

INFLUENCE OF STRUCTURE AND MATERIAL RESEARCH
ON ADVANCED LAUNCH SYSTEMS' WEIGHT,
PERFORMANCE, AND COST

Summary Report

By J. A. Boddy and J. C. Mitchell

Distribution of this report is provided in the interest of information exchange. Responsibility for the contents resides in the author or organization that prepared it.

Issued by Originator as SID 67-542-1

Prepared under Contract No. NAS 7-368 by
NORTH AMERICAN AVIATION, INC.
Downey, Calif.

for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

PRECEDING PAGE BLANK NOT FILMED.

ABSTRACT

This report summarizes Phase I and Phase II of the study effort completed under Contract NAS7-368, Development of Programmed Assistance in Directing Structures Research. The report covers the contract period from 25 May 1965 through 30 June 1967.

Phase I of this program involved modifying and utilizing existing automated analytical techniques to determine significant structures and materials research areas in current and predicted future expendable launch vehicle systems. The Phase I study covers the parametric synthesis of expendable launch vehicles and a more detailed design synthesis of some of the structural components of these vehicle systems. A definition of the vehicle systems and structural synthesis of Phase I is summarized in this volume.

The Phase II effort was an extension of the design synthesis to advanced structural concepts, application to the base-line vehicle systems of Phase I and the evaluation of their relative merits to provide direction for worthwhile areas for structures and material research. Parametric vehicle synthesis was further adapted to encompass vehicle systems with recoverable first stages. The recoverable stages considered here were expendable stages with recoverable features, i. e., winged body shapes with flyback propulsion and landing provisions. Major technical effort, methods of analysis and detail information is presented in Volume 2* of this study. A summary of the major information and technical findings are given in this volume.

This study is being funded by the National Aeronautics and Space Administration, Office of Advanced Research and Technology, under the direction of Mr. M.G. Rosche, Chief of Structures, assisted by Mr. D.A. Gilstad, Chief, Structural Loads and Cryogenic Structures.

Study effort was accomplished at the Space Division of North American Aviation, Inc., Downey, by the Structures and Materials Department, Research and Engineering Division, under the direction of Dr. L.A. Harris. Principal investigators included Messrs. J.C. Mitchell, L.A. Moss, and C.W. Martindale, with additional contributions by Messrs. D. Jones (Propulsion), and L.B. Norwood (Manufacturing). All work was under the supervision of Mr. W.D. McKaig, Project Manager, and J.A. Boddy, Project Engineer.

* NAA/SID 67-542-2

CONTENTS

	Page
SUMMARY	1
INTRODUCTION	4
EXPENDABLE VEHICLES	7
Parametric Synthesis	7
Structural Design Synthesis	10
Expendable Vehicle Component Assessment	17
RECOVERABLE VEHICLE SYNTHESIS	42
SYNTHESIS PROGRAMS	48
CONCLUSIONS	51
Construction Concepts	51
Material Strength Improvement	53
Experimental Verification	54
Manufacturing Development	55
Recoverable Vehicles	55
REFERENCES	56

ILLUSTRATIONS

Figure	Page
1. - Evaluation Logic	8
2. - Shell Unit Weights for Conventional Titanium and Aluminum Structures—130-Inch Radius, 300°F, No Pressure	19
3. - Shell Unit Weights for Conventional Titanium and Aluminum Structures—198-Inch Radius, 300°F, No Pressure	20
4. - Shell Unit Weights for Advanced Aluminum Structures—130-Inch Radius, 300°F, No Pressure	21
5. - Shell Unit Weights for Advanced Titanium Structures—130-Inch Radius, 300°F, No Pressure	22
6. - Shell Unit Weights for Advanced Titanium Structures—270-Inch Radius, 300°F, No Pressure	23
7. - Shell Unit Weights for Conventional Beryllium Structures—130-Inch Radius, 300°F, No Pressure	24
8. - Stiffener Positioning Effectiveness Ratio	25
9. - Relative Merit of Externally Stiffened Titanium Shells, Component Shell Radius Versus Load Intensity	26
10. - Merit Partial of 30 000-Pound-Payload Vehicle (Second Stage)	37
11. - Merit Partial for 240 000-Pound-Payload Vehicle (First Stage)	38
12. - Merit Partial for 240 000-Pound-Payload Vehicle (Second Stage)	39
13. - Merit Partial for 1 000 000-Pound-Payload Vehicle (First Stage)	40
14. - Effect of Expendable Upper Stages	44

TABLES

Table	Page
1. - GENERIC FAMILIES-TWO-STAGE LAUNCH VEHICLES, MINIMUM LIFTOFF MODE PROPORTIONED VEHICLES	10
2. - VEHICLE STATIONS AND DIAMETERS FOR THE BASE- POINT DESIGN (IN.)	11
3. - PERFORMANCE AND PAYLOAD EXCHANGE RATIOS FOR EXPENDABLE BASE-POINT VEHICLES	12
4. - VEHICLE WEIGHT STATEMENT FOR STAGE 1 (LB)	13
5. - VEHICLE WEIGHT STATEMENT FOR STAGE 2 (LB)	14
6. - STRUCTURAL COMPONENTS AND THEIR DESIGN ULTIMATE APPLIED LOAD (N_x IN POUNDS PER INCH)	15
7. - REPRESENTATIVE MATERIAL PROPERTIES AND ADVANCEMENTS.	18
8. - COMPONENT WEIGHT SUMMARY (LB), 30 000-LB PAYLOAD EXPENDABLE VEHICLE, CURRENT I_{sp}	28
9. - COMPONENT WEIGHT SUMMARY (LB), 100 000-LB PAYLOAD EXPENDABLE VEHICLE, 1985 I_{sp}	28
10. - COMPONENT WEIGHT SUMMARY (LB), 240 000-LB PAYLOAD EXPENDABLE VEHICLE, CURRENT I_{sp}	29
11. - COMPONENT WEIGHT SUMMARY (LB), 445 000-LB PAYLOAD EXPENDABLE VEHICLE, 1985 I_{sp}	29
12. - COMPONENT WEIGHT SUMMARY (LB), 1 000 000-LB PAYLOAD EXPENDABLE VEHICLE, CURRENT I_{sp}	30
13. - COMPONENT WEIGHT SUMMARY (LB), 2 000 000-LB PAYLOAD EXPENDABLE VEHICLE, 1985 I_{sp}	30
14. - VEHICLE STAGE EXCHANGE RATIO	31
15. - PAYLOAD WEIGHT CHANGE SUMMARY (CHANGE FROM ALUMINUM A INTEGRAL SKIN STRINGER BASEPOINT) 30 000-POUND PAYLOAD, EXPENDABLE VEHICLE, CURRENT I_{sp}	32
16. - PAYLOAD WEIGHT CHANGE SUMMARY (CHANGE FROM ALUMINUM A INTEGRAL SKIN STRINGER BASEPOINT) 240 000-POUND PAYLOAD, EXPENDABLE VEHICLE, CURRENT I_{sp}	33

17. - PAYLOAD WEIGHT CHANGE SUMMARY (CHANGE FROM ALUMINUM A INTEGRAL SKIN STRINGER BASEPOINT) 1 000 000-POUND PAYLOAD, EXPENDABLE VEHICLE, CURRENT I_{sp}	34
18. - COST RATIO SUMMARY (DOLLARS PER POUND OF PAYLOAD GAINED) VALUES NORMALIZED BETWEEN AND PRESSURIZED AND UNPRESSURIZED SHELLS .	35
19. - VEHICLE STATIONS AND DIAMETERS (IN.) FOR BASE-POINT DESIGN, RECOVERABLE FIRST-STAGE BOOSTER	45
20. - WEIGHT AND PERFORMANCE CHARACTERISTICS . .	46
21. - BOOST PHASE PRESSURE MATRIX (PSI). . . .	46
22. - APPLIED LOADS MATRIX FOR BASEPOINT DESIGNS, RECOVERABLE FIRST-STAGE BOOSTER	47
23. - PARAMETRIC VEHICLE SYNTHESIS PROGRAMS . . .	49
24. - PRELIMINARY STRUCTURAL DESIGN SYNTHESIS . .	50

INFLUENCE OF STRUCTURE AND MATERIAL RESEARCH ON
ADVANCED LAUNCH SYSTEMS' WEIGHT, PERFORMANCE, AND COST
SUMMARY REPORT

By J. A. Boddy and J. C. Mitchell
Space Division
North American Aviation, Inc.

SUMMARY

Launch Vehicle and Design Synthesis programs of the North American Aviation, Inc., Space Division were adapted to synthesize families of vertically launched, tandem staged, booster vehicles. The vehicles were two- and three-stage-to-orbit systems with expendable upper stages and expendable—Phase I—or recoverable (winged body)—Phase II—first stages. The major structural elements were investigated to assess the relative benefits to be derived from advanced structural designs and materials.

Base point expendable vehicles—Phase I—were developed using predicted improvements in propulsion and propellant characteristics, considering advances through three periods, i. e., the current year to 1970, 1970 to 1980, and the post-1980 period. For each of the periods, the equivalent 100-nautical-mile earth orbital payloads were classified into the following ranges:

30 000 to 100 000 pounds — medium range payload class

225 000 to 500 000 pounds — Saturn payload class

1 000 000 to 2 000 000 pounds — post-Saturn payload class

Phase II base point vehicles with winged body recoverable first stages and expendable second stages and payloads were synthesized for systems with launch weights of 1.3, 1.9, and 2.5 million pounds. These vehicle systems, with their upper stages subsequently replaced by recoverable wing body configurations, would effectively place in orbit payloads of 20 000, 40 000 and 60 000 pounds respectively.

These payload ranges were assumed to encompass anticipated future missions for the periods under consideration and resulted in the identification and definition, in sufficient detail, of typical vehicle systems on which to operate in order to assess the effects of structures and materials advances and to identify areas where research in structures and materials will be most effective from a technological and systems aspect. The size description and design loading environment are given in this volume.

Structural analyses were conducted on a spectrum of stage diameters (260 to 540 inches) and a range of loading intensities (2 000 to 20 000 pounds per inch), and included shell synthesis to obtain optimum weight for conventional construction concepts (monocoque, integral, top hat, Z, I section skin-stringers, honeycomb sandwich, ring-stiffened and waffle) and advanced concepts (corrugated sandwich, multiwall corrugated and double-wall skin-stringer stiffeners using sine-wave substructure). Materials investigated included aluminum, titanium and beryllium.

The method of evaluation involved a component-by-component substitution in the expendable base point vehicle systems. Estimated manufacturing complexity factors, material cost variations with time, and manhour requirements were included in the cost assessment. Cost assessment was accomplished by isolating each structural component and performing a comparative evaluation of the new component with respect to the base point component—this being considered to be aluminum integral skin-stringer construction. Final assessment is made in terms of the merit functions: component weight reduction, equivalent payload gained from this reduction, and cost ratio for the new component which is identified as additional (or decreased) dollars cost per pound of payload gained. The three merit functions are then organized in arrays to order their importance.

Although merit functions other than those used in this study do exist, e.g., effect of design changes upon production schedule, they are not readily analyzed numerically and, therefore, are not included in this report. The

study results, which are based upon weight, payload gain, and cost-ratio merit functions, indicated the following:

Multiwall and double-wall shell concepts for tanks and unpressurized structures offer distinct advantages, but research is required in design application, manufacturing techniques, core stiffness requirements, general instability analysis, and test verification.

Honeycomb sandwich is beneficial for most booster stage applications, especially for large systems where deep core is required. Related research in design application and manufacturing technology for these concepts is required.

Beryllium structures offer the most distinct weight advantages, though at more cost. Moderate cost improvements from materials and manufacturing research, along with design experience, will make beryllium structures highly competitive.

The most attractive current weight-to-cost design is aluminum skin-stiffened using Z- or hat-section stringers. Simplified construction, such as ring-stiffened, if used for first stages when cost and/or schedule considerations are paramount, results in moderate payload decreases.

Improvements in the strength properties of a given material should be directed to multiwall and honeycomb sandwich concepts only.

Externally positioned longitudinal stiffeners are most effective in beryllium designs. Aluminum and titanium designs require individual evaluation for small improvements in stiffener positioning, if any; eccentricity effects diminish with increased shell diameter.

Recoverable vehicle systems, with their small payload-to-launch-weight ratio, will benefit more from structural weight reductions than expendable systems will, especially in the upper stages.

Generally, research would be more beneficial when devoted to manufacturing and design development for new and advanced structural concepts and for developing materials with markedly improved mechanical and physical properties rather than by forcing improvement of current material ultimate strength properties.

INTRODUCTION

Effective and timely research in structural and material sciences can contribute significantly to further advances in the continuing development of launch-vehicle and space technology. In order to determine desirable directions for structural and materials research, a method is required that permits evaluation of predicted advances in terms of weight, performance, and cost benefits for the various classes or types of vehicles foreseen to fulfill the requirements of future space systems.

In order that decisions be sensible and timely, the spectrum of future vehicle systems, which result from predicted advances in all of the contributing technological disciplines, must be understood. Any technique to provide the necessary data for research and development planning must have the capability to synthesize these future vehicle systems and to measure the interactions of the basic launch vehicle parameters with the structural system as they affect vehicle weight, performance, and cost. This technique must of necessity, due to the complex systems being studied, be capable of starting with basic mission requirements and efficiently synthesize realistic vehicle systems to meet these requirements, evaluate the effects of suggested structures and materials advances, and identify the most useful application of an advancement. This application then must be related to specific vehicle system and type of component in terms of weight improvement, performance improvement, and cost change.

This is the report of contract NAS7-368 in which the Space Division of North American Aviation, Inc., has been involved in modifying, extending, and utilizing automated analytical techniques to determine significant structures and materials research areas in current and predicted launch vehicle systems.

Parametric synthesis¹ of two- and three-stage expendable vehicles were developed during the Phase I study. The vehicles of that series have current, near-term and future predicted propulsion and propellant systems. A summary of the base point vehicles, their description, size, performance structural component weights, and design loading environments are contained in this volume; additional details are to be found in the Phase I Interim Report.

¹Parametric synthesis: An automated technique in which numerous vehicle systems are synthesized using limited input parameters and resulting in lumped-mass definitions of vehicle stages and their primary subsystems, stage performance ratios, and gross size characteristics.

Future mission and economic considerations indicate the need for serious evaluation of launch vehicle recovery and reusability. Booster recovery with such devices as parachutes and retrosystems has been considered by NASA and the industry as an interim step before more sophisticated winged and powered recovery systems are developed. NASA studies, such as the Reusable Orbital Transport Study, have considered entirely new vehicle concepts with special body-shape characteristics, employing not only horizontal recovery, but horizontal take-off as well. It is considered that a reasonable vehicle evolution may well be to first modify the lower stages of the expendable system to a winged body system with powered flyback and horizontal landing while still retaining the expendable upper stage. The next step could include rendering the upper stage recoverable, using both winged body and lifting body shapes for the upper stage. The first step to modifying a lower stage to provide recoverability is covered in the present Phase II study and reported in summary form in this volume with the technical details reported in Volume 2.* Both study phases also consider preliminary design synthesis¹ of the major structural components of the expendable vehicle system.

During Phase I of this study, aluminum, titanium, and beryllium materials were utilized in monocoque, waffle, skin-stringer, and honeycomb sandwich shells, and their performance and cost merits were assessed within the basepoint vehicle families synthesized. Phase II extended the structural studies to cover corrugated, corrugated sandwich, and several multiwall shell concepts, as well as several bulkhead concepts, with merit functions assessed using the same basepoint expendable vehicles and the same material types and property predictions as utilized during Phase I.

A complete summary of the structural data and their application and benefits, if any, are presented in this volume. The technical analysis, approach, and structural details of Phases I and II are reported in reference 1 and Volume 2, respectively.

This report also includes a synopsis of the synthesis programs used, their capability and design options. The plan for turning over to NASA the computer programs is discussed in detail in Volume II.

¹Preliminary design synthesis: An automated technique in which a few vehicle systems are subjected to preliminary design analysis considering component design constraints and resulting in identification of optimum component design within the input constraints—in this study, considering only the structural subsystem.

The effort documented in this report utilizes the North American Aviation, Inc. , Space Division background in vehicle synthesis and computer-aided design by modifying and extending digital computer subroutines from these programs. It also draws considerably on work in recoverable launch vehicle systems studies performed by NAA/SD and others. Obviously, the background developed in Phase I of this contract is used extensively wherever possible and appropriate for the Phase II study.

EXPENDABLE VEHICLES

Parametric Synthesis

The synthesis of expendable vehicles was limited in the study to two- and three-stage vehicles, vertically-launched, tandem-staged, and using bipropellant systems. Construction and material design synthesis analyses and tradeoffs were made on the baseline vehicles for the pressurized and unpressurized cylindrical shells and for bulkheads. The shells were fabricated from aluminum, titanium, or beryllium, and the construction included conventional concepts (monocoque, ring-stiffened; waffle; Z, top hat, and I section and integral skin-stiffened, honeycomb sandwich) and advanced concepts (corrugated sandwich, double-wall skin stringer, and multiwall corrugated with sine wave substructures).

Figure 1 differentiates the parametric synthesis task from the preliminary design synthesis task and illustrates how the flow of information between program elements is effected. Vehicle synthesis is initiated by defining mission requirements (payload weight and velocity) and the propulsion characteristics for the mission (thrust levels, specific impulse, mixture ratio, propellant type, and density). A general configuration indicator for the vehicle is defined for the digital program. This permits identifying the proper stage sizing model to identify tankage arrangements, fineness ratios, diameters, bulkhead aspect ratios, etc.

Preliminary base point shell construction data are provided by the stress analysis subroutines and stored in terms of generalized (unit weight/radius) versus (applied load/radius) curves. The minimum liftoff mode of the stage proportioning subroutine (ref. 1, Appendix A) is used to initiate stage-wise performance characteristics for the stage mass fraction subroutine (ref. 1, Appendix B) which sizes base point vehicles and identifies mass fraction partials about the base points. The generalized shell weight curves are used to obtain structural weights of the vehicles in the mass fraction operation. The resulting mass fraction curves are then recycled through the maximum payload mode proportioning subroutine. When the vehicle has been proportioned satisfactorily, the generalized payload exchange ratios are produced for the base point vehicles. Printouts from the mass fraction operation are obtained to define vehicle geometry, weight statements, mechanical loading environment, and mass properties

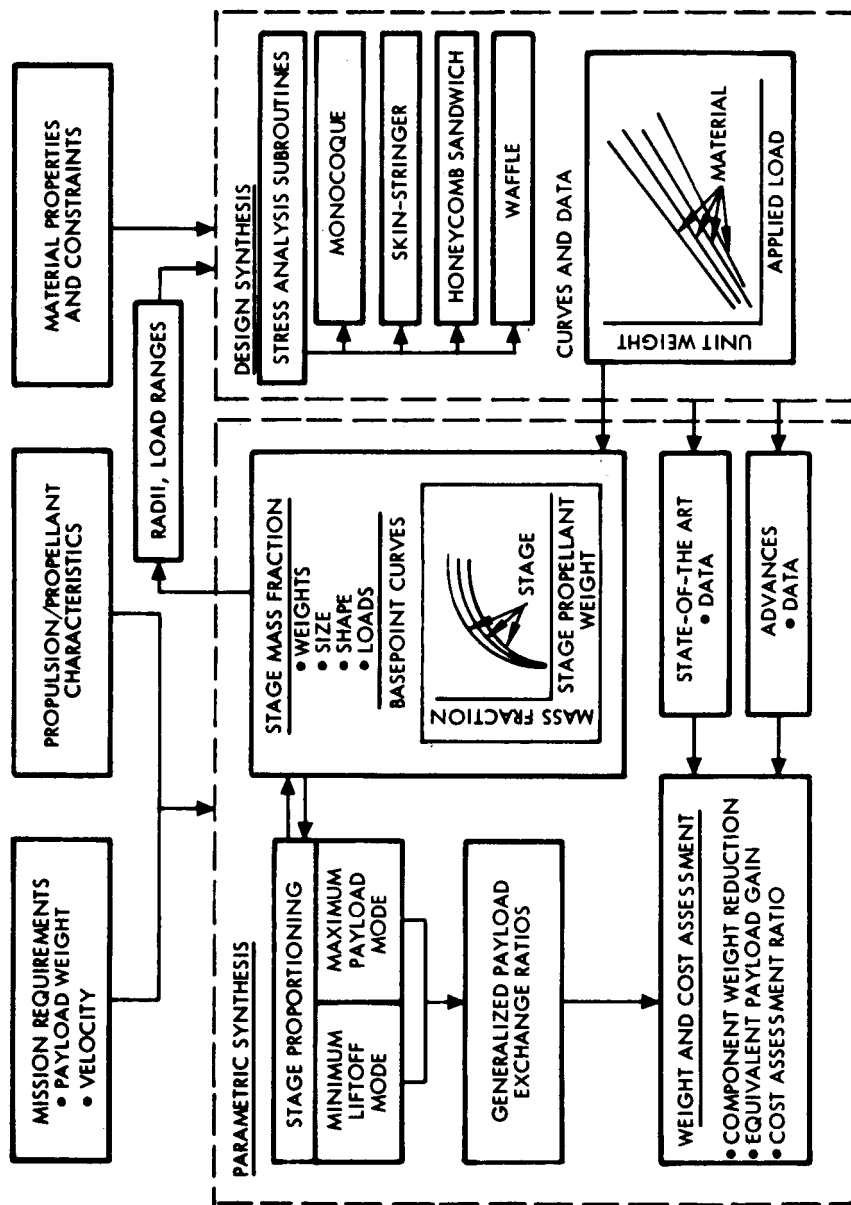


Figure 1. - Evaluation Logic

Sufficient data are then available describing the vehicle system, weight, performance, and stage mass fractions, to perform detail performance and load-environment evaluation, if required, with larger and more sophisticated analysis programs. This should be performed external to the synthesis evaluation. The improved data from these more sophisticated programs can provide an adjustment to the parametric values by updating the coefficients for the mass fraction subroutine and the parametric operation recycled.

When base point vehicles have been properly established, a range of loading intensities is obtained and used for the design synthesis stress analysis operation to provide design data covering all pertinent construction types and materials. These data, in terms of applied load, unit weight, radius, and pressure can be fed directly to the assessment model to determine the direct effect upon component weight, equivalent payload, and cost assessment ratio when one material-construction structural component is substituted for another. If desired, the generalized weight-load curves for these alternate designs can be used by the stage mass fraction subroutine and the proportioning operation to resize the entire vehicle. The built-in subroutine independency in the program logic provides flexibility that is demonstrated in reference 1 .

Initiation of the parametric synthesis task is dependent upon a definition of the missions to be investigated and technological predictions concerning the advances that might be expected in material properties, manufacturing techniques, and propulsion and propellant systems. For this study, these basic periods were selected for investigation:

Current period:	1966 to 1970
Near-term period:	1970 to 1980 (1975)
Future	1980+ (1985)

Propulsion and propellant predictions for these time periods were used for the baseline vehicles. The basic sizing information is shown in table 1. A data summary of the synthesized base point vehicles from Phase I are indicated in tables 2 through 6.

Payload exchange ratios, table 3, are quoted in equivalent payload gained in pounds per parameter-unit change. Parameters include thrust, specific impulse (I_{sp}), stage lift-off weight (W_O), structure weight (W_{ST}), propellant weight with fixed tank volume ($W_{P(F)}$), and rubberized tanks ($W_{P(NF)}$).

TABLE 1. - GENERIC FAMILIES - TWO-STAGE LAUNCH VEHICLES,
MINIMUM LIFTOFF MODE PROPORTIONED VEHICLES

Payload Class (lb)	Time Period	Stage Performance			
		Stage 1		Stage 2	
		ΔV	I_{sp} AV	ΔV	I_{sp} VAC
30 000	Current	10 402	289.8	20 600	424
240 000	Current	10 861	289.8	19 800	424
1 000 000	Current	11 123	289.8	19 400	424
100 000	1985	11 123	333.0	20 600	500
445 000	1985	11 535	333.0	20 000	500
2 000 000	1985	11 630	333.0	19 800	500
ΔV = Stage characteristic velocity in feet per second I_{sp} = Specific impulse in seconds					

Structural Design Synthesis

During this study, the portion of the automated program that describes the structural components was separated from the parametric synthesis section. This permitted the structural components to be analyzed individually without associating any of the structural components with a particular launch vehicle. In addition, the assessment of the effects of the substitution of different types of materials, constructions, manufacturing limitations, or analytical methods on the structural components could be obtained by an independent exercise of the design synthesis subroutines. The structural components were defined by a range of diameters, lengths, mechanical loads, and thermal environments representative of those associated with medium-range, Saturn V, and post-Saturn V payload class vehicles. The design synthesis determines the corresponding resultant unit shell weights for the entire spectrum of radii, mechanical loads and thermal environments.

TABLE 2. - VEHICLE STATIONS AND DIAMETERS FOR THE BASE-POINT DESIGN (IN.)

Vehicle Payload (lb)	Medium Range		Saturn Class		Post-Saturn	
	30 000	100 000	240 000	445 000	1 000 000	2 000 000
	1914.9	2444.3	3986.8	4384.8	6549.9	7902.3
	1672.9	2158.3	3551.2	3949.2	5955.9	7308.3
	1232.9	1638.3	2759.2	3157.2	4875.9	6228.3
	1155.1	1546.3	2619.2	3017.2	4684.9	6037.3
	220.0	260.0	396.0	396.0	540.0	540.0
	868.8	1119.7	2086.4	2357.9	3444.8	4182.7
	791.0	1027.8	1946.3	2217.8	3253.9	3991.8
	781.8	989.6	1924.4	2156.6	3064.7	3612.2
	742.9	943.6	1854.3	2086.6	2969.3	3516.7
	704.0	897.6	1784.3	2016.6	2873.8	3421.2
	689.9	877.0	1750.4	1977.8	2807.5	3339.1
	64.4	94.3	159.6	181.9	317.5	393.0
	97.1	142.2	240.7	274.3	478.8	592.6
	619.3	774.2	1580.6	1783.6	2475.7	2928.1
	608.3	761.2	1560.8	1763.8	2448.7	2901.1
	516.4	647.6	1420.9	1623.8	2222.4	2672.0
	260.0	321.1	396.0	396.0	640.0	648.0
	438.5	557.9	1000.8	1101.0	1656.5	1901.9
	346.5	444.3	860.8	961.0	1430.2	1672.8
	330.9	425.1	837.0	937.2	1391.8	1633.9
	239.0	311.5	697.0	797.2	1165.5	1404.8
	235.5	311.3	502.3	537.9	921.7	1034.1
	189.5	254.5	432.3	467.9	808.5	919.5
	143.6	197.7	362.2	397.9	606.4	805.0
	119.6	164.8	301.9	331.6	579.5	670.8
	112.1	154.9	289.9	317.5	563.9	652.0

*Diameters

Vehicle		Medium Range		Saturn Class		Post-Saturn
Stage 1	Payload (lb)	30 000	100 000	240 000	445 000	1 000 000
Stage mass fraction	0.9064	0.9101	0.9256	0.9258	0.9265	0.9254
Performance ratio	0.6720	0.6456	0.7056	0.6876	0.6964	0.6620
Stage velocity ft/sec	10402.0	11123.0	11410.0	12476.0	11123.0	11630.0
Stage Isp (sec)	290 AV	333 AV	290 AV	333 AV	290 AV	333 AV
Payload Exchange Ratios	Thrust (%)	0.02	0.02	0.02	0.02	0.02
	Isp (sec)	97.87	206.27	717.67	1022.28	3038.74
	WO (lb)	0.01	0.01	0.01	0.01	0.01
	WST (lb)	-0.09	-0.12	-0.11	-0.15	-0.11
	WP (F) (lb)	0.02	0.03	0.02	0.03	0.02
WP (NF) (lb)	0.01	0.01	—	—	0.01	0.02
Stage 2						
Stage mass fraction	0.8946	0.9032	0.9122	0.9136	0.9220	0.9207
Performance ratio	0.7788	0.7218	0.7587	0.6939	0.7585	0.7077
Stage velocity ft/sec	20600.0	20600.0	19412.0	19062.0	19400.0	19800.0
Stage Isp (sec)	424	500	424	500	424	500
Payload Exchange Ratios	Thrust (%)	0.03	0.05	0.02	0.03	0.03
	Isp (sec)	216.11	409.12	1359.56	1660.73	5500.14
	WO (lb)	0.01	0.05	0.05	0.09	0.04
	WST (lb)	-1.00	-1.00	-1.00	-1.00	-1.00
	WP (F) (lb)	0.14	0.17	0.14	0.19	0.14
WP (NF) (lb)	0.01	0.06	0.14	0.19	0.05	0.08

TABLE 4. - VEHICLE WEIGHT STATEMENT FOR STAGE 1 (LB)

Class		Medium Range		Saturn Class		Post-Saturn	
Item	Payload (lb)	Medium Range		Saturn Class		Post-Saturn	
		30 000	100 000	240 000	445 000	1 000 000	2 000 000
Structure							
Interstage		1 505	3 431	10 688	12 975	67 608	100 241
Forward skirt		1 458	2 840	6 638	7 187	33 230	40 906
Forward bulkhead		700	1 319	2 474	2 474	10 444	10 841
Forward tank wall		1 395	2 476	19 625	24 983	74 156	107 677
Int bulkhead		1 595	3 109	7 473	7 852	36 978	41 586
Center shell section		3 116	6 079	14 384	15 384	71 023	83 816
Int aft bulkhead		700	1 319	2 474	2 474	10 444	10 841
Aft tank wall		63	6	9 029	12 283	31 714	51 158
Aft bulkhead		1 598	3 119	7 355	7 690	36 396	40 607
Aft skirt		1 434	2 810	6 668	7 142	33 555	39 350
Thrust structure		7 605	14 133	46 952	55 913	168 054	221 946
Engines							
Propellant system		15 309	28 448	94 509	112 546	338 272	446 751
Ullage system		11 648	15 776	30 863	33 376	59 652	67 246
Separation system		0	0	0	0	0	0
Thrust vector control system		386	708	2 709	3 169	10 122	12 863
Fixed equipment		2 193	3 457	9 458	10 636	25 415	30 419
Residual propellant		2 649	3 881	6 568	7 486	13 063	16 170
Contingencies		8 918	16 361	62 613	73 223	233 903	297 252
		0	0	0	0	0	0
Stage burnout							
Stage propellant		62 273	109 273	340 481	396 792	1 254 028	1 619 671
Stage gross		602 999	1 106 198	4 233 452	4 950 839	15 814 960	20 098 176
Vehicle payload		665 272	1 215 471	4 573 934	5 347 631	17 068 988	21 717 847
Vehicle gross		232 010	497 961	1 426 066	1 852 369	5 641 232	8 643 258
		897 282	1 713 432	6 000 000	7 200 000	22 710 220	30 361 105

TABLE 5. - VEHICLE WEIGHT STATEMENT FOR STAGE 2 (LB)

Item	Class		Medium Range		Saturn Class		Post-Saturn	
	Payload (lb)		30 000	100 000	240 000	445 000	1 000 000	2 000 000
Structure								
Interstage			0	0	0	0	0	0
Forward skirt			752	1 302	5 017	5 197	15 286	16 604
Forward bulkhead			424	700	2 474	2 474	6 274	6 274
Forward tank wall			3 882	7 793	24 041	28 726	102 531	176 547
Int bulkhead			764	1 260	4 453	4 453	11 292	11 292
Center shell section			0	0	0	0	0	0
Int aft bulkhead			0	0	0	0	0	0
Aft tank wall			103	618	874	2 481	16 703	39 380
Aft bulkhead			1 315	2 387	10 887	11 296	40 930	46 729
Aft skirt			808	1 427	5 703	5 973	19 979	23 750
Thrust structure			1 610	2 863	6 330	7 709	17 852	24 627
Engines			4 218	7 503	16 587	20 203	46 782	64 536
Propellant system			2 943	4 151	7 202	7 850	14 323	17 124
Ullage system			0	0	0	0	0	0
Separation system			14	28	84	100	332	475
Thrust vector control system			286	479	1 095	1 247	3 072	4 016
Fixed equipment			1 784	3 257	5 046	6 874	10 300	14 566
Residual propellant			1 857	3 693	11 118	13 208	43 966	62 846
Contingencies			533	1 060	3 192	3 792	12 623	18 043
Stage burnout			21 294	38 522	104 103	121 583	362 246	526 809
Stage propellant			180 698	359 441	1 081 997	1 285 434	4 278 968	6 116 427
Stage gross			201 992	397 963	1 186 100	1 407 016	4 641 214	6 643 236
Vehicle payload			30 000	100 000	239 966	445 352	1 000 000	2 000 000
Vehicle gross			231 992	497 963	1 426 066	1 852 369	5 641 214	8 643 236

TABLE 6. - STRUCTURAL COMPONENTS AND THEIR DESIGN ULTIMATE APPLIED LOAD
(N_x IN POUNDS PER INCH)

Vehicle Payload Class	Medium Range		Saturn		Post-Saturn	
	Current	1985	Current	1985	Current	1985
<u>Stage 1</u>						
Interstage	2 885	3 273	7 965	8 685	20 120	23 100
Forward skirt	2 905	3 340	8 005	8 730	20 210	26 000
Forward tank wall	1 950	2 700	7 400	8 100	17 180	22 160
Center section	2 100	2 950	8 365	9 115	17 500	23 500
Aft tank wall	—	—	9 700	9 745	18 500	22 500
Aft skirt	1 800	2 285	6 965	7 535	9 300	17 500
<u>Stage 2</u>						
Forward skirt	1 245	1 530	2 750	2 895	4 355	6 510
Forward tank wall	1 295	1 650	3 070	3 255	5 535	7 240
Aft tank wall	1 650	1 950	6 300	6 780	8 640	9 635
Aft skirt	2 180	3 170	6 765	8 650	18 150	22 800

Unit shell weights are finally associated with various components for specific vehicles in the assessment portion of the program. Each of these structural components is subjected to various design loading conditions resulting from various portions of the vehicle trajectory flight path. The design analysis considers the tensile and compressive loading intensity with its associated thermal environment for these different portions of flight trajectory. For example, the unpressurized shell experiences temperatures varying from room temperature during prelaunch conditions up to a maximum thermal environment of approximately 300 to 400 degrees F. The various components of the vehicle stages are considered in this study to be subjected to the maximum compressive or tensile loading intensities either at prelaunch, at the max q α flight regime, or at end boost. In order to consider all of these different loading and thermal environment factors, the structural design synthesis was conducted for ranges of loading intensities, cylindrical diameters, and thermal environments. The thermal regimes considered are room temperature (prelaunch), cryogenic temperature, and maximum external temperature associated with the end-boost condition.

All of these loading intensities are subjected to various representative safety factors for the design loading criteria. These factors are established external to the synthesis portion of the computer program. Therefore, the synthesis considers only an ultimate tensile or an ultimate compressive load intensity. In this study, the limit factor is 1.1 and the ultimate factor is 1.4. (It may be noted that effects of factor of safety variation on vehicle weight and performance can be easily evaluated by the synthesis programs and techniques developed.) Various analytical techniques for certain of the different construction configurations have been evaluated with the assumption that failure of the structural component will be precluded up to and including the ultimate loading intensity.

Numerous alterations of the structural design of a component must be considered to evaluate effectively the significance of technological advances. These include changing materials to evaluate increases in material allowables; for example, by increasing the compressive yield strength of the various baseline materials. In addition, significant weight reductions may be obtained by replacing the base point configuration and material combination with a different type of construction, material, or both. A third area which may result in significant weight reductions is the relaxation of the manufacturing restrictions placed on most structural components. In addition, the structural weight of the component may be reduced by improving the analytical methods that are used to perform the structural analysis in the design synthesis sub-routines. The stability analysis for the various structural configurations is based on small deflection theory. The results obtained from small deflection theory are modified by correction factors based on experimental data obtained from isotropic monocoque shells and the impact evaluated.

The material properties considered for the design synthesis study are shown in table 7 . These values formed the basis for the design evaluation of current materials from which a series of material properties improvements were considered. Table 7 shows the current material properties (material A) and two steps of upgrading designated material B and material C. These improvements were approximately 10 percent and 20 percent for aluminum, 5 percent and 10 percent for titanium, and 15 and 25 percent for beryllium. These percentage improvements in material properties were used to exercise the preliminary design synthesis routines, and the range of improvements covering the predicted material advances are discussed in the Parametric Synthesis section.

Pictorial representations of the design synthesis results are shown in figures 2 through 7 and are ordered by their relative unit shell weights. These figures quickly indicate the weight criteria associated with each construction and material combination for the spectra of cylindrical radii and compressive loading intensities.

The importance of the eccentricity or one-sidedness of the cylindrical shell's stiffening elements in determining the allowable buckling strength has been discussed by various authors. Their results have tended to indicate the distinct improvement in a cylinder's buckling strength when the stiffeners are placed externally, even with very large diameter cylinders of "practical" proportion, and, therefore, should be accounted for in any buckling analysis.

A large selection of the synthesized designs from Phase I, results which were considered representative of light weight and practical design configurations, were investigated to find the effect of stiffener eccentricity. Figures 8 and 9 are simplified pictorial maps of the aluminum and titanium designs considered and show how the improvement depends upon the structural configuration and material involved. The cross-hatched areas in these figures indicate where there is an advantage to be gained by having external stiffeners.

Expendable Vehicle Component Assessment

In order to obtain conclusive evidence as to where and when it is advantageous to achieve material-property or construction-type improvements, it is necessary to assess the effects of these improvements on specific structural components in particular vehicle systems. General conclusions cannot be drawn without citing ground rules and criteria for each case in question. To define an effective approach requires a clear definition of the merit functions upon which decisions are to be based. Three merit functions have been used in this study and they are:

TABLE 7. - REPRESENTATIVE MATERIAL PROPERTIES AND ADVANCEMENTS

Temperature (Degrees F)	Aluminum A			Aluminum B			Aluminum C		
	Fcy (psix 10 ⁻³)	Ftu (psix 10 ⁻³)	E (psix 10 ⁻⁶)	Fcy (psix 10 ⁻³)	Ftu (psix 10 ⁻³)	E (psix 10 ⁻⁶)	Fcy (psix 10 ⁻³)	Ftu (psix 10 ⁻³)	E (psix 10 ⁻⁶)
-300	65	75	10.6	75	80	10.6	75	85	10.6
300	50	55	10.0	55	60	10.0	60	65	10.0
	Titanium A.			Titanium B			Titanium C		
	120	135	15.8	125	140	15.8	145	150	15.8
	100	115	14.0	105	120	14.0	110	125	14.0
	Beryllium A			Beryllium B			Beryllium C		
	48	63	43	55	70	43	60	75	43
	48	63	43	55	70	43	60	75	43

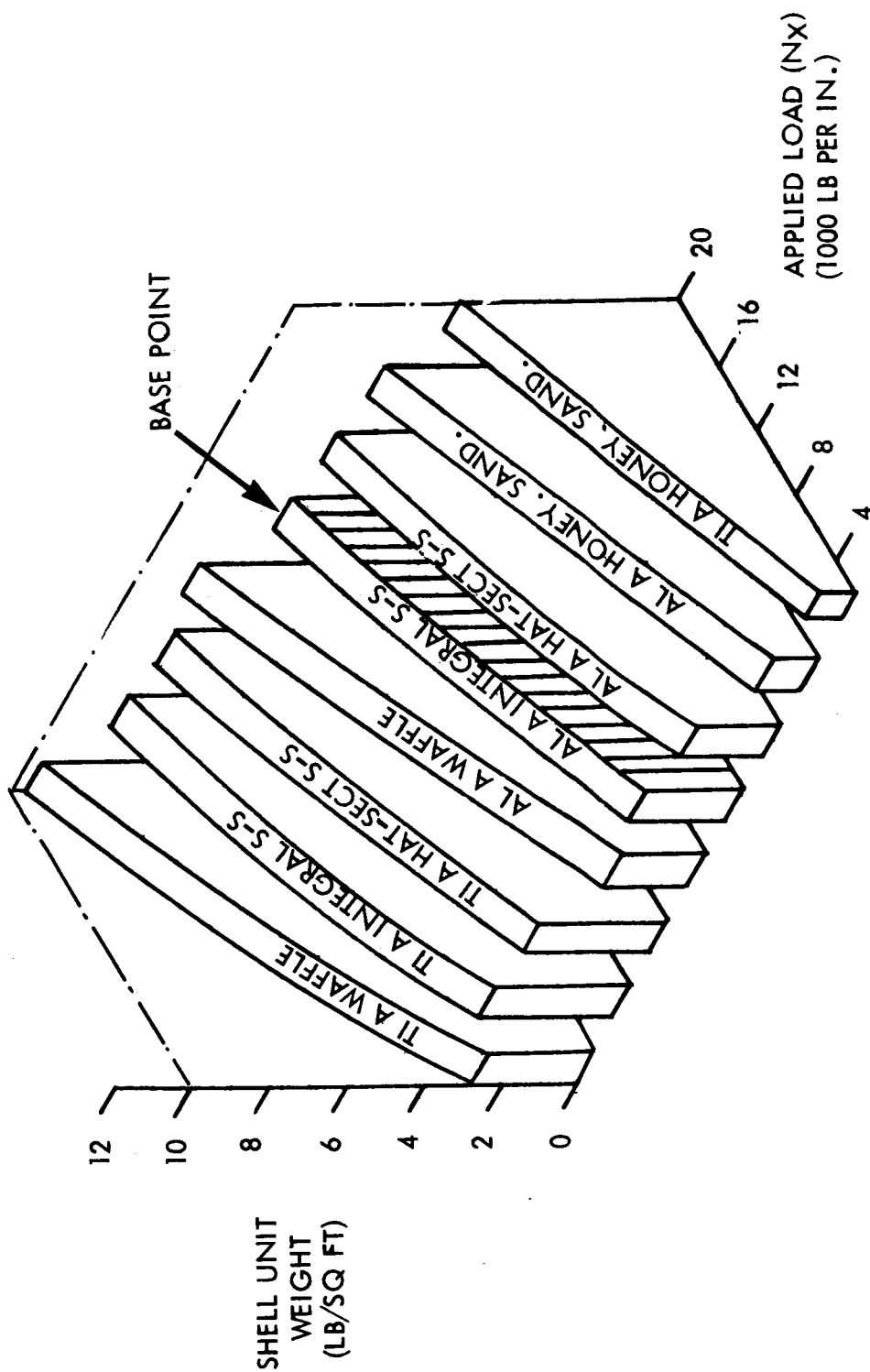


Figure 2. Shell Unit Weights for Conventional Titanium and Aluminum Structures—130-Inch Radius, 300°F, No Pressure

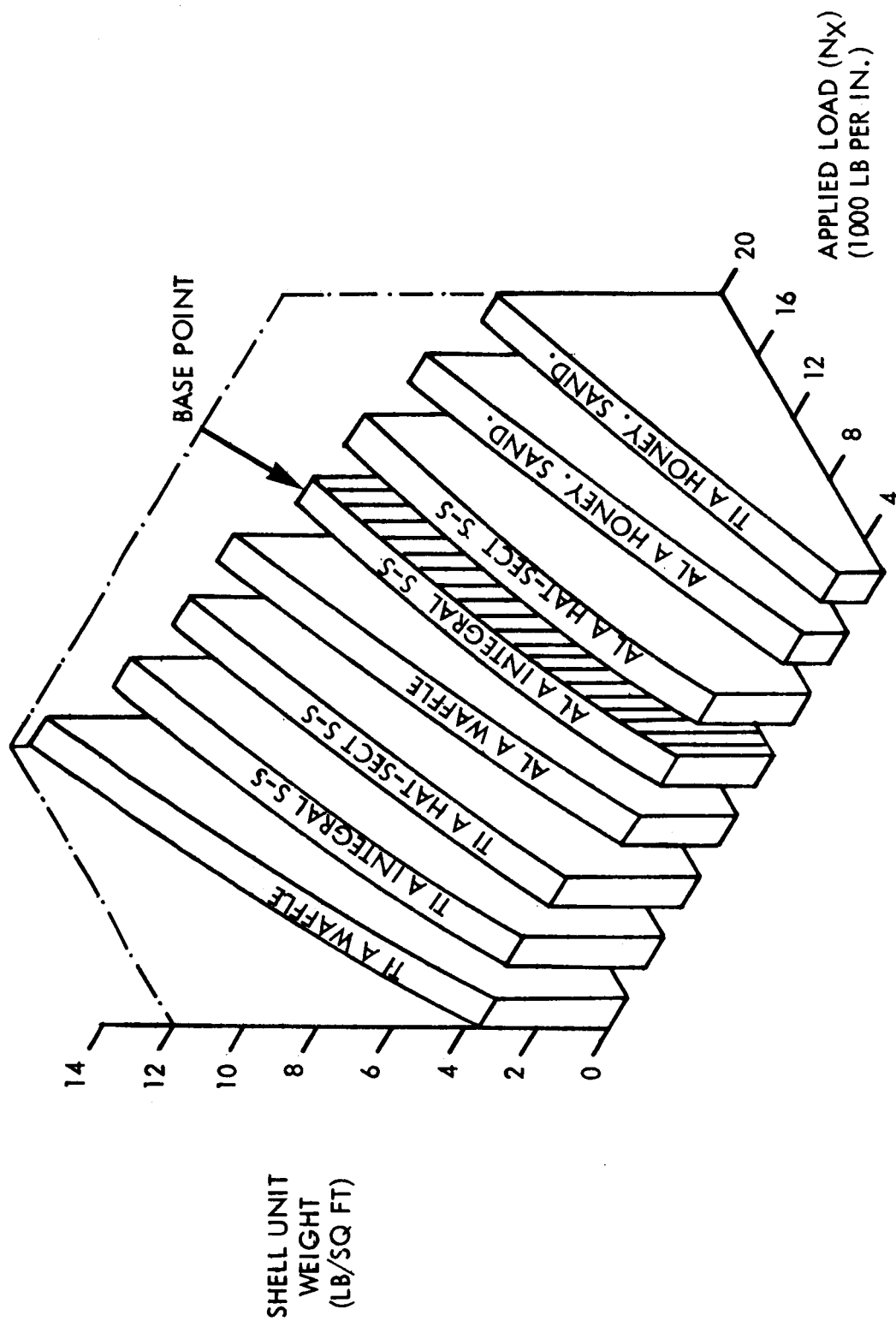


Figure 3. Shell Unit Weights for Conventional Titanium and Aluminum Structures—198-Inch Radius, 300°F, No Pressure

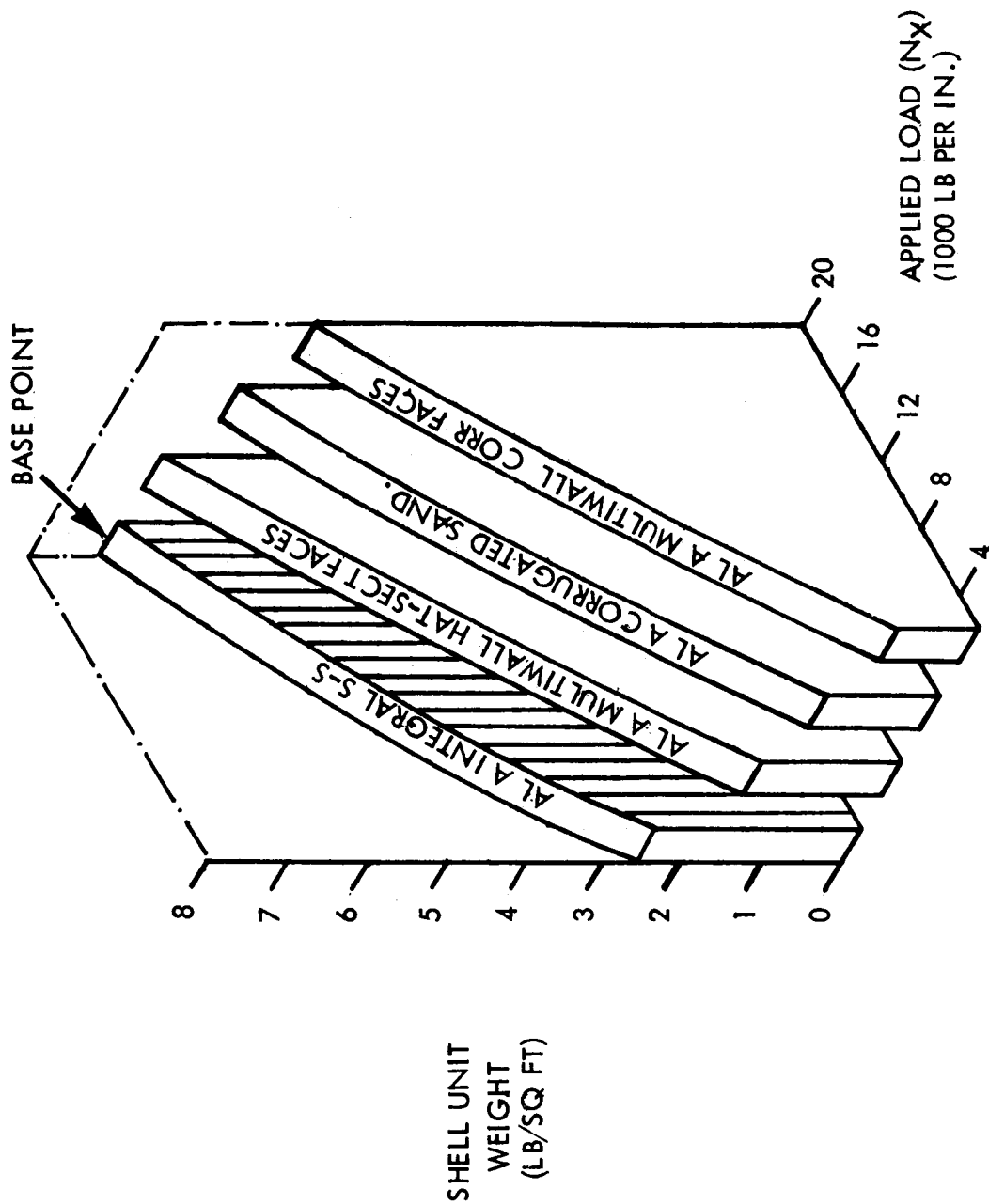


Figure 4. Shell Unit Weights for Advanced Aluminum Structures—
130-Inch Radius, 300°F, No Pressure

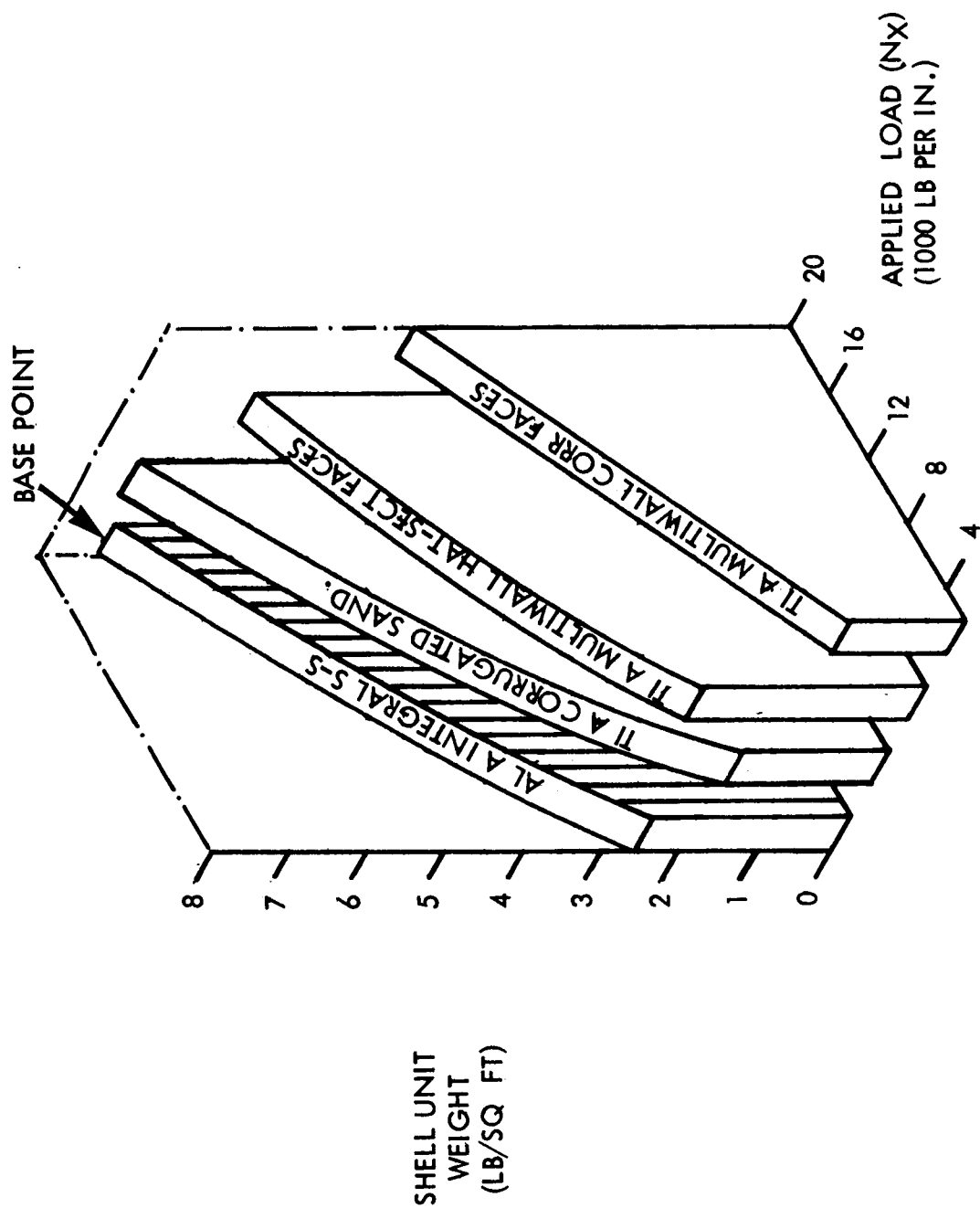


Figure 5. Shell Unit Weights for Advanced Titanium Structures —
130-Inch Radius, 300°F, No Pressure

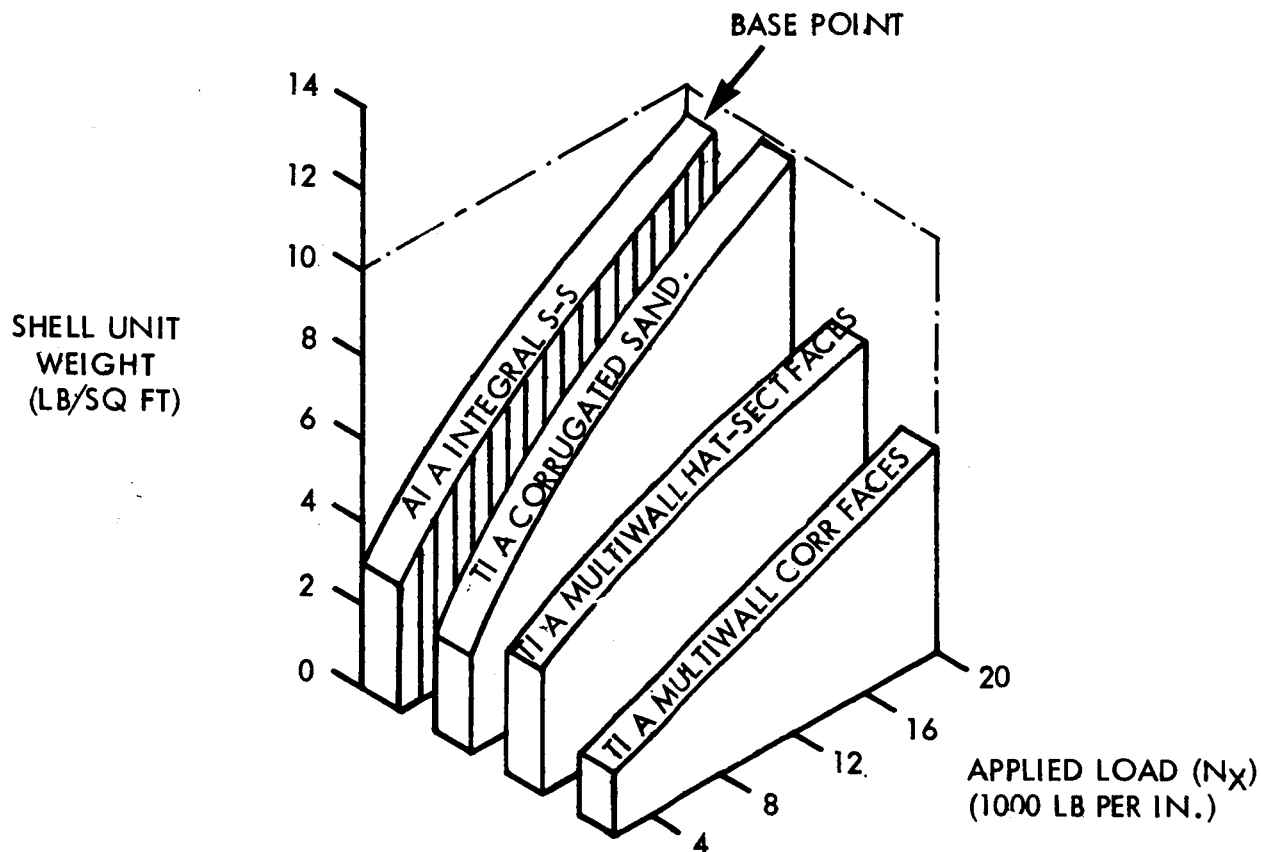


Figure 6. Shell Unit Weight for Advanced Titanium Structures—
270-Inch Radius, 300°F, No Pressure

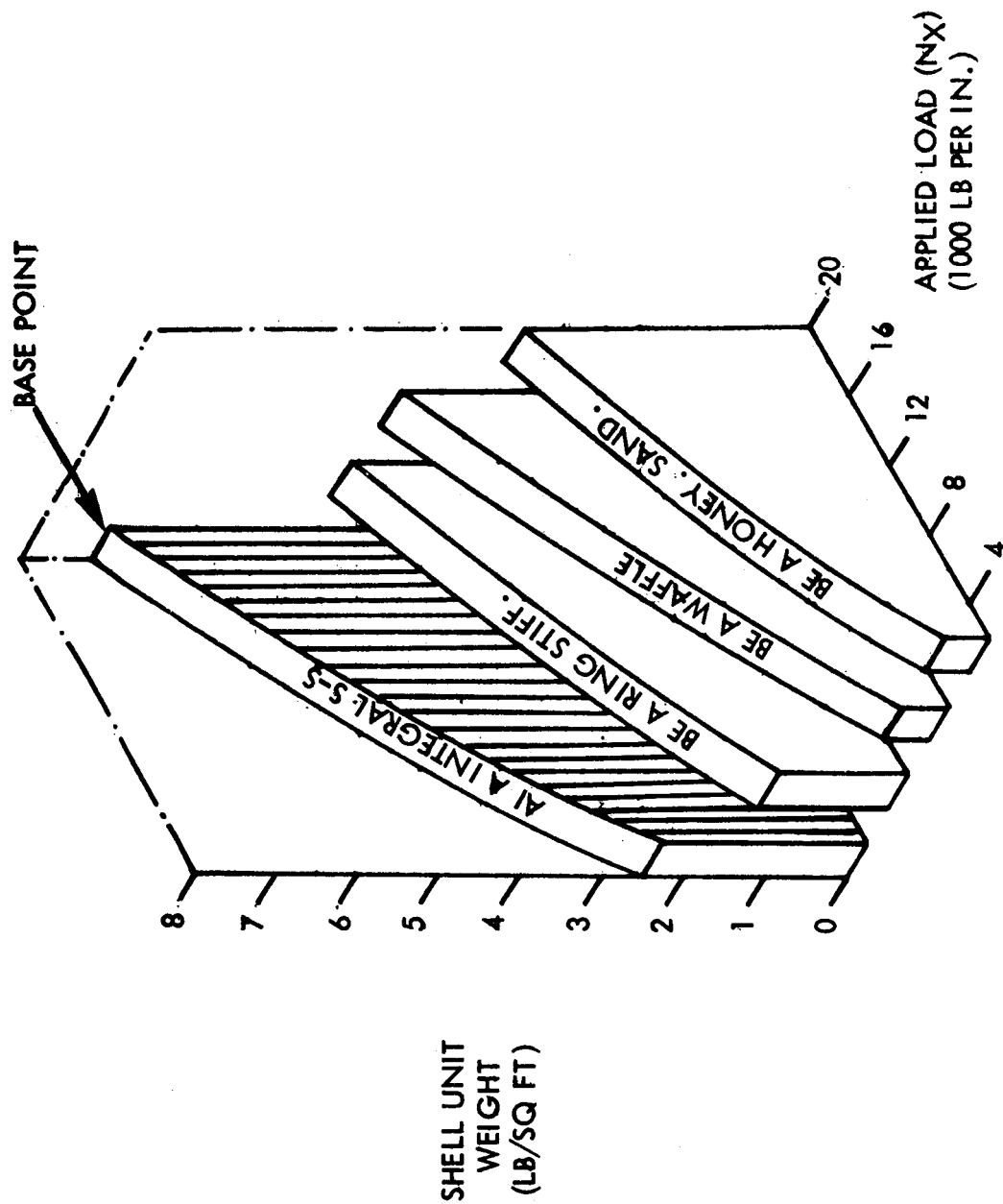


Figure 7. Shell Unit Weights for Conventional Beryllium Structures—
130-Inch Radius, 300°F, No Pressure

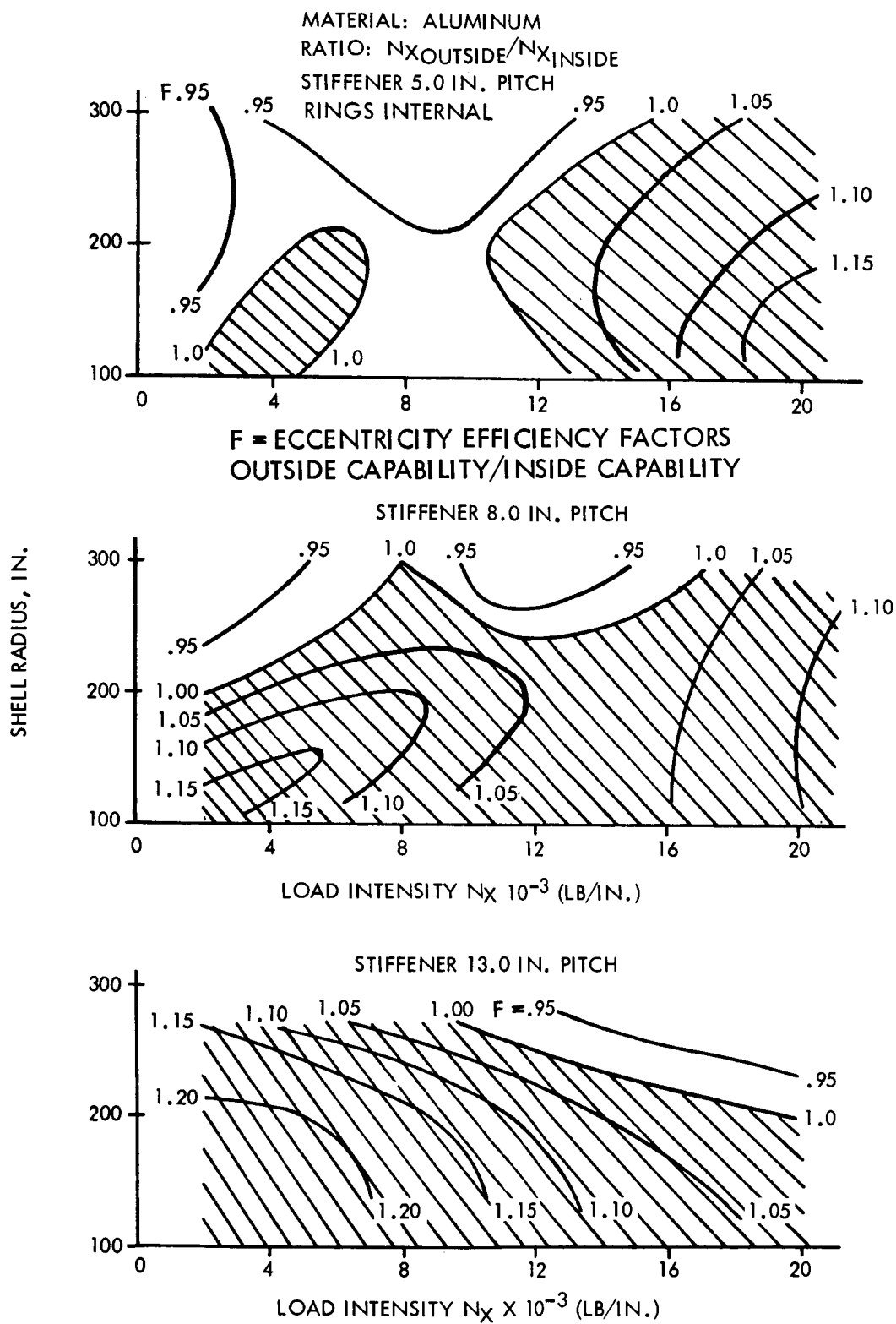


Figure 8. - Stiffener Positioning Effectiveness Ratio

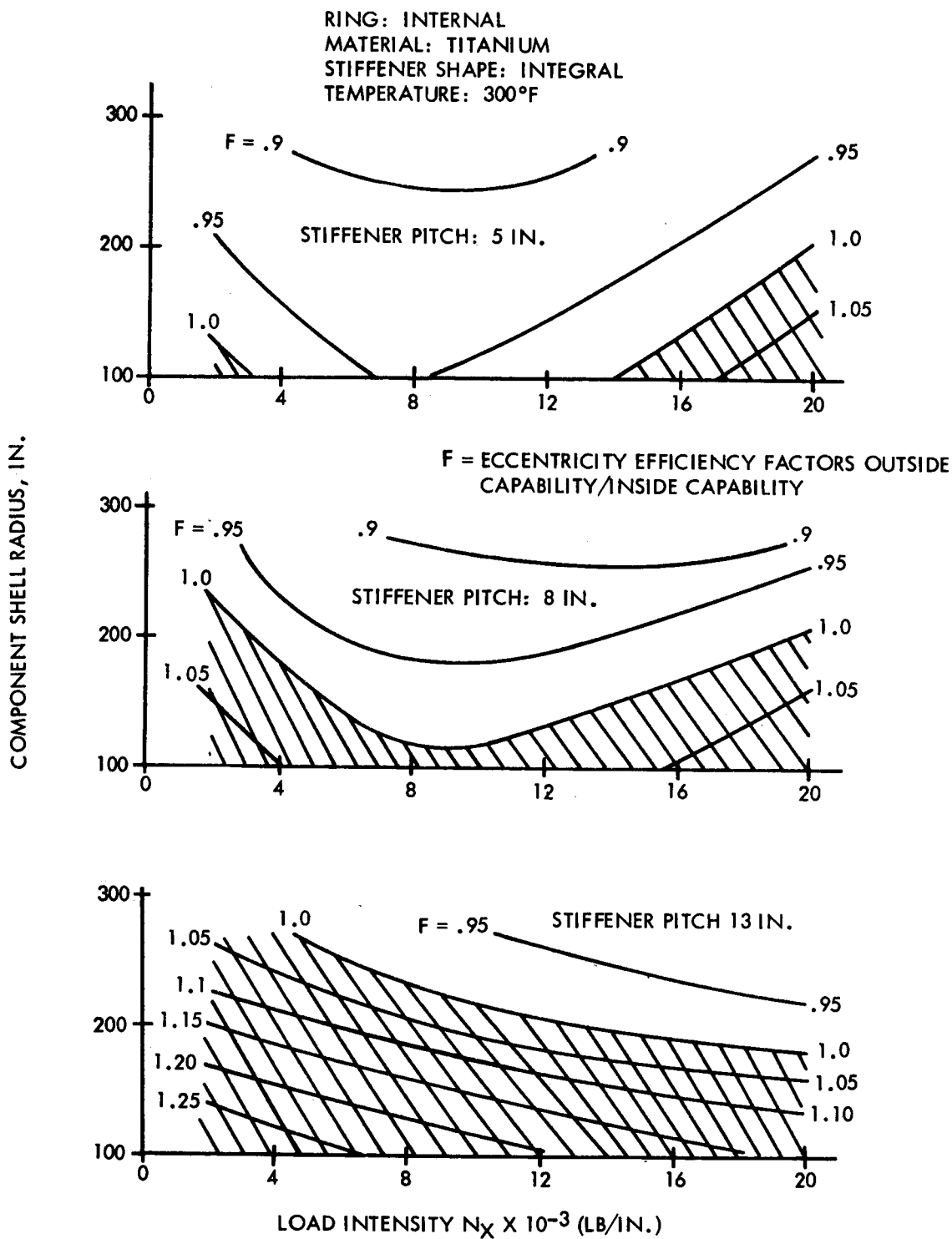


Figure 9. - Relative Merit of Externally Stiffened Titanium Shells, Component Shell Radius Versus Load Intensity

$$\text{Weight Reduction} = \text{Component } W_{T_{\text{Base Point}}} - \text{Component } W_{T_{\text{Alternate}}}$$

$$\text{Payload Gained} = \text{Payload}_{\text{Alternate}} - \text{Payload}_{\text{Base Point}}$$

$$\text{Cost Index} = \frac{\text{Component Cost}_{\text{Alternate}} - \text{Component Cost}_{\text{Base Point}}}{\text{Payload Gained}}$$

The most obvious of these is the weight reduction which arises from a structures and materials advancement for each of the structural components in a particular vehicle system. This merit function gives a clear indication of the weight (poundwise) savings that can be directly obtained from a structural improvement.

Sometimes use of only one merit function, weight reduction per se, does not result in a true indication of the significance of the reduction. Its effect on over-all system performance should be considered in terms of payload improvements resulting from the structural component weight decrease. These payload gains provide useful information for making management decisions, but still do not present a complete picture. A measurement must also be included which translates the component pounds saved and the payload pounds gained into a cost index which demonstrates whether or not the advancement is economically justifiable from a structures and materials standpoint.

It is true, depending upon the circumstances, that management decisions can be based on each of these merit functions by themselves; however, the objective of this study is to indicate and demonstrate a method which provides these interrelated merit functions. (Weight reduction, payload gain, and cost index are considered as a set of indexes unique to a component change in a particular vehicle base point.) Typical results are indicated, which are restricted to six vehicles selected for demonstration of the approach.

If the objective is only to remove a maximum number of pounds from a particular stage, weight changes from base point designs that result from material and structures improvements may give a clue as to where research effort should be concentrated. Isolating weight as the only merit function simplifies the process. The various component weights are shown in tables 8 through 13 for the baseline vehicles. These weight data merely indicate what type and where weight reduction may be anticipated. Decisions as to their worth, with this limited data, must be made by management, using additional criteria upon which to base judgments.

The second merit function is the equivalent payload gained from a structural component weight reduction. Weight savings in the uppermost stage in a launch vehicle system, though smaller in magnitude than in the lower stages, potentially result in a larger payload improvement. In most systems, a pound saved in upper stage structural weight is a pound gained in payload weight. The exchange ratios for the first stage of the baseline vehicles are shown in table 14.

TABLE 8. - COMPONENT WEIGHT SUMMARY (LB), 30 000-LB
PAYLOAD EXPENDABLE VEHICLE, CURRENT I_{sp}

Component	Aluminum A										Honeycomb Sandwich		
	Integral Skin Stringer	Waffle	Hat-Sect. Skin Stringer	Monocoque	Ring Stiffened	Honeycomb Sandwich	Corrugated Sandwich	Multiwall Corrugated	Double-Wall Hat Section	Double-Wall Z Section	Aluminum		Beryllium A
											B	C	
Stage I													
Interstage	1 505	1 231	1 480	3 012	2 442	621	852	603	1 166	1 278	621	580	101
Forward skirt	1 458	1 169	1 428	2 869	2 341	593	811	570	1 116	1 220	558	535	293
Forward tankwall	1 395	1 159	1 287	2 708	2 097	1 260	1 158	1 380	1 136	1 251	1 235	1 158	283
Center section	3 116	2 646	3 023	6 718	5 099	1 270	1 745	1 322	2 432	2 670	1 243	1 190	700
Aft tankwall	63	53	57	128	92	57	47	50	47	53	55	52	18
Aft skirt	1 434	1 220	1 374	2 965	2 251	693	757	613	1 130	1 242	586	522	298
Forward bulkhead	700	-	-	-	-	-	-	-	-	-	657	617	573
Internal bulkhead	1 595	-	-	-	-	-	-	-	-	-	1 495	1 405	1 304
Internal aft bulkhead	700	-	-	-	-	-	-	-	-	-	657	617	573
Aft bulkhead	1 598	-	-	-	-	-	-	-	-	-	1 499	1 410	1 307
Stage II													
Forward skirt	752	732	701	1 810	1 315	370	582	396	791	868	365	360	229
Forward tankwall	3 882	2 994	1 876	6 832	4 690	3 212	2 660	4 182	2 530	3 390	3 407	3 006	786
Aft tankwall	103	86	78	193	139	89	76	111	74	82	89	89	22
Aft skirt	808	790	728	1 947	1 521	400	544	408	732	796	397	348	160
Forward bulkhead	424	-	-	-	-	-	-	-	-	-	397	374	351
Internal bulkhead	764	-	-	-	-	-	-	-	-	-	716	674	632
Aft bulkhead	1 315	-	-	-	-	-	-	-	-	-	1 232	1 160	1 085

TABLE 9. - COMPONENT WEIGHT SUMMARY (LB), 100 000-LB
PAYLOAD EXPENDABLE VEHICLE, 1985 I_{sp}

Component	Aluminum A										Honeycomb Sandwich		
	Integral Skin Stringer	Waffle	Hat-Sect. Skin Stringer	Monocoque	Ring Stiffened	Honeycomb Sandwich	Corrugated Sandwich	Multiwall Corrugated	Double-Wall Hat Section	Double-Wall Z Section	Aluminum		Beryllium A
											B	C	
Stage I													
Interstage	3 431	2 799	3 048	6 727	5 191	1 720	2 071	1 380	2 655	2 708	1 540	1 465	811
Forward skirt	2 840	2 361	1 262	5 530	4 317	1 297	1 681	1 076	2 267	2 306	1 201	1 124	665
Forward tankwall	2 476	1 937	2 106	4 293	3 329	1 559	1 776	1 908	2 420	2 498	1 466	1 396	1 152
Center section	6 079	5 078	5 525	11 858	9 368	2 828	3 689	2 398	4 878	4 960	2 644	2 480	1 502
Aft tankwall	-	-	-	-	-	-	-	-	-	-	-	-	-
Aft skirt	2 810	2 274	2 539	5 440	4 225	1 269	1 664	1 125	2 159	2 195	1 215	1 143	714
Forward bulkhead	1 319	-	-	-	-	-	-	-	-	-	1 237	1 164	1 078
Internal bulkhead	3 109	-	-	-	-	-	-	-	-	-	2 916	2 742	2 542
Internal aft bulkhead	1 319	-	-	-	-	-	-	-	-	-	1 237	1 164	1 078
Aft bulkhead	3 119	-	-	-	-	-	-	-	-	-	2 925	2 752	2 551
Stage II													
Forward skirt	1 302	1 383	543	3 510	2 580	558	824	690	1 317	1 352	614	565	384
Forward tankwall	7 793	6 449	6 300	15 380	11 550	5 842	6 664	6 792	8 394	8 650	5 651	5 461	3 230
Aft tankwall	618	528	518	1 244	968	460	532	608	766	791	445	430	364
Aft skirt	1 427	1 349	1 199	3 232	2 518	781	943	684	1 254	1 285	709	668	418
Forward bulkhead	700	-	-	-	-	-	-	-	-	-	657	617	573
Internal bulkhead	1 260	-	-	-	-	-	-	-	-	-	1 183	1 111	1 040
Aft bulkhead	2 387	-	-	-	-	-	-	-	-	-	2 239	2 106	1 953

TABLE 10. - COMPONENT WEIGHT SUMMARY (LB), 240 000-LB
PAYLOAD EXPENDABLE VEHICLE, CURRENT Isp

Component	Aluminum A										Honeycomb Sandwich		
	Integral Skin Stringer	Waffle	Hat-Sect. Skin Stringer	Monocoque	Ring Stiffened	Honeycomb Sandwich	Corrugated Sandwich	Multiwall Corrugated	Double-Wall Hat Section	Double-Wall Z Section	Aluminum		Beryllium A
											B	C	
Stage I													
Interstage	10 688	10 665	9 370	24 284	17 711	6 372	7 605	5 785	8 091	8 131	5 987	5 664	3 665
Forward skirt	6 638	6 760	5 801	15 031	11 002	3 940	4 714	3 566	5 088	5 113	3 704	3 504	2 018
Forward tankwall	19 625	19 652	17 257	43 574	32 285	11 287	15 063	15 406	13 919	14 109	10 487	9 838	8 811
Center section	14 384	14 619	12 613	32 207	23 343	8 640	10 273	7 586	11 116	11 274	8 113	7 665	4 424
Aft tankwall	9 029	9 370	8 004	19 538	13 179	4 873	6 687	6 288	6 472	6 534	4 550	4 274	3 615
Aft skirt	6 668	6 662	5 835	15 012	12 316	3 778	4 679	3 374	4 974	5 042	3 563	3 388	1 136
Forward bulkhead	2 474	-	-	-	-	-	-	-	-	-	2 320	2 183	2 041
Internal bulkhead	7 473	-	-	-	-	-	-	-	-	-	7 004	6 595	6 166
Internal aft bulkhead	2 474	-	-	-	-	-	-	-	-	-	2 320	2 183	2 041
Aft bulkhead	7 355	-	-	-	-	-	-	-	-	-	6 907	6 490	6 069
Stage II													
Forward skirt	5 017	5 530	4 326	12 978	11 570	2 372	3 344	3 147	4 840	4 928	2 285	2 197	1 261
Forward tankwall	24 041	26 738	20 998	61 896	48 029	22 795	26 172	32 512	22 758	23 165	21 023	19 492	17 878
Aft tankwall	874	951	794	2 131	1 599	626	777	813	727	737	578	544	460
Aft skirt	5 703	6 065	5 128	13 791	11 483	3 435	4 324	3 038	4 727	4 790	3 235	3 073	1 768
Forward bulkhead	2 474	-	-	-	-	-	-	-	-	-	2 320	2 183	2 041
Internal bulkhead	4 453	-	-	-	-	-	-	-	-	-	4 176	3 929	3 670
Aft bulkhead	10 887	-	-	-	-	-	-	-	-	-	10 224	9 606	8 983

TABLE 11. - COMPONENT WEIGHT SUMMARY (LB), 445 000-LB
PAYLOAD EXPENDABLE VEHICLE, 1985 Isp

Component	Aluminum A										Honeycomb Sandwich		
	Integral Skin Stringer	Waffle	Hat-Sect. Skin Stringer	Monocoque	Ring Stiffened	Honeycomb Sandwich	Corrugated Sandwich	Multiwall Corrugated	Double-Wall Hat Section	Double-Wall Z Section	Aluminum		Beryllium A
											B	C	
Stage I													
Interstage	12 975	13 512	11 472	28 952	20 374	8 096	9 430	7 562	10 008	10 119	7 606	7 184	4 709
Forward skirt	7 187	7 594	6 414	16 251	11 357	4 497	5 236	4 189	5 605	5 667	4 226	3 991	2 320
Forward tankwall	24 983	25 695	22 289	55 962	39 452	13 830	18 678	18 144	18 678	19 345	12 541	11 785	10 411
Center section	15 384	15 964	13 720	34 614	24 167	9 764	11 278	9 033	11 904	12 009	9 137	8 615	8 928
Aft tankwall	12 283	13 795	10 958	27 645	18 831	6 606	9 141	8 497	8 829	8 933	6 170	5 962	4 906
Aft skirt	7 142	7 747	6 275	16 216	12 050	4 228	5 078	4 613	5 783	5 849	4 015	3 802	2 192
Forward bulkhead	2 474	-	-	-	-	-	-	-	-	-	2 320	2 183	2 041
Internal bulkhead	7 852	-	-	-	-	-	-	-	-	-	7 359	6 929	6 479
Internal aft bulkhead	2 474	-	-	-	-	-	-	-	-	-	2 320	2 183	2 041
Aft bulkhead	7 690	-	-	-	-	-	-	-	-	-	7 222	6 785	6 345
Stage II													
Forward skirt	5 197	5 761	4 558	13 421	11 817	2 516	3 538	2 224	4 991	5 166	2 447	2 360	1 166
Forward tankwall	28 726	34 077	25 570	72 858	56 044	25 567	32 703	36 337	27 707	28 343	23 586	21 966	20 165
Aft tankwall	2 481	2 674	2 265	5 990	4 409	1 563	2 050	2 129	1 998	2 035	1 532	1 386	1 204
Aft skirt	5 973	6 181	5 502	14 505	11 327	3 767	4 568	3 441	5 096	5 156	3 576	3 386	1 948
Forward bulkhead	2 474	-	-	-	-	-	-	-	-	-	2 320	2 183	2 041
Internal bulkhead	4 453	-	-	-	-	-	-	-	-	-	4 176	3 929	3 670
Aft bulkhead	11 296	-	-	-	-	-	-	-	-	-	10 608	9 967	9 320

TABLE 12. - COMPONENT WEIGHT SUMMARY (LB), 1 000 000-LB
PAYLOAD EXPENDABLE VEHICLE, CURRENT Isp

Component	Aluminum A										Honeycomb Sandwich		
	Integral Skin Stringer	Waffle	Hat-Sect. Skin Stringer	Monocoque	Ring Stiffened	Honeycomb Sandwich	Corrugated Sandwich	Multiwall Corrugated	Double-Wall Hat Section	Double-Wall Z Section	Aluminum		Beryllium A
											B	C	
Stage I													
Interstage	67 608	58 202	55 975	132 057	85 177	44 741	47 950	33 117	45 589	45 891	41 835	38 808	23 335
Forward skirt	33 230	29 003	27 110	64 980	43 944	21 033	22 786	16 119	21 252	21 440	20 876	19 437	19 718
Forward tankwall	74 156	64 014	58 251	135 759	86 310	37 478	46 813	41 459	37 684	37 821	35 762	34 114	40 635
Center section	71 023	62 609	56 435	139 990	92 427	45 026	49 051	33 633	45 299	45 766	41 888	39 432	41 478
Aft tankwall	31 714	28 358	24 829	61 812	39 523	16 593	20 909	18 607	16 145	16 273	15 634	14 771	18 671
Aft skirt	33 555	34 092	41 039	68 643	44 769	18 674	22 558	13 104	15 304	15 491	17 176	15 023	16 755
Forward bulkhead	10 444	-	-	-	-	-	-	-	-	-	9 792	9 216	8 618
Internal bulkhead	36 978	-	-	-	-	-	-	-	-	-	34 662	32 626	33 466
Internal aft bulkhead	10 444	-	-	-	-	-	-	-	-	-	9 792	9 216	8 618
Aft bulkhead	36 396	-	-	-	-	-	-	-	-	-	34 123	32 114	32 942
Stage II													
Forward skirt	15 286	20 093	13 702	26 431	27 332	10 342	10 960	5 648	10 025	10 212	7 933	7 303	3 850
Forward tankwall	102 531	66 641	66 367	155 759	107 270	54 303	64 773	77 418	34 845	35 548	44 557	37 595	42 957
Aft tankwall	16 703	12 232	10 050	33 056	19 858	8 340	10 740	11 493	6 971	7 076	7 676	7 282	6 633
Aft skirt	19 979	20 655	18 537	47 170	29 429	15 698	17 057	11 712	16 145	16 384	14 815	13 717	14 147
Forward bulkhead	6 274	-	-	-	-	-	-	-	-	-	5 882	5 536	5 680
Internal bulkhead	11 292	-	-	-	-	-	-	-	-	-	10 586	9 964	10 214
Aft bulkhead	40 930	-	-	-	-	-	-	-	-	-	38 370	36 117	37 043

TABLE 13. - COMPONENT WEIGHT SUMMARY (LB), 2 000 000-LB
PAYLOAD EXPENDABLE VEHICLE, 1985 Isp

Component	Aluminum A										Honeycomb Sandwich		
	Integral Skin Stringer	Waffle	Hat-Sect. Skin Stringer	Monocoque	Ring Stiffened	Honeycomb Sandwich	Corrugated Sandwich	Multiwall Corrugated	Double-Wall Hat Section	Double-Wall Z Section	Aluminum		Beryllium A
											B	C	
Stage I													
Interstage	100 241	81 921	84 941	198 538	121 028	70 142	72 663	50 990	58 298	70 730	65 354	61 490	40 956
Forward skirt	40 906	33 517	34 644	82 237	49 197	28 742	29 818	20 859	23 971	29 476	27 732	26 057	26 262
Forward tankwall	107 677	90 390	85 542	209 616	119 572	63 607	75 043	59 070	62 284	66 820	61 433	58 692	69 089
Center section	83 816	68 854	71 422	168 763	97 119	59 829	61 576	43 474	49 485	61 576	57 243	54 167	54 931
Aft tankwall	51 158	43 182	40 703	99 505	58 354	30 347	35 727	28 151	30 123	33 082	29 496	28 241	33 306
Aft skirt	39 350	31 662	32 761	78 669	45 361	28 864	27 920	19 703	22 046	27 095	23 828	23 696	23 828
Forward bulkhead	10 841	-	-	-	-	-	-	-	-	-	10 163	9 567	8 947
Internal bulkhead	41 586	-	-	-	-	-	-	-	-	-	38 986	36 693	37 636
Internal aft bulkhead	10 841	-	-	-	-	-	-	-	-	-	10 163	9 567	8 947
Aft bulkhead	39 350	-	-	-	-	-	-	-	-	-	36 890	34 722	35 613
Stage II													
Forward skirt	16 604	16 662	14 727	41 110	25 098	9 213	12 287	6 469	9 817	10 889	8 762	8 536	4 985
Forward tankwall	176 547	123 599	117 346	316 835	186 647	90 363	112 546	126 556	68 679	72 351	74 430	62 822	80 348
Aft tankwall	39 380	29 761	26 939	69 020	44 171	19 386	25 682	26 549	16 479	18 454	17 954	17 046	18 336
Aft skirt	23 750	22 685	20 927	50 144	30 459	19 249	20 317	14 708	16 931	20 380	19 022	17 890	17 931
Forward bulkhead	6 274	-	-	-	-	-	-	-	-	-	5 882	5 536	5 680
Internal bulkhead	11 292	-	-	-	-	-	-	-	-	-	10 586	9 964	10 214
Aft bulkhead	23 750	-	-	-	-	-	-	-	-	-	22 264	20 957	21 494

TABLE 14. - VEHICLE STAGE EXCHANGE RATIO

Vehicle Payload (lb)	Term	First-Stage Exchange Ratio
30 000	Current	0.09
100 000	1985	0.12
240 000	Current	0.11
445 000	1985	0.15
1 000 000	Current	0.11
2 000 000	1985	0.13

For example, in the first vehicle above (30 000-pound payload), nine percent of the affected weight saving in a component can be added as an equivalent payload gain. The payload exchange ratio, as described in reference 2, results from the stage proportions in the total vehicle stack and their velocity characteristics, so that each case must be treated separately. A summary of the equivalent payload changes reflected for the different constructions and materials are shown in tables 15 through 17.

Another merit function that is a good indicator of any subsystem performance is its cost index. The total cost of a structural component is composed of several contributing factors: development, production (fabrication, tooling and equipment), and testing (static and flight vehicles). For this study, where all components were compared to a base point design, it was assumed that the development and testing costs were identical for both the improved component and the base point design; therefore, the only cost differences considered between the two structural components were production costs. The cost figure of merit is the cost difference between the improved and base point designs and the relative payload gained, and uses an index of dollars per pound in orbit for the ordering effectiveness

$$CR = \frac{(\$ \text{PRODUCTION})_{\text{ADVANCE}} - (\$ \text{PRODUCTION})_{\text{BASE POINT}}}{(W \text{ PAYLOAD})_{\text{ADVANCE}} - (W \text{ PAYLOAD})_{\text{BASE POINT}}}$$

Table 18 presents a summary of the cost ratio information based upon complexity factors cited in Volume 2. The cost ratio has been "normalized" for each stage by averaging values for components displaying typical trends and not including ratios for components where the component is small in size. Except for those items indicated by asterisks on the table, all values may be scanned for the maximized negative value. Because of the ground rules adopted for this study, no material and construction combination

TABLE 15. - PAYLOAD WEIGHT CHANGE SUMMARY (POUND)
 (CHANGE FROM ALUMINUM A INTEGRAL SKIN STRINGER BASEPOINT)
 30 000-POUND PAYLOAD, EXPENDABLE VEHICLE, CURRENT I_{sp}

Component	Aluminum A							Honeycomb Sandwich					
	Waffle	Hat- Section Skin Stringer	Mono- coque	Ring Stiffened	Honey- comb Sand- wich	Corru- gated Sand- wich	Multi- Wall Corru- gated	Double- Wall Hat-Sect. Skin- Stringer Faces	Double- Wall Z-Sect. Skin- Stringer Faces	Aluminum		Tita- nium A	Beryl- lium A
										B	C		
Stage I													
Interstage	25	2	-136	-84	80	59	81	31	20	80	83	82	108
Forward skirt	26	3	-127	-80	78	58	80	31	21	81	83	80	105
Forward tankwall	21	10	-118	-63	12	21	1	23	13	14	21	31	100
Center section	42	8	-324	-178	166	122	161	62	40	169	173	169	217
Aft tankwall	1	1	-6	-3	2	1	2	1	1	1	1	1	4
Aft skirt	19	5	-138	-73	67	61	74	27	17	76	82	81	102
Forward bulkhead	—	—	—	—	—	—	—	—	—	4	7	6	11
Internal bulkhead	—	—	—	—	—	—	—	—	—	9	17	15	26
Internal aft bulkhead	—	—	—	—	—	—	—	—	—	4	7	6	11
Aft bulkhead	—	—	—	—	—	—	—	—	—	9	17	15	26
Stage II													
Forward skirt	20	51	-1058	-563	302	170	356	—	—	392	387	369	523
Forward tankwall	888	2006	-2950	-808	670	1222	-300	1352	492	475	876	1117	3096
Aft tankwall	17	25	-90	-36	14	7	-8	29	14	14	14	21	81
Aft skirt	18	80	-1139	-713	408	264	400	76	12	411	460	479	648
Forward bulkhead	—	—	—	—	—	—	—	—	—	27	50	39	73
Internal bulkhead	—	—	—	—	—	—	—	—	—	48	90	72	132
Aft bulkhead	—	—	—	—	—	—	—	—	—	83	155	125	230

TABLE 16. - PAYLOAD WEIGHT CHANGE SUMMARY (POUNDS)
(CHANGE FROM ALUMINUM A INTEGRAL SKIN STRINGER BASEPOINT)
240 000-POUND PAYLOAD, EXPENDABLE VEHICLE, CURRENT I_{sp}

Component	Aluminum A							Honeycomb Sandwich					
	Waffle	Hat- Section Skin Stringer	Mono- coque	Ring- Stiffened	Honey- comb Sand- wich	Corru- gated Sand- wich	Multi- Wall Corru- gated	Double- Wall Hat-Sect. Skin- Stringer Faces	Double- Wall Z-Sect. Skin Stringer Faces	Aluminum		Tita- nium A	Beryl- lium A
										B	C		
Stage I													
Interstage	3	145	-1 496	-772	475	339	539	286	281	517	553	528	773
Forward skirt	-13	92	-923	-480	297	212	338	171	168	323	345	330	508
Forward tank wall	-3	260	-2 634	-1 393	917	502	464	628	607	1 005	1 077	808	1 190
Center section	-26	195	-1 961	-985	632	452	748	359	342	690	739	707	1 096
Aft tank wall	-38	113	-1 156	-456	457	258	302	281	274	493	523	415	596
Aft skirt	1	92	-918	-621	318	219	362	186	179	342	361	345	609
Forward bulkhead	—	—	—	—	—	—	—	—	—	17	32	142	48
Internal bulkhead	—	—	—	—	—	—	—	—	—	52	97	78	144
Internal aft bulkhead	—	—	—	—	—	—	—	—	—	17	32	142	48
Aft bulkhead	—	—	—	—	—	—	—	—	—	49	95	77	142
Stage II													
Forward skirt	-513	691	-7 961	-6 553	2 645	1 673	2 870	177	89	2 732	2 820	2 680	3 756
Forward tank wall	-2 697	3 043	-37 855	-23 988	1 246	-2 131	-8 470	1 283	876	3 018	4 549	119	6 163
Aft tank wall	-77	80	-1 257	-725	248	97	61	147	137	296	330	244	414
Aft skirt	-362	575	-8 088	-5 780	2 268	1 379	2 665	976	913	2 468	2 630	2 493	3 935
Forward bulkhead	—	—	—	—	—	—	—	—	—	154	291	1 294	433
Internal bulkhead	—	—	—	—	—	—	—	—	—	277	524	2 328	783
Aft bulkhead	—	—	—	—	—	—	—	—	—	663	1 281	1 032	1 904

TABLE 17. - PAYLOAD WEIGHT CHANGE SUMMARY (POUNDS)
 (CHANGE FROM ALUMINUM A INTEGRAL SKIN STRINGER BASEPOINT)
 1 000 000-POUND PAYLOAD, EXPENDABLE VEHICLE, CURRENT I_{sp}

Component	Aluminum A										Honeycomb Sandwich			
	Waffle	Hat- Section Skin Stringer	Mono- coque	Ring- Stiffened	Honey- comb Sand- wich	Corru- gated Sand- wich	Multi- Wall Corru- gated	Double- Wall Hat-Sect. Skin- Stringer Faces	Double- Wall Z-Sect. Skin- Stringer Faces	Aluminum		Tita- nium A	Beryl- lium A	
										B	C			
Stage I														
Interstage	1 035	1 280	-7 089	-1 933	2 515	2 162	3 794	2 422	2 389	2 835	3 168	3 035	4 868	
Forward skirt	465	673	-3 493	-1 179	1 342	1 149	1 882	1 318	1 297	1 359	1 517	1 486	2 446	
Forward tank wall	1 116	1 750	-7 882	-1 337	4 035	3 008	3 597	4 012	3 997	4 223	4 405	3 687	5 306	
Center section	926	1 605	-7 586	-2 354	2 860	2 417	4 113	2 830	2 777	3 205	3 475	3 250	5 429	
Aft tank wall	369	757	-3311	-859	1663	1189	1442	1713	1698	1769	1864	1435	2193	
Aft skirt	-59	-823	-3 860	-1 234	1 637	1 210	2 250	2 008	1 987	1 802	2 038	1 848	2 680	
Forward bulkhead	—	—	—	—	—	—	—	—	—	72	135	109	201	
Internal bulkhead	—	—	—	—	—	—	—	—	—	254	479	386	712	
Internal aft bulkhead	—	—	—	—	—	—	—	—	—	72	135	109	201	
Aft bulkhead	—	—	—	—	—	—	—	—	—	250	471	380	700	
Stage II														
Forward skirt	-4 807	1 584	-11 145	-12 046	4 944	4 326	9 638	5 261	5 074	7 353	7 983	7 464	11 436	
Forward tank wall	35 890	36 164	-53 228	-4 739	48 228	37 758	25 113	67 686	66 983	57 974	64 936	54 772	59 574	
Aft tank wall	4471	6653	-16353	-3155	8363	5963	5210	9732	9627	9027	9421	8861	10070	
Aft skirt	-676	1 442	-27 191	-9 450	4 281	2 922	8 267	3 834	3 595	5 164	6 262	5 832	11 867	
Forward bulkhead	—	—	—	—	—	—	—	—	—	392	738	594	1 097	
Internal bulkhead	—	—	—	—	—	—	—	—	—	706	1 328	1 078	1 981	
Aft bulkhead	—	—	—	—	—	—	—	—	—	2 560	4 813	3 887	7 163	

**TABLE 18. - COST RATIO SUMMARY
(DOLLARS PER POUND OF PAYLOAD GAINED)
VALUES NORMALIZED BETWEEN PRESSURIZED AND UNPRESSURIZED SHELLS**

Aluminum A															Honeycomb Sandwich			
Vehicle/Payload	Stage	Integral Skin Stringer	Waffle	Hat-Section Skin Stringer	Mono-coque	Ring Stiffened	Honeycomb Sandwich	Corrugated Sandwich	Multi-Wall Corrugated	Double-Wall Hat-Sect. Skin-Stringer Faces	Double-Wall Z-Sect. Skin-Stringer Faces	Aluminum		Titanium A	Beryllium A			
												B	C					
30 000-pound payload	1	0	120	-4100	120*	220*	-15	25	45	160	234	-15	-13	900	900			
	2	0	90	-170	12*	30*	-7	-12	-3	20	40	-8	-7	90	90			
100 000-pound payload	1	0	80	-550	90*	170*	20	60	55	170	165	20	20	620	830			
	2	0	20	-50	8*	20*	-6	3	10	40	27	-6	-6	90	120			
240 000-pound payload	1	0	-1200**	-380	36*	75*	100	185	185	290	300	90	85	910	1120			
	2	0	-25**	-65	5*	7*	10	0	3	80	100	7	5	135	250			
445 000-pound payload	1	0	390*	-280	25*	60*	80	150	150	250	260	75	70	710	910			
	2	0	-40**	-70	5*	7*	9	3	2	100	400	7	6	310	220			
1 000 000-pound payload	1	0	-230**	-130	30*	130*	160	240	180	240	240	160	140	970	1180			
	2	0	-55**	-40	6*	40*	20	30	25	30	30	14	12	110	140			
2 000 000-pound payload	1	0	140	-120	20*	170*	180	240	170	200	280	160	150	1000	1300			
	2	0	20	-25	3*	30*	30	30	24	24	35	20	16	125	165			

Note: See Appendix D for additional details and for bulkhead ratios.
*Ratio results from dollar reduction, additional weight and payload loss.
**Ratio results from additional dollars, additional weight and payload loss.

Note: See Appendix D for additional details and for bulkhead ratios.

*Ratio results from dollar reduction, additional weight and payload loss.

**Ratio results from additional dollars, additional weight and payload loss.

appears to be more beneficial cost-wise than the aluminum hat-section skin-stringer. Honeycomb sandwich appears to be more beneficial cost-wise in the small vehicle class. Ratios shown in table 18 for beryllium and titanium indicate that the present manufacturing state of the art needs significant improvement to make the use of either material beneficial from a cost standpoint.

Figures 10 through 13 display the assessment merit functions (weight, payload weight, and cost) in a more general fashion. In these figures the following parameters are plotted:

Alternate component weight versus base point component weight
Alternate component cost versus base point component cost
Payload weight gained versus base point component weight

These parameters are differentiated into four quadrants surrounding a locus of 1.0, 1.0, 0.0 for the base point aluminum integral skin stringer, with each quadrant representing the following:

- Quadrant I - The most desirable representing a weight decrease, payload gain, and reduced cost
- Quadrant II - Next in desirability resulting from a weight decrease, a payload gain, but costing dollars to achieve
- Quadrant III - Represents a reduced cost but a gain in component weight and a decrease in payload weight
- Quadrant IV - Least desirable, showing increased cost, increased weight, and payload loss

When consideration is restricted to a particular stage, the percent of change in weight (and cost or payload) associated with substituting one component type with another is relatively independent of the stage component selected. Major restrictions to this generalization occur when the compressive loading intensities, coupled with internal pressures, are sufficiently small that the skin thicknesses required are determined by minimum gages, or by the pressure requirements. In figure 10, the components are lightly loaded, minimum gauge designs tend to move toward quadrants III and IV. Values which fall in quadrants II and III have to be assessed individually to assess their effectiveness by offering a justification of a "worth index," or, how much is the payload worth? Without this index it appears that aluminum honeycomb sandwich, aluminum corrugated sandwich, and aluminum multi-wall construction with corrugated sandwich facings offer the greatest potential. Reductions in manufacturing cost complexity factors would easily shift these

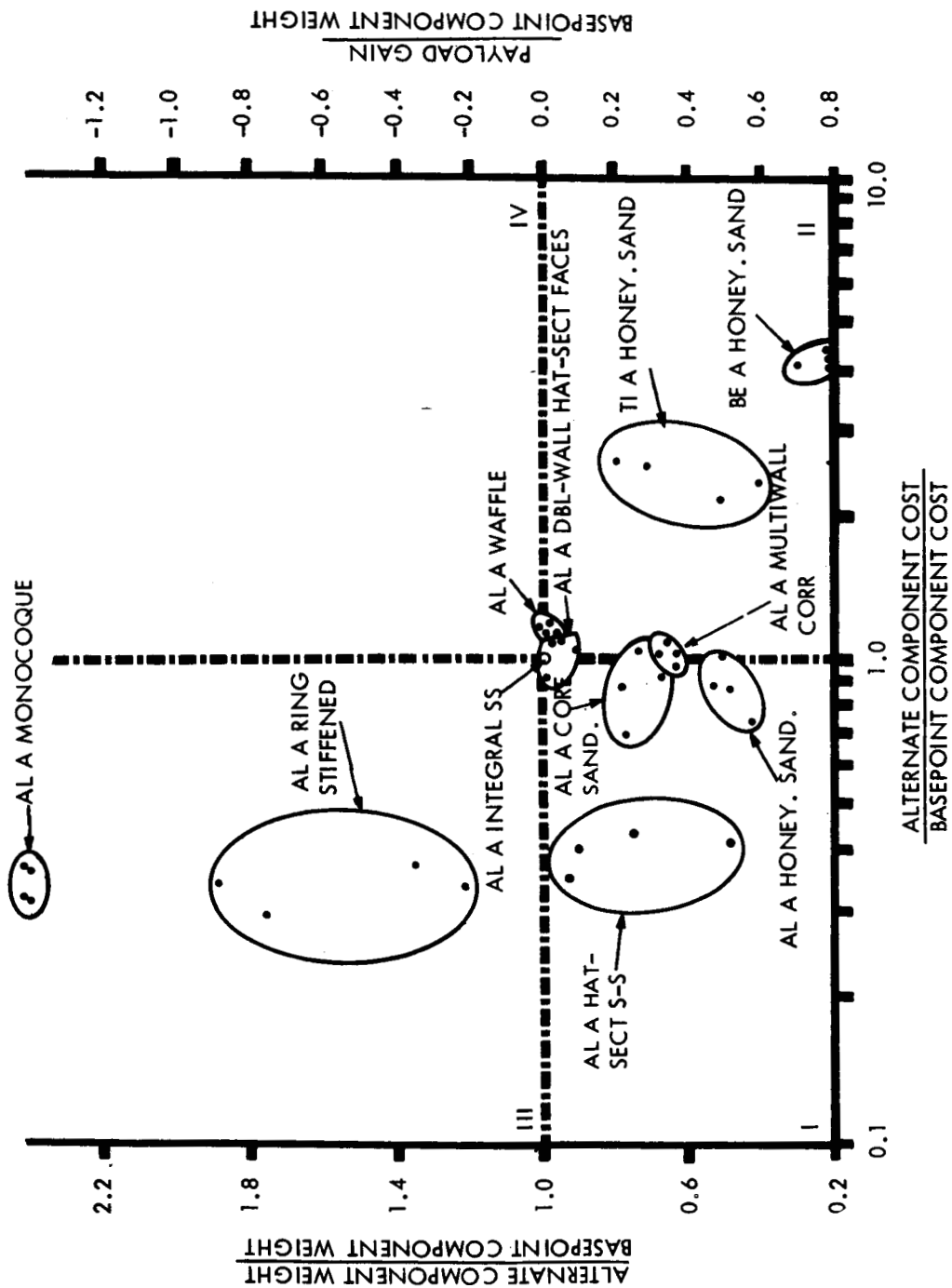


Figure 10. Merit Partials for 30 000-Pound-Payload Vehicle
(Second Stage)

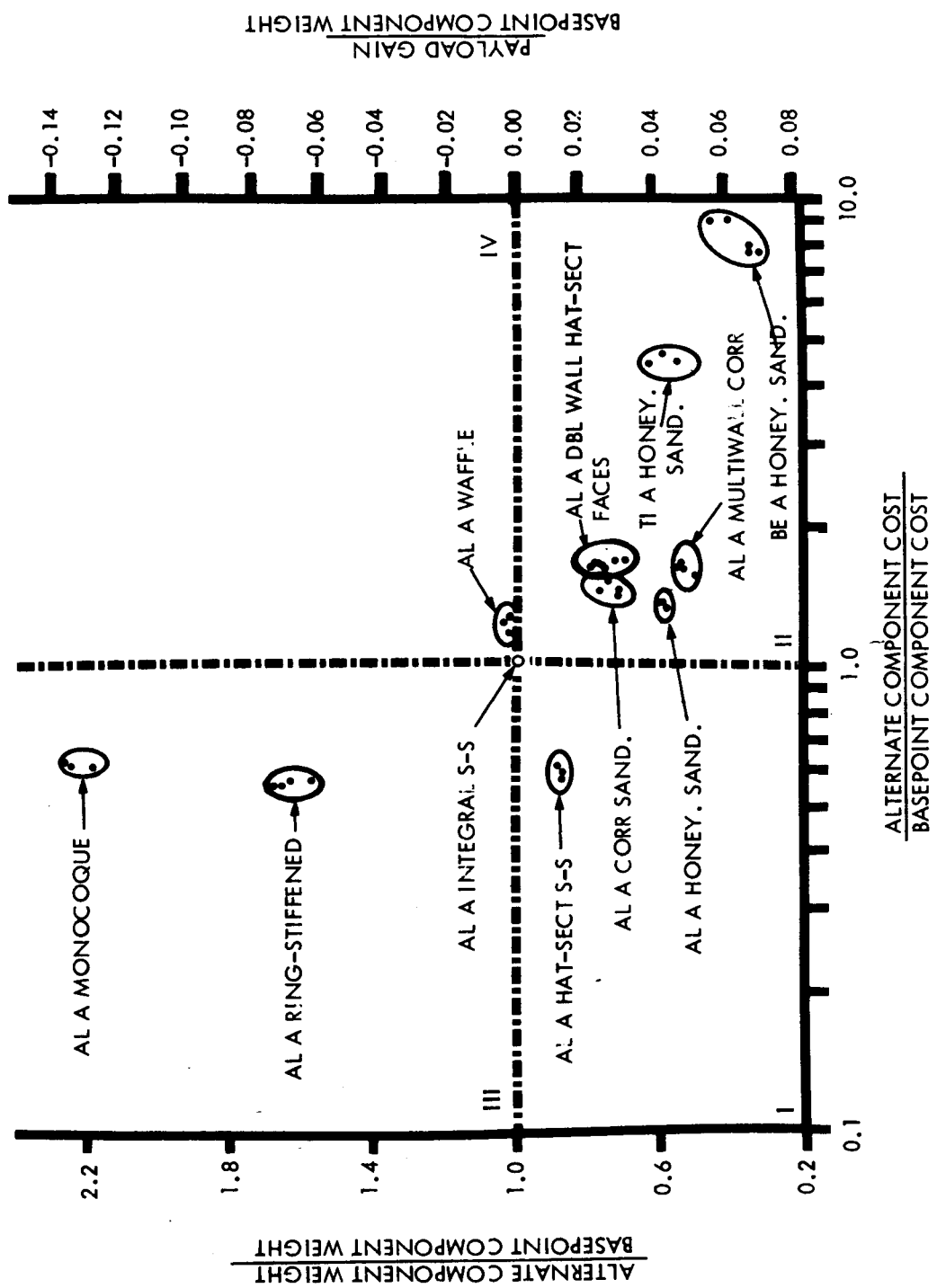


Figure 11. Merit Partial for 240 000-Pound-Payload Vehicle (First Stage)

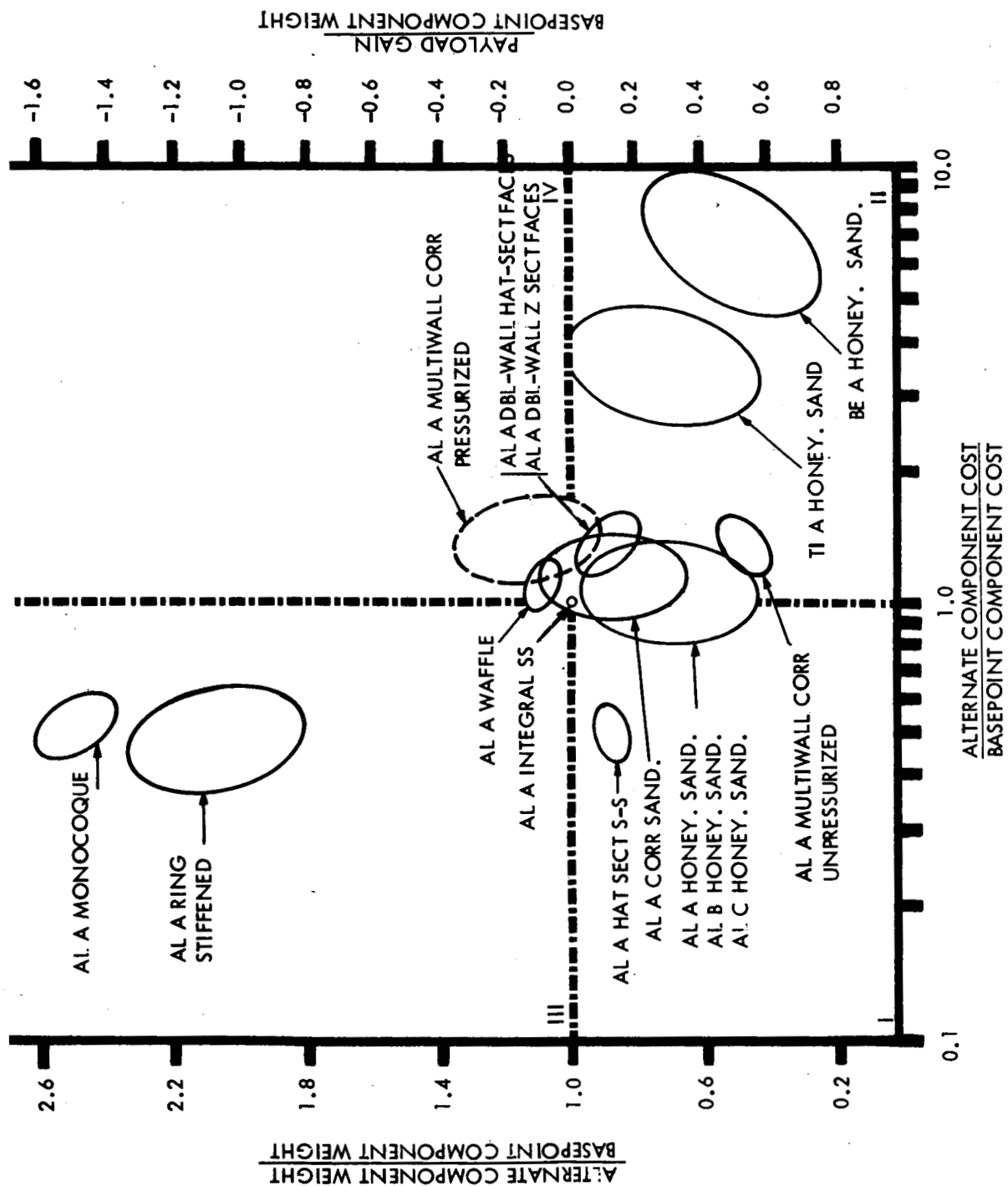


Figure 12. Merit Partial for 240 000-Pound-Payload Vehicle (Second Stage)

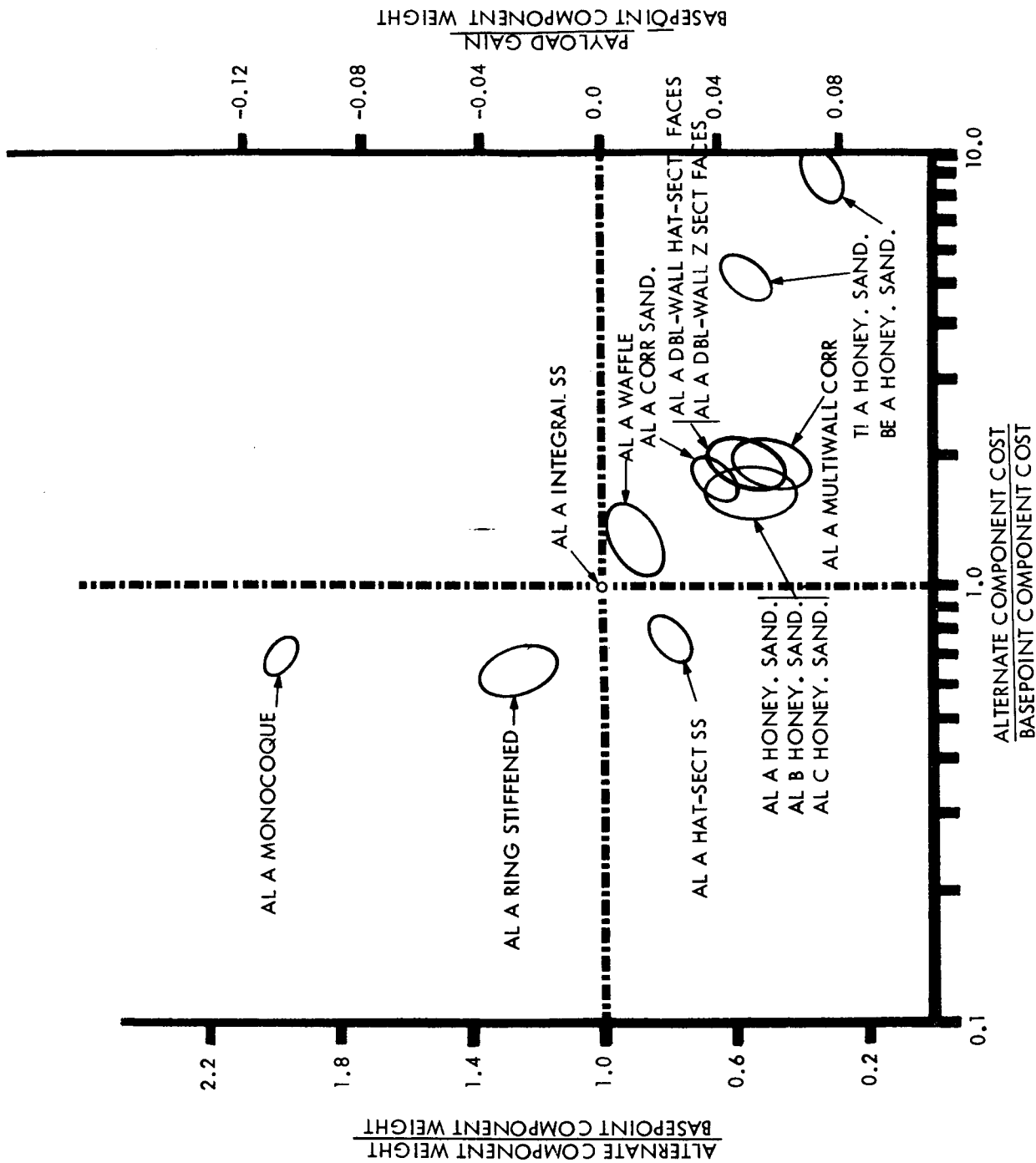


Figure 13. Merit Partial for 1 000 000-Pound-Payload Vehicle (First Stage)

partials to the left further into Quadrant I. The beryllium sandwich offers the greatest potential, weight-wise, if costs of this concept could be reduced. A 50-percent reduction in its cost complexity would position this partial favorably in Quadrant I.

In figure 11, the partials fall close together because of a higher loading intensity and a smaller percentage of difference in design loadings between components, some of the data points being identical in value. Zones of interest have shifted to the right of the figure, this resulting from component size characteristics and smaller payload exchange ratios. The only competitive material and construction type displayed in Quadrant I is aluminum hat-section skin-stringer. Again, this does not rule out Quadrant II constructions if cost complexities can be reduced or a worth index is introduced. Figure 12 illustrates the partials for the upper stage of the 240 000 lb payload vehicle. When compared to figure 10 for the smaller vehicle, the egg-shaped zones are broadened by the influence of the more lightly loaded pressurized shells. It is interesting to note that the A, B, and C aluminums (0, 10, 20 percent material property improvements) for honeycomb sandwich fall into the same general area, indicating that material improvement is not as significant as a change in basic construction.

In figure 13, for the first stage of the 1 000 000-pound payload vehicle, distribution of the partials fit the same pattern as previously displayed, except that the aluminum waffle structure is more performance competitive, probably being regulated by the input design constraints for both integral skin-stringer and waffle.

RECOVERABLE VEHICLE SYNTHESIS

In order to investigate the effects and benefits from material and structural research as applied to vehicle systems, a realistic series of base point vehicle systems is required. This requirement is more applicable when structural improvements are assessed against a vehicle system which possesses a recoverable stage. For such a system, the payload weight to vehicle lift-off weight can be about three to four-percent, and any weight reductions will have a noticeable effect on payload improvement.

The major objectives of the parametric synthesis during the second phase were to synthesize recoverable first stages for a series of base point vehicle systems. The vehicles considered were to be vertical-launched, tandem staged, bipropellant systems. Major elements of the study were the evaluation of comparative configurations and their performance for several orbital transport systems having recoverable first stages with a typical range of payload capability.

In order to enhance the comparison with expendable vehicle systems, identical system design philosophy was maintained, where possible. Consequently, both systems utilized the same tandem stage and tankage arrangement, vertical take-off mode, boost trajectory profile, and design and load criteria.

Sensitivity of gross weight of the major subsystems to parameter variations were established to indicate the system feasibility to several of the basic assumptions. Parametric trade-off exercises were conducted for staging conditions, trajectory profile, flyback range, mixture ratio, vehicle geometry, design criteria, safety factors, materials, etc.; these are shown in Volume 2.

Advance propulsion systems investigated during Phase I of the study were taken to be applicable for the recoverable vehicle systems. In order to preserve consistency between the two phases of this study, identical characteristics were used and are as follows:

Near-term: post-1975

First stage: LO_2/RP_1 system, 308 seconds average

Second stage: LO_2/LH_2 system, 460 seconds

Future: post-1985

First stage: LO_2/RP_1 system, 340 seconds average

Second stage: LO_2/LH_2 system, 500 seconds

Recoverable vehicles were synthesized with the near-term propulsion system for a range of payloads injected into Earth orbit. An optimum staging velocity for two-stage recoverable vehicles was found to be in the neighborhood of 6800 feet per second. The total velocity requirements for each stage are defined in Volume 2. The launch weights of the fully recoverable vehicles defined during this study are as follows:

Fully Recoverable Orbital Payload Weight, lb	Launch Weight, lb
20 000 lb	1.3×10^6 lb
40 000 lb	1.9×10^6 lb
60 000 lb	2.5×10^6 lb

Since these launch weights are required to inject 20 000 to 60 000 pounds of payload into orbit in a fully recoverable mode, the launch weights were used to determine payload capability for the mode with an expendable upper stage Figure 14. This could be considered in the building block approach of gradually evolving from an expendable vehicle system and initially adding wings to a first stage for its recovery. The performance, size and design loading environment for the baseline recoverable-expendable vehicles are given in tables 19 through 22 with any additional details supplied by Volume 2. The major structural shell elements of the fuselage of these base point vehicles will be subjected during Phase III to a detailed structural and material investigation similar to that performed on the fully expendable vehicles.

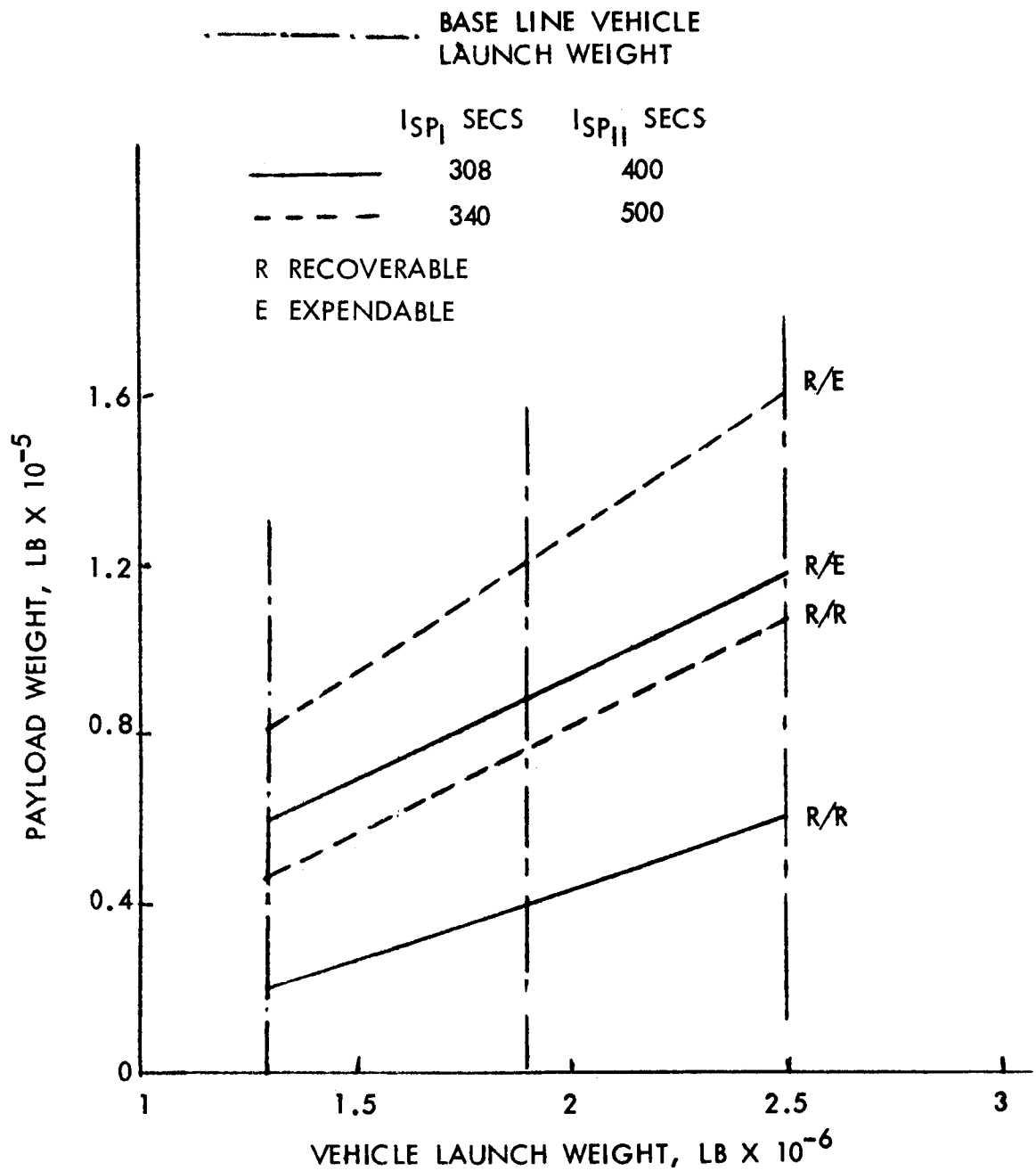


Figure 14. Effect, of Expendable Upper Stages

TABLE 19. - VEHICLE STATIONS AND DIAMETERS (IN.) FOR BASE POINT DESIGN, RECOVERABLE
FIRST - STAGE BOOSTER

Key	Item	Launch Weight (pounds)	1.3 x 10 ⁶		1.9 x 10 ⁶		2.5 x 10 ⁶	
			Near-Term	Future	Near-Term	Future	Near-Term	Future
	Payload	Propulsion System						
N	Nose		2025	2076	2233	2283	2429	2475
P	Shoulder		1869	1919	2047	2098	2215	2261
DM ₂	Stage 2		220	220	260	260	300	300
F ₂	Stage diameter		1759	1809	1917	1968	2065	2111
E ₂	Forward bulkhead/tank wall		1681	1731	1825	1876	1959	2005
C ₂	Tank wall/common bulkhead		1255	1175	1293	1383	1428	1423
B ₂	Tank wall/aft bulkhead		1124	1107	1251	1233	1405	1384
A ₂	Aft bulkhead crown		1046	1029	1159	1141	1299	1278
O ₂	Engine exit plane		1026	1008	1135	1115	1272	1248
DM ₁	Stage 1		260	260	300	300	320	320
G ₁	Stage diameter		916	890	1002	973	1119	1085
F ₁	Separation plane		786	760	852	823	959	925
E ₁	Forward crew compartment		694	668	780	752	895	862
D ₁	Forward bulkhead/tank wall		525	515	603	592	677	664
C ₁	Tank wall/first aft bulkhead		325	316	373	362	431	419
B ₁	Second forward bulkhead/tank wall		265	265	313	314	350	351
A ₁	Tank wall/second aft bulkhead		173	173	207	208	237	238
O ₁	Aft bulkhead crown		0	0	0	0	0	0
CT ₁	Engine exit plane		216	213	258	255	295	292
CR ₁	Wing tip chord		479	473	573	567	655	648
S ₁	Wing root chord		521	516	617	612	694	689

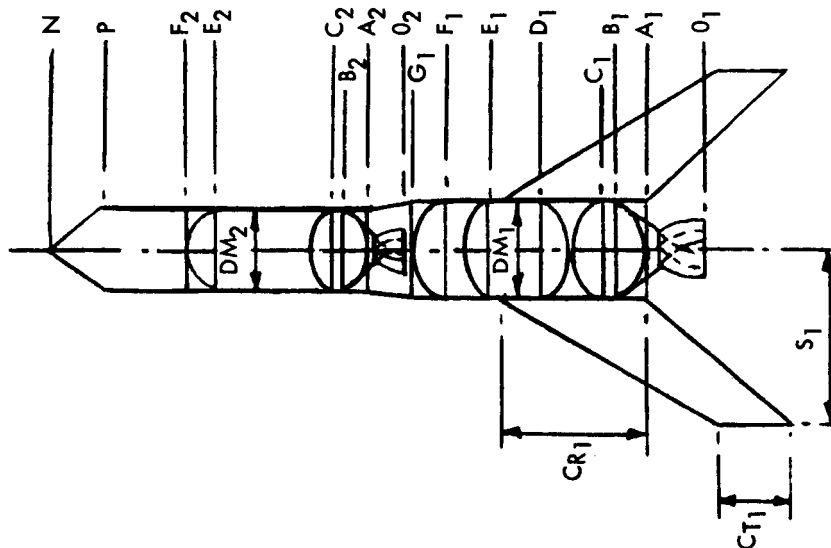


TABLE 20. - WEIGHT AND PERFORMANCE CHARACTERISTICS

Item	Launch Weight (lb)	1.3 x 10 ⁶ lb		1.9 x 10 ⁶ lb		2.5 x 10 ⁶ lb	
	Propulsion System	Near-Term	Future	Near-Term	Future	Near-Term	Future
STAGE 1							
Weights (lb)							
Payload		339,212	389,469	499,852	572,358	663,651	758,655
Burnout		133,664	130,778	189,155	185,669	242,936	238,750
Structures and subsystems		111,764	108,878	157,746	154,260	202,083	197,896
Engines		21,900	21,900	31,409	31,409	40,854	40,854
Propellant		831,124	783,754	1,210,993	1,141,972	1,593,412	1,502,595
Stage		964,788	914,531	1,400,148	1,327,642	1,836,349	1,741,345
Ratios							
Performance		0.63736	0.60104	0.63736	0.60104	0.63736	0.60104
Mass fraction		0.86146	0.85700	0.86490	0.86015	0.86771	0.86289
Delta velocity (fps)		10060	10060	10060	10060	10060	10060
Specific impulse (sec)		308	340	308	340	308	340
STAGE 2							
Weights (lb)							
Payload		58,528	80,351	88,023	120,232	117,696	160,220
Burnout		30,492	33,403	43,153	46,939	56,467	61,364
Structures and subsystems		23,296	25,417	33,514	36,263	44,530	48,161
Engines		7,196	7,986	9,639	10,676	11,936	13,203
Propellant		250,192	275,715	368,675	405,187	489,489	537,071
Stage		280,684	309,117	411,829	452,126	545,955	598,435
Ratios							
Performance		0.73757	0.70793	0.73757	0.70793	0.73757	0.70793
Mass fraction		0.89137	0.89194	0.89522	0.89618	0.89657	0.89746
Delta velocity (fps)		19815	19815	19815	19815	19815	19815
Specific impulse (sec)		460	500	460	500	460	500

TABLE 21. - BOOST PHASE PRESSURE MATRIX (PSI)

Item	Launch Weight (lb)	1.3 x 10 ⁶ lb				1.9 x 10 ⁶ lb				2.5 x 10 ⁶ lb			
	Propulsion System	Near-Term		Future		Near-Term		Future		Near-Term		Future	
	Trajectory Regime	Max q _e	Boost	Max q _e	Boost	Max q _e	Boost	Max q _e	Boost	Max q _e	Boost	Max q _e	Boost
STAGE 1													
Aft tank		39.0	39.0	39.0	39.0	39.0	39.0	39.0	39.0	39.0	39.0	39.0	39.0
Forward tank		39.0	39.0	39.0	39.0	39.0	39.0	39.0	39.0	39.0	39.0	39.0	39.0
Aft bulkhead		45.8		45.5		46.9		46.6		47.4		47.1	
Forward bulkhead		39.0	39.0	39.0	39.0	39.0	39.0	39.0	39.0	39.0	39.0	39.0	39.0
Aft tank forward		39.0	39.0	39.0	39.0	39.0	39.0	39.0	39.0	39.0	39.0	39.0	39.0
Forward tank aft		43.8		43.6		44.6		44.3		44.9		44.7	
STAGE 2													
Aft tank		45.7	55.5	46.4	56.0	46.0	56.1	46.7	56.6	45.6	55.3	46.3	55.8
Forward tank		38.7	41.4	38.8	41.4	38.9	41.8	39.0	41.7	38.9	41.9	39.0	41.8
Aft bulkhead			61.2		61.5		62.9		63.1		63.2		63.4
Forward bulkhead		36.0	36.0	36.0	36.0	36.0	36.0	36.0	36.0	36.0	36.0	36.0	36.0
Aft tank forward		36.0	36.0	36.0	36.0	36.0	36.0	36.0	36.0	36.0	36.0	36.0	36.0
Forward tank aft			0.0		0.0		0.0		0.0		0.0		0.0

**TABLE 22. - APPLIED LOADS MATRIX FOR BASE POINT DESIGNS,
RECOVERABLE FIRST-STAGE BOOSTER**

Launch Weight 1.3×10^6 lb, Near-Term Propulsion System

Station	Prelaunch NX	Max q NX	End Boost NX	Max NX/R
173	2732	2834	3058	23.5239
265	2401	-76	179	18.4683
325	2190	2310	2920	22.4585
525	1541	-1128	-63	11.8571
694	1054	1307	2604	20.0288
786	793	1360	2547	19.5901
916	725	1413	2443	18.7928
1046	793	1807	2740	24.9107
1124	704	-204	303	6.4018
1177	646	1741	2331	21.1931
1255	568	-315	-75	5.1671
1681	193	763	725	6.9398
1759	126	510	478	4.6407
1759	126	510	478	4.6407

Launch Weight 1.3×10^6 lb, Future Propulsion System

Station	Prelaunch NX	Max q NX	End Boost NX	Max NX/R
173	2747	2834	3086	23.7355
265	2419	-32	213	18.6099
325	2245	2398	2971	22.8503
515	1599	-983	6	12.3023
668	1161	1309	2701	20.7735
760	900	1370	2651	20.3900
890	830	1436	2559	19.6838
1029	909	1840	2884	26.2181
1107	818	-156	454	7.4362
1175	740	1789	2463	22.3941
1253	661	-254	64	6.0102
1731	238	795	828	7.5238
1809	170	555	599	5.4444
1809	170	555	599	5.4444

Launch Weight 1.9×10^6 lb, Near-Term Propulsion System

Station	Prelaunch NX	Max q NX	End Boost NX	Max NX/R
207	3371	3567	3867	25.7768
313	2949	245	505	19.6570
373	2720	3054	3699	24.6575
603	1884	-917	197	12.5584
780	1311	1359	3296	21.9726
887	973	1376	3222	21.4789
1002	911	1428	3122	20.8105
1159	968	1747	3415	26.2689
1251	853	-639	476	6.5637
1293	801	1669	2924	22.4932
1385	698	-759	22	5.3712
1825	252	758	949	7.2983
1917	160	503	609	4.6816
1917	160	503	609	4.6816

Launch Weight 1.9×10^6 lb, Future Propulsion System

Station	Prelaunch NX	Max q NX	End Boost NX	Max NX/R
208	3387	3568	3901	26.0057
314	2968	294	547	19.7857
362	2785	3142	3761	25.0710
592	1952	-765	282	13.0151
752	1441	1597	3414	22.7617
858	1104	1470	3349	22.3276
973	1040	1479	3260	21.7336
1141	1107	1813	3583	27.5613
1233	989	-562	656	7.6091
1291	916	1743	3078	23.6795
1383	811	-675	188	6.2379
1876	308	808	1074	8.2605
1968	216	565	759	5.8362
1968	216	565	759	5.8362

Launch Weight 2.5×10^6 lb, Near-Term Propulsion System

Station	Prelaunch NX	Max q NX	End Boost NX	Max NX/R
237	4158	4394	4776	29.8482
350	3664	893	1122	22.8989
431	3320	3886	4563	28.5197
677	2346	-420	744	14.6635
895	1584	1827	4070	25.4349
1008	1192	1679	3984	24.9027
1119	1128	1582	3883	24.2658
1299	1097	1779	3924	26.1627
1405	953	-1002	485	6.3554
1428	923	1676	3388	22.5850
1534	791	-1142	-10	5.2735
1959	305	774	1152	7.6770
2065	186	501	706	4.7045
2065	186	501	706	4.7045

Launch Weight 2.5×10^6 lb, Future Propulsion System

Station	Prelaunch NX	Max q NX	End Boost NX	Max NX/R
238	4173	4396	4818	30.1095
351	3683	945	1173	23.0188
419	3397	3982	4640	28.9969
664	2427	-254	847	15.1681
862	1740	2101	4214	26.3395
975	1350	1949	4139	25.8704
1085	1284	1800	4049	25.3037
1278	1252	1876	4110	27.3970
1384	1105	-894	688	7.3648
1423	1052	1773	3556	23.7066
1529	918	-1035	176	6.1214
2005	369	837	1290	8.5987
2111	249	576	877	5.8450
2111	249	576	877	5.8450

Note: NX = Applied Load Intensity (lb/in.)

SYNTHESIS PROGRAMS

During both phases of the contract reported in this volume, a number of computer programs and subroutines were modified, developed, and exercised to meet the study requirements. There are two basic classes of subroutines:

1. Parametric synthesis programs, which size and evaluate performance of optimum vehicle systems to meet a series of mission requirements, and then assess structural design trade-offs on the major shell components of the baseline vehicles to develop weight, payload, and cost merit functions (table 23).
2. Preliminary design synthesis programs, which are detail structural analysis programs to synthesize different construction concepts, materials, sizes, load environments, etc., to produce detail dimensional data and unit shell weights (table 24); information is used for the assessment portion of parametric synthesis programs

The various subroutines can be operated individually or linked together. Each of the design synthesis subroutines can be used as a tool for preliminary design evaluation, to investigate the effects of manufacturing restrictions imposed upon any given design concept and to evaluate the weight penalties associated with design control decisions. The operating cycle of the individual subroutines per design case is of the order of one second and less, thus allowing numerous parameter changes for sensitivity studies to be conducted economically. A summary description of these elements is contained in tables 23 and 24. These programs are documented in detail in reference 1 and in Volume 2.

TABLE 23. - PARAMETRIC VEHICLE SYNTHESIS PROGRAMS

Program Name	Capability	Options
TRANUB (mass fraction expendable stages)	Derives size, mass properties, weights, geometry, and mass fractions of expendable vehicles to stage velocity requirements	Size from payload weight, size from first-stage thrust; common or separate bulkheads; change engine, load, structure parameters
MAXPL (maximum payload for "n"-stage vehicle)	Optimally proportions vehicle to achieve maximum payload weight from given take-off weight and final burnout velocity requirements; dynamic programming optimization techniques	Fixed or "rubberized" stages; constant or time-variant velocity losses
MINTO (minimum take-off for "n"-stage vehicle)	Optimally proportions vehicle from given payload and range of final velocities.	Fixed or "rubberized" stages; constant or variant velocity losses
PART (payload exchange ratios)	Derives stage payload exchange for unit or specific changes in stage parameters.	Unit or specific changes in thrust, propellant weight, I_{sp} , vehicle gross weight, stage burnout weight
START (cost starter package)	Adjusts component weights of base point and alternate designs to match non-optimum weight factors	Weight complexity factors; unit shell weight conversion for structural component
COSTPA (cost analysis)	Defines assessment merit functions (basepoint and alternate), weight, payload change, cost ratio	Material cost curves, cost complexity factors, learning curves, fabrication cost, scheduling, number of units, time element
RECNUB (mass fraction, recoverable first stages)	Derives size, mass properties, weights, geometry and mass fractions for recoverable winged body lower stages plus expendable upper stages	Payload or thrust sizing modes, range and landing parameters, crew compartment, manned and unmanned; flyback and fuel engine; wind-profiles (prelaunch and dynamic pressure region); thermal environments (body and wings); wing sizing and geometry

TABLE 24. - PRELIMINARY STRUCTURAL DESIGN SYNTHESIS

Program Name	Capability	Options
SKINST (skin-stringer shells)	Synthesize optimum design, with or without design restrictions Strength analysis Stability analysis (local and general) Orthotropic Isotropic (inside-outside stiffeners) Experimental correction factors	Types: integral, hat-section, I-section, Z-section Preset stringer and frame spacing Material properties, F_{cy} , F_{Tu} , E Pressure (burst and relief) Minimum gauge (skin stiffeners) Stiffener section properties Buckled or unbuckled design
MONO (monocoque shells)	Same as above	Material properties, minimum gauge, pressurized and unpressurized
SAND (honeycomb sandwich shells)	Same as above, plus Intercell buckling Face-sheet wrinkling	Material properties, minimum gauge and core density, sandwich heights, cell size, bonding and adhesive Pressure (burst and relief)
WAFF (waffle shells)	Same as above	Waffle orientation Minimum skin gauge, maximum web heights Cell geometry Pressure and burst and relief Material properties
CORRUG (corrugated sandwich shells)	Same as above	Core height, minimum skin gauge Corrugation angle Pressure Material properties
RINGS (ring-stiffened shells)	Same as above, plus Ring area and stiffness requirements	Material properties, minimum gauge, ring spacing, pressure
CORRMW	Same as above, plus Substructure stability requirements analyzed	Material properties, minimum gauges, core depth, substructure depth, maximum pressure
SKINDW (double-wall skin-stringer)	Same as above	Material properties, minimum gauges, ring-spacing, stringer section (hat, I, Z, integral), stringer spacing, core depth, pressure
OBDOME (oblate bulkhead)	Synthesize optimum bulkhead weight and thicknesses	Material properties, specific oblate shapes, pressures, diameters, minimum gauges
ELDOME (ellipsoidal bulkhead)	Same as above	Material properties, various ellipsoidal shapes, minimum gauges, pressures, diameters
TORUS (semitoroidal bulkhead)	Same as above	Material properties, height radius and inner-outer radius parameters, pressures, minimum gauges

CONCLUSIONS

The study objectives were to develop and apply analytical techniques for determining areas wherein research and development in the structural sciences will yield significant improvements in future space vehicle systems. Both the method employed and the results obtained are products of constraints and design criteria imposed upon the baseline vehicle systems. These constraints have been defined elsewhere in this report. Statements which follow apply only within this context. Material and structural assessment pertained to expendable launch vehicles, whose generic categories were defined during Phase 1. The following general conclusions and directions can be made from the results obtained for the vehicle systems and structural concepts considered during this study.

Construction Concepts

Multiwall and double-wall concepts offer distinct weight advantages for unpressurized shells over integrally stiffened, single-sheet designs. The multiwall construction with corrugated face sheets offers the lightest weight concept in aluminum rather than in titanium. From a weight loading standpoint, the advanced structural concepts using either aluminum or titanium offer effective weight reductions, but they are not competitive weight-wise with single-wall concepts using beryllium. Advanced concepts offer payload increases from the baseline construction of approximately 1 percent for first-stage designs, 2.5 percent for medium- and Saturn-class upper stages, and 10 percent for post-Saturn-class upper stages. The payload increase in the latter vehicle is due to large diameter, moderate compressive load intensity tank walls using double-wall skin stringer design. Medium- and Saturn-class payload improvements with advanced structural concepts are comparable to unrestricted sandwich honeycomb designs using deep core construction. For pressurized shells (propellant tanks) the multiwall concept for the lightly loaded, small-diameter upper stages is inferior to conventional waffle or skin stringer. Multiwall and double-wall concepts for large vehicle systems offer good weight and relative cost advantages and should be considered when beryllium structures are excluded due to high cost, availability criteria, etc.

Application of double-wall and multiwall concepts to tank walls offers weight advantages, but presents design problems in trapped propellant, tank volume degradation, leakage and insulation. The major surface areas of the boost vehicle systems are the tank walls, and as such they represent potential research areas for weight saving.

Honeycomb sandwich is an overall light-weight design with a moderate structural cost (costs greater than skin stringer but appreciably less than structures fabricated with beryllium). The aluminum honeycomb sandwich is one of the lightest design concepts with the exception of beryllium constructions. It is competitive cost-wise with skin-stringer concepts for use in upper-stage components and is appreciably lighter. It offers a potential payload improvement from four percent for the medium class vehicle to nine percent with the post-Saturn class when compared to the integrally stiffened baseline vehicles. Large radii and load intensities result in potential weight and cost advantages only with deep core sandwich. Analysis and "knockdown" factors on both general instability and core shear properties tend to dictate deep core as a requirement for optimum weight designs. With no factors required, optimum designs have one- to two-inch core heights. If experimental verification justifies these factors and deep core is required, then design could present fabrication difficulties. Large height restrictions could impose severe weight penalties and result in honeycomb sandwich being inferior to other types of double-wall and multiwall designs. Therefore, honeycomb sandwich should be considered as a light-weight design concept for all vehicle systems, especially with large diameter components. The "knock down" factors and manufacturing feasibility require verification.

The most attractive weight-to-cost design is an aluminum skin-stiffened concept using Z sections or top-hat stringers. Although other designs exist which are lighter, their structural costs are appreciably higher. A relative payload "worth index" must be assigned to the vehicle system before the best choice is defined. If a structural worth index of 300 dollars per pound of payload is assigned, then it is best to use the stringer stiffened skin concept for the first stages, while for the upper stage the honeycomb sandwich should be used, i. e., more potential weight reduction and within the assigned worth index.

Although designs fabricated from beryllium offer the greatest weight advantages, their present structural costs do not justify their general application to large structural components for the boost stages considered. The major disadvantage investigated for the beryllium designs was an extremely high structural cost index, this being due to both the high cost of material and its fabrication difficulties. If demand and application increases, these two costs will decrease and with complexity factors reduced by 50 percent from those assigned for this study, the beryllium designs are effective, structural

cost-wise, with light weight aluminum concepts. It is recognized that other design problems will still exist due to the present brittleness of materials, etc.

Simplified construction (ring-stiffened) when used for the first stage results in moderate payload decreases. If a simplified design for cost or schedule reasons is considered, then the payload degradation is less noticeable when the design is applied to the first stage. With the ring-stiffened concepts using close-pitch rings, the payloads were only decreased by 2 percent with first-stage application and from 5 to 15 percent when used in the upper stage. The justification of using this design concept for any structural component has been made upon the basis of required payload capability and the "worth index" associated with the payload.

Material Strength Improvement

Application of improved-strength material should be to multiwall and sandwich construction concepts. Improvement in the material's compressive yield and ultimate tensile stress is beneficial and should be applied to constructions having very thin facing sheets which are highly loaded. An ordering of constructions which most benefit by material improvements is as follows:

Aluminum: Honeycomb sandwich, multiwall corrugated, and double-wall skin stiffened.

Titanium: Honeycomb sandwich and multiwall corrugated.

Beryllium: Honeycomb sandwich, multiwall corrugated, double-wall skin stiffened, corrugated sandwich, skin-stringer, and waffle.

Percentage increases in the material properties do not correspond to identical percentage weight reductions. At best, the effect of a 10-percent compressive-yield increase results in an 8-percent weight reduction if the designs considered are both optimum concepts (minimum weight). Large-radius tank walls whose shell's skin thickness is dictated solely by the burst pressure requirements will benefit slightly. A 10-percent material property improvement could reduce the shell's unit weight by approximately two-percent for the lightly loaded 270-inch-radius shell.

Experimental Verification

General instability "knock down" factors influence the choice of optimum weight construction concept and its relative configuration details. The small-deflection theoretical critical buckling load for all constructions is multiplied by a stability correction factor to obtain an effective design load. Theoretical upper-bound stability stresses have been attained with carefully controlled test specimens and testing conditions. As a result of this, the correction factor is believed to include the effects of initial imperfections, differences in boundary conditions, etc. However, these influences with deep sections (double-wall, multiwall, and deep-core honeycomb) may be appreciably less, and the concepts are being unfairly penalized. Relaxing of these factors would decrease the unit weight slightly for optimum designs and greatly influence the detail element design. The core and substructure depths for honeycomb and multiwall concepts respectively are controlled by these factors. Justification of applying these "knock down" factors to advanced construction concepts and to large diameter shells is required.

Experimental verification is required of core shear stiffness for double-wall and multiwall concepts which are competitive as light-weight attractive structural cost designs. The general instability analysis for the double-wall and corrugated concepts is based, to a large extent, on theoretical shear stiffnesses of the substructure and core. This shear stiffness is believed to represent an upper bound. Hence, additional investigations, primarily of an experimental nature, are required to define the percentage of the theoretical shear stiffness that can be obtained with the sine-wave substructure and to determine the most efficient substructure arrangement and the weight penalties incurred, if any.

The evaluation of candidate structural concepts is highly dependent on the analytical techniques utilized. For the advanced structural concepts, the unknowns associated with inaccurate assessment of the shear stiffnesses may result in the interchange of the ordering of two structural concepts on the structural evaluation curve. With the present synthesis evaluation, the multi-wall and double-wall concepts are lighter than single-wall construction and slightly heavier than sandwich honeycomb for the same material.

Longitudinal stiffeners should be positioned externally for most beryllium designs; aluminum and titanium designs require individual assessment for small changes if any; eccentricity effects diminish with increased shell diameter. The effects of the positioning of the longitudinal stiffeners, either internally or externally, indicated weight benefits either way depending upon the loading, size, and material. All circumferential rings were considered internal. Greatest benefits from external stiffeners were achieved with beryllium shells of small diameter which were moderately loaded. Titanium

structures appeared not to notice the effects of stiffener eccentricity. Aluminum structures with the synthesized light-weight design configurations considered could benefit from either position, depending upon the individual designs.

Manufacturing Development

The above discussions consistently allude to the fact that research would be highly beneficial when devoted to increasing "know-how" in manufacturing of new and advanced structural concepts and in the development of the manufacturing technology to fabricate structures from highly advanced materials or from new materials with radically different properties. Such efforts would undoubtedly lead to reduced structures and materials costs and make the advanced structural concepts much more competitive cost-wise than presently. From the study results, it appears that research in improvement of the strength properties of current material does not offer significant advantages. Improvement of the material properties which influence the fabrication process, while not analyzed in detail in this study, will effectively reduce construction costs and save weight of the secondary structure, such as weld lands, attachment points, etc.

Recoverable Vehicles

Recoverable vehicle systems with their small payload-to-launch-weight ratios will greatly benefit from structural weight reduction of the upper stages. With a fully recoverable vehicle system, the payload-to-launch-weight ratio is one to two percent; therefore, structural weight reduction is important. Any structural weight saving in recoverable vehicles is compounded by additional savings in the flyback recovery features. Lighter shell structures for the boost vehicle result in smaller burnout weight requiring recovery and, therefore, smaller wings, less flyback fuel, etc.

REFERENCES

1. Boddy, J.A.; and J.C. Mitchell: Development of Programmed Assistance In Directing Structures Research. NAA/SD SID 66-408, June 1966.
2. White, J. Frederick: Flight Performance Handbook for Powered Flight Operations. Space Tech. Lab., Inc., March 1962.