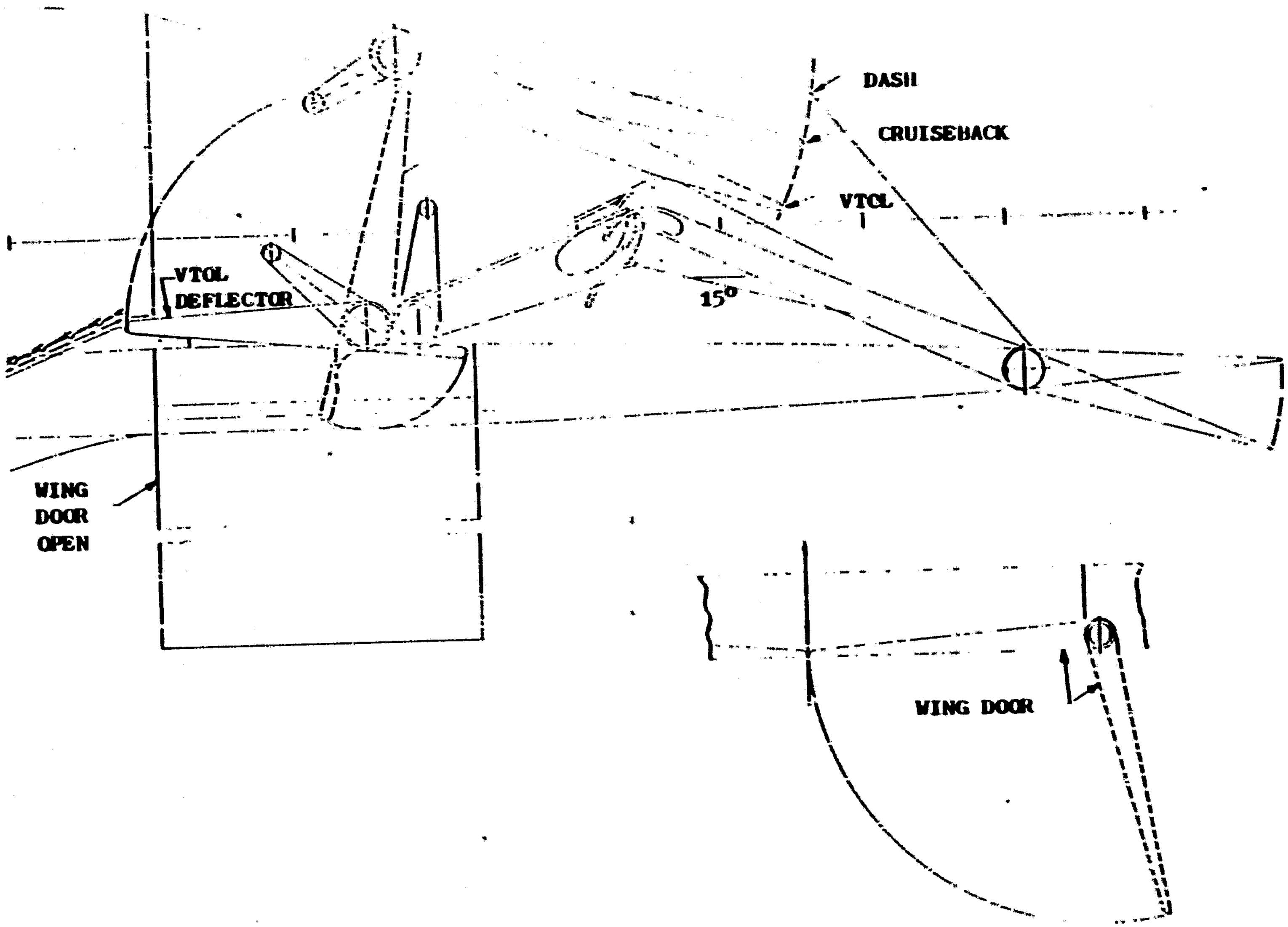
- Preserve as much wing through-structure as possible (as opposed to actuating large wing sections in concepts #1, #2, #3).
- Simplify the system mechanically
- Obtain shallower boattail angles for cruise.

Concept #4, (GE 4013266-166) shown schematically in Figure 6, exemplifies a simple mechanical arrangement. A one piece pivotable cowl flap is used for A8 and A9 control during cruise and serves to block the flow with the raised expansion ramp for VTOL. The VTOL deflector is also a simple rotating flap. Its main functions are to serve as a sealed blocker during cruise and STOL modes; and as a vectoring flap for VTOL. Two pivotable "bomb bay" type doors have been included for opening the VTOL port on the bottom side of the wing.

In Concept #5 (GE 4013266-167), Figure 7a, A8 and A9 are independently controlled. A linear hydraulic actuator is used for positioning the primary flap. A rotary hydraulic actuator is mounted on the primary flap and is used for setting A9. On this basis, together with a properly positioned expansion ramp, (15° for cruise, nominally 30° for STOL) the internal flowpath can be tuned to achieve maximum possible performance for all cruise and STOL power settings.

For VTOL, the expansion ramp is raised to its maximum angular displacement as shown in Figure 7b and, together with the cowl, blocks and diverts the flow internally into the ventral port. The VTOL deflector is supported by pivots and drive system housed in two localized fairing sections that extend through the wing's bottom surface. A pivotable flap fairs with the wing's bottom surface when stowed and controls vector angle when deployed. The rotating deflector and pivoting flap are independently controlled to provide any combination of A8 and vector angle when in VTOL mode. Accordingly, Concept #5 represents a fully variable concept capable of maximum internal performance at any flight condition.

VEO-VTOL CONCEPT #4



WING DOOR
AFT LOOKING FORWARD

FIGURE 6.

VEO-VTOL CONCEPT #5

STOL/CRUISE POSITION

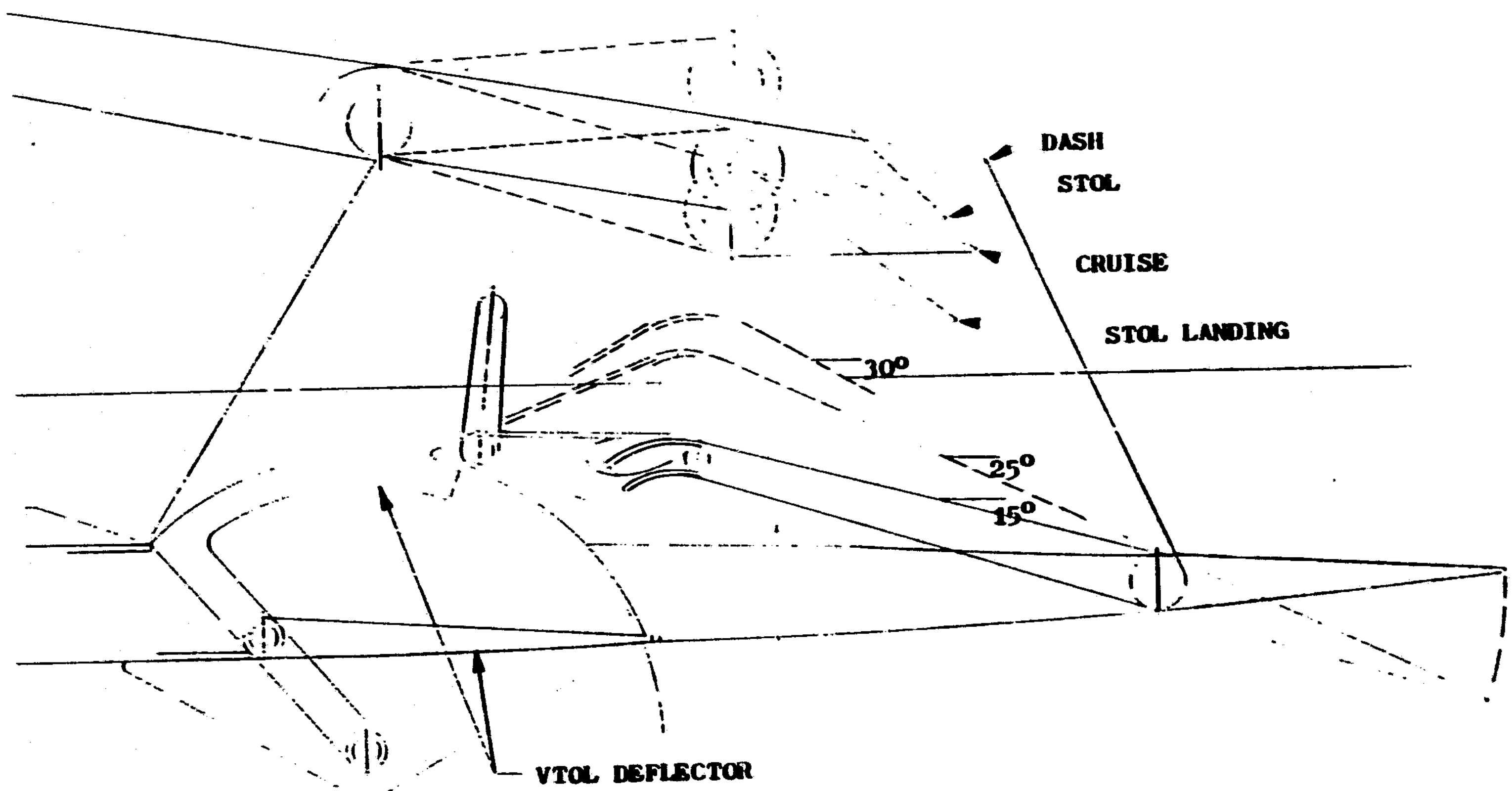


FIGURE 7a

VEO-VTOL CONCEPT #5

VTOL POSITION

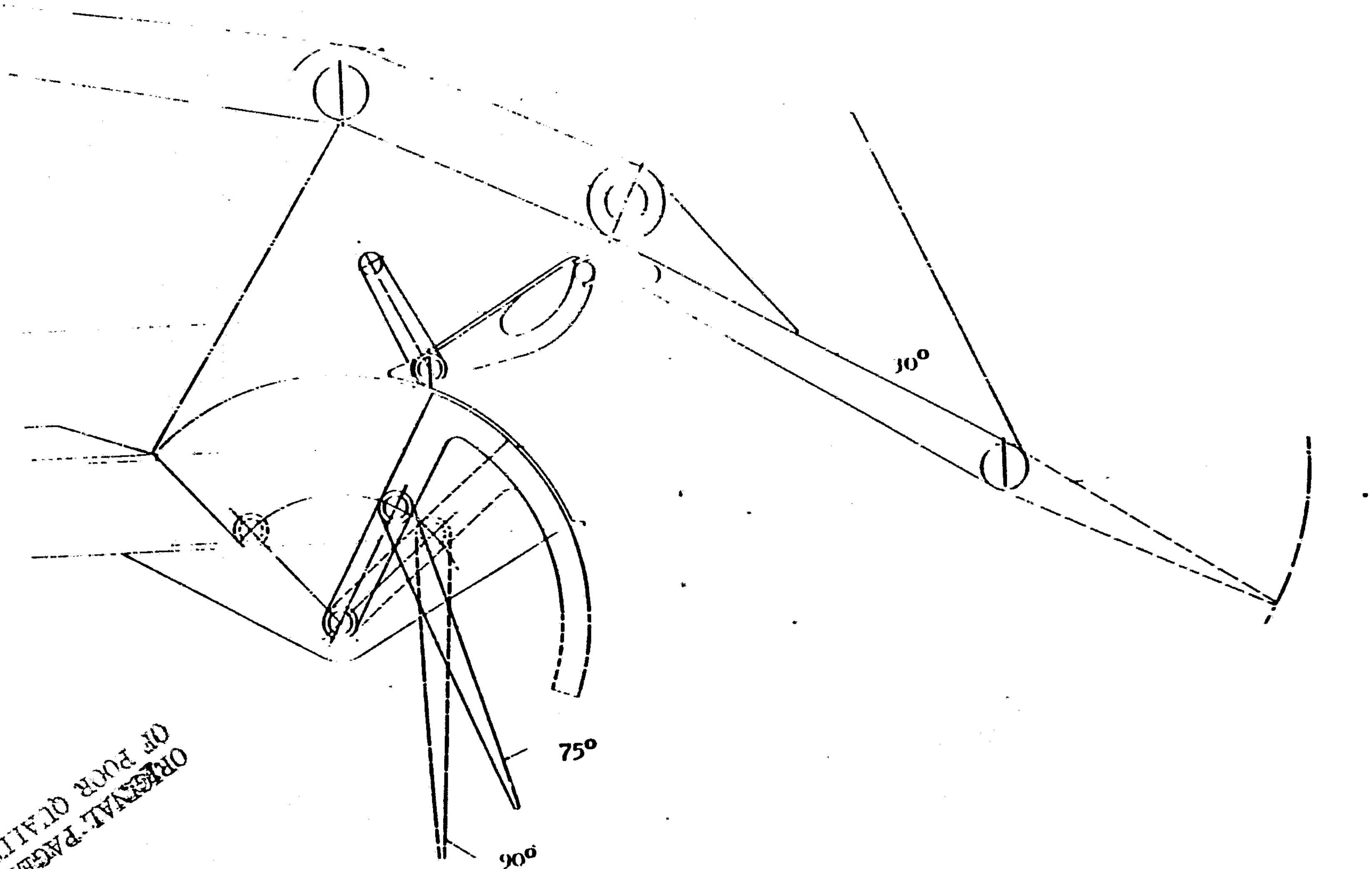


FIGURE 7b

Figure 8 presents Concept #6 (GE 4013266-168) which has the same expansion ramp design as concepts #4 and #5 but differs in cowl flap and VTOL systems. The cowl secondary flap has been scheduled as a function of primary flap position, thus requiring only one actuation system (Concept #5 requires two actuation systems) to obtain area variation and provide blocking for VTOL. Performance would be sacrificed at some operating conditions to realize this reduction in control complexity.

The VTOL system for concept #6 is made up of a large pivoted flap and a smaller pivoted flap to provide sealed blocking and wing bottom surface , respectively, when stowed. The large flap has a large radius contour to provide coanda turning for the VTOL flow. The primary function of the smaller aft flap is to control A8. However, it also aids flow turning for high vector angles where the coanda effect has been reduced.

Concepts #7 and #8 (GE drawings 4013266-169 and -170) differ from previous concepts in the method for achieving VTOL flow diversion and deflection, see Figures 9 and 10. Both concepts hold VTOL throat area approximately constant when vectored 90 ± 15 degrees. GE studies and tests with VTOL exhaust systems has established that very fast response thrust modulation is possible over a broad range by controlling engine speed and augmentor fuel flow. This alleviates the need for variable A8 during VTOL and substantially reduces the structural and control complexity for the VEO-VTOL exhaust system.

Concept #7, Figure 9, uses an internally deployed reverser type blocker which forms the internal flowpath for cruise flight conditions and blocks and turns the flow for VTOL mode. A pivoted flap fairs with the bottom wing surface when stowed and relies on coanda turning to control vector angle when deployed. Consideration was also given to the possibility of linking the vectoring flap pivot to the blocker and providing positive flow deflection (as opposed to coanda turning) for thrust angle control. However, mechanical and structural arrangements could not be defined with acceptable VTOL flow paths. Accordingly, at the present time, it appears that Concept #7 must use a coanda type flap to get continuous vectoring from 45 to 105 degrees. The remaining expansion ramp and cowl flap components for #7 are the same as that used in Concept #6.

VEO-VTOL CONCEPT #6

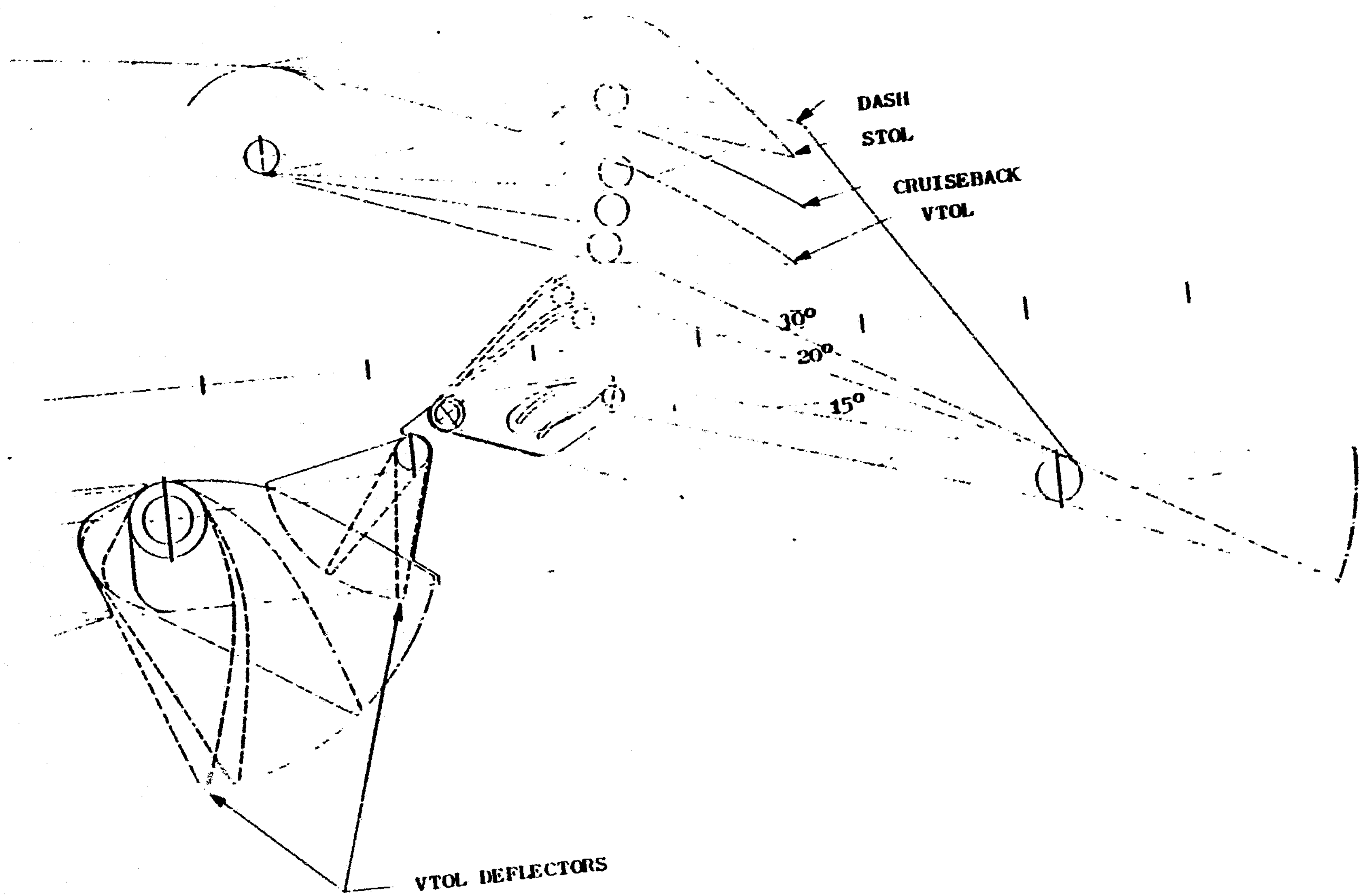


FIGURE 8

VEO-VTOL CONCEPT #7

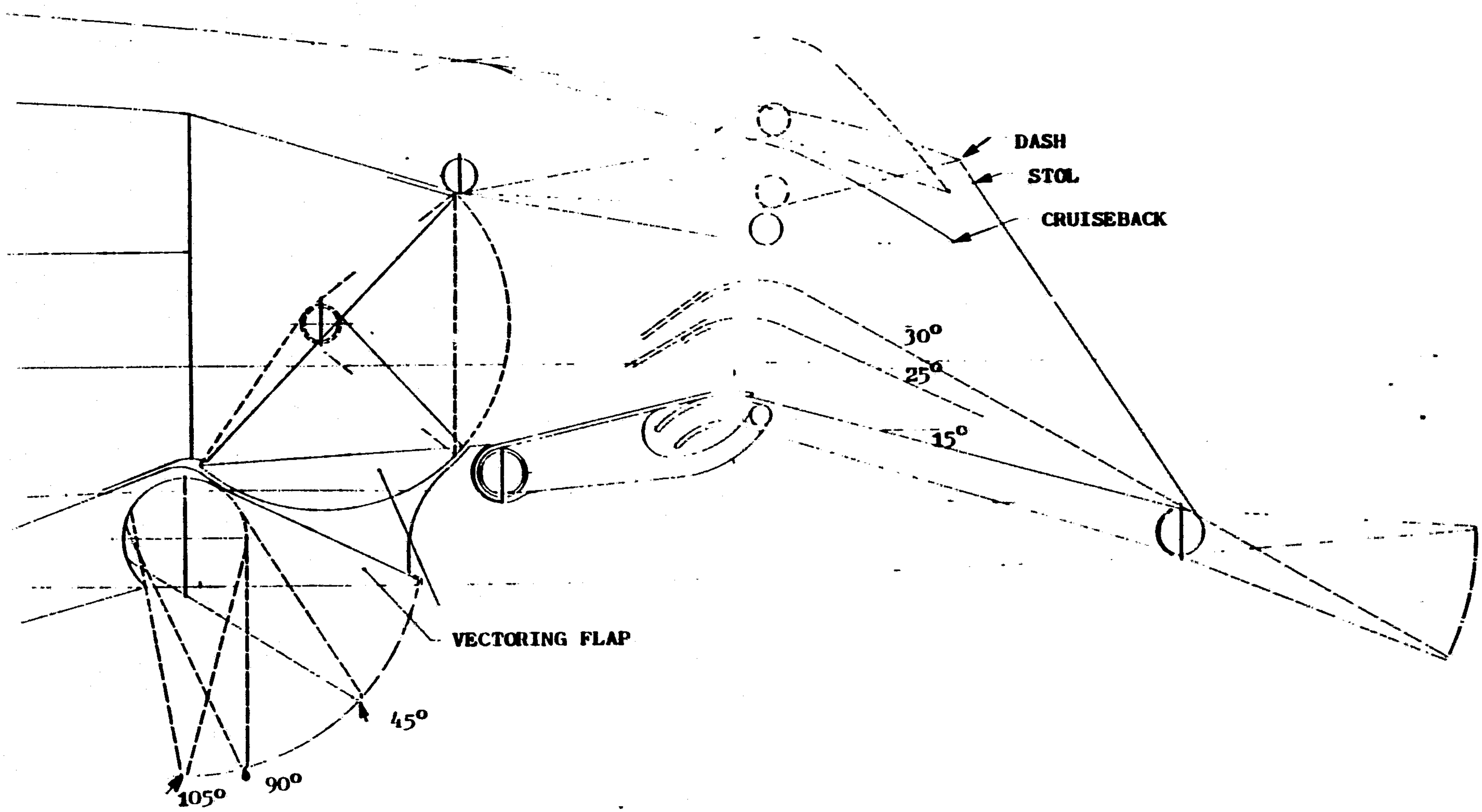


FIGURE 9

VEO-VTOL CONCEPT #8

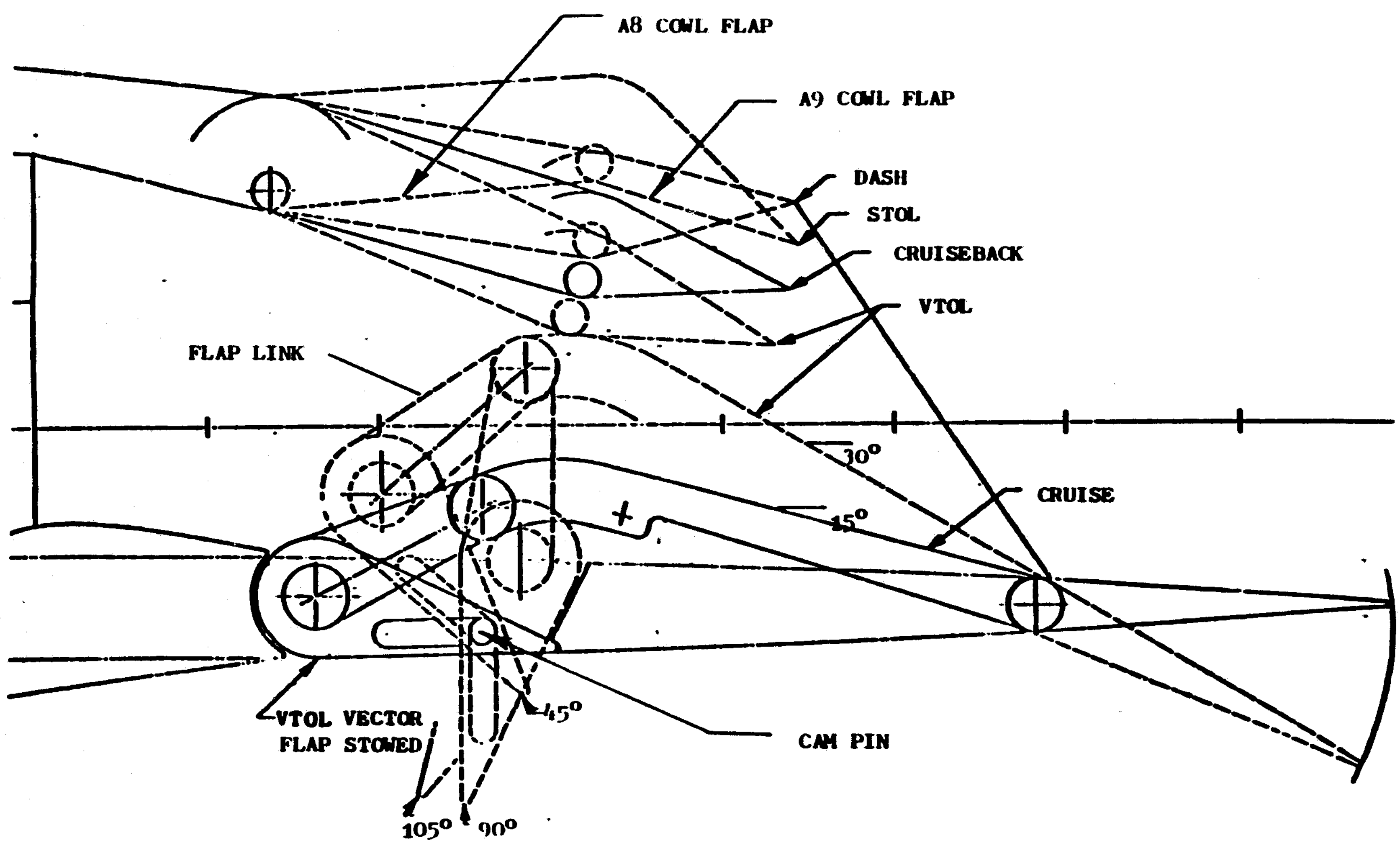


FIGURE 10

Concept #8, Figure 10, represents another step towards control simplification by combining expansion ramp and VTOL functions. Only two actuation systems are required to provide all the necessary nozzle settings. The first is used to drive the A8 and scheduled A9 cowl flaps. This flap system serves to control area during cruise and STOL modes and serves to block the flow during VTOL. The second actuation system positions the three lower flaps with respect to the aft expansion ramp pivot and a grounded cam pivot that guides the motion of the lowermost VTOL flap. These three flaps are linked together forming the nozzle expansion ramp and a two flap blocker/deflection section. The uppermost flap link of this pair forms a convergent internal flowpath for cruise and STOL modes. It also serves as a flow diverter for VTOL. The lowest flap is the final flow deflector for VTOL vectoring. While these jet deflection flaps could be cammed to provide motion in any of a number of ways a typical sequential motion would proceed as follows. Initially, the expansion ramp would be raised to its uppermost (30 degrees) position pulling with it the flap link and pivoting the deflector flap about its cam pin. As actuation continues, the expansion ramp remains fixed in its uppermost position while the flap link and vectoring flap continue to increase flow area and deflection angle to its VTOL or 90 degree position. Simultanfously, the cowl flaps would be moved to their flow blocking position to complete the flow switching process and form the VTOL flowpath. In VTOL mode, a small increase or reduced actuation of the lower flaps would only change the VTOL vector angle $\pm$ 15 degrees.

5.0 CONCEPT SELECTION

The selection process consisted of establishing a broad set of performance and mechanical design characteristics for the conceptual designs. These were compared on a relative basis to narrow the field down to concepts #4 and #8. Following design modifications to overcome aerodynamic objections, Concept #8 was selected for preliminary design.

5.1 Comparative Analysis

To provide a quantitative basis for comparison a broad range of characteristics were established which define nozzle performance and mechanical features. Performance in the form of thrust coefficients was determined for each of seven operating points. Nozzle leakage and cooling derates were then estimated using conceptual design definitions of leakage flowpaths and cooled surfaces. Both derates are essentially equivalent for all designs as shown in Tables 4 and 5. This resulted in derated thrust coefficients, Table 6, that are also generally equivalent leading to the conclusion that there is no justification for selecting one concept over another on the basis of performance.

Mechanical features are summarized in Tables 7 and 8 for previous and new concepts, respectively. Each table presents characteristics ranging from actuation needs to performance estimates and generalized assessments. For the new concepts, Table 8, two or three optional actuation arrangements are possible leading to related variations in weight estimates. As a typical example, for Concept #4, the cowl flap may be a simple, one piece flap requiring only one out of three actuation systems. The other two are used to vary the lower expansion ramp and VTOL deflector. This combination has the lightest actuation weight of 64 lbs, and a total weight of 610 lbs. If the cowl flap has a variable divergent flap driven according to an A8 schedule, the number of actuation systems is still three but the actuation weight increases to 83 lbs. and the total weight to 629 lbs. If the divergent flap is independently variable with its own actuator, the number of actuators required increases to four and associated actuator weight becomes 93 lbs. This brings the total weight for Concept #4 to 639 lbs. The remaining concepts are presented with both the scheduled A9 flap and independently variable flap options.

VEO–VTOL EXHAUST SYSTEM CONCEPTS
NOZZLE LEAKAGE LOSS, $\Delta CFGL$

	VTOL		STOL				
CONCEPT	TAKEOFF	LANDING	TAKEOFF	APPROACH	DASH	COMBAT	CRUISEBACK
#1	.01	.01	.01	.01	.01	.01	.01
#2	.01	.01	.01	.01	.01	.01	.01
#3	.02	.02	.01	.03	.01	.01	.02
#4	.01	.01	.01	.02	.01	.01	.01
#5	.01	.02	.01	.02	.01	.01	.01
#6	.01	.02	.01	.02	.01	.01	.01
#7	.01	.02	.01	.02	.01	.01	.01
#8	.01	.01	.01	.02	.01	.01	.01

TABLE 4

VEO–VTOL EXHAUST SYSTEM CONCEPTS
NOZZLE COOLING LOSS, $\Delta CFGC$

	VTOL		STOL				
CONCEPT	TAKEOFF	LANDING	TAKEOFF	APPROACH	DASH	COMBAT	CRUISEBACK
#1	.02	.02	.02	.02	.01	.01	.01
#2	.02	.02	.02	.02	.01	.01	.01
#3	.02	.02	.02	.02	.01	.01	.01
#4	.02	.02	.02	.02	.01	.01	.01
#5	.02	.02	.02	.02	.01	.01	.01
#6	.02	.02	.02	.02	.01	.01	.01
#7	.02	.02	.02	.02	.01	.01	.01
#8	.02	.02	.02	.02	.01	.01	.01

TABLE 5

VEO–VTOL EXHAUST SYSTEM CONCEPTS
NOZZLE PERFORMANCE, CFG
DERATED FOR LEAKAGE, COOLING LOSSES

	VTOL		STOL				
CONCEPT	TAKEOFF	LANDING	TAKEOFF	APPROACH	DASH	COMBAT	CRUISEBACK
#1	.94	.94	.95	.96	.96	.97	.96
#2	.94	.94	.95	.96	.96	.96	.96
#3	.93	.93	.94	.94	.95	.96	.95
#4	.94	.94	.94	.96	.96	.96	.96
#5	.94	.94	.95	.95	.96	.96	.96
#6	.94	.93	.95	.92	.96	.96	.96
#7	.94	.93	.95	.92	.96	.96	.96
#8	.94	.94	.95	.93	.96	.96	.96

TABLE 6

PREVIOUS
VEO NOZZLE CONCEPTS
MECHANICAL SUMMARY

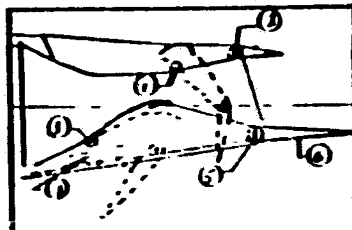
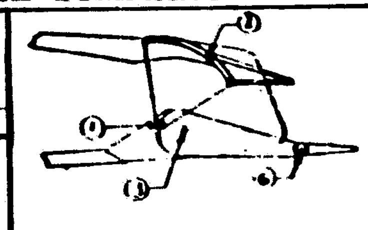
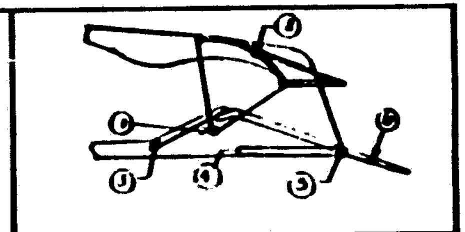
			
TYPE NOZZLE	CLAMSHELL/SINGLE RAMP DESIGN CONCEPT -#1	CLAMSHELL/TANDEM RAMP DESIGN CONCEPT - #2	CLAMSHELL/TRANSLATING RAMP DESIGN CONCEPT - #3
DRAWING NUMBER	4013237-603	4013237-597	4013237-660
ACTUATION SYSTEMS	TYPE: MOM OR FORCE	TYPE: MOM OR FORCE	TYPE: MOM OR FORCE
A8 ①	HYD. CYL. 30,000 LBS.	POWER HINGE 65,500 In-LBS.	HYD. CYL. 12,500 LBS.
A8/VECTORING ②	POWER HINGE 130,000 In-LBS.	HYD. CYL. 12,500 LBS.	HYD. CYL 12,500 LBS.
VECTORING ③	POWER HINGE 280,000 In-LBS.	POWER HINGE 285,000 In-LBS.	POWER HINGE 65,000 In-LBS.
VECTORING ④	SCREW JACK 10,000 LBS.	----------	SCREW JACK 10,000 LBS.
VECTORING ⑤	POWER HINGE 100,000 In-LBS.	----------	POWER HINGE 100,000 IN-LBS.
NO. ACT. SYSTEMS	5	4	5
ACTUATION WEIGHT	163 LBS.	90 LBS.	107 LBS.
TOTAL WEIGHT	781	680	853
COMPLEXITY	HIGH	MEDIUM	HIGH
COOLED SURFACE AREA	7760 In.^{2}	7260 In.^{2}	8350 In.^{2}
% COOLING FLOW	17.6	16.5	18.9
LEAKAGE AREA	2.96 In.^{2}	2.26 In.^{2}	5.4 In.^{2}
AFT FLAP ⑥	ENGINE MOUNTED	ENGINE MOUNTED	ENGINE MOUNTED
A.F. STRUCTURAL INTERFERENCE	SEVERE	SEVERE	SEVERE

TABLE 7

NEW
VEO NOZZLE CONCEPTS
MECHANICAL SUMMARY

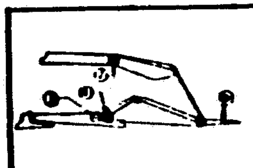
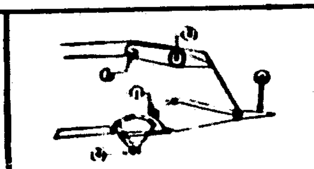
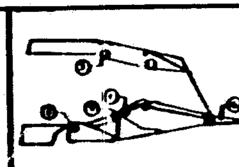
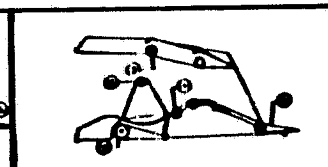
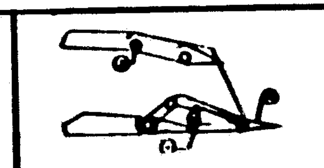
					
TYPE NOZZLE	ROTATING VENTRAL FLAP DESIGN CONCEPT - #4	ROTATING VENTRAL DEFLECTOR DESIGN CONCEPT - #5	DESIGN CONCEPT - #6	DESIGN CONCEPT - #7	DESIGN CONCEPT - #8
DRAWING NUMBER	4013266-166	4013266-167	4013266-168	4013266-169	4013266-170
ACTUATION SYSTEMS	TYPE: NUM OR FORCE	TYPE: NUM OR FORCE	TYPE: NUM OR FORCE	TYPE: NUM OR FORCE	TYPE: NUM OR FORCE
A8 ①	HYD. CYL. 30,000 LBS	HYD. CYL. 30,000 LBS.	HYD. CYL. 50,000 LBS.	HYD. CYL. 30,000 LBS.	HYD. CYL. 30,000 LBS.
A8/VECTORING ②	HYD. CYL. 30,000 LBS.	HYD ROTARY ACT. 65,000 In-LBS.	----------	----------	----------
VECTORING ③	HYD. CYL. 20,000 LBS.	HYD. CYL. 30,000 LBS.	HYD. CYL. 40,000 LBS.	HYD. CYL. 30,000 LBS.	HYD. CYL. 30,000 LBS.
VECTORING ④	----------	HYD. CYL. 20,000 LBS.	HYD. CYL. 20,000 LBS.	HYD. CYL. 20,000 LBS	----------
VECTORING ⑤	----------	----------	HYD. CYL. 30,000 LBS.	HYD. CYL. 30,000 LBS.	----------
NO. ACT. SYSTEMS	4/3/3	4/3	5/4	5/4	3/2
ACTUATION WEIGHT	93/83/64 LBS	91/81 LBS.	86/76 LBS.	86/76 LBS.	58/48 LBS.
TOTAL WEIGHT	638/628/610	656/646	637/627	677/667	508/508
COMPLEXITY	MEDIUM/LOW	MEDIUM	MEDIUM	MEDIUM	MEDIUM
COOLED SURFACE AREA	6610 In.^{2}	7400 In.^{2}	7200 In.^{2}	7000	7000
% COOLING FLOW	15.0	16.8	16.3	17.8	17.8
LEAKAGE AREA	3.08 In.^{2}	3.61 In.^{2}	4.39 In.^{2}	3.91 In.^{2}	2.88 In.^{2}
AFT FLAP ⑥	WING MOUNTED	WING MOUNTED	WING MOUNTED	WING MOUNTED	WING MOUNTED
A.F. STRUCTURAL INTERFERENCE	MINOR	MINOR	MINOR	MINOR	MINOR

TABLE 8

Features showing significant differences between previous and new concepts can be condensed to the following items:

	PREVIOUS DESIGN	NEW DESIGNS
Number of actuators	4 - 5	2 - 4
Total weight	680# - 853#	588# - 677#
Complexity	Medium - High	Low - Medium
Aft Flap Mounting	Engine	Wing
Airframe Structure Interference	Severe	Minor

The new concepts are clearly more viable than the previous designs for all these features. This summary also indicates that within each category the final selection will be based on the first three items within which differences still appear. On this basis, initial selection converged on two concepts - #4 and #8. #4 had low complexity but slightly higher weight. #8 had medium complexity, but lowest weight. However, both selected designs had objectionable characteristics requiring modification.

The VTOL deflector flap for Concept #4 was designed to be internally stowed, to remain a reasonably sized structure. Accordingly, additional pivotable bomb bay type doors were provided to cover the VTOL port. When these doors were opened for VTOL, see Figure 6, they interfere with the flow over the bottom wing surface reducing wing lift. Therefore, to remain a viable candidate the pivotable bomb bay type doors would have to be replaced with a non-interfering system.

The objection to Concept #8 is due to the fact that a part of the exhaust flow is diverted through the VTOL port during STOL. General Dynamics analyses indicated that this VTOL flow reduces the effectiveness of the VEO-VTOL system in obtaining lift enhancement. Therefore, a request was made to consider a modification to Concept #8 and have all jet flow directed over the top of the expansion ramp for STOL.

5.2 Concept Modifications and Selection

The bomb bay doors were redesigned for Concept #4 to be translatable rather than pivotable as originally conceived, Figure 11. The two doors actuate away from each other in a spanwise direction along the bottom wing surface to uncover the VTOL port. They could be actuated either under the bottom wing surface or buried within the casing section if space permits.

IMPROVED VEO-VTOL CONCEPT #4
WITH TRANSLATING VTOL DOORS

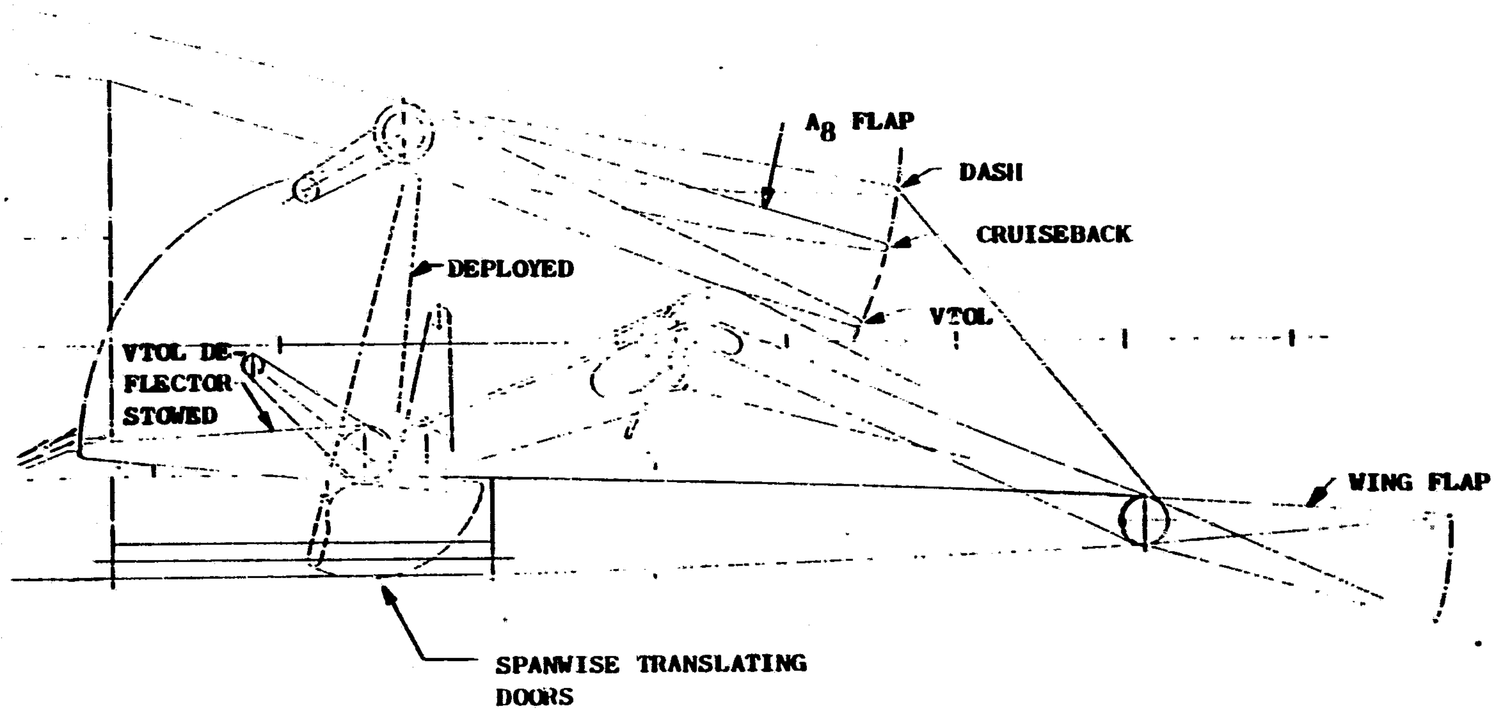


FIGURE 11

In Concept #8, Figure 10, the VTOL deflector breaks seal and uncovers the VTOL port as soon as the nozzle expansion ramp is raised to its STOL position. As a result, this concept as originally conceived would have part of the flow vectoring over the ramp and the remainder vectoring through the VTOL port during STOL. The objection is that this VTOL port flow also interferes with VEO lift effects. Two different methods were considered for maintaining a VTOL port seal during STOL. One was to translate the upstream primary and deflector flaps relative to the ramp and thus disengage the ramp and deflector motions during STOL. The other was to keep the present flap design and provide a translating and pivoting seal that would follow the deflector flap motion during STOL. The mechanical and structural problems associated with the latter approach would require considerably more effort to resolve. Consequently, it was concluded that a translatable flap would best satisfy the modification needs of Concept #8.

The modified approach features operation of the two members with a single actuation system such that the VTOL vector flap moves only slightly, with the seal engaged, during motion of the expansion ramp between 15 degrees and 30 degrees, see Figures 12, 13 and 14. As the expansion ramp angle increases from 30 degrees to 45 degrees, the VTOL vector flap begins to open and the expansion ramp dwells at 45 degrees as the vector flap rotates full travel to the 110 degree position.

Each of these members dwells during a portion of the actuation stroke. The VTOL vector flap dwells during the initial expansion ramp motion by use of a toggle link mechanism, and the expansion ramp dwells at 45 degrees during rotation of the vector flap by use of a cam dwell. This approach still uses only a single actuator to drive the lower flaps and consequently has the simplest control system and lowest weight of all concepts. On this basis it was selected and approved for preliminary design by General Dyndmics and NASA Ames Research Center.

IMPROVED VEO-VTOL EXHAUST CONCEPT #8

(1) CRUISE

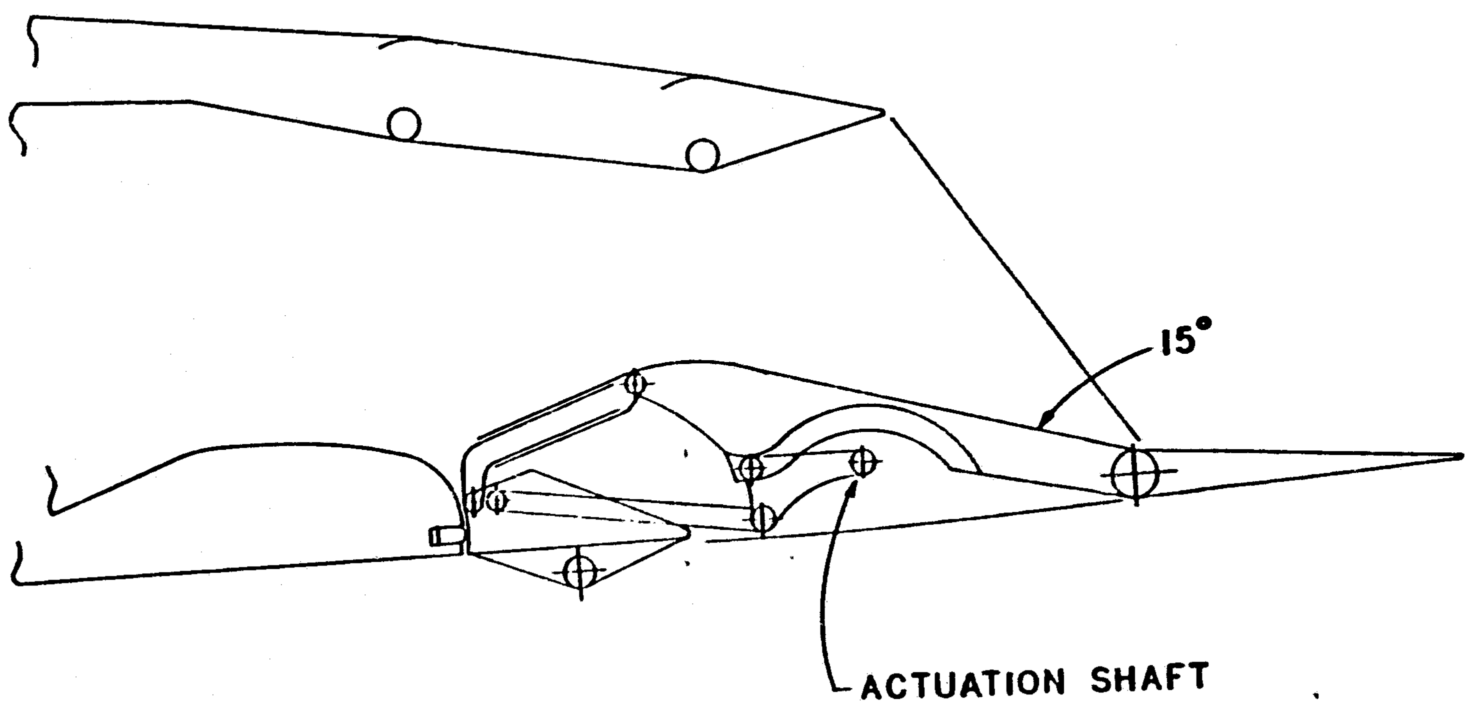


FIGURE 12

IMPROVED VEO-VTOL EXHAUST CONCEPT #8

(2) STOL

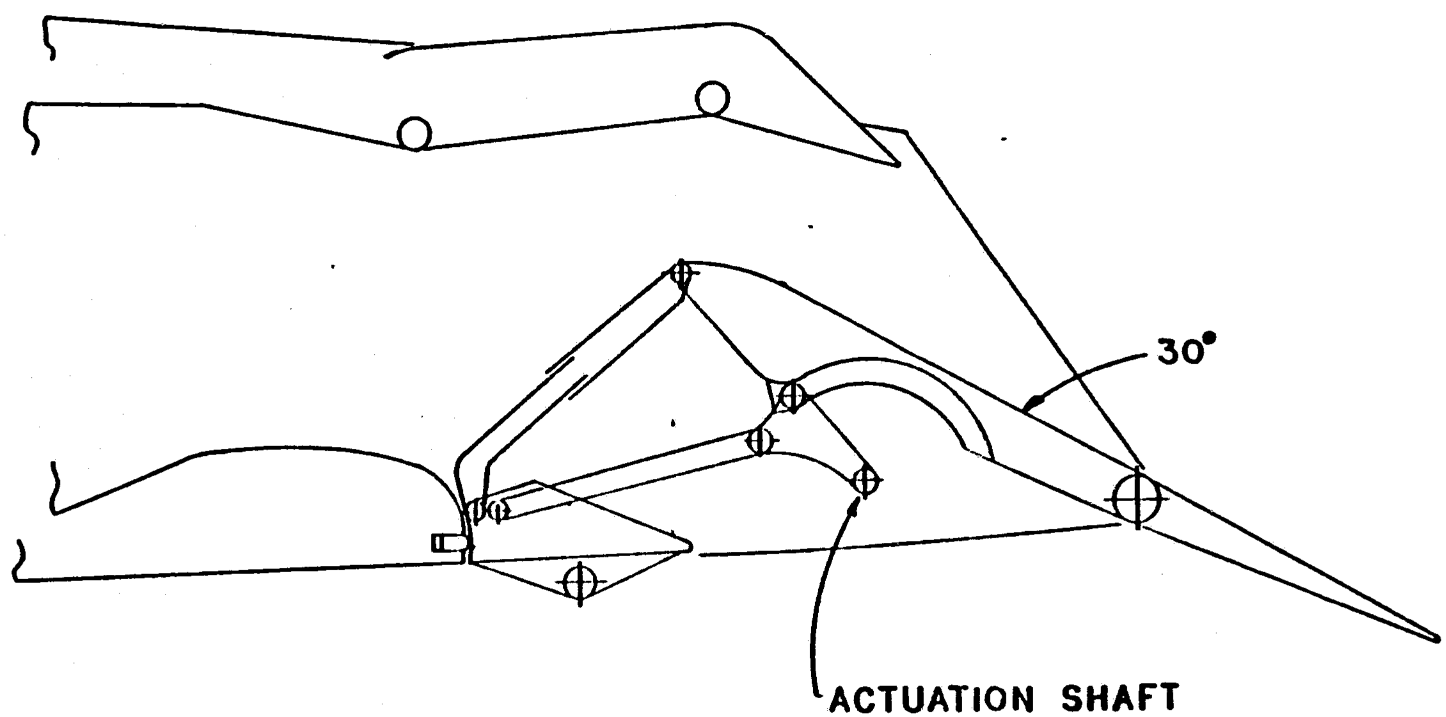


FIGURE 13

IMPROVED VEO-VTOL EXHAUST CONCEPT #8

3 VTOL

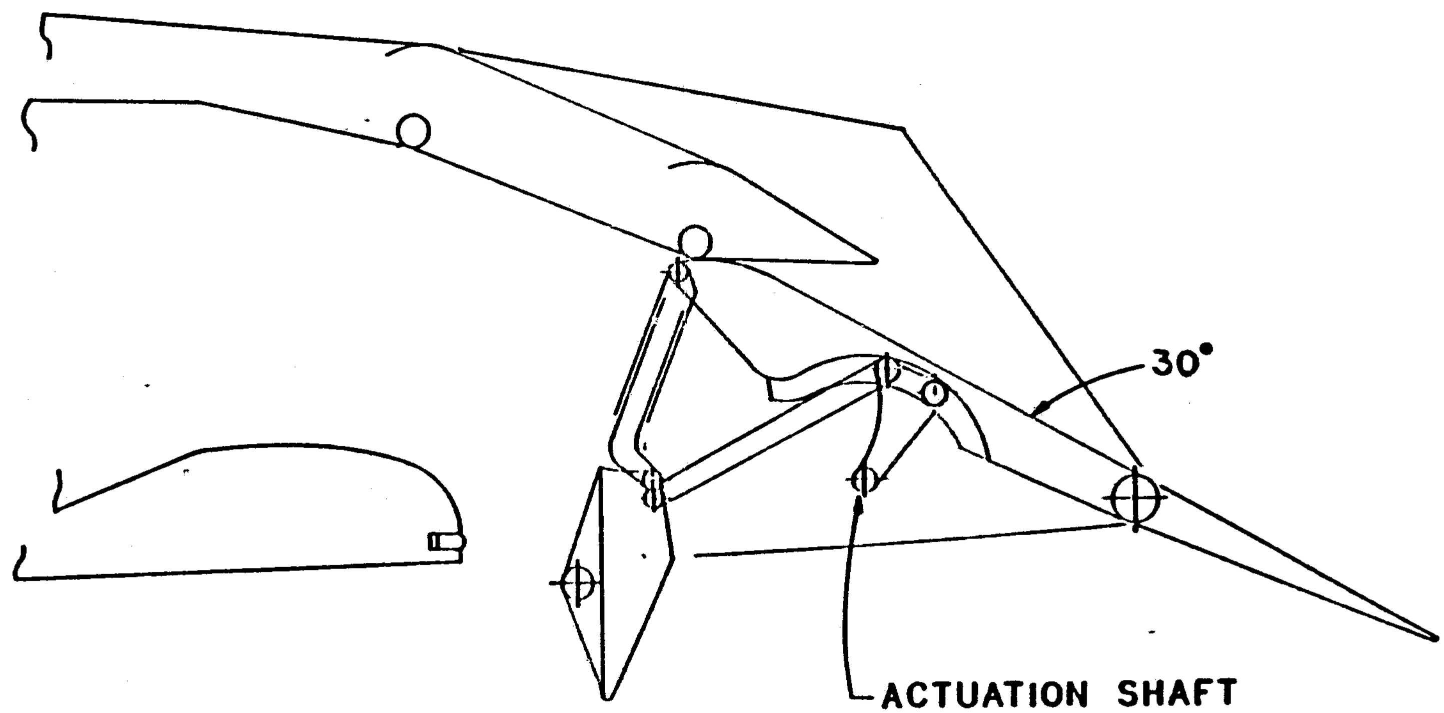


FIGURE 14

6.0 PRELIMINARY DESIGN OF SELECTED CONCEPT

The preliminary design study began with a detailed examination of kinematics and flowpath during transition from cruise to VTOL mode. Loads were determined for nozzle components including flaps, hinges, cams and links for several points along the motion. It was determined that the VTOL deflector flap support became unstable at its 90 degree position. On further study, the conclusion was reached that a mechanically supported deflector, translating flap and expansion ramp system was not viable. Accordingly, the decision was made to position the VTOL deflector and expansion ramp with two independently controlled actuation systems rather than one. Pressure balancing was also adopted as a means for partially unloading the translating flap and providing a source of cooling airflow for the lower nozzle components.

The following sections outline the resulting VEO-VTOL exhaust system design. The mechanical design is described in more detail in Section 6.1. Nozzle cooling and sealing is discussed in Sections 6.2 and 6.3. This is followed by a discussion of component material selection and construction. Section 6.5 concludes with a presentation of estimated performance and weight for the designed system.

6.1 Mechanical Design

The preliminary design of the selected VEO-VTOL concept is shown in Figures 15 thru 17 and consists of a variable two dimensional (2D) flap section nozzle and an interconnecting transition section between the engine's circular augmentor and rectangular nozzle. In general, the nozzle provides the normal jet area setting functions and also is capable of repositioning the flap section to obtain flowpaths for STOL or VTOL vectored modes, Figures 16 and 17. The nozzle produces the complete range of jet areas necessary for dry to maximum afterburner power while in cruise or STOL mode. It operates with constant jet area from dry to afterburner power while in VTOL mode similar to the demonstrated ADEN exhaust system.

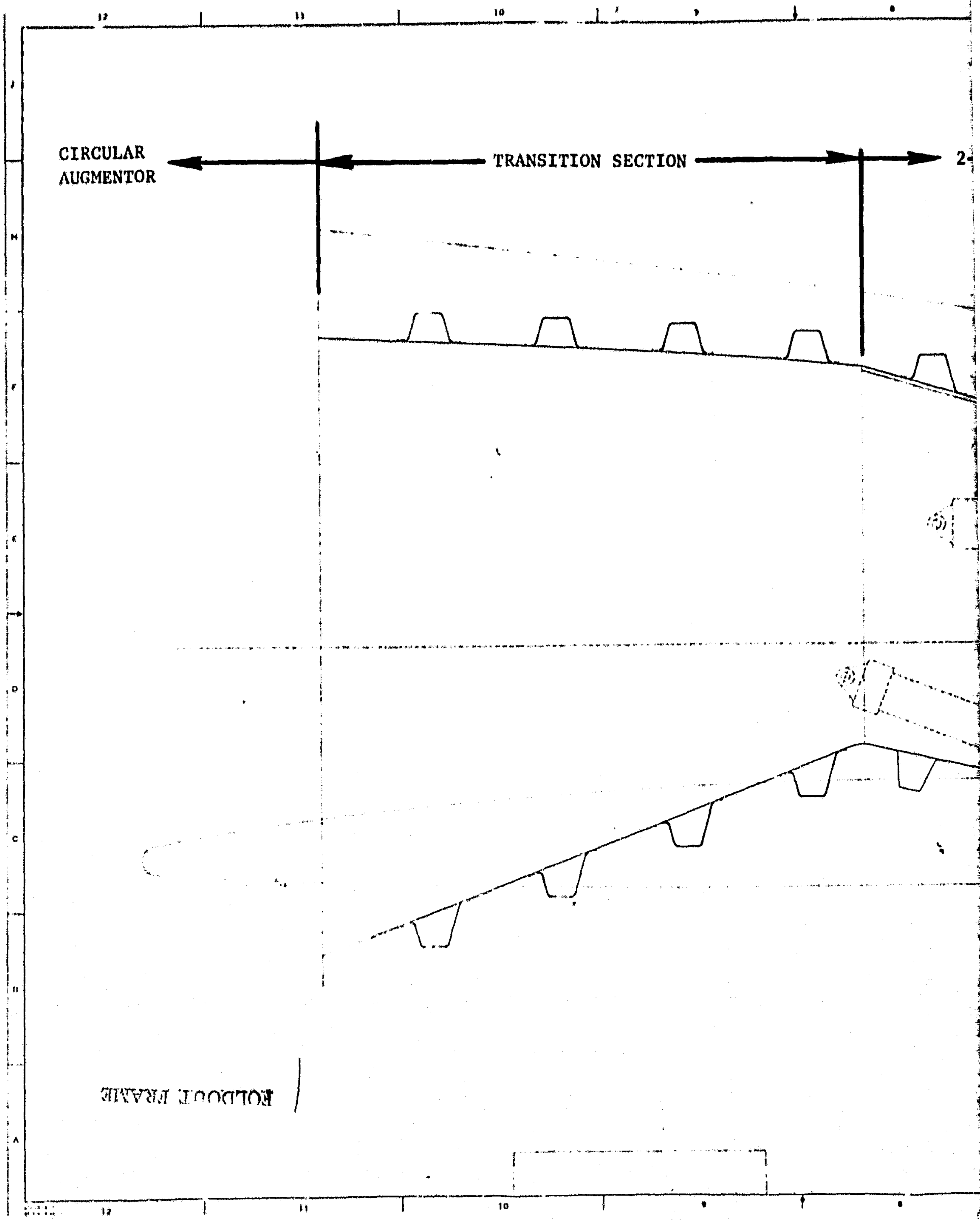
Major nozzle components include the fully modulated upper cowl A8 and A9 flaps, the expansion ramp, translating flap and VTOL deflector. For cruise flight, Figure 15, the expansion ramp is set at 15 degrees and together with the wing flap at zero degrees form the lower flowpath boundary. The upper convergent-divergent boundary is controlled by the upper cowl flaps.

For STOL, Figure 16, the expansion ramp is raised to its 30 degree position and the wing flap is deflected 30 degrees while the VTOL deflector remains stowed. The upper cowl flap is positioned to provide correct A8 and the A9 flap is set to direct the jet flow along the expansion ramp.

The VTOL flowpath is achieved by a continuation of the STOL flap motion, Figure 17. The expansion ramp remains at 30 degrees while the VTOL deflector has been pivoted to open the VTOL port and the translating flap has been shortened. At the same time the cowl flaps proceed to their blocking position and the VTOL deflector angle is displaced 90 degrees.

The nozzle's operation is best described by continuing to refer to Figure 15, 16 and 17.

In the cruise mode, Figure 15, the ventral flaps are in the down position with a 15^{o} expansion ramp angle on the divergent flap. The flaps are held in this position by two rotary actuators mounted in the cavity below the flaps. The throat area, A8, can be fully modulated from min to max A/B by rotating the upper cowl primary flap about its forward hinges. The flap is operated by two hydraulic actuators mounted


CIRCULAR
AUGMENTOR
TRANSITION SECTION

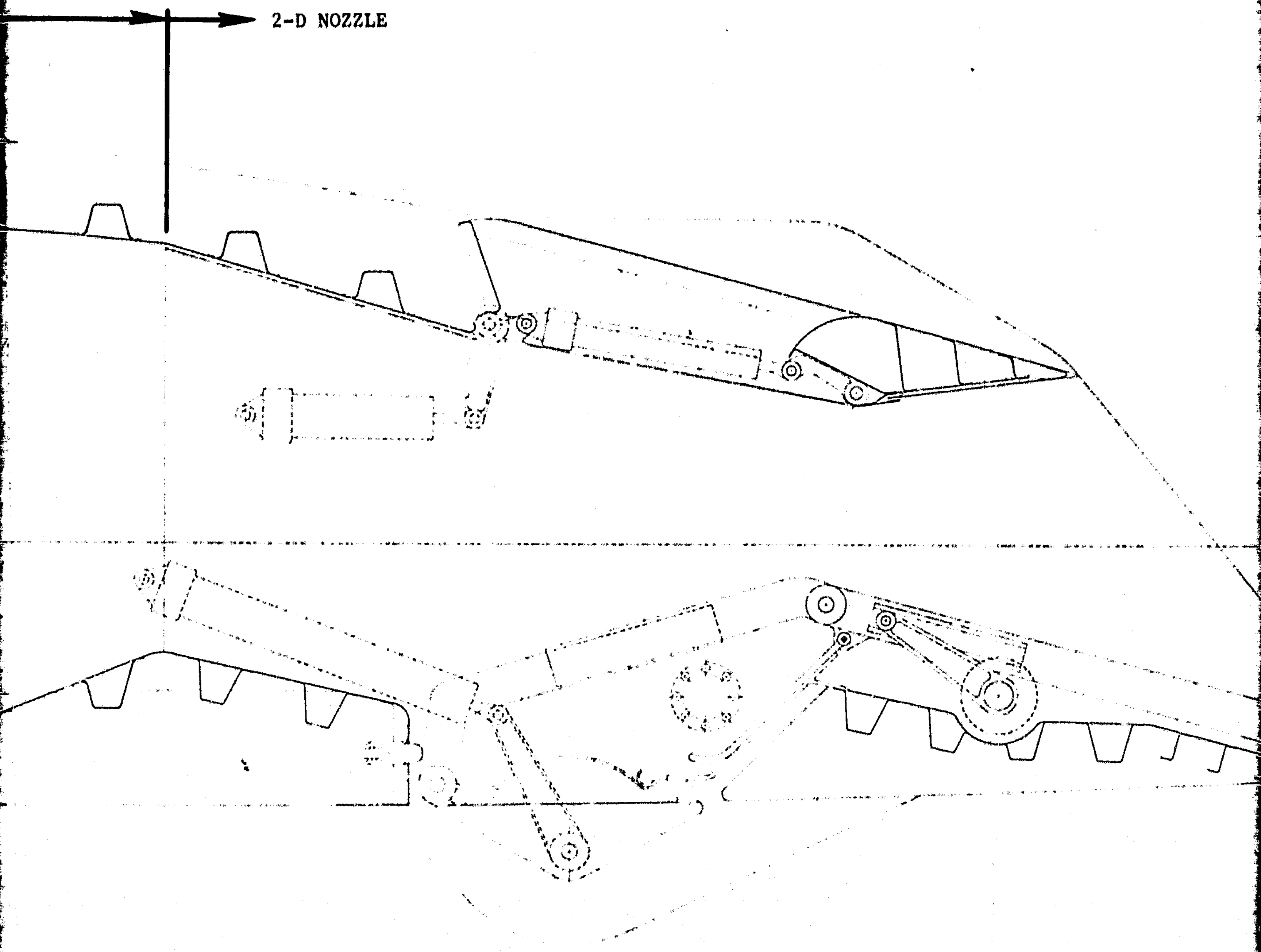


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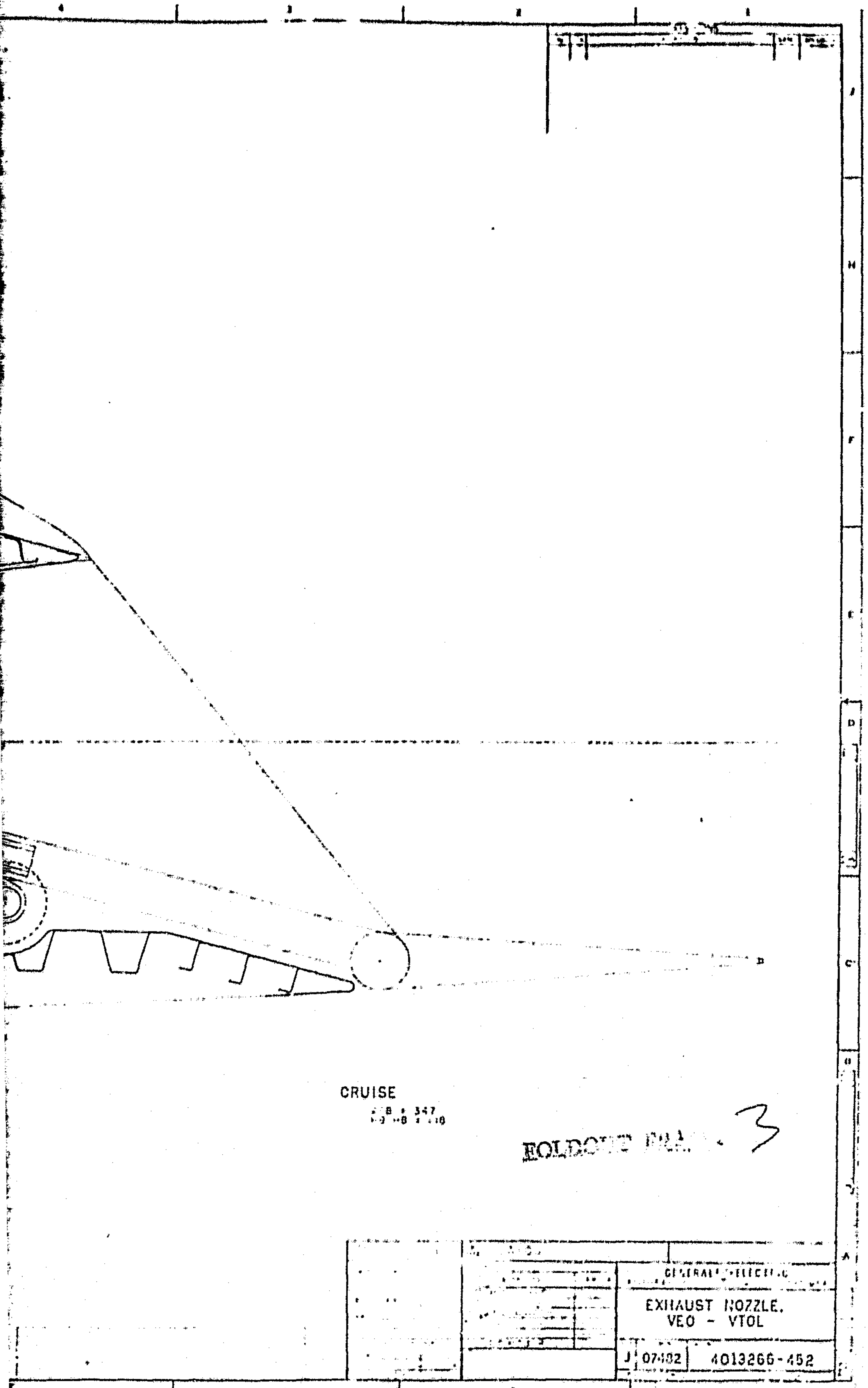
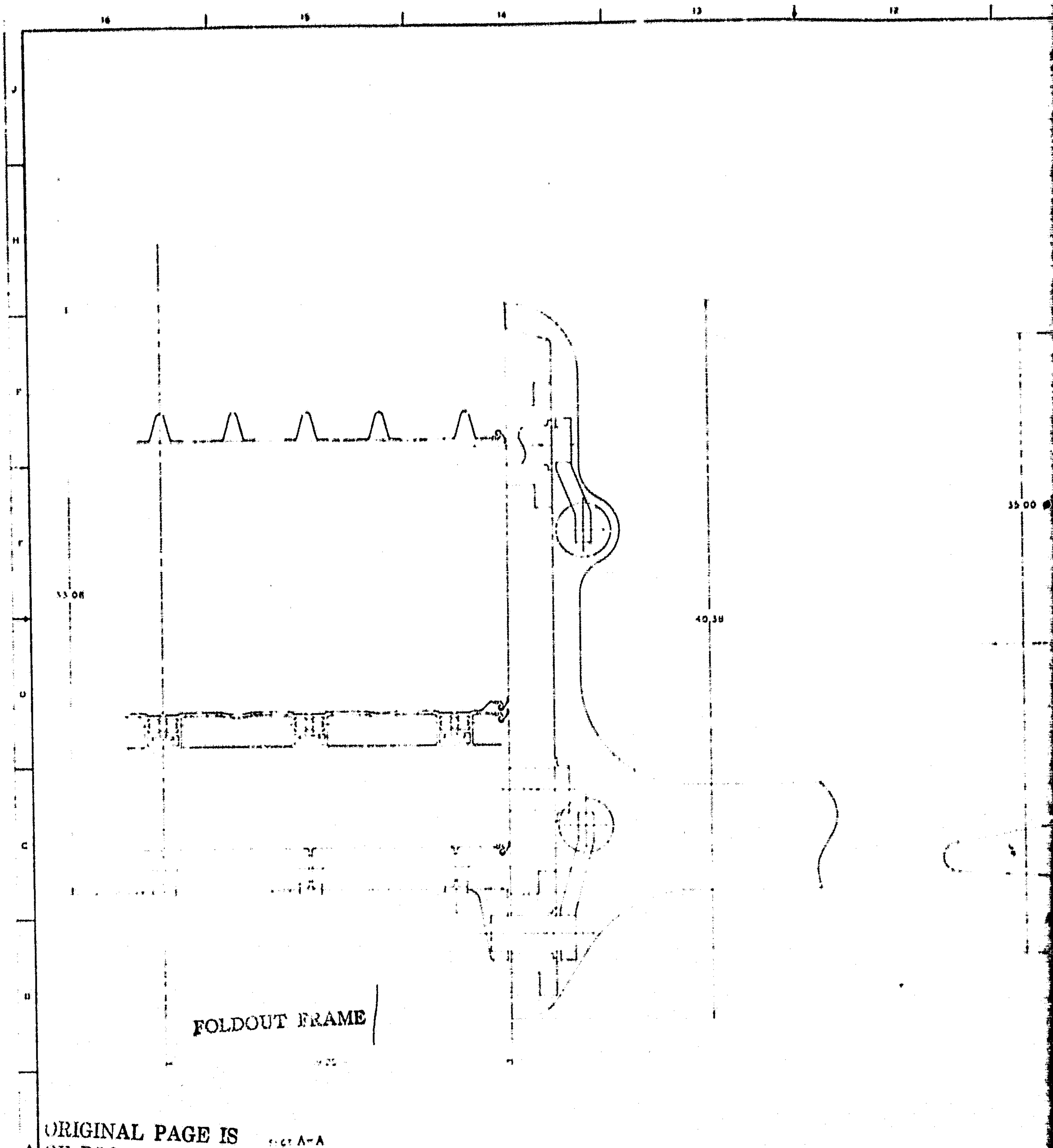
FIGURE 15



FOLDOUT FRAME 3



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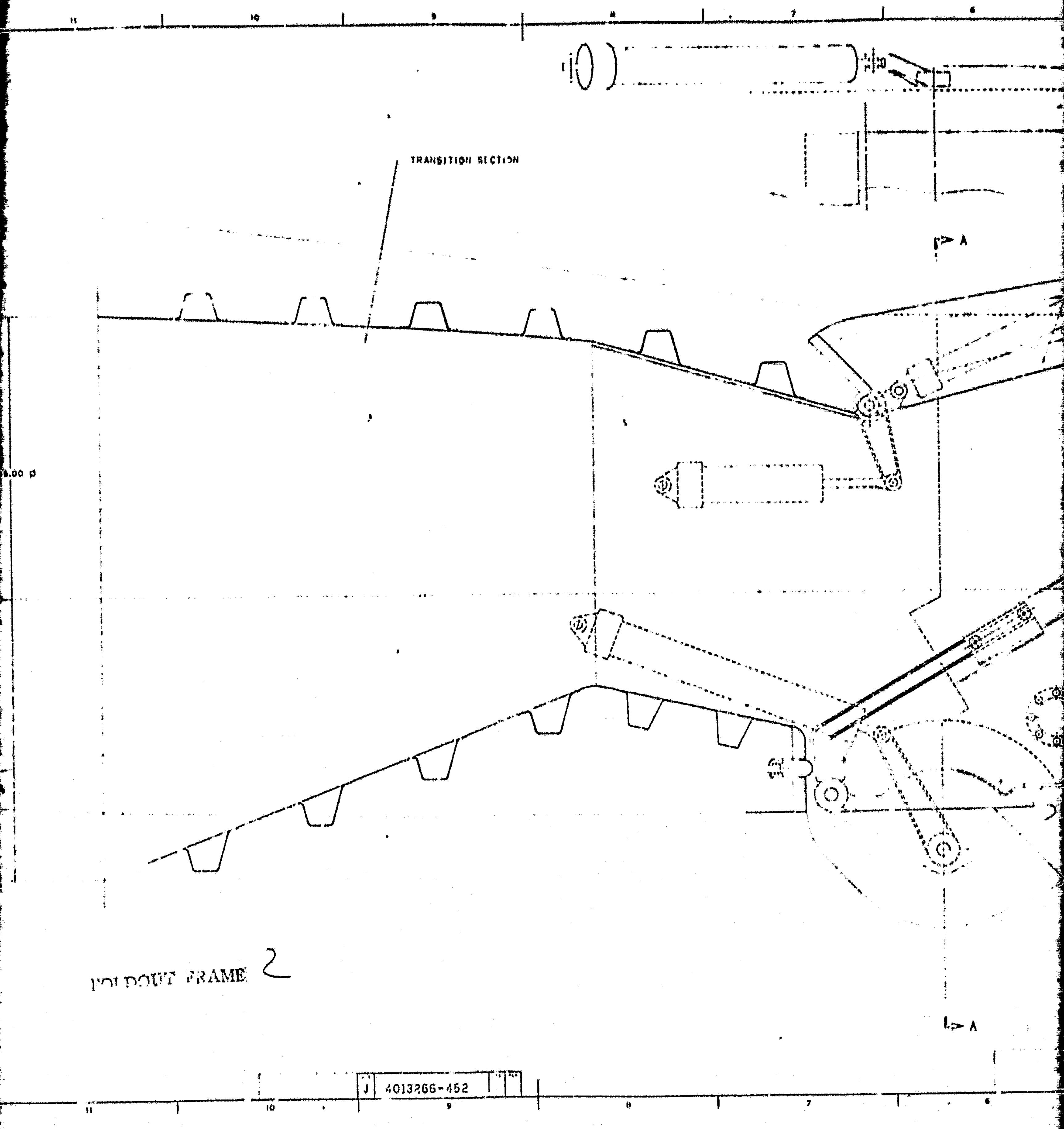
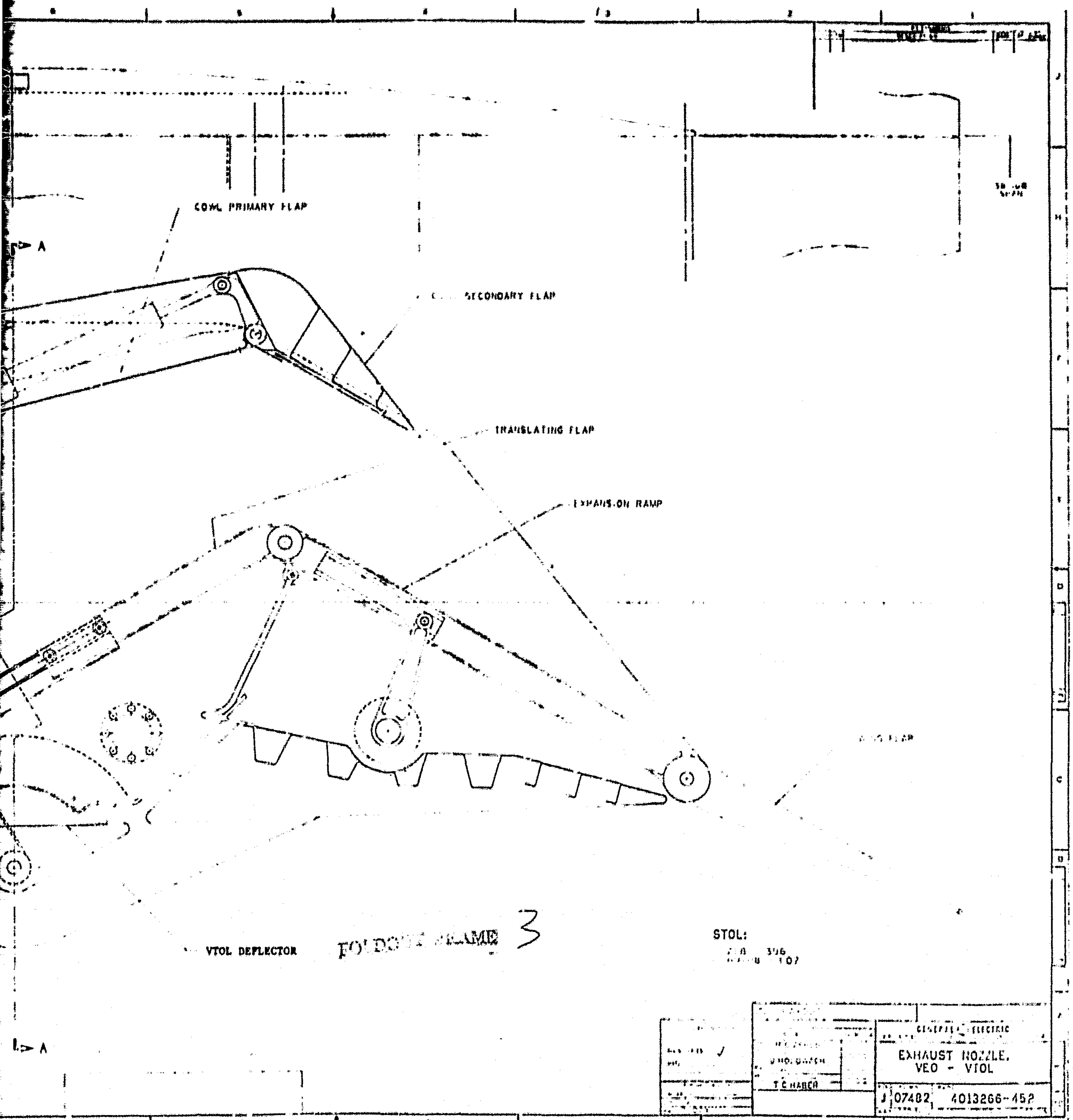
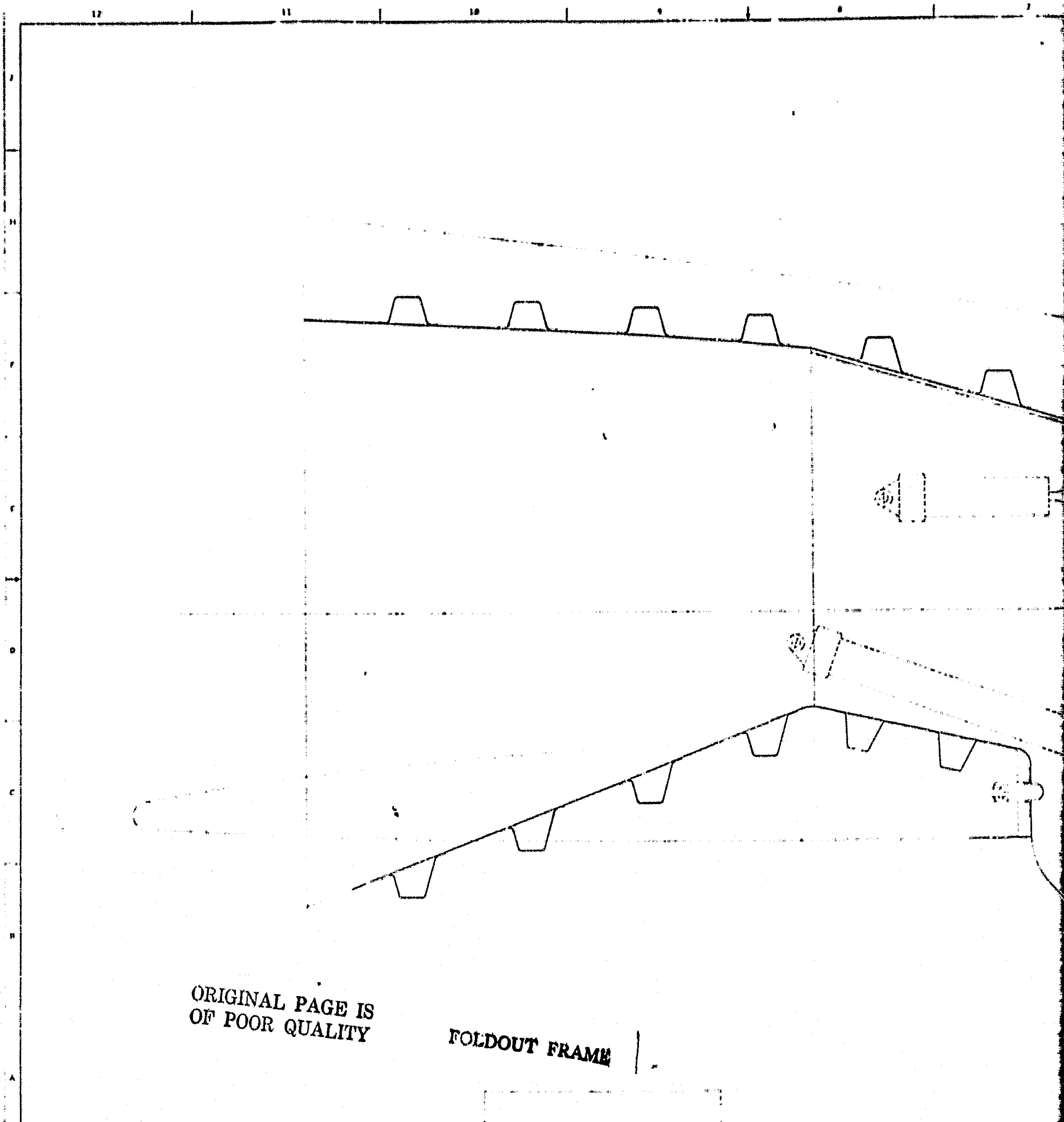


FOLDOUT FRAME 2



COWL PRIMARY FLAP
SECONDARY FLAP
TRANSLATING FLAP
EXPANSION RAMP
VTOL DEFLECTOR
FOLDOUT FRAME 3
STOL:
GENERAL ELECTRIC
EXHAUST NOZZLE, VEO - VTOL
T C HABER
07482
4013266-452



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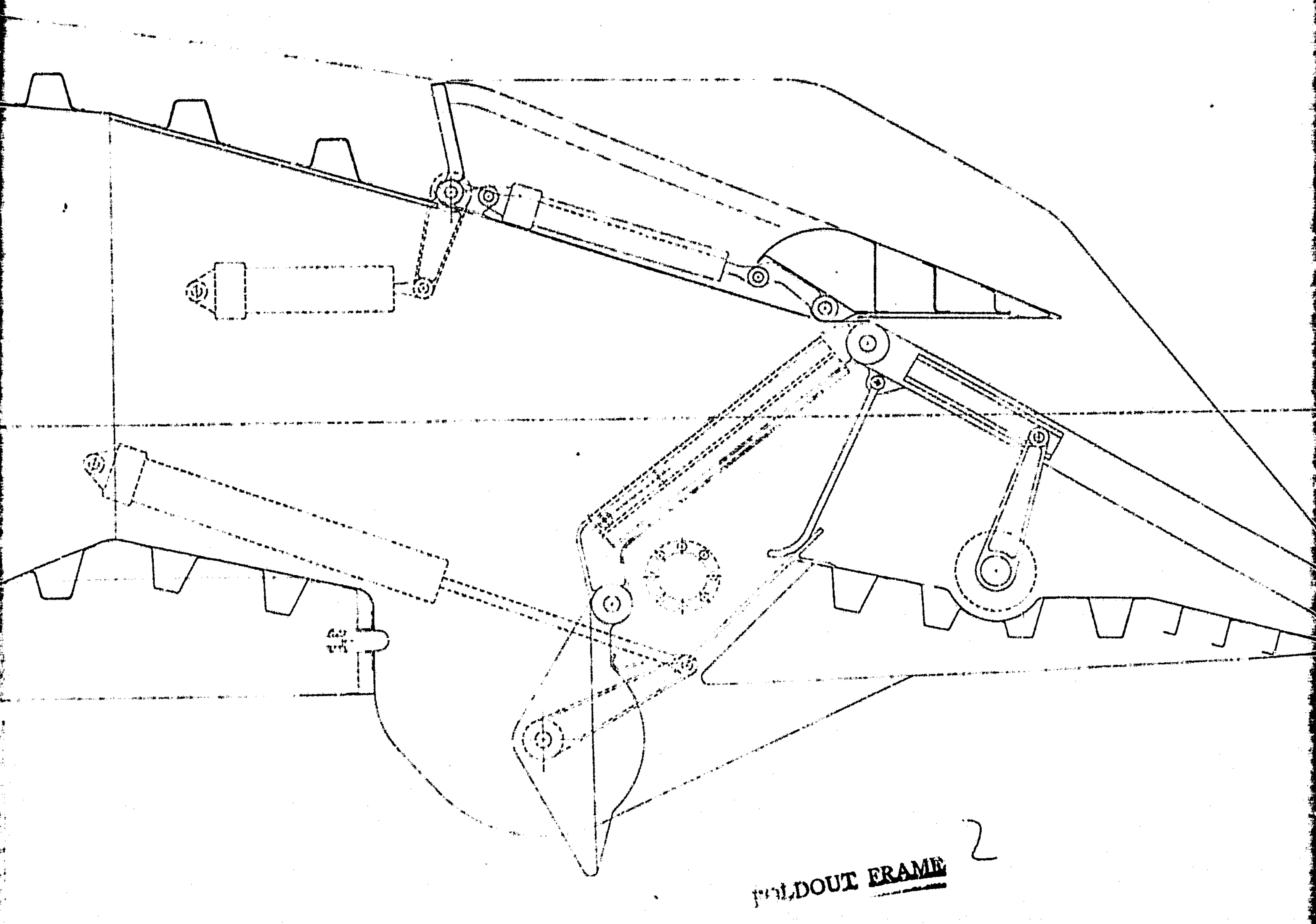

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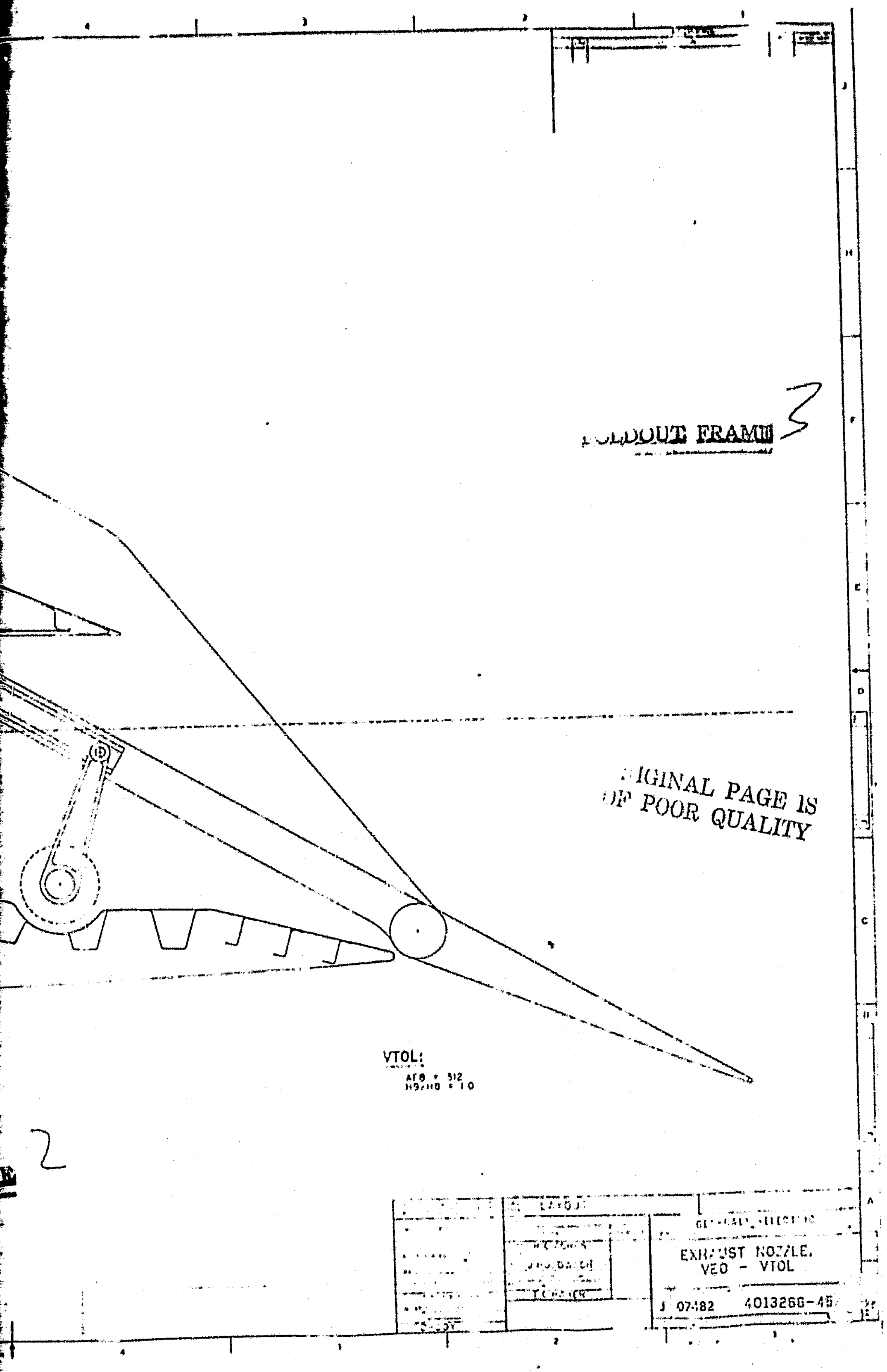
FIGURE 17



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on the sides of the nozzle. The hydraulic actuators drive a crank arm that is attached to the torque tube which is integral with the primary flap thus converting the linear motion to rotary motion. The divergent flap is held in a fixed position relative to the primary flaps during cruise operation by two hydraulic actuators that are mounted on the upper primary flaps. The degree of divergence of the divergent flap increases as the primary flap is rotated up from the min to max A/B position. The hydraulic actuators remain in the retracted position for all cruise positions and are only actuated for STOL operation.

In the STOL mode, Figure 16, the lower expansion ramp is raised to its 30° position by a rotary actuator. The translating convergent flap is rotated about its forward hinge by the expansion ramp. This flap is of a telescoping design to accommodate the flap length change required in moving the expansion ramp from the 15° to 30° position. With the VTOL deflector remaining in a fixed position, the upper cowl primary flap provides the required throat area for either augmented or dry operation in the STOL mode. The two actuators attached to the upper divergent flap are extended to rotate the upper divergent flap to the - 30° position required to direct the gas flow downward for generating jet lift in the STOL mode.

In the VTOL mode, the expansion ramp is held in the 30° position by the rotary actuator. The two linear hydraulic actuators attached to the side of the nozzle drive the crank arms attached to the VTOL deflector. The deflector rotation uncovers a ventral opening in the casing for the exhaust gases to exit downward for lift. The thrust vectoring angle can be modulated between 75° and 105° by rotation of the deflector. During operation of the VTOL deflector, the change in length required by the lower primary flap is accommodated by the telescoping action in the translating flap that was also required for the STOL operation.

A pressure balance feature was designed into the VEO-VTOL exhaust nozzle to reduce the actuation force required to operate the ventral flaps and provide a cooling air supply for the lower flap and VTOL deflector flap system during augmented operation. Other advantages of the pressure balanced translating flap is that the core gas leakage is reduced and seal life is improved since they operate at a lower temperature and the air leakage into the aircraft nacelle is low temperature bypass air.

The main function of the pressure balance cavity is to provide a high pressure plenum between the translating flap and nozzle casing. Pressure is maintained by fan air ducted through the sides of the casing wall. This lower temperature fan air is higher pressure than the core gas flow pressure and can therefore be used as a source of coolant air for the flaps during augmented operation.

The differential pressure forces acting on the convergent flap is a function of the cavity pressure and the pressure distribution on the core side. By increasing the plenum pressure, the actuation force required to operate the expansion ramp can be significantly reduced. In the case studied, the actuation force was reduced from 13,000 lbs. with the plenum chamber at 14.7 psi to 5,000 lbs. when the pressure was increased to 60 psi as shown in Figures 18a and 18b.

Consideration was also given to increase cavity size in an effort to decrease flap loads further. However, if the cavity size was increased to include the area under the expansion ramp as shown in Figure 18c, the actuation force actually increased from 5,000 to 20,000 lbs. Another disadvantage to increasing the plenum size is that a large pressure differential requires additional reinforcing beams to maintain its structural integrity and therefore increases nozzle weight. Effect of plenum pressure on actuation force were also studied for the 15^{o} cruise and VTOL modes but were found to be less critical than the STOL mode.

6.2 Cooling Design

A conventional augmented exhaust system has only minor changes in pressure and velocity along the flowpath. This means that efficient film cooling can be achieved by the use of constant area slots for injecting the cooling film, with only minor changes in coolant flow resulting as the operating conditions are varied. By comparison, the cooling system for the VEO-VTOL exhaust system is subjected to large, varying gas stream pressure gradients during the transient between the cruise and the vectored mode that could disturb or even reverse the normal flow of cooling air provided by a conventional cooling system design. The area to be cooled in the VEO-VTOL nozzle also changes between the cruise and vectored mode operation. A detailed cooling analysis will be required and confirmatory scale model heat transfer tests should be made to determine optimum cooling flow rates for each operating condition. However, first level cooling estimates were made to assess system requirements and determine cooling losses.

STOL MODE LOAD DIAGRAM

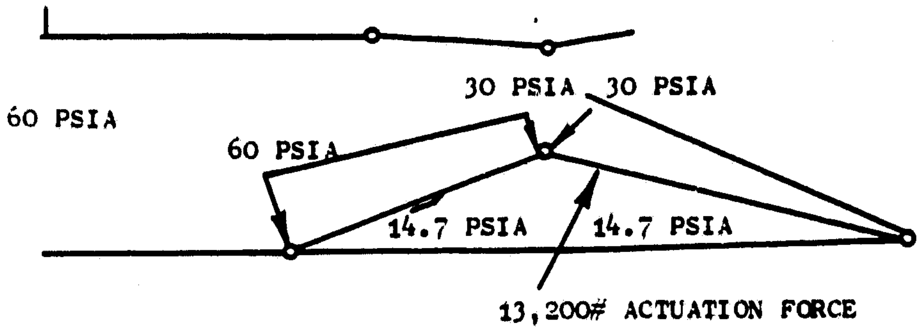


FIGURE 18A. NO PRESSURE CAVITY

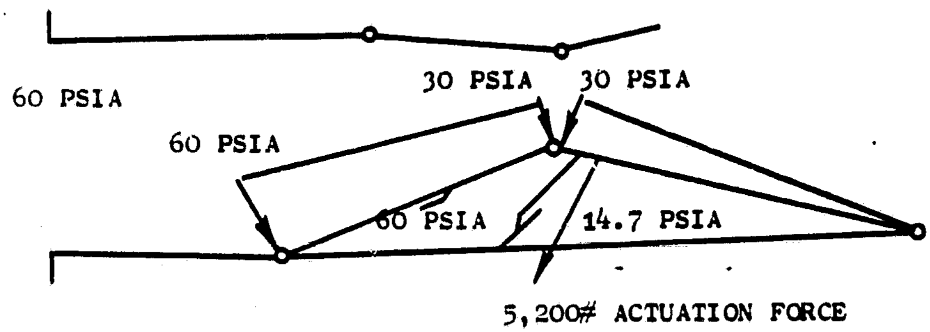


FIGURE 18B. PARTIAL FLAP PRESSURIZATION

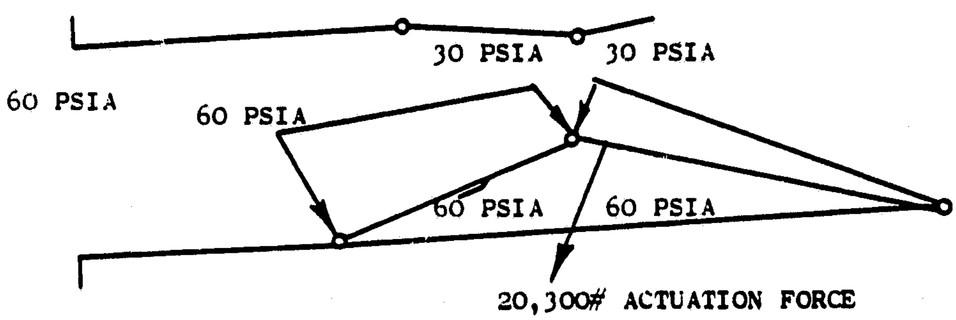


FIGURE 18C. FULL FLAP PRESSURIZATION

Cooling requirements for the exhaust nozzle in the VTOL mode depart from the conventional exhaust nozzle in that the high velocity exhaust gas is turned 90° prior to exhausting through the ventral opening. The pressure distribution resulting from blocking the axial flow and turning it downward results in lower velocities but higher static pressure on the blocking surfaces than are found in the normal cruise and STOL modes. To meet these requirements a successful cooling design may require a combination of convection, film and impingement cooling to keep metal components at or below their safe operating temperature.

An estimate of the cooling flow rate to maintain metal surfaces at a maximum temperature of 1600°F during VTOL augmented operation is shown diagramatically in Figure19. The coolant rates are based on gross effectiveness factors that correlate the rate of cooling air required as a function of core gas temperature and mass velocity. The gross effectiveness factors were established from heat transfer data collected from current and advanced engines operating in the augmented mode.

Screech suppression flow is shown separately from the nozzle coolant flow since it is injected well upstream and effectively enters the combustion process and consequently represents a lessor performance penalty than the nozzle cooling flow. Screech flow is required in all augmented nozzle systems to prevent acoustic resonance and is not part of the nozzle cooling design.

An example of the detailed type of cooling and heat shields that would probably be required for the flat casing walls is shown in Figure 20. The shields consist of panels equipped with integral impingement baffles. After impingement, the cooling air is injected into the gas stream and the film cools the shields. The shields are mounted in tracks which are attached to the casing wall. This type of shielding effectively limits the temperature difference in the casing structural wall to 200°F, thus avoiding thermal distortion and fatigue problems.

The pressure balance plenum incorporated in the design to reduce actuation forces on the ventral flaps is also an ideal source of high pressure coolant air for cooling the ventral flaps. The air pressure is supplied by low profile ducts incorporated in the structural members of the casing. The coolant air enters the plenum through the side wall and is then used to cool the ventral flaps and deflector by a combination of impingement, film and convection cooling.

VEO COOLING SUMMARY

	% W8
SCREECH	1.74
TRANSITION	3.34
EXHAUST DUCT	3.83
UPPER FLAP	1.94
VENTRAL FLAP	1.04
DEFLECTOR	0.67
TOTAL	12.56

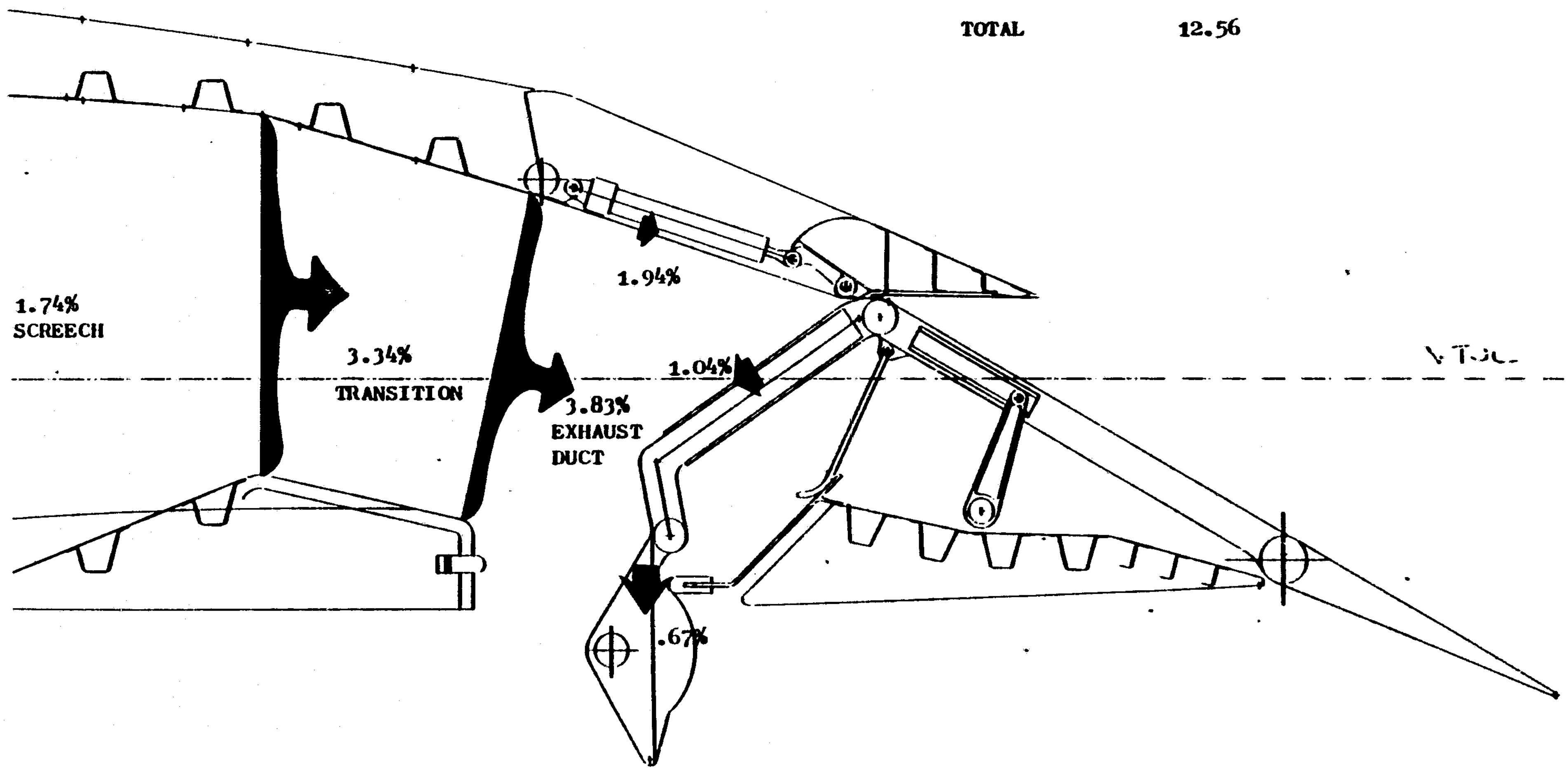


FIGURE 19. VEO-VTOL EXHAUST NOZZLE COOLING REQUIREMENTS

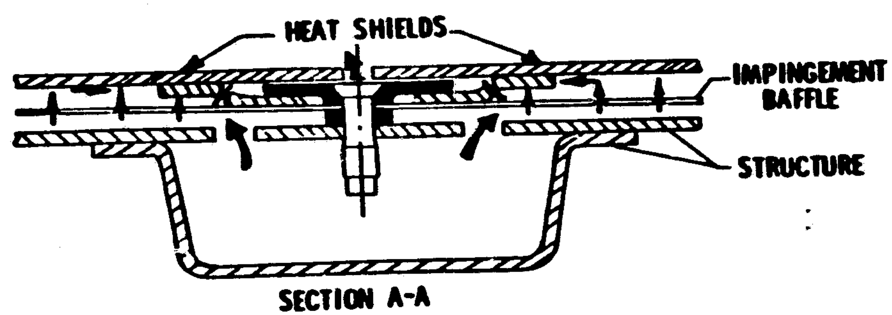


FIGURE 20. SIDEWALL HEAT SHIELD IMPINGEMENT COOLING

Cooling of the exhaust nozzle during the cruise and STOL modes does not present any new design problems since the gas temperature and pressure distribution are predictable. Available heat transfer design techniques can be used to predict the required coolant flow rate, slot geometry and metal temperatures required for safe augmented operation.

An estimate of the cooling flow rate required to maintain surface temperatures at a maximum of 1600°F during augmented operation is shown diagramatically in Figures 21 and 22 for the STOL and cruise mode. These estimates are based on previous 2D nozzles with similar configurations. The higher coolant flow rate required for the cruise and STOL mode is due to the additional exposed area of the divergent flaps which are not exposed to the core gas during VTOL operation. Adjustable slot height and flow dams will be required to regulate the coolant flow rate as the flight mode and operating conditions change. Higher temperature materials such as oxidation resistant coated carbon-carbon or ceramics are now being considered for aircraft engine applications. These could significantly reduce the coolant flow requirement by operating at temperatures above the 1600°F design temperature.

VEO COOLING SUMMARY	%W8
SCREECH	1.74
TRANSITION	3.34
EXHAUST DUCT	3.80
UPPER FLAPS	1.94
VENTRAL FLAPS	3.09
VEER	1.10
TOTAL	15.01

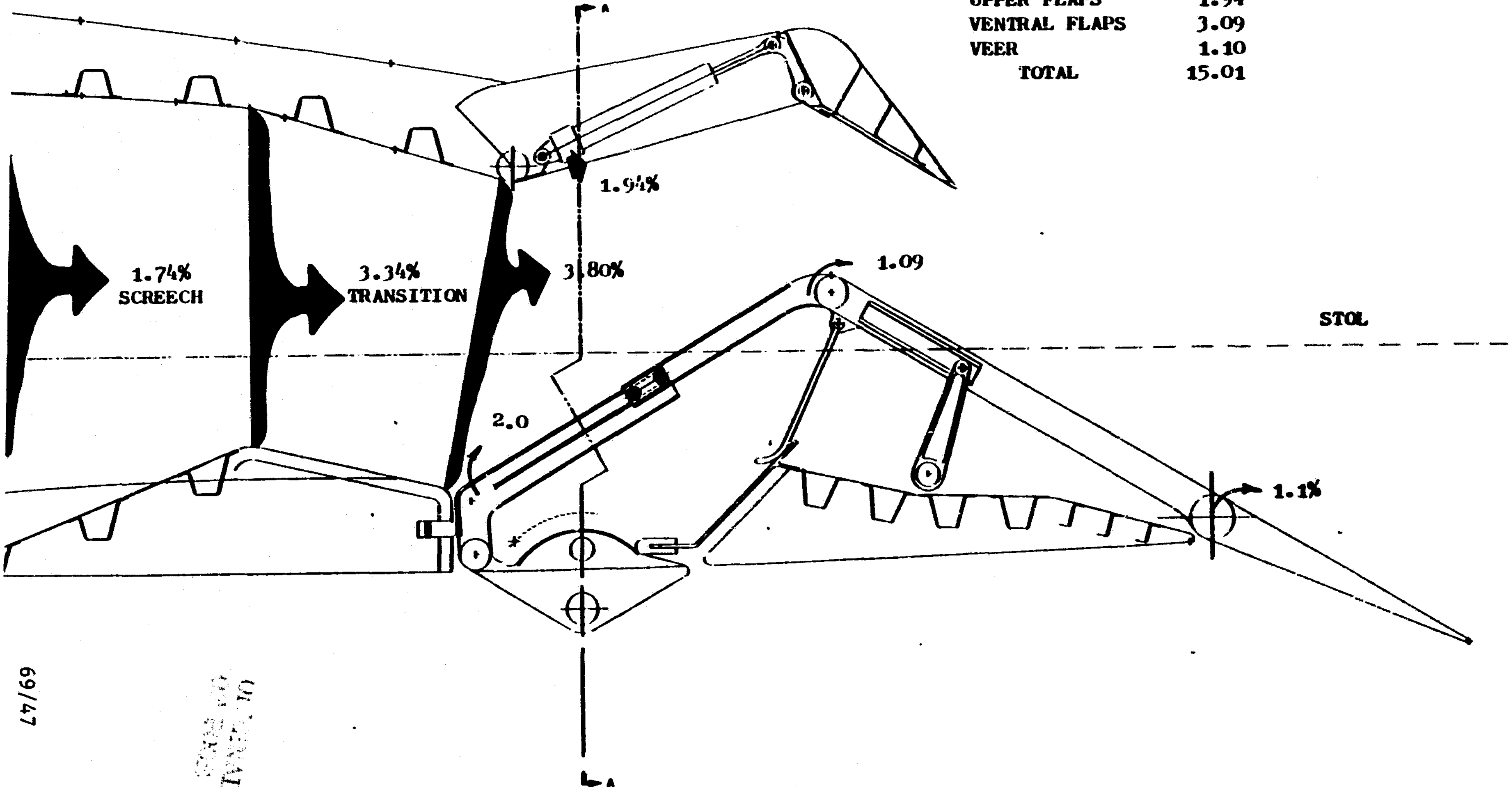


FIGURE 21. VEO-VTOL EXHAUST NOZZLE COOLING REQUIREMENTS

VEO COOLING SUMMARY

	%W8
SCREECH	1.74
TRANSITION	3.34
EXHAUST DUCT	3.80
UPPER FLAPS	1.94
VENTRAL FLAPS	2.09
VEER	1.10
TOTAL	14.01

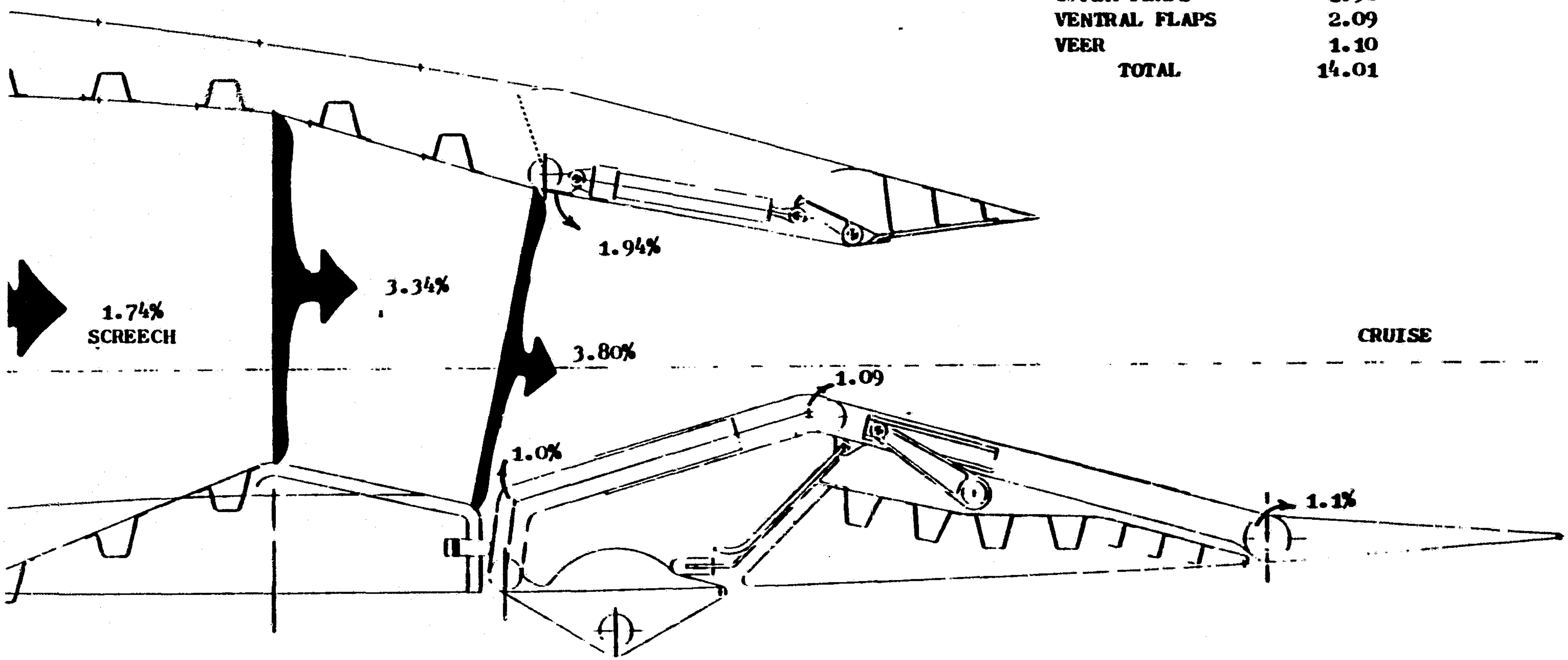


FIGURE 22 . VEO-VTOL EXHAUST NOZZLE COOLING REQUIREMENTS

6.3 Seal Design

Effective high pressure gas sealing is required for a high performance exhaust nozzle. The seals must be conformable and capable of accommodating load deflections, thermal expansion and manufacturing tolerances. The experience gained with effective sealing techniques in previous exhaust nozzles and thrust reversers would be incorporated in the present design. The three different types of seals that would be used in the exhaust nozzle are shown in Figure 23. High excursion seals will be used in the flap edges and in the deflector to accommodate flaps and side wall deflections. In areas where gap variations are small, such as the primary flap hinge, simple elastic seals can be used.

An estimate of the leakage paths is shown diagramatically in Figure 24 for the cruise, STOL and the VTOL case. The effective gap is based on test data of similar seals used in other exhaust nozzle applications. An estimate of the leakage flow rate and its effect on performance can be estimated based on the leakage area, the differential pressure across the seal and the leakage location and direction.

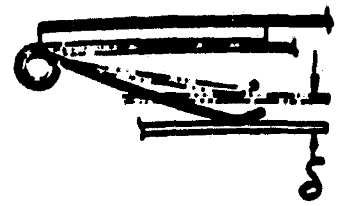
6.4 Component Materials and Construction

The VEO-VTOL Exhaust Nozzle with its nonaxisymmetric geometry and augmented vectoring represents a significant advance in exhaust nozzle technology, however, the materials and processes to be used are much the same as those used on the current exhaust nozzles and augmentors. As an example, chem-milling would be used to provide weight effective material distribution throughout the structure. This method of varying thickness in sheet metal structures is preferrable to the use of attached reinforcements since stress concentration at the attachment welds can lead to fatigue cracking.

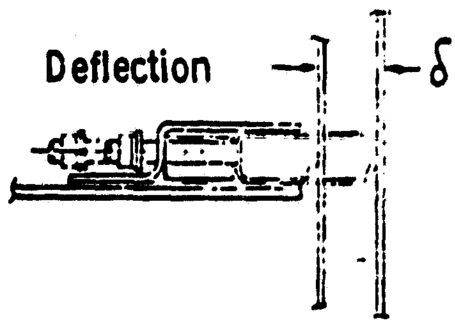
The exhaust duct would be primarily fabricated from sheet material with formed ribs and stiffness. Resistance welding, rivets and bolts will be used for joining the sheet and ribs. This type of construction is preferred over sandwich construction for the following reasons:

- o The sheet and rib construction would be used extensively to distribute cooling air

DEFLECTOR SEAL



FLAP EDGE SEAL



FLAP HINGE SEAL

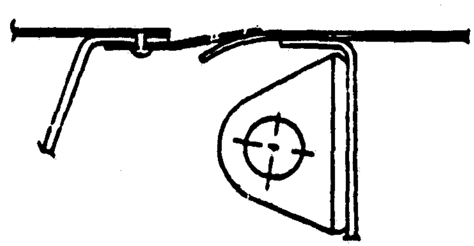
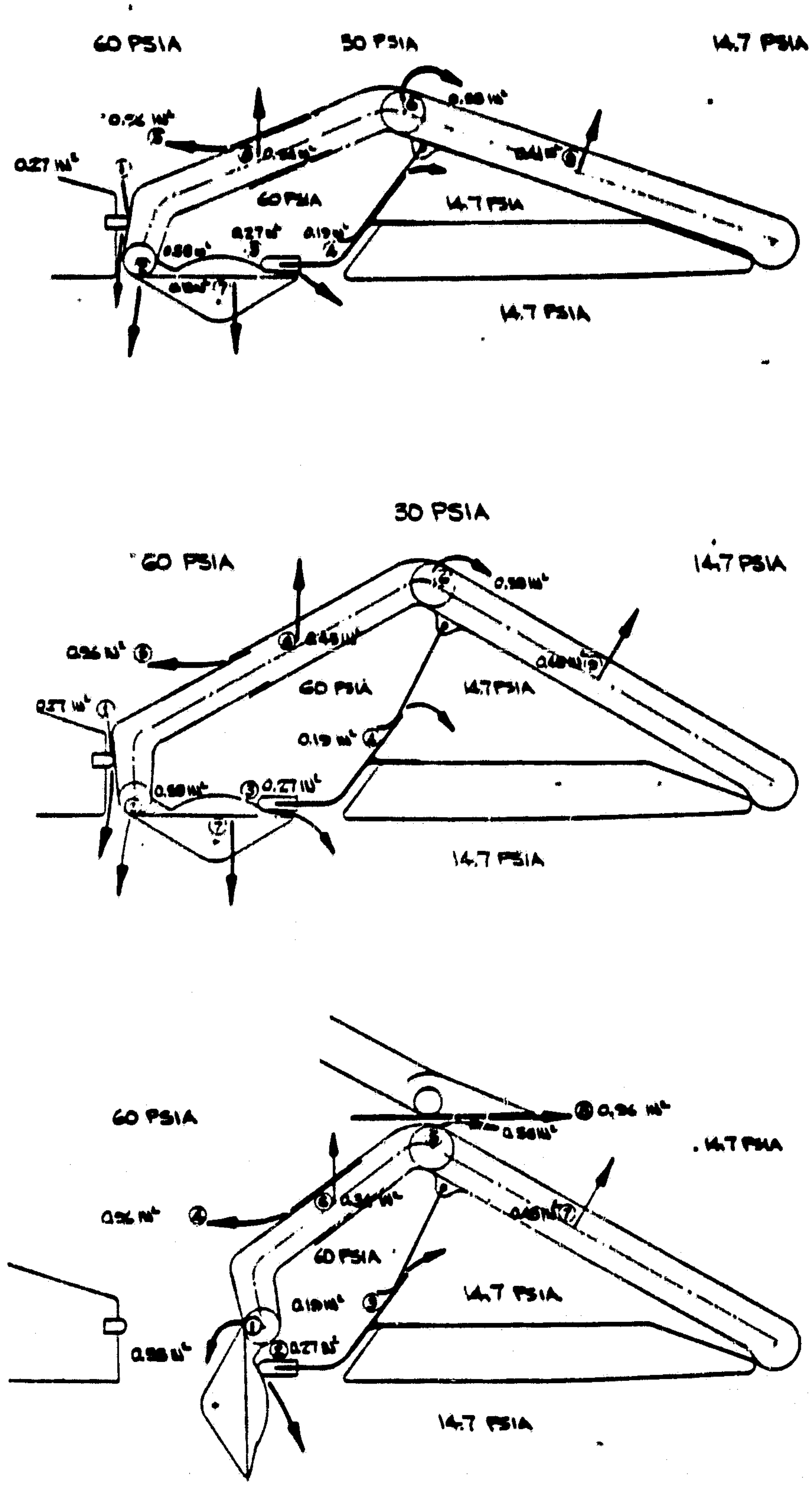


FIGURE 23. TYPICAL FLAP AIR SEAL

VEO-VTOL NOZZLE CRUISE CASE LEAKAGE PATHS



CRUISE

STOL

VTOL

FIGURE 24

- Tests have shown that this construction is more thermal fatigue resistant than sandwich construction

- Lower cost

Figure25 shows the type of materials to be used in the construction of the exhaust nozzle. Titanium would be used in relatively low temperature applications and for the actuator links and mounts. Inconel 625 would be used for intermediate temperatures and low stress areas and Inconel 718 would be used for intermediate temperature but high stressed areas. R41 would be used for the high temperature, high stress application. Material selection is based on cost, formability, weldability and thermal fatigue properties in addition to its strength characteristics. In general the exhaust nozzle can be designed and fabricated using conventional engine exhaust system construction techniques to ensure low weight and long service life with reasonable manufacturing costs.

In the 1980 to 1990 time period several promising high temperature materials that are currently being investigated by General Electric may significantly reduce the weight of the VEO/VTOL exhaust nozzle and increase the overall engine performance by reducing the amount of cooling air required to protect nozzle components. These materials include high temperature alloys such as MA 956, oxide dispersion strengthened chromium-Aluminum alloy, and oxidation resistent coated carbon-carbon. These materials are similar in composition to that used for the thermal shielding of the leading edge of space shuttle wings.

The MA 956 projected useful temperature is 2300°F. Carbon-carbon useful temperature range may be in excess of 2300°F.

The new materials are particularly attractive for advanced two-dimensional V/STOL or inflight vectoring nozzles. These nozzles tend to be heavier and require more cooling flow than the conventional round nozzles. Weight savings are desirable for V/STOL systems since the weight reduction shifts the engines center-of-gravity (CG) forward. This CG shift will significantly benefit most aircraft installations and reduce the bending stress on the augmentor duct.

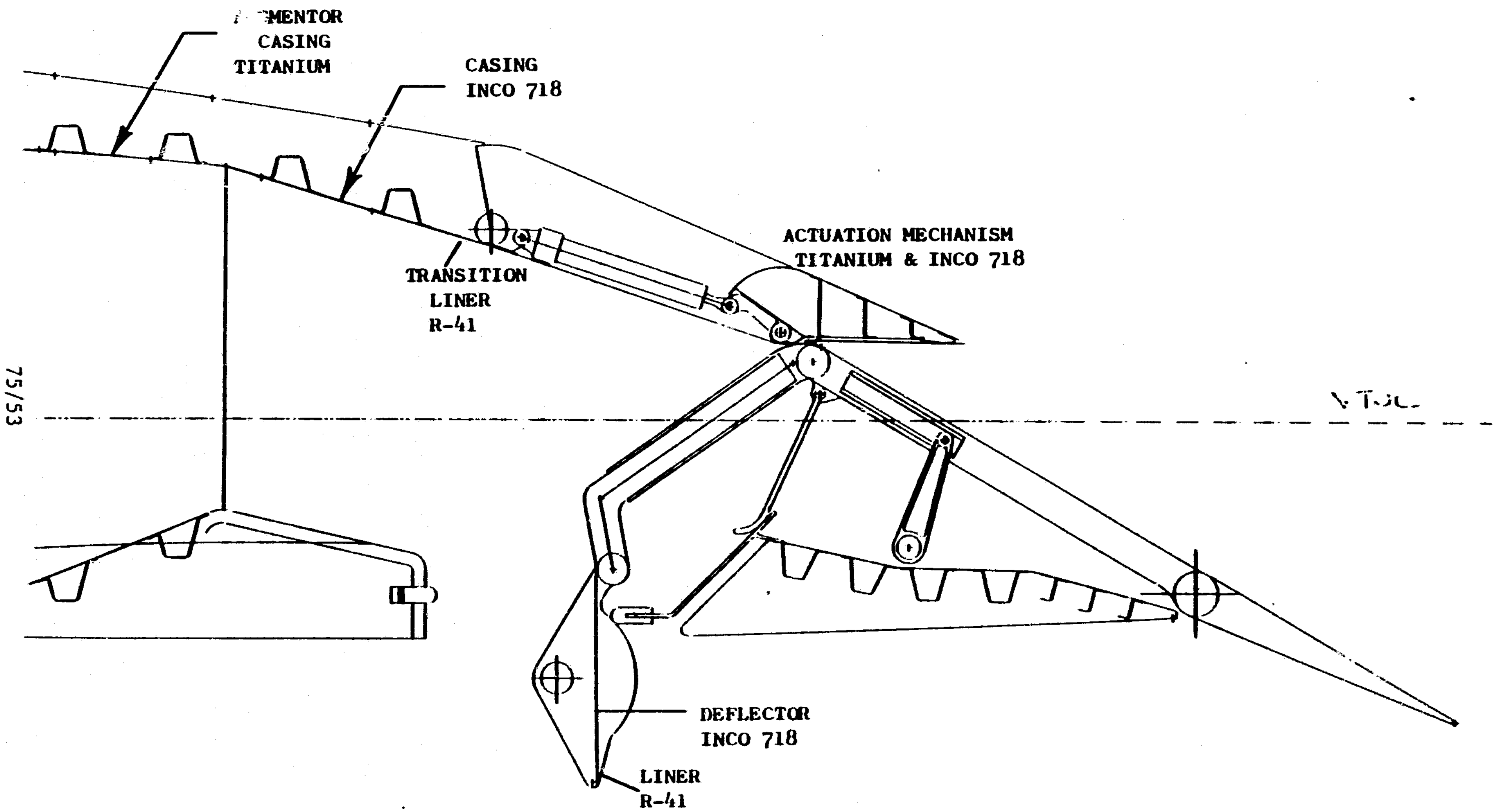


FIGURE 25. VEO-VTOL EXHAUST NOZZLE MATERIALS

6.5 Performance and Weight Estimate

Leakage and cooling requirements described in Section 6.2 were used to estimate leakage and cooling losses in terms of incremental thrust coefficients. These were found to be unchanged from the losses estimated for the original concept and presented in Tables 4 and 5. Therefore the derated thrust coefficients are also unchanged.

A preliminary weight estimate based on the conceptual design is shown in Figure 26. The 632# total weight is 34# heavier than the original concept (see Table 8). The increased weight is primarily due to the increased structure required for the translating flap and the added actuators for driving the divergent cowl flap. The estimated weight includes only hardware directly related to the nozzle. It does not include estimated weights for external control system components such as hydraulic lines, pumps, servo valves and sensors. These were judged to have essentially equivalent weight for all concepts as well as the preliminary designed VEO-VTOL nozzle.

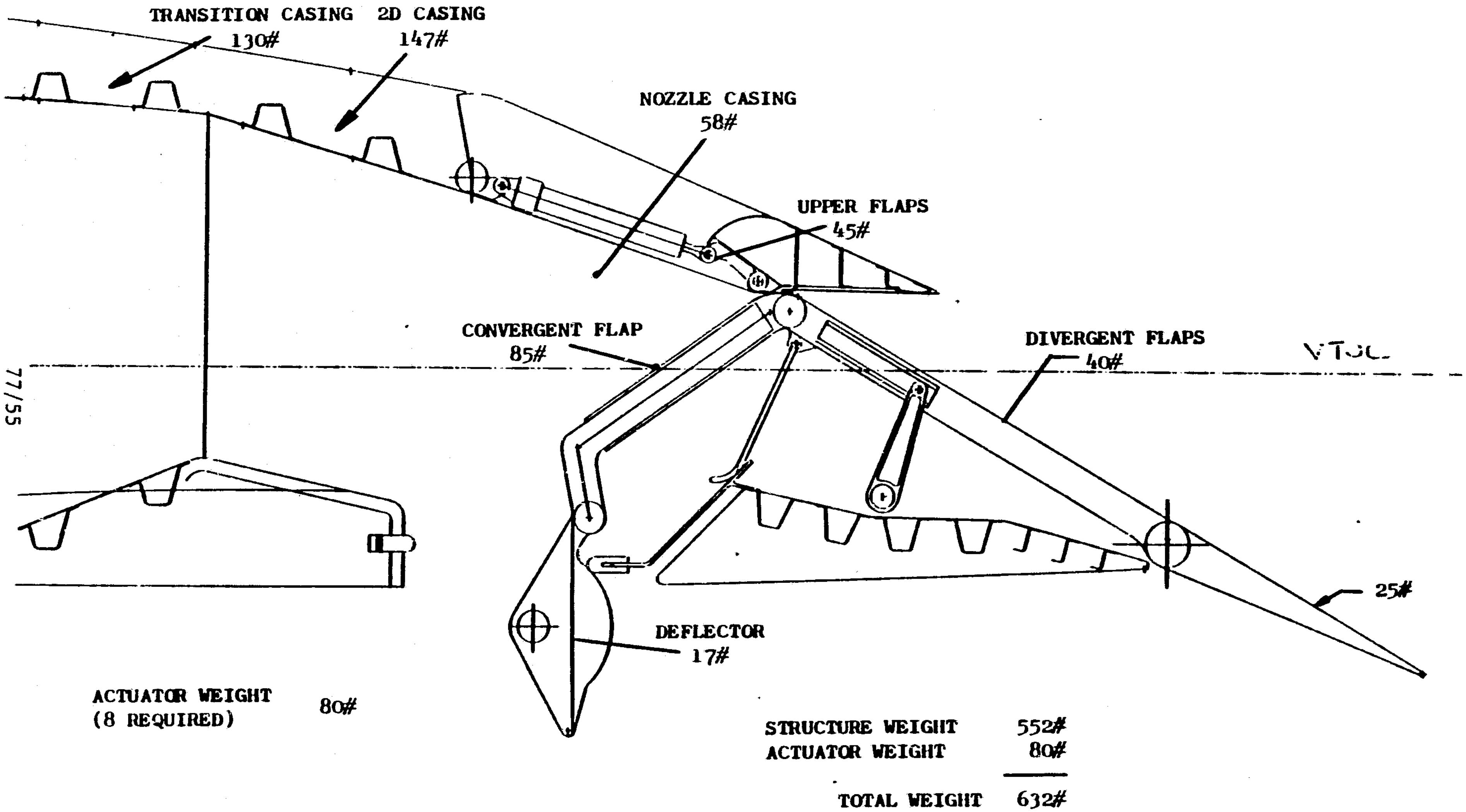


FIGURE 26. VEO/VTOL EXHAUST NOZZLE WEIGHT ESTIMATE

7.0 CONCLUSIONS AND RECOMMENDATIONS

1. Two classes of single expansion exhaust systems were conceived which fully satisfy area control and vectoring requirements for General Dynamic's VEO-VTOL aircraft. In one class of previous designs, VTOL vectoring is accomplished by turning the jet flow around the aft end of the nozzle. In the other, the VTOL jet was turned internally and expanded through a ventral port in the wing. The ventral port concepts were generally superior with lowest weight and simplest mechanical characteristics.

2. Ventral Concept #8 was selected for preliminary design on the basis of low weight and control simplicity (only two actuation systems required).

3. In the preliminary design of Concept #8, modifications were imposed which resulted in increased weight and one additional actuation system. The modifications were instituted to satisfy the requirement that all flow be directed over the expansion ramp during STOL mode. This was due to a General Dynamic's analysis indicating that jet flow through the wing is detrimental to STOL performance. It is recommended that this analytic result be tested to establish if the gain in STOL performance is worth the loss in mechanical simplicity.

4. Concept #4 was evaluated as the runner up system for preliminary design. This is due to the extra weight of the bomb bay type ventral port doors and their actuation. Elimination of these doors and a redesign of the VTOL deflector flap to form the wing bottom surface when stowed could result in reduced weight, simplify the controls, and make Concept #4 strongly competitive as a VEO-VTOL exhaust system.

5. The VEO-VTOL Exhaust systems conceived in this program employ flow blocking during VTOL. This can be used to advantage to provide the exhaust system with a thrust reverser and thus increase its versatility with relatively small weight penalty.