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9 DEC 1969

HYPERSONIC CRUISE VEHICLE WING STRUCTURE EVALUATION

(NASA-CR-135941) HYPERSONIC CRUISE VEHICLE WING STRUCTURE EVALUATION (Lockheed Missiles and Space Co.) 79 p

N90-70113

Unclas
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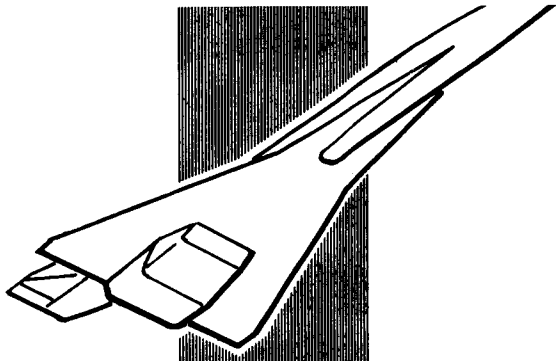


PREPARED FOR NASA LANGLEY RESEARCH CENTER
NASA CONTRACT NAS 1-7573

LOCKHEED MISSILES & SPACE COMPANY
A GROUP DIVISION OF LOCKHEED AIRCRAFT CORPORATION
SPACE SYSTEMS DIVISION · SUNNYVALE, CALIFORNIA

INTRODUCTION

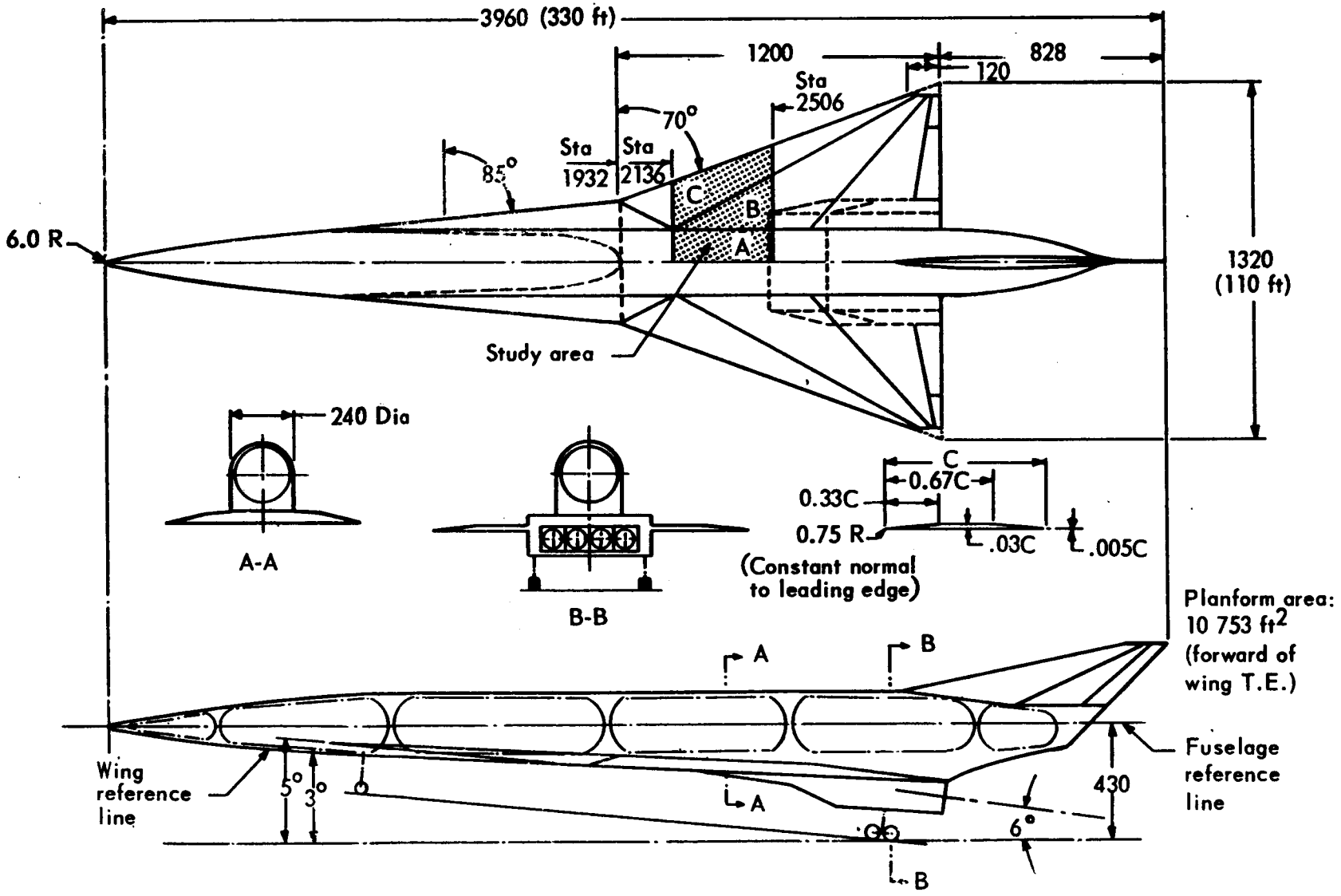
WING STRUCTURE INVESTIGATION

- HYPERSONIC CRUISE VEHICLE
  - OPERATE AT MACH 8
  - MAXIMUM DYNAMIC PRESSURE 2200 psf
  - LIFE OF 10,000 HR
- INVESTIGATE PROBLEM AREAS
  - PRIMARY STRUCTURE
  - THERMAL-PROTECTION SYSTEM
  - LEADING EDGE
- RATING SYSTEM
  - WEIGHT
  - COST
  - RELIABILITY
  - PERFORMANCE
  - INTERACTION (BASIS OF MINIMUM TOTAL SYSTEM COST)

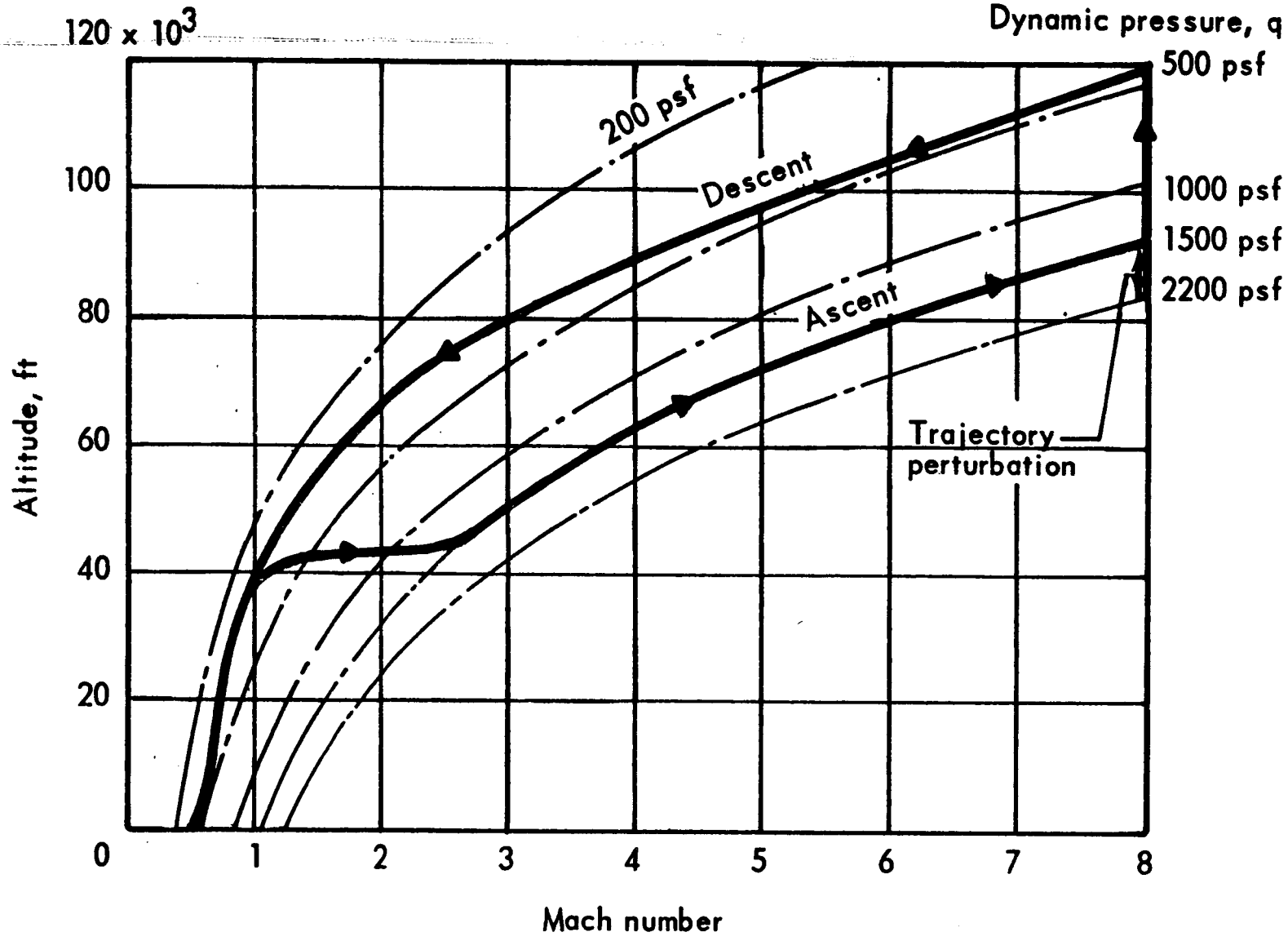
DESIGN CRITERIA

- CONFIGURATION CRITERIA
- PERFORMANCE CRITERIA
- STRUCTURAL CRITERIA

BASELINE HYPERSONIC CRUISE VEHICLE



FLIGHT SCHEDULE



STRUCTURAL CRITERIA

- LIFE – 10000 HR
- CREEP –.5% PERMAMENT DEFORMATION
- SONIC FATIGUE (BOUNDARY LAYER AND ENGINE)
- PANEL AND VEHICLE FLUTTER – FACTOR OF SAFETY OF 1.3 q
- ULTIMATE LOADS (MAXIMUM LIMIT LOAD CONDITION +2.0 g MANEUVER)

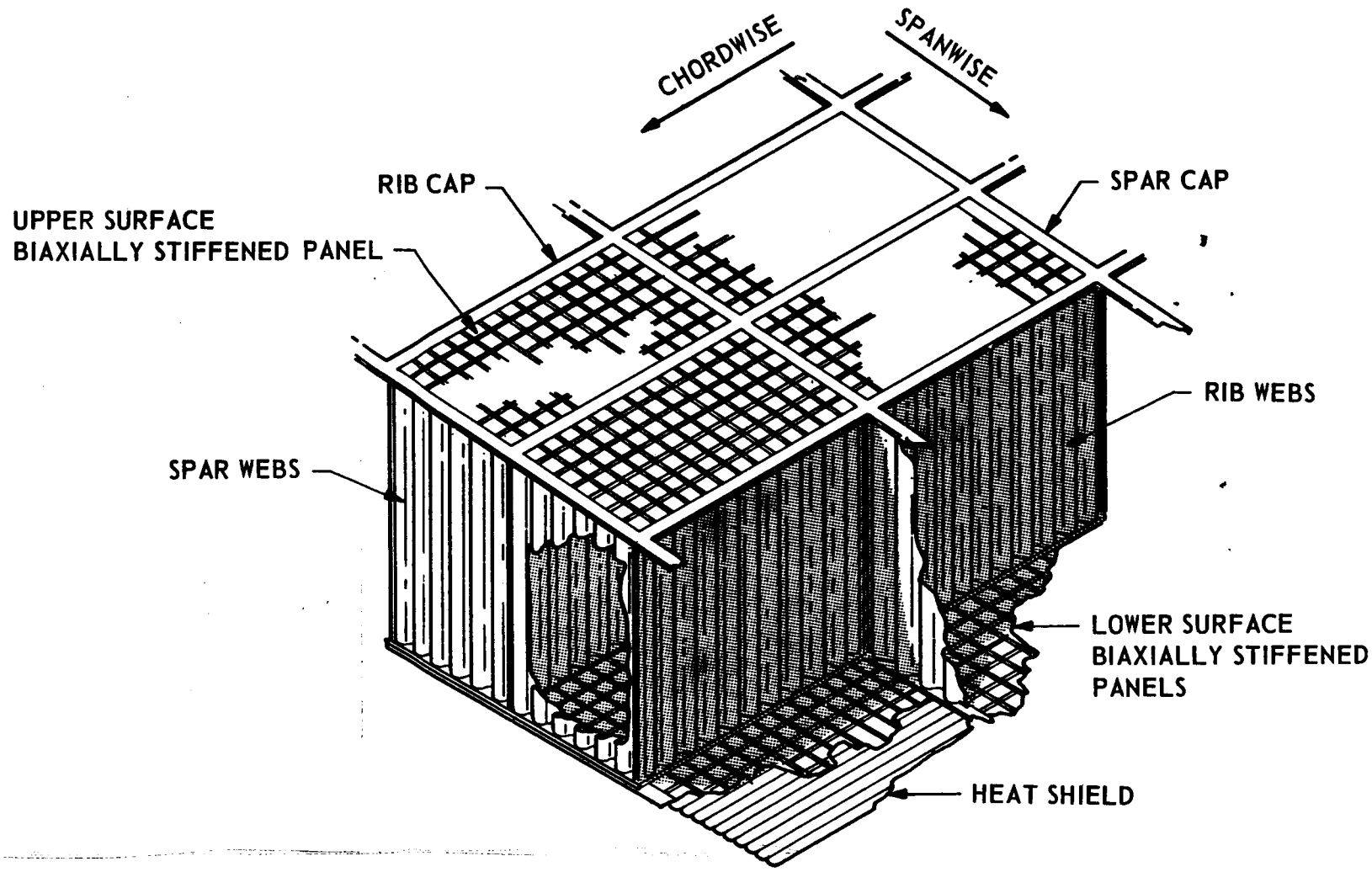
  AIRLOADS – (1.3 X 1.5) X LIMIT AIRLOADS

  THERMAL – 1.3 X LIMIT

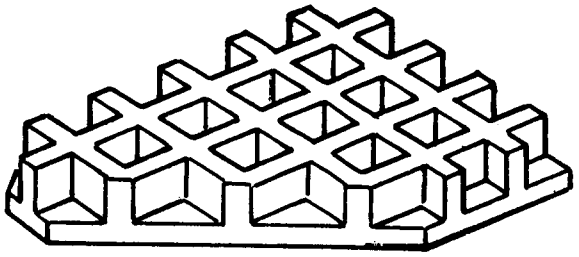
STRUCTURAL CONCEPTS

- PRIMARY STRUCTURE
- THERMAL - PROTECTION SYSTEM
- LEADING EDGE

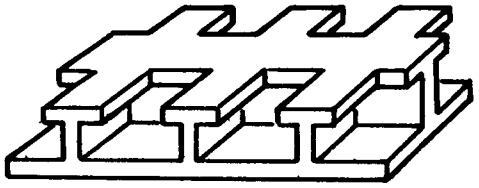
TYPICAL PRIMARY-STRUCTURE CONCEPT



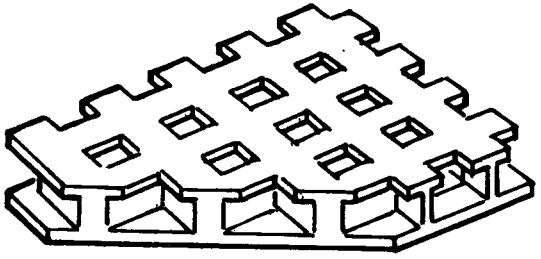
MONOCOQUE PANEL CONSTRUCTIONS



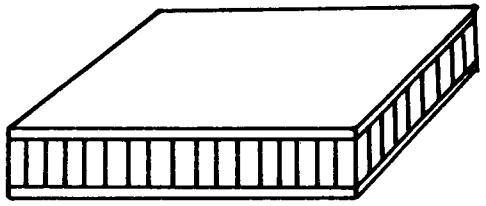
Waffle grid — 45° x 45° unflanged



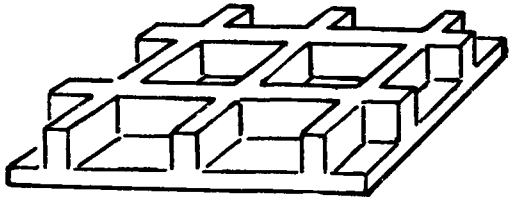
Waffle grid — 0° x 90° tee-flanged



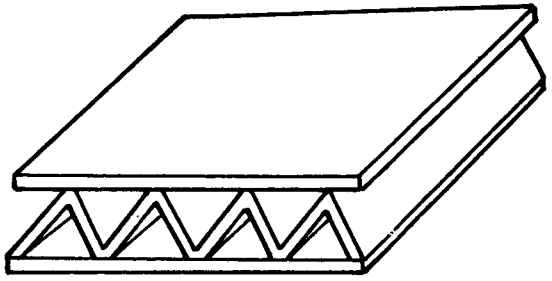
Waffle grid — 45° x 45° tee-flanged



Honeycomb-core sandwich

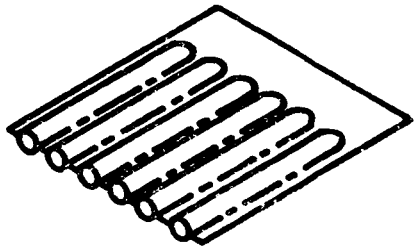


Waffle grid — 0° x 90° unflanged

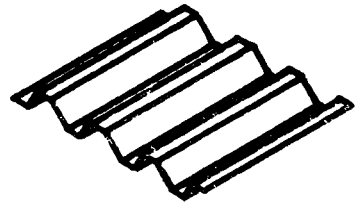


Truss-core sandwich

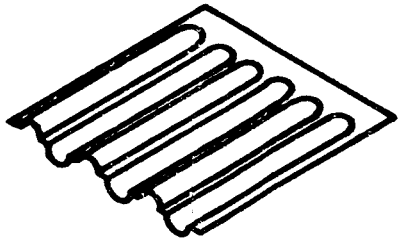
SEMIMONOCOQUE SPANWISE-STIFFENED PANELS



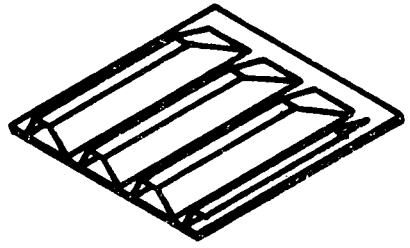
Tubular



Trapezoidal corrugation

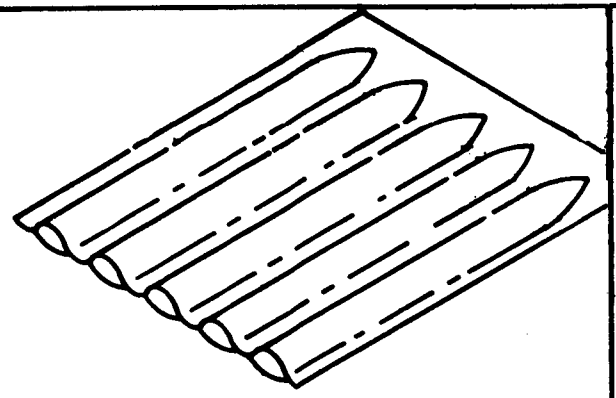


Beaded



Corrugation-stiffened

SEMIMONOCOQUE CHORDWISE STIFFENED PANELS

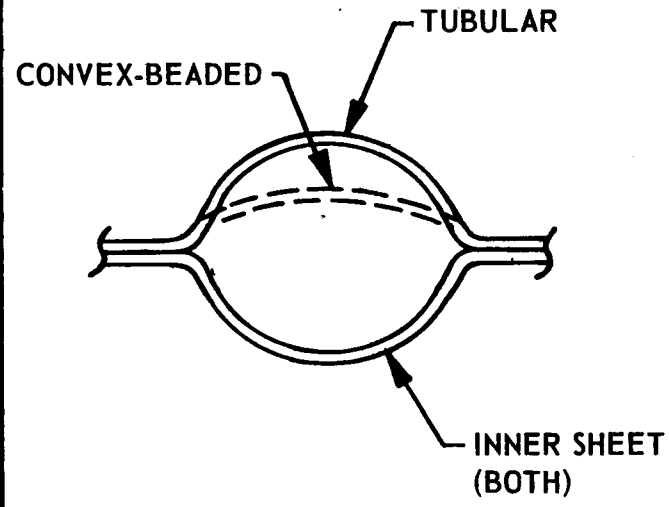


CONVEX-BEADED

TUBULAR

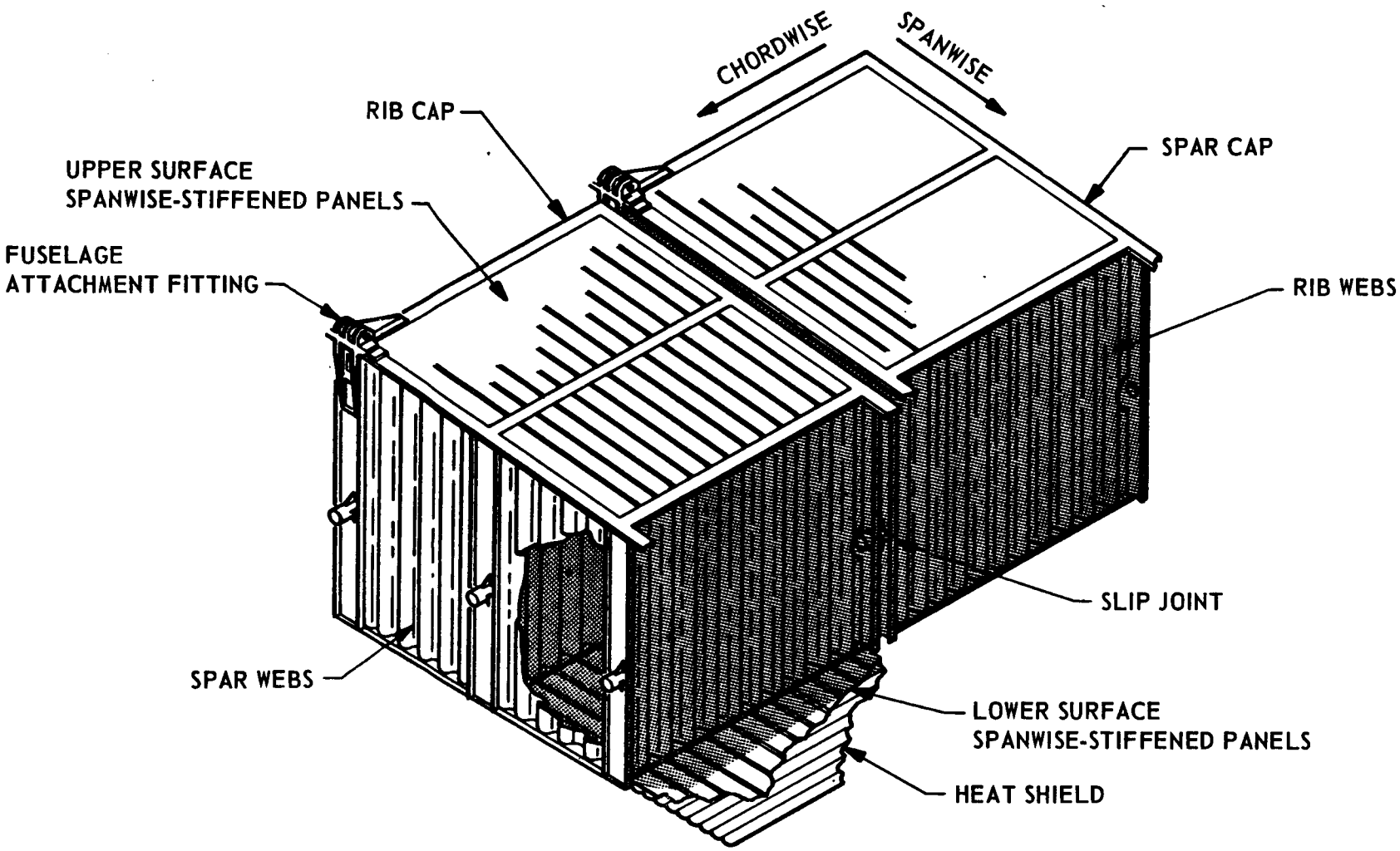
BEADED

TRAPEZOIDAL CORRUGATION

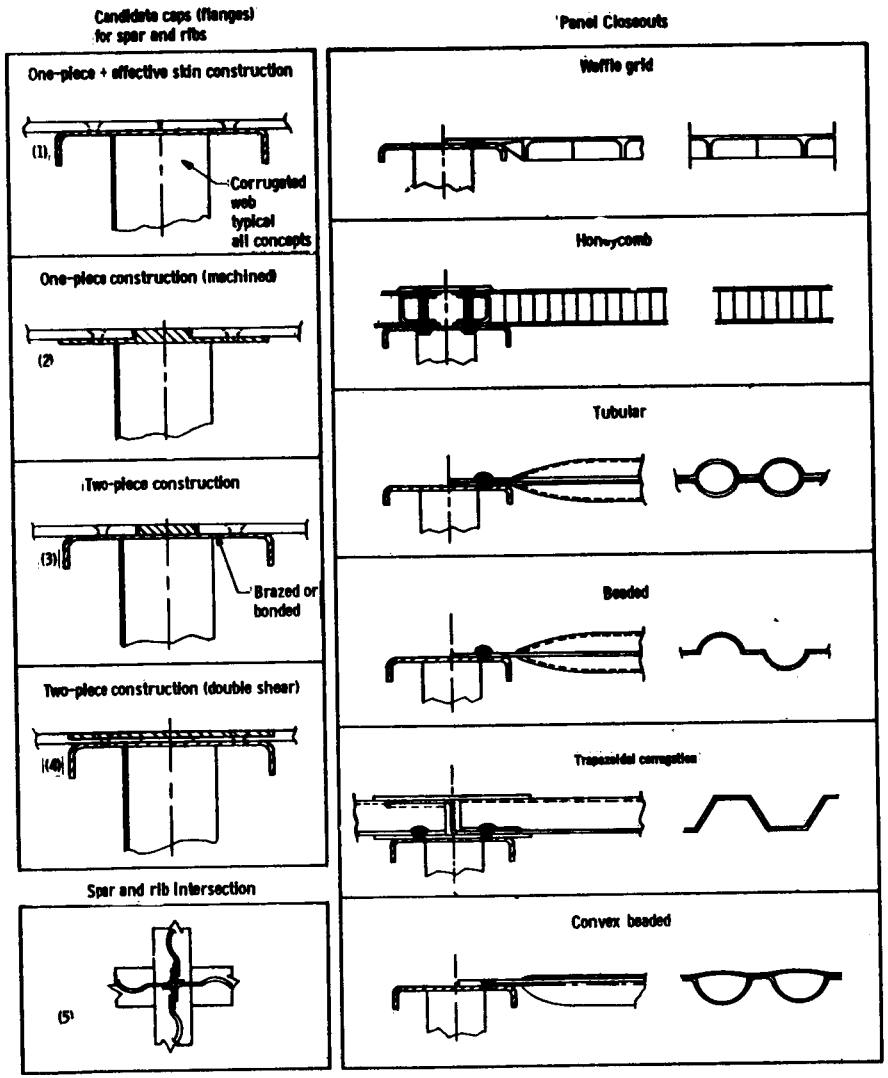


TUBULAR AND CONVEX-BEADED CONSTRUCTION

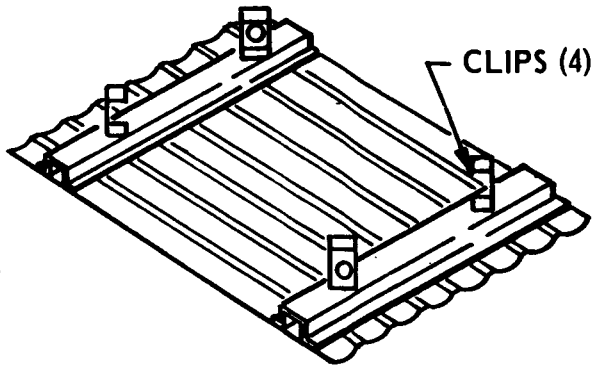
TYPICAL STATICALLY DETERMINATE CONCEPT



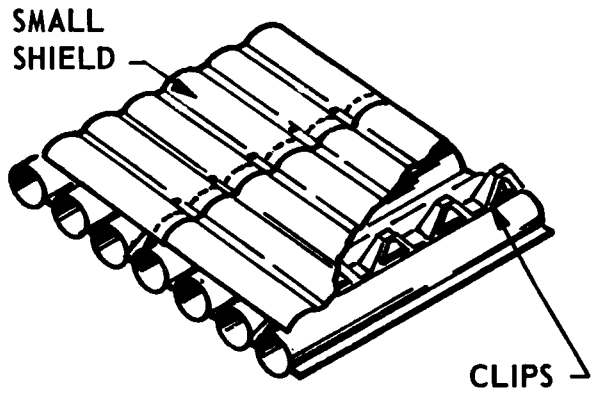
TYPICAL CAP AND CLOSEOUT CONFIGURATIONS



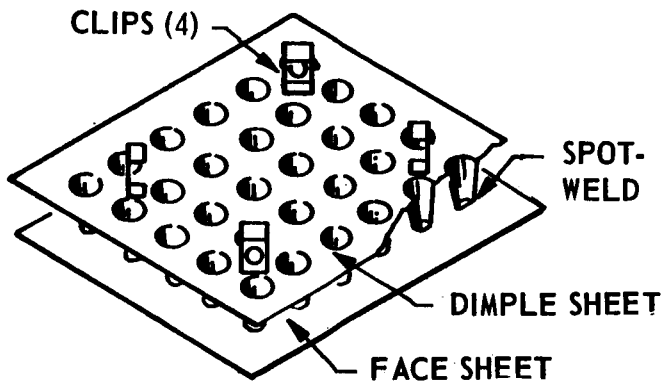
REFURBISHABLE HEAT-SHIELD CANDIDATES



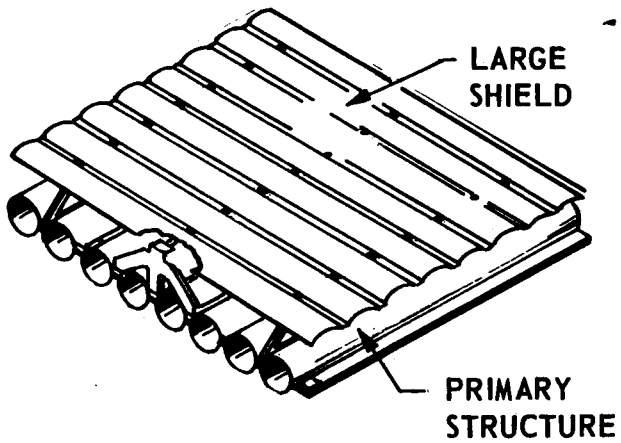
HAT-SECTION STIFFENED



SIMPLE SUPPORTS

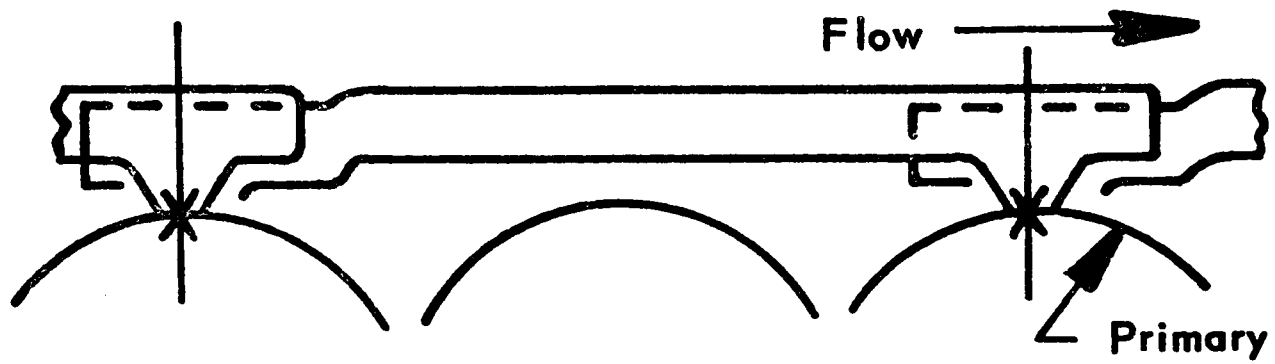


FLAT-SKIN DIMPLED

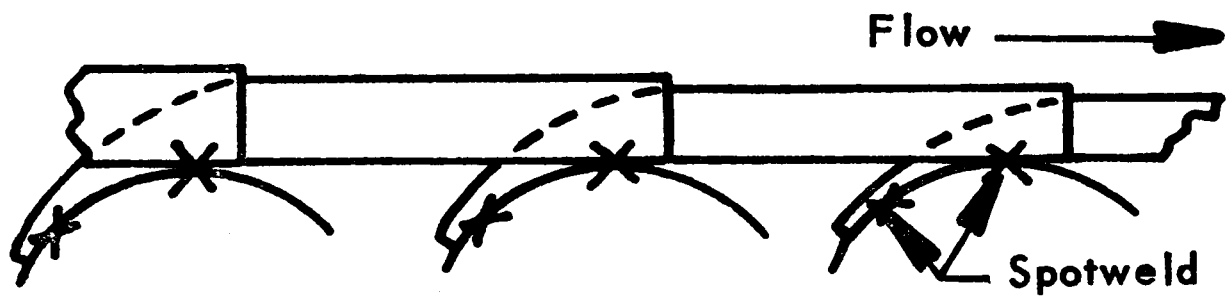


MULTIPLE SUPPORTS

PERMANENTLY ATTACHED HEAT-SHIELD CANDIDATES



Modular simply supported

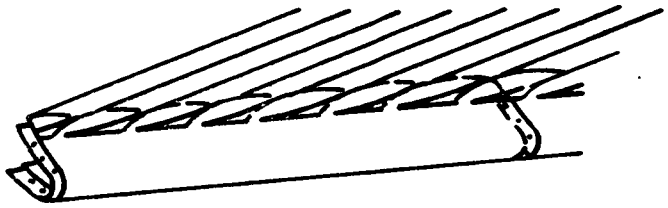


Modular cantilevered

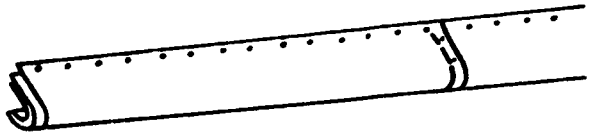
LEADING-EDGE CONCEPTS

CONTINUOUS CONCEPT

FOR HEAT-SHIELD APPLICATION

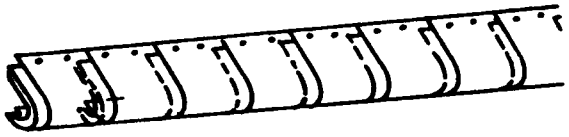


FOR MONOCOQUE APPLICATION

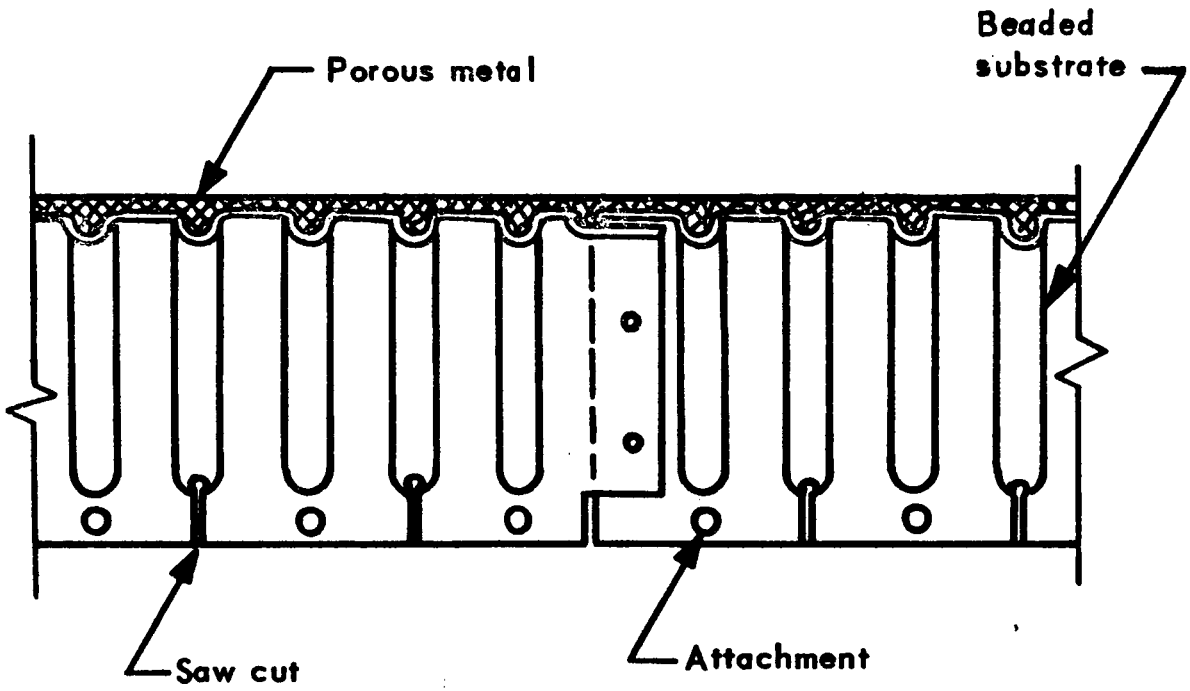


SEGMENTED

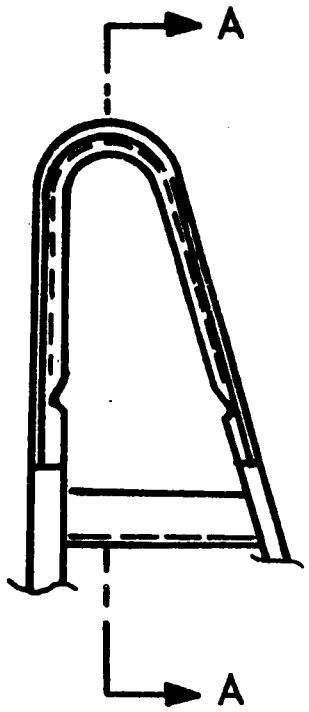
SEGMENTED (SLIP JOINTS)



POROUS-METAL CONTINUOUS LEADING-EDGE



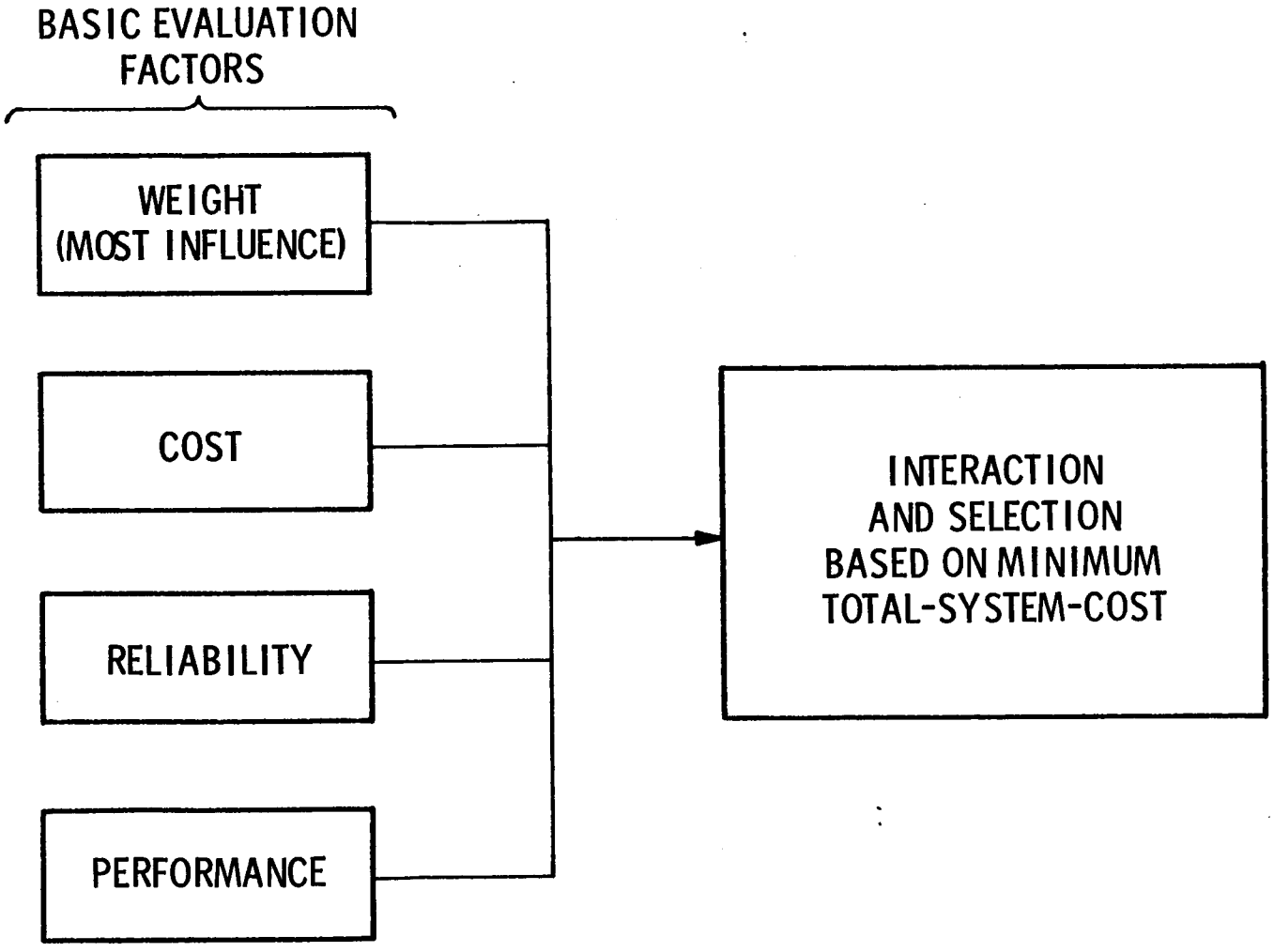
Section AA



CONCEPT EVALUATION PROCEDURE

- ENVIRONMENT
- MATERIALS
- WEIGHT
  - INITIAL SCREENING
  - INTERMEDIATE SCREENING
  - FINAL STRUCTURAL ANALYSIS
  - HEAT SHIELD
  - LEADING EDGE
- COST
- PERFORMANCE
- RELIABILITY
- RATING-FACTOR INTERACTION
  - INTERACTION PROCEDURE
  - VEHICLE WEIGHT-COST SIZING METHOD

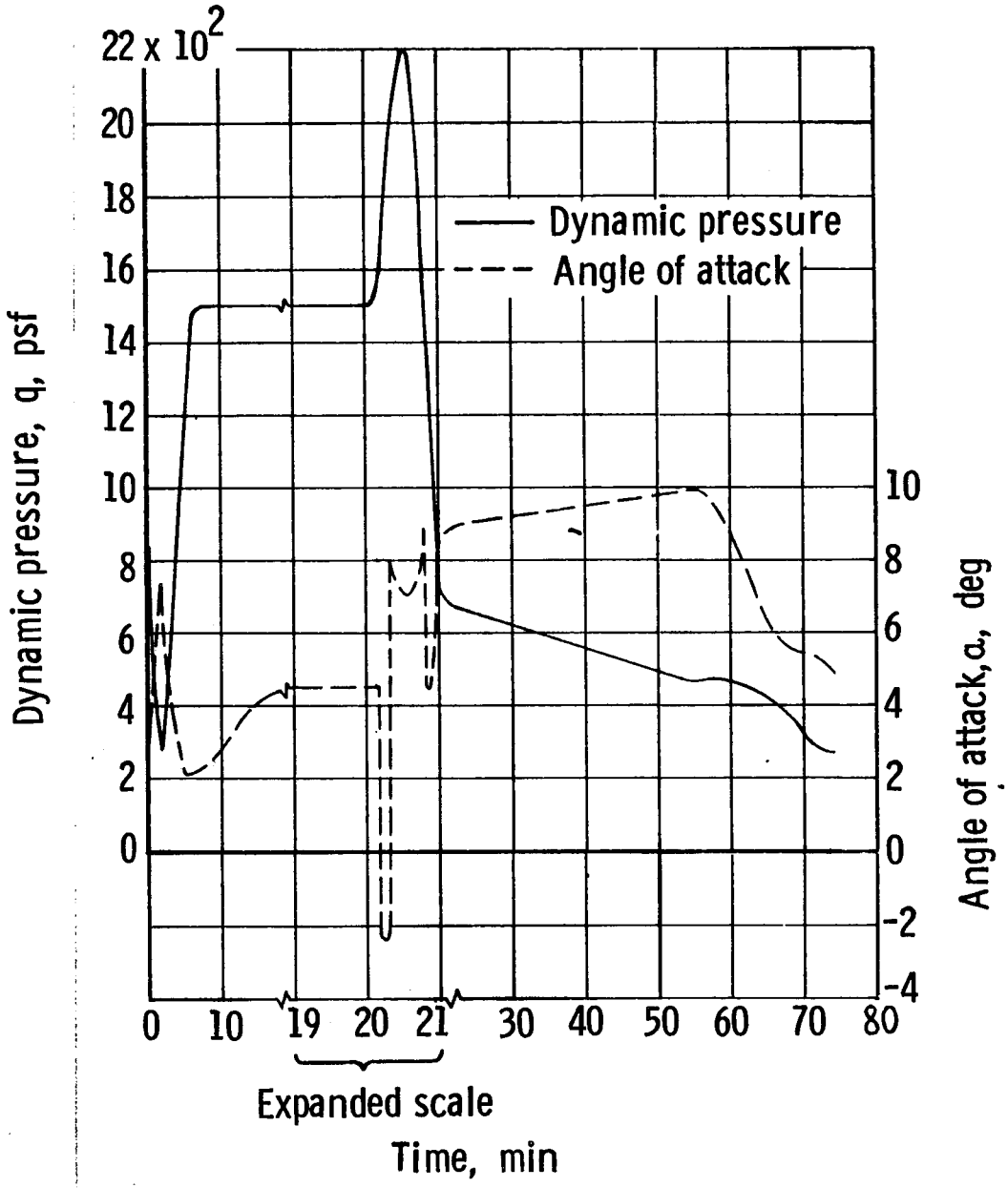
RATING SYSTEM



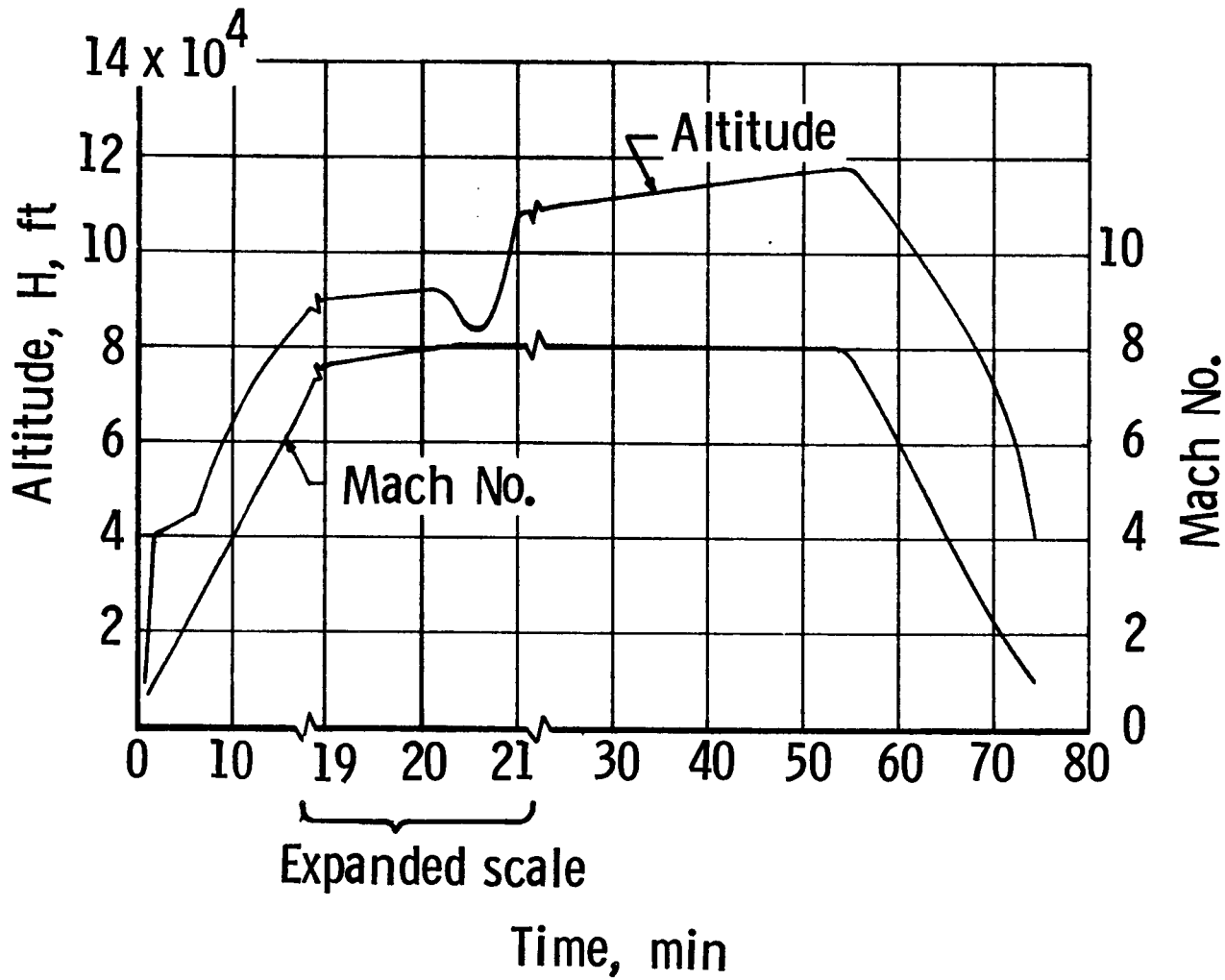
EVALUATION RESULTS

- ENVIRONMENTAL ANALYSIS

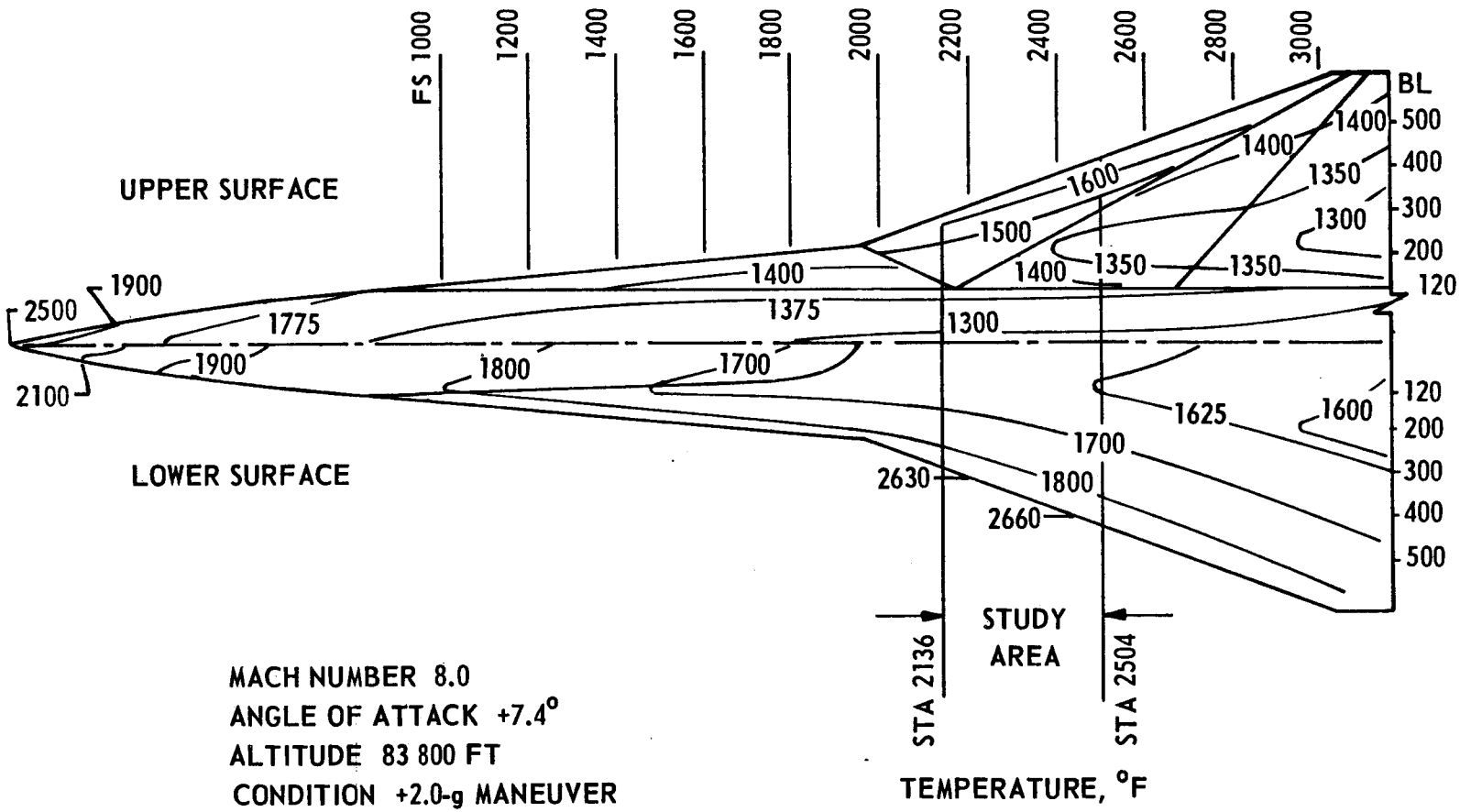
HYPERSONIC CRUISE VEHICLE TRAJECTORY



HYPERSONIC CRUISE VEHICLE TRAJECTORY



TYPICAL WING TEMPERATURE DISTRIBUTION



MACH NUMBER 8.0
ANGLE OF ATTACK +7.4°
ALTITUDE 83 800 FT
CONDITION +2.0-g MANEUVER

VEHICLE WING PRESSURES

Location \ Condition	Limit pressure Δp, psi [a, b, c]								
	BL 0-120			BL 120-212			BL 212-350		
	-0.5-g	+2.0-g	Cruise	-0.5-g	+2.0-g	Cruise	-0.5-g	+2.0-g	Cruise
Lower surface structural panels	-0.53	-0.97	-0.73	-0.51	-1.46	-0.97	-0.54	-0.98	-0.73
All heat shields & upper surface panels	±0.50								

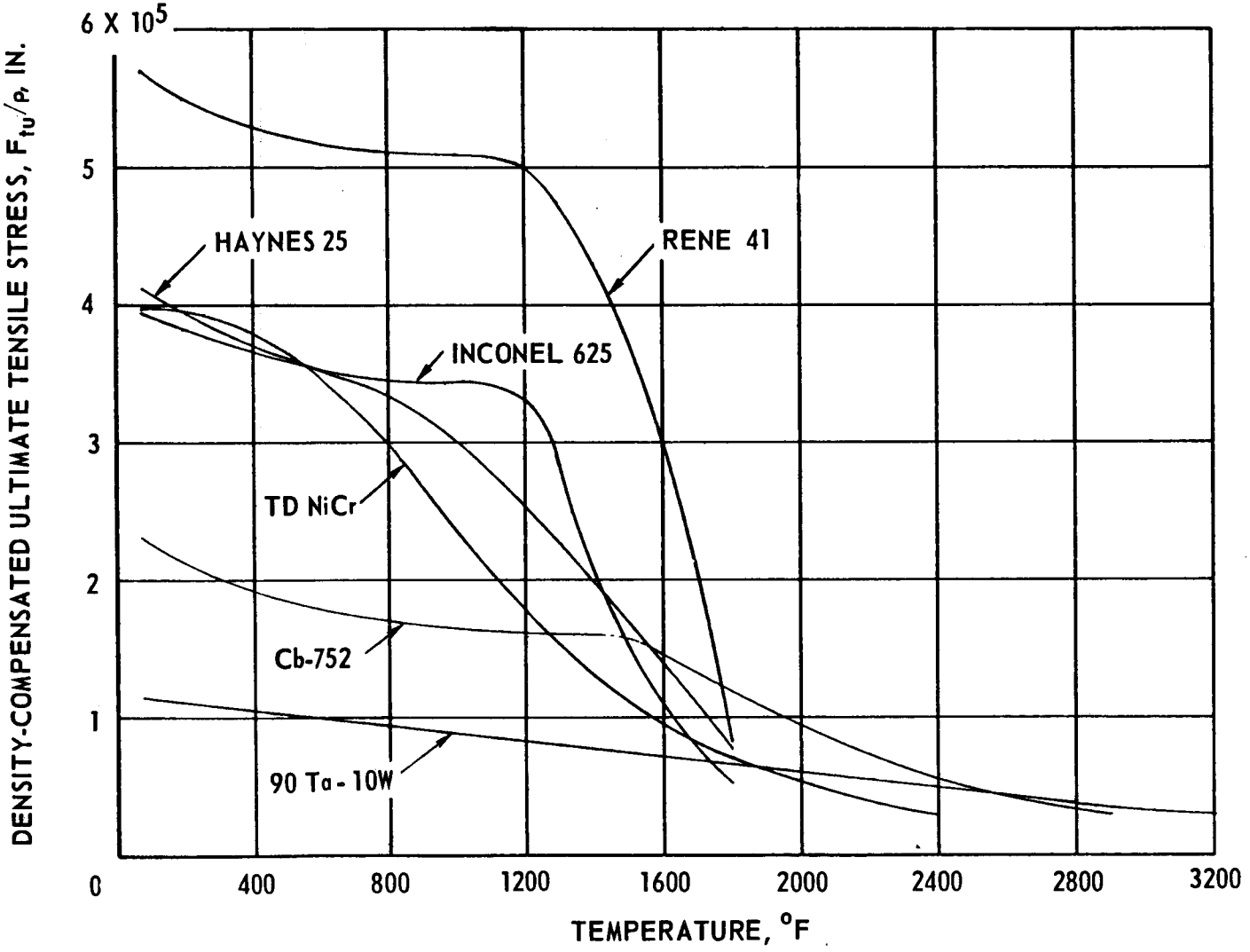
[a]For ultimate design pressures, multiply (1.3) (1.5) by limit pressures shown.
[b]Negative values indicate inward-acting pressures;positive values indicate outward-acting pressures.
[c]Sta. 2274-2366.

EVALUATION RESULTS

- MATERIAL ANALYSIS

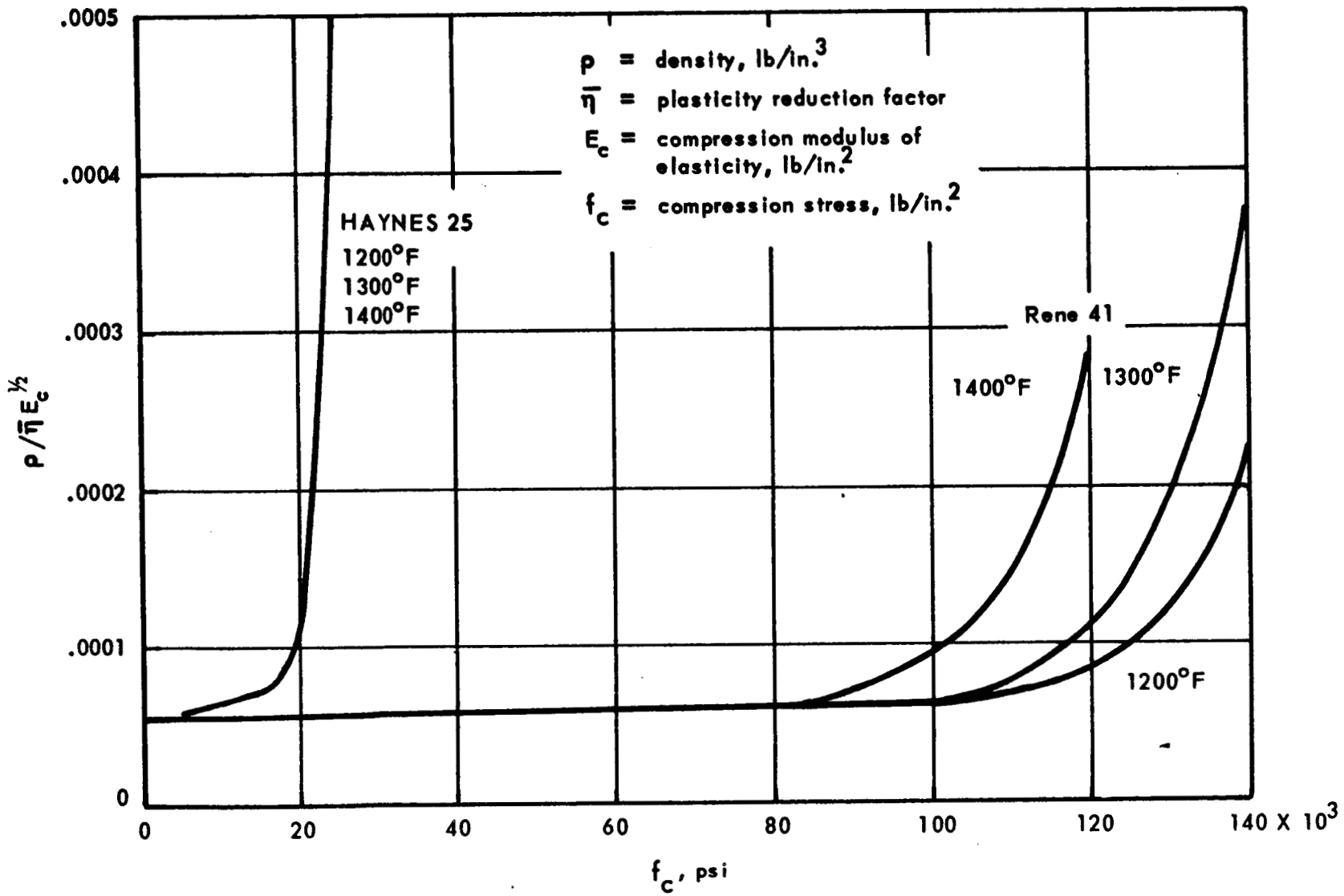
ULTIMATE STRENGTH COMPARISON

HIGH-TEMPERATURE CANDIDATE MATERIALS



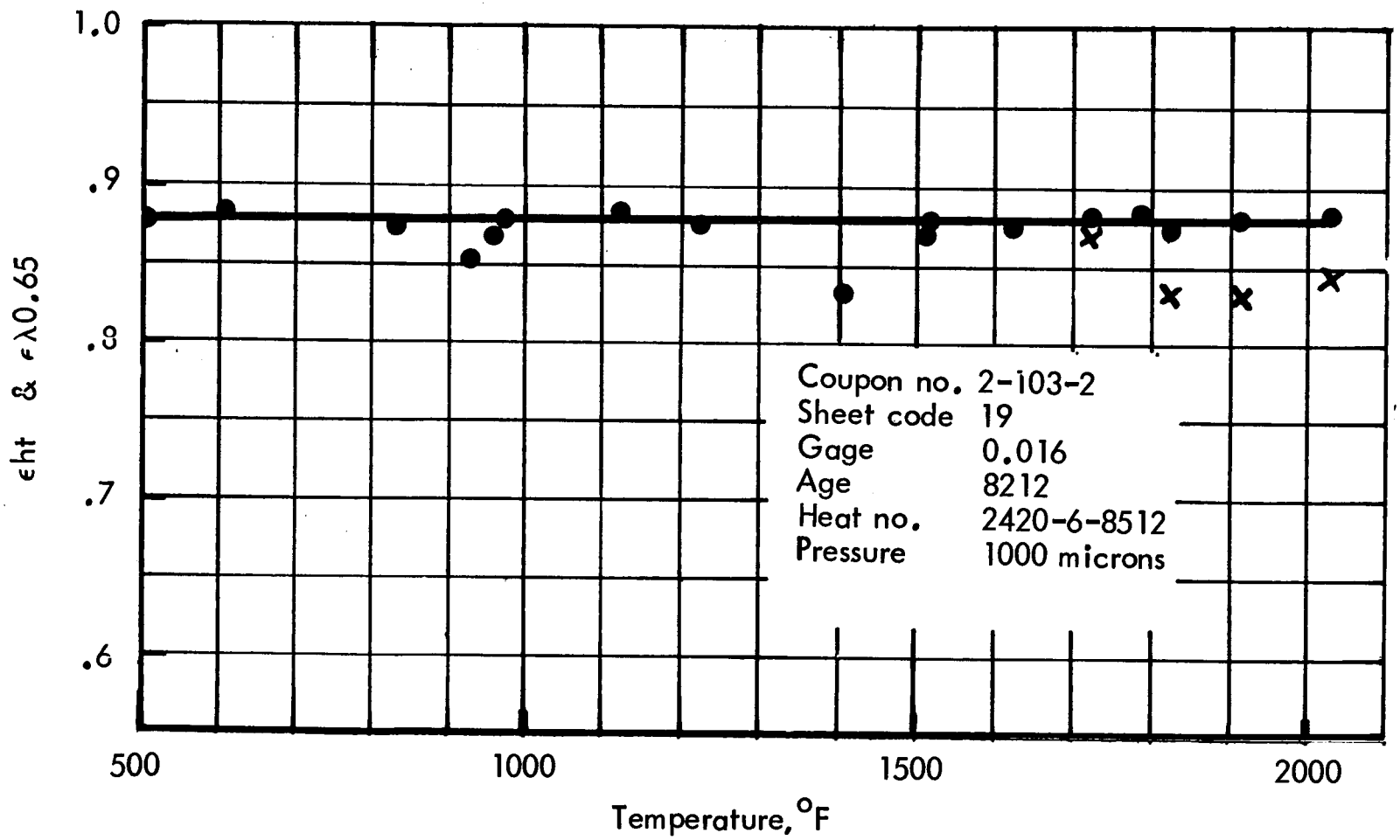
STRUCTURAL STABILITY COMPARISON

PRIMARY-STRUCTURE MATERIAL



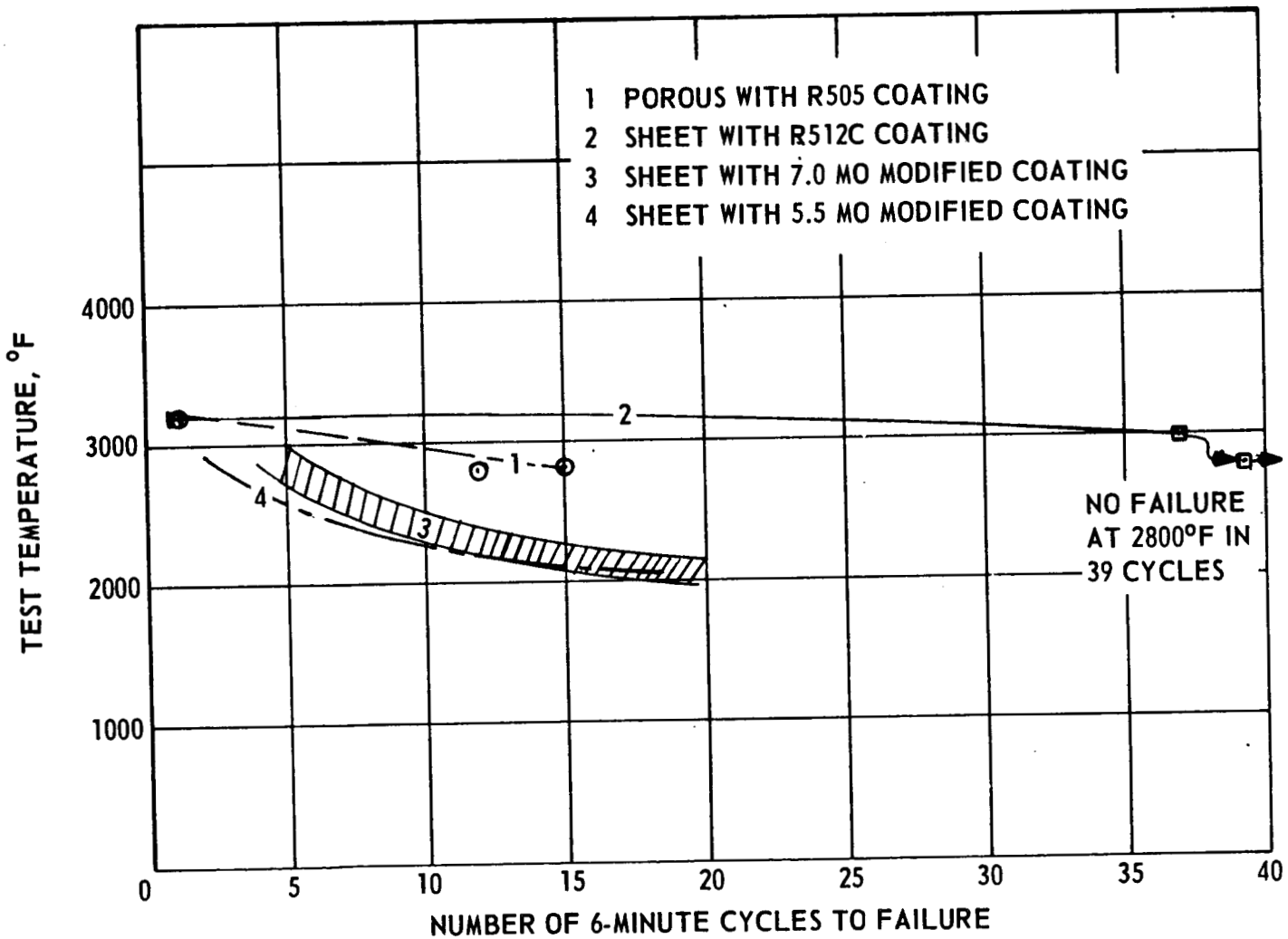
TYPICAL EMITTANCE TEST DATA

RENÉ 41



LEADING-EDGE COATING LIFE TEST

REFRACTORY METAL Ta-10W



STRUCTURAL JOINT TEST (LAP JOINT)

RENE 41

Material	Heat no.	Gage, in.	Condition	Method of joining	Thermal Exposure		Ultimate load, lb/spot		
					hr	°F	RT	1200°F	1500°F
Rene 41	2490-6-8512	0.015	Aged	Resistance spot	None		612	405	294
			Annealed				532	442	234
			Aged		250	1500	632	–	–
			Annealed				629	–	–
	2490-7-8513		Aged		None		682	516	301
			Annealed				579	461	286
			Aged		250	1500	560	–	–
			Annealed				586	–	–
	2490-6-8512		Aged	Diffusion spot	None		557	313	181
			Annealed				524	420	163
			Aged		250	1500	548	–	–
			Annealed				559	–	–

STRUCTURAL JOINT TEST (LAP JOINT)

TD NiCr

Material	Heat no.	Gage, in.	Material condition	Method of joining	Test temperature			
					RT	RT	2000°F	2200°F
					Ultimate, lb/spot	Yield	Ultimate, lb/spot	Ultimate, lb/spot
TD NiCr	2862-1	0.010	Annealed	Diffusion spot bond	247	–	38	31
	2862-1	0.030	Annealed	Diffusion spot bond	942	–	63	40
	2862-1	0.010	Annealed	Brazed spot	488	–	52	39
	2862-1	0.030	Annealed	Brazed spot	1098	–	92	67
	2901	0.030	Annealed	Riveted	596[a]	367[a]	84[a]	73[a]
	2891	0.060	Annealed	Riveted	1730[a]	915[a]	220[a]	176[a]
	2862-1	0.010	Annealed	Continuous braze	1910[b]	–	180[b]	118[b]

[a]Pounds per rivet.
[b]Total load on specimen (brazed area 1 in. by 2 in.).

EVALUATION RESULTS

- PRIMARY-STRUCTURE WEIGHT ANALYSIS
  - INITIAL WEIGHT SCREENING
  - INTERMEDIATE WEIGHT SCREENING
  - FINAL STRUCTURAL WEIGHTS

INITIAL PANEL-WEIGHT SCREENING RESULTS

Panel construction	Panel dimensions, in.		Nonoptimum factor	René 41 Panel unit weight,[a] lb/ft^2	Haynes 25 Panel unit weight,[a] lb/ft^2
	"a"	"b"			
Monocoque					
45° by 45° Unflanged waffle	40	20	1.24	4.37 ←	7.96
45° by 45° Tee-flanged waffle	40	20	1.30	4.70	N.A.[b]
0° by 90° Unflanged waffle	40	20	1.38	4.56 ←	8.72
0° by 90° Tee-flanged waffle	40	20	1.40	4.86	8.92
Honeycomb sandwich	40	20	1.80	5.18	10.79
Truss-Core sandwich	40	20	1.50	6.24	9.58
Semimonocoque spanwise					
Tubular	43	30	1.15	4.51 ←	5.16
Beaded skin	43	30	1.17	3.75 ←	4.34
Trapezoidal corrugation	43	30	1.20	3.79 ←	4.39
Corrugation-stiffened	43	30	1.20	3.92 ←	4.34
Semimonocoque chordwise					
Convex-beaded	30	43	1.20	3.20 ←	4.32
Tubular	30	43	1.15	4.51 ←	6.19
Beaded-skin	30	43	1.17	3.75	5.48
Trapezoidal corrugation	30	43	1.20	4.20	5.92

[a]Includes upper and lower surface weights.

[b]Not available.

INTERMEDIATE WEIGHT SCREENING RESULTS

RENE 41 PANELS

Primary structure	Location area	Spacing, in.		Design temperature, °F		Weight,[a] lb/ft²
		Rib	Spar	Lower surface	Upper surface	
Monocoque						
45° by 45° Unflanged waffle	B	20	40	1600	1400	8.90 ←
	C	20	40	1600	1400	8.50
0° by 90° Unflanged waffle	B	20	40	1600	1400	9.24
Semimonocoque spanwise						
Trapezoidal corrugation upper surface panel	B	30	90		1300	1.20[b]
Corrugation stiffened upper surface panel	B	30	90		1400	3.26[b]
Tubular	B	40	90	1400	1300	5.70
	C	44	90	1500	1400	5.11 ←
Beaded-skin	B	48	90	1400	1300	4.93
	C	50	90	1500	1400	4.42 ←
Trapezoidal-corrugation	B	30	90	1400	1300	6.56
	C	31	90	1500	1400	5.64
Semimonocoque chordwise						
Tubular	B	90	46	1400	1300	6.44
Tubular lower convex-beaded upper surfaces	B	90	46	1400	1400	5.92 ←

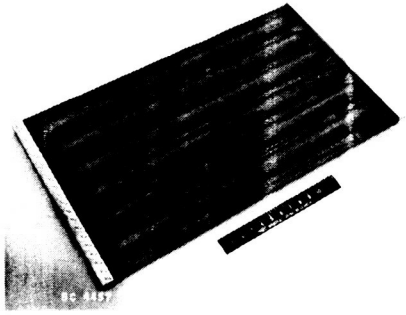
[a]Panels, heat shields, spars and ribs, and closeouts.

[b]Upper surface panels only.

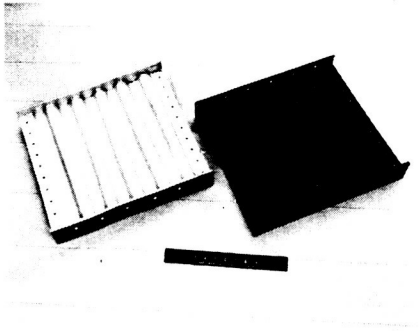
STRUCTURAL-ELEMENT TEST SCHEDULE

Test-panel configuration	Type of test	Number of panels tested					
		End closeout	Crippling		Column		Inplane shear
	Temp, °F	RT	RT	1400	RT	1400	RT
Tubular		1	1	1	1	1	–
Beaded		1	1	1	1	–	–
Corrugation-stiffened		1	1	1	1	1	–
Trapezoidal-corrugation		–	1	1	1	1	–
Shear web		–	–	–	–	–	2
Channel spar cap		–	1	–	–	–	–
Total number of panels		3	5	4	4	3	2
Grand total							21

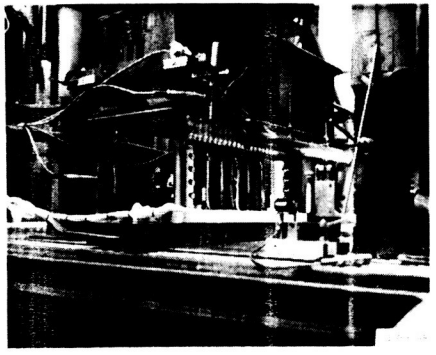
STRUCTURAL/MATERIAL DEVELOPMENT (RENE 41)



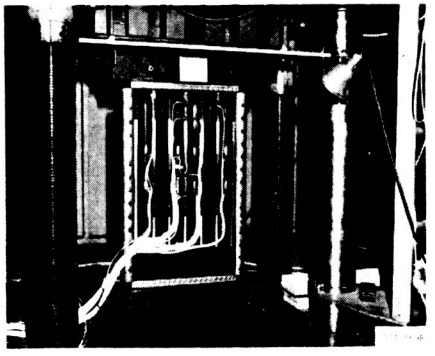
TYPICAL WING COVER PANEL



TYPICAL RIB/ SPAR PANEL



TYPICAL CRIPPLING PANEL TEST



TYPICAL COLUMN PANEL TEST

SUMMARY OF CONCEPT WEIGHTS

BASELINE VEHICLE

CONCEPT	UNIT WEIGHT, LB/FT^2				
	WING SECTION A	WING SECTION B	WING SECTION C	SECTION AVERAGE	TOTAL WING AVERAGE
MONOCOQUE					
WAFFLE	10.717	12.033	9.437	10.494	10.380
HONEYCOMB-CORE	6.250	6.346	6.752	6.472	6.585
SEMIMONOCOQUE SPANWISE					
BEADED	4.457	5.377	5.374	5.060	6.197
TUBULAR	4.824	5.610	5.699	5.376	6.532
SEMIMONOCOQUE CHORDWISE					
TUBULAR	6.948	6.797	6.333	6.666	7.412
STATICALLY DETERMINATE					
BEADED	5.210	6.005	5.542	5.550	6.769

STRUCTURAL MARGINS OF SAFETY

- ULTIMATE LOAD
- PANEL FLUTTER
- WING FLUTTER
- SONIC FATIGUE
- LOAD FATIGUE
- CREEP

} **POSITIVE MARGINS OF SAFETY**

FINAL STRUCTURAL WEIGHT ANALYSIS

WING CONCEPT LOAD COMPARISON

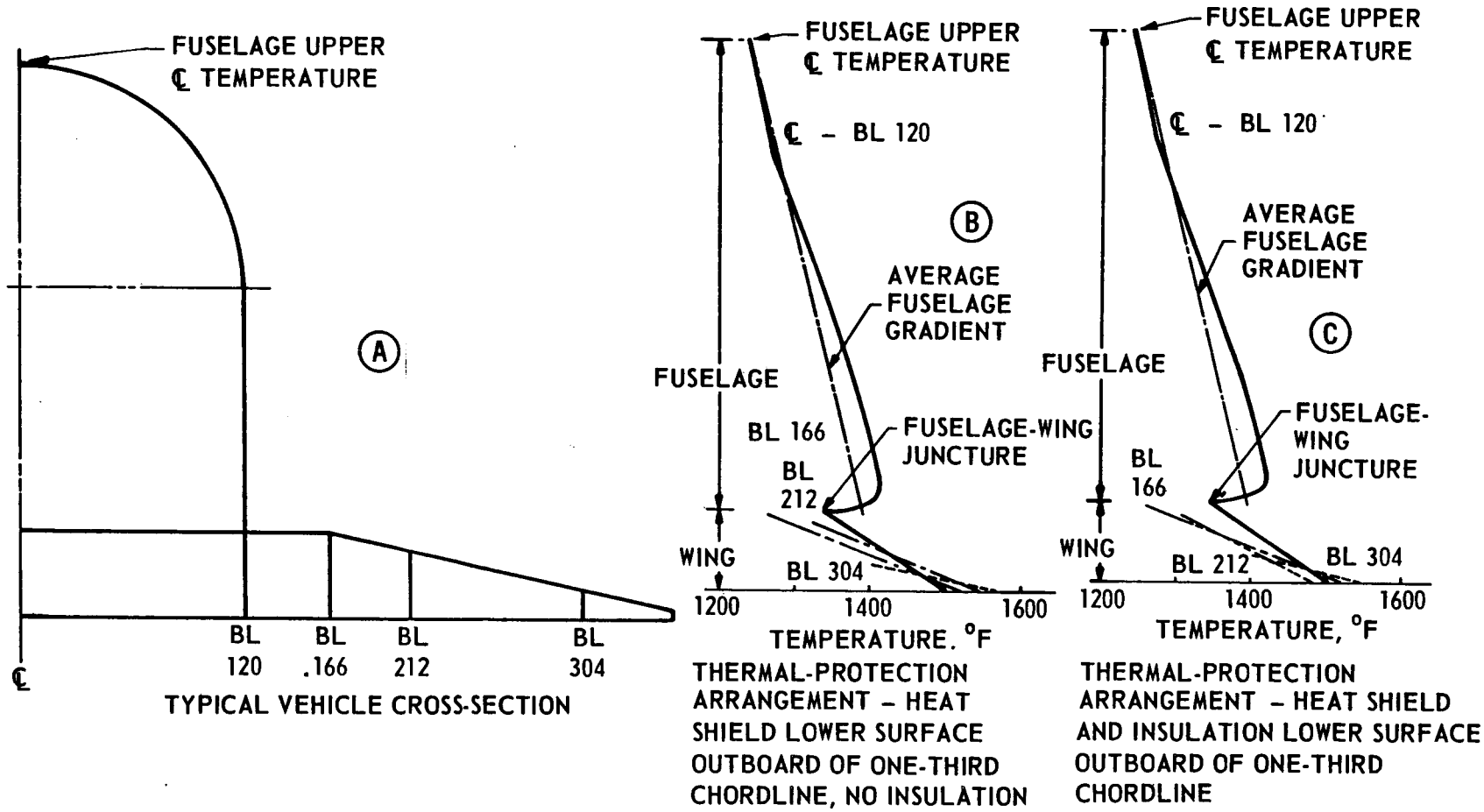
WING CONCEPT	LOAD DIRECTION	ULTIMATE LOADS, LB/IN.	
		UPPER SURFACE	LOWER SURFACE
MONOCOQUE	N_x	-331 (899)	-387 (-959)
	N_y	-589 (-96)	559 (100)
	N_{xy}	-302 (109)	-193 (181)
SEMIMONOCOQUE SPANWISE	N_x	-269 (127)	-385 (10)
	N_y	-496 (-32)	576 (51)
	N_{xy}	-176 (-11)	139 (14)
SEMIMONOCOQUE CHORDWISE	N_x	-353 (658)	-680 (-327)
	N_y	-965 (27)	865 (99)
	N_{xy}	-461 (206)	359 (-38)
STATICALLY DETERMINATE	N_x	0 (0)	0 (0)
	N_y	-535 (-65)	538 (65)
	N_{xy}	-147 (-16)	147 (16)

(1) AVERAGE LOADS BETWEEN STA 2274 AND 2366, AREA BL 120 TO BL 212.

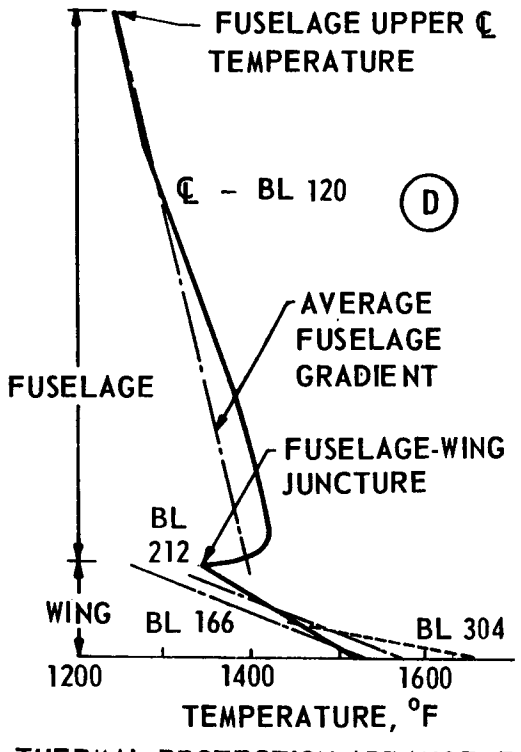
(2) FLIGHT CONDITION: +2.0 G MANEUVER.

WING/FUSELAGE TEMPERATURE PROFILES

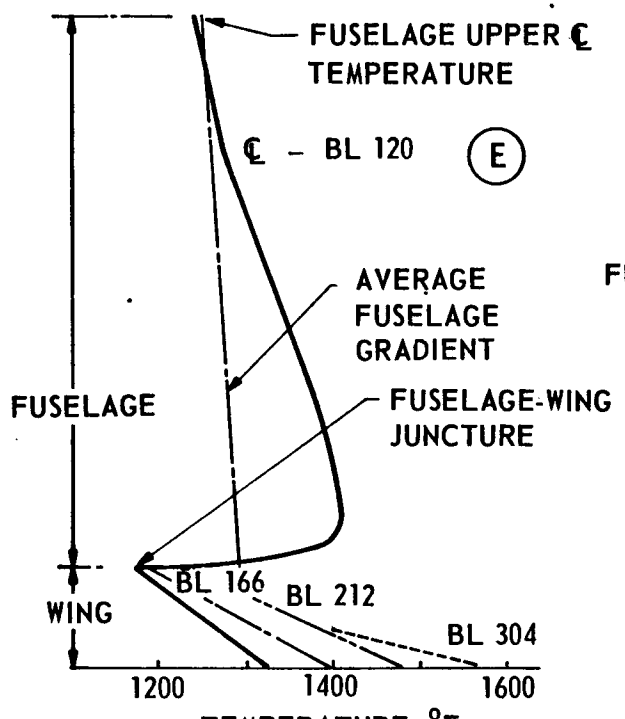
(FOR CANDIDATE THERMAL-PROTECTION ARRANGEMENTS)



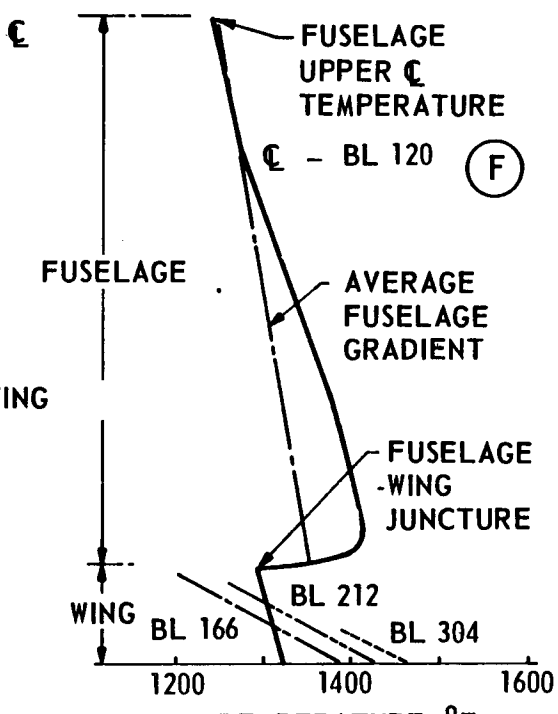
WING/FUSELAGE TEMPERATURE PROFILES



THERMAL-PROTECTION ARRANGEMENT – NO HEAT SHIELD, NO INSULATION



THERMAL-PROTECTION ARRANGEMENT – HEAT SHIELDS ON ENTIRE LOWER SURFACE, NO INSULATION



THERMAL-PROTECTION ARRANGEMENT – HEAT SHIELD ON ENTIRE LOWER SURFACE, INSULATION LOWER SURFACE OUTBOARD OF ONE-THIRD CHORDLINE

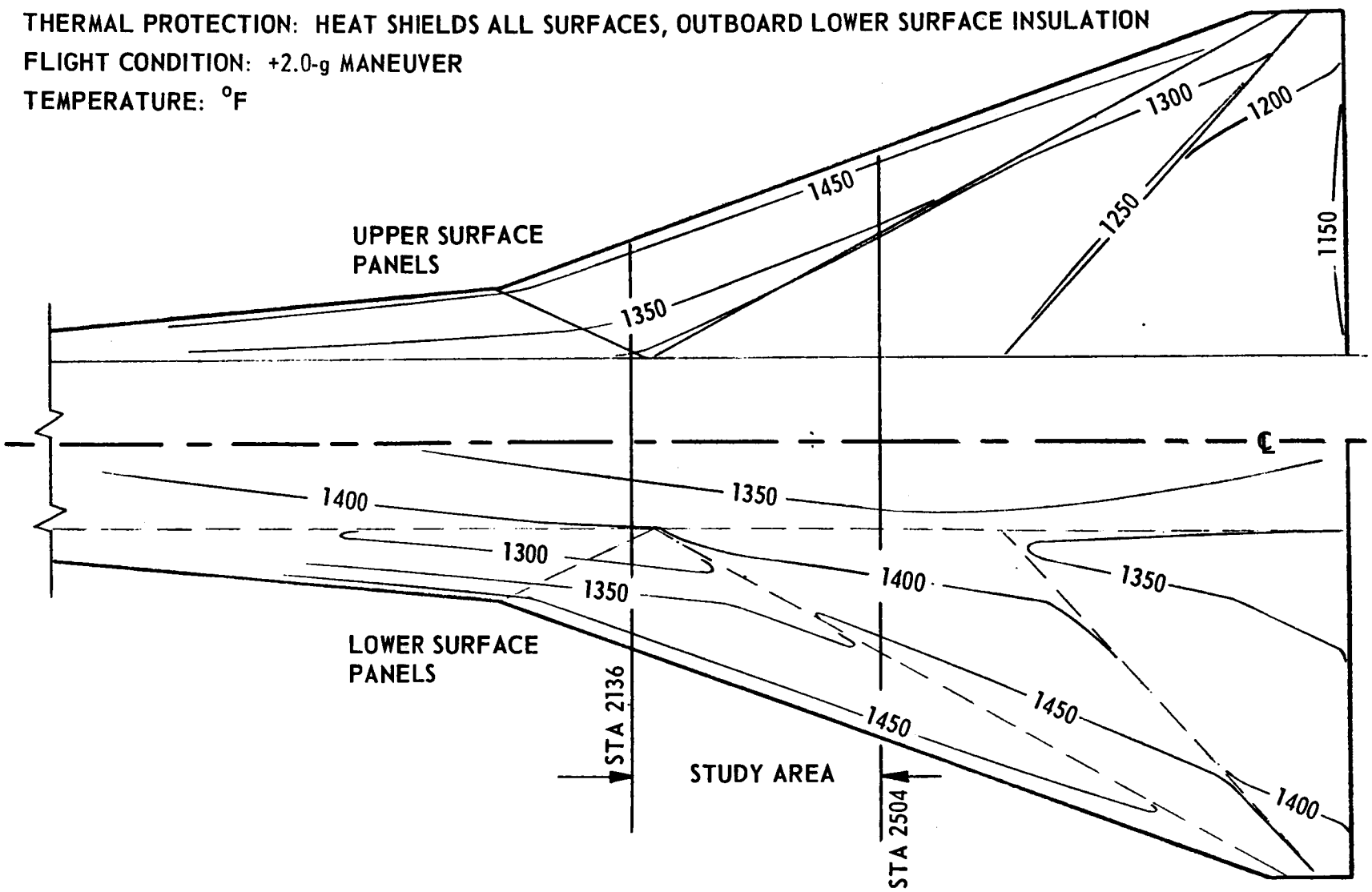
WING TEMPERATURES

SEMIMONOCOQUE SPANWISE CONCEPT

THERMAL PROTECTION: HEAT SHIELDS ALL SURFACES, OUTBOARD LOWER SURFACE INSULATION

FLIGHT CONDITION: +2.0-g MANEUVER

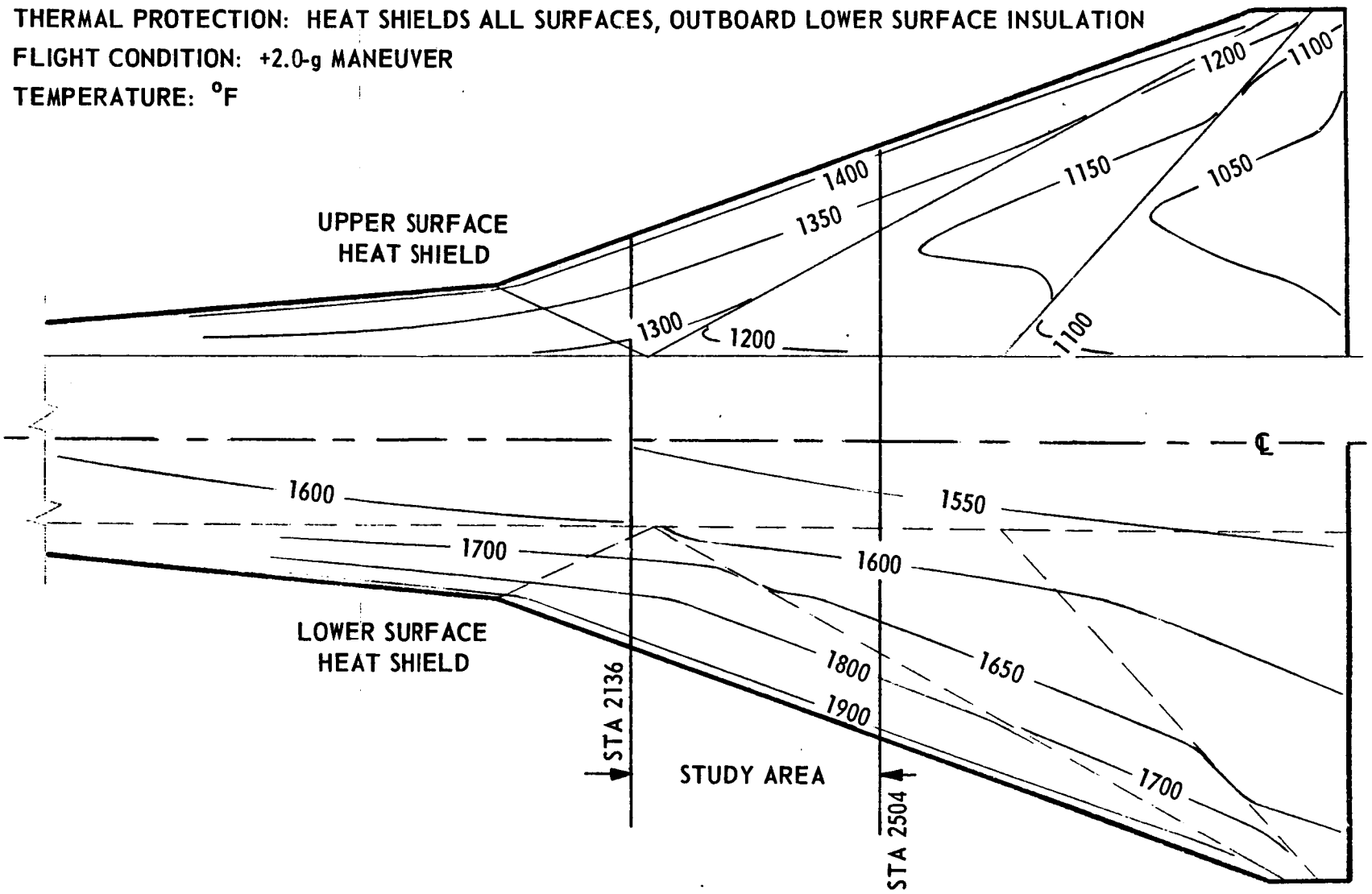
TEMPERATURE: °F



HEAT SHIELD TEMPERATURES

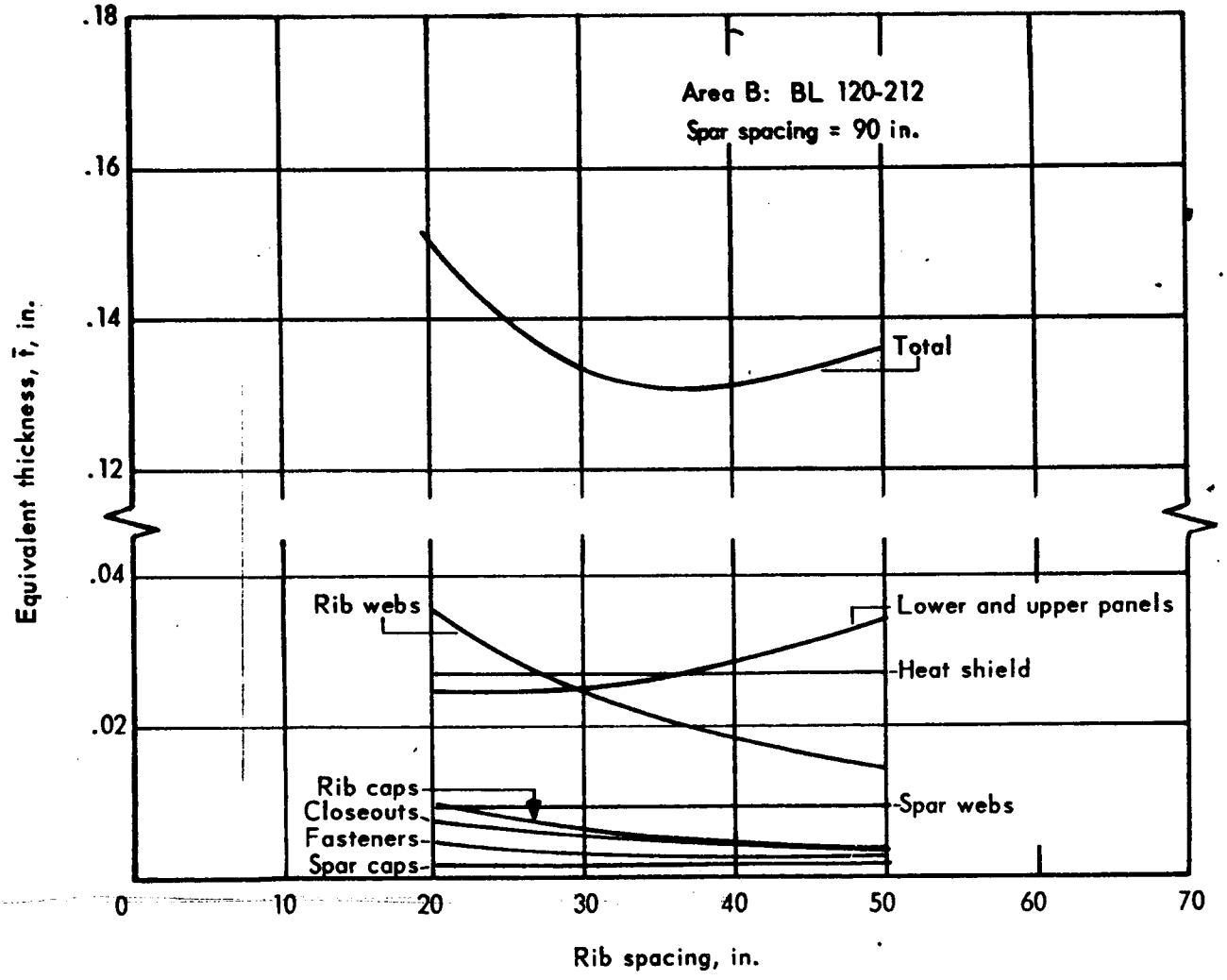
SEMIMONOCOQUE SPANWISE CONCEPT

THERMAL PROTECTION: HEAT SHIELDS ALL SURFACES, OUTBOARD LOWER SURFACE INSULATION
FLIGHT CONDITION: +2.0-g MANEUVER
TEMPERATURE: °F

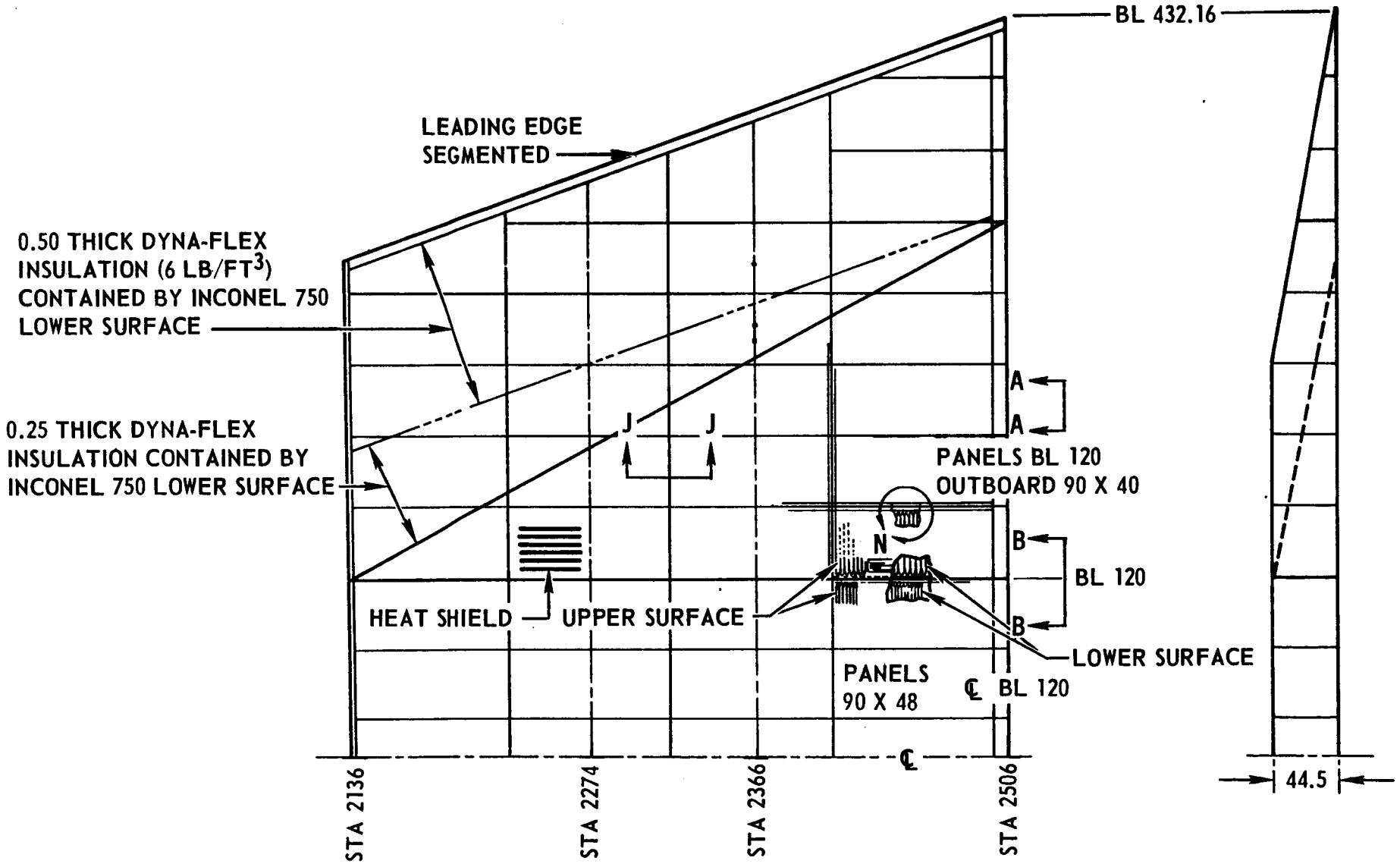


RIB SPACING OPTIMIZATION

SEMIMONOCOQUE SPANWISE BEADED CONCEPT
(THERMAL-PROTECTION SYSTEM: HEAT SHIELDS ON ALL EXPOSED SURFACES WITH INSULATION ON LOWER OUTBOARD SURFACE)



SEMIMONOCOQUE SPANWISE BEADED CONCEPT

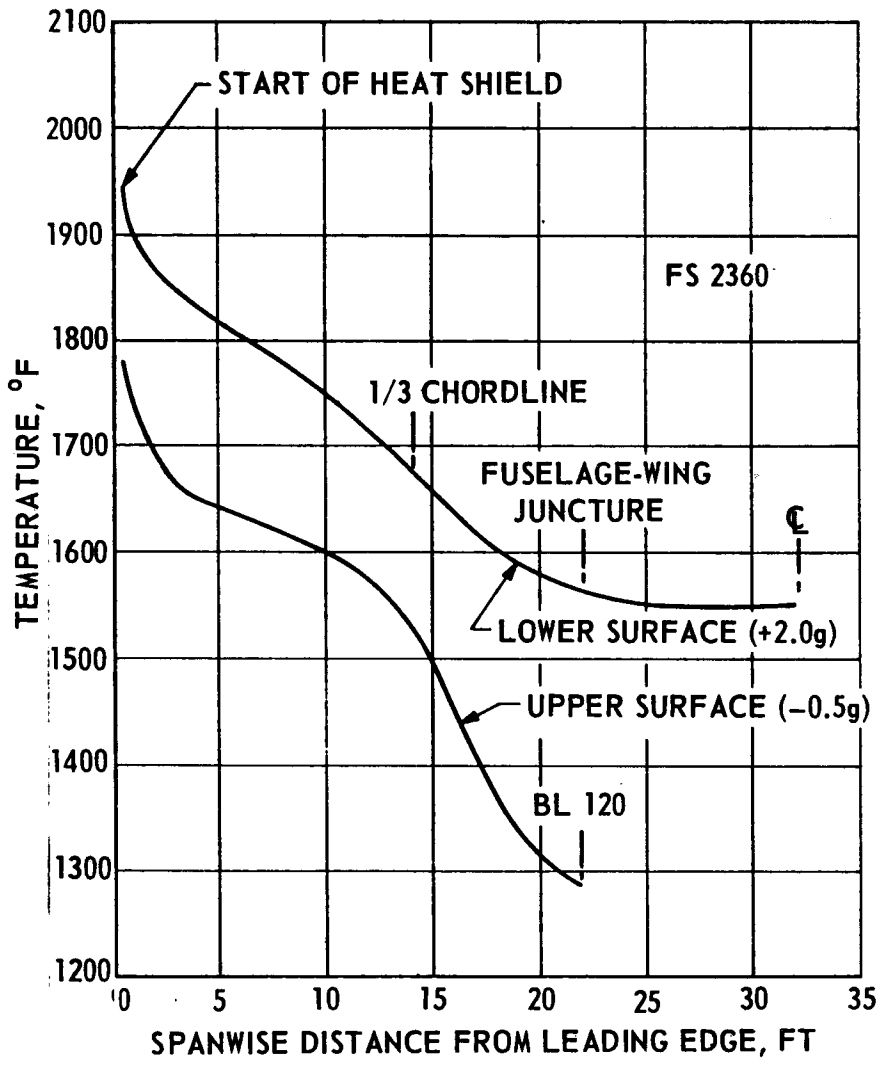


EVALUATION RESULTS

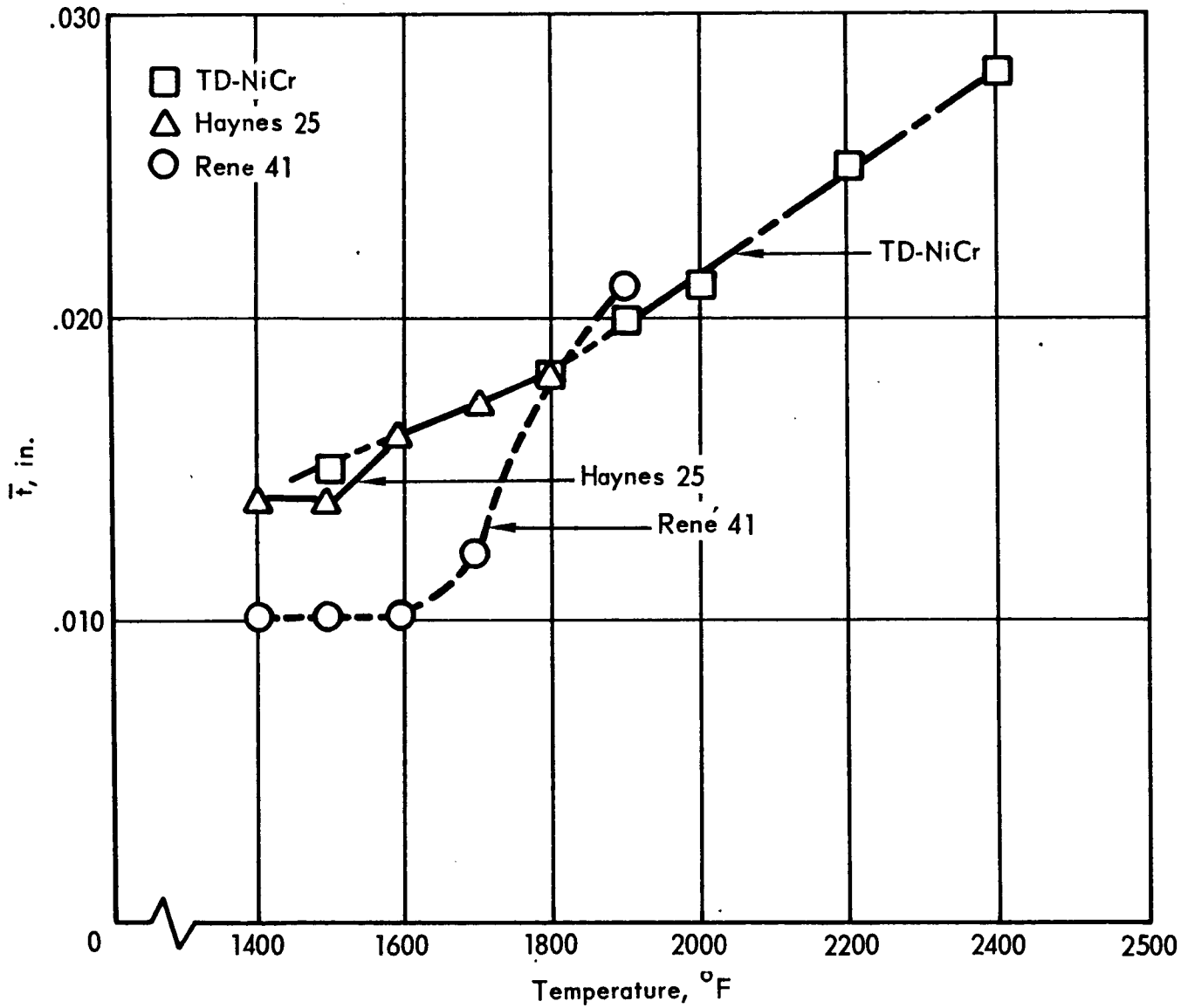
- HEAT-SHIELD WEIGHT ANALYSIS

HEAT-SHIELD TEMPERATURES

HEAT-SHIELD WEIGHT ANALYSIS



WEIGHT COMPARISON OF HEAT-SHIELD MATERIALS



RESULTS OF HEAT-SHIELD STUDY

Heat shield concept		Panel aspect ratio	Support spacing, in.	Maximum deflection, in. [b]	$\Sigma\bar{t}$ in.	Weight, lb/ft^2
Refurbishable	Corrugated skin hat-section stiff. with clip supports	1	15.3	0.380	0.0165	0.707
	Corrugated skin with simple supports	–	15.3	0.360	0.0147	0.630
	Corrugated skin with multiple supports	–	13.1	0.242	0.0131	0.562
	Flat-skin dimple-stiffened with clip supports		15.3	0.173	0.0298	1.28
Permanently attached	Modular, simply supported	–	10.4 [c]	0.195 [d]	0.0118	0.507
	Modular, cantilevered	–	2.61 [c]	0.0073 [d]	0.0123	0.528

[a] Design temperature = 1600°F; oxidation effects not included.

[b] Thermal deflections not included.

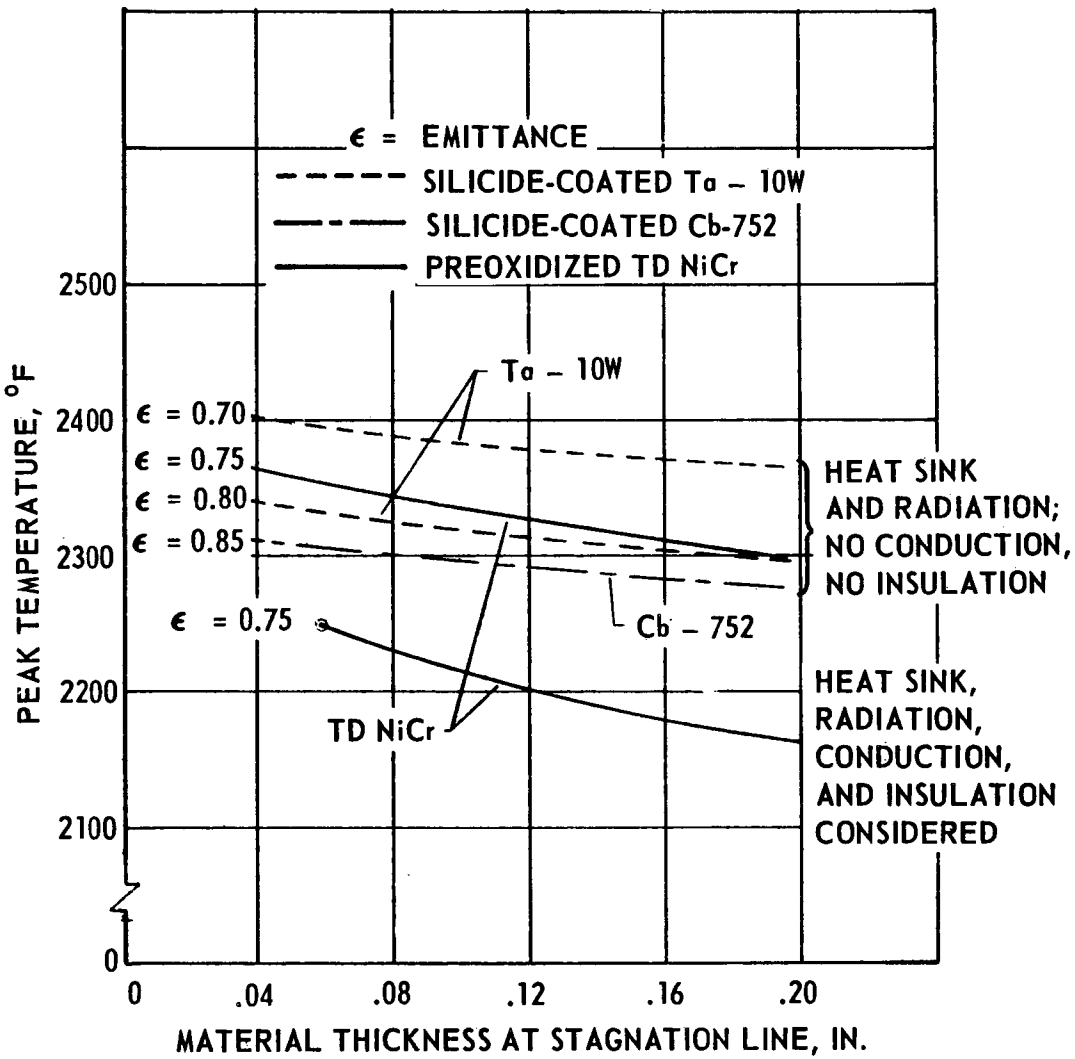
[c] Maximum length allowed due to high bending in wing-panel tube wall from heat-shield loads.

[d] Local deflections of supports not included.

EVALUATION RESULTS

- LEADING-EDGE WEIGHT ANALYSIS

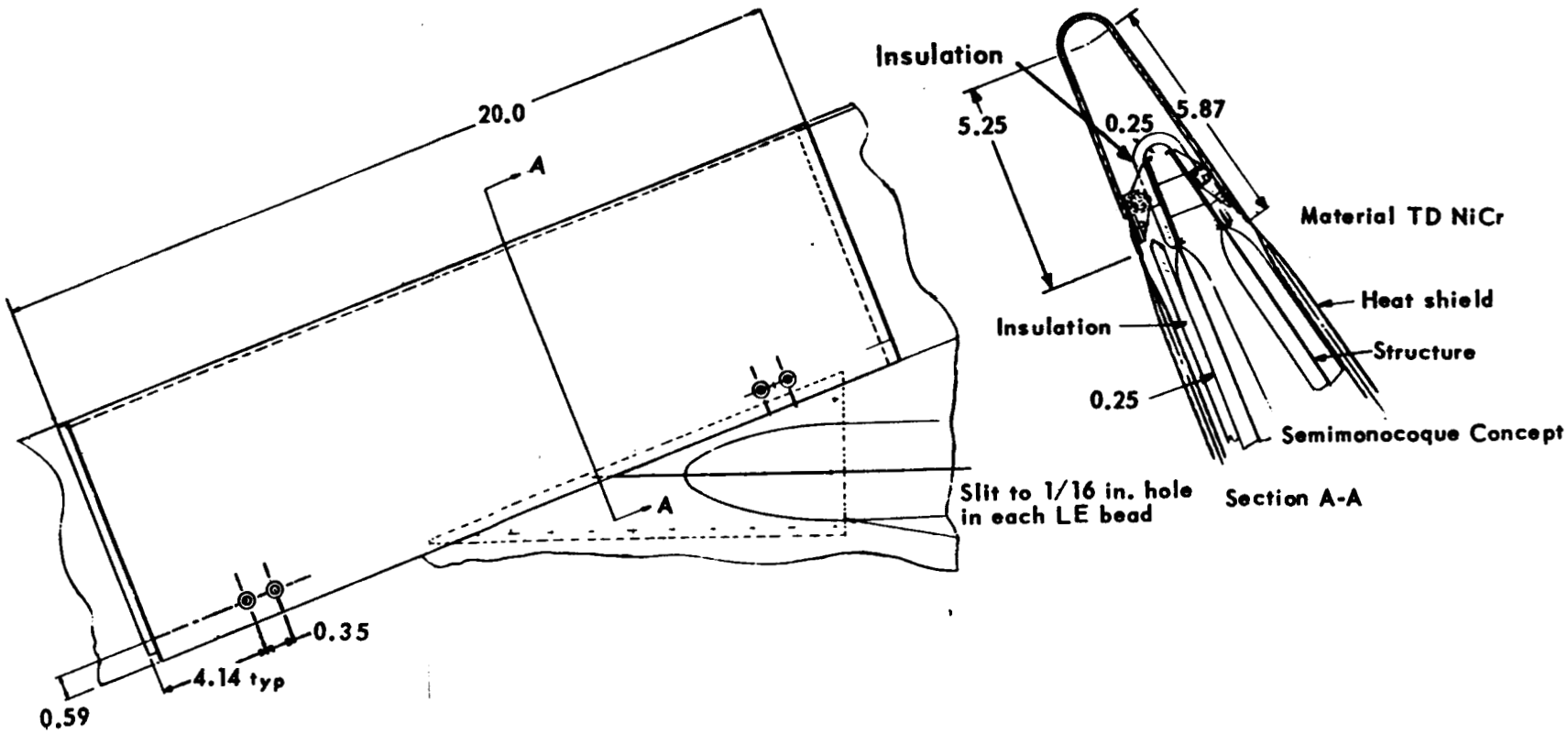
TEMPERATURE VS MATERIAL THICKNESS COMPARISON



LEADING-EDGE DESIGN AND WEIGHT DATA

Item	Selected leading-edge concept	
	Continuous leading-edge concept	Segmented leading-edge concept
Leading edge material	TD NiCr	TD NiCr
Leading edge thickness, in.	0.625	0.125
Flat thickness, in.	0.060	0.030
Segment length, in.	–	20.0
Maximum temperature, ^{o}F (stagnation point, +2-g condition)	2050	2200
Maximum limit elastic thermal strain, ϵ_T, in./in.	-0.00647	-0.000850
Maximum depth of oxidation, δ, in./side (stagnation point, 10,000-hr vehicle life)	0.00151	0.00165
Local buckling margin of safety	High	0.43
Low-cycle fatigue life, flights	12	11.9×10^5
Unit weight, lb/ft^2	8.31	4.89

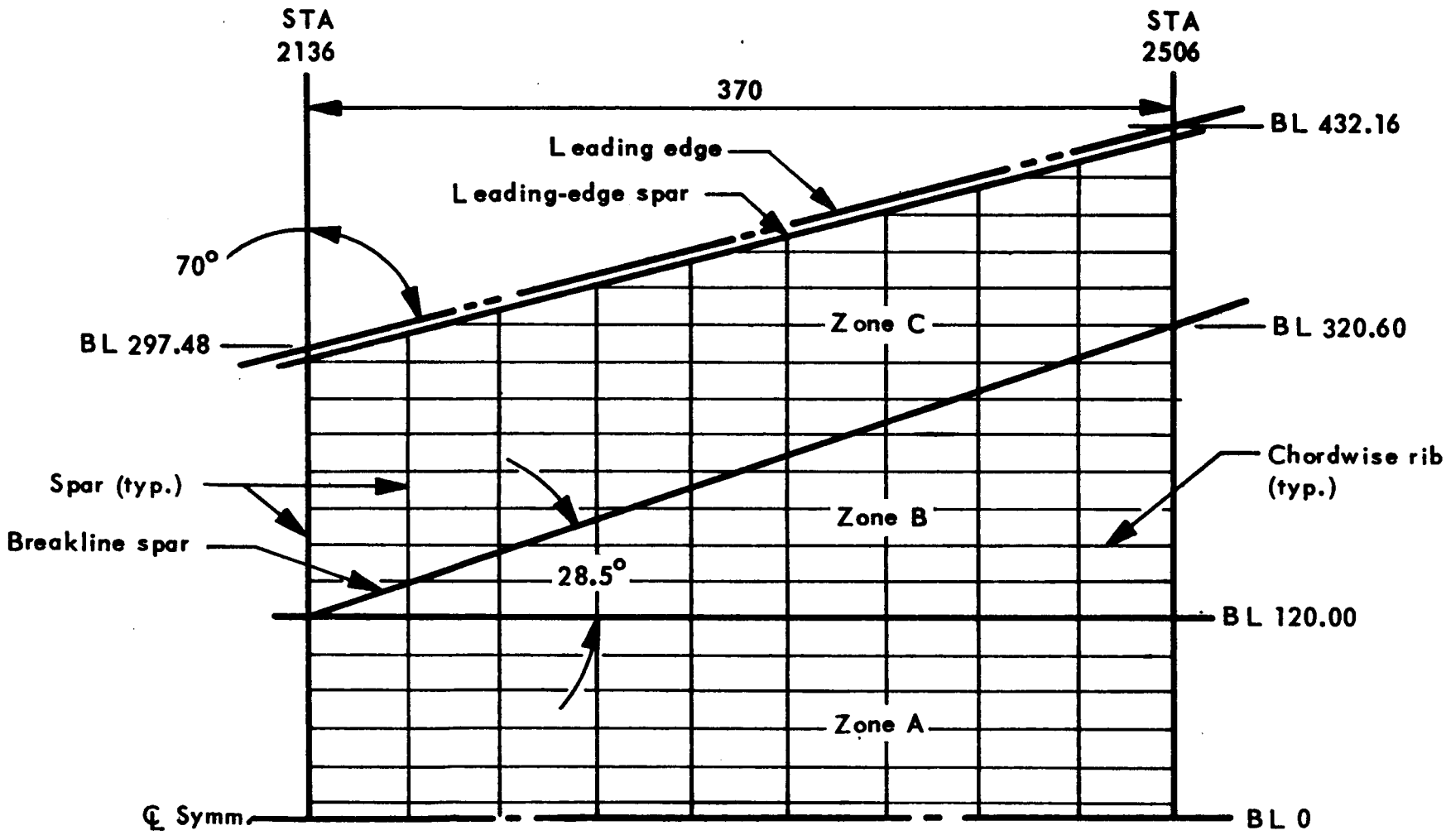
SEGMENTED LEADING-EDGE DESIGN



EVALUATION RESULTS

- COST ANALYSIS

WING COST SEGMENT



PRIMARY-STRUCTURE MANUFACTURING COST

(100 VEHICLES)

Structure Concept	Monocoque		Semimonocoque			Statically determinate
			Spanwise		Chord-wise	Spanwise
	Waffle	Honeycomb-core	Tubular	Beaded	Convex beaded tubular	Beaded
Labor, $	$222 030	$198 740	$112 442	$106 889	$148 038	$136 453
Material, $	461 400	213 964	126 900	120 953	150 741	137 624
Tooling, $	35 125	28 507	33 708	40 922	31 083	42 442
Total cost per unit, $	718 555	441 211	273 050	268 764	329 862	316 519
Weight, lb	9 760	5 970	4 958	4 670	6 150	4 843
Dollars per lb	73	74	55	58	53	65
Dollars per ft^2	779	480	296	291	358	343

Wing segment costed area = 922 ft^2.

BASELINE VEHICLE TOTAL WING MANUFACTURING COSTS

(100 VEHICLES)

PRIMARY STRUCTURE CONCEPT	MONOCOQUE		SEMIMONOCOQUE			STATICALLY DETERMINATE
			SPANWISE		CHORDWISE	SPANWISE
	WAFFLE	HONEYCOMB	TUBULAR	BEADED	CONVEX-BEADED/ TUBULAR	BEADED
LABOR, $\$ \times 10^3$	4 247	3 218	2 457	2 357	3 386	3 846
MATERIAL, $\$ \times 10^3$	11 138	5 337	4 086	3 964	4 834	5 276
TOOLING, $\$ \times 10^3$	1 414	1 024	1 133	1 176	1 186	1 299
TOTAL COST, COST, $\$ \times 10^3$	16 799	9 579	7 676	7 497	9 406	10 421
WEIGHT, LB	99 876	61 568	60 771	57 391	69 657	63 170
DOLLARS/LB	168	156	126	131	135	165
DOLLARS/FT^2	1 719	980	785	767	962	1 066

[a]TOTAL COSTED WING AREA = 9774 FT^2.

HEAT-SHIELD COST EVALUATION

(100 VEHICLES)

Cost evaluation factor	Heat-shield concept			
	Refurbishable		Permanently attached	
	Corrugated skin multiple supports	Flat-skin dimple-stiffened clip-supported	Simply supported	Canti-levered
Material and labor, $ per ft^2	24.5	40.1	44.2	36.4

LEADING-EDGE COST EVALUATION

(100 VEHICLES)

Leading-Edge Concept	Primary structure	Dollars/lb			Dollars/linear ft		
		Labor	Material[b]	Total	Labor	Material	Total
Segmented[a]	Monocoque	22.90	77.55	100.45	97.40	329.60	427.00
	Semimonocoque and Statically determinate	19.90	67.40	87.30	97.40	329.60	427.00
Continuous	Monocoque	51.33	199.13	250.46	387.01	501.34	888.35
	Semimonocoque and Statically determinate	47.50	180.22	227.72	394.79	497.68	892.47

[a]20-in. segments.

[b]TD NiCr.

EVALUATION RESULTS

- PERFORMANCE ANALYSIS

PRIMARY-STRUCTURE CONCEPT PERFORMANCE EVALUATION

FUEL INCREMENT, LB	MONOCOQUE		SEMIMONOCOQUE			STATICALLY DETERMINATE BEADED SKIN
	WAFFLE	HONEYCOMB SANDWICH	SPANWISE TUBULAR	SPANWISE BEADED SKIN	CHORDWISE TUBULAR/ CONVEX BEADED	
UNIFORMLY DISTRIBUTED ROUGHNESS	0	0	0	0	0	0
SHEETMETAL JOINTS AND FASTENERS	19	155	23	23	32	30
SURFACE WAVINESS, LB	31	282	73	81	159	195
CORRUGATION	118	118	427	427	1841	427
DEFORMATION OF PRIMARY STRUCTURE	611	458	314	314	521	388
TOTAL-WING-STRUCTURE CONCEPT	779	1013	837	845	2553	1040
TOTAL-NOMINAL WING ROUGHNESS AND DISTORTION	1110	1110	1110	1110	1110	1110
NET FOR WING ROUGHNESS AND DISTORTION	-331	-97	-273	-265	+1443	-70
FUEL MASS FRACTION	0.3994	0.3998	0.3995	0.3995	0.4026	0.3999

HEAT-SHIELD CONCEPT PERFORMANCE EVALUATION

SURFACE U / L / FUEL INCREMENT, LB	CORRUGATED / CORRUGATED	FLAT-SKIN DIMPLE / FLAT-SKIN DIMPLE	SIMPLY SUPPORTED MODULAR / CORRUGATED	CANTILEVERED MODULAR / CORRUGATED
UNIFORMLY DISTRIBUTED ROUGHNESS	0	0	0	0
SHEET-METAL JOINTS AND FASTENERS	23	31	58	149
SURFACE WAVINESS	73	43	5	5
CORRUGATIONS	427	0	231	231
DEFORMATION OF PRIMARY STRUCTURE	314	314	314	314
TOTAL-WING ROUGHNESS AND DISTORTION	837	388	608	699
TOTAL-NOMINAL WING ROUGHNESS AND DISTORTION	1110	1110	1110	1110
NET FUEL INCREMENT-WING ROUGHNESS AND DISTORTION	-273	-722	-502	-411

LEADING-EDGE CONCEPT PERFORMANCE EVALUATION

PERFORMANCE \ CONCEPT	CONTINUOUS LEADING-EDGE	SEGMENTED LEADING-EDGE
FUEL INCREMENT DUE TO SHEET-METAL JOINTS AND FASTENERS, LB	10.0	14.5
FUEL INCREMENT DUE TO SURFACE WAVINESS, LB	-	6.0
TOTAL FUEL INCREMENT DUE TO ROUGHNESS AND DISTORTION, LB	10.0	20.2

EVALUATION RESULTS

- RELIABILITY ANALYSIS

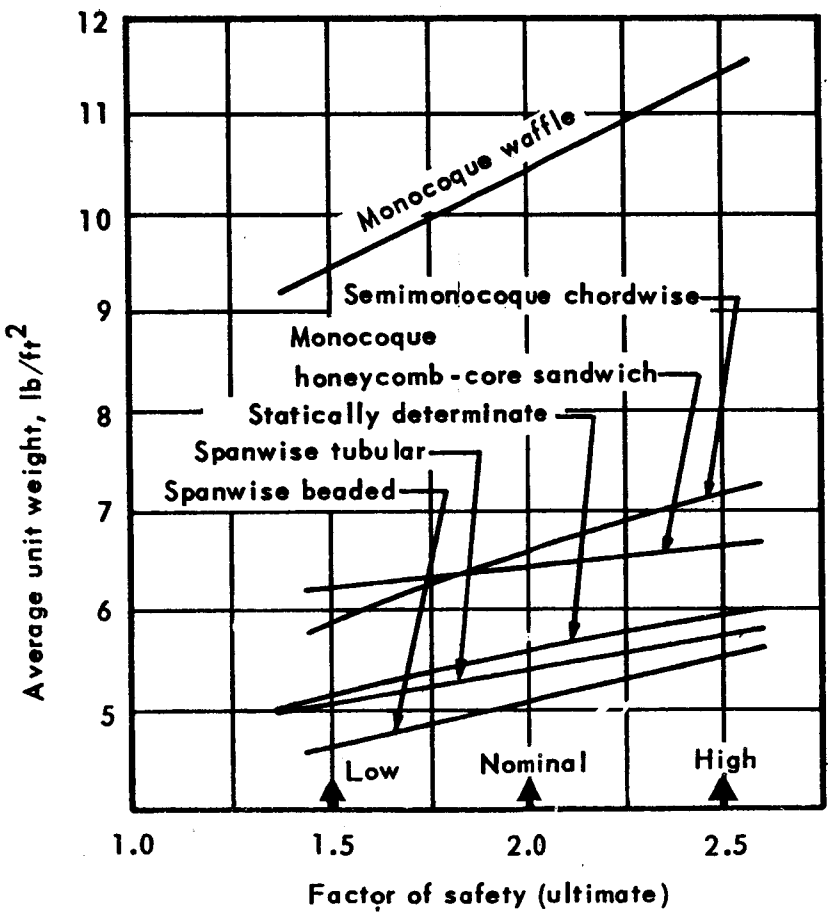
RELIABILITY EVAL WING WEIGHTS FOR BASELINE VEHICLE

Structural concept	Investigation Area		Total wing weight, lb [a]	Total wing average unit weight, lb/ft^2 [b]
	Reliability level	Avg. unit weight, lb/ft^2		
Monocoque waffle	Low	9.446	94 388	9.350
	Nominal	10.494	103 086	10.212
	High	11.402	110 373	10.933
Monocoque honeycomb-core sandwich	Low	6.285	63 254	6.266
	Nominal	6.472	64 778	6.417
	High	6.739	66 756	6.613
Spanwise tubular	Low	5.058	61 114	6.054
	Nominal	5.376	63 981	6.338
	High	5.755	67 418	6.678
Spanwise beaded-skin	Low	4.640	56 753	5.622
	Nominal	5.060	60 601	6.003
	High	5.519	64 766	6.416
Semimonocoque chordwise	Low	5.959	67 000	6.637
	Nominal	6.666	72 867	7.218
	High	7.134	76 742	7.602
Statically determinate	Low	5.139	62 607	6.202
	Nominal	5.550	66 380	6.575
	High	5.912	69 763	6.911

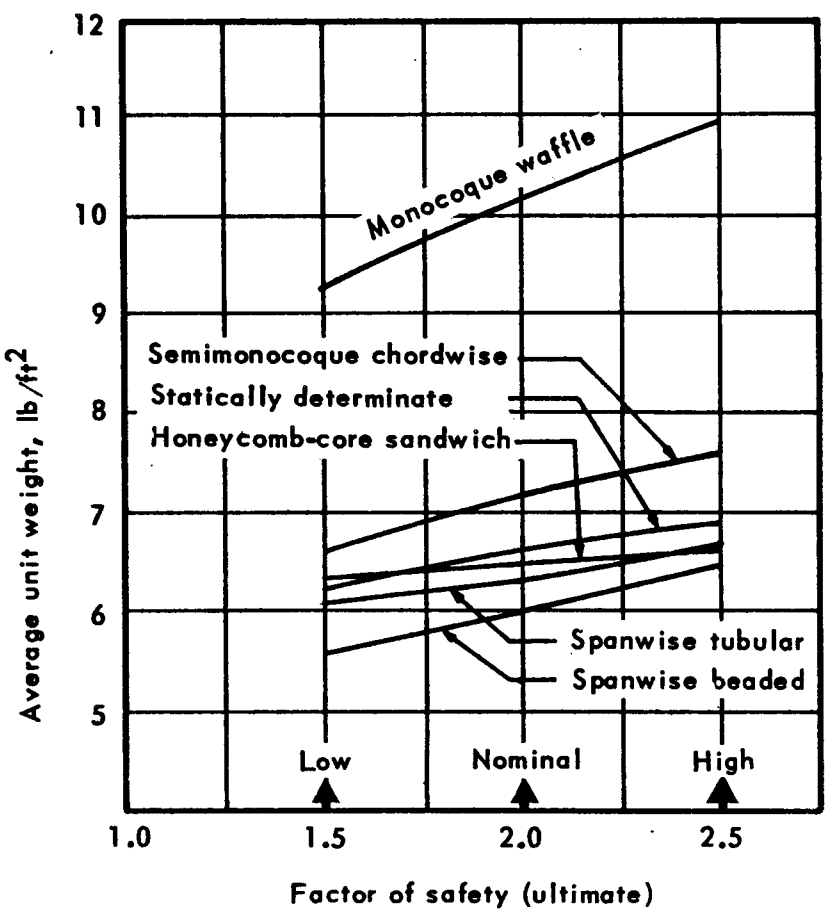
[a]Includes elevon and basic wing weights less leading-edge weight.

[b]Wing area = 10,095 ft^2.

WEIGHT VS FACTOR OF SAFETY



WING INVESTIGATION AREA



TOTAL WING

HEAT-SHIELD RELIABILITY EVALUATION

HEAT-SHIELD CONCEPT		EQUIVALENT PANEL THICKNESS, $\bar{t}$, in.		
		LOW ULTIMATE LOAD FACTOR = 1.5 p_{ult} = 0.75 psi	NOMINAL ULTIMATE LOAD FACTOR = 2.0 p_{ult} = 1.0 psi	HIGH ULTIMATE LOAD FACTOR = 2.5 p_{ult} = 1.25 psi
REFURBISHABLE	CORRUGATED, MULTISUPPORTED	0.0127	0.0131	0.0135
	FLAT-SKIN DIMPLE-STIFFENED, CLIP-SUPPORTED	0.0291	0.0298	0.0298
PERMANENTLY	MODULAR SIMPLY SUPPORTED	0.0118	0.0118	0.0118
	MODULAR CANTILEVERED	0.0123	0.0123	0.0123

[a] P_{LIMIT} = 0.5 PSI

LEADING-EDGE RELIABILITY EVALUATION

Structural arrangement	Leading-edge life (number of flights)		
	Level of reliability [a] [b]		
	Low scatter factor = 1.0	Nominal scatter factor = 1.5	High scatter factor = 2.0
Segmented leading edge t_{NOSE} = 0.125 in. t_{FLAT} = 0.030 in. Length = 20.0 in.	10.0×10^6	11.9×10^5	2.5×10^5
Continuous leading edge t_{NOSE} = 0.625 in. t_{FLAT} = 0.060 in.	74	12	2

[a] Scatter factor applied to low-cycle fatigue strain allowable.

[b] Fatigue quality index, K_Q = 2 (thermal strain).

EVALUATION RESULTS

- INTERACTION OF EVALUATION FACTORS

SUMMARY OF PRIMARY STRUCTURE COST

(CENTS PER TON-MILE)

Structure concept	Level of reliability	Vehicle weight, lb	Vehicle length, ft.	Wing unit weight, lb/ft^2	Payload, lb	Fleet size, no. veh.	Cost oper vehicles, cents/ton-mi
Semimonocoque spanwise beaded	Low	923 970	427	7.126	95 942	115	2.533
	Nominal	882 621	418	7.454	85 068	129	2.758
	High	836 824	407	7.784	74 056	149	3.039
Semimonocoque spanwise tubular	Low	874 287	416	7.497	83 324	132	2.784
	Nominal	840 670	408	7.716	75 618	145	2.975
	High	791 110	395	7.924	66 349	166	3.236
Monocoque honeycomb-core	Low	842 818	408	7.598	77 478	142	3.048
	Nominal	835 241	406	7.748	74 179	148	3.162
	High	799 753	398	7.841	68 388	161	3.317
Statically determinate spanwise beaded	Low	836 318	407	7.897[b]	71 933	153	3.245
	Nominal	797 493	397	8.186	62 906	175	3.574
	High	762 021	388	8.462	55 322	199	3.918
Semimonocoque chordwise tubular	Low	799 766	398	7.898	65 283	168	3.331
	Nominal	726 862	379	8.251	51 669	213	3.903
	High	709 737	375	8.596	45 085	244	4.373
Monocoque waffle	Low	599 236	344	9.809	20 903	526	8.830
	Nominal	562 904	334	10.432	10 748	1023	15.661
	High	529 254	323	10.888	3 323	3310	43.791

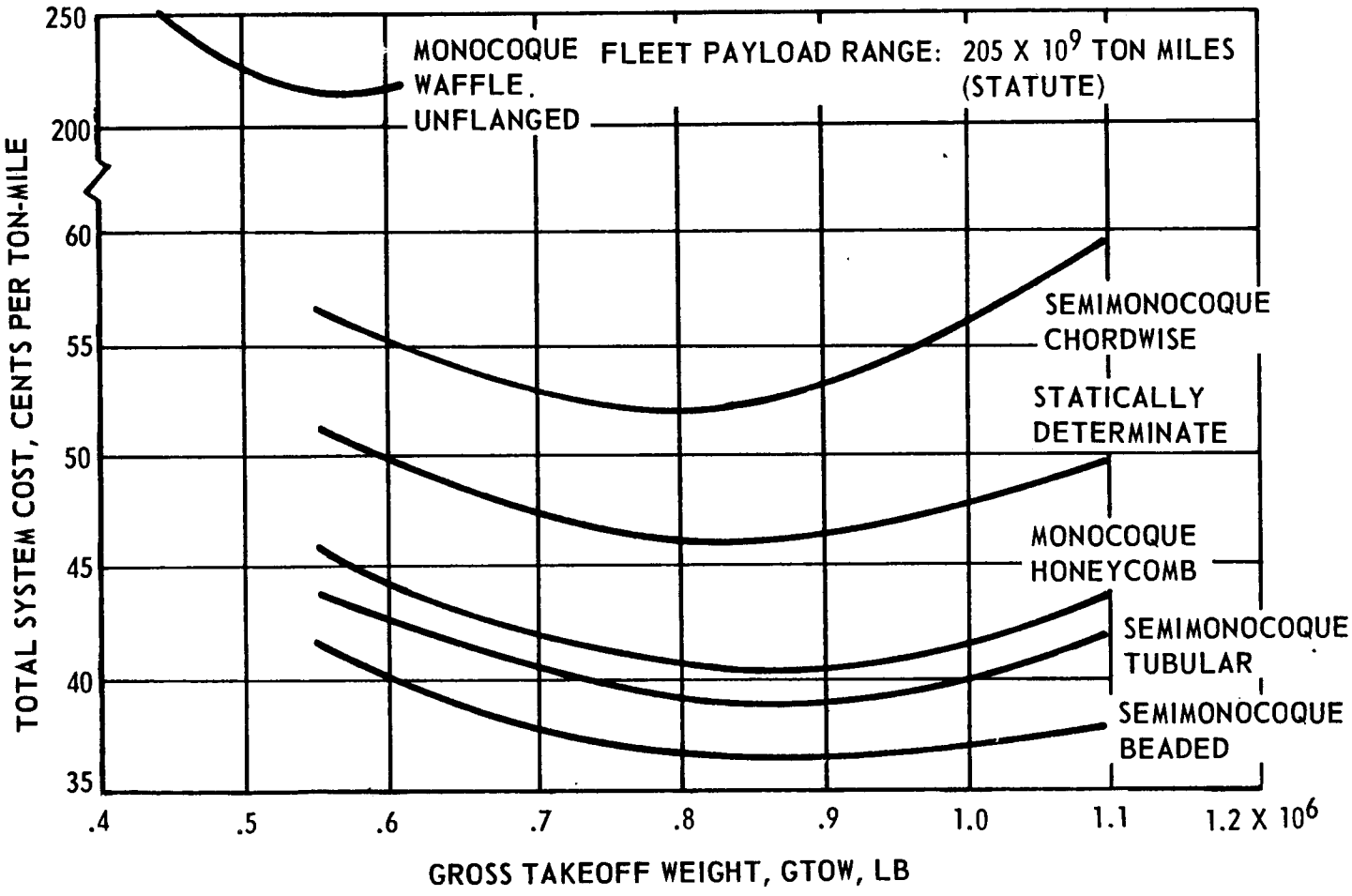
SUMMARY OF PRIMARY STRUCTURE COST

(CENTS PER TON-MILE)

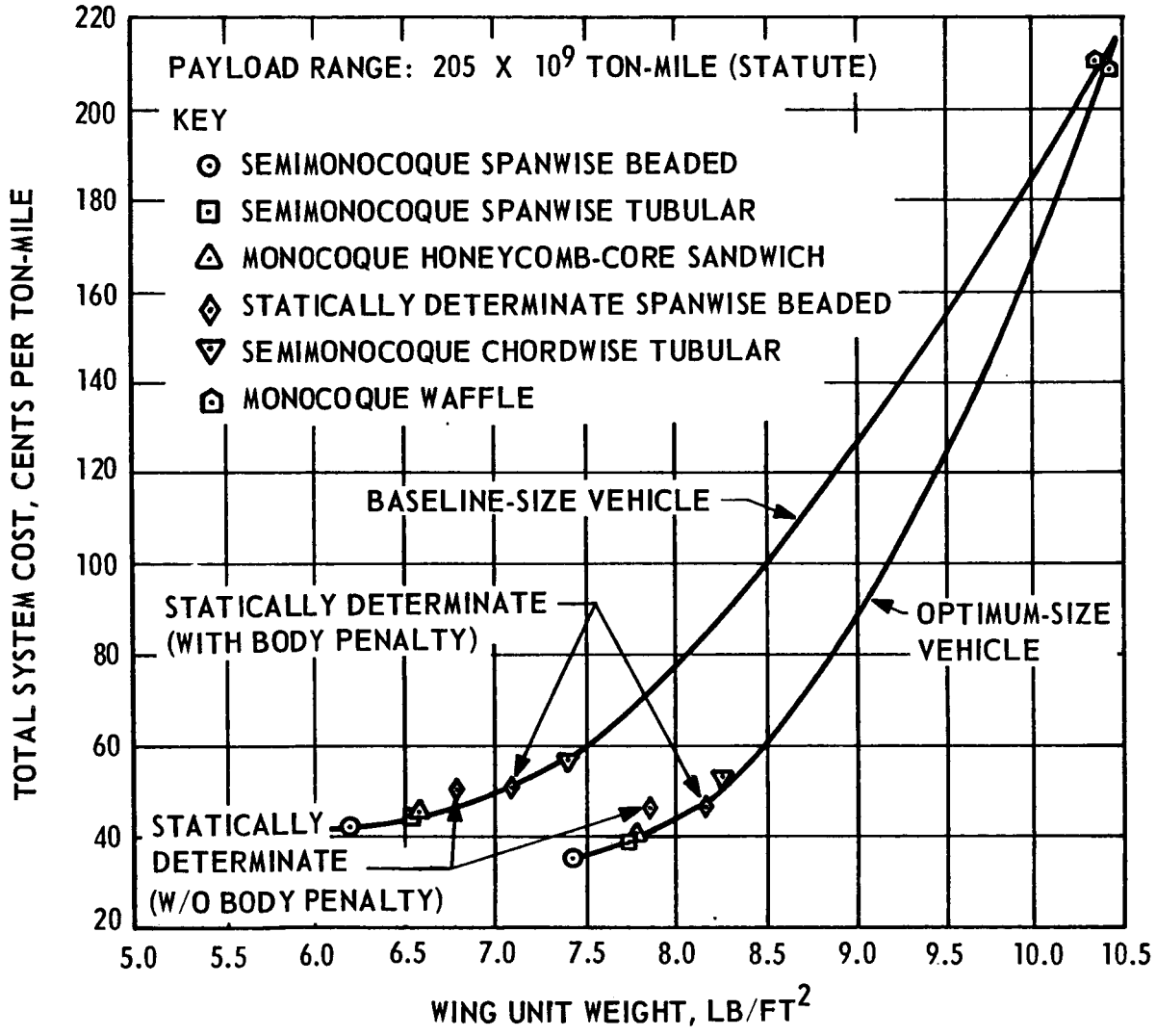
Structure concept	Initial investment[a] cents/ton-mi	DOC, cents/ ton-mi	IOC, cents/ ton-mi	Total operational cost, cents/ton-mi	Total-system-cost cents/ton-mi	Relative total-system-cost
Semimonocoque spanwise beaded	4.229 4.555 4.957	21.09 22.79 24.91	8.09 9.03 10.26	29.18 31.82 35.17	33.41 36.38 40.13	1.00
Semimonocoque spanwise tubular	4.589 4.864 5.235	23.04 24.48 26.29	9.21 10.07 11.41	32.25 34.55 37.70	36.84 39.41 42.94	1.083
Monocoque honeycomb-core	4.971 5.138 5.356	24.14 25.00 26.05	9.83 10.25 11.02	33.97 35.25 37.07	38.94 40.39 42.43	1.110
Statically determinate spanwise beaded	5.264 5.741 6.240	25.80 28.22 30.75	10.57 11.97 13.50	36.37 40.19 44.25	41.63 45.93 50.49	1.263
Semimonocoque chordwise tubular	5.379 6.204 6.895	27.26 31.51 35.30	11.55 14.34 16.36	38.81 45.85 51.66	44.19 52.05 58.56	1.431
Monocoque waffle	13.432 23.482 62.866	65.44 119.30 358.92	34.28 66.06 211.79	99.72 185.36 570.71	113.16 208.84 635.58	5.741

[a]Includes spares.
[b]Includes weight of fuselage body penalty.

COST VARIATION WITH GROSS TAKEOFF WEIGHT



TOTAL SYSTEM COST VS WING WEIGHT



WING WEIGHTS & RELATIVE TOTAL-SYSTEM COST

Wing-panel structure	Weight comparison for baseline-size vehicle		Minimum TSC comparison for optimum-size vehicles
	Wing weight, lb/ft^2	Relative weight	Relative cost
(1) Semimonocoque spanwise beaded	6.20	1.000	1.000
(2) Semimonocoque spanwise tubular	6.53	1.053	1.083
(3) Monocoque honeycomb-core	6.58	1.061	1.110
(4) Statically determinate spanwise beaded	6.77	1.092	1.263
(5) Semimonocoque chordwise tubular	7.41	1.195	1.431
(6) Monocoque unflanged waffle	10.38	1.674	5.741

CONCLUSIONS

- SELECTION OF MOST SATISFACTORY MATERIAL
- RANKING OF WING PRIMARY STRUCTURES
- SELECTION OF HEAT-SHIELD CONCEPT
- SELECTION OF LEADING-EDGE CONCEPT
- DEVELOPMENT OF RATING SYSTEM

MATERIAL SELECTION

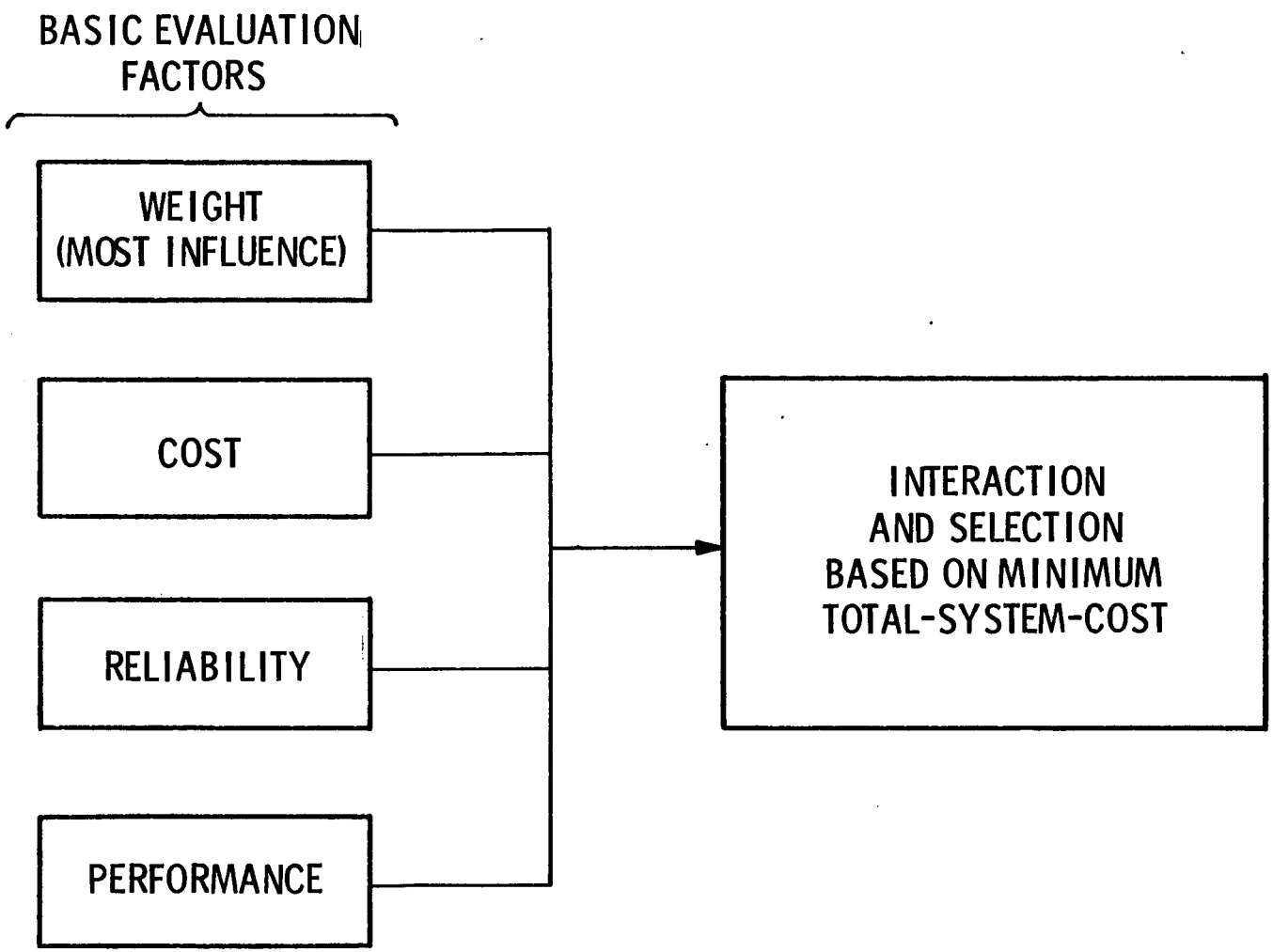
- PRIMARY STRUCTURE – RENÉ 41
- HEAT SHIELD – RENÉ 41 (BELOW 1800^{0}F) AND TD NiCr
- LEADING EDGE – TD NiCr (REFRACTORY METALS NOT REQUIRED)

WING PRIMARY-STRUCTURE RANKING

1. SEMIMONOCOQUE SPANWISE-STIFFENED BEADED SKIN
2. SEMIMONOCOQUE SPANWISE-STIFFENED TUBULAR
3. MONOCOQUE HONEYCOMB-CORE SANDWICH
4. STATICALLY DETERMINATE SPANWISE BEADED SKIN
5. SEMIMONOCOQUE CHORDWISE-STIFFENED TUBULAR
6. MONOCOQUE UNFLANGED WAFFLE

HEAT-SHIELD & LEADING-EDGE SELECTION

- HEAT SHIELD – REFURBISHABLE
  CORRUGATED SHIELD WITH MULTIPLE SUPPORTS

- LEADING EDGE – SEGMENTED

RATING SYSTEM