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MOTION STUDY OF THE SUCTION DUCTING ON THE S-IC STAGE OF THE SATURN V VEHICLE

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ABSTRACT

The design motion requirements of the gimbal joints, sliding joints and compensating joints for the S-IC Feed System of the Saturn V vehicle were determined by Kinematic Analysis using an IBM 7040 data processing system. This analysis provided a precise method of determining the axial and angular motion of each bellows in the S-IC Feed System for design purposes.

The mathematical method of analysis developed in this report can be applied to future designs instead of the graphical methods presently used. Author

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PROPULSION ENGINEERING BRANCH
PROPULSION DIVISION
PROPULSION AND VEHICLE ENGINEERING LABORATORY
RESEARCH AND DEVELOPMENT OPERATIONS

This report was prepared by Brown Engineering Company, Inc. under the direction of the Propulsion Engineering Branch, Propulsion Division, Propulsion and Vehicle Engineering Laboratory, Research and Development Operations, George C. Marshall Space Flight Center. TD-D1-PMD-019-3

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MOTION STUDY OF THE SUCTION DUCTING ON THE S-IC STAGE OF THE SATURN V VEHICLE

By

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SUMMARY

A motion study of the S-IC Propellant Feed System was made to determine the maximum compression and extension of each bellows for design purposes. These values were determined for the specifications. The mathematical approach was developed to determine the bellows requirements for various combinations of tolerance buildups, such as structural deflections and engine gimbal angles. The infinite number of combinations of these motions prevented the use of the conventional graphic motion study. The mathematical equations developed can readily be applied to new designs.

INTRODUCTION

The following ducts installed on the S-IC Stage of the Saturn V vehicle, convey liquid oxygen or RP-1 Fuel between the propellant storage tanks and the turbopumps of the F-1 Engines.

1. Outboard LOX pressure volume compensator duct
2. Outboard fuel pressure volume compensator duct
3. Inboard LOX pressure volume compensator duct
4. Inboard fuel pressure volume compensator duct
5. Outboard fuel suction duct
6. Inboard fuel suction duct
7. Outboard LOX suction duct
8. Inboard LOX suction duct

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* Brown Engineering Company, Inc., Technical Support Contractor

To aquaint the reader with the systems covered by this motion study and their orientation on the S-IC stage, an illustration of the LOX and fuel feed systems and a sectioned illustration of the outboard LOX pressure volume compensator (PVC) duct are shown in Figure 1 and 2 respectively.

These ducts are required to have a design capability to allow for all motions and deflections between the propellant tanks and the F-1 engines. The motions include stage manufacturing tolerances, motions caused by structural deflections, temperature differential, engine manufacturing tolerance, and engine gimballing. The purpose of this motion study is to determine the values of compression, extension and gimbal angles for the following conditions:

1. Specification requirements.
2. Installation tolerances and structural deflections.
3. Engine gimballing along the 'X', 'Y' and 'Z' axes.

For the purpose of developing equations, the ducts are divided into three basic types:

1. Pressure volume compensator (PVC)
2. Fuel suction
3. LOX suction

The PVC ducts consist of two gimbal joints and a compensator section. One end of the PVC is attached to the turbopump of the F-1 engine, which is offset from the engine gimbal center, and the forward flange is rigidly attached to the stage structure. The inboard engine does not gimbal; however, the same equations may be used for the inboard PVC by setting the engine gimbal angle equal to zero.

Two motion studies of the PVC's were required due to the variation in design (position of the gimbal joints relative to the end flanges) between the two suppliers, Arrowhead Products* and Flexonics.**

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* Arrowhead Products
Division of Federal-Mogul-Bower Bearing, Inc.
Los Alamitos, Calif.

** Flexonics
Division of Calumet and Hecla
Bartlett, Illinois

The configuration of the fuel suction ducts is similar to a hockey stick and consists of two gimbal joints and a sliding joint.

The LOX suction ducts are comprised of three sections; the lower section has two gimbals and a sliding joint; and the forward section, which is separated from the lower section by a long straight tube, has two gimbal joints.

Specification requirements for the LOX and fuel PVC's and suction ducts are set forth in the section titled DEVELOPMENT OF EQUATIONS.

Installation tolerances and structural deflection motions were determined for the outboard LOX and fuel and inboard LOX PVC's of the S-IC-T stage and are reported in the section titled S-IC-T MOTION LIMITS.

Outboard LOX and fuel PVC motions with the engine gimballing along the 'X', 'Y' and 'Z' axes are outlined in the section titled PLANES OF GIMBAL MOTION.

Acknowledgement is made of the technical assistance provided by P. L. Muller in the preparation of this document.

DEVELOPMENT OF EQUATIONS

PVC Ducts

The PVC ducts consist of two gimbal joints separated by a compensator section. The forward flange of the duct is rigidly attached to the stage structure, and the aft flange is attached to the F-1 engine turbopump, which has a nominal offset from the engine centerline of 50 inches. The F-1 engine gimbals about its own gimbal point in a $\pm 6^{\circ}$ square pattern with a resultant gimbal angle of $\pm 8.5^{\circ}$. Although the engine was designed to meet the $\pm 6^{\circ}$ square pattern requirement, design changes necessitated reducing the actuator motion to $\pm 5^{\circ}9'$. The remaining 51 minutes of the 6° engine angulation are to compensate for the engine dynamic misalignment.

To simplify calculations, the following assumptions were made:

1. Axial motion and lateral misalignment is induced at the aft flange of the duct.
2. Deformation of the individual parts is assumed to be negligible, and all misalignments are compensated by the gimbal joints.

A centerline diagram for PVC ducts is shown in Figure 3. The symbols and equations shown on the figure are also used in the computer program.

The results of the PVC motion study are given in the Tables I-VIII. The tables include "Life Cycle Motions" to be used for preflight certification testing.

Refer to Figure 3 for the definitions of the symbols used in these tables.

Note: Tables I - VIII give maximum motion values for each component part. The aft gimbal is at its maximum value when the PVC is in a fully compressed position with the flange tolerances added in the direction toward the engine gimbal point.

The maximum compression of the PVC occurs when the duct is in the maximum compressed position with the flange tolerances added in the direction away from the engine gimbal point. The maximum values of the component parts do not simultaneously coincide at any given condition.

LOX Suction Ducts

The LOX suction duct is comprised of three sections. The lower section with two gimbals separated by a sliding joint is rigidly supported by the stage structure. The central section, which is a long straight tube, is spring roller mounted to provide radial support in a tunnel which passes through the fuel tank. The forward section with two gimbal joints is attached to the LOX tank bulkhead.

To simplify calculations, the following assumptions were made:

1. Axial motion is induced at the forward end of the duct.
2. The long straight tubular section, which is statically indeterminate, is assumed to remain straight.
3. Deformation of the individual parts is assumed to be negligible, and all misalignments are compensated by the gimbal joints.

The centerline diagram of the LOX suction ducts is shown in Figure 4. The symbols and equations given on the figure are also used in the computer program.

The results of the LOX suction duct motion study are given in Tables IX and X. Refer to Figure 4 for the definitions of the symbols used in these tables.

These tables give maximum motion values for each component part determined for the duct in the life cycle test position to be used for preflight certification testing and the maximum values determined from the design requirement of the procurement specification.

It should be noted that the maximum values of the component parts do not simultaneously coincide at any given condition.

Fuel Suction Ducts

The fuel suction ducts consist of two gimbal joints separated by a sliding joint and a curved section between the aft gimbal joint and the aft flange. The forward flange is attached to the tank-mounted prevalve, and the aft flange is rigidly supported by the stage structure.

To simplify calculations, the following assumptions were made:

1. Axial motion and lateral misalignment is induced at the aft flange of the duct.
2. Deformation of the individual parts is assumed to be negligible, and all misalignments are compensated by the gimbal joints.

Figure 5 is a centerline diagram of the fuel suction ducts. The symbols and equations shown on the figure are also used in the computer program.

The results of the fuel suction duct motion study are given in Tables XI and XII. Refer to Figure 5 for the definitions of the symbols used in these tables.

Tables XI - XII give maximum motion values for each component part determined for the duct in the life cycle test position to be used for preflight certification testing and the maximum values determined from the design requirement of the procurement specification. Due to the unsymmetrical configuration of the duct, two positions of compression and two positions of extension were chosen for life cycle testing to simulate realistic duct positions.

It should be noted that the maximum values of the component parts do not simultaneously coincide at any given condition.

S-IC-T MOTION LIMITS

A practical analysis was necessary to confirm the theoretical analysis developed in the previous section. In this study, the practical analysis of the S-IC-T vehicle provided a means of proving or disproving the method and assumptions adopted for development of the equations and provided a means for correlating the values of gimbal joint angulation, extension, and compression of the PVC's and sliding joints obtained. This information was obtained from the computer runs in a form suitable for visual verification.

The tolerances and deflections for the LOX and outboard Fuel PVC's for the S-IC-T Stage are presented in Figure 6 through Figure 8.

The results which follow (see Tables XIII thru XV) confirm the mathematical approach performed in this study and can be summarized as follows:

1. The mathematical values for the S-IC-T determined by computer runs are within the limits of the design requirements. (see Tables I thru VIII).

2. The assumptions supporting the equations in this study caused negligible discrepancies between the mathematical values and the actual values obtained from the vehicle.

PLANES OF GIMBAL MOTION

Tables XVI through XIX present values of (outboard LOX and fuel) PVC motions obtained from the computer run covering all axes of gimbal motions. Data presented earlier in this report covered only the gimballing about XX axis where all maximum and minimum values of gimbal angles and extension and compression of the compensators occurs. PVC motions are given for engine gimballing in one degree increments up to a maximum of 6 degrees to keep the tables from becoming unwieldy.

The direction of rotation for the tabulation of PVC motion was obtained using the right hand rule. When the axis of rotation is held by the right hand, with the thumb pointing in the positive direction, the fingers are curved in the direction of positive rotation.

Figure 9 presents the engine gimbal pattern from which the tables were developed using specification requirements.

Originally these tables were used in the design analysis of the PVC's. Currently the tables are extremely useful in evaluating effects of design changes. In addition, remaining motion capability of the PVC's can be closely approximated for any given engine gimbal position if the actual manufacturing tolerances of the system are known.

CONCLUSIONS

This program demonstrates the mathematical approach of a kinematic analysis using a data processing system. It is superior in every way to standard graphical methods that, because of the infinite combinations of motions, would be prohibitive in manhours and cost.

The validity of the mathematical approach and the assumptions made during the development of equations can readily be seen by comparing the design requirement motions (Table I) and the S-IC-T motions (Table XIII).

APPENDIX

LIST OF APPLICABLE SPECIFICATIONS AND DRAWINGS

DUCT	MSFC SPEC. NO.	ARROWHEAD PRODUCTS DWG. NO.	FLEXONICS DWG. NO.
Outboard LOX PVC	20M02000	11711	107200
Outboard Fuel PVC	20M02001	11713	107207
Inboard LOX PVC	20M02002	11712	107204
Inboard Fuel PVC	20M02003	11714	107205
Outboard LOX Suction	20M02004	11715	
Outboard Fuel Suction	20M02006	11716	
Inboard LOX Suction	60B41001	11773	
Inboard Fuel Suction	60B43001	11868	

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TABLE I OUTBOARD LOX PVC SPECIFICATION REQUIREMENTS (S/N20M02000)
(Mfrs. Part No. 11711; see FIG 3)

	Engine Gimbal Angle ($\psi°$)	Aft Gimbal Angle ($a_1°$ max)	Fwd Gimbal Angle ($a_2°$ max)	ΔL_{max} (inches)	
				Extension	Compression
	±8.5	15.49	9.99	9.27	8.81
	±7.0	13.26	9.26	7.85	7.51
	±6.0	11.80	8.80	6.91	6.63
	±5.0	10.36	8.36	5.97	5.75
	±4.0	8.97	7.97	5.03	4.85
	±3.0	7.59	7.59	4.09	3.95
	±2.0	6.23	7.23	3.16	3.04
	±1.0	4.89	6.89	2.23	2.14
Life Cycle	+8.5	10.60	5.04	-	6.26
	-8.5	10.11	1.47	9.19	-

TABLE II OUTBOARD FUEL PVC SPECIFICATION REQUIREMENTS (S/N20M02001)
(Mfrs. Part No. 11713; see FIG 3)

	Engine Gimbal Angle ($\psi°$)	Aft Gimbal Angle ($a_1°$ max)	Fwd Gimbal Angle ($a_2°$ max)	ΔL_{max} (inches)	
				Extension	Compression
	±8.5	15.34	9.84	9.41	9.15
	±7.0	13.25	9.25	8.03	7.81
	±6.0	11.89	8.89	7.11	6.92
	±5.0	10.55	8.55	6.18	6.02
	±4.0	9.23	8.23	5.26	5.11
	±3.0	7.94	7.94	4.33	3.81
	±2.0	6.67	7.67	3.41	3.29
	±1.0	5.43	7.43	2.48	2.38
Life Cycle	+8.5	9.98	4.42	-	6.10
	-8.5	9.35	2.22	9.37	-

TABLE III INBOARD LOX PVC SPECIFICATION REQUIREMENTS (S/N20M02002)
(Mfrs. Part No. 11712; see FIG 3)

	Flange Position	Aft Gimbal Angle ($a_1°$)	Fwd Gimbal Angle ($a_2°$)	ΔL (inches)	
				Extension	Compression
Life Cycle	1	2.32	.73	-	1.94
	2	1.99	1.06	2.05	-
	3	8.30	10.69	-	1.77
	4	7.34	9.73	2.20	-
Maximums		8.30	10.69	2.20	2.00

TABLE IV INBOARD FUEL PVC SPECIFICATION REQUIREMENTS (S/N20M02003)
(Mfrs. Part No. 11714; see FIG 3)

	Flange Position	Aft Gimbal Angle ($a_1°$)	Fwd Gimbal Angle ($a_2°$)	ΔL (inches)	
				Extension	Compression
Life Cycle	1	2.83	.23	-	1.92
	2	2.43	.43	2.06	-
	3	7.66	10.07	-	1.79
	4	6.86	9.26	2.18	-
Maximums		7.66	10.07	2.18	2.00

TABLE V OUTBOARD LOX PVC SPECIFICATION REQUIREMENTS (S/N20M02000)
(Mfrs. Part No. 107200; see FIG 3)

Engine Gimbal Angle (ψ°)		Aft Gimbal Angle (a_1° max)	Fwd Gimbal Angle (a_2° max)	ΔL max (inches)	
				Extension	Compression
±8.5		15.19	9.69	9.25	8.81
±7.0		13.00	8.00	7.84	7.51
±6.0		11.57	8.57	6.90	6.64
±5.0		10.17	8.17	5.96	5.75
±4.0		8.79	7.79	5.02	4.85
±3.0		7.43	7.43	4.09	3.95
±2.0		6.09	7.09	3.15	3.04
±1.0		4.77	6.77	2.22	2.13
Life Cycle	+8.5	12.40	3.85	-	7.95
	-8.5	9.43	.87	6.00	-

TABLE VI OUTBOARD FUEL PVC SPECIFICATION REQUIREMENTS (S/N20M02001)
(Mfrs. Part No. 107207; see FIG 3)

Engine Gimbal Angle (ψ°)		Aft Gimbal Angle (a_1° max)	Fwd Gimbal Angle (a_2° max)	ΔL max (inches)	
				Extension	Compression
±8.5		14.98	9.48	9.41	9.15
±7.0		12.93	8.93	8.02	7.82
±6.0		11.59	8.59	7.10	6.92
±5.0		10.27	8.27	6.17	6.02
±4.0		8.97	7.97	5.25	5.12
±3.0		7.70	7.70	4.33	4.21
±2.0		6.45	7.45	3.40	3.29
±1.0		5.22	7.22	2.48	2.38
Life Cycle	+8.5	11.86	3.31		8.30
	-8.5	8.61	.13	5.68	

TABLE VII INBOARD LOX PVC SPECIFICATION REQUIREMENTS (S/N20M02002)
(Mfrs. Part No. 107204; see FIG 3)

Flange Position		Aft Gimbal Angle (a_1^0)	Fwd Gimbal Angle (a_2^0)	Δ L (inches)	
				Extension	Compression
Life Cycle	1	2.33	.70		1.94
	2	2.01	1.02	2.05	
	3	7.77	10.16		1.79
	4	6.92	9.30	2.18	
Maximum		7.77	10.16	2.18	2.00

TABLE VIII INBOARD FUEL PVC SPECIFICATION REQUIREMENTS (S/N20M02003)
(Mfrs. Part No. 107205; see FIG 3)

Flange Position		Aft Gimbal Angle (a_1^0)	Fwd Gimbal Angle (a_2^0)	Δ L (inches)	
				Extension	Compression
Life Cycle	1	2.95	.32		1.92
	2	2.53	.38	2.07	
	3	7.65	10.05		1.80
	4	6.85	9.24	2.18	
Maximum		7.65	10.05	2.18	2.00

TABLE IX OUTBOARD LOX SUCTION DUCT SPECIFICATION REQUIREMENTS (S/N20M02004)
(Mfrs. Part No. 11715; see FIG 4)

Flange Position		Aft Gimbal Angle (α_1°)	Aft Intermediate Gimbal Angle (α_2°)	Fwd Intermediate Gimbal Angle (α_3°)	Fwd Gimbal Angle (α_4°)	ΔL (inches) Extension	ΔL (inches) Compression
Life Cycle	Ext	9.77	5.77	9.83	11.33	3.85	
Life Cycle	Comp	10.91	6.91	9.83	11.33		2.25
Maximums		10.96	6.96	9.83	11.33	3.85	2.75

TABLE X INBOARD LOX SUCTION DUCT SPECIFICATION REQUIREMENTS (S/N60B41001)
(Mfrs. Part No. 11773; see FIG 4)

Flange Position		Aft Gimbal Angle (α_1°)	Aft Intermediate Gimbal Angle (α_2°)	Fwd Intermediate Gimbal Angle (α_3°)	Fwd Gimbal Angle (α_4°)	ΔL (inches) Extension	ΔL (inches) Compression
Life Cycle	Ext	8.71	5.21	10.93	12.43	3.84	
Life Cycle	Comp	9.73	6.23	10.93	12.43		2.24
Maximums		9.79	6.29	10.93	12.43	3.84	2.75

TABLE XI OUTBOARD FUEL SUCTION DUCT SPECIFICATION REQUIREMENTS (S/N20M02006)
(Mfrs. Part No. 11716; see FIG 5)

Flange Position		Aft Gimbal Angle (a_1°)	Fwd Gimbal Angle (a_2°)	ΔL (inches)	
				Extension	Compression
Life Cycle	1	16.77	13.80	-	2.78
	2	14.21	11.24	2.66	-
	3	3.37	6.28	-	3.16
	4	2.00	4.83	2.36	-
Maximums		16.77	13.80	2.66	3.85

TABLE XII INBOARD FUEL SUCTION DUCT SPECIFICATION REQUIREMENTS (S/N60B43001)
(Mfrs. Part No. 11868; see FIG 5)

Flange Position		Aft Gimbal Angle (a_1°)	Fwd Gimbal Angle (a_2°)	ΔL (inches)	
				Extension	Compression
Life Cycle	1	9.69	7.20	-	3.64
	2	8.82	6.33	2.58	-
	3	.20	2.63	-	3.79
	4	.45	2.13	2.45	-
Maximums		9.69	7.20	2.72	3.86

TABLE XIII S-IC-T OUTBOARD LOX PVC MOTIONS (20M02000)
(Mfrs. Part No. 11711; see FIG 3 and 6)

Engine Gimbal Angle (ψ^0)	Aft Gimbal Angle (a_1^0 max)	Fwd Gimbal Angle (a_2^0 max)	ΔL_{max} (inches)	
			Extension	Compression
8.5	15.25	6.01	8.35	8.45
7.0	13.04	5.30	6.96	7.47
6.0	11.61	4.87	6.04	6.31
5.0	10.20	4.56	5.12	5.77
4.0	8.81	4.07	4.20	4.90
3.0	7.45	3.71	3.29	3.94
2.0	6.11	3.37	2.38	3.15
1.0	4.80	3.06	1.47	2.27

TABLE XIV S-IC-T OUTBOARD FUEL PVC MOTIONS (20M02001)
(Mfrs. Part No. 11713; see FIG 3 and 7)

Engine Gimbal Angle (ψ^0)	Aft Gimbal Angle (a_1^0 max)	Fwd Gimbal Angle (a_2^0 max)	ΔL_{max} (inches)	
			Extension	Compression
8.5	14.42	5.18	8.13	8.98
7.0	12.38	4.64	6.78	7.70
6.0	11.05	4.31	5.88	6.83
5.0	9.74	4.00	4.98	5.97
4.0	8.46	3.72	4.08	5.09
3.0	7.20	3.47	3.18	4.22
2.0	5.97	3.23	2.29	3.33
1.0	4.76	3.02	1.39	2.45

TABLE XV S-IC-T INBOARD LOX PVC MOTIONS (20M02002)
(Mfrs. Part No. 11712; see FIG 3 and 8)

Aft Gimbal Angle (a_1^0)	Fwd Gimbal Angle (a_2^0)	ΔL (inches)	
		Extension	Compression
4.39	4.35	.62	1.56

TABLE XVI OUTBOARD LOX PVC GIMBALLING (20M02000)
(Mfrs. Part No. 11711)

About XX Axis

In a Positive (+) Direction

Maximum *	Engine Gimbal Angle ($\psi°$)	Flange Position	Aft Gimbal Angle ($a_1°$)	Fwd Gimbal Angle ($a_2°$)	ΔL (inches) + (extension) - (compression)
a	6	4	11.08	5.08	-3.49
COMP	6	2	4.45	-.05	-4.14
a	6	3	11.51	5.51	-5.95
COMP	6	1	4.69	.19	-6.60
a	5	4	9.72	4.72	-2.71
COMP	5	2	3.19	.19	-3.25
a	5	3	10.08	5.08	-5.18
COMP	5	1	3.32	-.18	-5.75
a	4	4	8.37	4.37	-1.92
COMP	4	2	1.90	-.10	-2.35
a	4	3	8.68	4.68	-4.40
COMP	4	1	2.02	.02	-4.85
a	3	4	7.05	4.05	-1.13
COMP	3	2	.63	-.37	-1.45
a	3	3	7.30	4.305	-3.61
COMP	3	1	.70	-.30	-3.95
a	2	4	5.76	3.76	-.33
COMP	2	2	-.03	-.53	-.54
a	2	3	5.95	3.95	-2.82
COMP	2	1	-.01	.51	-3.04
a	1	4	4.48	3.48	.48
COMP	1	2	1.98	.98	.46
a	1	3	4.62	3.62	-2.01
COMP	1	1	.013	.013	-2.14

In a Negative (-) Direction

Maximum *	Engine Gimbal Angle ($\psi°$)	Flange Position	Aft Gimbal Angle ($a_1°$)	Fwd Gimbal Angle ($a_2°$)	ΔL (inches) + (extension) - (compression)
a	6	1	10.36	4.36	4.44
EXT	6	2	10.04	4.04	6.91
a	5	1	9.24	4.24	3.49
EXT	5	2	8.94	3.94	5.97
a	4	1	8.09	4.09	2.55
EXT	4	2	7.83	3.83	5.02
a	3	1	6.92	3.92	1.60
EXT	3	2	6.71	3.71	4.09
a	2	1	5.74	3.74	.666
EXT	2	2	5.56	3.56	3.16
a	1	1	4.53	3.53	-.268
EXT	1	2	4.40	3.40	2.23

About YY Axis

In a Positive and Negative Direction

Maximum	Engine Gimbal Angle ($\psi°$)	Flange Position	Aft Gimbal Angle ($a_1°$)	Fwd Gimbal Angle ($a_2°$)	ΔL (inches) + (extension) - (compression)
a	6	3	10.89	4.89	-.75
COMP	6	1	4.50	-.03	-1.41
EXT	6	4	10.52	4.52	1.71
a	5	3	9.63	4.63	-.84
COMP	5	1	3.24	.24	-1.39
EXT	5	4	9.30	4.30	1.63
a	4	3	8.37	4.37	-.93
COMP	4	1	1.96	-.04	-1.36
EXT	4	4	8.09	4.09	1.55
a	3	3	7.11	4.11	-1.00
COMP	3	1	.69	-3.10	-1.33
EXT	3	4	6.87	3.87	1.48
a	2	3	5.81	3.84	-1.07
COMP	2	1	0	-.50	-1.30
EXT	2	4	5.66	3.66	1.42
a	1	3	4.57	3.57	-1.14
COMP	1	1	0	0	-1.26
EXT	1	4	4.44	3.44	1.36

*In Tables XVI through XIX the first line gives the value of ΔL when the gimbal angles (a) are maximum. The second line gives values of the gimbal angles when ΔL is maximum. For example, in Table XVI the last column (first line) shows the amount of compression (ΔL = -3.49) when gimbal angles are maximum (a_1 = 11.08; a_2 = 5.08). The fourth column shows that aft gimbal angle a_1 = 4.45, and the fifth column that fwd gimbal angle a_2 = -.05, when compression is maximum (ΔL = -4.14).

Direction of rotation about an axis is obtained from the right hand rule.

TABLE XVII OUTBOARD LOX AND FUEL PVC GIMBALLING

LOX PVC (20M02000)

About WW Axis

In a Positive (+) Direction

Maximum	Engine Gimbal Angle ($\psi°$)	Flange Position	Aft Gimbal Angle ($\alpha_1°$)	Fwd Gimbal Angle ($\alpha_2°$)	ΔL (inches) + (extension) - (compression)
α	6	1	10.51	4.51	2.92
EXT	6	2	10.17	4.17	5.39
α	5	1	9.35	4.35	2.22
EXT	5	2	9.04	4.04	4.70
α	4	1	8.17	4.17	1.53
EXT	4	2	7.91	3.91	4.01
α	3	1	6.97	3.97	.84
EXT	3	2	6.75	3.75	3.33
α	2	1	5.77	3.77	.156
EXT	2	2	5.59	3.59	2.65
α	1	1	4.54	3.54	- .523
COMP	1	1	0	0	- .65
EXT	1	2	4.41	3.41	1.97

In a Negative (-) Direction

Maximum	Engine Gimbal Angle ($\psi°$)	Flange Position	Aft Gimbal Angle ($\alpha_1°$)	Fwd Gimbal Angle ($\alpha_2°$)	ΔL (inches) + (extension) - (compression)
α	6	4	10.90	4.90	-1.96
COMP	6	2	4.39	-.11	-2.61
α	6	3	11.32	5.32	-4.43
COMP	6	1	4.62	.12	-5.10
α	5	4	9.59	4.59	-1.44
COMP	5	2	3.15	.15	-1.98
α	5	3	9.94	4.94	-3.91
COMP	5	1	3.28	-.22	-4.47
α	4	4	8.29	4.29	- .90
COMP	4	2	1.88	-.12	-1.34
α	4	3	8.59	4.59	-3.38
COMP	4	1	2.003	.003	-3.83
α	3	4	7.00	4.00	- .36
COMP	3	2	.63	-.37	- .686
α	3	3	7.24	4.24	-2.85
COMP	3	1	.697	-.30	-3.19
α	2	3	5.92	3.92	-2.30
COMP	2	1	-.01	-.50	-2.53
EXT	2	2	5.73	3.73	.185
α	1	3	4.60	3.60	-1.76
COMP	1	1	.01	.01	-1.88
EXT	1	2	4.46	3.46	.74

FUEL PVC (20M02001)

About XX Axis

In a Positive (+) Direction

Maximum	Engine Gimbal Angle ($\psi°$)	Flange Position	Aft Gimbal Angle ($\alpha_1°$)	Fwd Gimbal Angle ($\alpha_2°$)	ΔL (inches) + (extension) - (compression)
α	6	4	10.75	4.75	-3.30
COMP	6	2	3.68	-.32	-3.93
α	6	3	11.29	5.29	-6.25
COMP	6	1	- .06	3.94	-6.92
α	5	4	9.49	4.49	-2.50
COMP	5	2	2.49	-.05	-3.03
α	5	3	9.96	4.96	-5.46
COMP	5	1	2.68	-.32	-6.02
α	4	4	8.26	4.26	-1.70
COMP	4	2	1.32	-.68	-2.12
α	4	3	8.65	4.65	-4.67
COMP	4	1	1.44	-.56	-5.12
α	3	4	7.05	4.05	- .89
COMP	3	2	.17	-.83	-1.21
α	3	3	7.37	4.37	-3.87
COMP	3	1	.23	-.77	-4.20
α	2	4	5.85	3.85	- .07
COMP	2	2	.184	-.81	- .29
α	2	3	6.11	4.11	-3.06
COMP	2	1	.19	-.81	-3.29
α	1	4	4.68	3.68	.74
COMP	1	2	2.03	1.03	.708
α	1	3	4.87	3.87	-2.25
COMP	1	1	.01	.01	-2.38

In a Negative (-) Direction

Maximum	Engine Gimbal Angle ($\psi°$)	Flange Position	Aft Gimbal Angle ($\alpha_1°$)	Fwd Gimbal Angle ($\alpha_2°$)	ΔL (inches) + (extension) - (compression)
α	6	1	10.11	4.11	4.14
EXT	6	2	9.70	3.70	7.11
α	5	1	9.07	4.07	3.21
EXT	5	2	8.71	3.71	6.18
α	4	1	8.02	4.02	2.28
EXT	4	2	7.70	3.70	5.26
α	3	1	6.95	3.95	1.35
EXT	3	2	6.68	3.68	4.33
α	2	1	5.87	3.87	.42
EXT	2	2	5.64	3.64	3.41
α	1	1	4.77	3.77	- .51
EXT	1	2	4.59	3.59	2.48

TABLE XVIII OUTBOARD FUEL PVC GIMBALLING (20M02001)
(Mfrs. Part No. 11713)

Fuel PVC Flange No. 1

About YY Axis

In a Positive (+) Direction

Maxi-mum	Engine Gimbal Angle ($\psi°$)	Flange Position	Aft Gimbal Angle ($a_1°$)	Fwd Gimbal Angle ($a_2°$)	ΔL (inches) + (extension) - (compression)
a	6	1	10.36	4.36	1.63
EXT	6	2	4.93	3.93	4.59
a	5	1	9.26	4.26	1.11
EXT	5	2	8.88	3.88	4.08
a	4	1	8.16	4.16	.60
EXT	4	2	7.83	3.83	3.58
a	3	1	7.04	4.04	.09
EXT	3	2	6.76	3.76	3.07
a	2	1	5.92	3.92	-.42
EXT	2	2	5.69	3.69	2.56
a	1	1	4.79	3.79	-.93
EXT	1	2	4.61	3.61	2.06

In a Negative (-) Direction

Maxi-mum	Engine Gimbal Angle ($\psi°$)	Flange Position	Aft Gimbal Angle ($a_1°$)	Fwd Gimbal Angle ($a_2°$)	ΔL (inches) + (extension) - (compression)
a	6	4	10.46	4.46	.79
COMP	6	2	3.61	-.39	-1.41
a	6	3	10.96	4.96	-3.74
COMP	6	1	3.85	-.15	-4.40
a	5	4	9.28	4.28	- .40
COMP	5	2	2.45	-.55	- .90
a	5	3	9.72	4.72	-3.37
COMP	5	1	2.64	-.36	-3.92
a	4	4	8.11	4.11	- .02
COMP	4	2	1.31	.69	- .43
a	4	3	8.48	4.48	-2.99
COMP	4	1	1.43	-.57	-3.43
a	3	4	6.95	3.95	.37
COMP	3	2	4.31	1.31	.32
a	3	3	7.26	4.26	-2.61
COMP	3	1	.23	-.76	-2.94
a	2	4	5.80	3.80	.77
COMP	2	2	3.16	1.16	.72
a	2	3	6.05	4.05	-2.22
COMP	2	1	.20	-.79	-2.45
a	1	4	4.65	3.65	1.16
COMP	1	2	2.01	1.01	1.13
a	1	3	4.85	3.84	-1.83
COMP	1	1	.01	.01	-1.96

About WW Axis

In a Positive (+) Direction

Maxi-mum	Engine Gimbal Angle ($\psi°$)	Flange Position	Aft Gimbal Angle ($a_1°$)	Fwd Gimbal Angle ($a_2°$)	ΔL (inches) + (extension) - (compression)
a	6	1	10.07	4.04	4.52
EXT	6	2	9.67	3.67	7.48
a	5	1	9.04	4.04	3.53
EXT	5	2	8.68	3.68	6.50
a	4	1	4.00	8.00	2.53
EXT	4	2	7.68	3.68	5.51
a	3	1	6.94	3.94	1.54
EXT	3	2	6.67	3.67	4.52
a	2	1	5.86	3.86	.54
EXT	2	2	5.63	3.63	3.53
a	1	1	4.76	3.76	-.45
EXT	1	2	4.58	3.58	2.55

In a Negative (-) Direction

Maxi-mum	Engine Gimbal Angle ($\psi°$)	Flange Position	Aft Gimbal Angle ($a_1°$)	Fwd Gimbal Angle ($a_2°$)	ΔL (inches) + (extension) - (compression)
a	6	4	10.79	4.79	-3.67
COMP	6	2	- .31	3.69	-4.31
a	6	3	11.34	5.34	-6.63
COMP	6	1	3.96	.04	-7.30
a	5	4	9.53	4.53	-2.81
COMP	5	2	2.49	.5	-3.3
a	5	3	9.99	4.99	-5.78
COMP	5	1	2.69	.31	-6.34
a	4	4	8.28	4.28	-1.95
COMP	4	2	1.32	.68	-2.37
a	4	3	8.68	4.68	-4.92
COMP	4	1	1.45	.55	-5.37
a	3	4	7.06	4.06	-1.08
COMP	3	2	.17	.83	-1.40
a	3	3	7.38	4.38	-4.06
COMP	3	1	.23	.77	-4.40
a	2	4	5.86	3.86	- .2
COMP	2	2	.18	.82	- .42
a	2	3	6.11	4.11	-3.19
COMP	2	1	.19	.81	-3.42
a	1	4	4.68	3.68	.68
COMP	1	2	2.03	1.03	.64
a	1	3	4.87	3.87	-2.31
COMP	1	1	.01	.01	-2.45

TABLE XIX OUTBOARD FUEL PVC GIMBALLING THROUGH CENTERLINE OF FLANGE (20M02001)
(Mfrs. Part No. 11713)

Fuel PVC Flange No. 1

About ZZ Axis

In a Positive (+) Direction

Maxi-mum	Engine Gimbal Angle ($\psi°$)	Flange Position	Aft Gimbal Angle ($a_1°$)	Fwd Gimbal Angle ($a_2°$)	ΔL (inches) + (extension) - (compression)
a	6	4	10.36	4.36	.13
COMP	6	2	3.58	.42	-.49
a	6	3	10.85	4.85	-2.83
COMP	6	1	3.82	.18	-3.48
a	5	4	9.21	4.21	.36
COMP	5	2	6.57	1.57	.30
a	5	3	9.64	4.64	-2.61
COMP	5	1	2.62	.38	-3.15
a	4	4	8.06	4.06	.59
COMP	4	2	5.42	1.42	.54
a	4	3	8.43	4.43	-2.38
COMP	4	1	1.42	.57	-2.82
a	3	4	6.92	3.92	.83
COMP	3	2	4.28	1.28	.78
a	3	3	7.22	4.22	-2.15
COMP	3	1	.24	.76	-2.48
a	2	4	5.78	3.78	1.07
COMP	2	2	3.14	1.14	1.03
a	2	3	6.02	4.02	-1.92
COMP	2	1	.21	.79	-2.14
a	1	4	4.65	3.65	1.32
COMP	1	2	2.0	1.0	1.28
a	1	3	4.83	3.83	-1.68
COMP	1	1	0	0	-1.81

In a Negative (-) Direction

EXT	6	2	10.01	4.01	3.68
a	6	1	10.45	4.45	.72
EXT	5	2	8.94	3.94	3.32
a	5	1	9.34	4.34	.35
EXT	4	2	7.87	3.87	2.97
a	4	1	8.21	4.21	-.01
EXT	3	2	6.79	3.79	2.61
a	3	1	7.08	4.08	-.37
EXT	2	2	5.71	3.71	2.26
a	2	1	5.94	3.94	-.73
EXT	1	2	4.62	3.62	1.91
a	1	1	4.80	3.80	-1.08

About AA Axis

In a Positive (+) Direction

Maxi-mum	Engine Gimbal Angle ($\psi°$)	Flange Position	Aft Gimbal Angle ($a_1°$)	Fwd Gimbal Angle ($a_2°$)	ΔL (inches) + (extension) - (compression)
a	6	1	10.05	4.05	4.80
EXT	6	2	9.65	3.65	7.76
a	5	1	9.02	4.02	3.76
EXT	5	2	8.67	3.67	6.73
a	4	1	7.99	3.99	2.71
EXT	4	2	7.67	3.67	5.69
a	3	1	6.93	3.93	1.68
EXT	3	2	6.65	3.65	4.66
a	2	1	5.85	3.86	.64
EXT	2	2	5.63	3.63	3.62
a	1	1	4.76	3.76	-.40
EXT	1	2	4.58	3.58	2.59

In a Negative (-) Direction

a	6	4	10.83	4.83	-3.95
COMP	6	2	3.70	.30	-4.59
a	6	3	11.38	5.38	-6.90
COMP	6	1	3.97	.03	-7.58
a	5	4	9.55	4.55	-3.04
COMP	5	2	2.50	.50	-3.58
a	5	3	10.02	5.02	-6.01
COMP	5	1	2.69	-.31	-6.57
a	4	4	8.3	4.3	-2.13
COMP	4	2	1.32	.68	-2.56
a	4	3	8.69	4.69	-5.11
COMP	4	1	1.45	.55	-5.55
a	3	4	7.07	4.07	-1.22
COMP	3	2	.17	-.83	-1.53
a	3	3	7.39	4.39	-4.20
COMP	3	1	.23	.77	-4.53
a	2	4	5.87	3.87	-.29
COMP	2	2	.18	.82	-.51
a	2	3	6.12	4.12	-3.28
COMP	2	1	.19	.81	-3.51
a	1	4	4.68	3.68	.63
COMP	1	2	2.04	1.04	.60
a	1	3	4.87	3.87	-2.36
COMP	1	1	0	0	-2.49

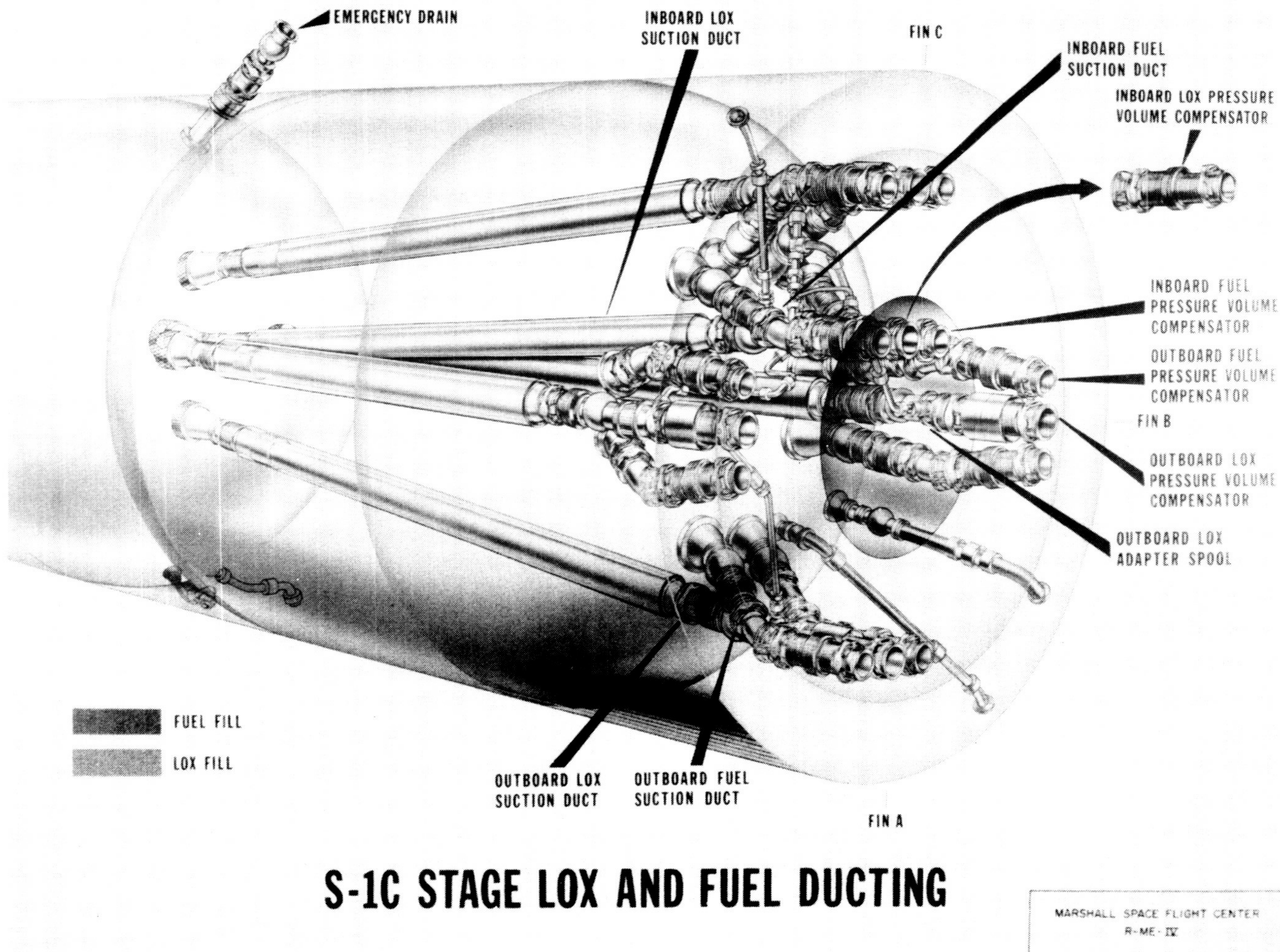


FIGURE 1 S-IC STAGE LOX AND FUEL DUCTING

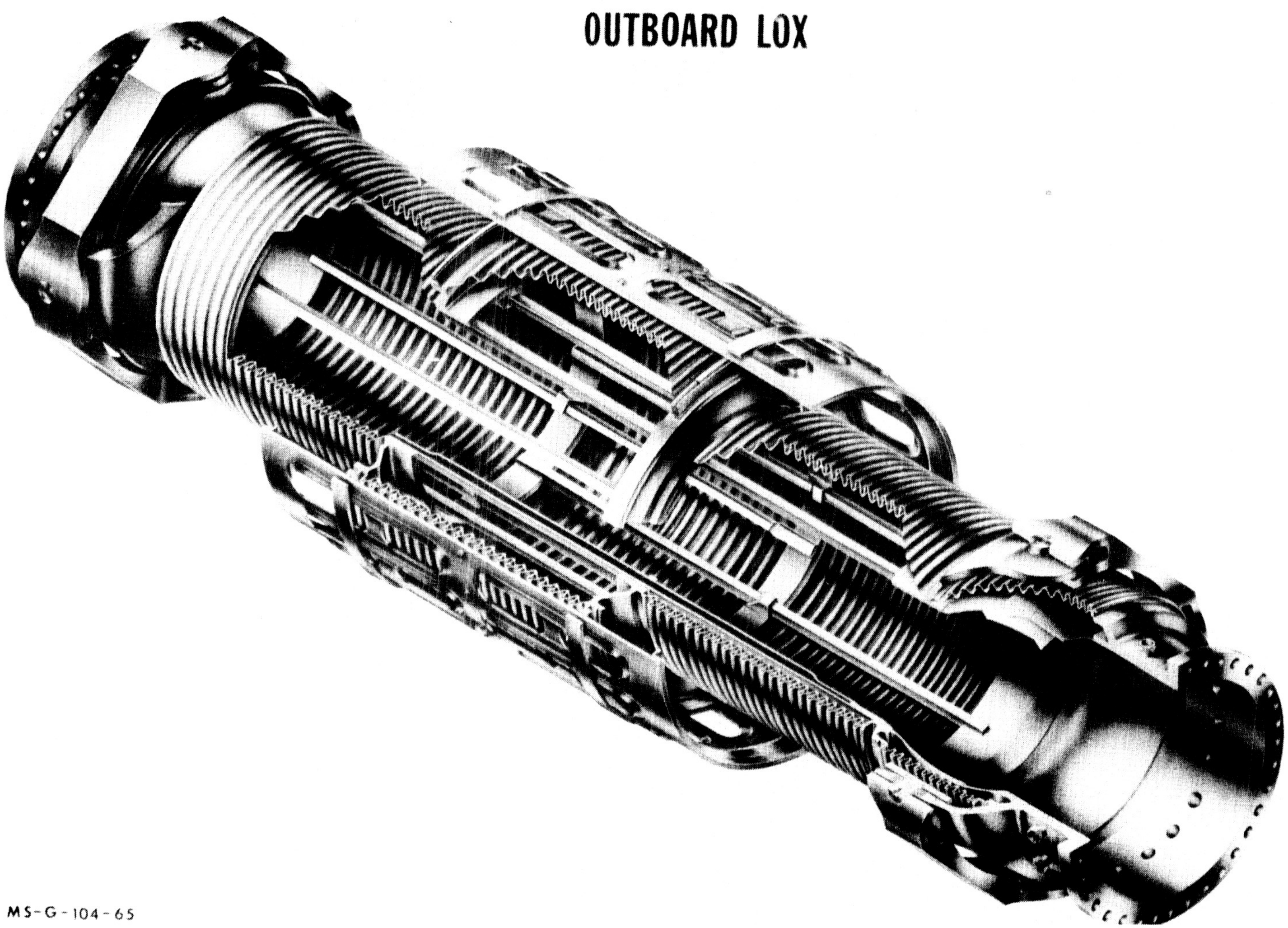
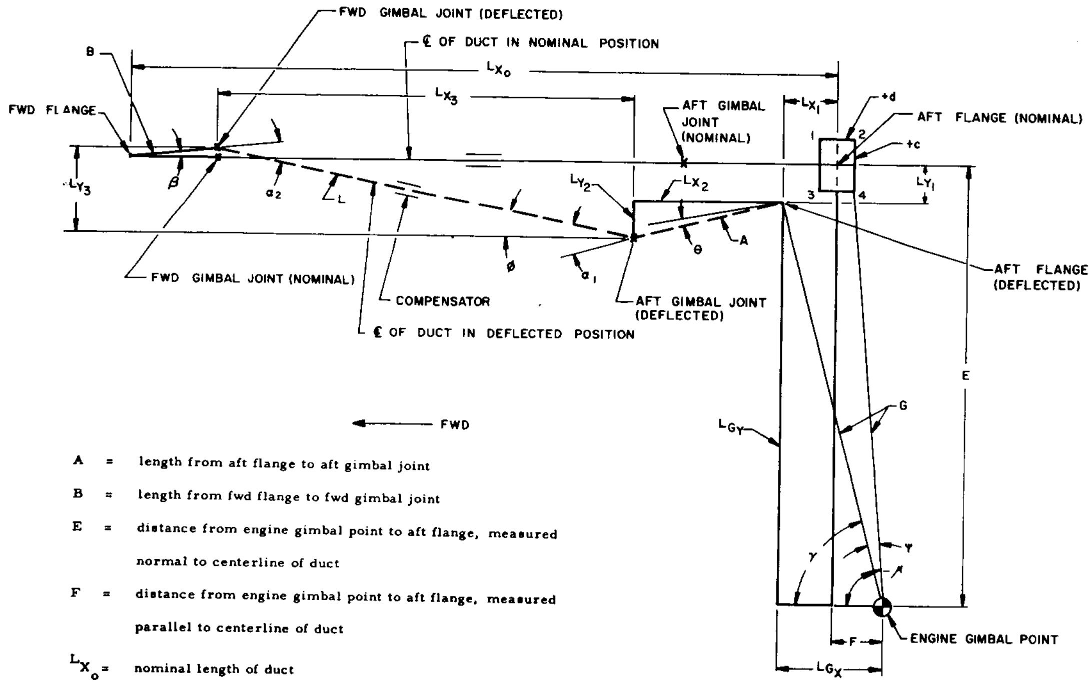


FIGURE 2 PRESSURE VOLUME COMPENSATING DUCT - OUTBOARD LOX



A = length from aft flange to aft gimbal joint

B = length from fwd flange to fwd gimbal joint

E = distance from engine gimbal point to aft flange, measured normal to centerline of duct

F = distance from engine gimbal point to aft flange, measured parallel to centerline of duct

L_{X_0} = nominal length of duct

c = radial misalignment at aft flange

d = axial misalignment at aft flange

θ = angular misalignment at aft flange

β = angular misalignment at fwd flange

ψ = engine gimbal angle

α_1 = aft gimbal angle

α_2 = fwd gimbal angle

ΔL = change in length of compensator

$\mu = \arctan\ [(E + c)/(F - d)]$

$\gamma = \mu - \psi$

$G = \sqrt{(E + c)^2 + (F - d)^2}$

$L_{G_Y} = G \sin \gamma$

$L_{G_X} = G \cos \gamma$

$L_{Y_1} = E - L_{G_Y}$

$L_{X_1} = L_{G_X} - F$

$L_{X_2} = A \cos(\psi + \theta)$

$L_{Y_2} = A \sin(\psi + \theta)$

$L_{X_3} = L_{X_0} - B \cos \beta - L_{X_1} - L_{X_2}$

$L_{Y_3} = L_{Y_1} + L_{Y_2} + B \sin \beta$

$\phi = \arctan\ (L_{Y_3} / L_{X_3})$

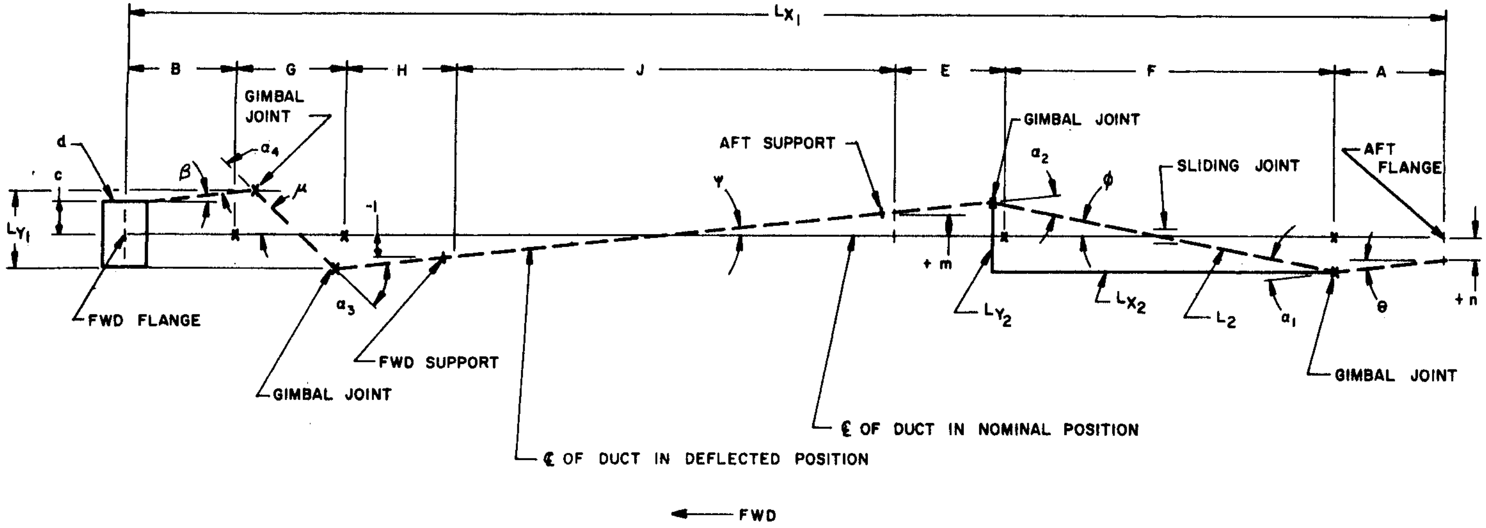
$L = \sqrt{L_{Y_3}^2 + L_{X_3}^2}$

$\alpha_1 = \phi + \psi + \theta$

$\alpha_2 = \phi + \beta$

$\Delta L = L - L_{X_0} - A - B$

FIGURE 3 CENTERLINE DIAGRAM FOR PVC DUCTS



A = length from aft flange to aft gimbal joint

B = length from fwd flange to fwd gimbal joint

E = length from aft intermediate gimbal joint to aft support

G = length from fwd gimbal joint to fwd intermediate gimbal joint

H = length from fwd intermediate gimbal joint to fwd support

J = length between fwd and aft supports

F = nominal length between aft gimbal joint and aft intermediate gimbal joint

c = radial misalignment at fwd flange

d = axial misalignment at fwd flange

β = angular misalignment at fwd flange

l = radial misalignment at fwd support

m = radial misalignment at aft support

n = radial misalignment at aft flange

θ = angular misalignment at aft flange

α_1 = aft gimbal angle

α_2 = aft intermediate gimbal angle

α_3 = fwd intermediate gimbal angle

α_4 = fwd gimbal angle

ΔL = change in length of sliding joint

$\psi = \arc \sin \left[(m - l)/J\right]$

$L_{Y_1} = B \sin\beta + c - l + H \sin\psi$

$\mu = \arc \sin (L_{Y_1}/G)$

$L_{X_2} = L_{X_0} - d - B \cos\beta - G \cos\mu - A \cos\theta - (J + H + E) \cos\psi$

$L_{Y_2} = m + E \sin\psi - n - A \sin\theta$

$L_2 = \sqrt{L_{X_2}^2 + L_{Y_2}^2}$

$\phi = \arc \tan (L_{Y_2}/L_{X_2})$

$\alpha_1 = \theta + \phi$

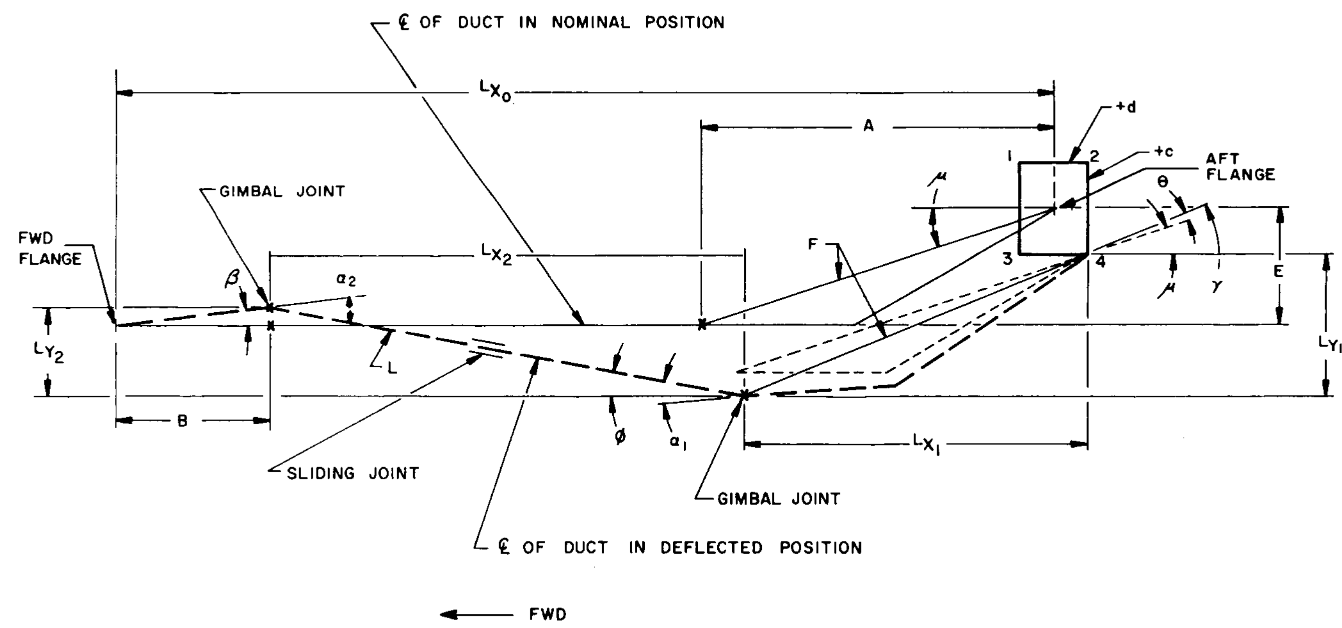
$\alpha_2 = \phi + \psi$

$\alpha_3 = \psi + \mu$

$\alpha_4 = \mu + \beta$

$\Delta L = L_2 - F$

FIGURE 4 CENTERLINE DIAGRAM FOR LOX SUCTION DUCTS



A = length from aft flange to aft gimbal joint

B = length from fwd flange to fwd gimbal joint

E = offset of aft flange

L_{X_o} = nominal length of duct

c = radial misalignment at aft flange

d = axial misalignment at aft flange

θ = angular misalignment at aft flange

β = angular misalignment at fwd flange

α_1 = aft gimbal angle

α_2 = fwd gimbal angle

ΔL = change in length of sliding joint

$\mu = \arctan (E/A)$

$F = \sqrt{A^2 + E^2}$

$\gamma = \theta + \mu$

$L_{X_1} = F \cos \gamma$

$L_{Y_1} = F \sin \gamma$

$L_{X_2} = L_{X_o} - B \cos \beta - L_{X_1} + d$

$L_{Y_2} = B \sin \beta - E - c + L_{Y_1}$

$L = \sqrt{L_{X_2}^2 + L_{Y_2}^2}$

$\phi = \arctan (L_{Y_2} / L_{X_2})$

$\alpha_1 = \phi + \theta$

$\alpha_2 = \phi + \beta$

$\Delta L = L - L_{X_o} + A + B$

FIGURE 5 CENTERLINE DIAGRAM FOR FUEL SUCTION DUCTS

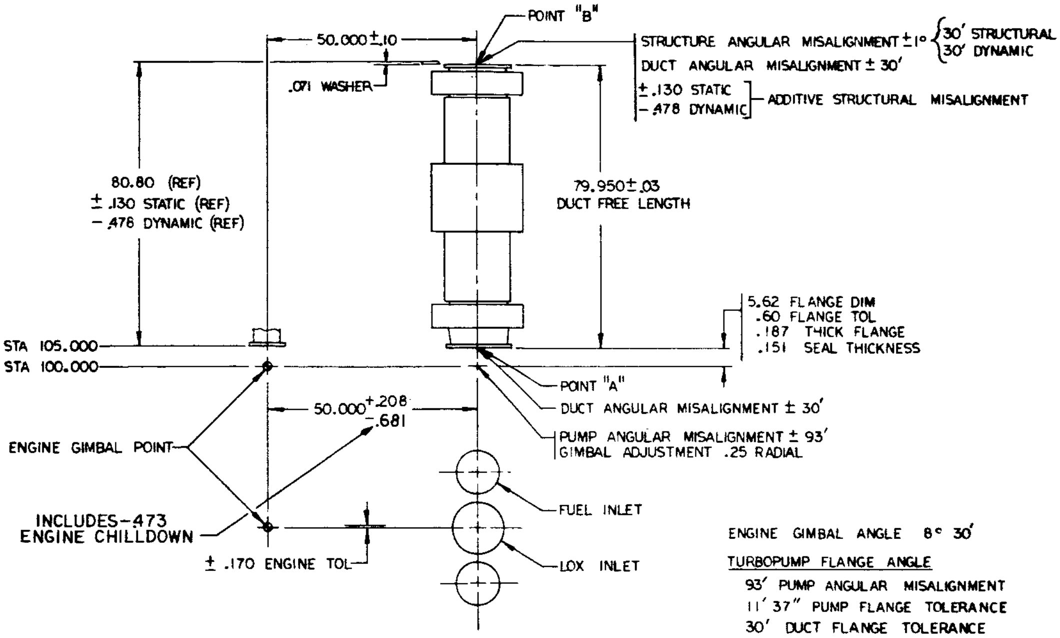


FIGURE 6 S-IC-T TOLERANCES AND DEFLECTIONS FOR THE OUTBOARD LOX PVC

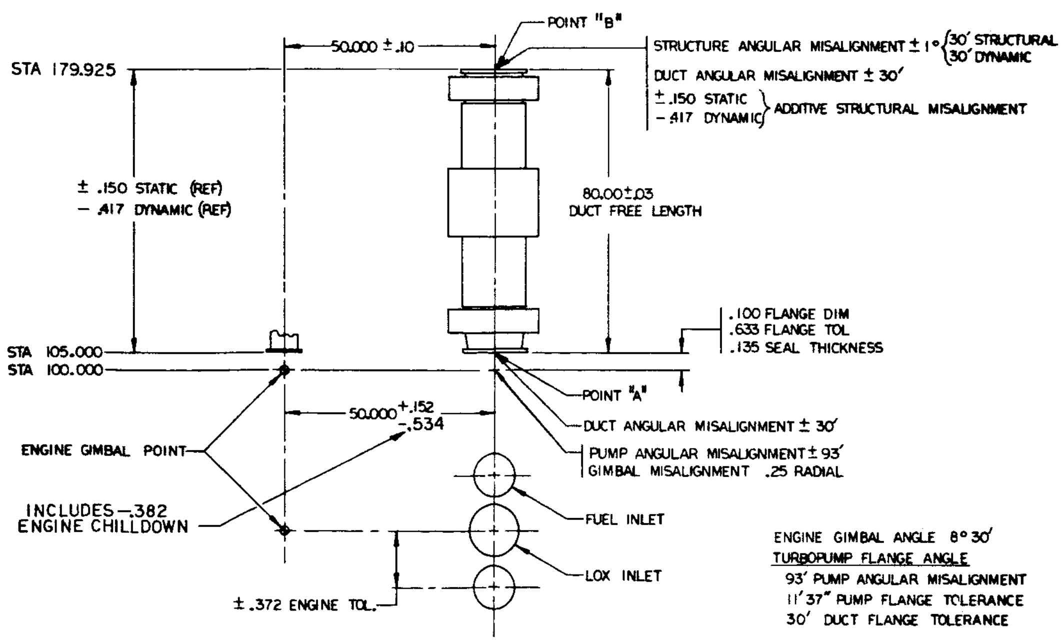


FIGURE 7 S-IC-T TOLERANCES AND DEFLECTIONS FOR THE OUTBOARD FUEL PVC

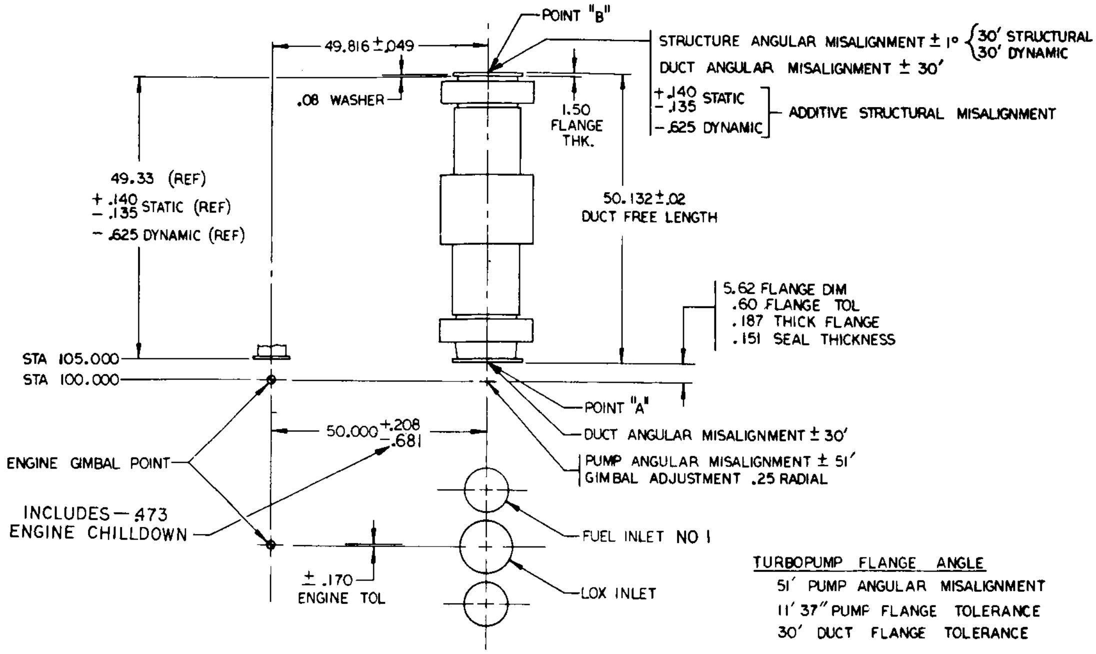


FIGURE 8 S-IC-T TOLERANCES AND DEFLECTIONS FOR THE INBOARD LOX PVC

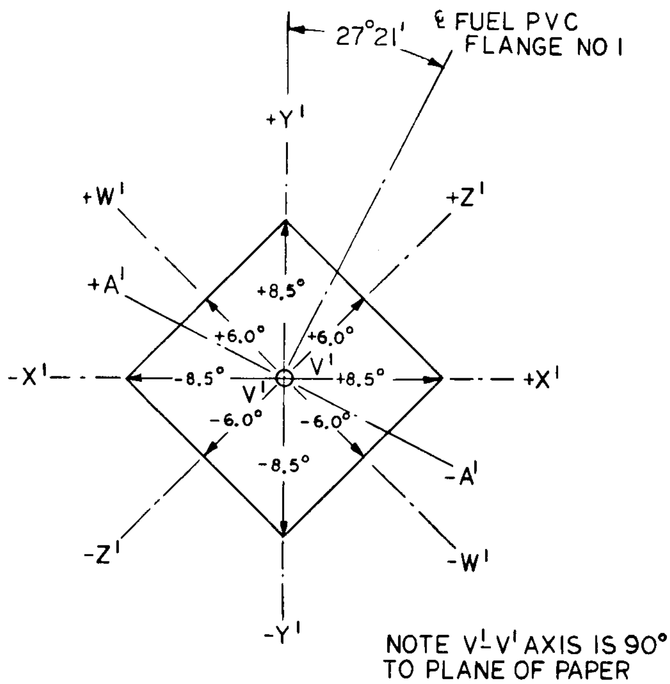


FIGURE 9 ENGINE GIMBAL PATTERN

June 22, 1966 APPROVAL TM X-53471

MOTION STUDY OF THE SUCTION DUCTING ON THE S-IC STAGE OF THE SATURN V VEHICLE

By H. E. Fursdon

The information in this report has been reviewed for security classification. Review of any information concerning Department of Defense or Atomic Energy Commission programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

This document has also been reviewed and approved for technical accuracy.

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