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STRUCTURAL ANALYSIS, DESIGN, AND DEVELOPMENT

OF AN

S-IC SKIN PANEL

CONTRACT NO. NAS8-20530

NORTH AMERICAN AVIATION, INC. / LOS ANGELES DIVISION

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S-IC SKIN PANEL

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FOREWORD

This report presents the structural analysis of Phase I of the "Titanium S-IC Skin Section Program" for the Saturn Project. The report covers the period 1 July 1965 to 10 December 1965.

North American Aviation, Inc., Los Angeles Division (NAA/LAD) is conducting the program under Contract Number NAS8-20530, awarded by the George C. Marshall Space Flight Center, National Aeronautics and Space Administration (NASA/MSFC), Huntsville, Alabama.

Publication of this report does not constitute NASA/MSFC endorsement of NAA/LAD findings or conclusions. It is published to disseminate the information compiled to date and for the exchange and stimulation of ideas.

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ABSTRACT

Phase I, the development phase, was concluded with the successful fabrication of four 9 x 38-inch developmental panels and the testing of elemental specimens for bond strength.

A typical panel selection involved the roll diffusion bonding of discrete titanium strips (8Al-1Mo-1V) to produce integral-type Tee-section stiffeners on flat sheet panel specimens.

The technical feasibility and structural integrity of the roll diffusion bonding process as it relates to the fabrication of highly-efficient integrally stiffened skin panel sections as production items was demonstrated.

The technical successes achieved to date justified the sizing and selection of the configuration for the full-scale production panels (9.75 by 28 feet) listed as the major objective of the program (Phases II, III, and IV).

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Section I

INTRODUCTION

A technical plan was organized for the early definition and selection of configurations for the initial development packs.

Potential concepts were screened, and a computer program was synthesized that determined relative efficiency in strength and weight. Parallel studies were conducted on cost and technical feasibility of the roll diffusion bonding process as related to the conceptual designs under study.

Results of the parallel studies were integrated into the six development phase packs that were sized and selected for rolling. These consisted of a Tee-section stiffener for both the internal and external stiffener panel designs. Four of the packs have been rolled and completely processed. The other two are being fabricated and will be completed soon. One will be used as the 38.5-inch column test specimen.

Two conditions were critical in sizing the cross-sectional configurations. One condition, ground wind (N_x = 10,540 lb/in), produced the critical stability that influenced the shaping and sizing of the stiffening elements. The other condition, rebound, sized the shell wall for internal pressure (p = 65.5 psi) and biaxial failure stress for combined loadings.

One compromise, resulting in a six percent weight penalty, consisted of adjusting the optimum selection dimensions of the development panel cross-sections so that standard, off-the-shelf, steel bars could be used as fillers between the stiffeners. This compromise was not used in the final selection of the full-scale production panel.

A preliminary process specification was prepared, detailing the step by step processing procedures recommended for successful diffusion bonding of titanium alloys. It is included as Appendix A of this report.

An analytical study was conducted, to establish the structural advantages of external versus internal stiffening of cylindrical shells. A definite strength advantage was indicated for the external stiffeners. However, after analysis of such parameters as attachment of external stiffeners to internal frames every 38.5 inches, feasible alignment with the best designs of the Y-rings at the ends, etc., the external stiffener design was rejected. NASA/MSFC concurred with this finding. The selected version consists of the internal Tee-section stiffeners, since it was considered the optimum compromise for all the parameters concerned.

Section II

DESIGN AND ANALYSIS

DESIGN LOADS AND CRITERIA

LOADS

The NAA/LAD design loads used in this program are essentially the same as those used by the Boeing Company for the original design (see Table I). These loads represent the critical design loads taken from the NASA/MSFC load tables. The two NAA/LAD rebound load conditions at Station 362 should be combined when calculating critical biaxial stresses. The NASA table lists only the maximum loads for each condition.

DESIGN CRITERIA

The criteria used in designing the titanium panel were the same as those used on the original aluminum tank. These criteria are:

1. Factors of safety
   a. Ultimate safety factor = 1.4
   b. Yield safety factor = 1.1
2. Hydrostatic test pressures
   a. 39.30 psig at Station 698
   b. 51.41 psig at Station 362
   c. Pressure varies linearly between pressures a. and b.
3. Design pressures
   a. Ultimate design pressure = 1.4 times maximum total pressure
   b. Yield design pressure = 1.05 times hydrostatic test pressure.

Design Conditions

Design conditions included fabrication simplicity, minimum weight, minimum cost (weight, or the weight-cost ratio, is the most important condition), and prevention of fuel slosh. The original design used the cylinder frames as slosh baffles. This approach was also used in the NAA/LAD design, because it proved to be adequate, as well as being the best configuration from a structures-weight point of view. The frame-slosh baffles are 30 inches deep, with a spacing of 38.5 inches.

		← NASA										NAA/LAD LOADS →	
		ULLAGE PSIG		N_c (ULT.) LB/IN.		M x 10^{-6}	TOTAL PRESSURE PSTG				N_c ULT. LB/IN.	ULT. PRESS. TOTAL PSIG
						ULT.	(LIMIT)		(ULT.)			
CONDITION	Y-RING STA	FWD (LIM)	AFT (LIM)	FWD.	AFT.	(LB/IN.)	MAX.	MIN.	MAX.	MIN.	LB/IN.	
Ground Wind	362	0	0	10,540	12,230	381					10,540	
	698	0	0	9,840	10,030	351						
Rebound	362	23	0	8,290	12,500	243	46.8	38.8	65.5	54.3	8,290 7,186	54.3 65.5
	698	0	23	9,970	7,940	212	34.36	26.36	48.1	36.9		
Q Max	362	24.6	0	8,690	12,770	181	40.45	34.05	56.6	47.7		
	698	0	24.6	12,370	10,430	337	31.0	24.6	43.4	34.4		
αQ Max	362	23.3	0	8,750	12,790	195	41.4	33.65	58.0	47.1		
	698	0	23.3	12,340	10,550	352	31.0	23.3	43.4	32.6		
Cutoff	362	26.5	0	7,840	10,650	0	31.0	26.5	43.4	37.1		
	698	0	26.5	9,450	7,840	0	31.0	26.5	43.4	37.1		

Tension Load at Y-Ring (Sta 362 Approx) +1723

Table I. LOADS AND PRESSURES FOR TITANIUM S-IC FUEL TANK

MATERIAL PROPERTIES

Ti-8Al-1Mo-1V, single or duplex annealed, is a recent development in the family of titanium alloys, and the information available is of necessity limited. Extensive scanning of the literature produced data that could only be considered typical. For an effective analysis, typical properties and minimum guaranteed values must be known. A more balanced analysis and design can be effected in this manner. The same situation prevailed with respect to weld allowables.

NAA/LAD decided to list the NAA-generated and processed data (Tables II and III) as the minimum guaranteed values and data compiled in NASA/Langley SST studies as typical values (Table IV). This classification was justified by a comparison of similar type values. The minimum values (NAA) were used in the stress analysis of the skin section, and the higher (NASA) values in the failure analysis of the biaxial stresses from pressure and axial loads.

Only one set of values was used for the weld allowables. They are shown in figure 1.

The 2219-T87 aluminum alloy properties (Table V) are the minimum values listed in MIL-HDBK-5, 1962 Edition. In areas where welds were used, the reduction in strength is accommodated by increasing the land thickness by the necessary amount.

DEVELOPMENT PANEL DESIGN PHASE

OPTIMIZATION STUDIES

The four concepts shown in figure 2 are composed of two internal and two external stiffener configurations. From a theoretical weight standpoint, the tee-flanged skin proved to be the most efficient for both internal and external stiffeners (Concepts A and C, respectively). With these two concepts as a basepoint, a detailed optimization study was conducted.

Internal Stiffeners, Tee-Flanged

The classical approach to simultaneous buckling mode design was used for a preliminary sizing of the cross section for a uniform axial load of 10,540 pounds (ult) per inch of circumferential width. Panel instability between frames (spaced at intervals of 38.5 inches) was predicted, using the Euler column theory. Coupled local buckling coefficients of the Tee and skin combination were obtained in Reference 1.

The first sizing is shown in Configuration VII of figure 3. Internal pressure requirements (65.5 psi ultimate) dictated a minimum skin gage of 0.100 inch and, consequently, the preliminary sizing was parametrically varied until the cross section shown in Configuration VIII of figure 3 was obtained. Configurations I through VI in figure 3 were also evaluated during

TABLE II

MATERIAL PROPERTIES

Ti-8Al-1Mo-1V, Duplex Annealed

MECHANICAL PROPERTIES		STRENGTH PROPERTIES, ROOM TEMPERATURE	
CONSTITUENTS		F_{tu}	135,000 psi
		F_{ty}	125,000 psi
ρ (density)	.158 lb/in.^{3}	F_{cy}	135,000 psi
M.P.	°F	F_{su}	90,000 psi
Thermal Conductivity	68(600°F)BTU/hr/ft^2/in/°F	F_{bru} (1)	232,000 psi
EMISSIVITY	(2)	F_{bry} (1)	187,000 psi
WELD:		E_t	17.5 x 10^6 psi
ARC	Yes	E_c	18.1 x 10^6 psi
FUSION	Yes	G	6.60 x 10^6 psi
RESIST.	Yes	μ	.33
BRAZE	Yes	α -Coeff. of Thermal Exp.	4.68 (150°F) (3)
ALLOY		e	13
HEAT TREATMENT		$F_{.7}$	136.0 ksi
		$F_{.85}$	135.5 ksi
		$T_{crit.}$	
		P.L.	126.0 ksi

STRENGTH PROPERTIES - ELEVATED TEMPERATURES

TEMP. °F	200	300	400	500	600	700	800	900	1000
F_{tu} (ksi)	128.	121.	115.	110.	107.	102.5	97.	90.	
F_{ty} (ksi)	116.	109.	101.	95.	90.	85.0	80.	78.	
F_{cy} (ksi)	121.	107.	98.	95.	90.	85.0	80.	74.	
F_{su} (ksi)	85.	80.6	76.4	73.0	71.4	68.2	64.4	60.2	
(1) F_{bru} (ksi)	218.	212.	203.	192.	183.	176.	174.	170.	
(1) F_{bry} (ksi)	176.	169.	161.	154.	148.	142.	134.	125.	
E_t x 10^6	16.9	16.45	16.1	15.8	15.4	14.8	14.	13.1	
E_c x 10^6	16.7	16.2	16.0	15.75	15.3	14.9	14.45	14.0	
G x 10^6	6.32	6.14	6.0	5.85	5.69	5.48	5.19	4.80	
μ	.337	.342	.346	.351	.354	.357	.359	.359	
α x 10^{-6}	4.71	4.78	4.86	4.94	5.04	5.14	5.25	5.37	
e									
$F_{.7}$ (ksi)			99.3	94.8	91.0				
$F_{.85}$ (ksi)			98.5	92.7	89.8				
P.L. (ksi)			90.0	84.0	81.0				

NOTES: (1) e/d = 2.0 (2) R.T., RMS 16 (3) in/in/°F x 10^{-6} (From R.T. to temp. shown)

TABLE III

MATERIAL PROPERTIES
Ti-8Al-1Mo-1V Alloy, Annealed

MECHANICAL PROPERTIES	
CONSTITUENTS	
ρ (density)	.158 lb/in.^{3}
M.P.	°F
Thermal Conductivity	68(600°F)BTU/hr/ft^2/in/°F
EMISSIVITY	②
WELD:	
ARC	Yes
FUSION	Yes
RESIST.	Yes
BRAZE	Yes
ALLOY	
HEAT TREATMENT	

STRENGTH PROPERTIES, ROOM TEMPERATURE	
F_{tu}	140,000 psi
F_{ty}	126,000 psi
F_{cy}	130,500 psi
F_{su}	93,000 psi
F_{bru} ①	287,000 psi
F_{bry} ①	204,000 psi
E_t	18.0 x 10^{-6} psi
E_c	18.0 x 10^{-6} psi
G	6.9 x 10^{-6} psi
μ	.3 in./in.
α-Coeff. of Thermal Exp.	5.4(68-932°F) ③
e	
$F_{.7}$	133.0 ksi
$F_{.85}$	123.7 ksi n = 13.25
$T_{crit.}$	
P.L.	82.0 ksi

STRENGTH PROPERTIES - ELEVATED TEMPERATURES

TEMP. °F	200	300	400	500	600	700	800	900	1000
F_{tu} (ksi)	128.	121.	116.	111.	107.	101.	94.	85.	
F_{ty} (ksi)	111.	102.	94.	88.	82.	77.	73.	70.	
F_{cy} (ksi)				85.3					
F_{su} (ksi)	86.	81.	78.	74.	71.5	67.5	63.		
① F_{bru} (ksi)	246.		228.		206.		197.		
① F_{bry} (ksi)	171.		166.	158.	132.				
E_t x 10^6	17.1	16.4	15.7	15.0	14.4	13.7	13.0	12.3	
E_c x 10^6	17.1	16.4	15.7	15.0	14.4	13.7	13.0	12.3	
G x 10^6				5.8					
μ				.3					
α x 10^{-6}									
e									
$F_{.7}$ (ksi)				85.8					
$F_{.85}$ (ksi)				77.2					
P.L. (ksi)				52.0					

NOTES: ① e/d = 2.0 ② R.T., RMS 16 ③ in/in/°F x 10^{-6} (From R.T. to temp. shown)

TABLE IV

MATERIAL ~ Ti-8Al-1Mo-1V

Mill Annealed 1450°F, 8 Hours

Data From NASA Lewis Research Center

Unnotched (Smooth) Specimens No Exposure Prior to Test (Ref. 3)

F_{TU}	Longitudinal Transverse	156.4 KSI 144.4 KSI
F_{TY}	Longitudinal Transverse	146.3 KSI 138.9 KSI
Percent Elongation		18.0

TABLE V

MATERIAL PROPERTIES

Aluminum Alloy, 2219-T87, .040 < t < 2.000

MECHANICAL PROPERTIES

CONSTITUENTS	
ρ (density)	.102 lb/in.^{3}
C	.23 BTU/lb (°F)
Thermal Conductivity	74 BTU/hr/ft^2/ft/°F
EMISSIVITY	(2)
WELD:	
ARC	Yes
FUSION	Yes
RESIST.	Yes
BRAZE	Yes
ALLOY	
HEAT TREATMENT	

STRENGTH PROPERTIES, ROOM TEMPERATURE

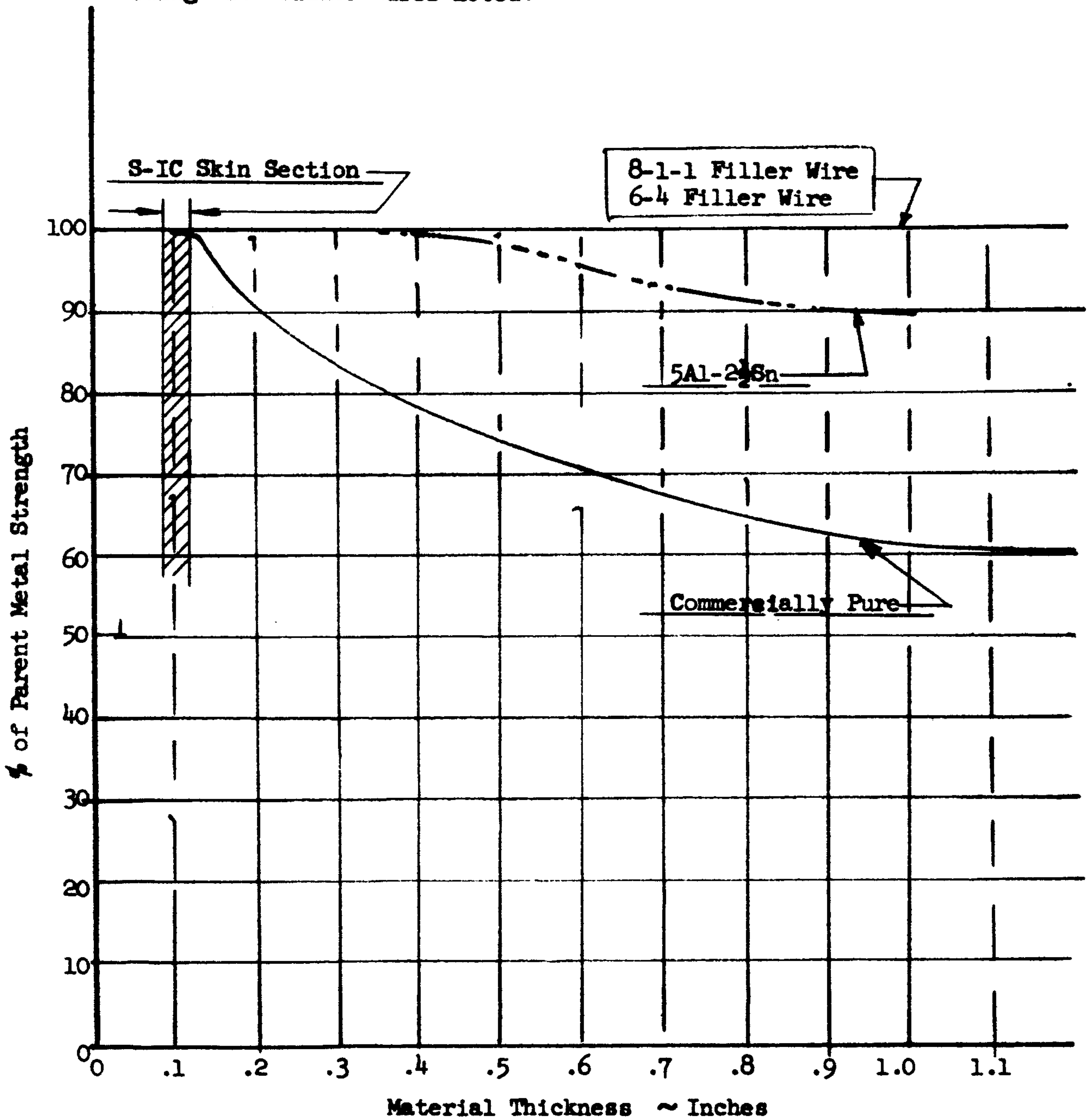
F_{tu}	62,000 psi (L) 63,000 (LT)
F_{ty}	50,000 psi
F_{cy}	50,000 psi (L) 53,000 (LT)
F_{su}	36,000 psi
F_{bru} (1)	123,000 psi
F_{bry} (1)	95,000 psi
E_t	10.5 x 10^{-6} psi
E_c	10.8 x 10^{-6} psi
G	4.0 x 10^{-6} psi
μ	.32
α-Coeff. of Thermal Exp.	12.4 (3)
e	5% elong.
$F_{.7}$	
$F_{.85}$	
T_{crit}	
P.L.	

STRENGTH PROPERTIES - ELEVATED TEMPERATURES

TEMP °F	200	300	400	500	600	700	800	900	
F_{tu} (ksi)	56.	49.	37.2	25.4	18.3	8.1	2.8		
F_{ty} (ksi)	45.	39.5	30.	20.5	14.8	6.5	2.3		
F_{cy} (ksi)									
F_{su} (ksi)									
(1) F_{bru} (ksi)									
(1) F_{bry} (ksi)									
E_t x 10^6									
E_c x 10^6									
G x 10^6									
μ	.327	.333	.335	.344	.350				
α x 10^{-6}									
$F_{.7}$ (ksi)									
$F_{.85}$ (ksi)									
P.L. (ksi)									

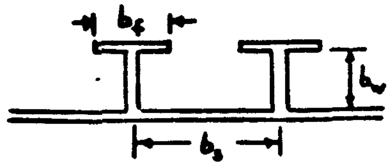
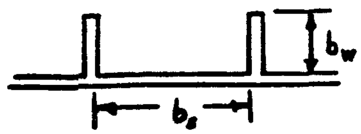
NOTES: (1) e/d = 2.0 (2) R.T., RMS 16 (3) in./in./°Fx10^{-6} (From R.T. to temp shown)

NOTE: Values are applicable to ultimate and yield strength. TIG fusion welding with filler wires noted.

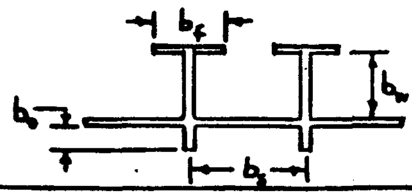
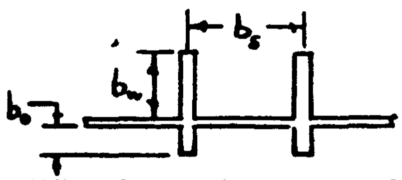


Filler Wire	
8Al-1Mo-1V	LB0170-126 Class 4
6Al-4V	LB0160-126 Class 3 or 7
Comm. Pure	LB0170-126 Class 1

Figure 1 . Typical Static Tensile Strength - Fusion Butt Weld 8-1-1 Titanium, Duplex Annealed

	A	$\alpha = 1.00 + 2.200\, r_{bw} r_{tw}$ $\beta = 1.700\, r_{bw}^2 r_{tw}$ $\gamma = 1.533\, r_{bw}^3 r_{tw}$	$t_f = 2t_w$ $b_f = 0.6 b_w$
	B	$\alpha = 1.00 + r_{bw} r_{tw}$ $\beta = 0.500\, r_{bw}^2 r_{tw}$ $\gamma = 0.333\, r_{bw}^3 r_{tw}$	

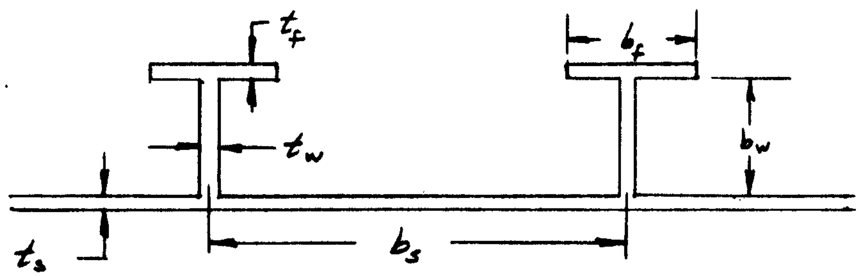
a. Internal Stiffeners

	C	$\alpha = 1.00 + 2.325\, r_{bw} r_{tw}$ $\beta = 1.708\, r_{bw}^2 r_{tw}$ $\gamma = 1.534\, r_{bw}^3 r_{tw}$	$b_f = 0.6 b_w$ $b_o = .125 b_w$ $t_f = 2 t_w$
	D	$\alpha = 1.00 + 1.125\, r_{bw} r_{tw}$ $\beta = 0.5078\, r_{bw}^2 r_{tw}$ $\gamma = 0.334\, r_{bw}^3 r_{tw}$	$b_o = .125 b_w$ $t_o = t_w$

b. External Stiffeners

Figure 2. Concept Optimization

this iteration process. No interaction between longitudinal compression and internal pressure was considered, since the maximums of these two loading effects do not occur simultaneously. The weight penalty associated with the skin gage constraint was a 6.4 percent increase over the cross-section without an internal pressure requirement. This pressure requirement would cause approximately a 30 percent weight increase in the Y-Tee skin concept shown in figure 4 (titanium weight trade-off study).



p_{max} = 65.5 psi
N_c = 10,540 lbs/in.
Frame spacing = 38.5 in.
Cyl. R = 198 in.
ρ = .158 lb/in.^{3}

CONFIG.	t_s (IN.)	b_s (IN.)	t_w (IN.)	b_w (IN.)	t_f (IN.)	b_f (IN.)	$\bar{t}$ (IN.)	W_T (LB/FT^2)	STRESS APPLIED (KSI)	STRESS ALLOW. (KSI)
I	.101	2.905	.040	1.743	.081	1.046	.155	3.51	68.0	67.0
II	.107	3.339	.053	1.670	.107	1.002	.166	3.77	63.5	62.5
III	.114	3.501	.046	1.751	.092	1.050	.165	3.75	64.0	63.9
IV	.118	4.040	.070	1.616	.141	.970	.180	4.08	58.6	56.5
V	.111	3.926	.078	1.570	.156	.942	.181	4.10	58.3	55.2
VI	.135	4.395	.054	1.758	.108	1.055	.183	4.15	57.8	57.0
VII ①	.085	2.144	.034	1.715	.068	1.029	.145	3.30	72.7	76.8
VIII	.101	2.905	.040	1.743	.081	1.046	.155	3.51	68.2	67.0
IX ②	.101	3.000	.062	1.800	.100	.812	.165	3.76	64.0	65.8

NOTES:
① Concept VII does not satisfy pressure requirements.
② Selected concept.

Figure 3. Skin Panel, Internal Stringers, Titanium

The cross-section shown in Configuration IX of figure 3 represents the Cost-Fabrication/Weight trade-off selection. These dimensions, which reflect a 7.2 percent increase over the weight optimum cross section of Configuration VIII of figure 3, were established through a detailed compromise effort between the Structures and Manufacturing Groups. The final dimensions represent a configuration attainable with standard stock size steel rolling bars. "Standardized" rolling bars were used because of the anticipated high cost of machining the rolling bars necessary to conform to the sizings of Configuration VIII of figure 3. Manufacturing assures the Structures Group that the 7.2 percent weight increase was warranted, since the dollars saved by use of standardized bars were extremely high. This procedure will only be necessary for the two experimental packs of Phase I. Nonstandard rolling bars will be available for follow-up phases with large members of packs.

For the frame spacing and cylinder under consideration, the technique proposed by DeLuzio et al, Reference 2, showed that the effects of curvature and eccentricity were negligible for internal stiffening (but not for external stiffening) and, therefore, the Euler theory could be relied upon to adequately predict panel stability between frames for the case of internal stiffening only. The weight of the titanium cross-section shown in Configuration IX of figure 3 if 3.76 lbs/sq ft. This represents a 10 percent weight savings over the present S-IC aluminum design (4.19 lb/sq ft). It should be noted that the aluminum skin gage was apparently sized for an internal pressure requirement of approximately 58.5 psi (ult), whereas the titanium design was sized for 65.5 psi (ult). In addition, a stability analysis of the aluminum design showed an axial load-carrying capability of approximately 13,300 lb/in., compared with the 10,540 lb/in. requirement used for the titanium design.

External Stiffeners - Tee-Flanged

For the purposes of establishing a basepoint design, classical theory was applied, treating panel stability between frames as a Euler column problem. The synthesis process described for the internal Tee stiffeners was applied, as shown in figure 5. Configuration IX of figure 5 shows the selected cost/weight effective cross-section. The selection represents a 7.2 percent weight saving over the current aluminum design. This section was then analyzed in greater detail as an orthotropic shell, with the effects of curvature and eccentricity accounted for. It was found that a margin of 50 percent existed in the general failure mode. A machine program was written in an effort to "trim" this margin by a successive trials procedure. Twenty-six permutations of cross-section dimensions eventually resulted in a new balanced design (figure 6), i.e., simultaneous occurrence of the orthotropic general mode and local instability under the applied stress. The weight savings was 6 percent over the previous design (Configuration IX of figure 5). This concept, figure 6, represents a 12.6 percent weight savings over the existing aluminum design.

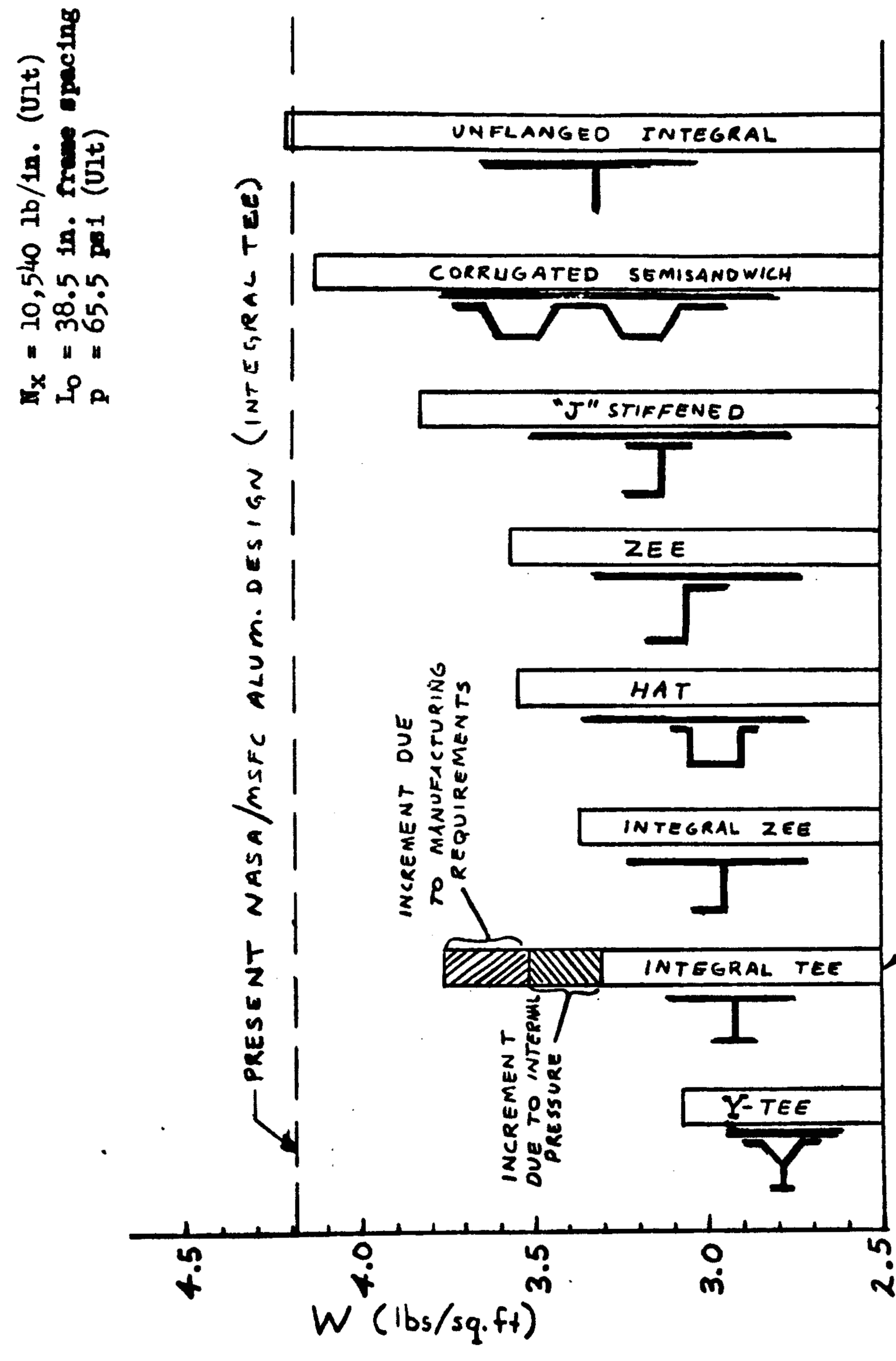
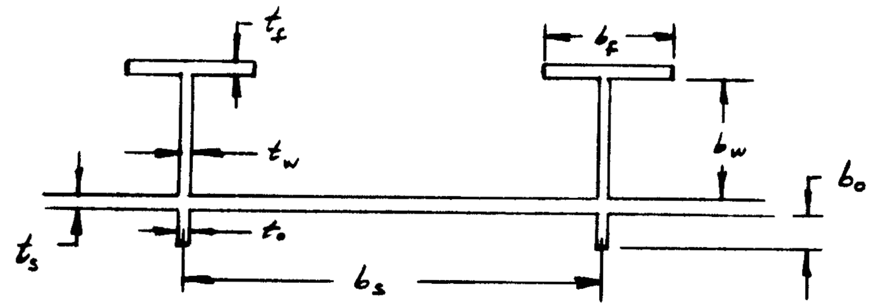


Figure 4. Titanium Weight Trade-Off Study



P_{max} = 65.5 psi
N_c = 10,750 lb/in.
Frame Spacing = 38.5 in.
Cyl R = 198 in.
ρ = .158 lb/in.^{3}

Config.	t_s (in.)	b_s (in.)	t_w (in.)	b_w (in.)	t_f (in.)	b_f (in.)	t_o (in.)	b_o (in.)	$\bar{t}$ (in.)	Weight (Lb/Ft^2)	STRESS Applied (KSI)	STRESS Allow. (KSI)
I	.111	4.133	.078	1.653	.155	.992	.078	.207	.183	4.16	57.6	44.3
II	.117	4.254	.070	1.702	.140	1.021	.070	.213	.182	4.14	57.9	46.8
III	.106	3.516	.053	1.758	.106	1.055	.053	.220	.168	3.82	62.8	56.0
IV	.100	3.059	.040	1.835	.080	1.101	.040	.229	.157	3.56	67.0	65.8
V	.125	4.403	.062	1.761	.125	1.057	.062	.220	.183	4.16	57.6	49.2
VI	.114	3.689	.046	1.844	.081	1.107	.046	.231	.167	3.80	63.2	59.0
VII (1)	.095	2.579	.038	2.063	.038	1.238	.038	.619	.152	3.47	69.3	83.6
VIII	.100	3.059	.040	1.835	.080	1.101	.040	.229	.157	3.56	67.2	65.8
IX (2)	.100	3.000	.062	1.800	.100	.812	.100	.200	.171	3.89	61.7	68.3

(1) Concept VII does not satisfy pressure requirements.

(2) Selected Concept

Figure 5. Skin Panel, External Stringers, Titanium

External Stiffener Design

(Includes curvature and eccentricity effects)

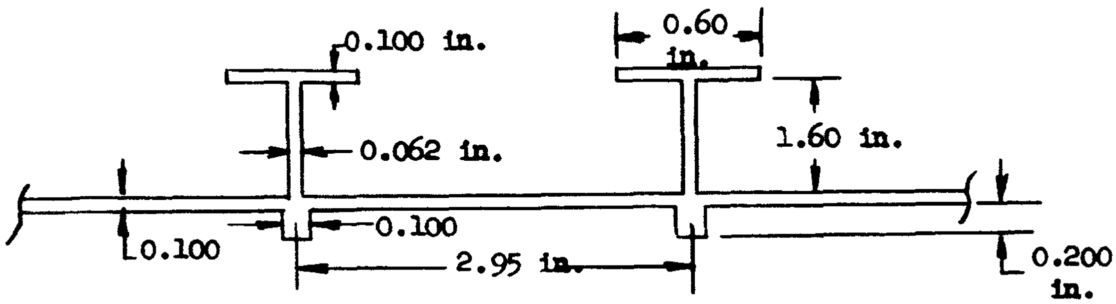


Figure 6. Concept C With Orthotropic General Mode Analysis, External Stringer

($W = 3.66$ lb/ft^2)

$p = 65.5$ psi (ult)

$N_x = 10{,}540$ lb/in. (ult)

L (Frame Spacing) = 38.5 in.

R = 198 in.

$\sigma_{local} = 71{,}050$ psi

$\sigma_{gen.out} = 67{,}600$ psi

$\sigma_{app} = 65{,}570$ psi

General Mode Equations: (Reference 2)

$$(N_x)_{cr} = \pi^2 \frac{EI_x}{L_o^2} + \frac{Et_s^2\sqrt{\bar{t}/t_s}}{R\sqrt{3(1-\mu^2)}}\,\bar{N}$$

where $\bar{N} = \left[\frac{1}{4\alpha\beta^4} + \frac{\alpha(\beta^2 - F)^2}{(1 + \beta^2)^2}\right]$

and β satisfies the equation: $\frac{(1 + \beta^2)}{\beta^6} = 4\alpha(1 + F)(\beta^2 - F)$

and where $\alpha = \frac{\sqrt{3(1 - \mu^2)}}{\pi^2 n'} \frac{L^2}{Rt_s}\sqrt{t_s/\bar{t}}$, $n' = 1$ for $L_o/R << 1$

$$F = e_x R(\pi/L)^2 \sqrt{\bar{t}/t_s}$$

Figure 7 was compiled to show the relative variation in weight (lb/ft^{-2}) and effective thickness ($\bar{t}$) between the various configurations studied. The figure includes both the internal and external stiffener combinations. The weight equivalent for the current S-IC aluminum design was also shown for purposes of comparison. As stated previously, the two configurations designated as No. IX were selected for the two experimental packs. Some preliminary cost calculations comparing the cost differences between the optimum weight configuration (VIII) and the optimum cost/weight configuration (IX) are shown in Table VI. Both internal and external stiffener designs are included. It will be noted that the external Configuration IX is shown to be more expensive than any of the others by a considerable amount. The selected designs for the two experimental packs were priced out as the least expensive.

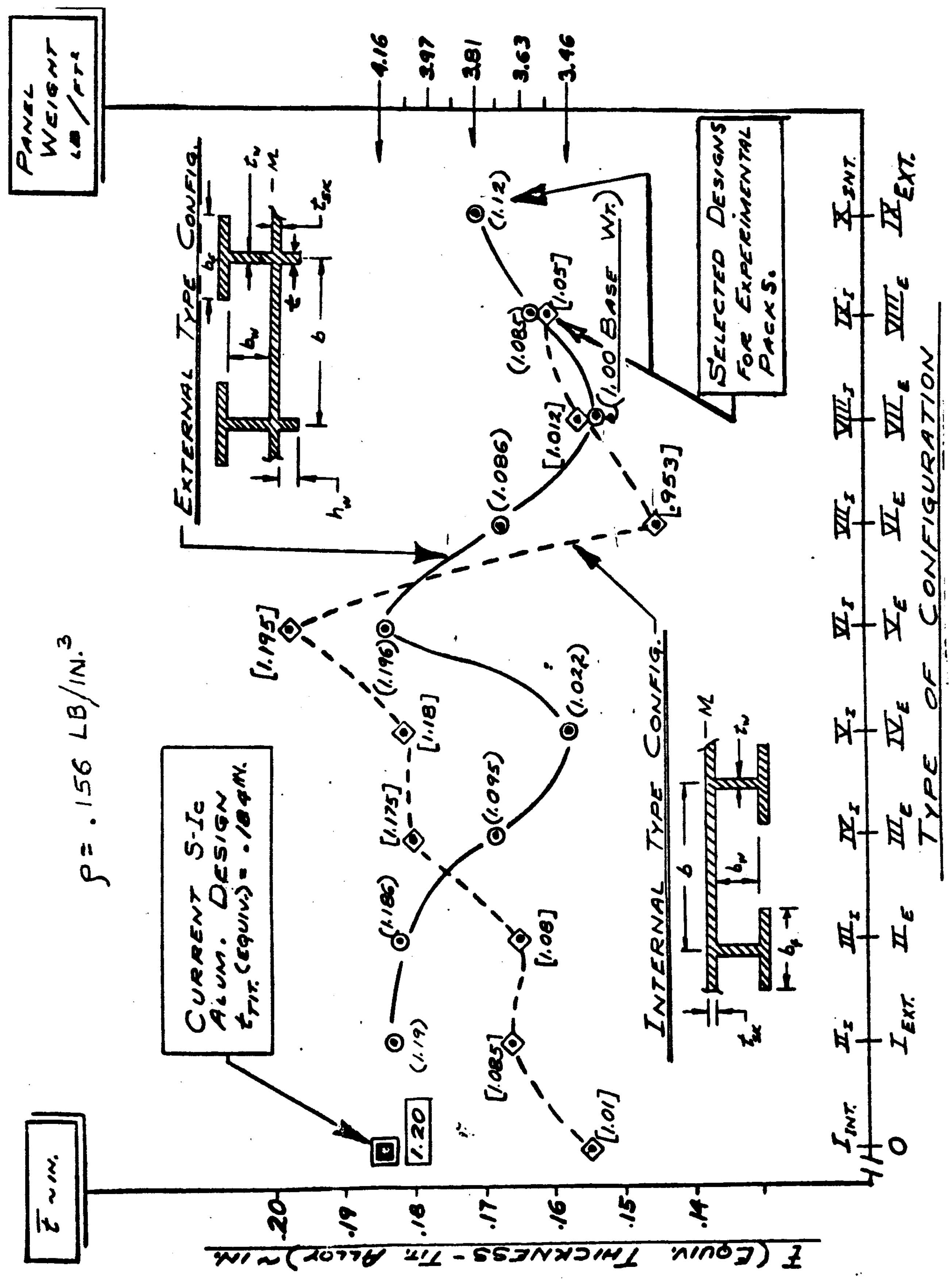


Figure 7. Candidate Configurations, 8-1-1 Titanium Alloy

Table VI

PRELIMINARY COST CALCULATIONS

Costs	Internal Stiffeners (Figure 3)		External Stiffeners (Figure 5)	
	Config. IX Standard (1)	Config. VIII Machined	Config. IX Standard (1)	Config. VIII Machined
Material	109.84	109.34	121.55	146.69
Labor and Burden	40.00	125.00	90.00	540.00
Total per 2 Panels ($)	149.84	234.34	211.55	686.69

Notes:

1. Optimum cost/weight configuration panels are to determine if standard cold rolled bar stock sizes and surfaces will give satisfactory surface finishes for rolled diffusion bonded structures. If finishes prove satisfactory, special mill run sizes could be purchased for production run quantities.

2. Estimates do not allow for rejection or rework.

3. Estimates are of manufacturing costs only and do not include engineering cost, administrative overhead, profit, etc., utilized in establishing final price.

Preliminary Design Stress Analysis

The minimum weight analysis described in the preceding section depends on stability and pressure requirements. The skin is sized by hoop tension, and the stiffeners by stability. The equation for local and general instability is stated below. The following analysis also includes a redundant solution for the attachment loads between the inside stringer and the slosh baffle frame.

Since the optimization process includes stress analysis, this section describes theory pertinent to the analysis, as well as calculations of margins of safety.

Local Instability

K = coupled local buckling coefficient

$$F_L = .904\ K\ E\ \left(\frac{t_s}{b_s}\right)^2$$

A plasticity correction was not required because the allowables fell in the elastic range.

General Instability

The following general mode equations are taken from Reference 2. This equation is essentially the Euler column equation modified to account for shell curvature and eccentricity.

$$(N_x)_{CR} = \pi^2\ \frac{E\ I_x}{L^2} + \frac{E\ t_s^2 \sqrt{\frac{t_x}{t_s}}}{R\sqrt{3\ (1 - \mu^2)}}\ \tilde{N}$$

where:

$$\tilde{N} = \frac{1}{4\alpha\beta^4} + \frac{\alpha\ (\beta^2 - F)^2}{(1 + \beta^2)^2}$$

The parameters involved are:

$$\alpha = \frac{\sqrt{3\ (1 - \mu)}}{\pi^2} \times \frac{L^2}{Rt_s}\sqrt{\frac{t_s}{t_x}}$$

$$F = e_x\ R\ \left(\frac{\pi}{L}\right)^2\sqrt{\frac{t_x}{t_s}}$$

> 0 Stiffener internal

< 0 Stiffener external

And where β must satisfy

$$\frac{(1 + \beta^2)}{\beta^6} = 4\ \alpha\ (1 + F)\ (\beta^2 - F)$$

Instability Check

F_A = the smallest stress of either the local or general allowable stresses

= 65.8 ksi

f = applied load stress

= 64.0 ksi

$$M.S. = \frac{65.8}{64.0} - 1 = .03$$

Stresses are obtained from figure 3.

Stiffener Crippling

Since the skins were initially sized to resist pressure, the only remaining item to check is stiffener crippling.

P_{CC}(Ti-8Al-1Mo-1V duplex annealed at R.T.; t = .10 in. and b = .406 in.)
= 11,650 pounds

P_{CC}(Ti-8Al-1Mo-1V duplex annealed at R.T.; t = .062 in. and b = .90 in.)
= 8,260 pounds

$A = .10(.812) + .062(1.8/2) = .137 \text{ in.}^2$

$$F_{CC} = \frac{2(11,650) + 8,260}{.137} = 230,000 \text{ psi}$$

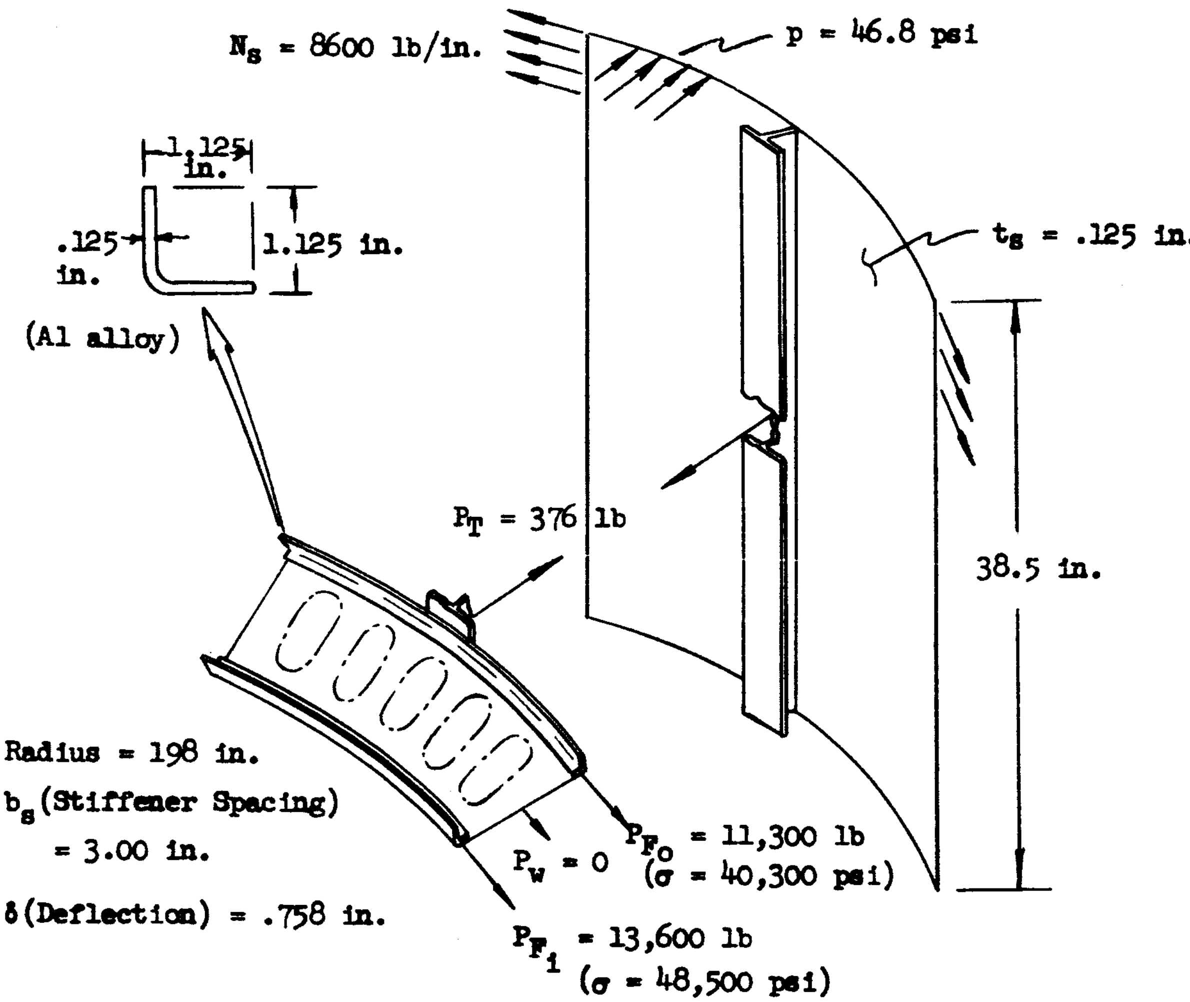
or 135,000 psi F_{cy}

M.S. = 135/64 - 1 = HIGH

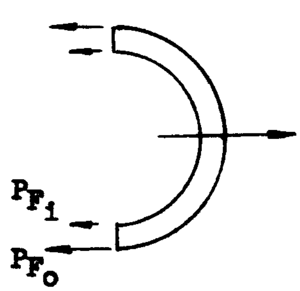
Therefore, the panel has sufficient strength.

REDUNDANT FRAME ANALYSIS

This analysis evaluates the redundant load between the frame and the integrally stiffened titanium panel.



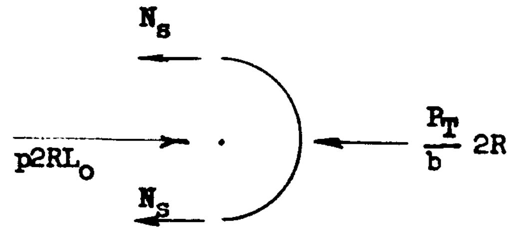
1. **Frame Equilibrium**



$$\Sigma P_T \sin\theta_N = \frac{P_T}{b_s} 2R$$

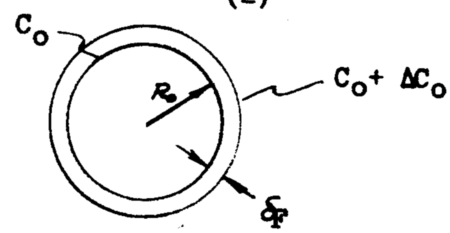
$$\Sigma F_x:\ 2P_{F_i} + 2P_{F_o} = \frac{P_T}{b_s} 2R \qquad (1)$$

II Skin Equilibrium



$$\Sigma F_x: \quad 2N_s L_o + \frac{P_t}{b_s} 2R = p2RL_o \qquad (2)$$

III Frame Deformation



(Outer cap) $\Delta C_o = \epsilon_o 2\pi R.$

$$C_o = 2\pi R_o \qquad C_o + \Delta C_o = 2\pi (R_o + \delta_F)$$

$$\therefore \; C_o = 2\pi R_o + 2\pi \delta_F - 2\pi R_o \Rightarrow \delta_F = \frac{\Delta C_o}{2\pi} = \epsilon_o R_o.$$

$$\epsilon_o = \frac{P_{Fo}}{A_F E_{Al}} \qquad \delta_F = \frac{P_{Fo} R_o}{A_F E_{Al}} = \frac{P_{Fi} (R_o - d)}{A_F E_{Al}} \qquad (3)$$

IV Skin Deformation

$$\delta_s = \frac{\Delta C_s}{2\pi} = \epsilon_s R_o, \quad \epsilon_s = \frac{N_s}{t_s E_{Ti}}$$

$$\therefore \; \delta_s = \frac{N_s R_o}{t_s E_{Ti}}$$

Continuity requires that $\delta_F = \delta_s$ (at skin/frame attachment line)

$$\therefore \; \frac{N_s R_o}{t_s E_{Ti}} = \frac{P_{Fo} R_o}{A_F E_{Al}} \qquad (4)$$

V <u>Solution</u>

There are four unknowns, viz. P_T, P_{Fo}, P_{Fi}, and N_s. Starting with four equations (two equilibrium and two deformation) and substituting known parameters, Equation (2) becomes

$$(38.5)2\, N_s + \frac{P_T}{(3.00)} (396.0) = 46.8\, (396.0)\, (38.5)$$

Equation (1) becomes:

$$2P_{Fi} + 2P_{Fo} = \frac{P_T}{3.00} (396.0)$$

Equation (3) becomes:

$$198.0\, P_{Fo} = (198 - 33.0) P_{Fi}$$

Equation (4) becomes:

$$\frac{N_s}{(.125)\ 18} = \frac{P_{Fo}}{(.281)\ 10.5}$$

Simplifying

(2) $7.7\ N_s + 132.0\ P_T = 713{,}000$

(1) $P_{Fi} + P_{Fo} = 66.0\ P_T$

(3) $P_{Fi} = 1.20\ P_{Fo}$

(4) $P_{Fo} = 1.31\ N_s$

Combining Equations (3) and (4),

$P_{Fi} = 1.575\ N_s$

$\therefore\ 1.575\ N_s + 1.31\ N_s = 66.0\ P_T = 2.885\ N_s$

$77\ N_s + 5.77\ N_s = 713{,}000$

$$N_s = \frac{713{,}000}{82.8} = 8{,}600 \text{ lb/in.}$$

$$P_T = \frac{2.885\ N_s}{66.0} = \frac{2.885\ (8{,}600)}{66.0} = 376.0 \text{ lb.}$$

$P_{Fo} = 1.31\ N_s = 1.31\ (8{,}600) = 11{,}300$ lb. ($\sigma_o = 40{,}300$ psi)

$P_{Fi} = 1.20\ (11{,}300) = 13{,}600$ lb. ($\sigma_i = 48{,}500$ psi)

$$\delta_F = \delta_s = \frac{8{,}600\ (198)}{(.125)\ 18 \times 10^6} = 0.758 \text{ in.}$$

K_s = spring constant of frame

$$= \frac{376.0}{.758} = 496 \text{ lb/in.}$$

DEVELOPMENT PANEL SELECTION

A large number of panel configurations were analyzed, and nine possible designs were selected (figures 3 and 5). They are also graphically summarized in figure 7. Both the internal and external stiffener configurations are shown, as well as the current S-IC aluminum design. The final selected configurations are shown on figure 8).

STRUCTURAL TESTING

A limited number of static tests have been scheduled for specimens taken from the selected design of the development pack series. The test specimens are internally stiffened versions of the panel wall.

One 8.102-inch long specimen (figures 9 through 15) was loaded in block compression to determine its postbuckling strength. The test unit axial load at failure was N_x = 140,750/8.713 = 16,154 lb/in. (ultimate).

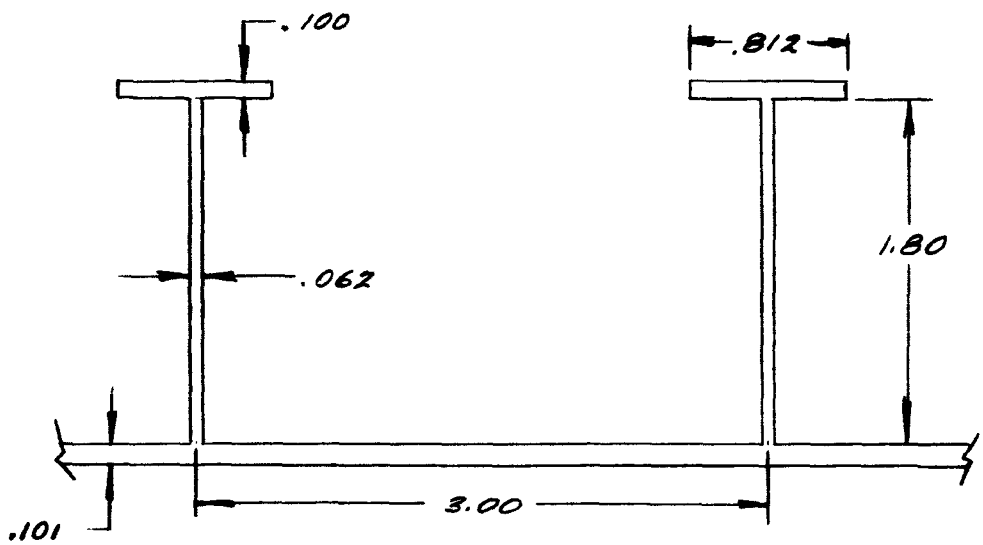
Figure 10 illustrates the close tolerance produced by the rolling operation. Figure 11 shows the degree of distortion and irregularity in the short column test specimen, prior to testing. Figures 12 through 15 show four views of the test specimen prior to testing.

The critical design load given by the ground wind condition is N_x = 10,540 lb/in. Hence, M.S. (ult) = 16,154/10,540 - 1 = +.53. The test results show that the local instability of the design exceeds the required strength (figure 16). This test has provided what can be considered an upper limit of strength for the selected configuration.

A 38.5-inch specimen will be loaded in compression, simulating a simply-supported wide column axial member. This test will provide a lower limit of strength for the selected design. The data compiled from these tests will provide estimates of strength anticipated from similar specimens whose dimensions and boundary conditions simulate those already tested. It is noted that the design selection for the final production pack panel approximates very closely the design selection tested here.

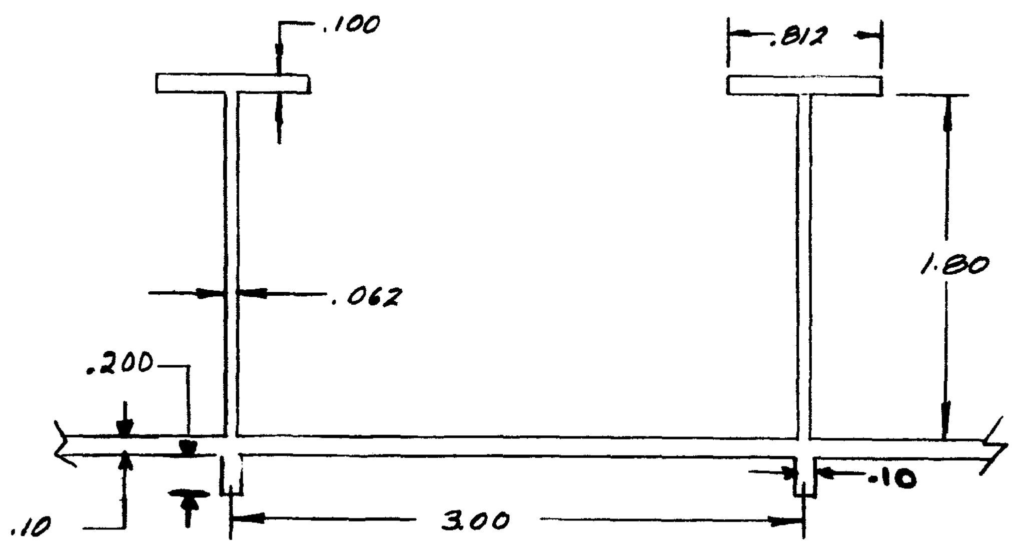
The following steps were used in testing the short column specimen:

1. Specimen was loaded to 120,000 pounds without failure. Free edges buckled, but returned when load was removed.
2. Specimen width was reduced by 1/2 inch on each side.
   New specimen size: End No. 1: 8.102 long x 8.713 wide
   End No. 2: 8.102 long x 8.716 wide
3. Retest. Specimen started yielding at 140,750 pounds. Load was reduced to 100,000 pounds.
4. Reloaded to 139,000; load dropped.
5. Failure load = 140,750 pounds.
6. Unit axial load = 140,750/8.713 = 16,154 lb/in.



Weight = 3.78 lb/ft^2

a. Internal Integral Tee Configuration



Weight = 3.89 lb/ft^2

b. External Integral Tee Configuration

Figure 8. Development Panel Selection

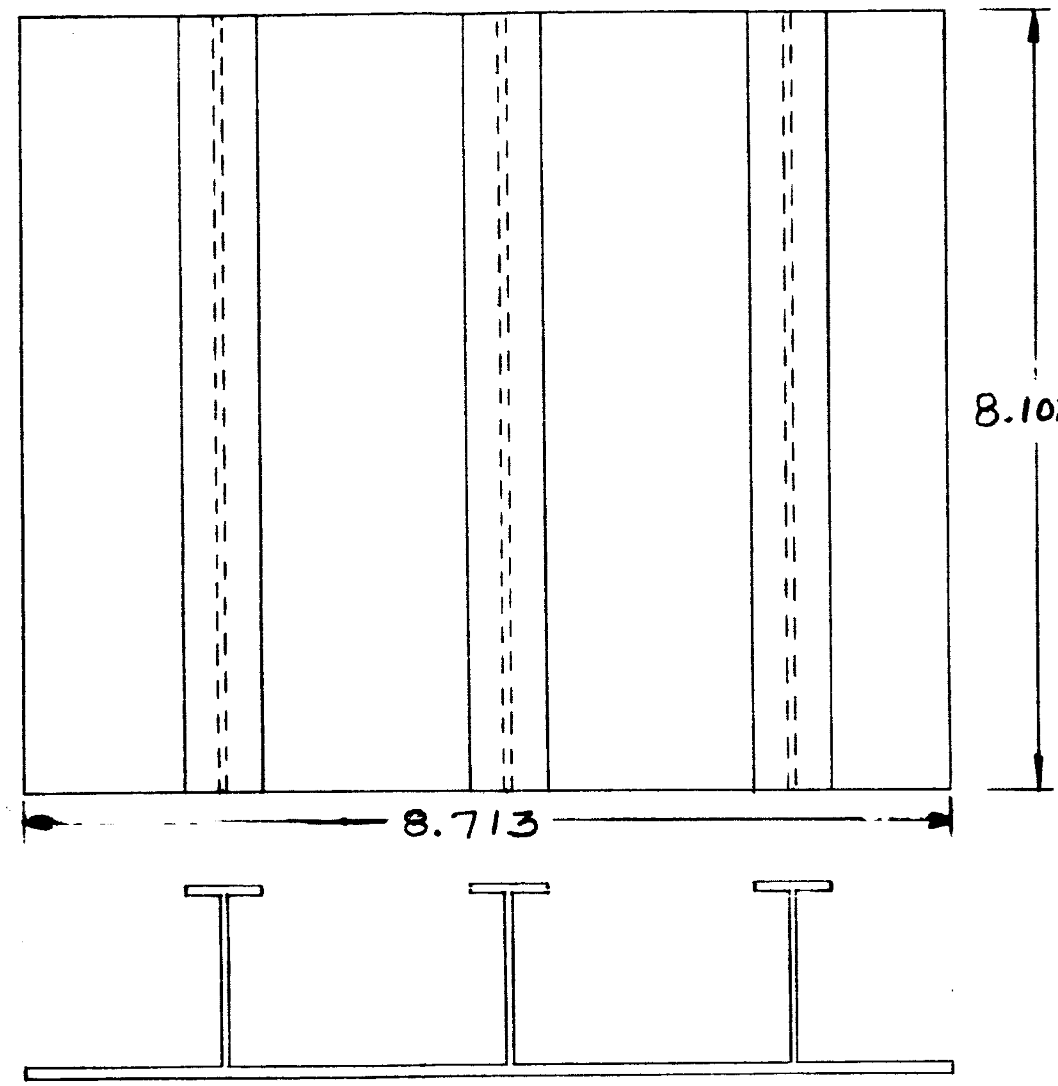
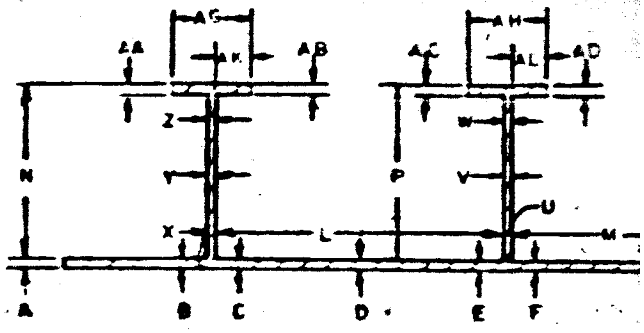


Figure 9. Test Specimen

NOTES:

1. Area of panel = 8.713 (8.102) = 70.5 in.^{2}
2. Weight of test panel = 1.95 - (8.102)(1)(.158)(.1) = 1.822 lb
3. Weight of panel per ft^2 = 1.822(144)/70.5 = 3.74 lb/ft^2
4. Calculated weight of panel = 3.76 lb/ft^2

   % Diff. = 3.76/3.74 - 1 = 0.3% (small)
5. Calculated local instability allowable = 70,000 psi
6. Test value local instability = 98,300 psi
7. Maximum applied axial stress = 63,950 psi
8. M.S. (ult) = 98,300/63,950 - 1 = +.53



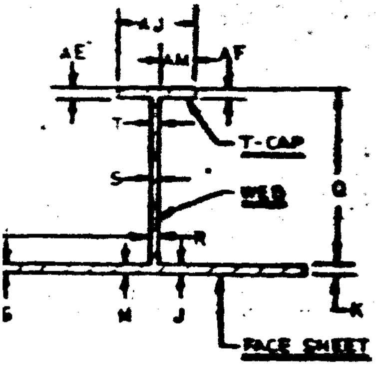
SECTION A

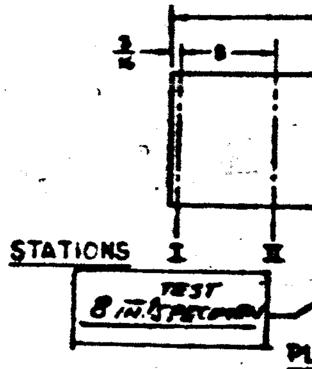
FACE SHEET THICKNESS MAX. .102 MIN. .095 AVG.	STA.	A	B	C	D	E	F	G
TARGET DIM. .100 ± .002	I	.100	.102	.097	.098	.096	.099	.098
	II	.101	.100	.096	.098	.096	.100	.099
	III	.099	.099	.096	.097	.095	.099	.097
	IV	.101	.100	.099	.099	.097	.100	.100
	V	.101	.100	.100	.100	.098	.100	.100

WEB THICKNESS MAX. .069 MIN. .061 AVG. .0648	STA.	R	S	T	U	V	W	X
TARGET DIM. ± .002 .062	I	.067	.066	.066	.065	.062	.062	.065
	II	.064	.064	.066	.065	.062	.062	.069
	III	.065	.065	.066	.066	.063	.063	.068
	IV	.065	.064	.065	.064	.064	.063	.067
	V	.064	.062	.066	.064	.061	.062	.065

42

10-1





A

...986 DEVIATION ± .0034 / .0036		
H	J	K
.100	.098	.101
.099	.098	.101
.098	.097	.099
.101	.098	.109
.100	.0	

T-HEIGHT MAX. 1.907 MIN. 1.884 AVG. 1.896 D...

TARGET DIM. 1.900

STA.	N	P	Q
I	1.892	1.898	1.896
II	1.891	1.900	1.899
III	1.897	1.904	1.907
IV	1.897	1.896	1.898
V	1.889	1.890	1.884

DEVIATION ± .0042 / .0038	
Y	Z
.066	.065
.066	.067
.066	.067
.067	.066
.066	.064

T-CAP THICKNESS MAX. .115 MIN. .106 AVG. .11...

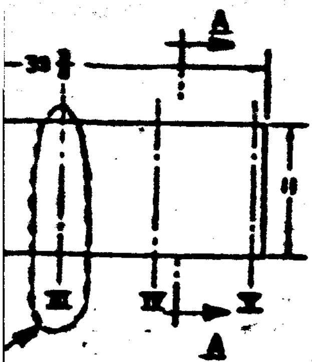
TARGET DIM. .100 ±.002

STA.	AA	AB	AC	AD
I	.111	.110	.111	.111
II	.111	.111	.111	.110
III	.112	.112	.111	.111
IV	.109	.108	.109	.110
V	.107	.106	.107	.108

T-CAP WIDTH MAX. .801 MIN. .780 AVG. .795 DEV.

TARGET DIM. .812 ±.010

STA.	AG	AH	AJ
I	.788	.780	.784
II	.797	.799	.791
III	.800	.796	.791
IV	.801	.796	.792
V	.801	.790	.789



AN VIEW OF PANEL

NOTE: ALL DIMENSIONS TO THE NEAREST .001

EVIATION ± .011 / .012

T-SPACING MAX. 3.108 MIN. 3.026 AVG. 3.072 DEVIATION ± .036 / .046

TARGET DIM. 3.000 ±.010

STA.	L	M
I	3.026	3.036
II	3.077	3.098
III	3.085	3.108
IV	3.077	3.104
V	3.092	3.065

DEV. ± .005 / .004

AE	AF
112	.112
111	.113
114	.115
111	.111
109	.110

± .000 / .013

T-CAP ALIGN. WITH WEB MAX. .374 MIN. .360 AVG. .364 DEV. ± .010 / .004

TARGET DIM. .375 ±.010

STA.	AK	AL	AM
I	.363	.360	.360
II	.370	.360	.360
III	.372	.362	.360
IV	.373	.363	.360
V	.374	.361	.362

Figure 10-3

PACK "B"
CONFIG. #1 WITH .200 STRINGERS REMOVED

DIMENSIONS TAKEN BEFORE GRIT BLASTING & PICKLE OPERATIONS WHICH REMOVE .002 FROM ALL SURFACES.

NORTH AMERICAN AVIATION INC.
INTERNATIONAL AIRPORT
LOS ANGELES 45 CALIFORNIA

DIMENSIONAL ANALYSIS OF 2624-001 CONFIG.#2
S-IC TITANIUM ROLL DIFFUSION BOND-PACK ASSY

2624-009

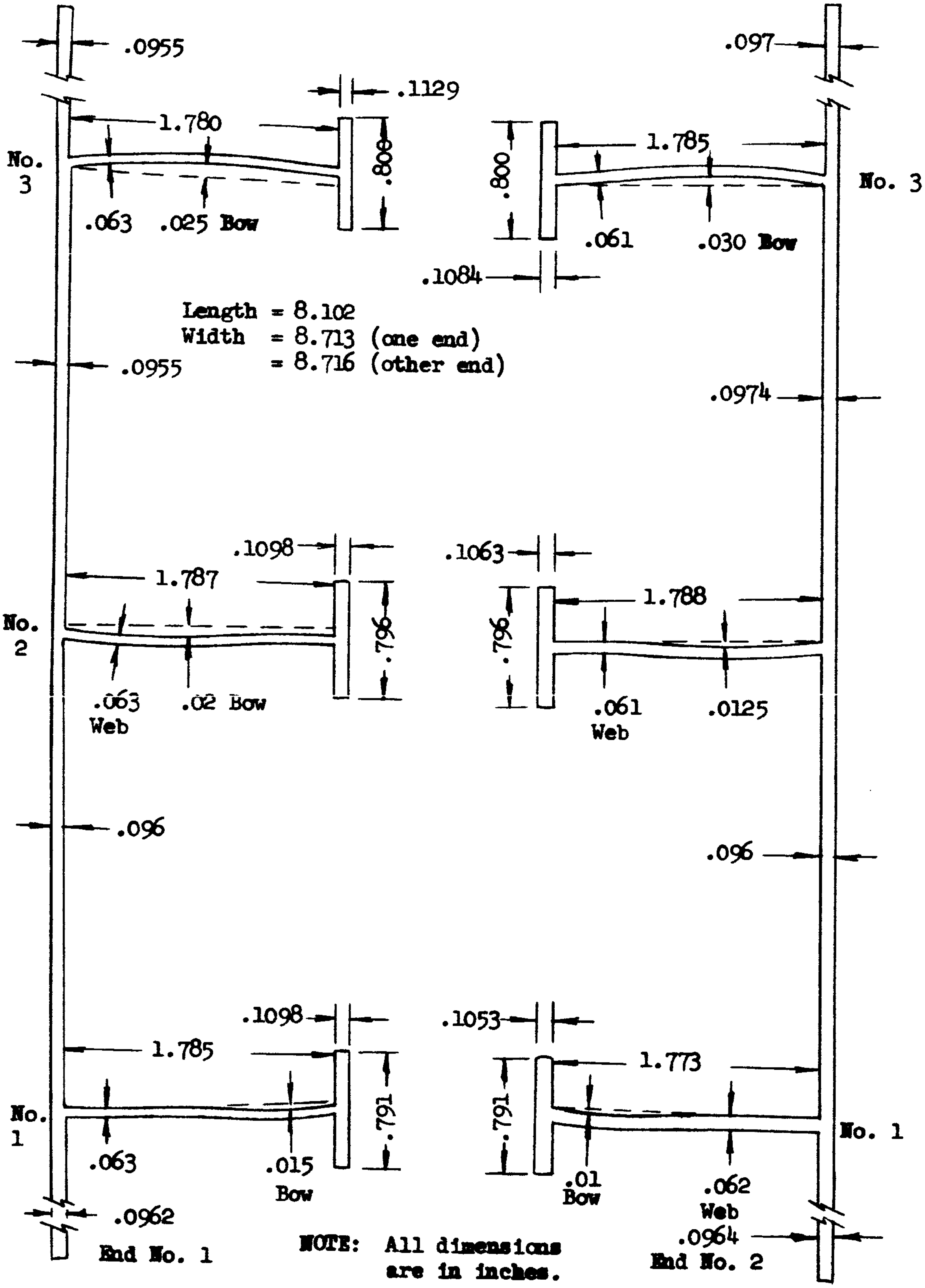


Figure 11. Short Column Test Specimen, Dimensions

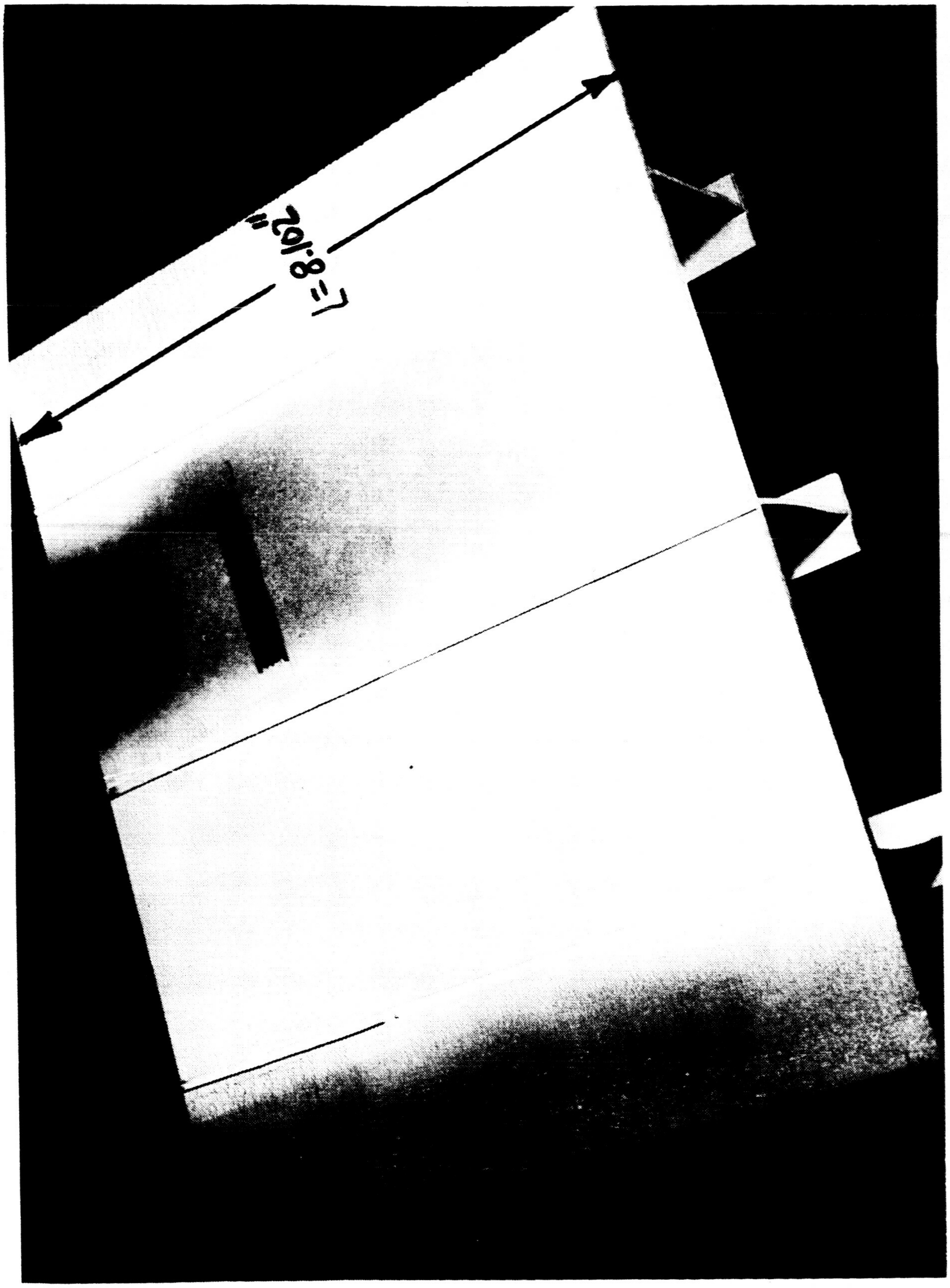


Figure 12. Short Column Test Specimen, View A

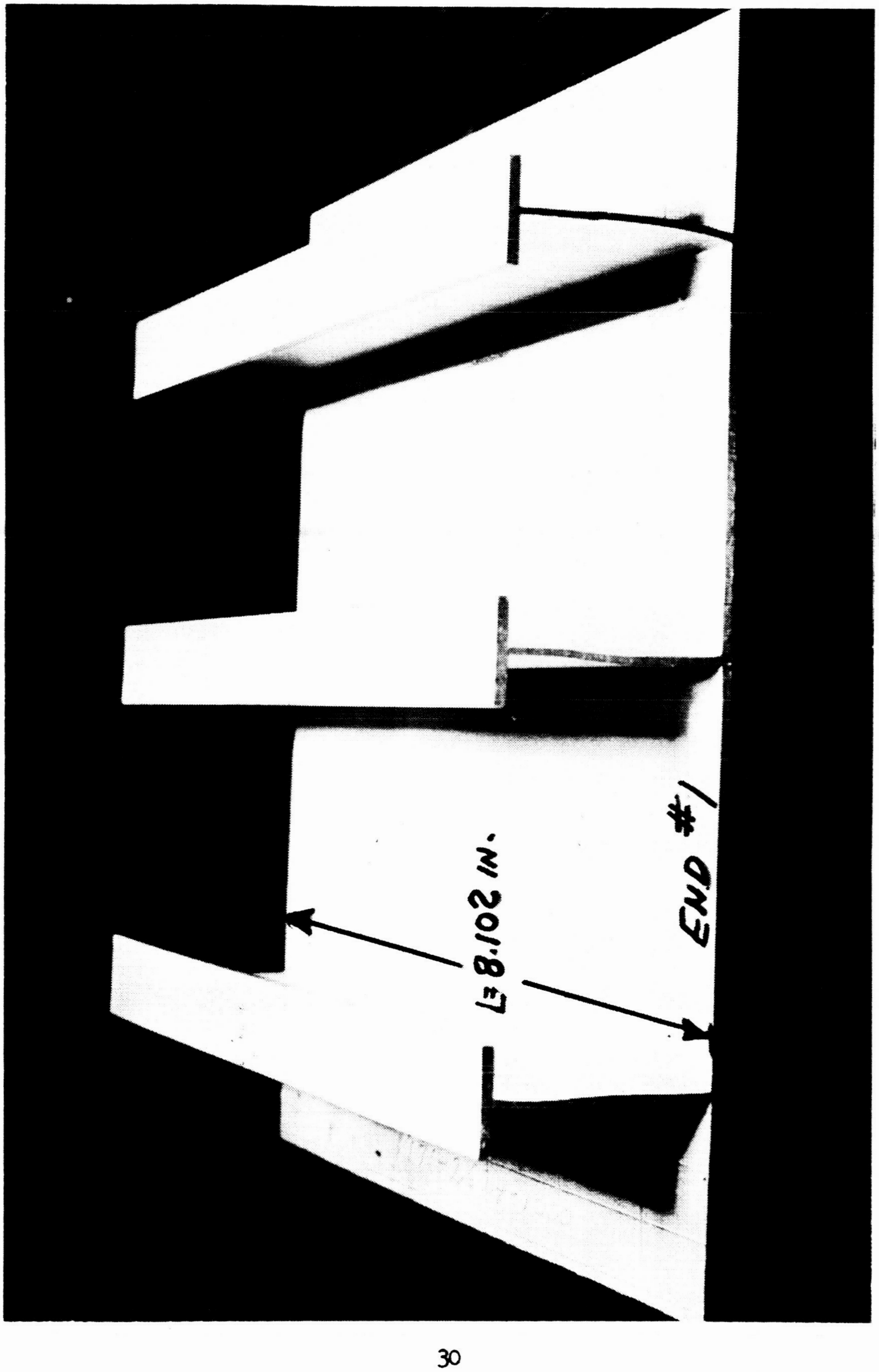


Figure 13. Short Column Test Specimen, View B

Figure 14. Short Column Test Specimen, View C

Figure 15. Short Column Test Specimen, View D

Saturn S-IC Skin Panel

Integral Tee Configuration

Short Column Test

Ti-8Al-1Mo-1V Duplex Annealed

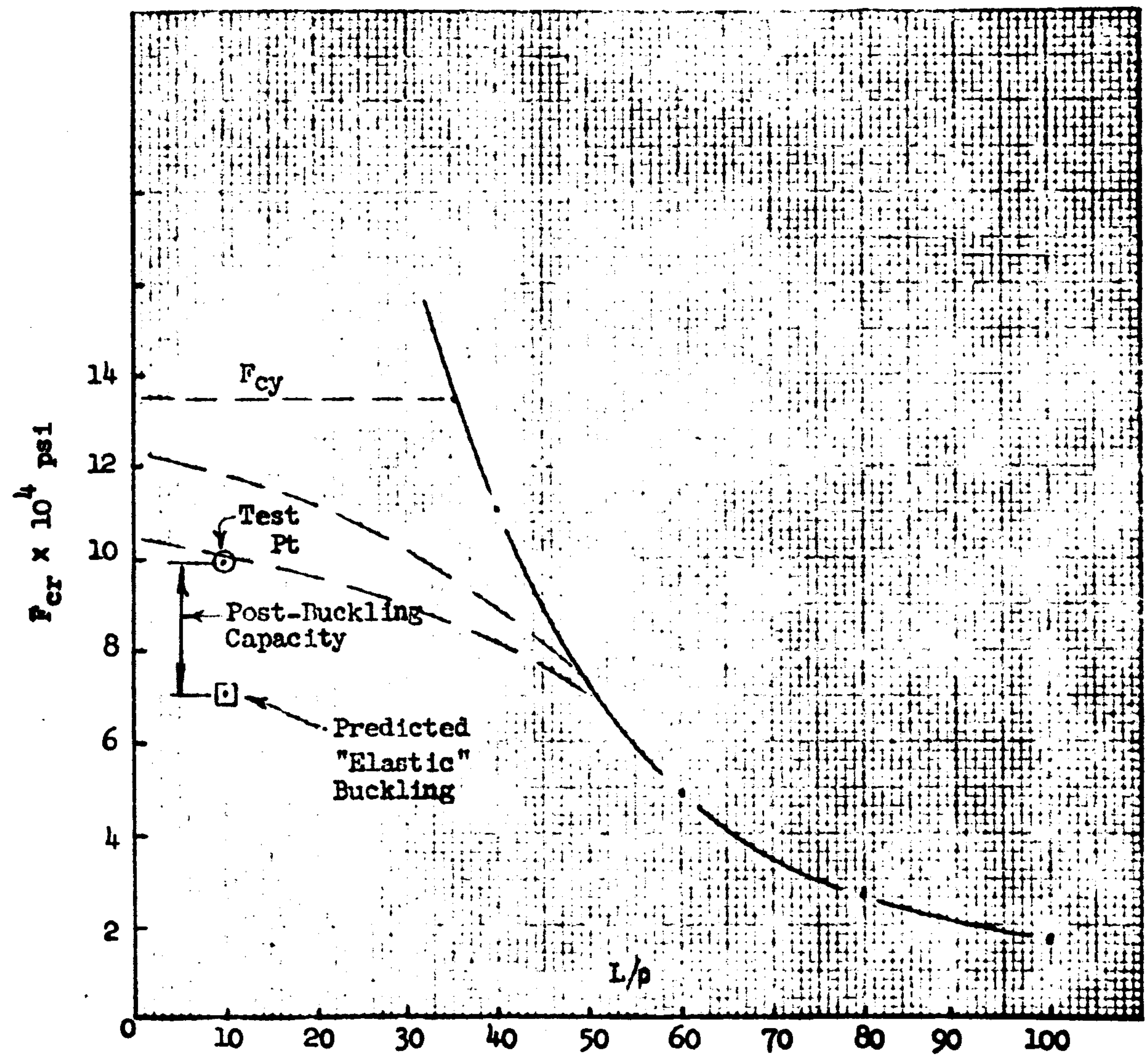


Figure 16. Short Column Test

7. Figures 17 through 21 show the specimen after testing to 140,750 pounds load.

NOTE: No cracks, breaks, or ruptures were indicated after the test. The diffusion bonded joints of the test specimen showed no indication of damage, such as separation.

PRODUCTION PANEL DESIGN PHASE

OPTIMIZATION STUDIES

Because of the redefinition of the S-IC tank loads, it was necessary to repeat the panel sizing optimization process. The load change did not involve a change in magnitude of the load; however, it did involve the addition of biaxial load effects. To design for this type of loading, an effective stress was calculated from the biaxial stresses, by means of the Hencky-Von Mises maximum distortion energy theory. The effective stress was then compared with the tension ultimate of the material, to find the desired skin thickness.

Titanium Skin Panel Sizing

The skins have not been sized for the combined effects of pressure plus axial load. This condition is treated in the following analysis.

$$f = \frac{pr}{t} = \frac{65.5 \times 198}{t}$$

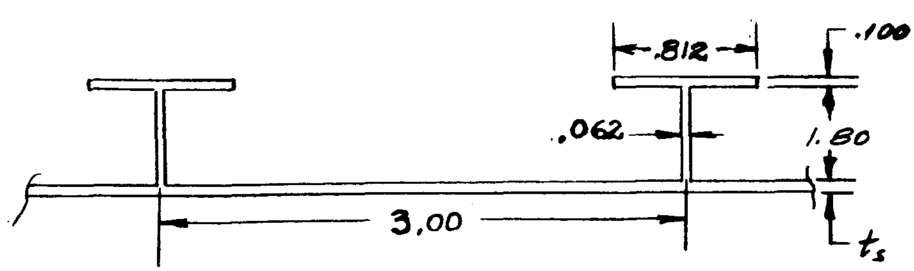
F_{TU} (Ti-8Al-1Mo-1V duplex annealed, at R.T.) = 135 ksi

$$t = \frac{65.5 \times 198}{135{,}000} = .096 \text{ in.}$$

This thickness is for pressure only. The skin thickness for combined pressure plus axial loads will now be evaluated, using the Hencky-Von Mises maximum distortion energy theory.

$$\sigma_1^2 - \sigma_1 \sigma_2 + \sigma_2^2 \leq F_{TU}^2$$

The stiffener to be used in calculating the longitudinal stresses will be the same as the preliminary design selection.



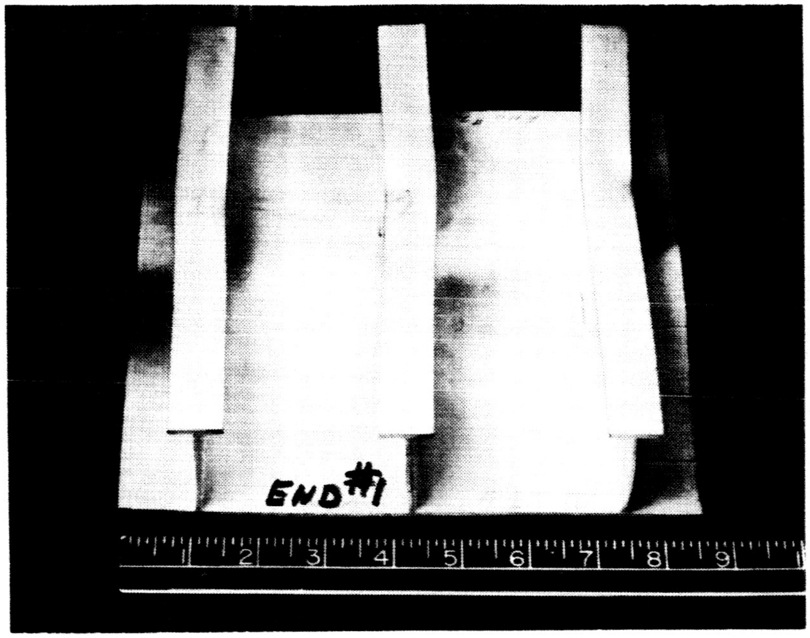


Figure 17. Specimen After Test, View A

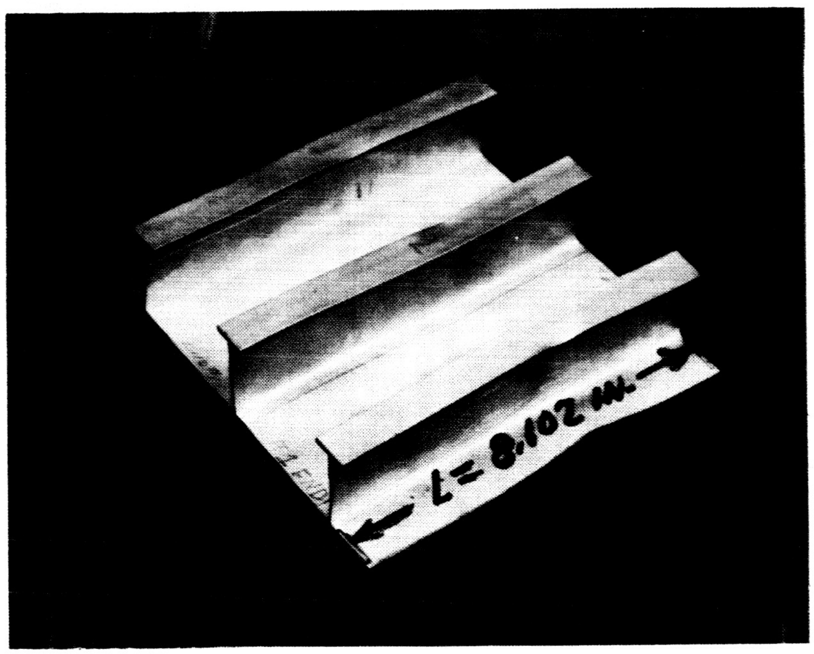


Figure 18. Specimen After Test, View B

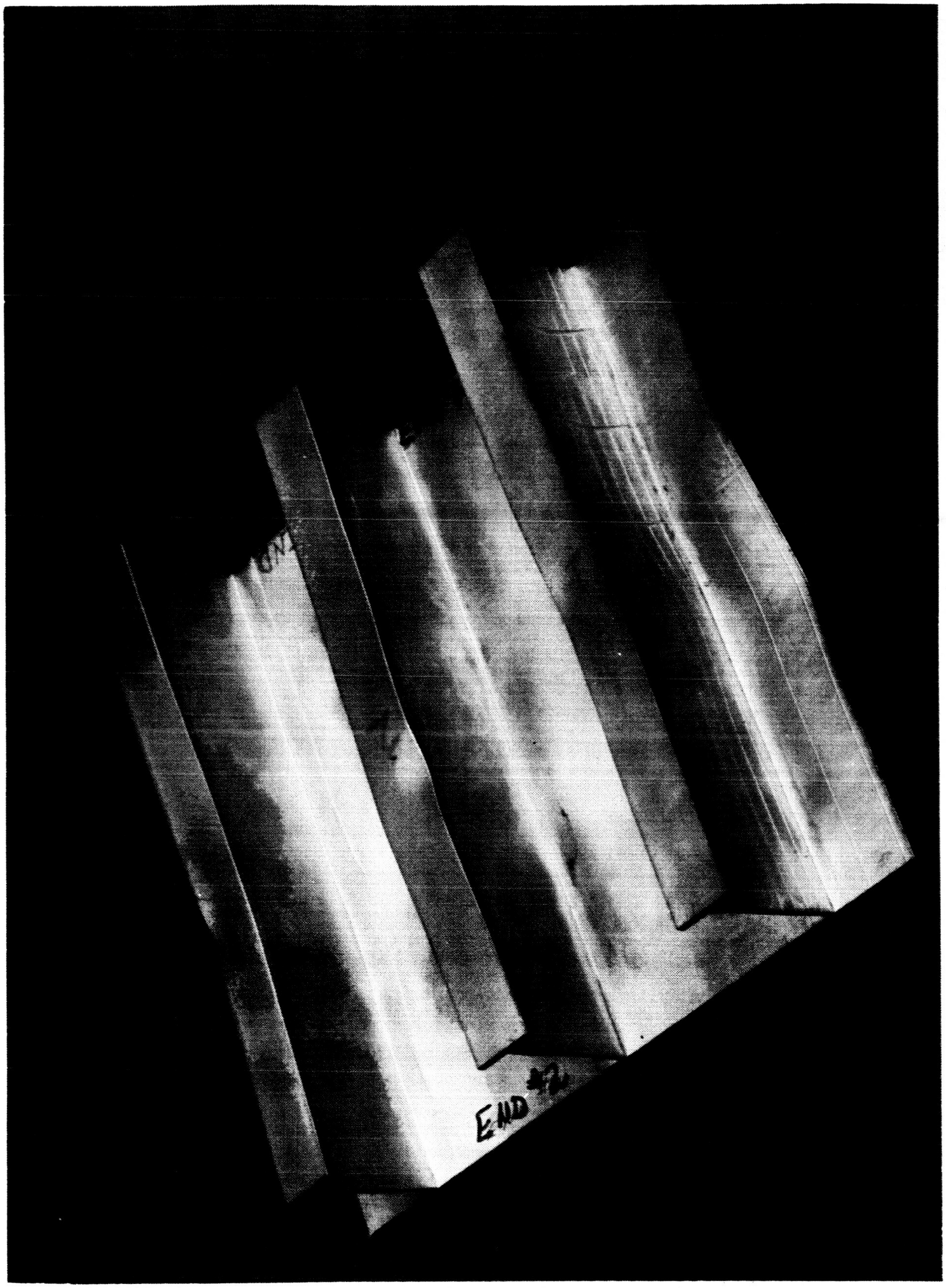


Figure 19. Specimen After Test, View C

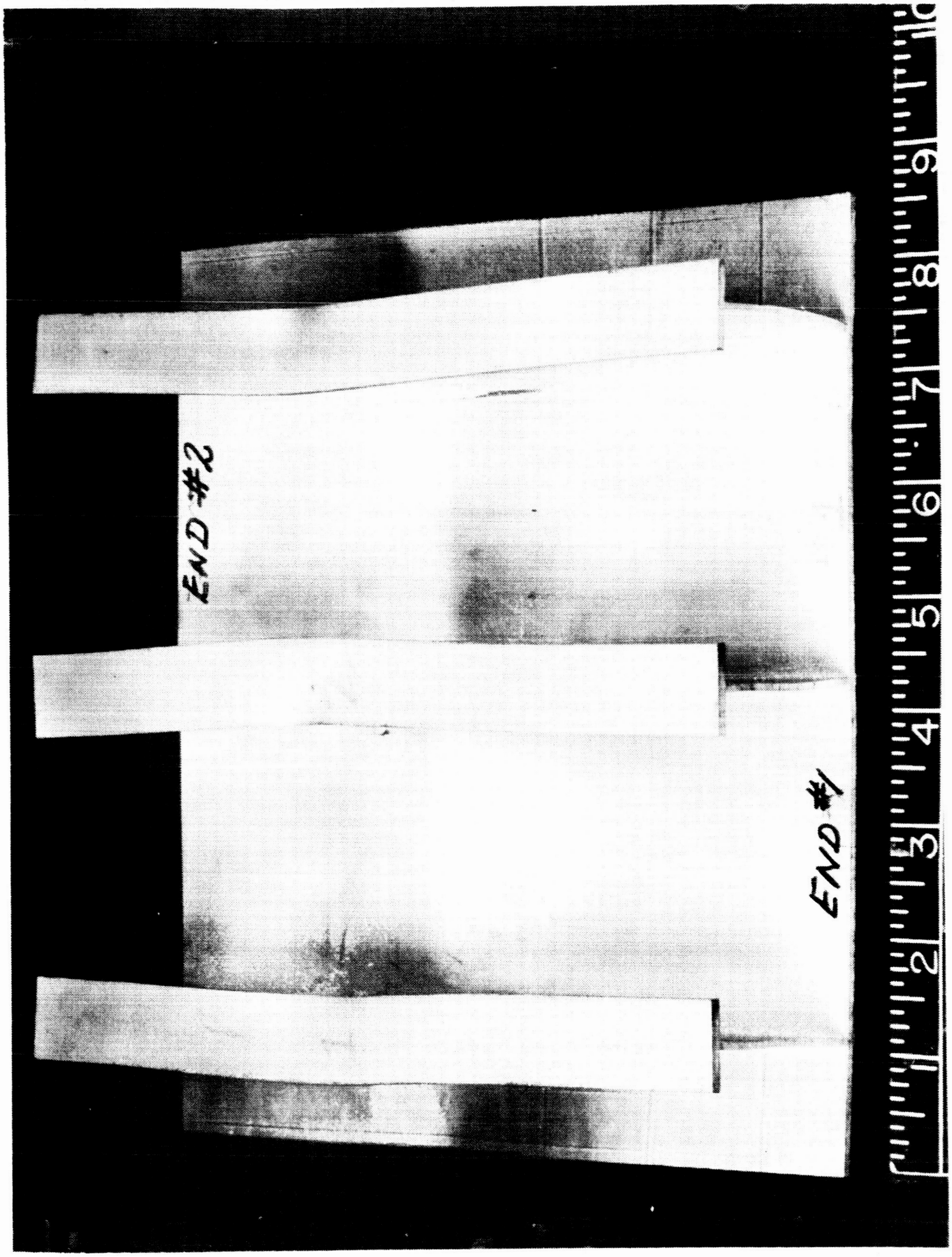


Figure 20. Specimen After Test, View D

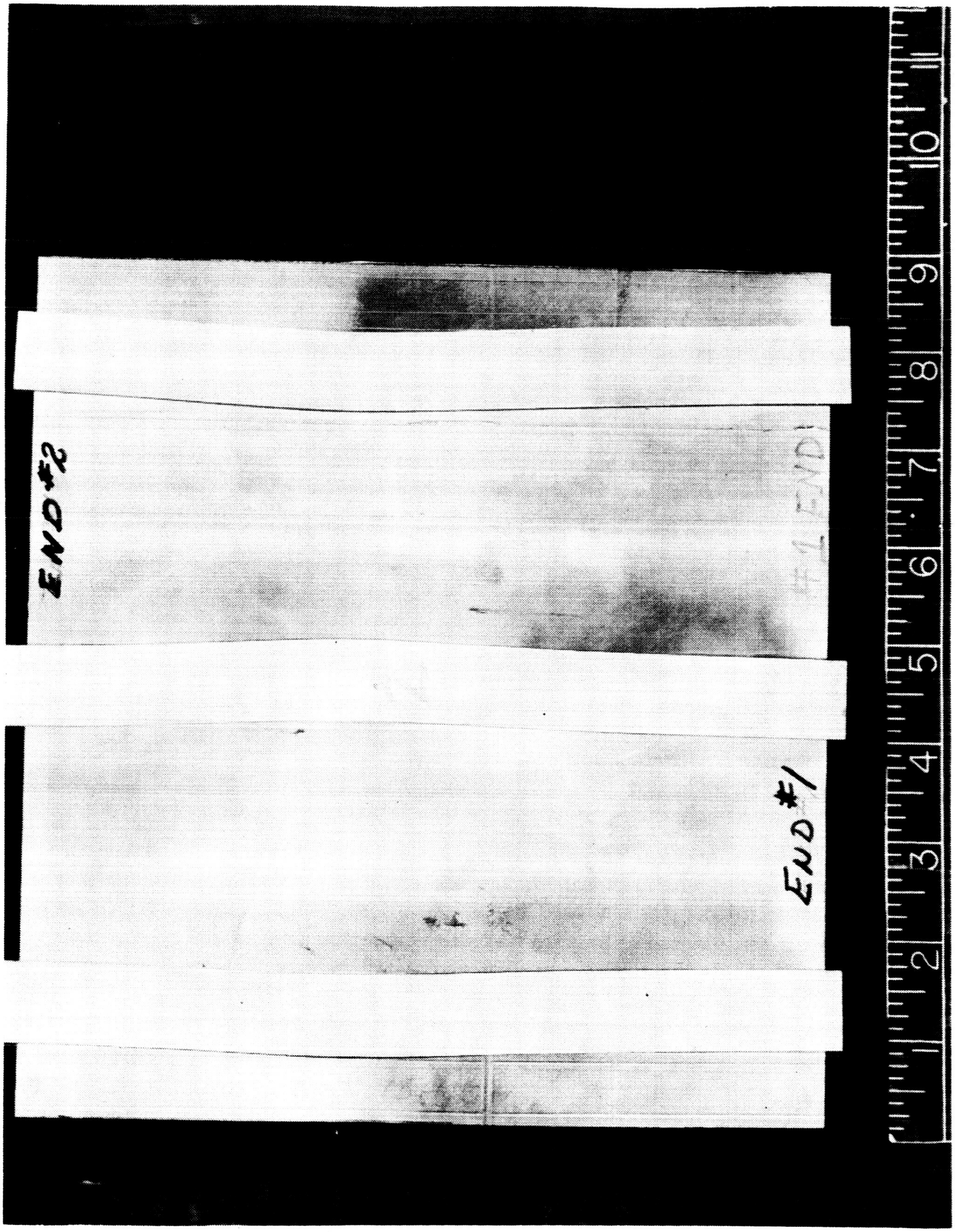


Figure 21. Specimen After Test, View E

$$\bar{t} = \frac{3\ t_s + .062\ (1.8) + .1\ (.812)}{3} = t_s + .0643$$

$$\sigma_1 \text{ (hoop stress)} = \frac{pr}{t_s} = \frac{54.3 \times 198}{t_s} = \frac{10,750}{t_s}$$

$$\sigma_2 \text{ (axial stress)} = \frac{Nc}{\bar{t}} = \frac{-8290}{.0643 + t_s}$$

$$\sigma_e = \sigma_1^2 - \sigma_1 \sigma_2 + \sigma_2^2$$

t_s	$\bar{t}$	σ_1 KSI	σ_2 KSI	σ_e KSI
.090	.1543	119.5	-53.7	153.5
.100	.1643	107.5	-50.4	139.8
.110	.1743	97.7	-47.6	128.2
.120	.1843	89.6	-45.0	118.7

$$\sigma_1 = \frac{65.5 \times 198}{t_s} = \frac{12,970}{t_s}$$

$$\sigma_2 = \frac{-7186}{\bar{t}}$$

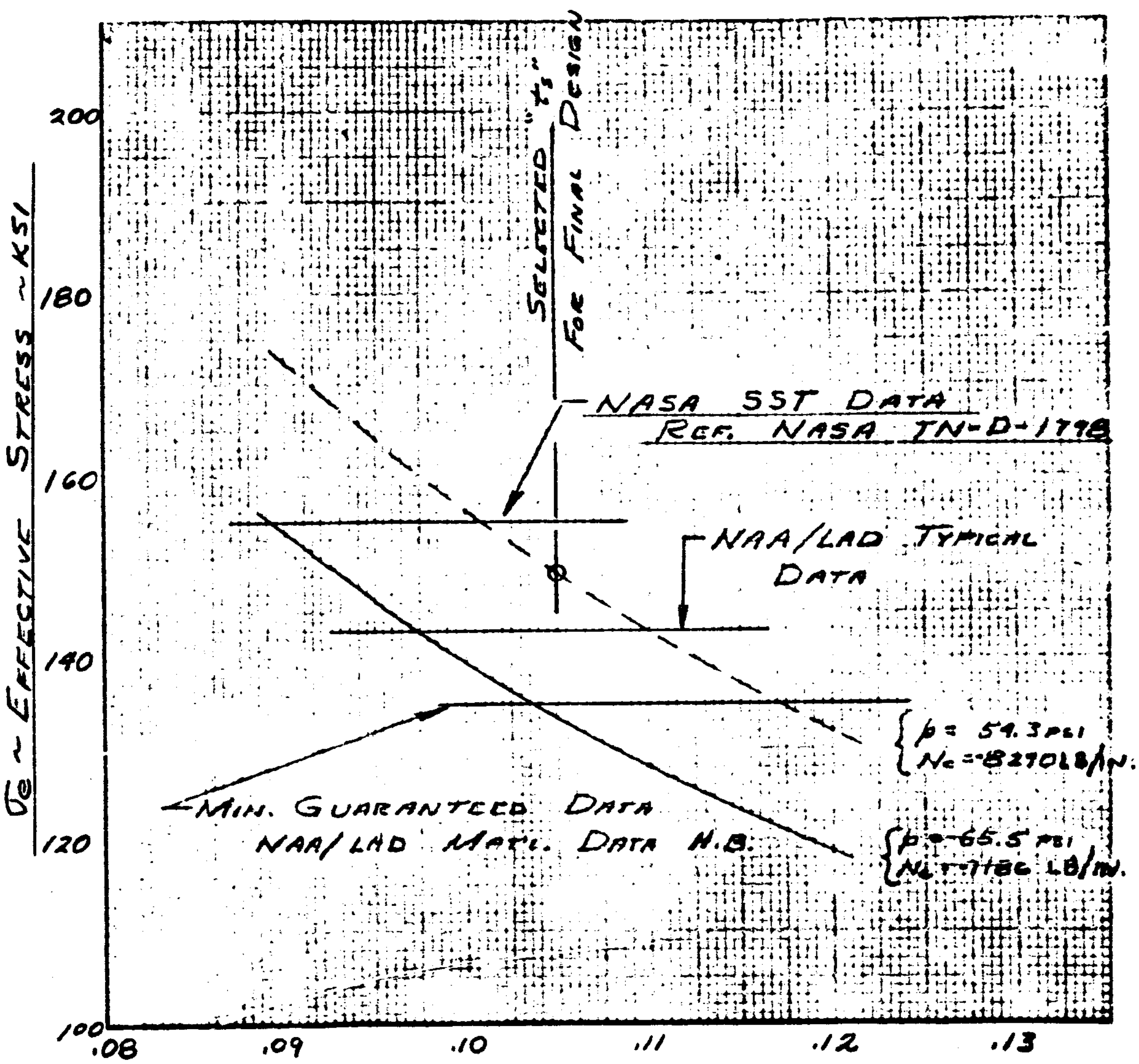
t_s	$\bar{t}$	σ_1 KSI	σ_2 KSI	σ_e KSI
.090	.1543	144.1	-46.6	172.3
.100	.1643	129.7	-43.8	156.2
.110	.1743	117.8	-41.2	143.0
.120	.1843	108.0	-39.0	132.0

These results are plotted on figure 22.

$$\sigma_e = \sigma_1^2 - \sigma_1\sigma_2 + \sigma_2^2$$

σ_1 = Hoop Stress

σ_2 = Axial Stress



Thickness in Inches

Figure 22. Titanium Skin Panel Sizing

Design Selection Procedure

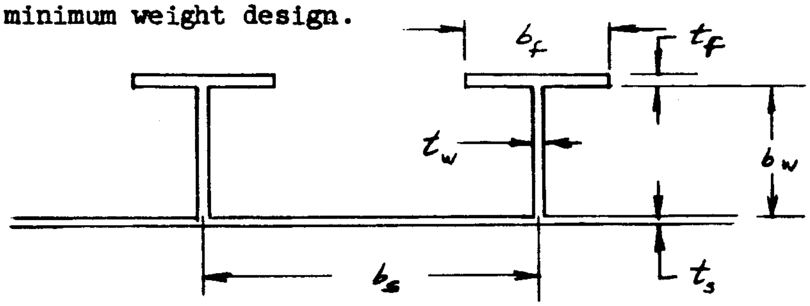
The procedure for selecting the final design is:

1. Use preliminary design results as a basepoint for subsequent selection.

2. Increase skin gage to accommodate axial + pressure loads.

3. Parametrically vary the panel dimensions about the basepoint selection, using the increased t_s.

4. Select minimum weight design.



The Preliminary Design Selection was:

Panel	t_s	t_w	t_f	b_s	b_w	b_f	Weight
A	.101	.062	.100	3.0	1.8	.812	3.76 lb/ft^2

The Panels Investigated were:

Panel	t_s	t_w	t_f	b_s	b_w	b_f	Weight
I	.105	.060	.100	3.28	1.8	.900	3.76
II	.105	.060	.100	3.28	1.8	1.000	3.83
III	.105	.060	.100	3.28	1.8	1.200	3.97
IV	.105	.060	.100	3.38	1.8	.900	3.72
V	.105	.060	.100	3.38	1.8	1.000	3.78
VI	.105	.060	.100	3.38	1.8	1.200	3.92

Panel I was the final selection. Although slightly understrength, it had the best weight/strength ratio. This strength deficiency can be corrected with the following changes in dimensions.

t_f = .102 in.

b_f = 9 (.102) = .922 in.

Comparison of Panel Parameters:

Panel	$(b/t)_s$	$(b/t)_w$	$(b/t)_f$
A	31.2	30.0	9.0
I	29.7	29.0	8.1

STRUCTURAL ANALYSIS

The integral Tee-stiffened panel was redesigned to accommodate the biaxial stresses produced by pressure and axial loads. The final selection was described in the preceding section and is analyzed in this section. The analytical methods are the same as those used in the preceding design and analysis sections.

Local Instability

Coupled local buckling coeff. = 3.5

F_L = local buckling stress

$$= 3.5 \times 18 \times 10^6 \left(\frac{.105}{3.28}\right)^2 = 64{,}500 \text{ psi}$$

f_A = applied load stress = 63,700

$$\text{M.S.} = \frac{64.5}{63.7} = .01$$

Column Stability

F_e = Euler column allowable stress

$$= \frac{\pi^2 E}{(L/\rho)^2} = \frac{\pi^2 EI_o}{AL^2}$$

$$A = .105\ (3.28) + .06\ (1.8) + .102\ (.922) = .546 \text{ in.}^2$$

$$\Sigma AY = 1/2 \times .06\ (1.8)^2 + .102\ (.922)\ (1.8) = .266 \text{ in.}^3$$

$$I_o = .102\ (.922)\ (1.8)^2 + 1/3\ (.06)\ (1.8)^3 - \frac{.266^2}{.546} = .292 \text{ in.}^4$$

$$F_e = \frac{\pi^2 \times 18 \times 10^6 \times .292}{.546 \times 38.5^2} = 64{,}000 \text{ psi}$$

$$\text{M.S.} = \frac{64.0}{63.7} - 1 = 0.005$$

Crippling, Integral Tee

F_{CC} (Ti-6Al-4V annealed, $b/t = \frac{.45}{.1} = 4.5$) = 120 ksi

F_{CC} (Ti-6Al-4V annealed, $b/t = \frac{1.8}{.06} = 30$) = 83 ksi

Ti-6Al-4V annealed $\begin{cases} E = 15.8 \times 10^6 \text{ psi} \\ F_{cy} = 120 \text{ ksi} \end{cases}$

Ti-8Al-1Mo-1V $\begin{cases} E = 18.0 \times 10^6 \text{ psi} \\ F_{cy} = 135 \text{ ksi} \end{cases}$

F_{CC} (Ti-8Al-1Mo-1V duplex annealed; b/t = 4.5)

$$= \sqrt{\frac{18 \times 135}{15.8 \times 120}} \times 120 = 1.125 \times 120 = 135 \text{ ksi}$$

F_{CC} (Ti-8Al-1Mo-1V duplex annealed; b/t = 30)

$$= 1.125\ (83) = 93.3 \text{ ksi}$$

$$F_{CC} = \frac{135\ (.9 \times .1) + 93.3\ (.9 \times .06)}{(.9 \times .1) + (.9 \times .06)} = 119.5 \text{ ksi}$$

$f = 63{,}740$ psi

$$\text{M.S.} = \frac{119.5}{63.74} - 1 = .87$$

Internal Pressure

The following analysis is to check the selection of skin gauge for the final design.

$$\bar{t} = .105 + \frac{.06\ (1.8) + .102\ (.922)}{3.28} = .167 \text{ in.}$$

$$\sigma_1 \text{ (hoop stress)} = \frac{65.5\ (198)}{.105} = 129.8 \text{ ksi}$$

$$\sigma_2 \text{ (axial stress)} = \frac{-7186}{.167} = -43 \text{ ksi}$$

$$\sigma_e = \left[129.8^2 - 129.8\ (-43) + 43^2 \right]^{1/2} = 151 \text{ ksi}$$

F_{TU} (Ti-8Al-1Mo-1V at R.T.; Ref. NASA TN D-1798) = 155 ksi

$$\text{M.S.} = \frac{155}{151} - 1 = 2.5$$

Panel Weight

$$A = .546 \text{ in.}^2$$

$$\bar{t} = \frac{.546}{3.28} = .166 \text{ in.}$$

$$W_T = 144 \times .158 \times .166 = 3.79 \text{ lb/ft}^2$$

PRODUCTION PANEL SELECTION

Figure 23 is a diagram of the final production panel. The cross-sectional dimensions are shown on figure 24. The weight per square foot of panel is also included for comparison purposes. The titanium panel shows a significant weight saving over that of the aluminum panel. There is little difference between the two titanium panels, because of the difference in design conditions. The development panel design was restricted to dimensions that would accommodate standard mild steel filler bars. This restriction was not placed on the production panel.

The weight of the panel is presented on Table VII.

PRODUCTION PANEL DESIGN DRAWING

Figure 25 is the production drawing based on the final configuration selection. The final panel is comprised of a complete panel from one pack welded to a partial panel from a second pack welded together. The production drawing shows the completed panel which NAA/LAD will deliver to NASA.

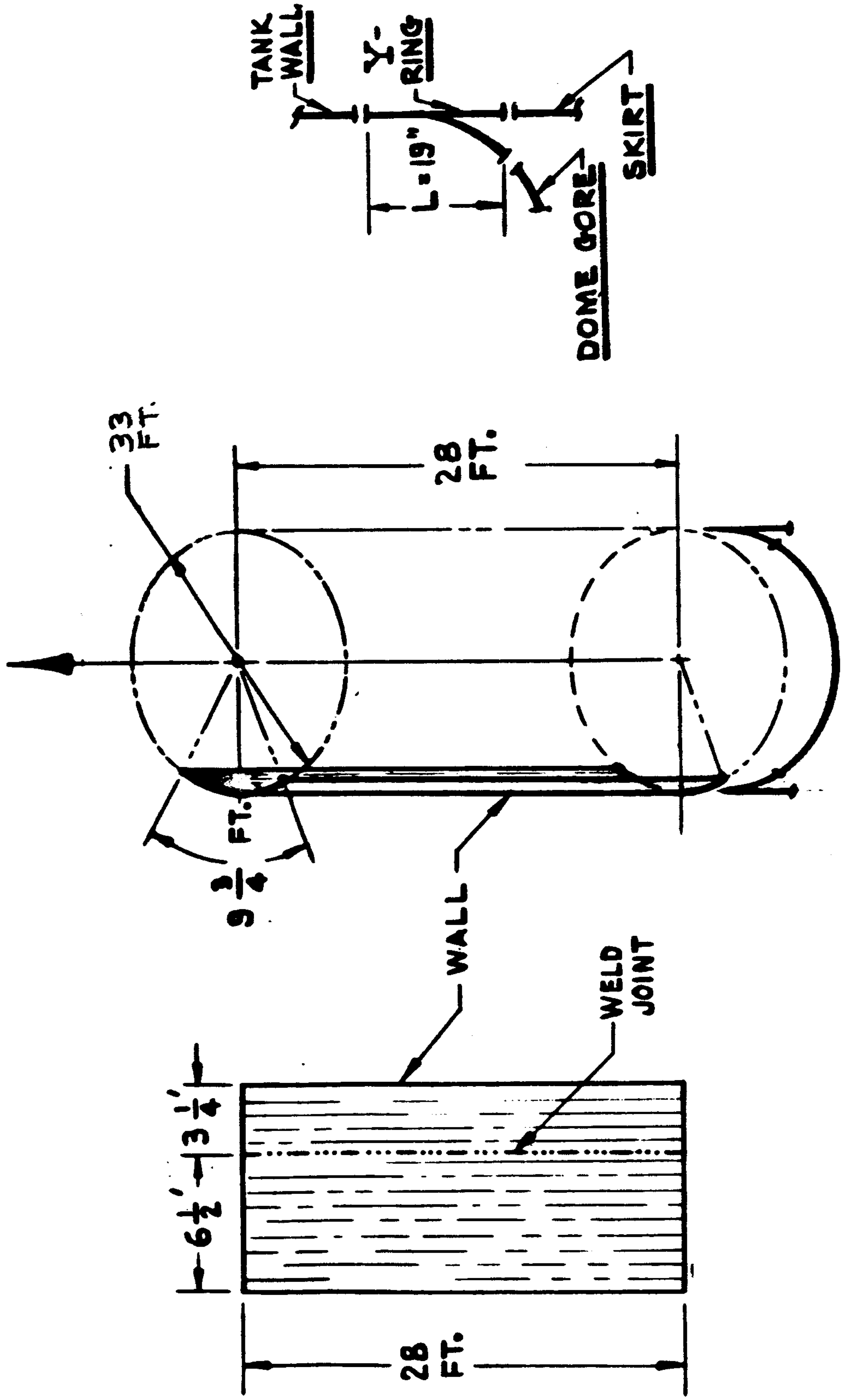
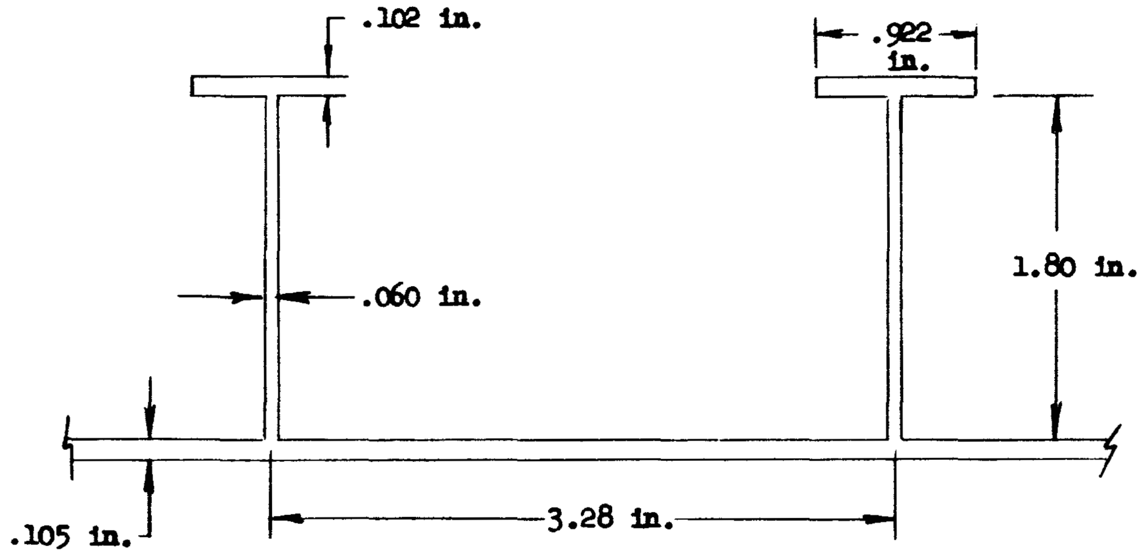


Figure 23. Final Production Panel



Material: Ti-8Al-1Mo-1V Duplex Annealed

Wt(Prod. Panel) = 3.79 lb/ft^2

Wt(Dev. Panel) = 3.78 lb/ft^2

Wt(Aluminum Panel = 4.21 lb/ft^2

Figure 24. Integral Tee-Configuration - Stiffeners Inside Cylinder

Table VII

S-IC SKIN PANEL WEIGHT

(a) Area = 9.75 (28) = 273 ft^2

(b) Wt/ft^2 = 3.79

Total Panel Weight = 273 (3.39) = 1035 lb

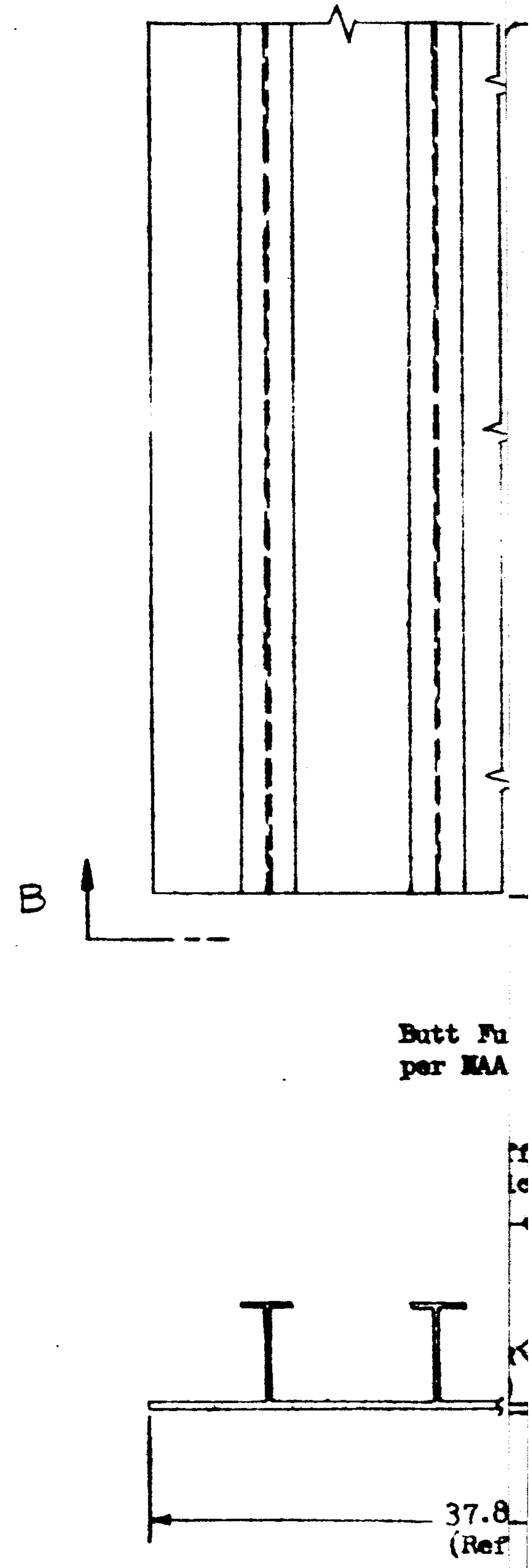
Total Shell Weight = C/9.75 (1035) = πd/9.75 (1035) =

Total Shell Weight = 103.5/9.75 (1035) = 11,000 lb

Y-Ring Weight (Tentative Selection)

$Weight_Y$ = 1485 lb

Total Weight:	Tank Wall	=	11,000 lb
	Y-Ring	=	1,485 lb
	Σ	=	12,485 lb


B
Butt Fu
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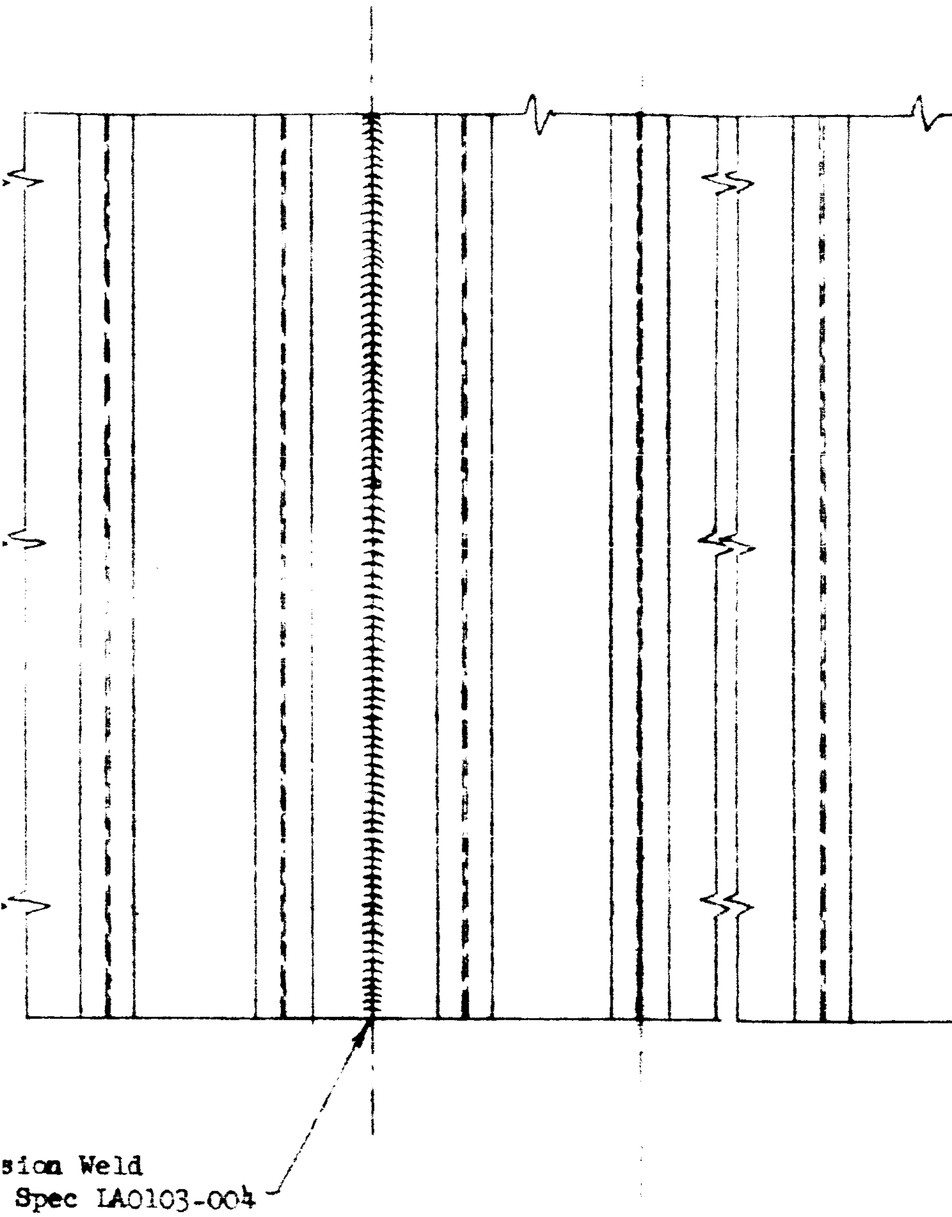
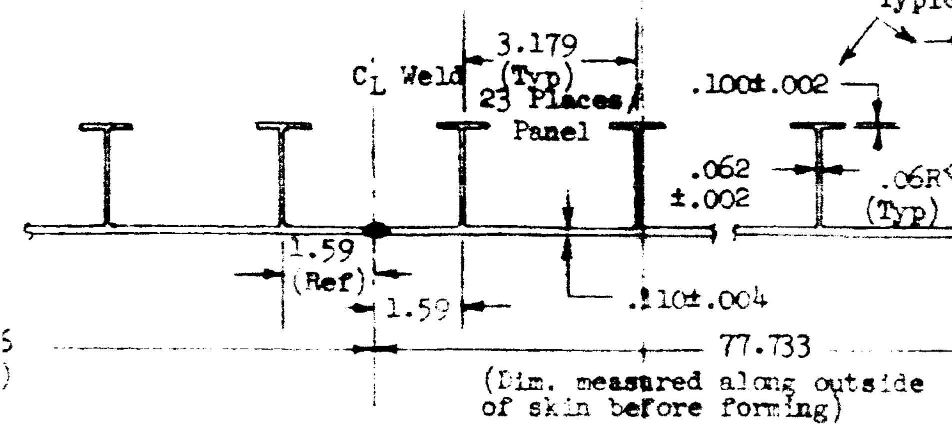
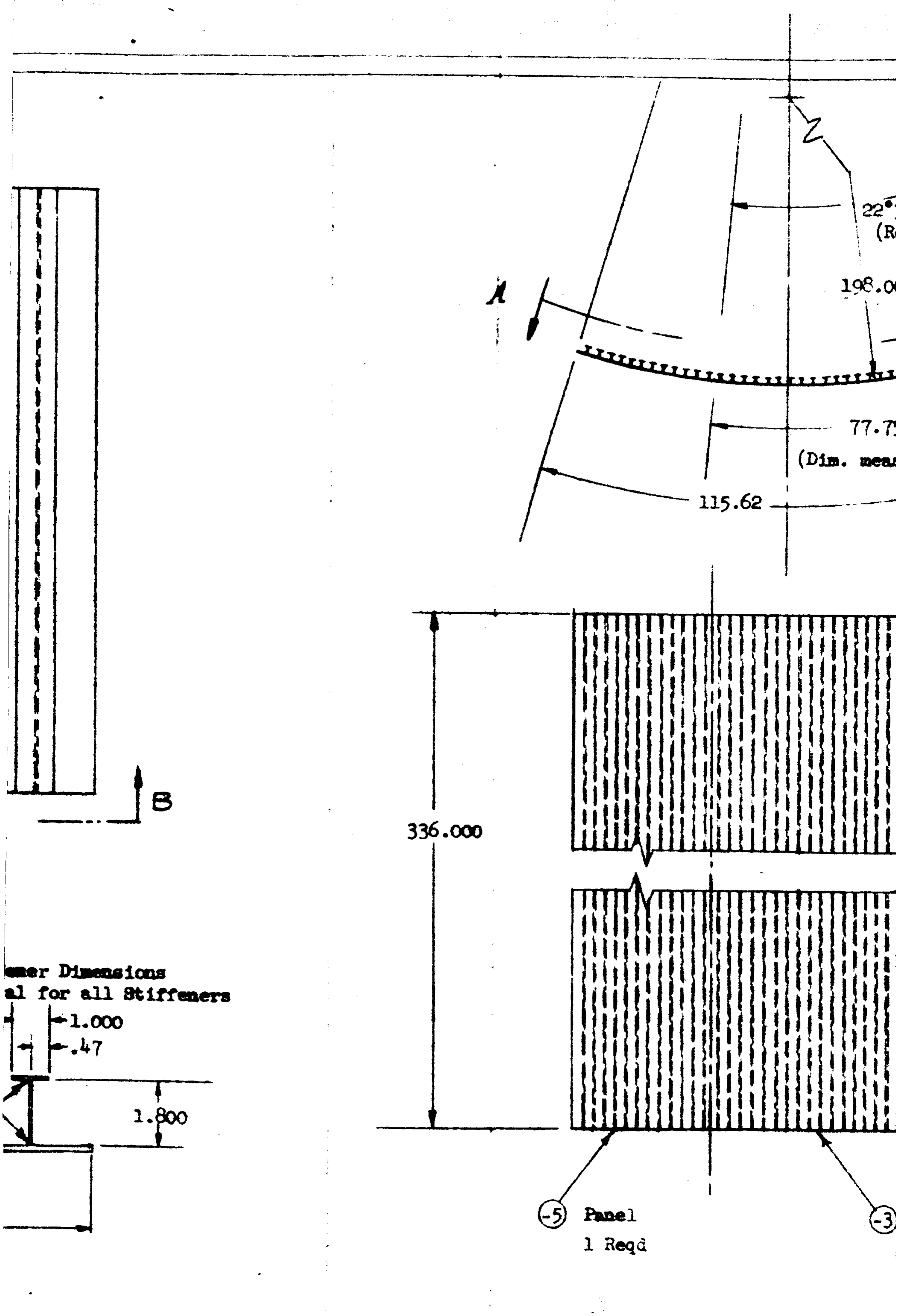


View A-A
Full Size (Flat Pattern Development)



View B-B - Full Size



22°
(R
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B
336.000
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1.000
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-5 Panel
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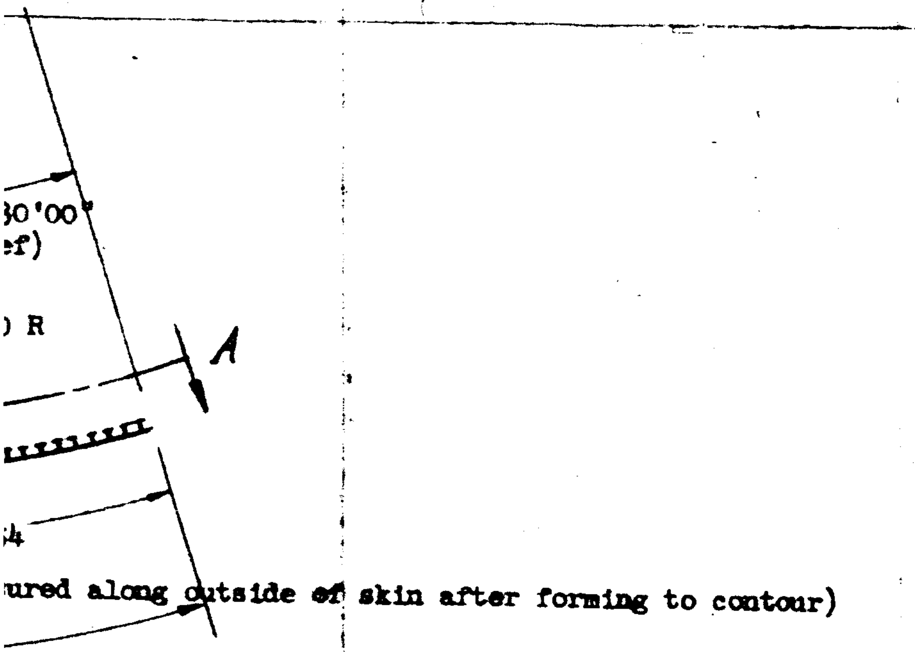
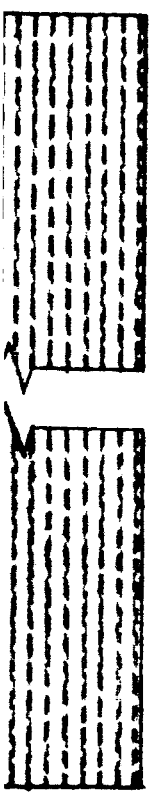
-3





MATERIALS: (-5) Make from 1/2 of -3 panel.

(-3) Make all elements from 8Al-1V-1Mo titanium alloy Cond A LB0170-177

NOTES: (Unless otherwise noted)

7. Diffusion bond per specification.
6. Heat treat -3 and -5 panels to Cond "DA" before welding per Specification LA0111-028.
5. Chem-Mill per Specification LA0103-003.
4. Machine per Specification LA0103-004.
3. Standard detail per Specification LA0102-012.
2. Inspect per Specification MIL-I-6870 (LQ0501-007).
1. Dimensions are in inches.
   Tolerance on decimals - 2 place (.XX) = ±.03
   3 place (.XXX) = ±.010
   Angles ±30'

Panel
1 Reqd

2624-202

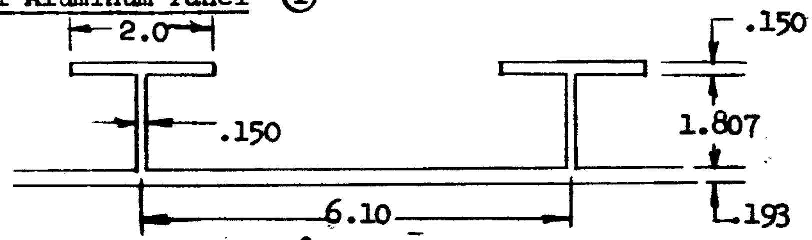
Figure [illegible] SKIN SECTION - Roll Diffusion Bonded Titanium S-IC Test Panel

DESIGN COMPARISON, TITANIUM VS ALUMINUM

The objective of this program is to show the weight advantages of titanium vs aluminum S-IC tank structure. To do this, the results of the NAA/LAD titanium design program were compared with an equivalent aluminum structure component. During this program, it became evident that the original tank was designed to different loads than were used in the NAA/LAD titanium program, as shown in the following analysis. Therefore, comparison of the original aluminum design and the NAA design would not be valid. To overcome this difficulty, an aluminum design was generated, using NAA/LAD design loads. The new aluminum panel was optimized by the same synthesis process described earlier in this report. The panel resulting from this process was then compared with the titanium panel selected for the production run.

ALUMINUM SKIN PANEL, ORIGINAL DESIGN

Original Aluminum Panel ①



L = frame spacing = 38.5 in.

R = 198 in.

$$\bar{t} = .193 + \frac{1.807\,(.15) + 2\,(.15)}{6.1} = .287 \text{ in.}$$

$$W_T = 144\rho\bar{t} = 144 \times .102 \times .287 = 4.21 \text{ lb/ft}^2$$

Internal Pressure

$P_{max} = 65.5$ psi

$$f = \frac{P_{max} \times R}{t_s} = \frac{65.5 \times 198}{.193} = 67{,}200 \text{ psi}$$

F_{TU} (2219-T87 Al. Al. at R.T.) = 62 ksi

$$M.S. = \frac{62}{67.2} - 1 = -.077$$

① Per NASA/MSFC Dwg 60B24322.

Local Instability

$F = 3.44\ E(t_s/b_s)^2 = 3.44 \times 10.5 \times 10\ (.193/6.10)^2 = 36{,}300$ psi

This gives the lowest allowable.

$(b/t)_s = 37.5$, $(b/t)_w = 12$, and $(b/t) = 6.7$

$f = \frac{Nc}{\bar{t}} = \frac{10{,}540}{.287} = 36{,}800$ psi M.S. $= \frac{36.3}{36.8} - 1 = -1.3$

General Stability

$\Sigma A_y = \frac{.150}{2}(1.807)^2 + .150(2.0)(1.807) = .786$ in.^{3}

$\Sigma I_{xx} = .15(2.0)(1.807)^2 + 1/3(.150)(1.803)^3 = 1.273$ in.^{4}

$\Sigma A = b_s \times \bar{t} = 6.10 \times .287 = 1.749$ in.^{2}

$I_o = 1.273 - \frac{.786^2}{1.749} = .921$ in.^{4}

$\rho = \left[\frac{.921}{1.749}\right]^2 = .725$ in.

$F_{cr} = \frac{\pi^2 E}{(L/\rho)^2} = \frac{\pi^2 \times 10.5 \times 10^6}{(38.5/.725)^2} = 36{,}700$ psi M.S. $= \frac{36.7}{36.8} = 0.0$

Crippling Integral Tee

$F_{cc}\left(\text{2024-T4 Al Al; } b/t = \frac{.792}{.122} = 6.5\right) = 40$ ksi

$F_{cc}\left(\text{2024-T4 Al Al; } b/t = \frac{2.5}{.076} = 33\right) = 27.5$ ksi

2024-T4 Al Al $\{F_{cy} = 40$ ksi

2219-T87 Al Al $\{F_{cy} = 50$ ksi

$F_{cc}(\text{2219-T87 Al Al } b/t = 6.5) = \sqrt{\frac{50}{40}} \times 40 = 1.117(40) = 44.7$ ksi

$F_{cc}(\text{2219-T87 Al Al } b/t = 33) = 1.117(27.5) = 30.7$ ksi

$$F_{cc} = \frac{44.7(1.585 \times .122) + 30.7(2.5 \times .076)}{(1.585 \times .122) + (2.5 \times .076)} = 37.8 \text{ ksi}$$

$f = 36{,}800$ psi $\qquad$ $M.S. = \frac{37.8}{36.8} - 1 = .03$

The panel is understrength, per loads on Table I, particularly with respect to pressure.

DESIGN FOR NAA/LAD LOADS

It has been shown that the original panel was designed to different loads. Comparing NAA/LAD's and the original design would not, therefore, be a valid comparison. To correct this, an aluminum panel was designed using the same approach used for the titanium design. This aluminum design is given on the following pages.

<u>Skin Sizing</u>

$$f = \frac{pR}{t_s} = \frac{65.5 \times 198}{t_s}$$

F_{tu}(2219-T87 Al Al at R.T.) = 62 ksi

$$t_s = \frac{65.5 \times 198}{62{,}000} = .209 \text{ in.}$$

This thickness is for pressure only. This thickness will increase for the combined pressure plus axial load conditions. For the combined conditions, the thickness is evaluated from the Von Mises-Hencky maximum distortion energy theory.

$$\sigma_1^2 - 2\sigma_1\sigma_2 + \sigma_2^2 = \sigma_e \leq F_{tu}$$

The skin will be sized for two biaxial load conditions. Both conditions occur for a rebound-type loading shown in Table I for Missile Station 362.

Cond. I $N_c = -8290$ lb/in., $p = 54.3$ psi (ult)

Cond. II $N_c = -7187$ lb/in., $p = 65.5$ psi (ult)

$$\sigma_1 \text{(Hoop Stress)} = \frac{54.3(198)}{t_s} = \frac{10{,}750}{t_s}$$

"$\bar{t}$" is calculated using the stiffness from the original design.

$$\bar{t} = t_s + \frac{.15(1.657 + 2.0)}{6.1} = t_s + .090$$

σ_2(Axial Stresses) $= \dfrac{-8290}{t_s + .090}$

F_{tu}(2219-T87 Al Al at R.T., 90% Probability Value) = 65.4 ksi

$$\left[\left(\frac{10,750}{t_s}\right)^2 - \left(\frac{10,750}{t_s}\right)\left(\frac{-8290}{t_s + .090}\right) + \left(\frac{-8290}{t_s + .090}\right)^2\right]^{1/2} = 65,400$$

t_s = .224 in.

The second condition is:

$$\sigma_1 = \frac{65.5(198)}{t_s} = \frac{12,970}{t_s}$$

$$\sigma_2 = \frac{-7186}{t_s + .09}$$

$$\left[\left(\frac{12,970}{t_s}\right)^2 - \left(\frac{12,970}{t_s}\right)\left(\frac{-7186}{t_s + .09}\right) + \left(\frac{-7186}{t_s + .09}\right)^2\right]^{1/2} = 65,400$$

The final skin thickness is t_s = .248 inches.

Summarizing the results,

t_s(Pressure Only, p = 65.5 psi) = .209 in.

t_s(p = 54.3 psi; N_c = -8290 lb/in.) = .224 in.

t_s(p = 65.5 psi; N_c = -7186 lb/in.) = .248 in.

Parametric Weight/Strength Study

The detailed dimensions of an integral tee-stiffened panel can be reduced to four parameters

$$\eta = f(t_s,\ b_s/t_s,\ b_w,\ t_f/t_m)$$

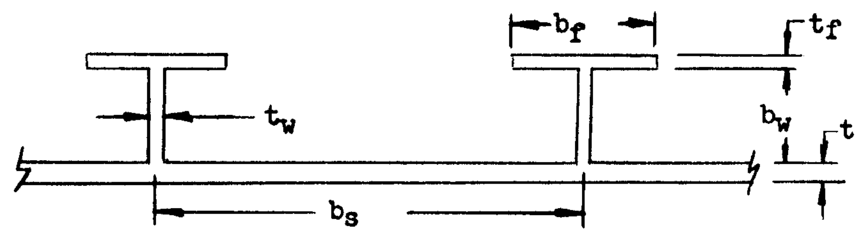
The skin thickness (t_s) can be sized initially to satisfy pressure plus axial loads. The remainder of the element dimensions can be obtained by considering parameters.

Table VIII lists the assumed parameters and the resulting allowable stresses and panel weights.

NOTE: Skin thickness is set by tank pressure plus axial load.

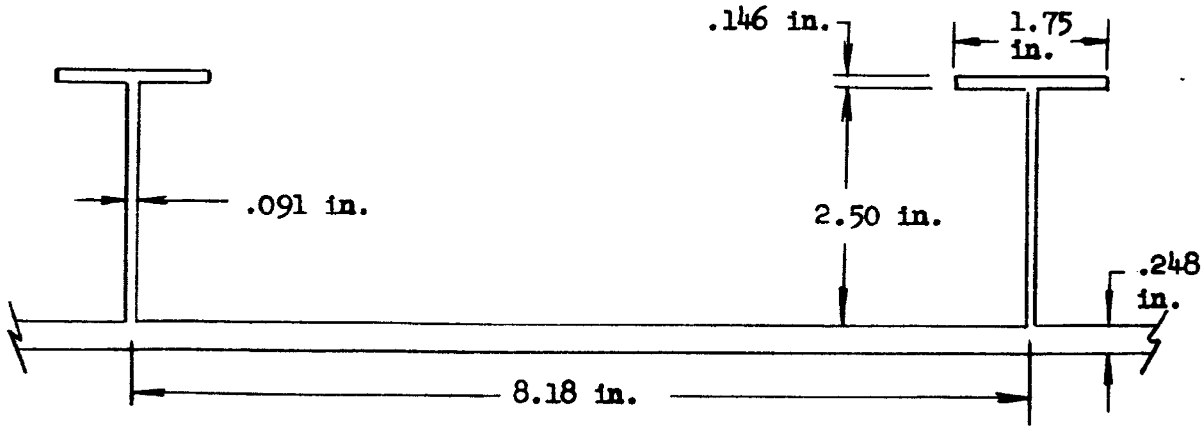
Table VIII

RESULTS OF PARAMETRIC WEIGHT/STRENGTH STUDY



No.	$(b/t)_s$	(t_f/t_w)	t_w in.	t_f in.	b_s in.	b_w in.	b_f in.	Wt in.	Stress Applied ksi	Stress Allowable ksi
1	27	1.6	.067	.107	6.70	1.5	1.07	4.11	37.6	14.5
2			.089	.143		2.0	1.43	4.48	34.5	31.9
3			.111	.162		2.5	1.62	4.83	32.1	52.0
4	30	1.6	.060	.090	7.44	1.5	.99	4.00	38.7	12.5
5			.080	.128		2.0	1.41	4.31	35.9	27.9
6			.100	.160		2.5	1.76	4.69	33.0	42.2
7	33	1.6	.055	.088	8.18	1.5	1.06	3.96	39.1	12.1
8			.073	.117		2.0	1.41	4.20	36.8	25.0
9			.091	.146		2.5	1.75	4.51	34.3	34.9
10	30	1.3	.060	.078	7.44	1.5	.86	3.95	39.2	11.3
11			.080	.104		2.0	1.15	4.19	36.9	22.9
12			.100	.130		2.5	1.43	4.50	34.4	42.2
13	30	1.0	.060	.060	7.44	1.5	.66	3.90	39.7	9.9
14			.080	.080		2.0	.88	4.10	37.8	18.4
15			.100	.100		2.5	1.10	4.35	35.6	35.0

The parameters listed in the preceding table were selected so that the weight results could be cross-plotted to arrive at a geometry which would give the lowest weight. Plotting was not necessary, however, since Panel No. 9 proved to have the desired results. Panel No. 9 is shown in the following figure.



ANALYSIS OF NAA/LAD DESIGN

The following analysis will verify or modify the aluminum design from the preceding section to meet the strength requirements of Panel 9.

Internal Pressure

In Panel 9, t_s = .248 in. was inadequate, because of the reduction in stiffener cross-sectional area with respect to the original design. Assume t_s = .255 inch.

$$\sigma_1 = \frac{pR}{t_s} = \frac{65.5(198)}{.255} = 50{,}800 \text{ psi}$$

$$\bar{t} = .255 + \frac{.091(2.5) + .146(1.75)}{8.18} = .314 \text{ in.}$$

$$\sigma_2 = \frac{-7186}{.314} = -22{,}900 \text{ psi}$$

$$\sigma_e = [50.8^2 - 50.8(-22.9) + 22.9^2]^{1/2} = 65.4 \text{ ksi}$$

F_{tu}(2219-T87 Al alloy at R.T.; 90% Probability Value) = 65.5 ksi

$$\text{M.S.} = \frac{65.5}{65.4} - 1 = 0.0$$

Stability Check

The following results are from the NAA "Shell Stability" computer program.

S_A(Applied Load Stress) = 32.3 ksi

S_L(Local Stability Allowables) = 33.2 ksi

S_C(Wide Column Stability Allowable, Curvature Effects Included) = 35.1 ksi

$$M.S. = \frac{33.2}{32.3} - 1 = 0.03$$

COMPARISON - TITANIUM VERSUS ALUMINUM DESIGN

The following comparison is between an aluminum and titanium integral tee-stiffened panel. The two panels have been sized by the same design method and for NAA/LAD loads. A comparison based on the original design would not have been valid because of the difference in design loads.

Panel Weights

Aluminum Design

$\bar{t}$ = .314 in.

$W_T = 144\rho\bar{t} = 144 \times .102 \times .314 = 4.61$ lb/ft^2

Titanium Design

$\bar{t}$ = .166 in.

$W_T = 144 \times .158 \times .166 = 3.8$ lb/ft^2

$$\text{Percent Difference} = \frac{4.6}{3.8} - 1 = 21.0\%$$

Section III

PROCESS DEVELOPMENT

DEVELOPMENT PACKS

TENSILE PROPERTIES

Three test specimens (Bars A, B, and C in figure 27) were tensile tested in accordance with Federal Test Method Standard 151. Specimens A and B showed good strength, but low elongation. The specimen material (hot-rolled plate from U. S. Steel) was known to contain an oxygen enriched surface which was not completely removed during fabrication of the details, because of dimensional tolerances. Therefore, in the original testing, the oxygen enriched surface was removed; to establish a correlation, the surfaces of Bar C were also machined (approximately 0.011 inch per surface). The resultant elongation was satisfactory (13 percent). The data are shown in Table IX.

BOND ADHESION

Eleven bond adhesion specimens (figure 27) were machined to the configuration shown in figure 26.

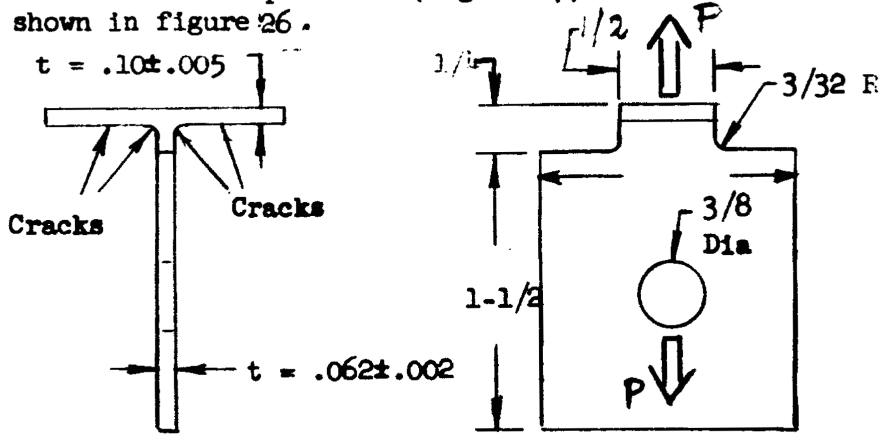


Figure 26. Bond Adhesion Test Specimens

All of the specimens had cracks on the surfaces and radii (figure 26). The specimens were hand filed and pickled in an attempt to remove the cracks.

When tested, the specimens all failed through the upper cap strip or face sheet, as shown in figure 28. All failures were found to have initiated in surface cracks. Testing resulted in the following stresses being applied to the bonded intersections, with no failures occurring in the intersections:

Resultant Stress, ksi: 51.3, 59.4, 59.5, 66.9, 72.9, 104.2, 105.0, 113.8, 118.1, 122.1, and 134.1.

These data indicate that the titanium details were metallurgically bonded and, when crack-free parts are available, the testing method should adequately test the strength of the bonds.

TABLE IX

TENSILE CORRELATION, PANEL FACE SHEET (INTERNAL STIFFENERS)

	BAR	YIELD (KSI)	ULTIMATE (KSI)	ELONGATION (% IN 2 INCHES)
Raw Material Prior to Rolling		133.6	149.1	15.0
Face Sheet of Finish Part	A	140.5	154.1	8.5
	B	138.1	151.4	9.0
	C	142.2 (1)	155.4	13.0
Required (2)		125.0	135.0	10.0

NOTES:

(1) Approximately 0.011 inch machined from each surface.
(2) Per Table II.

MICROSTRUCTURE

Specimens for metallographic examination were taken at 16 locations in the part, most of which are identified in figure 27, e.g., 2-A, 3-A, 5-A, 9-A, etc. Eleven of the samples were taken from intersections adjacent to bond adherence specimens, and the rest from areas containing cracks.

The structure of the bonds at the 11 cross-sections showed complete bonding, with no voids or unusual alloy segregation. Figures 29 and 30 show some typical structures. Examples of the surface cracks are shown in figure 29.

DISCUSSION

The major metallurgical problem concerning packs with internal stiffeners is that of cracking. The more severe cracking can be attributed to the thermal shock treatment and, therefore, can be prevented. The cause of the smaller surface cracks is not completely known, but it can be assumed to be the result of a combination of factors. The surfaces in question would contain the greatest amount of embrittling contamination due to their direct contact with the iron filler bars and the pressures exerted by rolling. The pack was water quenched from 1420°F at the rolling mill and subjected to

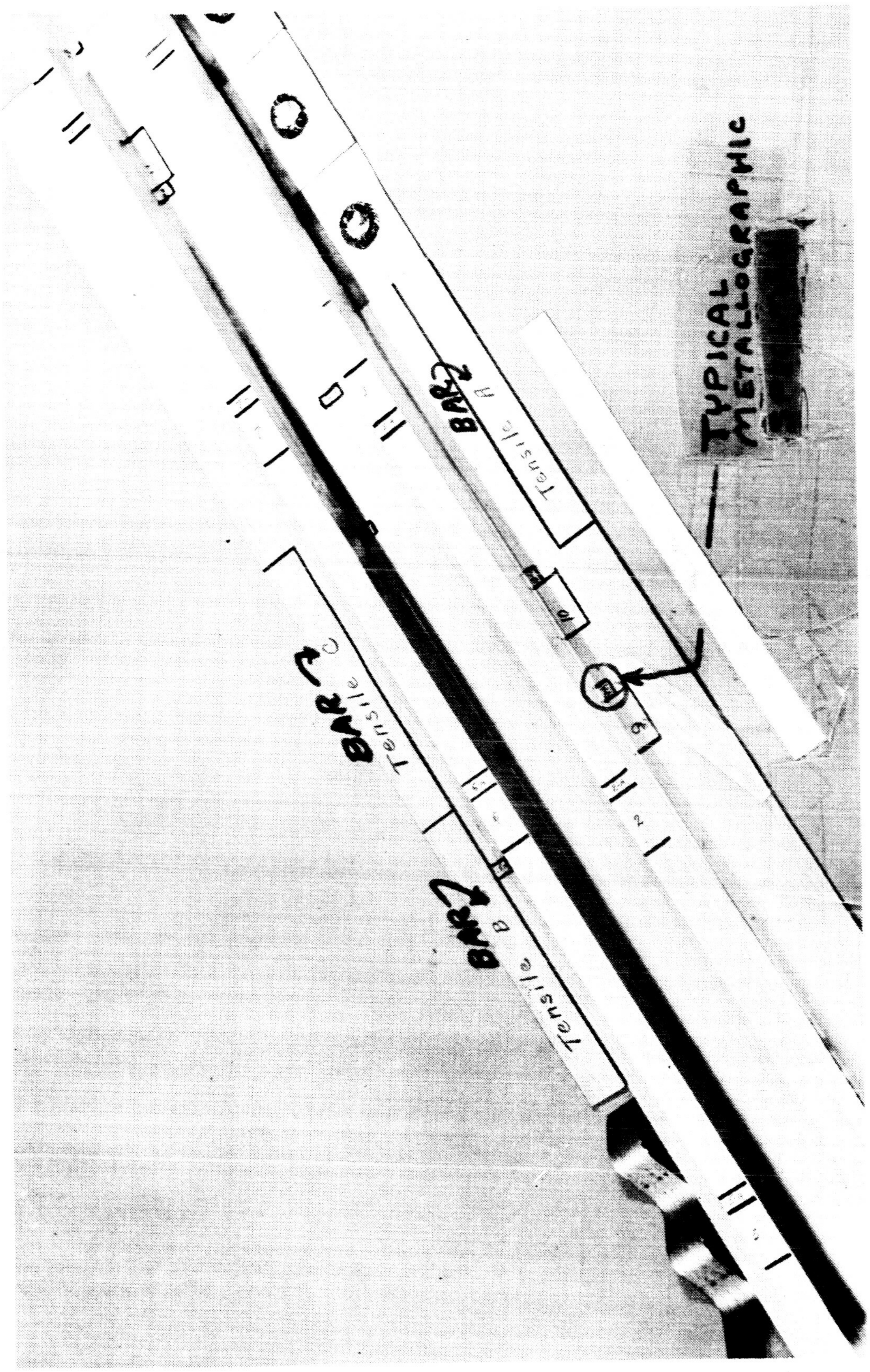


Figure 27. Tensile Test Specimens

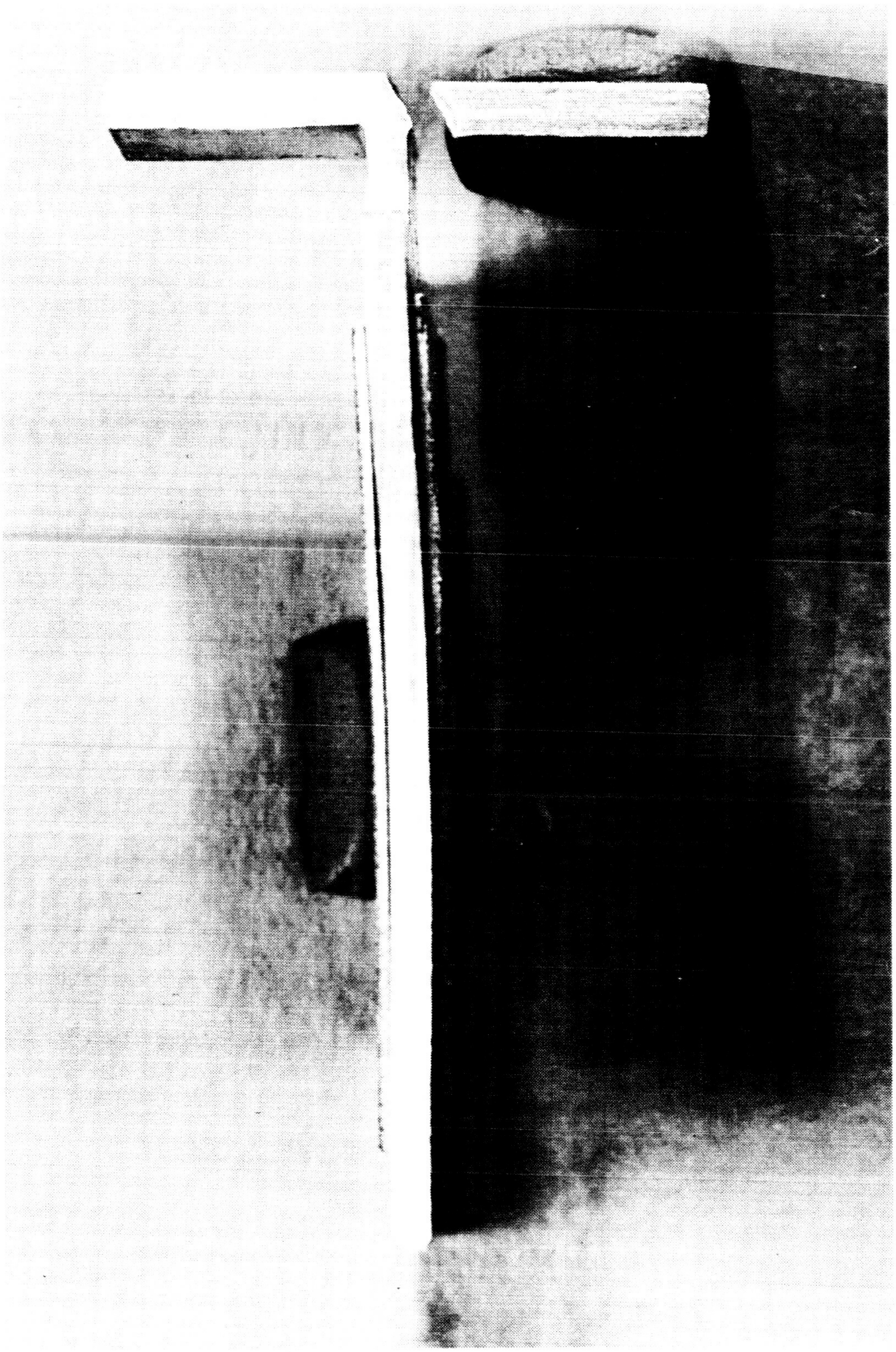
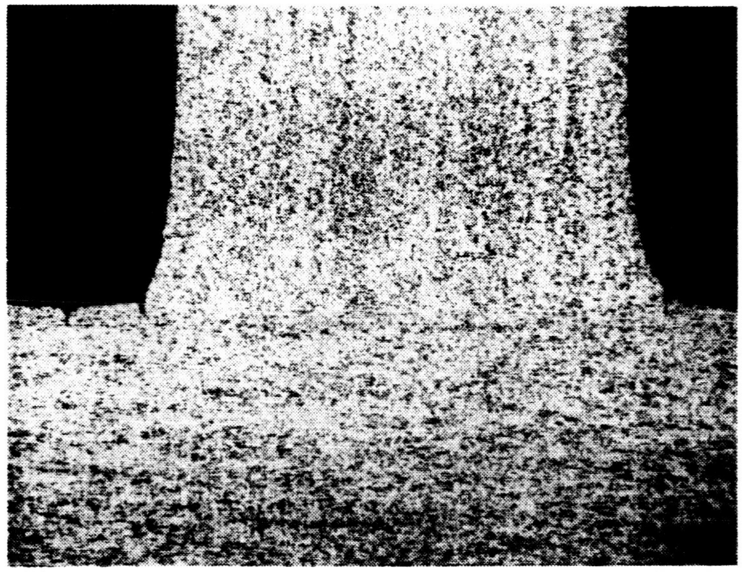
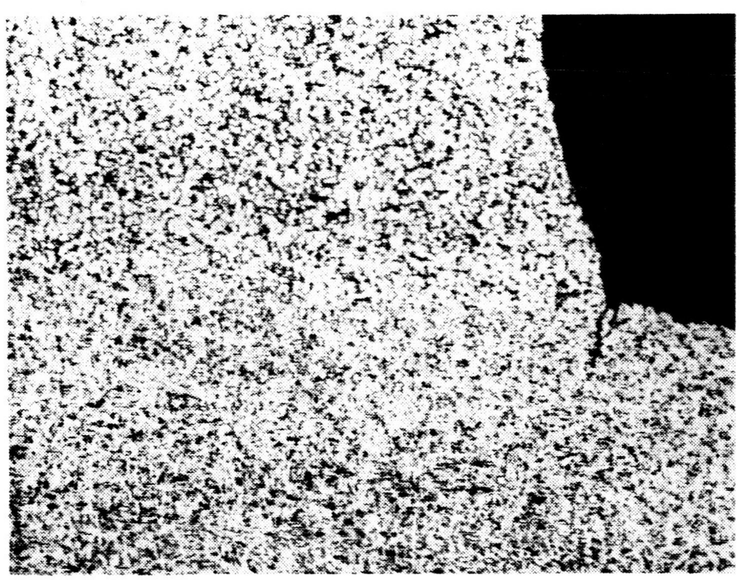


Figure 28. Failed Specimen

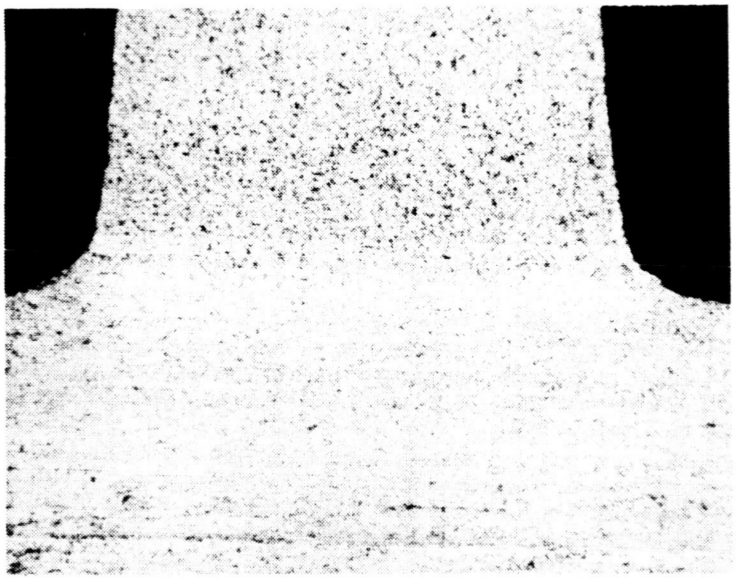


a. 50X

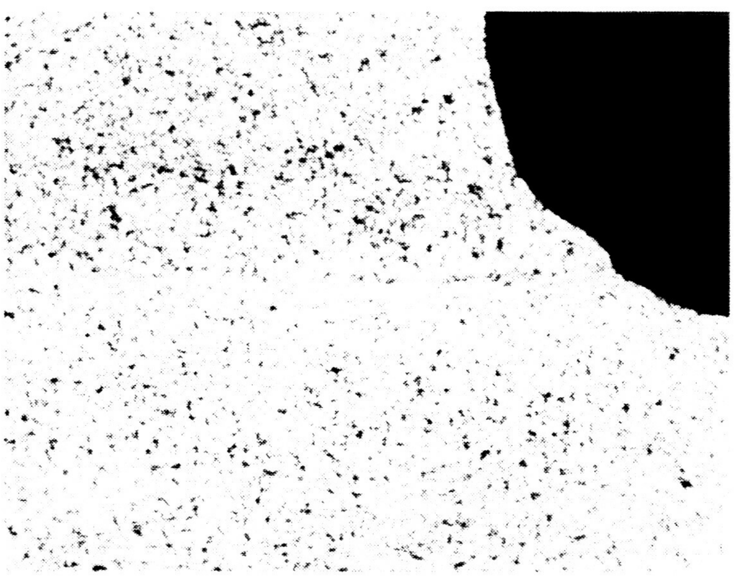


b. 175X

Figure 29. Microstructure of Face Sheet to Web Joint at Location 11-A of Panel



a. 50X



b. 175X

Figure 30. Microstructure of Cap Strip to Web Joint at Location 5-A of Panel

severe thermal shock treatments at NAA. All of these processes would tend to build up residual stresses in the material sufficient to cause micro cracks in the brittle surface layer. In addition, subsequent pickling of the part caused the cracks to grow and may have initiated new cracks by a stress corrosion process.

Another metallurgical problem is that of interstitial pick-up during fabrication. In order to assure a nonembrittled part, the amount of pick-up must be better controlled, or tighter restrictions must be placed on the chemical content of the original material.

Results of mechanical testing revealed that there was some contamination on the surface of the skin. The results of the bend tests showed the contamination was insufficient to cause cracking; however, tensile tests showed contamination was enough to produce a reduction in ductility. This agrees with the known fact that titanium can absorb a limited amount of interstitials which will tend to reduce ductility, but not necessarily render the material completely brittle.

PROCESS SPECIFICATION

A preliminary process specification has been prepared for roll diffusion bonding of titanium alloys and is included as Appendix A.

PRODUCTION PACKS

The technical effort for the production packs has been completed, with the release of the production panel design drawing, No. 2624-202. The analysis phase has also been completed. Some minor dimensional changes were incorporated in the final selected configuration for the production panel. They were based on additional optimization analyses performed after the sizing operation had been concluded for the development packs. A small weight saving and a simpler design resulted from these changes.

Technical benefits expected to result from the large-scale manufacturing operation of the production panel include:

1. Demonstration of the feasibility of fabricating large-scale specimens akin to those used in production of usable hardware.

2. A worthwhile demonstration of welding together large parts will be possible.

3. From a structural standpoint, this operation will provide a full-scale basepoint panel for use in comparisons, trade-offs, and future selection studies.

4. Demonstration of accuracy of tolerances, flatness of large parts, and dimensional stability that can be realized with this method.

5. Major problems if present, will reveal themselves more readily in large-scale operations than in subscale models.

6. The ability to test a full-scale specimen under highly realistic testing conditions.

Section IV

CONCLUSIONS

The results achieved in the S-IC skin section program indicate that:

1. The roll diffusion bonding process is highly satisfactory, in its application to titanium alloys and configuration shapes of the type covered in this effort.

2. Parent or near-parent material strength is achievable at all diffusion bonded joints, without impairment to other properties of the material at or near the bond areas. This conclusion is based on the fact that no changes have been observed of the types common to, e.g., welded joints, such as grain growth, embrittlement, and residual stresses.

3. This process provides flexibility in the sizing, shaping, and detail configuration that can be selected and made to fit a wide range of applications. This, in turn, provides a highly desirable potential, because other competitive processes are usually restricted by many limitations.

4. A preliminary cost comparison indicated a potential cost saving attributable to the roll-bonded panel versus a comparable design machined from plate stock. However, since the study was cursory in nature, further study is necessary to verify and expand these conclusions.

Section V

RECOMMENDATIONS

On the basis of the five months of research and development effort of Phase I of this program, the following recommendations are made for the continued research effort of the S-IC skin section program:

1. Utilize internal tee-stringers, in preference to external tee-stringers.

2. Utilize the roll diffusion bonding process with 60 percent rolling reduction, in preference to fabrication by machining or extruding the skin/stringer panel.

3. Verify the roll diffusion bonding process for a full size panel, by fabrication of two panels approximately 7 by 30 feet.

REFERENCES

1. Crawford, R. F., and Burns, A. B., "Minimum Weight Potentials and Design Information for Stiffened Plates and Shells", Launch Vehicles; Structures and Materials Conference, Phoenix, Arizona, 3-5 April 1962.

2. DeLuzio, A. J., "Influence of the Stiffener Eccentricity and End Moment on The Stability of Cylinders in Compression", AIAA 6th Structures and Materials Conference, April 1965, pp. 117-123.

3. NASA TN D-1798, Progress Report of The NASA Special Committee on Materials Research for Supersonic Transports, by Richard H. Raring - NASA and J. W. Freeman, J. W. Schultz, and H. R. Voorhees - University of Michigan.

APPENDIX A

PRELIMINARY PROCESS SPECIFICATION FOR ROLL DIFFUSION BONDING OF TITANIUM ALLOYS

PREPARED BY	CODE IDENT. NO. 43999	NUMBER NA-65-1004 Appendix A
C. H. Hall	NORTH AMERICAN AVIATION, INC.	TYPE
APPROVALS	LOS ANGELES DIVISION	DATE 11-30-65
	INTERNATIONAL AIRPORT	SUPERSEDES SPEC. DATED:
	LOS ANGELES 9, CALIFORNIA	REV. LTR.
	SPECIFICATION	PAGE 1 of

TITLE

ROLL DIFFUSION BONDING OF TITANIUM ALLOYS

TABLE OF CONTENTS

1. SCOPE

1.1 This specification establishes the materials and procedures for roll diffusion bonding of Titanium-6Al-4V and Titanium-8Al-1Mo-1V alloy structures. These structures are fabricated by laying up a pack of titanium elements with iron tooling and hot rolling this pack through a rolling mill to obtain the desired titanium joints and configurations. Configurations which may be rolled include truss-core, tee stiffened, and rib stiffened structures.

1.2 When the requirements of this specification differ from those of the governing drawing(s), the requirements of the drawing(s) shall take precedence.

2. APPLICABLE DOCUMENTS

The latest issue of the following documents form a part of this specification to the extent specified. When the requirements of an applicable document differ from those of this specification, the requirements of this specification shall take precedence.

2.1 Material Specifications

LB0170-177	Titanium Alloy Sheet, Strip, and Plate (8Al-1Mo-1V)
LB0170-110	Titanium Alloy (6Al-4V) Bar, Billet and Forgings
LB0170-113	Titanium Alloy Sheet, Strip, and Plate (6Al-4V)
LB0170-185	Titanium Alloy (8Al-1Mo-1V) Bar, Billet, and Forgings
LB0170-147	Titanium Alloy (6Al-4V) Rods, Bars and Shapes, Extruded
LB0170-112	Titanium and Titanium Alloy Rods, Bars and Shapes: Tolerances
ASTM A-269	Steel Tubing, Corrosion and Heat Resistant, Welded and Drawn.
A6-61T	Steel for Bridges and Buildings (ASTM)
QQ-5-633 FS1018	Bar and Forging (MIL-S-7952)
QQ-S-741	Sheet, Plate 1020-1025
MIL-A-18455	Argon, Technical

2.2 Process Specification

LA0111-026	Heat Treatment of Titanium Alloys
LA0107-004	Fusion Welding
LA0111-028	Thermal Processing of 8Al-1Mo-1V Titanium Alloy Components for Saturn Cross Beam.
LA0102-003	Elevated Temperature Forming and Sizing of Titanium and Titanium Alloy Parts
LA0110-008	Cleaning Titanium and Titanium Alloys
LA0104-003	Marking of Parts and Assemblies
AA 0115-002	Dust, Humidity, and Temperature Controlled Environments.
LAD103-003	Chem-Mill Processing of Titanium Alloys

2.3 Quality Control Documents

LQ0402-003	Process Control of Fusion Welding
LQ	Quality Control Requirements for Roll Diffusion Bonded Titanium Structure

2.4 Test Methods

MA0115-116	Leak Detection - Aerospace Plumbing System Details

3. MATERIALS

3.1 Titanium Details

3.1.1 The 6Al-4V titanium alloy details to be used in the diffusion bonding process shall be in Condition A or in Condition STA, free from surface contamination, and conform to the applicable Titanium Alloy Material Specification requirements.

3.1.2 The 8Al-1Mo-1V titanium alloy details to be used in the diffusion bonding process shall be in Condition Mill Annealed or Condition Duplex Annealed, free from surface contamination, and conform to the applicable Titanium Alloy Material Specification requirements.

3.1.3 The 6Al-4V or 8Al-1Mo-1V titanium alloy details to be used in the diffusion bonding process may contain fusion weldments made according to the requirements of this specification.

3.2 Carbon Steel Details

3.2.1 Carbon steel details for the roll diffusion bonding process shall be in the fully killed condition, free from surface contamination, and conform to the applicable Steel Material Specification requirements.

3.2.2 Carbon steel details for the roll diffusion bonding process may contain fusion weldments made according to the requirements of this specification.

4. PACK CLEANING AND LAY-UP

4.1 Prefit

4.1.1 Prior to final cleaning for pack layup, all titanium and tooling details shall be measured and prefitted together to determine that the dimensional coordination of the pack is obtained as required by the governing drawing(s).

4.1.2 Prior to prefit all details shall be solvent wiped to remove surface contaminants. The use of chlorinated solvents to clean titanium or steel is prohibited.

4.1.3 No materials shall be included in the pack other than those conforming to the material specifications referred to in the governing drawing(s).

4.1.4 Hand fitting of pack details, such as cold straightening, sanding, and filing, are permissible in order to achieve the required dimensional fitup.

4.2 Cleaning

4.2.1 After prefit and prior to layup of the pack for bonding all titanium details and all tooling details, such as steel filler bars, cover plates, and yokes, shall be cleaned as specified below. Cleaning shall be conducted in such a manner that all details are free of any visible contaminants, such as oxides, dirt, oil, and grease.

4.2.2 After cleaning all details shall be handled only with clean white gloves.

4.2.3 All steel details shall be packaged as specified as quickly as possible after cleaning in order to prevent rusting.

4.2.4. Titanium Details

a. Acid descale per Table II of specification LA0110-008, followed by dionized water rinse and oven dry.
b. Cool and wrap in neutral kraft paper.

4.2.5 Steel Details

4.2.5.1 Cold Finished Steel: Clean by the following procedure:

a. Alkaline clean in Delchem 2368 at a concentration of 6-8 oz/gal. for 5-15 minutes - Temperature 180-200F.
b. Spray rinse until free rinsing.
c. Immersion rinse for 2-3 minutes.
d. Acid pickle in Oakite 33 at a concentration of 25 percent by volume for 2-3 minutes at room temperature.
e. Hot rinse at a temperature of 120-160F for 2-3 minutes.
f. Oven dry.
g. Cool, package in sealed polyethylene bags filled with nitrogen.

4.2.5.2 Steel With Machined or Ground Surfaces: Clean by the following procedure:

a. Solvent wipe with MEK or acetone.
b. Alkaline clean in Delchem 2368 at a concentration of 6-8 oz/gal. for 5-15 minutes temperature 180-200F.
c. Spray rinse until free rinsing.
d. Immersion rinse for 2-3 minutes.
e. Blow dry and then oven dry
f. Cool, package, and seal in polyethylene bags.

4.3 Handling and Storage

After cleaning, all detail parts and inner pack tooling shall be handled with clean white gloves. White gloves used must not leave any lint on the details. Cleaned titanium details shall be protected by dust-free neutral kraft paper wrappers. Cleaned steel details shall be protected by polyethylene bags. Details with any visible dust, rust or finger prints are to be re-cleaned. Panel details shall be assembled in dust-free rooms within 48 hrs after cleaning. Tooling details (filler bars etc) shall be laid up in dust-free rooms and purged within 48 hours after cleaning.

4.4 Layup

4.4.1 Pack lay-up shall be performed in a dust-free clean room complying with Class E requirements.of NAA Specification AA0115-002. All personnel engaged in the lay-up operation shall be required to wear clean white gloves when handling clean parts.

4.4.2 Only descaled and clean metallic tooling shall be used inside the pack containing the part. The use of graphite, refrasil, ceramics and other non-metallic materials which give off contaminants is prohibited.

4.4.3 During the layup operation, all detail parts and tooling shall be assembled to obtain the dimensional coordination specified by the governing pack assembly drawing(s).

4.4.4 Immediately following layup, the top cover sheet shall be positioned for fusion welding. Welding operations may be conducted outside the clean room area.

5. WELDING

5.1 Titanium Details

5.1.1 The welding of Titanium 6Al-4V alloy roll bonding pack details shall be performed in accordance with specification LA0107-004 and LQ0402-003 requirements.

5.1.2 The welding of Titanium 8Al-1Mo-1V alloy roll bonding pack details shall be performed in accordance with the requirements of sections 2, 3, and 4 of specification LA0111-028 and the requirements of specification LQ042-003.

5.2 Steel Details

5.2.1 The welding of pack steel cover plates and yokes shall be performed in accordance with the requirements of specifications LA0107-004 and LQ0402-003.

5.2.2 The welding of the cover plates to the yokes shall be conducted with the pack internal cavity shielded by commercially pure helium and/or welding grade argon (MIL-A-18455). The inert gas protection shall be continued until the parts have cooled to 600F maximum.'

5.3 All welds shall be free of visible cracks, porosity, and slag.

6. ATMOSPHERE REQUIREMENTS

6.1 Leak Check of Pack Weldments

6.1.1 The pack shall be helium leak checked using the procedures outlined in Specification MA0115-016.

6.1.2 When leakage is determined to be in excess of the requirements of para. 7.1.1 the leaks shall be located and repaired.

6.2 Purging

6.2.1 General Requirements

6.2.1.1 Purge lines shall be fabricated from type 321 stainless steel or as called out on the governing drawing(s). The purge line inside diameter shall be a minimum of .300 inches (.375 O.D. x .035 wall) and shall be kept as large as possible. Length of purge lines shall be kept to a minimum and a minimum number of fittings and valves shall be used.

6.2.1.2 Vacuum valves used for purging shall be high quality full flow valves. The use of needle valves is not permissible.

6.2.1.3 Any high quality vacuum diffusion pump may be used for purging.

6.2.1.4 The purge gas shall be pure argon (MIL-A-18455). Moisture content of the argon shall not exceed 8 parts per million as measured with an electrolytic hygrometer.

6.2.2 Purging After Pack Layup

6.2.2.1. A single purge cycle shall consist of evacuating the pack to 760 mm Hg and back filling with argon until a slight positive pressure exists within the pack.

6.2.2.2. Prior to hot purging all packs are required to be purged at room temperature a minimum of 5 cycles as specified in paragraph 6.2.2.1.

6.2.2.3 All packs shall be hot purged prior to shipping to the rolling mill.

6.2.2.4 Hot purging shall consist of continuously repeating the purge cycles as specified in paragraph 6.2.2.1 while the pack is heated to a temperature of 1600F ± 25F. The purge cycles shall be continuously repeated while the pack is held for one hour at temperature.

6.2.2.5 During cool down from hot purging a continuous vacuum shall be drawn on the pack.

6.2.2.6 After cool down to room temperature following hot purging, the part shall be back filled with argon to a positive pressure of not more than 25.4 mm Hg and the vacuum valve closed and capped prior to shipping.

6.2.2.7 Adequate provision shall be made to protect the purge tube and vacuum valve during shipment to the rolling mill.

6.3 Leak Checking and Purging at the Rolling Mill

6.3.1 When received at the rolling mill, the packs shall be leak checked as follows: The pack shall be connected to a suitable vacuum pump and evacuated to 760 mm Hg. After reaching this vacuum, the pump shall be shut off and the part must show no loss of vacuum in excess of 762 microns per hour at room temperature during 1 hour.

6.3.2 If leakage is found to be in excess of that specified, the leak must be located and repaired. In such case, the pack shall be repurged as specified by an authorized North American Representative and rechecked for leaks.

6.4 Seal Off

6.4.1 When the procedures outlined in para. 6.3 are completed, a vacuum of 760 mm Hg shall be drawn on the pack and the purge tube sealed. Sealing shall be accomplished by heating and forging the purge tube closed four to five inches from the pack. Forging shall be accomplished so that the pinched off section of the purge tube is hermetically sealed and is leak tight.

6.4.2 The excess of the purge tube shall be removed prior to rolling.

7. ROLLING

7.1 The packs shall be heated to the rolling temperature specified on the governing NAA drawing(s) and soaked 60 mins. per inch of pack thickness. Heating shall be measured by chromel-alumel thermocuples located as specified by governing NAA documents. Permanent records of the thermal cycle shall be obtained on continuous recorders.

7.2 Upon removal from the furnace, the pack shall be immediately transferred to the rolling mill. A maximum of 1-1/2 minutes from the furnace to the first pass in the rolling mill is desired. Temperature at the beginning of the first pass shall meet the requirements of the governing NAA documents as determined by optical pyrometer readings.

7.3 Pack rolling schedules will be provided by authorized NAA Representatives or governing NAA documents. Authorized NAA Representatives shall coordinate each pack rolling operation.

7.4 All of the required rolling information will be noted, recorded, and reported to NAA in the certified test report.

8. ROLLING TEMPERATURE REQUIREMENTS

8.1 Any type of furnace may be used provided that the part is completely and uniformly heated to the specified temperatures.

8.2 A temperature tolerance of ±25F is required at rolling temperature but a deviation from this shall not by itself be a cause for rejection.

8.3 Chromel-alumel thermocuples calibrated to an accuracy of ±5F shall be used in conjunction with a suitable recorder to furnish a permanent record of the thermal cycle.

8.4 Optical pyrometer temperature readings shall be used during the rolling operation.

8.5 All pertinent temperature data including requirement deviations shall be recorded in the certified test reports. Original charts, recording etc. shall be identified and stored for future reference.

9. HOT FORMING

9.1 Hot forming of and sizing of Titanium 6Al-4V alloy, A and STA, and Titanium 8Al-1Mo-1V alloy, Mill Annealed, pack details shall be performed in accordance with Specification LA0102-003.

9.2 Hot forming and sizing of Titanium 8Al-1Mo-1V alloy, Duplex Annealed, pack details shall be performed in accordance with Sections 2, 3, and 4 of Specification LA0111-028.

10 HEAT TREATMENT

10.1 Heat treatment of Titanium 6Al-4V alloy pack details shall be performed in accordance with Specification LA0111-026.

10.2 Heat treatment of Titanium 8Al-1Mo-1V alloy, pack details shall be performed in accordance with sections 2, 3, and 4 of specification LA0111-028.

11. PACK DISASSEMBLY

11.1 All steel pack details such as pack covers, yokes, filler bars and shims shall be removed from the roll diffusion bonded assembly without damage to the titanium structure.

11.2 Pack covers and yokes may be removed by flame cutting, sawing, radiac cutting or machining. Removal by these means shall be conducted such that the cutting line essentially coincides with the outline of the enclosed titanium part. Accurate layouts shall be made to insure the location of the cuts.

11.3 After removal of side and end yoke members, the cover plates may be removed by mechanical means. Permissible mechanical methods for such removal are as follows:

1. Thermal shock
2. Mechanical wedging
3. Peeling
4. Vibration

11.4 All methods of steel detail removal shall be conducted in accordance with governing NAA documents.

11.5 Internally located tooling which cannot be mechanically removed may be removed by chemical leaching. Chemical leaching, if required, may only be conducted under rigidly controlled conditions as described in section 12 of this document.

11.6 Reuse of steel tooling which has been through the roll diffusion bonding process is not permissible.

12. CHEMICAL LEACHING

Chemical leaching may be specified as a method for removing filler bars and other internal steel tooling required during the bonding process. When specified this operation shall be performed in accordance with the following procedure:

12.1 The part shall be solvent degreased, if necessary, to remove excessive surface contaminants which might affect the leaching solution.

12.2 The parts shall be immersed in the leaching tank with the leaching solution at 100F ± 10°F. Insulation such as teflon supports shall be provided to insulate the part from the tank to prevent galvanic action.

12.3 Heat shall be applied as required to bring the leaching solution to 190F ± 10F and the bath shall be maintained at this temperature throughout the process. The leach tank shall be provided with a means for suitably agitating the solution throughout the leaching operation (e.g. air agitation).

12.4 When the steel is completely removed as determined by visual inspection the part shall be removed and thoroughly rinsed in water and dried.

12.5 Following leaching the parts shall be chemically milled per specification LA0103-003 to remove any iron-titanium compounds from the surfaces.

12.6 The leaching solution as made up shall consist of 40%±5% nitric acid -60% water (by weight). As leaching proceeds, the solution shall be periodically checked and maintained at 40%±5% (by weight) nitric acid. If the leaching solution begins to precipitate iron oxide or nitrate compounds, the solution shall be discarded and a new solution prepared.

12.7 If the leaching action stops prior to the removal of the steel, the following procedure shall be observed:

a. Determine acid concentration and adjust if necessary.
b. If the above procedure does not restore suitable activity, remove the part from the solution, thoroughly rinse with water and immerse in a solution of 5%±2% hydrochloric acid (with 0.5% chromic acid inhibitor) at 75F±10F for 15 minutes. Remove and thoroughly rinse the part with water and return to the leaching solution.
c. If suitable activity is not restored by the above procedures, prepare a fresh leaching solution and proceed as indicated in section 12.1 through 12.5.

13. QUALITY ASSURANCE

13.1 The roll diffusion bonding process and all applicable conjugate processes shall meet the requirements of Specification LQ ——— "Quality Control Requirements for Roll Diffusion Bonded Titanium Structure".

13.2 Quality Control shall establish the means by which a permanent record of the processing of each roll bonded pack is maintained. This record shall include such items as roll bonding temperature, rolling reductions, and all deviations from the requirements of governing documents.

13.3 Quality Control shall establish additional quality assurance measures as necessary to ensure proper processing and high quality parts in accordance with this specification.