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

Summary Report

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

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## 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.


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## SUMMARY REPORT

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## 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 synthesis[1] 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.

[1]Parametric 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 synthesis[1] 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.

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[1]Preliminary 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.

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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

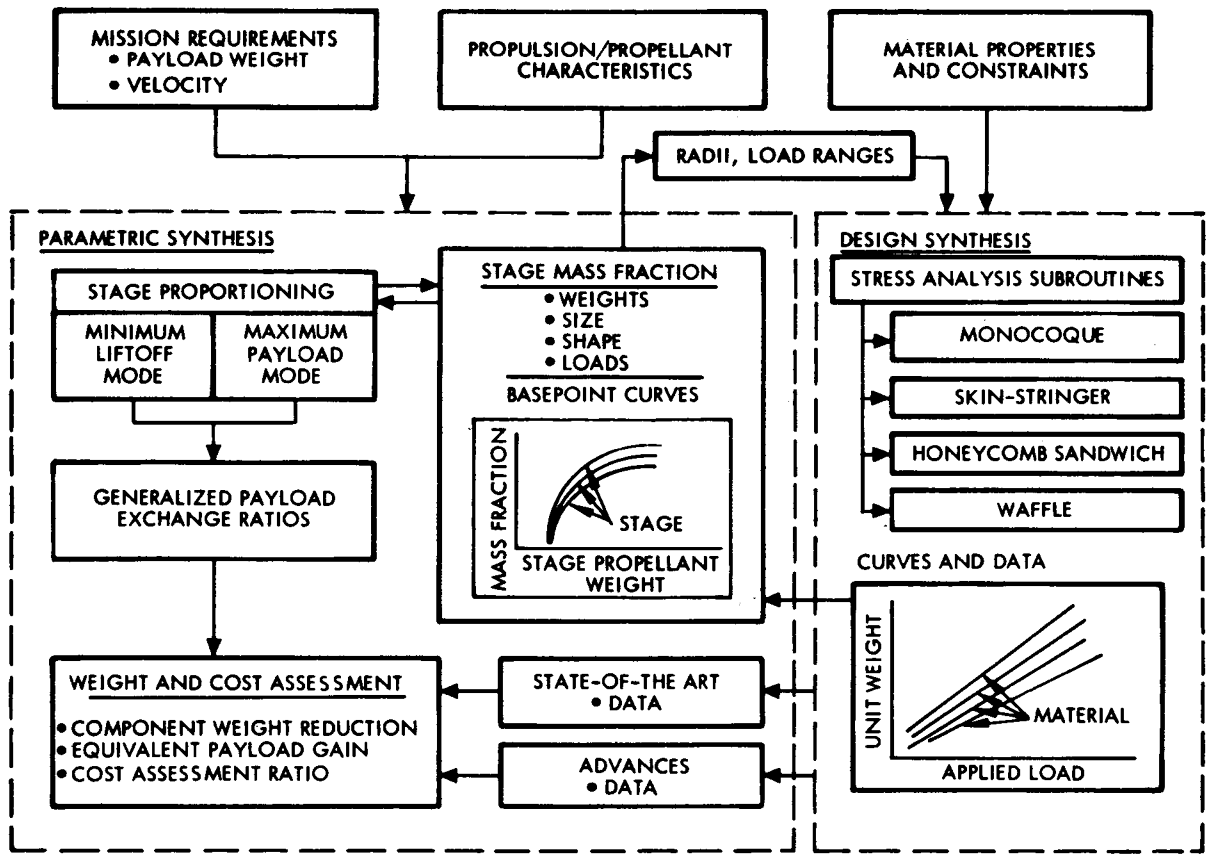



Figure 1. - Evaluation Logic

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

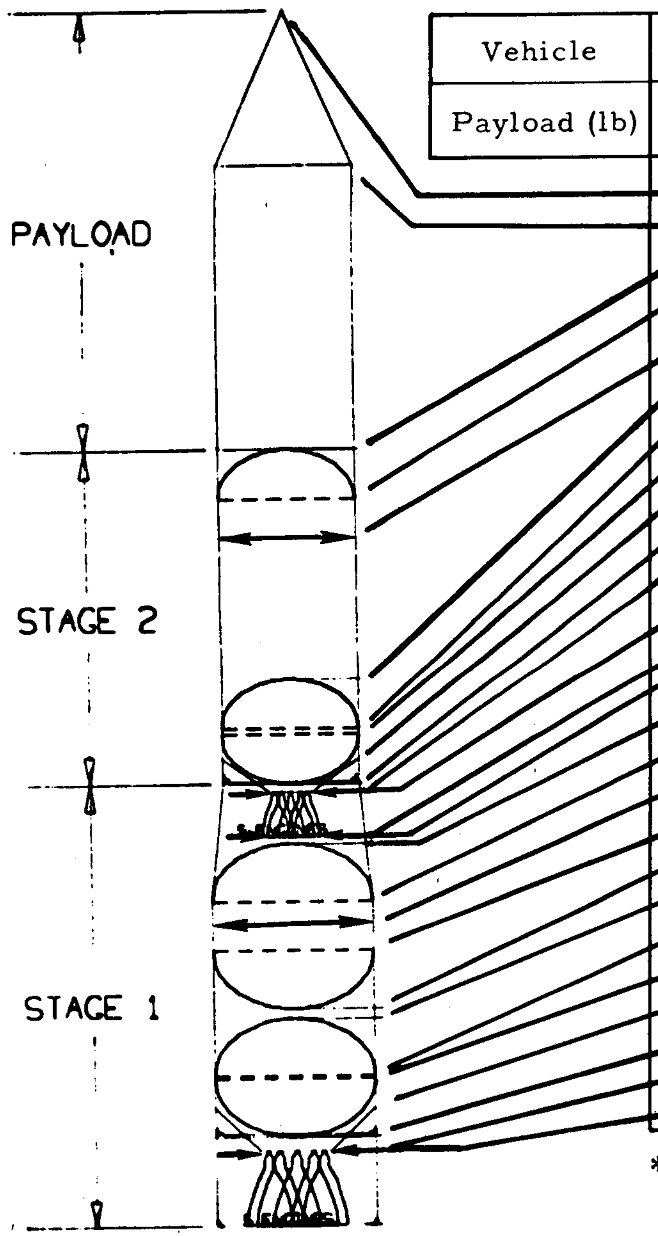
| Payload Class (lb) | Time Period | Stage Performance | | | |
|---|---|---|---|---|---|
| | | Stage 1 | | Stage 2 | |
| | | ΔV | $I_{sp}$ AV | ΔV | $I_{sp}$ VAC |
| 30 000 | Current | 10 402 | 289.8 | 20 600 | 424 |
| 240 000 | Current | 10 861 | 289.8 | 19 800 | 424 |
| 1 000 000 | Current | 11 123 | 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 | Medium Range | | Saturn Class | | Post-Saturn | | |
|---|---|---|---|---|---|---|---|
| Payload (lb) | 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

TABLE 3. - PERFORMANCE AND PAYLOAD EXCHANGE RATIOS FOR EXPENDABLE BASE-POINT VEHICLES

| Vehicle | | Medium Range | | Saturn Class | | Post-Saturn | |
|---|---|---|---|---|---|---|---|
| Stage 1 | Payload (lb) | 30 000 | 100 000 | 240 000 | 445 000 | 1 000 000 | 2 000 000 |
| 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 $I_{sp}$ (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 | 0.02 |
| | $I_{sp}$ (sec) | 97.87 | 206.27 | 717.67 | 1022.28 | 3038.74 | 4212.97 |
| | WO (lb) | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.02 |
| | WST (lb) | -0.09 | -0.12 | -0.11 | -0.15 | -0.11 | -0.13 |
| | WP (F) (lb) | 0.02 | 0.03 | 0.02 | 0.03 | 0.02 | 0.03 |
| | 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 $I_{sp}$ (sec) | | 424 | 500 | 424 | 500 | 424 | 500 |
| Payload Exchange Ratios | Thrust (%) | 0.03 | 0.05 | 0.02 | 0.03 | 0.03 | 0.04 |
| | $I_{sp}$ (sec) | 216.11 | 409.12 | 1359.56 | 1660.73 | 5500.14 | 7436.39 |
| | WO (lb) | 0.01 | 0.05 | 0.05 | 0.09 | 0.04 | 0.07 |
| | WST (lb) | -1.00 | -1.00 | -1.00 | -1.00 | -1.00 | -1.00 |
| | WP (F) (lb) | 0.14 | 0.17 | 0.14 | 0.19 | 0.14 | 0.18 |
| | WP (NF) (lb) | 0.01 | 0.06 | | | 0.05 | 0.08 |

TABLE 4. - VEHICLE WEIGHT STATEMENT FOR STAGE 1 (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 | 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 | 15 309 | 28 448 | 94 509 | 112 546 | 338 272 | 446 751 |
| Propellant system | 11 648 | 15 776 | 30 863 | 33 376 | 59 652 | 67 246 |
| Ullage system | 0 | 0 | 0 | 0 | 0 | 0 |
| Separation system | 386 | 708 | 2 709 | 3 169 | 10 122 | 12 863 |
| Thrust vector control system | 2 193 | 3 457 | 9 458 | 10 636 | 25 415 | 30 419 |
| Fixed equipment | 2 649 | 3 881 | 6 568 | 7 486 | 13 063 | 16 170 |
| Residual propellant | 8 918 | 16 361 | 62 613 | 73 223 | 233 903 | 297 252 |
| Contingencies | 0 | 0 | 0 | 0 | 0 | 0 |
| Stage burnout | 62 273 | 109 273 | 340 481 | 396 792 | 1 254 028 | 1 619 671 |
| Stage propellant | 602 999 | 1 106 198 | 4 233 452 | 4 950 839 | 15 814 960 | 20 098 176 |
| Stage gross | 665 272 | 1 215 471 | 4 573 934 | 5 347 631 | 17 068 988 | 21 717 847 |
| Vehicle payload | 232 010 | 497 961 | 1 426 066 | 1 852 369 | 5 641 232 | 8 643 258 |
| Vehicle gross | 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 | |
|---|---|---|---|---|---|---|
| Sizing Parameters (Isp, thrust) | Current | 1985 | Current | 1985 | Current | 1985 |
| Stage 1 | | | | | | |
| 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 |
| Stage 2 | | | | | | |
| 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 $q\alpha$ 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 subroutines. 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 | | |
| -300 | 120 | 135 | 15.8 | 125 | 140 | 15.8 | 145 | 150 | 15.8 |
| 300 | 100 | 115 | 14.0 | 105 | 120 | 14.0 | 110 | 125 | 14.0 |
| | Beryllium A | | | Beryllium B | | | Beryllium C | | |
| -300 | 48 | 63 | 43 | 55 | 70 | 43 | 60 | 75 | 43 |
| 300 | 48 | 63 | 43 | 55 | 70 | 43 | 60 | 75 | 43 |

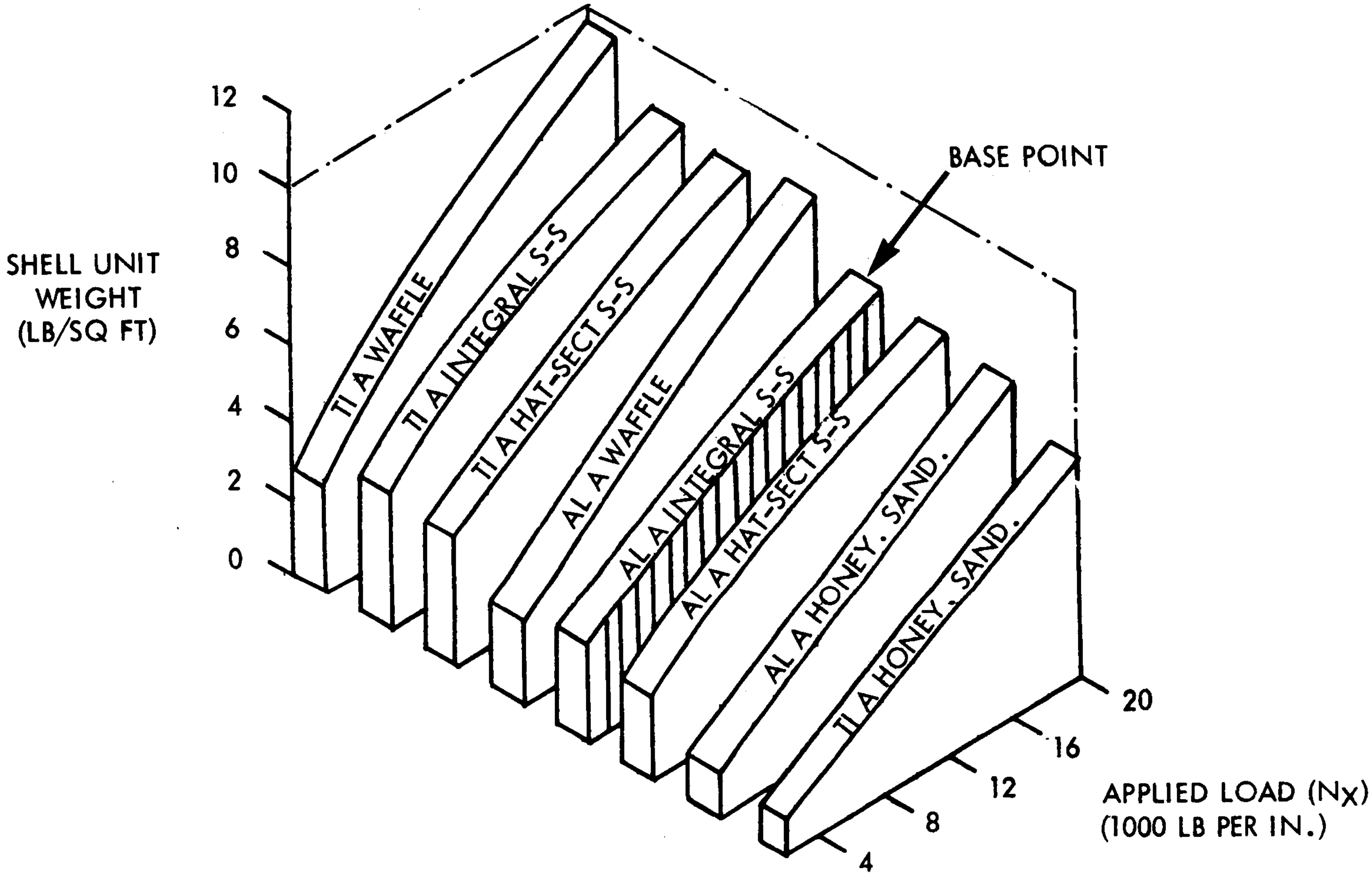



Figure 2. Shell Unit Weights for Conventional Titanium and Aluminum Structures—130-Inch Radius, 300°F, No Pressure

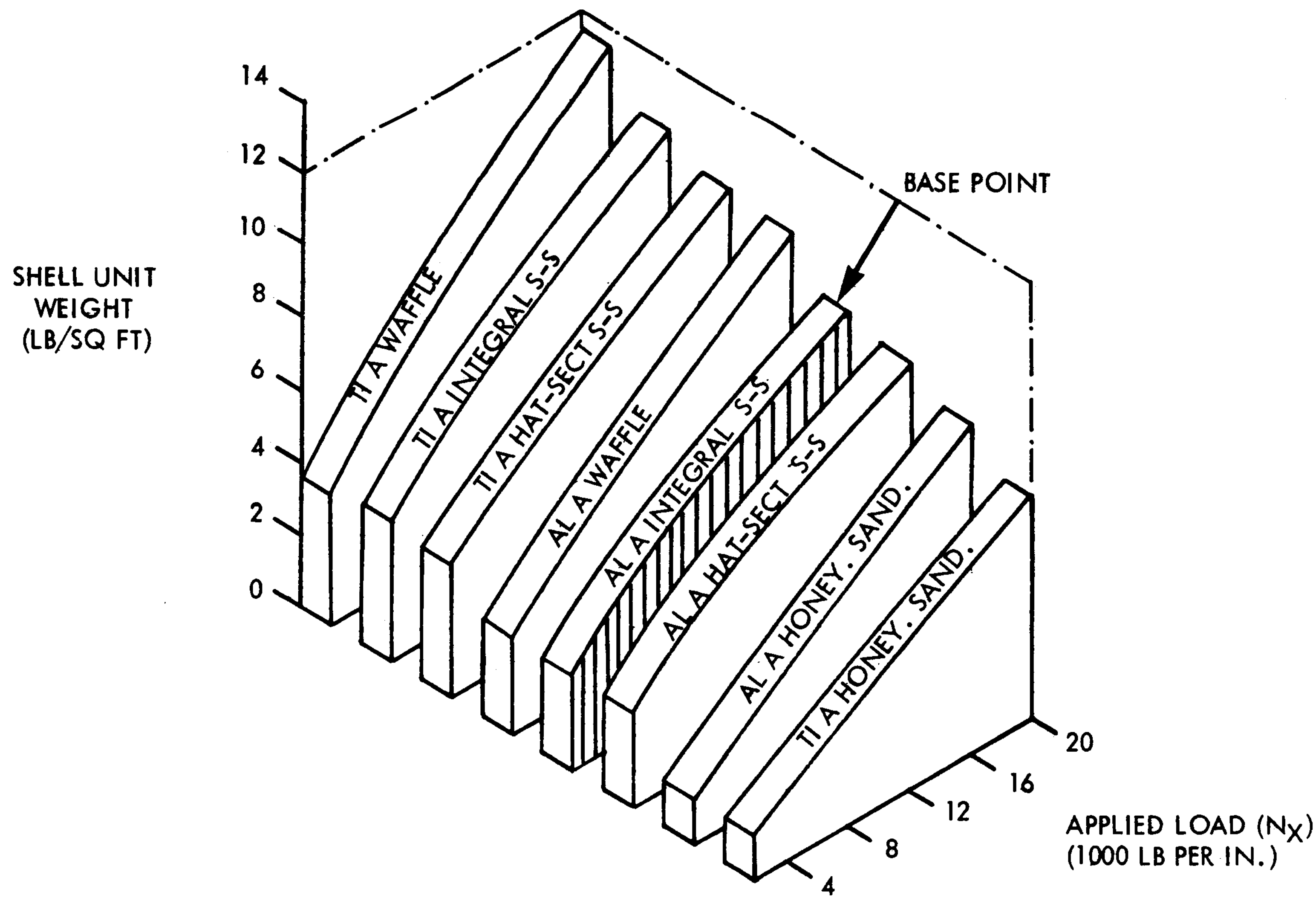



Figure 3. Shell Unit Weights for Conventional Titanium and Aluminum Structures—198-Inch Radius, 300°F, No Pressure

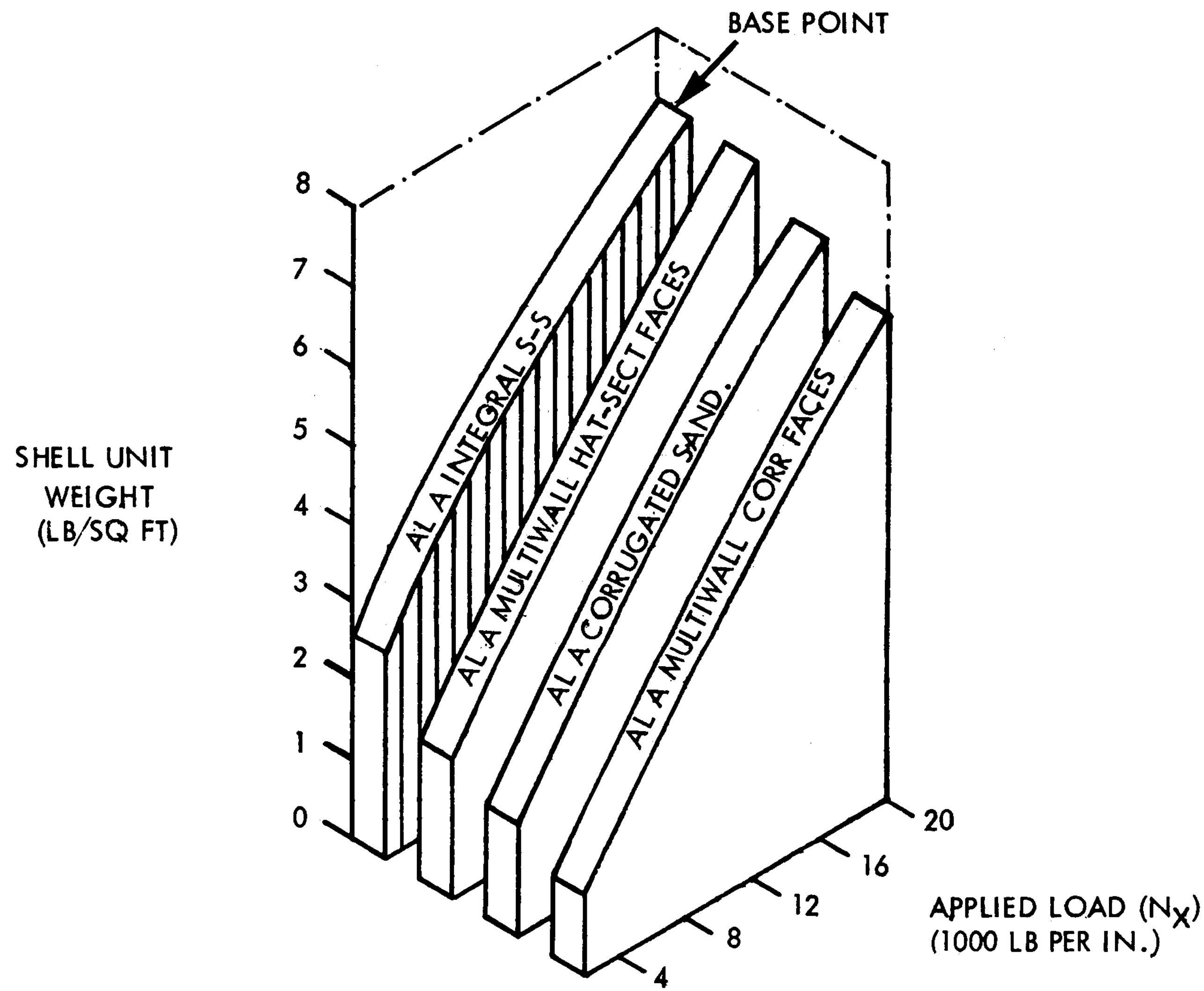



Figure 4. Shell Unit Weights for Advanced Aluminum Structures—130-Inch Radius, 300°F, No Pressure

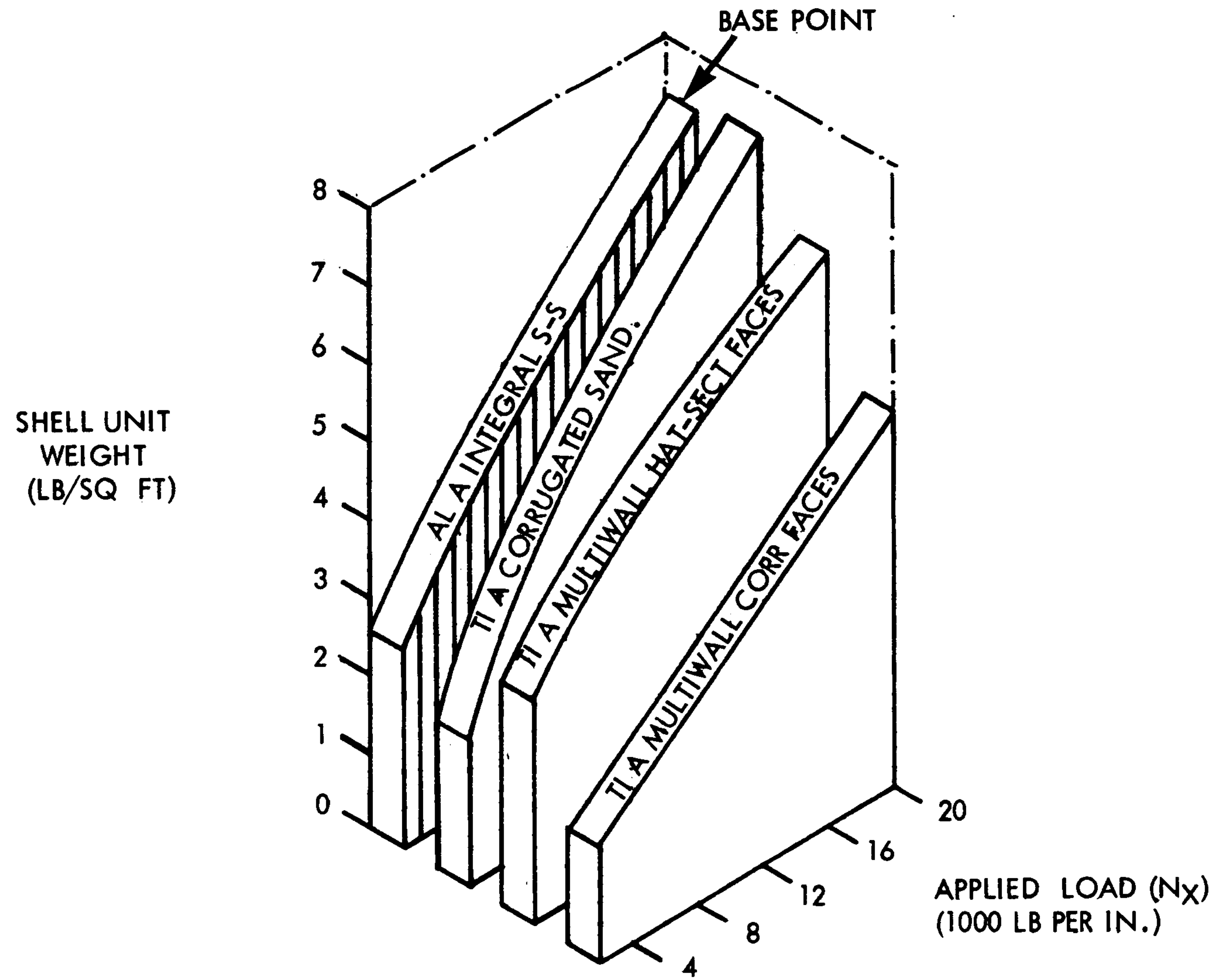



Figure 5. Shell Unit Weights for Advanced Titanium Structures—130-Inch Radius, 300°F, No Pressure

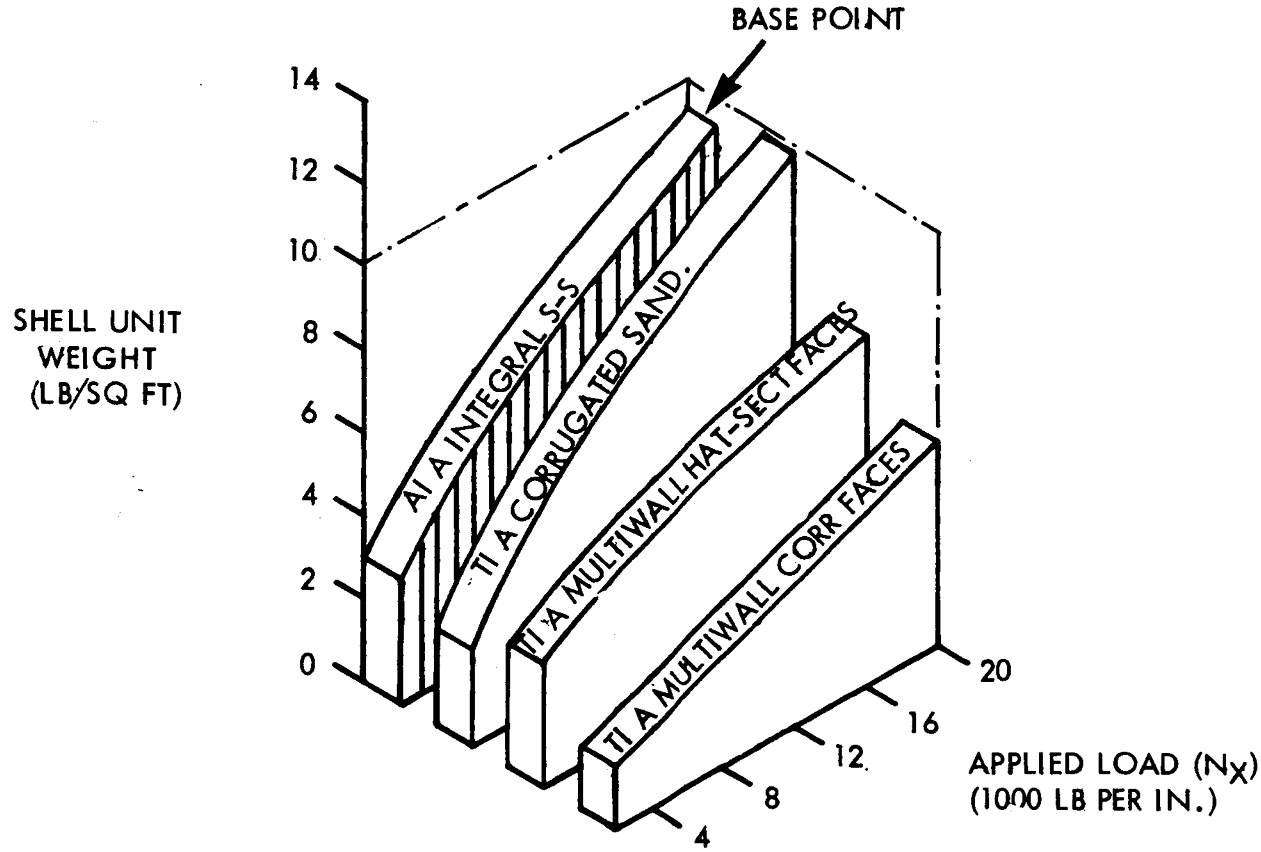



Figure 6. Shell Unit Weight for Advanced Titanium Structures—270-Inch Radius, 300°F, No Pressure

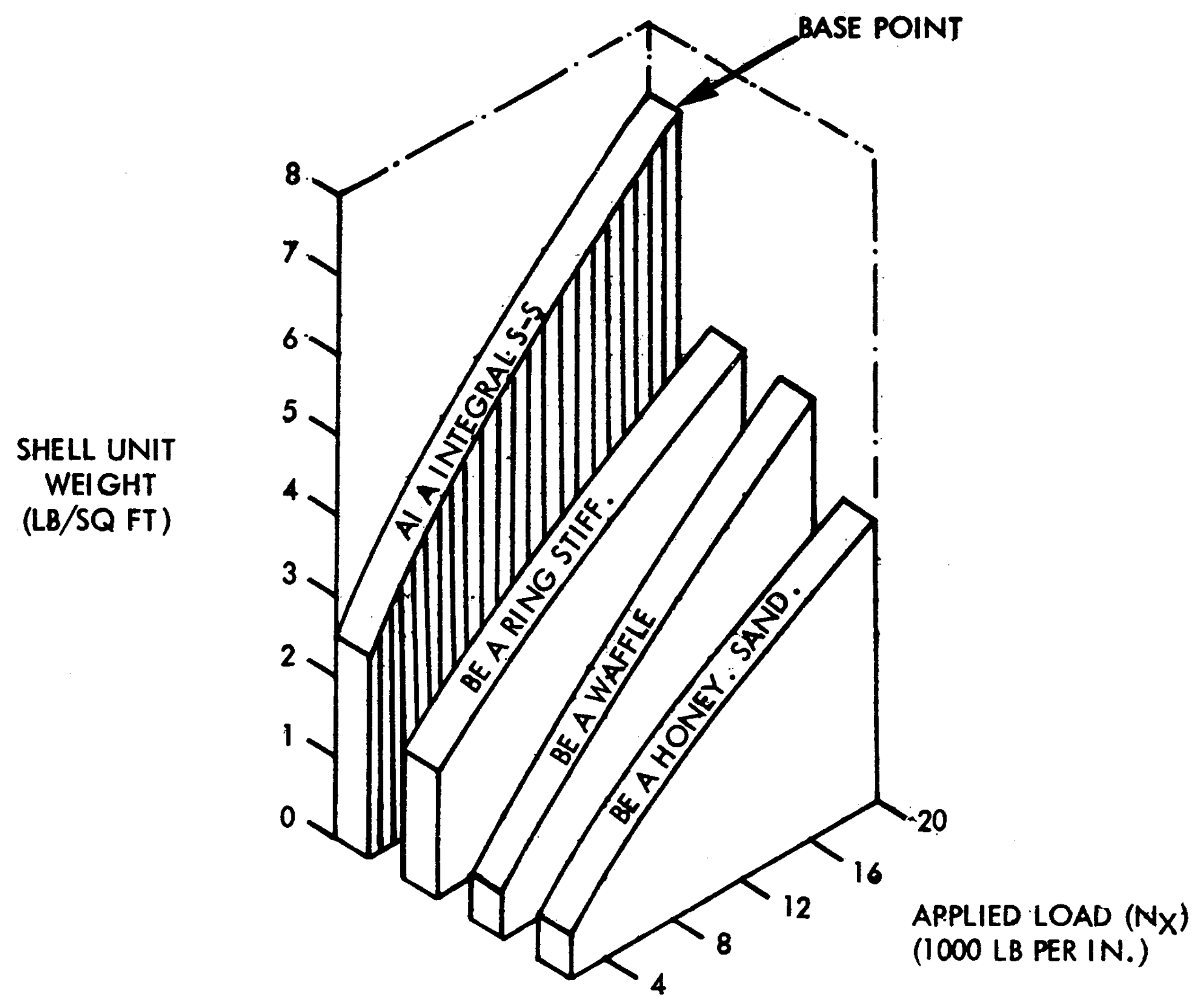



Figure 7. Shell Unit Weights for Conventional Beryllium Structures—130-Inch Radius, 300°F, No Pressure

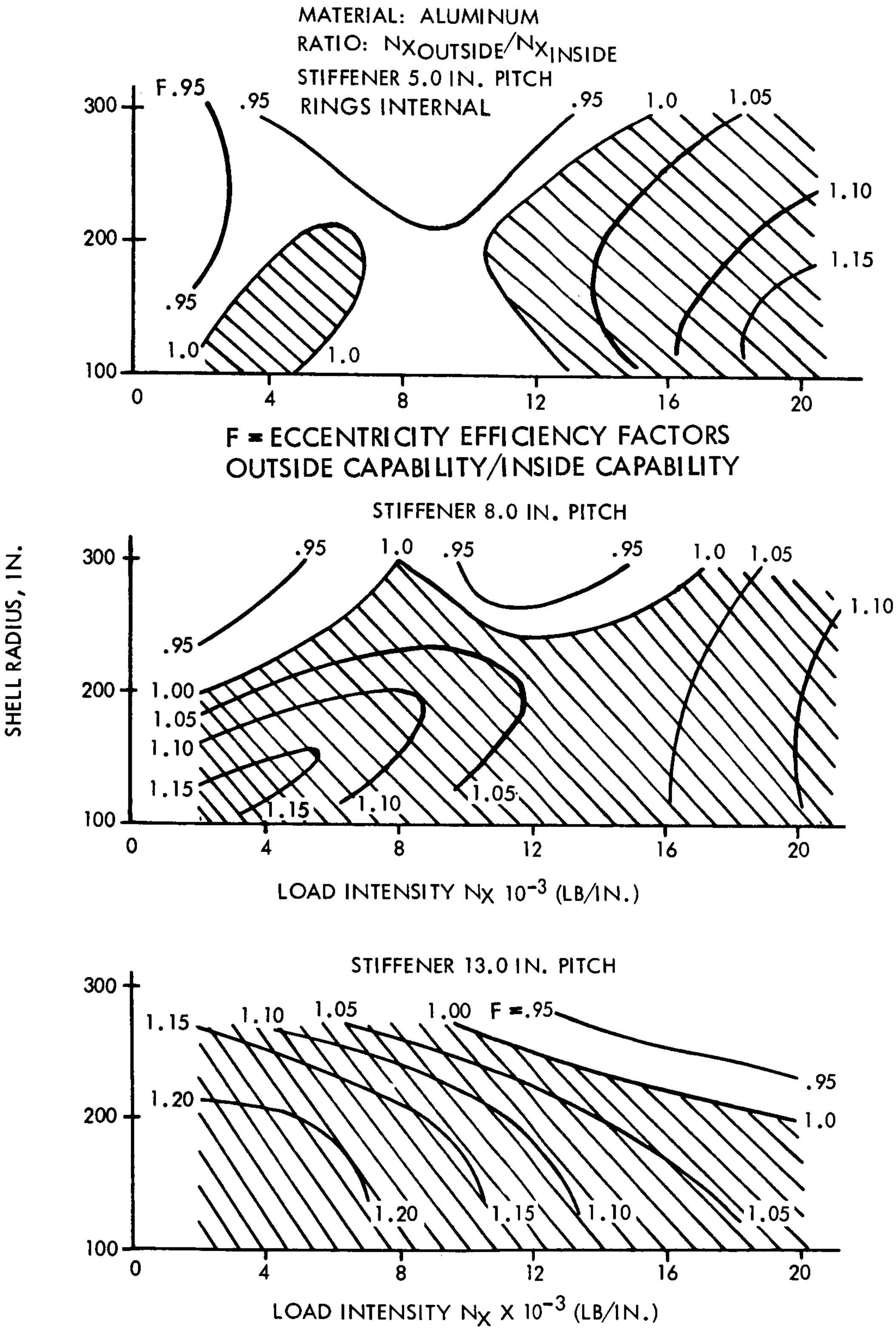



Figure 8. - Stiffener Positioning Effectiveness Ratio

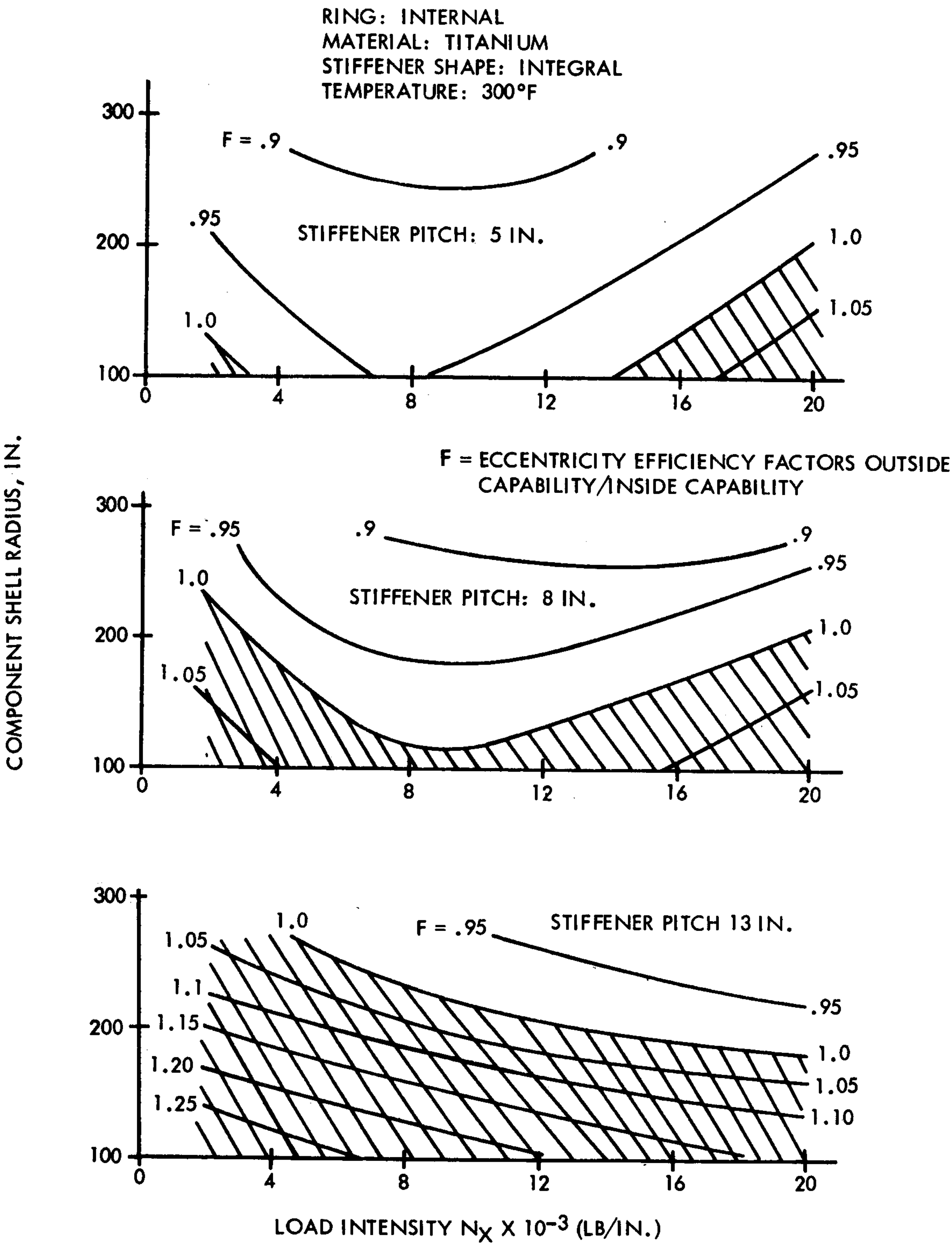



Figure 9. - Relative Merit of Externally Stiffened Titanium Shells, Component Shell Radius Versus Load Intensity

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

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

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

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 $I_{sp}$

| | Aluminum A | | | | | | | | | | Honeycomb Sandwich | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | Aluminum | | | |
| Component | 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 | B | C | Titanium A | Beryllium A |
| **Stage I** | | | | | | | | | | | | | | |
| Interstage | 1 505 | 1 231 | 1 480 | 3 012 | 2 442 | 621 | 852 | 603 | 1 166 | 1 278 | 621 | 580 | 598 | 301 |
| Forward skirt | 1 458 | 1 169 | 1 428 | 2 869 | 2 341 | 593 | 811 | 570 | 1 116 | 1 220 | 558 | 535 | 570 | 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 | 1 054 | 283 |
| Center section | 3 116 | 2 646 | 3 023 | 6 718 | 5 099 | 1 272 | 1 745 | 1 322 | 2 432 | 2 670 | 1 243 | 1 190 | 1 243 | 700 |
| Aft tankwall | 63 | 53 | 57 | 128 | 92 | 57 | 47 | 50 | 47 | 53 | 55 | 52 | 47 | 18 |
| Aft skirt | 1 434 | 1 220 | 1 374 | 2 965 | 2 251 | 693 | 757 | 613 | 1 130 | 1 242 | 586 | 522 | 538 | 298 |
| Forward bulkhead | 700 | - | - | - | - | - | - | - | - | - | 657 | 617 | 628 | 573 |
| Internal bulkhead | 1 595 | - | - | - | - | - | - | - | - | - | 1 495 | 1 405 | 1 429 | 1 304 |
| Internal aft bulkhead | 700 | - | - | - | - | - | - | - | - | - | 657 | 617 | 628 | 573 |
| Aft bulkhead | 1 598 | - | - | - | - | - | - | - | - | - | 1 499 | 1 410 | 1 434 | 1 307 |
| **Stage II** | | | | | | | | | | | | | | |
| Forward skirt | 752 | 732 | 701 | 1 810 | 1 315 | 370 | 582 | 396 | 791 | 868 | 365 | 360 | 383 | 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 | 2 765 | 786 |
| Aft tankwall | 103 | 86 | 78 | 193 | 139 | 89 | 76 | 111 | 74 | 89 | 89 | 89 | 82 | 22 |
| Aft skirt | 808 | 790 | 728 | 1 947 | 1 521 | 400 | 544 | 408 | 732 | 796 | 397 | 348 | 329 | 160 |
| Forward bulkhead | 424 | - | - | - | - | - | - | - | - | - | 397 | 374 | 385 | 351 |
| Internal bulkhead | 764 | - | - | - | - | - | - | - | - | - | 716 | 674 | 692 | 632 |
| Aft bulkhead | 1 315 | - | - | - | - | - | - | - | - | - | 1 232 | 1 160 | 1 190 | 1 085 |

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

| | Aluminum A | | | | | | | | | | Honeycomb Sandwich | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | Aluminum | | | |
| Component | 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 | B | C | Titanium A | Beryllium A |
| **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 | 1 529 | 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 | 1 201 | 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 | 1 458 | 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 | 2 623 | 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 | 1 206 | 714 |
| Forward bulkhead | 1 319 | - | - | - | - | - | - | - | - | - | 1 237 | 1 164 | 1 183 | 1 078 |
| Internal bulkhead | 3 109 | - | - | - | - | - | - | - | - | - | 2 916 | 2 742 | 2 790 | 2 542 |
| Internal aft bulkhead | 1 319 | - | - | - | - | - | - | - | - | - | 1 237 | 1 164 | 1 183 | 1 078 |
| Aft bulkhead | 3 119 | - | - | - | - | - | - | - | - | - | 2 925 | 2 752 | 2 798 | 2 551 |
| **Stage II** | | | | | | | | | | | | | | |
| Forward skirt | 1 302 | 1 383 | 543 | 3 510 | 2 580 | 558 | 824 | 690 | 1 317 | 1 352 | 614 | 565 | 607 | 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 | 5 588 | 3 230 |
| Aft tankwall | 618 | 528 | 518 | 1 244 | 968 | 460 | 532 | 608 | 766 | 791 | 445 | 430 | 440 | 369 |
| Aft skirt | 1 427 | 1 349 | 1 199 | 3 232 | 2 518 | 781 | 943 | 684 | 1 254 | 1 285 | 709 | 668 | 698 | 418 |
| Forward bulkhead | 700 | - | - | - | - | - | - | - | - | - | 657 | 617 | 628 | 573 |
| Internal bulkhead | 1 260 | - | - | - | - | - | - | - | - | - | 1 183 | 1 111 | 1 140 | 1 040 |
| Aft bulkhead | 2 387 | - | - | - | - | - | - | - | - | - | 2 239 | 2 106 | 2 142 | 1 953 |

## TABLE 10. - COMPONENT WEIGHT SUMMARY (LB), 240 000-LB PAYLOAD EXPENDABLE VEHICLE, CURRENT $I_{sp}$

| Component | Aluminum A: Integral Skin Stringer | Aluminum A: Waffle | Aluminum A: Hat-Sect. Skin Stringer | Aluminum A: Monocoque | Aluminum A: Ring Stiffened | Aluminum A: Honeycomb Sandwich | Aluminum A: Corrugated Sandwich | Aluminum A: Multiwall Corrugated | Aluminum A: Double-Wall Hat Section | Aluminum A: Double-Wall Z Section | Honeycomb Sandwich: Aluminum B | Honeycomb Sandwich: Aluminum C | Honeycomb Sandwich: Titanium A | Honeycomb Sandwich: Beryllium A |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **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 | 5 886 | 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 | 3 641 | 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 | 12 279 | 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 | 7 955 | 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 | 5 258 | 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 | 3 536 | 1 136 |
| Forward bulkhead | 2 474 | - | - | - | - | - | - | - | - | - | 2 320 | 2 183 | 1 181 | 2 041 |
| Internal bulkhead | 7 473 | - | - | - | - | - | - | - | - | - | 7 004 | 6 595 | 6 765 | 6 166 |
| Internal aft bulkhead | 2 474 | - | - | - | - | - | - | - | - | - | 2 320 | 2 183 | 1 181 | 2 041 |
| Aft bulkhead | 7 355 | - | - | - | - | - | - | - | - | - | 6 907 | 6 490 | 6 658 | 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 | 2 337 | 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 | 23 922 | 17 878 |
| Aft tankwall | 874 | 951 | 794 | 2 131 | 1 599 | 626 | 777 | 813 | 727 | 737 | 578 | 544 | 630 | 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 | 3 210 | 1 768 |
| Forward bulkhead | 2 474 | - | - | - | - | - | - | - | - | - | 2 320 | 2 183 | 1 181 | 2 041 |
| Internal bulkhead | 4 453 | - | - | - | - | - | - | - | - | - | 4 176 | 3 929 | 2 125 | 3 670 |
| Aft bulkhead | 10 887 | - | - | - | - | - | - | - | - | - | 10 224 | 9 606 | 9 855 | 8 983 |

## TABLE 11. - COMPONENT WEIGHT SUMMARY (LB), 445 000-LB PAYLOAD EXPENDABLE VEHICLE, 1985 $I_{sp}$

| Component | Aluminum A: Integral Skin Stringer | Aluminum A: Waffle | Aluminum A: Hat-Sect. Skin Stringer | Aluminum A: Monocoque | Aluminum A: Ring Stiffened | Aluminum A: Honeycomb Sandwich | Aluminum A: Corrugated Sandwich | Aluminum A: Multiwall Corrugated | Aluminum A: Double-Wall Hat Section | Aluminum A: Double-Wall Z Section | Honeycomb Sandwich: Aluminum B | Honeycomb Sandwich: Aluminum C | Honeycomb Sandwich: Titanium A | Honeycomb Sandwich: Beryllium A |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **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 | 7 451 | 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 | 4 139 | 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 | 14 809 | 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 | 4 996 |
| 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 | 7 063 | 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 | 3 948 | 2 192 |
| Forward bulkhead | 2 474 | - | - | - | - | - | - | - | - | - | 2 320 | 2 183 | 1 181 | 2 041 |
| Internal bulkhead | 7 852 | - | - | - | - | - | - | - | - | - | 7 359 | 6 929 | 7 108 | 6 479 |
| Internal aft bulkhead | 2 474 | - | - | - | - | - | - | - | - | - | 2 320 | 2 183 | 1 181 | 2 041 |
| Aft bulkhead | 7 690 | - | - | - | - | - | - | - | - | - | 7 222 | 6 785 | 6 961 | 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 | 2 499 | 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 | 26 917 | 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 | 1 672 | 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 | 3 517 | 1 948 |
| Forward bulkhead | 2 474 | - | - | - | - | - | - | - | - | - | 2 320 | 2 183 | 1 181 | 2 041 |
| Internal bulkhead | 4 453 | - | - | - | - | - | - | - | - | - | 4 176 | 3 929 | 2 125 | 3 670 |
| Aft bulkhead | 11 296 | - | - | - | - | - | - | - | - | - | 10 608 | 9 967 | 10 226 | 9 320 |

# TABLE 12. - COMPONENT WEIGHT SUMMARY (LB), 1 000 000-LB PAYLOAD EXPENDABLE VEHICLE, CURRENT $I_{sp}$

| | Aluminum A | | | | | | | | | | Honeycomb Sandwich | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | Aluminum | | | |
| Component | 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 | B | C | Titanium A | Beryllium A |
| **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 | 40 019 | 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 | 10 991 |
| Forward tankwall | 74 156 | 64 014 | 58 251 | 145 814 | 86 310 | 37 478 | 46 813 | 41 459 | 37 684 | 37 821 | 35 762 | 34 114 | 40 635 | 25 920 |
| 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 | 21 665 |
| 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 | 11 780 |
| 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 | 9 194 |
| Forward bulkhead | 10 444 | - | - | - | - | - | - | - | - | - | 9 792 | 9 216 | 9 454 | 8 618 |
| Internal bulkhead | 36 978 | - | - | - | - | - | - | - | - | - | 34 662 | 32 626 | 33 466 | 30 505 |
| Internal aft bulkhead | 10 444 | - | - | - | - | - | - | - | - | - | 9 792 | 9 216 | 9 454 | 8 618 |
| Aft bulkhead | 36 396 | - | - | - | - | - | - | - | - | - | 34 123 | 32 114 | 32 942 | 30 029 |
| **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 | 7 822 | 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 | 47 759 | 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 | 7 842 | 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 | 8 112 |
| Forward bulkhead | 6 274 | - | - | - | - | - | - | - | - | - | 5 882 | 5 536 | 5 680 | 5 177 |
| Internal bulkhead | 11 292 | - | - | - | - | - | - | - | - | - | 10 586 | 9 964 | 10 214 | 9 311 |
| Aft bulkhead | 40 930 | - | - | - | - | - | - | - | - | - | 38 370 | 36 117 | 37 043 | 33 767 |

# TABLE 13. - COMPONENT WEIGHT SUMMARY (LB), 2 000 000-LB PAYLOAD EXPENDABLE VEHICLE, 1985 $I_{sp}$

| | Aluminum A | | | | | | | | | | Honeycomb Sandwich | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | Aluminum | | | |
| Component | 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 | B | C | Titanium A | Beryllium A |
| **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 | 62 162 | 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 | 16 776 |
| 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 | 45 022 |
| 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 | 54 587 | 34 931 |
| 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 | 23 361 |
| Aft skirt | 39 350 | 31 662 | 32 761 | 78 669 | 45 381 | 28 864 | 27 920 | 19 703 | 22 046 | 27 095 | 23 828 | 23 696 | 23 828 | 15 150 |
| Forward bulkhead | 10 841 | - | - | - | - | - | - | - | - | - | 10 163 | 9 567 | 9 813 | 8 947 |
| Internal bulkhead | 41 586 | - | - | - | - | - | - | - | - | - | 38 986 | 36 693 | 37 636 | 34 311 |
| Internal aft bulkhead | 10 841 | - | - | - | - | - | - | - | - | - | 10 163 | 9 567 | 9 813 | 8 947 |
| Aft bulkhead | 39 350 | - | - | - | - | - | - | - | - | - | 36 890 | 34 722 | 35 613 | 32 463 |
| **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 | 8 794 | 4 985 |
| Forward tankwall | 176 547 | 123 599 | 117 346 | 316 835 | 186 647 | 90 363 | 112 546 | 126 556 | 68 676 | 72 351 | 74 430 | 62 822 | 80 348 | 71 612 |
| 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 | 15 558 |
| 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 | 11 508 |
| Forward bulkhead | 6 274 | - | - | - | - | - | - | - | - | - | 5 882 | 5 536 | 5 680 | 5 177 |
| Internal bulkhead | 11 292 | - | - | - | - | - | - | - | - | - | 10 586 | 9 964 | 10 214 | 9 311 |
| Aft bulkhead | 23 750 | - | - | - | - | - | - | - | - | - | 22 264 | 20 957 | 21 494 | 19 594 |

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

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

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 B | Aluminum C | Tita-nium A | Beryl-lium A |
| **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 | 382 | 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 B | Aluminum C | Tita-nium A | Beryl-lium A |
| **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 B | Aluminum C | Tita-nium A | Beryl-lium A |
| 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

| Vehicle/Payload | Stage | Aluminum A | | | | | | | | | | Honeycomb Sandwich | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Integral Skin Stringer | 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 B | Aluminum C | Tita-nium A | Beryl-lium A |
| 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.

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 multiwall construction with corrugated sandwich facings offer the greatest potential. Reductions in manufacturing cost complexity factors would easily shift these

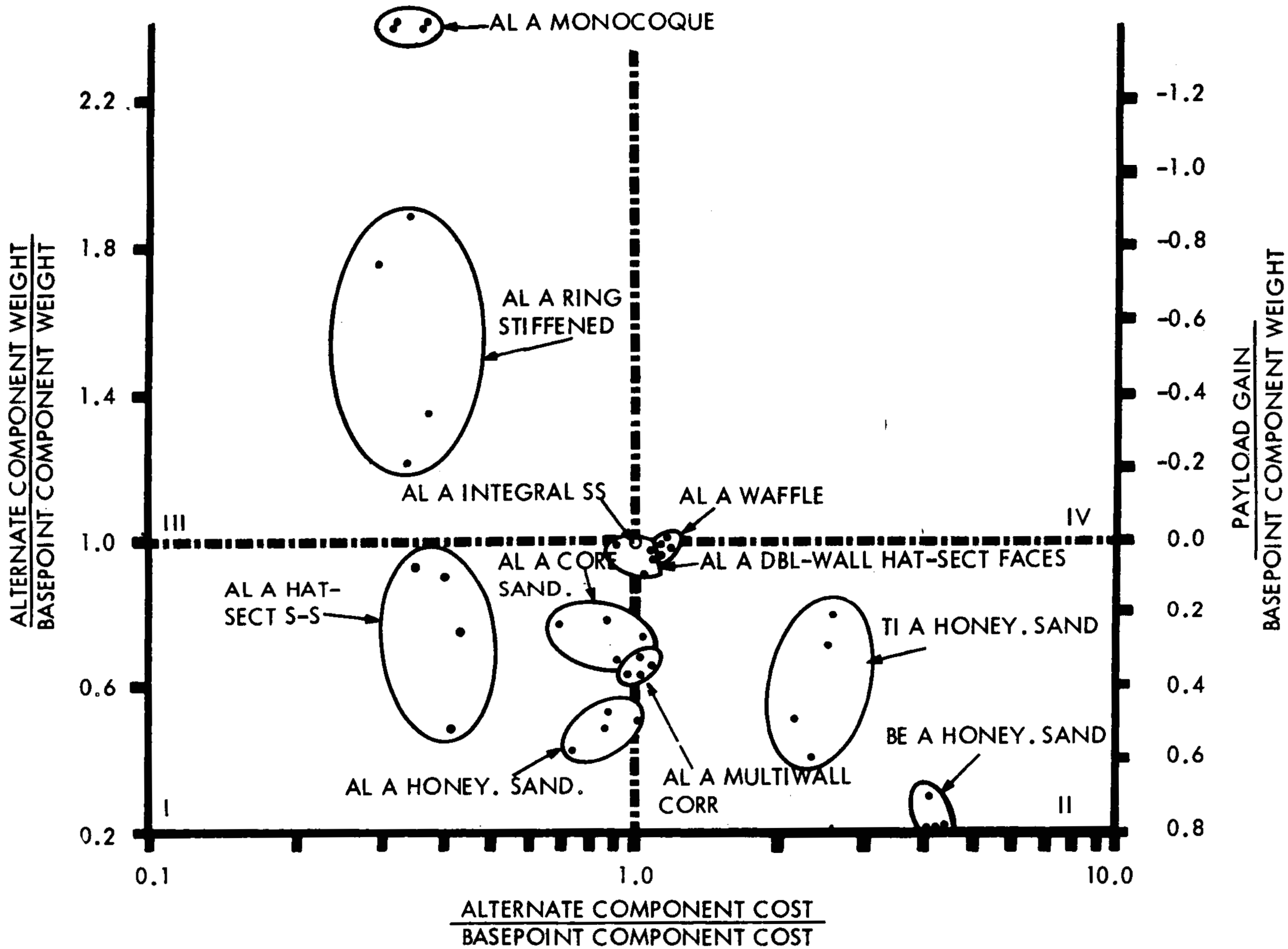



**Figure 10. Merit Partials for 30 000-Pound-Payload Vehicle (Second Stage)**

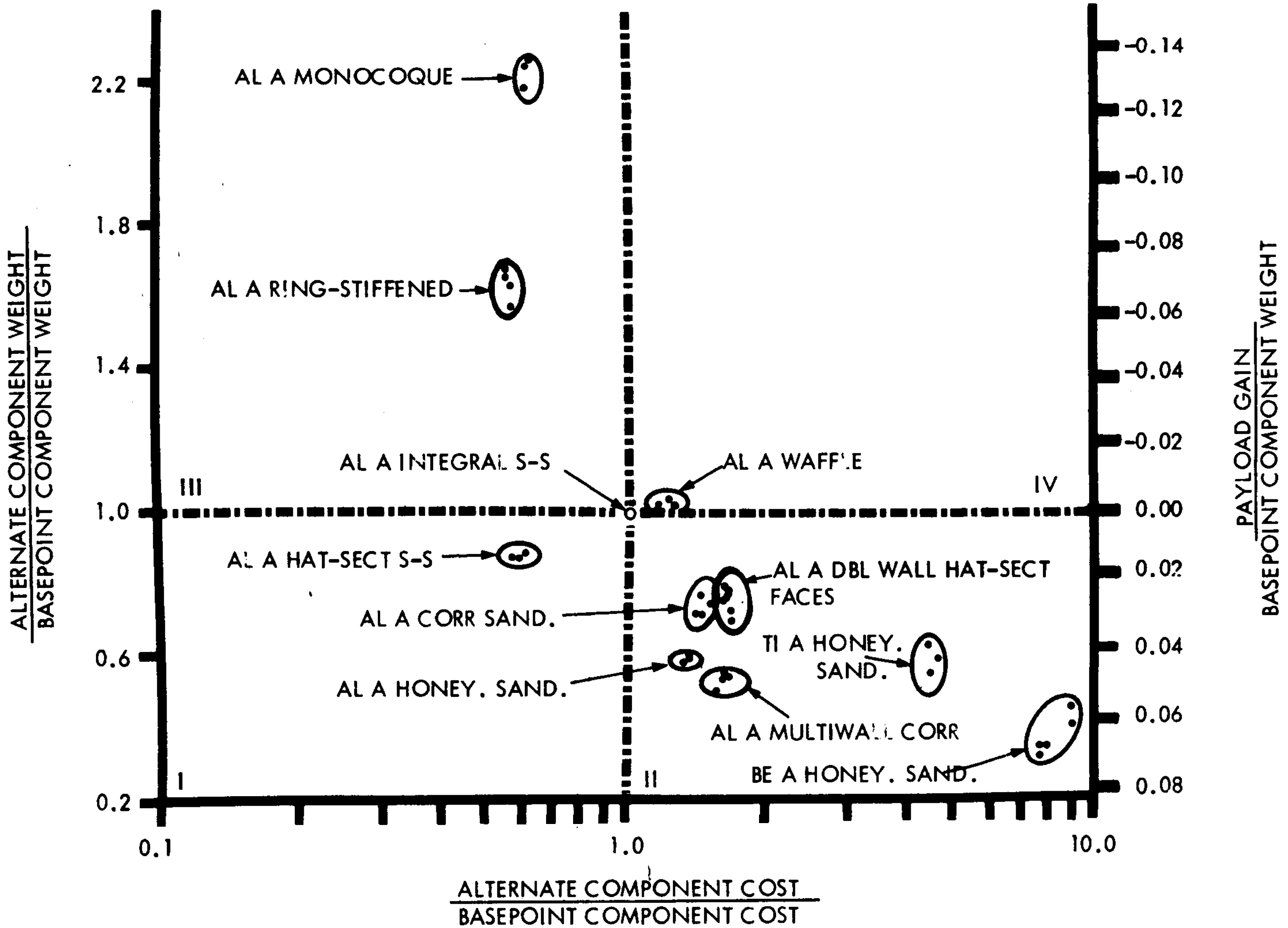



**Figure 11. Merit Partials for 240 000-Pound-Payload Vehicle (First Stage)**

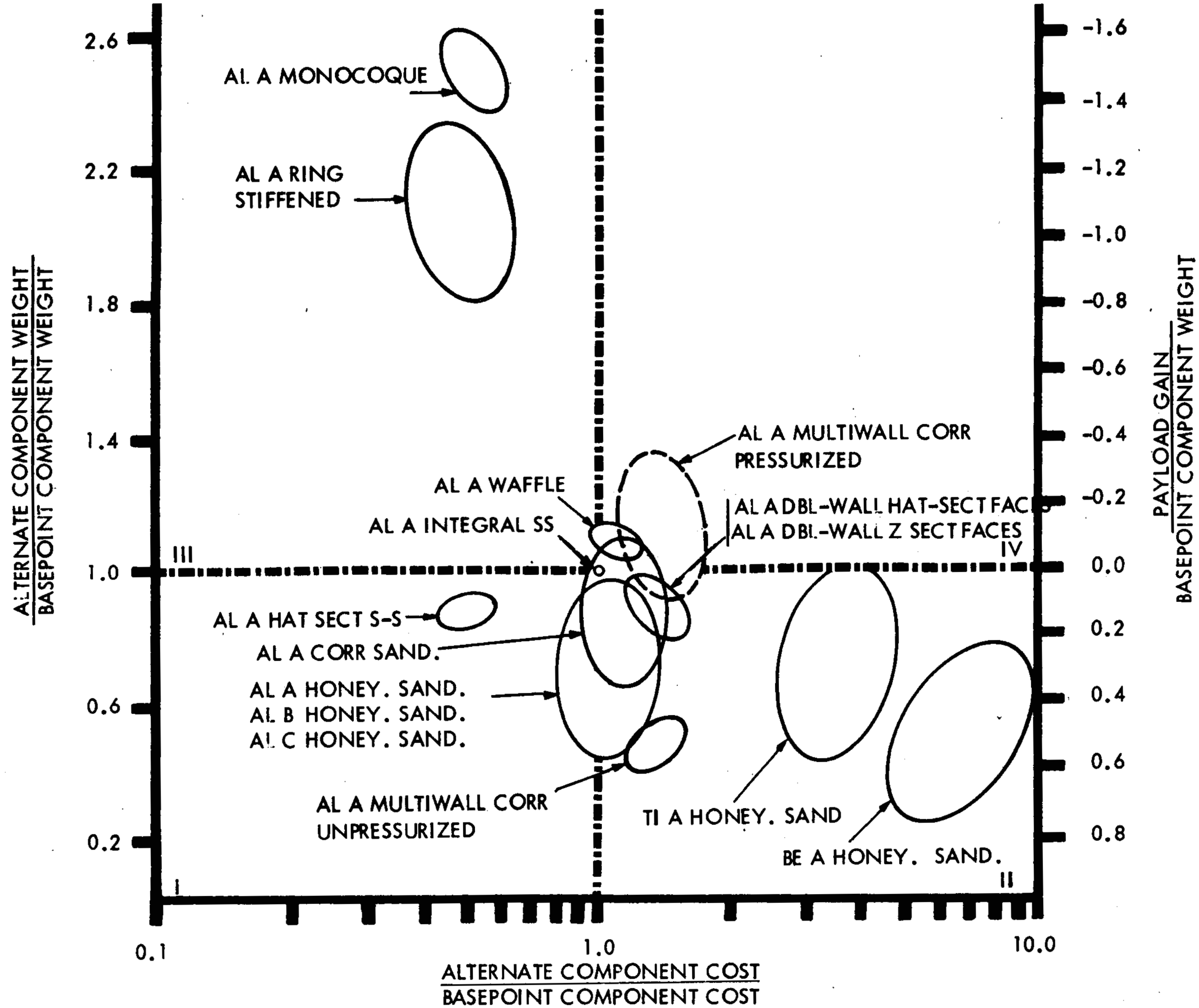



Figure 12. Merit Partials for 240 000-Pound-Payload Vehicle (Second Stage)

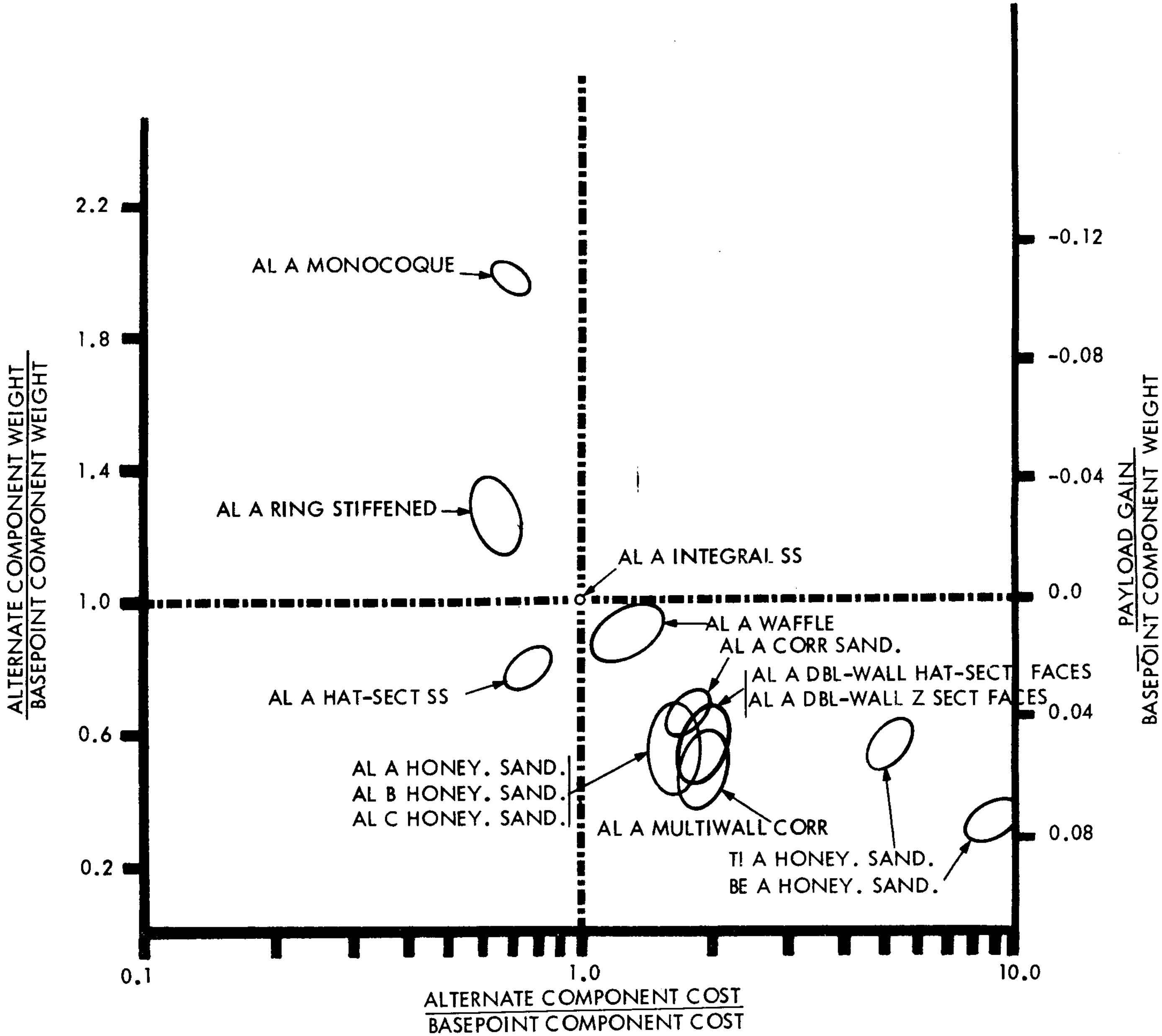



Figure 13. Merit Partials for 1 000 000-Pound-Payload Vehicle (First Stage)

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 | $1.3 \times 10^6$ lb |
| 40 000 lb | $1.9 \times 10^6$ lb |
| 60 000 lb | $2.5 \times 10^6$ 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.

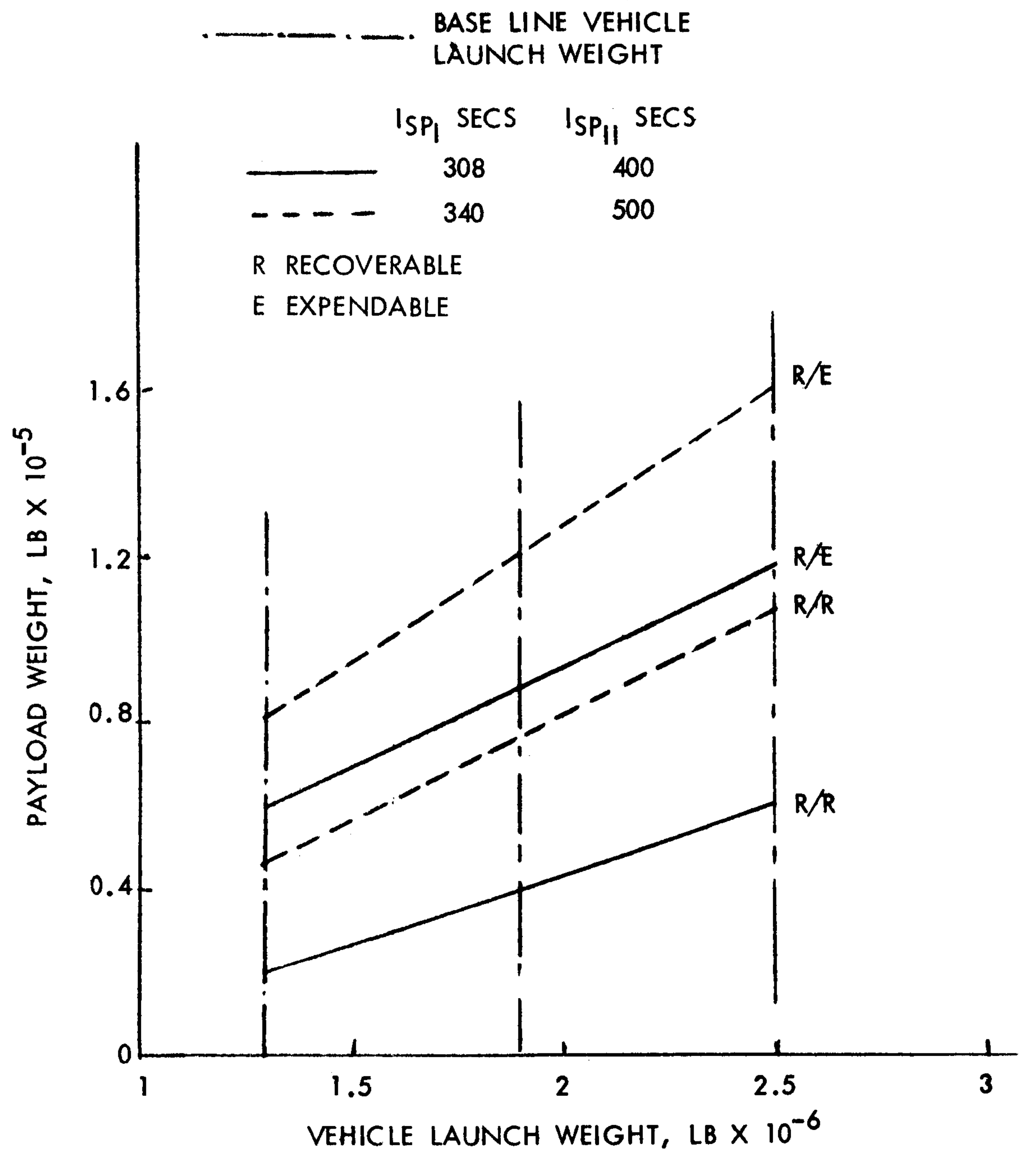
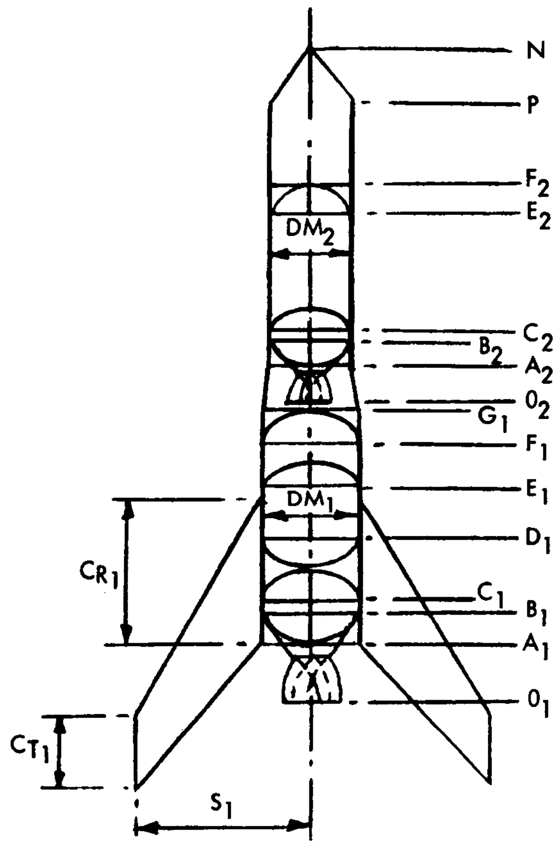



Figure 14. Effect of Expendable Upper Stages

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




| Key | Item | Launch Weight (pounds) / Propulsion System | $1.3 \times 10^6$ Near-Term | $1.3 \times 10^6$ Future | $1.9 \times 10^6$ Near-Term | $1.9 \times 10^6$ Future | $2.5 \times 10^6$ Near-Term | $2.5 \times 10^6$ Future |
|---|---|---|---|---|---|---|---|---|
| | Payload | | | | | | | |
| N | Nose | | 2025 | 2076 | 2233 | 2283 | 2429 | 2475 |
| P | Shoulder | | 1869 | 1919 | 2047 | 2098 | 2215 | 2261 |
| | Stage 2 | | | | | | | |
| $DM_2$ | Stage diameter | | 220 | 220 | 260 | 260 | 300 | 300 |
| $F_2$ | Forward bulkhead crown | | 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 |
| | Stage 1 | | | | | | | |
| $DM_1$ | Stage diameter | | 260 | 260 | 300 | 300 | 320 | 320 |
| $G_1$ | Separation plane | | 916 | 890 | 1002 | 973 | 1119 | 1085 |
| $F_1$ | Forward crew compartment | | 786 | 760 | 852 | 823 | 959 | 925 |
| $E_1$ | Forward bulkhead/tank wall | | 694 | 668 | 780 | 752 | 895 | 862 |
| $D_1$ | Tank wall/first aft bulkhead | | 525 | 515 | 603 | 592 | 677 | 664 |
| $C_1$ | Second forward bulkhead/ tank wall | | 325 | 316 | 373 | 362 | 431 | 419 |
| $B_1$ | Tank wall/second aft bulkhead | | 265 | 265 | 313 | 314 | 350 | 351 |
| $A_1$ | Aft bulkhead crown | | 173 | 173 | 207 | 208 | 237 | 238 |
| $O_1$ | Engine exit plane | | 0 | 0 | 0 | 0 | 0 | 0 |
| $CT_1$ | Wing tip chord | | 216 | 213 | 258 | 255 | 295 | 292 |
| $CR_1$ | Wing root chord | | 479 | 473 | 573 | 567 | 655 | 648 |
| $S_1$ | Wing semi-span | | 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 $q\alpha$ | Boost | Max $q\alpha$ | Boost | Max $q\alpha$ | Boost | Max $q\alpha$ | Boost | Max $q\alpha$ | Boost | Max $q\alpha$ | 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 x $10^6$ lb, Near-Term Propulsion System

| Station | Prelaunch NX | Max q α 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 x $10^6$ lb, Future Propulsion System

| Station | Prelaunch NX | Max q α NX | End Boost NX | Max NX/R |
|---|---|---|---|---|
| 173 | 2747 | 2834 | 3086 | 23.7355 |
| 265 | 2419 | -32 | 213 | 18.6099 |
| 316 | 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 x $10^6$ lb, Near-Term Propulsion System

| Station | Prelaunch NX | Max q α 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 x $10^6$ lb, Future Propulsion System

| Station | Prelaunch NX | Max q α 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 x $10^6$ lb, Near-Term Propulsion System

| Station | Prelaunch NX | Max q α 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 x $10^6$ lb, Future Propulsion System

| Station | Prelaunch NX | Max q α 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<br>Strength analysis<br>Stability analysis (local and general)<br>Orthotropic<br>Isotropic (inside-outside stiffeners)<br>Experimental correction factors | Types: integral, hat-section, I-section, Z-section<br>Preset stringer and frame spacing<br>Material properties, $F_{cy}$, $F_{Tu}$, E<br>Pressure (burst and relief)<br>Minimum gauge (skin stiffeners)<br>Stiffener section properties<br>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<br>Intercell buckling<br>Face-sheet wrinkling | Material properties, minimum gauge and core density, sandwich heights, cell size, bonding and adhesive<br>Pressure (burst and relief) |
| WAFF (waffle shells) | Same as above | Waffle orientation<br>Minimum skin gauge, maximum web heights<br>Cell geometry<br>Pressure and burst and relief<br>Material properties |
| CORRUG (corrugated sandwich shells) | Same as above | Core height, minimum skin gauge<br>Corrugation angle<br>Pressure<br>Material properties |
| RINGS (ring-stiffened shells) | Same as above, plus<br>Ring area and stiffness requirements | Material properties, minimum gauge, ring spacing, pressure |
| CORRMW | Same as above, plus<br>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 multiwall 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.



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