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7 June 1966

7770:L3076

R. W. Schroeder
Space Nuclear Propulsion Office
Cleveland Extension - NASA
21000 Brookpark Road
Cleveland, Ohio 44135

Attention: G. K. Sievers

Subject: CFDTs Lower Thrust Structure

Dear Mr. Schroeder:

Enclosure (1) presents the evaluation of the instrumented structural proof test performed at the fabrication vendor's facility prior to delivery of the assembly to Aerojet. The testing demonstrated the integrity of the assembly for CFDTs and provided development information for the X-engine program. At present the assembly is being used in the CFDTs program.

Very truly yours,

AEROJET-GENERAL CORPORATION

C. M. Rice
C. M. Rice
Program Manager
Rocket Engine Operations - Nuclear

RWT:db

Enclosure (1) BN-TM-0339, dated 19 March 1966;
Lower Thrust Structure, S/N 0000012
Structural Test Evaluation

cc: M. M. Carness, SNPO-C Representative @ Sacto, W/Enclosure
J. W. Gilray, SNPO-C Representative @ Sacto, W/Enclosure

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RN-TM-0339

19 March 1966

REON TECHNICAL MEMORANDUM
LOWER THRUST STRUCTURE S/N 0000012
STRUCTURAL TEST EVALUATION

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ABSTRACT

A series of four structural tests were successfully completed on an XE-1 type NERVA lower thrust structure fabricated for the Cold Flow Development Test Program. The testing consisted of applying axial tension loads to the lower thrust structure while assembled to the CFDTS upper thrust structure and applying axial tension and compression loads and lateral shear loads to the lower thrust structure alone. Based on the strain gage and dial indicator data obtained during the tests it was concluded that the lower thrust structure successfully demonstrated structural integrity for CFDTS load conditions. These tests also supplied significant data applicable to the design of the Lower Thrust Structure for the X-Engine Program.

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I. INTRODUCTION

This report describes the testing of an XE-1 type NERVA lower thrust structure (LTS) and includes the experimental findings and conclusions derived. The testing was performed by the Aeronca Manufacturing Corporation, the LTS Vendor, at their Aerocal Facility located at Torrance, California, during the month of December, 1964. Test specifications were provided by AGC Memorandum 7456:M2359⁽¹⁾. The primary purpose of the testing was to demonstrate the structural adequacy of the LTS, prior to shipment to AGC Sacramento, for use on the Cold Flow Development Test System Program, (CFDTS).

A total of four tests were conducted: The first test, an axial tension load of 20 Kips conducted with the LTS assembled to the UTS, and the fourth test, a lateral shear load of 5 Kips conducted on the LTS alone, served as proof that the design would satisfy requirements for CFDTS testing operations and expected ground handling requirements. Two additional tests based on preliminary XE load criteria were included in the test plans to provide design data for X-engine LTS development⁽²⁾. These tests, an axial tension load of 20 Kips and an axial compression test of 100 Kips were also conducted on the LTS alone.

-
- (1) Memo 7456:M2355 "Test Plan for the Component Static Load Proof Test of the CFDTS Upper and Lower Thrust Structure Assemblies", dated 13 November 1964, with Amendments 1, 25 November 1964, and 2, 14 December 1964 (U)
- (2) AGC, RN-DR-0020 "Preliminary Design Specification, Engine, Nuclear, XE-1 (C/RD) and AGC RN-TM-0159, "Basic Loads and Structural Design Criteria for the XE-1 Engine" (U)

II. TEST OBJECTIVES

The objectives of this test were as follows:

- A. To demonstrate the structural integrity of the lower thrust structure when subjected to expected CFDTS loads.
- B. To provide data to compute the axial and lateral spring constant of the lower thrust structure.
- C. To provide data for the XE lower thrust structure development program.

III. DESCRIPTION OF TEST

A. Test Unit

The lower thrust structure subjected to the test loads described in this report was fabricated by the Aeronca Manufacturing Company of Torrance, California in accordance with Aerojet-General Corporation Drawing 706952 and all applicable specifications. The serial number of the part was S/N 0000012. The test unit was a truncated cone of aluminum alloy semi-monocoque construction. The overall dimensions were approximately 100 inches in diameter at the forward end, 56.8 inches in diameter at the aft end and 31.6 inches high. The primary structure consisted of 12 axial stringers of 1 1/2 inch x 2 inch x 3/16 inch extruded Tee sections and upper and lower circumferential ribs of hydroformed 1/8 inch sheet. A .040 inch thick skin was riveted to very other panel section to provide lateral stiffness. Each skin panel was stiffened with two longitudinal 1.0 inch x 1.0 inch x .094 inch angles. There were 12 fittings at each end of the structure for attachment to the upper thrust structure and to the CFDTS pressure vessel. Joining of the primary structural components was accomplished with lock bolts passing through the Tee sections, circumferential ribs, skin and attachment brackets.

All Tee and angle sections were made of 6061-T6 extrusions. The circumferential ribs were hydroformed of 6061-O sheet and heat treated to the T6 temperature. Skin material was 2024-T3 sheet. The end fittings were made from

6061-O plate, welded and heat treated to the T6 temper. Final assembly of the LTS was accomplished using an assembly jig.

For specific details and dimensions of the test unit AGC Drawing 706952-F is available for reference.

Variations of the parts from the drawing were minor with the exception of two Supplier Discrepancy Action Requests #11809 and #11810 on the radiographic quality of the end fitting welds. The basic problem involved lack of fusion and elongated or linear porosity. Engineering disposition made was "accept on bases of satisfying proof test requirements outlined in Department 7456, Memo #2355, Test Plan for the Component Static Load Proof Test of the CFDTs Upper and Lower Thrust Structure Assemblies". To add further confidence on the end fitting capability, a test evaluation program was conducted just prior to the proof test⁽³⁾. Three end fittings were successfully loaded in tension to 20 Kips and one was further tested to an ultimate load of 34 Kips. These loads were considerably higher than those predicted for CFDTs on the tests covered in this report. Although the end fitting evaluation tests were conducted on UTS fittings, the LTS fittings were of similar construction and the tests were considered representative for both the LTS and UTS configurations.

(3) Department 7456 Memo Report 2287 "End Fitting Structural Evaluation" 10 December 1964 (U).

B. Test Conditions

1. Test Condition 1 - 20 Kips Axial Tension

This test was conducted with the LTS assembled to the UTS. The forward end of the UTS was fastened to the base of the test fixture with 12 end fittings. The forward end of the LTS was fastened to the UTS with 9 end fittings and the aft end of the LTS was fastened to the loading adapter with 12 end fittings. A photo of the test setup is shown in Figure 1. The axial tension load was applied with a single calibrated 8" hydraulic cylinder.

2. Test Condition 2 - 20 Kips Axial Tension

This test was conducted using the LTS alone. The LTS was placed in the test stand with the forward end down and attached securely to the base of the test fixture with the 12 end fittings. The aft end of the LTS was attached to the loading adapter with 12 end fittings. A photograph of the test setup is shown in Figure 2. A single calibrated hydraulic cylinder was used to apply the axial tension load.

3. Test Condition 3 - 100 Kips Axial Compression Load

The LTS was set up as in the previous test and subjected to a 100 Kip axial compression load.

4. Test Condition 4 - 5 Kips Lateral Shear

The LTS was setup as in the previous test except that the axial loading hydraulic cylinder was removed and a 5 Kip lateral shear load was applied at the forward end of the structure, using a calibrated hydraulic cylinder. The test setup for this condition is shown in Figure 3.

A detailed parts list for all test conditions is given in Table I.

C. Instrumentation

Upon completion of fabrication the LTS was made available to the E & R Development Company of Lawndale, California, for mounting strain gages.

Strains were measured at 20 locations and deflections at 14 locations as shown in Figures 4 through 7. Data was acquired for each test condition as follows:

1. Test Condition 1: Strain gages S1 through S20; deflection gages D1 through D6.
2. Test Condition 2: Strain gages S3 - S8, S11 - S14, S17 - S20; deflection gages D1, D2, D7, D9, D13, and D14.
3. Test Condition 3: Strain gages S3 - S8, S11 - S14, S17 - S20; deflection gages D1, D2, D9, D13, and D14.
4. Test Condition 4: Strain gages S3 - S8, S11 - S14, S17 - S20, deflection gages D1, D2, D7 - D12.

All strain gages were uniaxial SR4 type A5-1 gages and were read at the specified load increments with a SR4 Baldwin Strain Indicator, Type M. The deflections were measured with dial indicators and were visually read at the specified load increments. Typical instrument installations are shown in Figures 8 through 10.

D. Test Operations

The following events summarize the test operations:

1. The 8 inch hydraulic cylinder was calibrated for 1.25 times the test loads in tension and compression. Since no requirement existed for compression testing with the 3 inch cylinder it was calibrated for 1.5 times the test load in tension only. The calibration curves are shown in Figures 11, 12, and 13.

2. The upper thrust structure was mounted forward end down in the test stand and fastened securely at the 12 end fittings. The forward end of the LTS was attached to the UTS with 9 end fittings. The aft end of the LTS was attached to a loading adapter with 12 end fittings. A 20 Kip axial tension load was applied and released in three loading cycles. On the first loading cycle all strain gages and deflection indicators specified for Test Condition 1 were read at 25%, 50%, 75%, 90% and 100% of full load on the loading phase and at 75%, 50% and zero return on the unloading phase except strain gages S1, S2, S9, S10, S15 and S16 which were read on the loading phase at 25% and 100% and on the unloading phase at 75%, 50% and zero return. On the second loading cycle all data was recorded at the prescribed loading increments. On the third cycle all data was recorded only at full load and the zero return.

3. The LTS was removed from the LTS-UTS assembly and a series of tests performed on the UTS alone. An evaluation of these tests is contained in REON Technical Memorandum 0227, dated 23 July 1965⁽⁴⁾. At the conclusion of the tests on the UTS, it was removed from the test stand and the LTS was reinstalled utilizing all 12 fastening points on each end of the LTS. A 20 Kip axial tension load was then applied in three loading cycles. On the first two cycles, all data specified for Test Condition 2 were recorded at 25%, 50%, 75%, 90% and 100% of full load on

(4) RN-TM-0227, dated 23 July 1965; "REON Technical Memorandum - Upper Thrust Structure S/N 0000009 Structural Test Evaluation"

the loading phase and on the unloading phase at 75%, 50%, and zero return.

4. The test setup used for the previous load condition was retained and a 100 Kip axial compression load was applied to the LTS. All strain gages and deflection gages specified for Test Condition 3 were read at 25%, 50%, 60%, 70%, 80%, 90% and 100% of full load on the loading phase and at 80%, 50% and zero return on the unloading phase. Due to skin buckling only one loading cycle was conducted for this test condition.

5. The axial loading cylinder was removed from the test setup and a tension link and hydraulic cylinder installed to provide a lateral shear loading condition at the aft end and perpendicular to the center line of the LTS. A 5 Kip lateral shear load was applied for four loading cycles. On the first two loading cycles, all strain and deflection data specified for Test Condition 4 were read at 25%, 50%, 75%, 90% and 100% of full load on the loading phase and at 75%, 50% and zero return during the unloading phase. On the third and fourth cycle data was taken only at full load and the zero return.

6. The LTS was removed from the stand, cleaned and prepared for shipment to Sacramento.

7. In each of the loading cycles, the loads were applied through the calibrated hydraulic cylinders utilizing hand operated pumps.

Figure 1
Test Set Up - LTS-UTS, Axial Tension

Figure 2
Test Set Up - LTS, Axial Tension and Compression

Figure 3
Test Set Up - LTS, Lateral Shear

TABLE I
PARTS LIST

<u>ITEM</u>	<u>DESCRIPTION</u>	<u>PART NUMBER</u>	<u>QUANTITY/TEST CONDITION</u>			
			1	2	3	4
1	Upper Thrust Structure	706963-4	1			
2	Lower Thrust Structure	706952-24	1			
3	LTS Load Application Adapter	T-605495	1			
4	Bolts (9/16 dia.)	AN-9-22	9			
5	Washers, Plain	AN910-D916	9			
6	Washers, C'sunk	MS2000269	9			
7	Nuts	AN345-916	9			
8	Base Interface Adapter	T-605489	1			
9	Bolts (1/2 in. dia.)	AN8-34	12			
10	Washers	AN960-D816	12			
11	Nuts	AN345-816	12			
12	Pump Support Panel Load Adapter	T-605491	1			
13	Bolts (3/8 in. dia.)	AN6-12	72			
14	Washers	AN960-D616	72			
15	Nuts	AN345-616	72			
16	Bolts	AN6-6	36			
17	Washers, C'sunk	MS2000266	36			
18	Overhead Test Structure	T-605490	1			
19	Hydraulic Jack (8 in. dia.)		1			
20	Hydraulic Jack (3 in. dia.)					1
21	Hydraulic Jack to Overhead Test Structure Adapter	SK10119-5	1			
22	Hydraulic Jack to Overhead Test Structure Adapter	SK10119-7		1		
23	Base Interface Adapter	T-605489		1

LTS-UTS DEFLECTION INSTRUMENT LOCATIONS

FIGURE 4

LTS DEFLECTION INSTRUMENT LOCATIONS

FIGURE 5

LTS STRAIN GAGE LOCATIONS

FIGURE 6

LTS STRINGER AND END FITTING
INSTRUMENTATION

FIGURE 7

Figure 8
Joint Rotation Instruments, 20 KIP Axial Tension Load: LTS-UTS

Figure 9
End Fitting Instruments, 20 KIP Axial Tension Load: LTS

Figure 10
Translation Instruments, 5 KIP Lateral Shear Load: LTS

8 INCH HYDRAULIC CYLINDER
COMPRESSION CALIBRATION

FIGURE 11

8 INCH HYDRAULIC CYLINDER

TENSION CALIBRATION

FIGURE 12

3 INCH HYDRAULIC CYLINDER
TENSION CALIBRATION

FIGURE 13

IV. EXPERIMENTAL RESULTS

A. Loads

The LTS was subjected to four different loading conditions at ambient conditions. Planned and actual test loads are shown in Figure 14. All test loads were applied to the planned value.

B. Deflections

Measured deflections for all loading conditions are presented in Tables 2 through 5. In addition, the deflections for the axial compression and lateral shear loading conditions are shown in graphical form as Figure 15. To prevent inclusion of any test stand movements and initial fitting slippage deflections, the axial tension and lateral shear conditions were determined by subtracting the dial indicator reading at the zero return from the 100% load reading. This procedure resulted in excellent repeatability in the data. All raw data was interpolated to the nearest .0001 inch.

Deflections encountered in the compression test were determined by subtracting the initial zero reading from the 100% load reading. A residual or permanent set was determined by comparing the before and after test zero readings. During the axial compression test, the skin of the LTS was observed to buckle at approximately 50% of full load as evidenced in the deflection data by a change of slope. The spring constant for the compression loading cycle was computed from the linear portion of the unloading phase of the test, since it more closely resembles the unbuckled condition contains no fitting slippage, and is in the expected operating range of the structure. Average deflection of the LTS during the 100 Kip compression test was .126 inch based on instruments D 13 and D 14 which were located on the attachment fittings.

The average axial growth for the LTS-UTS assembly during the 20 Kip axial load was .089 inch. The elongation of the UTS was determined to average

.009 inch. Average rotation of the mating surface of the UTS was .00198 radian or 6 minutes 47.6 seconds inboard. The calculations used to determine these values are given in the Appendix.

The average axial deflection during the 20 Kip axial load on the LTS alone without the attachment bracket deflection, was .009 inches. Some difficulty was encountered in establishing a zero reading from instrument D 9, therefore, only the readings from instruments D 1 and D 2 were used to determine this value. The observed elongation at the attachment brackets was .014 inch as determined from instruments D 13 and D14.

The maximum lateral translation of aft end of the LTS during the 5 Kip lateral shear load test was .018 inch. This deflected shape is shown in Figure 16. Rotation of the aft mating plane was 21.3 seconds and torsional rotation was 20.7 seconds counterclockwise when looking forward.

While skin buckling was evident at 45 Kips in the compression test, there was no catastrophic failure or evidence of yielding in either the skin or stiffeners. The buckles appeared to be elastic and disappeared after the load was removed. Although the LTS was able to withstand the 100 Kip compression load after skin buckling, such buckling would be undesirable in an XE-1 thrust structure application if instability is to be avoided.

C. Strain Distribution

Stress values at the stringer strain gage locations are presented in Tables 6 through 9.

The maximum measured strain values for the 20 Kip axial tension load on the assembled LTS-UTS was 635 μ /in/in tension at gage 14 and 22 μ /in/in tension at gage 13 indicating a significant amount of bending, however, the strains at this and all other locations were well below the proportional limit yield point of 3540 μ /in/in strain and the .2% offset yield point 5540 μ /in/in strain.

Strain values for the 20 Kip axial load on the LTS was significantly lower and in general showed a better stress distribution pattern due to the use of all twelve end fittings during the test.

The maximum compressive strain recorded during the 100 Kip axial compression was 1930 μ in/in strain at gage 12 and 55 μ in/in strain at gage 11. As in the axial tension test, stress distribution about the structure appeared to be excellent and the strains were well within the allowable material properties.

The strains recorded during the 5 Kip lateral shear test were too low to analyze with accuracy; however, the strains recorded at gages 7, 8, 13 and 14 showed a distribution of tensile and compressive strains that verified the deflected shape determined by the deflection indicators and shown in Figure 16.

From the strain data obtained in the compression test, the effective skin area was determined to be approximately 156t in the unbuckled condition and 65t in the buckled condition. Factors which contributed to the high effectiveness of the skin were the two stiffeners in each skin panel and the rigid connections of the forward and aft circumferential ribs to the stringers. Further increases in effectiveness of the skin panels could be obtained by the use of three stiffeners in each panel or by the use of sandwich type skin construction. Although effective skin area was high, 64% prior to buckling and 29% after buckling, the data showed the stringer to be carrying 3 times the skin load prior to buckling and 8 times the skin load after buckling, thus emphasizing the importance of the stringers as the principal load carrying elements.

TEST CONDITION	F ₁ KIPS		F ₂ KIPS		F ₃ KIPS		F ₄ KIPS	
	P	A	P	A	P	A	P	A
1	20	20	-	-	-	-	-	-
2	-	-	20	20	-	-	-	-
3	-	-	-	-	-100	-100	-	-
4	-	-	-	-	-	-	5	5

PLANNED AND ACTUAL TEST LOADS

FIGURE 14

TABLE 2
Measured Deflections For A 20 Kip
Axial Tension Load
Assembled UTS-LTS
Test Condition 1

<u>Location</u>	<u>Cycle</u>	<u>Deflection</u>	<u>Avg.</u>
D 1	1	.0920 in.	.093 in.
	2	.0959	
	3	.0925	
D 2	1	.0855	.086
	2	.0860	
	3	.0855	
D 3	1	.0151	.015
	2	.0159	
	3	.0150	
D 4	1	.0272	.027
	2	.0276	
	3	.0268	
D 5	1	.0142	.014
	2	.0142	
	3	.0131	
D 6	1	.0264	.026
	2	.0262	
	3	.0241	

TABLE 3
Measured Deflections For A 20 Kip
Axial Tension Load - LTS
Test Condition 2

<u>Location</u>	<u>Cycle</u>	<u>Deflection</u>	<u>Avg.</u>
D 1	1	.0086 in.	.009 in.
	2	.0083	
	3	.0088	
D 2	1	.0106	.009
	2	.0088	
	3	.0088	
D 9	1	.0026	.004
	2	.0038	
	3	.0050	
D 13	1	.0153	.015
	2	.0140	
	3	.0151	
D 14	1	.0152	.014
	2	.0135	
	3	.0135	
Average of D 13 and D 14			.0145

NOTE: See Figure 5 for Measurement Locations

TABLE 4
Measured Deflections For A 100 Kip
Axial Compression Load - LTS
Test Condition 3

<u>Location</u>	<u>Cycle</u>	<u>Deflection</u>	<u>Avg.</u>
D 1	1	.0823 in.	.095 in.
D 2	1	.0920	
D 9	1	.1095	
D 13	1	.1248	.126
D 14	1	.1278	

NOTE: See Figure 5 For Measurement Locations

TABLE 5
Measured Deflections For A 5 Kip
Lateral Shear Load - LTS
Test Condition 4

<u>Location</u>	<u>Cycle</u>	<u>Deflection</u>	<u>Avg.</u>
D 1	1	.0014 in.	.002 in
	2	.0015	
	3	.0012	
	4	.0030	
D 2	1	.0032	.002
	2	.0019	
	3	.0024	
	4	.0022	
D 7	1	.0094	.008
	2	.0078	
	3	.0097	
	4	.0064	
D 8	1	.0137	.014
	2	.0140	
	3	.0148	
	4	.0140	
D 9	1	.0080	.008
	2	.0079	
	3	.0080	
	4	.0080	
D 10	1	.0174	.018
	2	.0173	
	3	.0177	
	4	.0177	
D 11	1	.0080	.008
	2	.0079	
	3	.0079	
	4	.0077	
D 12	1	.0004	.0003
	2	.0003	
	3	.0004	
	4	.0001	

NOTE: See Figure 5 For Measurement Locations

TYPICAL DEFLECTION CURVES

FIGURE 16

FIGURE 16

TABLE 6
Measured Stringer Stresses For A
20 Kip Axial Tension Load
LTS-UTS Assembly
Test Condition 1

Gage	<u>CYCLE 1</u>		<u>CYCLE 2</u>		<u>CYCLE 3</u>	
	<u>u in/in</u>	<u>σ, psi</u>	<u>u in/in</u>	<u>σ psi</u>	<u>u in/in</u>	<u>σ psi</u>
1	-42	-425	-29	-293	-32	-323
2	305	3020	260	2580	251	2490
3	-37	-374	-58	-585	-56	-565
4	551	5450	482	4770	481	4760
5	160	1580	130	1290	114	1130
6	-35	-353	-46	-465	-53	-535
7	-71	-717	-66	-666	-50	-505
8	474	4650	430	4250	408	4050
9	185	1830	138	1370	127	1260
10	217	2150	186	1840	166	1640
11	5	49	-23	-232	-36	-363
12	560	5500	505	5000	491	4860
13	22	210	-3	-30	-10	-100
14	635	6290	576	5700	567	5510
15	196	1940	192	1900	190	1800
16	77	760	73	720	76	750
17	272	2690	249	2460	258	2550
18	116	1150	91	900	102	1010
19	395	3900	348	3440	354	3500
20	-21	-212	-36	-364	-3	-33

Where $\sigma = E (\epsilon)$ psi

$E_c = 10.1 \times 10^6$ psi

E_c = Young's Modulus in Comp.

$E_t = 9.9 \times 10^6$ psi

E_t = Young's Modulus in Tension

ϵ = Strain Micro inch/inch

NOTE: See Figures 6 and 7 for Strain Gage Locations

TABLE 7
Measured Stringer Stresses For A
20 Kip Axial Tension Load-LTS
Test Condition 2

Gage	<u>CYCLE 1</u>		<u>CYCLE 2</u>		<u>CYCLE 3</u>	
	<u>u in/in</u>	<u>σ, psi</u>	<u>u in/in</u>	<u>σ psi</u>	<u>u in/in</u>	<u>σ psi</u>
3	-50	-505	55	545	65	642
4	150	1485	205	2030	230	2280
5	5	50	75	740	90	890
6	210	2080	255	2520	270	2670
7	-10	-101	65	643	80	790
8	180	1780	230	2280	240	2380
11	-45	-455	10	99	25	248
12	315	3120	305	3020	325	3220
13	-50	-505	0	0	10	99
14	260	2570	280	2770	280	2770
17	100	990	40	395	35	346
18	90	890	40	395	40	395
19	90	890	45	445	35	346
20	80	790	25	248	-5	-50

Where $\sigma = E (\epsilon)$ psi
 $E = 10.1 \times 10^6$ psi
 $E_c = 9.9 \times 10^6$ psi
 $\epsilon =$ Strain Micro inch/inch
 $E_c =$ Young's Modulus in Compression
 $E_t =$ Young's Modulus in Tension

NOTE: See Figures 6 and 7 for Strain Gage Locations

TABLE 8
Measured Stringer Stresses For A
100 Kip Axial Compression Load-LTS
Test Condition 3

<u>Gage</u>	<u>u in/in</u>	<u>σ psi</u>
3	-445	-4,500
4	-1410	-14,250
5	-380	-3,840
6	-1280	-12,920
7	-320	-3,240
8	-1620	-16,400
11	-55	-556
12	-1930	-19,500
13	-75	-758
14	-1805	-18,250
17	-640	-6,460
18	-665	-6,730
19	-755	-7,630
20	-535	-5,400

Where $\sigma = E (\epsilon) \text{ psi}$ $E_c = \text{Young's Modulus in Compression}$
 $E_c = 10.1 \times 10^6 \text{ psi}$ $E_t = \text{Young's Modulus in Tension}$
 $E_t = 9.9 \times 10^6 \text{ psi}$
 $\epsilon = \text{Strain Micro inch/inch}$

NOTE: See Figures 6 and 7 for Strain Gage Locations

TABLE 9
Measured Stringer Stresses For
5 Kip Lateral Shear Load-LTS
Test Condition 4

Gage	<u>CYCLE 1</u>		<u>CYCLE 2</u>		<u>CYCLE 3</u>	
	<u>u in/in</u>	<u>,psi</u>	<u>u in/in</u>	<u>,psi</u>	<u>u in/in</u>	<u>psi</u>
3	20	198	15	148	15	148
4	-165	-1670	-170	-1720	-170	-1720
5	-110	-1110	-95	-960	-100	-1010
6	0	0	-5	-55	-5	-55
7	-85	-860	-65	-657	-70	-708
8	-35	-354	-50	-550	-50	-550
11	0	0	-5	-55	-10	-101
12	95	940	65	643	30	297
13	35	346	15	148	15	148
14	-135	-1365	-110	-1110	-125	-1265
17	50	495	40	396	35	346
18	25	248	20	198	15	149
19	-10	-101	0	0	-5	-50
20	-60	-606	-30	-304	-5	-50

Where $\epsilon = E (\epsilon)$ psi

$E_c = 10.1 \times 10^6$ psi

$E_t = 9.9 \times 10^6$ psi

$\epsilon =$ Strain Micro inch/inch

$E_c =$ Young's Modulus in Compression

$E_t =$ Young's Modulus in Tension

NOTE: See Figures 6 and 7 for Strain Gage Locations

V. EVALUATION OF TEST RESULTS

A. Structural Integrity

The lower thrust structure S/N 012 successfully demonstrated structural integrity for CFDTs conditions which consisted of:

1. Engine dead weight in Test Stand H-5.
2. On plant transportation of the engine.

The loads applied were greater than those required for the listed conditions. Using the strain data from the tee sections, maximum stringer stresses have been approximated for all load conditions and are presented in Table 10. A maximum stringer tensile stress of 6910 psi was attained during the 20 Kips axial tension test of the LTS-UTS assembly. Maximum stringer compression stress was -21,750 psi during the 100 Kip axial compression test of the LTS.

For 6061-T6 aluminum alloy extrusions, the minimum yield strength is 35,000 psi⁽⁵⁾. Therefore, for the loads applied, the margin of safety at all stringer locations measured was significantly greater than one (MS 1.0). The effect of deleting three fastening points during the 20 Kip axial tension test of the LTS-UTS assembly was clearly evident in the distribution of stringer stresses recorded in that test. The maximum tensile stringer stress, 6910 psi, was recorded on a stringer adjacent to one of the deleted fastening points, while the stringer with effective fastening points on either side, in addition to its own fastening point, recorded a maximum tensile stress of 2188 psi. In the subsequent 20 Kip axial tension test of the LTS, when all twelve fastening points were used, maximum and minimum stringer stresses were 3540 psi and 2933 psi.

Although most of the axial load is transmitted through the stringers, the skin riveted to the stringers and ribs is effective in resisting some loads.

(5) Based on .2% of offset.

Figure 17

Buckle Locations, 100 KIP Compression Test: LTS

The maximum skin stresses were calculated to be 7040 psi for the 20 Kip test on the UTS-LTS assembly and 3633 psi during the test on the LTS alone. For 2024-T3 aluminum alloy sheet the yield strength is 39,000 psi⁽⁵⁾. As with the stringers, the wide variation in stresses between the two tests is attributed to the deletion of three fastening points on the first test. For tensile conditions, the strain data recorded on the 20 Kip test of the LTS, indicated that the skin was carrying 33% of the axial load. Since the skin comprises 41% of the total cross sectional area it can be concluded that approximately 80% of the skin is effective in resisting tension loads. For the compression condition, however, only a small portion of the skin was effective after buckling had occurred. At 25 Kips compressive loading, prior to skin buckling, the effective skin area was estimated to be 64% of the total skin area. At the full 100 Kip load, with skin buckling present, only 29.5% of the skin was effective in carrying load. The maximum stress in the effective area of the skin was 22,200 psi, considerably below the minimum yield point for 2024-T3 material. The calculations used to determine effective skin area are given in the Appendix.

While there was no evidence of yielding or failure of structural components, buckling of the skin is considered undesirable. As shown by the deflection curves in Figure 15 skin buckling during application of a compression load causes a significant change in deflection slope and in the spring constant, thus altering the dynamic response of the entire engine assembly. The buckling pattern of the LTS is shown in Figure 17.

Stresses observed during the 5 Kip lateral shear test were quite low and indicated that the structure would be capable of withstanding lateral shear loads up to twice the XE-1 design loads of 12.5 Kips without detrimental effect on the primary structural members or buckling of the skin panels. Stresses monitored on the stringer in line with the loading direction indicated a bending moment existed which produced tension in the flange at the aft end of the stringer and tension in the stem at the forward end, thus verifying the deflected shape shown in

Figure 16. It was noted that a point of contraflexure or zero moment also existed in the stringer instrumented with strain gages 3, 4, 11 and 12. The existence of points of contraflexure in the stringers indicates that the primary joints of the structure were capable of resisting moment and the LTS was therefore acting as a continuous frame. Since compressive strains were recorded on the fitting located in line with the applied load and tensile strains were recorded on the fitting instrumented with gages 17 and 18, it is evident that the neutral axis of the structure had shifted toward the leading edge of the structure and rotated slightly counterclockwise when looking forward. The approximate location of the neutral axis for this loading condition is shown in the sketch below.

In all test phases, the end fitting stresses were found to be low in comparison with allowable material strength. The maximum stresses were -7620 psi on the 100 Kip compression test and 3500 psi on the 20 Kip axial tension test of the UTS-LTS assembly. However, the deflection data taken during the axial tension and compression tests indicate that there was some slippage in the fittings during the tests. Due to the absence of stresses in the yielding zone it is believed the permanent set recorded during the compression test is the result of end fitting slippage.

Table 10
CALCULATED MAXIMUM STRINGER AND SKIN STRESSES

<u>Ref.</u> <u>Gage No.</u>	<u>Load</u> <u>Condition</u>	<u>Edge</u>	<u>psi</u>	<u>Axial Load</u>	<u>Moment</u>
13 - 14	20 Kip Tension	Stem	-540	2880 lb	945 in.lb.
	LTS-UTS	Flange	7000		
		Skin	7160		
11-12	20 Kip Tension	Stem	-910	1330 lb	550 in.lb.
	LTS	Flange	3530		
		Skin	3620		
11-12	100 Kip Compression	Stem	1770	-8920 lb	2950 in.lb.
	LTS	Flange	-21,750		
		Skin	-22,200		
13-14	Shear	Stem	555	-550 lb	398 in.lb.
	LTS	Flange	-1570		
		Skin	-1610		

NOTE: SEE APPENDIX FOR SAMPLE CALCULATION.

B. STRUCTURAL STIFFNESS

The deflection data for each of the test conditions have been evaluated and the computed spring constants are shown below. These values were determined by the relationship:

$$k = \frac{F}{\delta}$$

where:

k = spring constant in direction of applied load, lbs/in

F = applied load, lbs

δ = deflection in direction of applied load, in.

CALCULATED SPRING CONSTANTS

<u>Assembly</u>	<u>Direction</u>	<u>k, lbs/in</u>
LTS-UTS	Axial Tension	211,000
LTS	Axial Tension	1,390,000
LTS	Lateral Shear	286,000
LTS	Axial Compression	1,620,000

The tension spring constant of the LTS-UTS assembly was calculated from the sum of the deflection from the LTS-UTS assembly and the deflection of the aft attach brackets of the LTS as determined from the 20 Kip axial load test on the LTS, thus providing a spring constant for all CFDTs components and attachment surfaces between the pressure vessel and test stand adapter.

The tension spring constant for the LTS was calculated from deflections taken at the attachment brackets since this also simulates the XE structure as it will be fastened between the pressure vessel and external shield.

The compression spring constant was determined from the slope of the deflection during the unloading phase of the 100 Kip axial compression test because this portion of the curve most closely represents the expected operating conditions.

The lateral spring constant was calculated from the maximum lateral deflection of the aft end of the LTS.

Although less of the skin is effective in compression than in tension the higher spring constant for the compressive cycle is not unexpected since compressive deflection of the forward end fitting is almost non-existent while deflection of the same end fitting in tension is significant in determining the spring constant. Calculations of the compression spring constant based on 60% of the skin, the stringers and only the aft fitting deflection give a total compressive deflection of .0122 inch with a resultant k of 1,640,000 lb/in. demonstrating close agreement between theoretical calculations and experimental results. While the individual spring constants of the LTS and UTS were 1.39×10^6 lbs/in. and 1.56×10^6 lbs/in respectively, the experimental results of the combined systems test yielded a tension spring constant of only 211,000 lb/in. This low value was attributed to flexibility in the end fittings when attached to each other. It is expected, however, that the insertion of a rigid attach surface such as the XE radiation shield between the LTS and UTS will substantially reduce end fitting deflections and thus significantly increase the tension spring constant for the combined system. Justification for

a reduction in end fitting deflections is based on close agreement between the experimental tension and compression spring constants for the LTS when attached to a rigid surface. Since compressive deflection of the forward end fitting is known to be small, such agreement between tension and compression spring constants is felt to demonstrate substantially identical deflections occur for all components of the structure, including the attach fittings. On this basis new fitting deflections were estimated and a predicted spring constant for the LTS - radiation shield - UTS assembly was computed. The spring constant thus derived, 775,000 lb/in, closely approximates 736,000 lb/in obtained by combining the individual experimental spring constants of the LTS and UTS.

VI. CONCLUSIONS

The test program met all objectives and based on the measured strain and deflection data obtained it is concluded that the LTS demonstrated structural integrity for all CPDS load conditions.

Strain readings and visual inspection of the discrepant end fittings at the conclusion of the test indicated completely satisfactory performance of the parts. Margins of safety at all measured locations were greater than 1.0. The tests also showed that the spring constants are quite dependent upon the stiffness of the adjacent assemblies. In future tests additional instrumentation should be included to provide more complete information on end fitting behavior.

Summarizing, the tests provided the following salient points of information for XE-1 thrust structure development:

1. The .040 in. skin thickness should be increased.
2. Three stiffeners should be used in each skin panel.
3. Each stringer must have an attach fitting at each end.

4. The connections between the skin, ribs, stringers and attach fittings should be improved to preclude attach fitting slippage.

5. The lower thrust structure performed as a space frame with moment connections and should be analyzed as a statically indeterminate structure.

APPENDIX
THEORETICAL AND SAMPLE CALCULATIONS

I. Mating Surface Rotation, 20 Kips Axial Tension - LTS-UTS Assembly

$\theta_1; \theta_2$ = mating surface rotation

Δ = elongation of UTS

θ_1 and θ_2 are 180° apart.

$$\begin{aligned}\tan \theta_1 &= \frac{D4 - D3}{6} \\ &= \frac{.0272 - .0153}{6} = .00198\end{aligned}$$

$$\theta_1 = .00198 \text{ radians}$$

$$\begin{aligned}\tan \theta_2 &= \frac{D6 - D5}{6} \\ &= \frac{.0256 - .0138}{6} = .00197\end{aligned}$$

$$\theta_2 = .00197 \text{ radians}$$

$$\theta_{\text{avg.}} = 6' 47''$$

$$\begin{aligned}\Delta &= \frac{D4 + D6}{2} - 8.75 (\tan \theta) \\ &= .0264 - 8.75 (.001975) \\ &= .0091 \text{ in.}\end{aligned}$$

NOTE: SEE FIGURE 4 FOR INSTRUMENT LOCATIONS

II. PREDICTED TENSION SPRING CONSTANT - LTS

Assumptions:

1. All skin effective
2. No fitting deflection

$$\text{Area of stringers} = .624 (12) = 7.55 \text{ sq. in.}$$

$$\text{Average area of skin} = 5.23 \text{ sq. in.}$$

$$\text{TOTAL} \quad 12.78 \text{ sq. in.}$$

$$\cos. \theta = \frac{30.65}{36.34} = .844$$

$$\theta = 32.5$$

$$F = 20 \text{ k} / \cos 32.5^\circ = 23.7 \text{ Kips}$$

$$\epsilon = \frac{\sigma}{E} = \frac{23.7 \text{ K}}{12.73} / 9.9 \times 10^6$$

$$\epsilon = .000187 \text{ in/in} \quad \Delta = 36.39 (.000187) \cos 32.5^\circ$$

$$= .00574 \text{ in.}$$

$$K = \frac{F}{\delta} = \frac{20,000}{.00574}$$

$$= 3,490,000 \text{ lb/in}$$

The spring constant thus derived contains no allowance for movement or deflection of the attach fittings. If the deflection of the aft end fitting measured in the LTS 20 Kip axial tension test, .0055 in., and the estimated deflection of the forward end fitting, .0022 in., are included in the calculation, the total deflection is .00574 + .0022 + .0055 = .0134 in. Then $K = 20,000 / .0134 = 1,440,000 \text{ lb/in}$, which provides a good correlation with experimental result.

III. PREDICTED TENSION SPRING CONSTANT LTS - RADIATION SHIELD - UTS ASSEMBLY

UTS Elongation (Table 2)	.0091 inch
UTS Bracket Elongation (Estimated)	.0022 inch
LTS Elongation (Table 3)	.0145 inch
<hr/>	
TOTAL	.0285

$$\text{then } K = 20000 / .0258 = 775,000 \text{ lb/inch}$$

The UTS bracket elongation was estimated by assuming that since bracket stresses on the LTS, when fastened to a rigid base, were reduced by 50%, then, under similar conditions, UTS bracket stresses and consequently deflections, would also be reduced by a like amount. The measured fitting gap at full load for the LTS-UTS assembly was .0090 inch with one half, .0045 inch, attributed to the UTS bracket deflection. Then .0045 is reduced to .0022 inch for the UTS fitting.

$$\text{LTS Experimental spring constant} = 1.39 \times 10^6$$

$$\text{UTS Experimental spring constant} = 1.56 \times 10^6$$

$$\frac{1}{K_T} = \frac{1}{K_L} + \frac{1}{K_U} = \frac{1}{1.39 \times 10^6} + \frac{1}{1.56 \times 10^6} = \frac{1}{.736 \times 10^6}$$

$$K_T = 736,000 \text{ lb/in}$$

$$\text{and } 736,000 \text{ lb/in} \approx 775,000 \text{ lb/in}$$

IV. TYPICAL STRINGER STRESS CALCULATION

$$A = 1.5 (.19) + 1.81 (.19) = .629 \text{ sq. in.}$$

$$NA = \frac{.285 (.095) + .344 (1.095)}{.629} = .642 \text{ in.}$$

$$I = \frac{1}{3} (1.31) (.19)^3 + \frac{1}{3} (.19) (2)^3 = .629 (.642)^2$$

$$= .003 + .507 = .510 = .251 \text{ in.}^4$$

NOTE: ALL CALCULATIONS ARE BASED ON THE STRAIN PLANE BEING LINEAR

$$\sigma = E \times \epsilon$$

where $E_c = 10.1 \times 10^6$; $E_T = 9.9 \times 10^6$, ϵ = unit elongation

$$\begin{aligned} a &= 2 \\ b &= .2 \\ c &= .19 \\ d &= 1.61 \\ e &= .452 \\ C &= .642 \end{aligned}$$

$$\epsilon_{\text{Stem}} = \epsilon_{\text{odd}} + \frac{b}{d} (\epsilon_{\text{odd}} - \epsilon_{\text{even}}); \quad \epsilon_{\text{flange}} = \epsilon_{\text{even}} - \frac{c}{d} (\epsilon_{\text{odd}} - \epsilon_{\text{even}})$$

$$\epsilon_{NA} = \epsilon_{\text{Even}} + \frac{e}{d} (\epsilon_{\text{odd}} - \epsilon_{\text{even}}); \quad M = (\sigma_{\text{Flange}} - \sigma_{NA}) \frac{I}{C}$$

$$P = \sigma_{NA} (A)$$

using S 11, 12 from Table 8

$$\begin{aligned}\epsilon_{\text{Stem}} &= -55 + \frac{.2}{1.61} \left[-55 - (-1930) \right] = -55 + .124 (1875) \\ &= 178 \text{ u in/in}\end{aligned}$$

$$\sigma_{\text{Stem}} = 4.9 \times 10^6 (177) = 1750 \text{ psi.}$$

$$\begin{aligned}\epsilon_{\text{Flange}} &= -1930 - \frac{.19}{1.61} (-55 + 1930) = -1930 - .118 (1875) \\ &= -2151 \text{ u in/in}\end{aligned}$$

$$\sigma_{\text{Flange}} = 10.1 \times 10^6 (-2151) = -21,750 \text{ psi}$$

$$\begin{aligned}\epsilon_{\text{NA}} &= -1930 + \frac{.452}{1.61} (-55 + 1930) = -1930 + .28 (1875) \\ &= -1405 \text{ u in/in}\end{aligned}$$

$$\sigma_{\text{NA}} = 10.1 \times 10^6 (-1405) = -14,200 \text{ psi}$$

$$\begin{aligned}M &= (21,750 - 14,200) \frac{.251}{.642} \\ &= (7550) .39 = 3030 \text{ in.lb.}\end{aligned}$$

$$\begin{aligned}P &= 14,200 (.629) \\ &= 8920 \text{ lb.}\end{aligned}$$

V. STRINGER - SKIN LOAD DISTRIBUTION

$$\text{Area of Stringers} = 12 (.629) = 7.55 \text{ in}^2$$

$$\text{Average Area of Skin} = 5.23 \text{ in}^2$$

$$\text{TOTAL} \quad 12.78 \text{ in}^2$$

EXPECTED LOAD DISTRIBUTION - ALL AREA EFFECTIVE

Axial Load	Vector Load (Axial Load/Cos θ)	Vector Stress (Vector Load/ 12.78)	Stringer Load (Vector Stress x <u>7.55</u>) 12	Skin Load 1/2 Panel (Vector Stress x 5.23) <u>12</u>
20 Kips	23.7 Kips	1850 psi	1160 lb	805 lb
25 Kips	29.7 Kips	2320 psi	1460 lb	1010 lb
100 Kips	118.5 Kips	9290 psi	5830 lb	4050 lb

Effective Skin in Tension

$$\text{Total expected load/ 1/2 panel} = 1965 \text{ lb}$$

$$\text{Avg. measured stringer load} = 1325 \text{ lb}$$

$$\text{Actual Skin Load} \quad 640$$

$$\% \text{ Load carried by skin} = \text{actual skin load/total expected load}$$

$$= 640/1965 = 32.6\%$$

$$\% \text{ Skin effective} = \% \text{ load carried by skin/ \% of skin area}$$

$$= 32.6/41 = 80\%$$

Effective Skin in Compression Before Buckling (25 Kips)

Total expected load/ 1/2 panel = 2470 lb

Avg measured stringer load = 1820 lb

Actual Skin Load = 650 lb

% Load carried by skin = actual skin load/total expected load.

= 650/2470 lb = 26.3%

% Skin effective = % load carried by skin/% of skin area

= 26.3/41 = 64%

Effective skin in compression after buckling (100 Kips)

Total expected load/ 1/2 panel = 9880 lb

Avg measured stringer load = 8670 lb

Actual Skin Load 1210

% Load carried by skin = actual skin load/total expected load

= 1210/9880 = 12.2%

% Skin effective = % load carried by skin/% of skin area

= 12.2/41 = 29.5%