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STUDY OF STRUCTURAL WEIGHT SENSITIVITIES FOR LARGE ROCKET SYSTEMS

FINAL REPORT

VOLUME 1 OF 2

SUMMARY

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APOLLO SUPPORT DEPARTMENT
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Apollo Support Department
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General Electric Company
Daytona Beach, Florida

FOREWORD

This report presents the findings of a study entitled "A Study of Structural Weight Sensitivities for Large Rocket Systems." The work on this study was performed by the General Electric Company for the National Aeronautics and Space Administration under Contract NAS2-3811, monitored by Mr. E. Gomersall and Mr. K. Nishioka of the Mission Analysis Division of the Office of Advanced Research and Technology.

This final report is presented in two volumes. Volume 1 serves as a Summary Report and is a concise account of the objectives, methods of analysis, and significant results of the study. Volume 2 presents a comprehensive account of the study including major input parameters, analyses, and detailed results. Appendices are included to discuss the computational system used and further details of certain of the special analysis techniques employed.

ABSTRACT

Study results are presented for parametric analyses performed with the objective of minimizing structural weight in large launch vehicles of the future. Several advanced structural analysis techniques, materials, and unique approaches to structural design are assessed. Advanced structural analysis techniques such as pressure coupling effects and various biaxial stress field failure theories are considered. Materials including filamentary composites, beryllium, titanium, and aluminum, together with various types of wall construction are considered. Impact of front-end steering, strap-ons, and advanced nozzles are noted. The effects of varying selected design criteria from values in use today are shown. Each new technology or approach is individually applied to several representative vehicles. Structural weights with and without the new technology or approach are compared. Interdependence effects also are investigated. The results may be used to assess the potential of each new technology or approach when applied to large launch vehicles of the future.

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SECTION 1

INTRODUCTION

Studies of launch systems have shown that even modest improvements in structural weight factors can provide significant increases in the ratio of payload to launch weight. Reduction of structural weight is therefore of considerable interest, particularly for the large launch vehicles of the future with earth orbit payloads of a million pounds or more.

The structure of a vehicle is influenced by many factors including loading conditions, design criteria, design arrangement, analysis techniques, materials, and fabrication methods. Consequently, the design of lighter structures depends to a great extent upon knowing how these affect structural weight. The normal design process, which involves numerous tradeoffs and compromises, masks the influence of individual parameters. As a result, this very useful structural weight sensitivity information is difficult to identify and apply.

Long-range plans for structural technology research will be most effective if they are formulated on the basis of hard information defining potential gains as a function of required effort. In terms of developing lighter advanced structures this means that structural weight sensitivities, corresponding to design-parameter variations ranging beyond the current state of the art, are necessary. Limited data of this type have been generated in the past; but a fundamental, inclusive analysis directed specifically to deriving information for research planning has been lacking.

This report documents a study, performed by the General Electric Company, which satisfies the need for comprehensive structural weight sensitivity data applicable to current and near-future design efforts and to the formulation of plans for effective research programs. The objective of the study, conducted under Contract NAS2-3811 with the NASA Office of Advanced Research and Technology, was the evaluation of the relative sensitivities of structural weight to variations in individual and selectively grouped design parameters and techniques. The desired time-range of application was achieved by relaxing the presently practical technology limitations and extending the parameter variations out into the realm of significant state-of-the-art advances.

The study was approached by selecting three baseline vehicles representing a span of vehicle design technology from the new to the very advanced. These were chosen from an earlier study of post-Saturn vehicles conducted by the Martin Company under Contract NAS8-5135. Two of the vehicles have two stages while the third is a single stage configuration, with each vehicle capable of carrying approximately one million pounds into a 100-nautical mile earth orbit. They range in size from 65 to 80 feet in diameter and in overall length from 402 to 423 feet. The only unique feature of the vehicles, other than their large size, was the use of advanced, high pressure engines for the two advanced technology configurations. Structurally, the baseline vehicles represent good current design practice, using high strength aluminum and integrally stiffened skin. All three vehicles were designed to criteria similar to those employed on the Saturn V vehicle and the Martin Company studies.

After establishing the nominal structural weights for the baseline configurations, weight sensitivities were determined by varying basic parameters or design features in the following areas:

a. Design Criteria.
b. Unique Design Approaches.
c. Materials and Fabrication.
d. Analysis Techniques.

In general, the first two categories included the major parameters affecting loads such as winds, acceleration profiles, tank pressures and steering methods. The categories of Materials and Fabrication and Analysis Techniques included the major parameters relating weight and stress.

Despite the fact that three baseline vehicles were employed, the number of parameters and design methods varied during the study produced analyses for the equivalent of tens of thousands of vehicles. Thus the study was not configuration limited, except for the general size of the vehicles considered, but was definitely technology oriented. Careful note should be taken of the vehicle size (million-pound payload class) as it is expected that the results presented in this report <u>may</u> not apply directly to smaller vehicles, say of the Saturn V class.

The determination of the sensitivity values entailed a two-way division of labor. The larger segment included those variations which influence weight primarily through axial loads, bending moments and tank pressures. These analyses were amenable to

direct overall vehicle computations and extensive use was made of a system of computer programs. The smaller segment consisted of special analytical studies and supporting efforts conducted by structures engineers.

The computational modules, developed by the General Electric Company in previous studies, were designed to calculate optimized structural weight. They allow for the inclusion of the properties of different materials, various construction types, acceleration profiles, etc. In addition, they include some practical considerations, which tend to bound solutions, such as minimum gages, sheet lengths and fabrication factors. Thus, the weight sensitivity values presented in this report represent optimal structures which have been adjusted to account for practical manufacturing considerations.

However, the study was not always constrained by current practicality. This was clearly necessary if profitable areas for future research were to be explored. In one investigation, for instance, the influence of material properties was studied by changing from aluminum to beryllium with its high modulus-to-density ratio without regard for recognized problems of fabrication and propellant compatibility.

The study was not intended to be a comprehensive design analysis of a family of launch vehicles but instead was restricted to parametric weight considerations. Accordingly, only "pure" weight sensitivity results were of interest. This means, for one thing, that only changes in structural weight and not in attendant equipment weights are reported. For example, weight variations associated with front-end steering are summarized only in terms of vehicle structural weight effects and do not reflect the weights of necessary equipments such as aerodynamic surfaces, actuators or engines (for jet steering); such equipment weights are included as separate results when available. The nature of the study also means that higher order design considerations such as elastic response, acoustic energy and thermal stress were neglected.

This investigation has resulted in a comprehensive evaluation of basic structural weight sensitivities to variations in vehicle design parameters and methods. It includes the exploration of a full spectrum of potential current and future weight reduction techniques and explicitly ranks reductions realizable from specific structural technology advances. The results of the study indicate that significant increases in payload and/or cost-effectiveness (through increased margin of safety) are currently plausible and that even greater benefits can result from a well-considered research program.

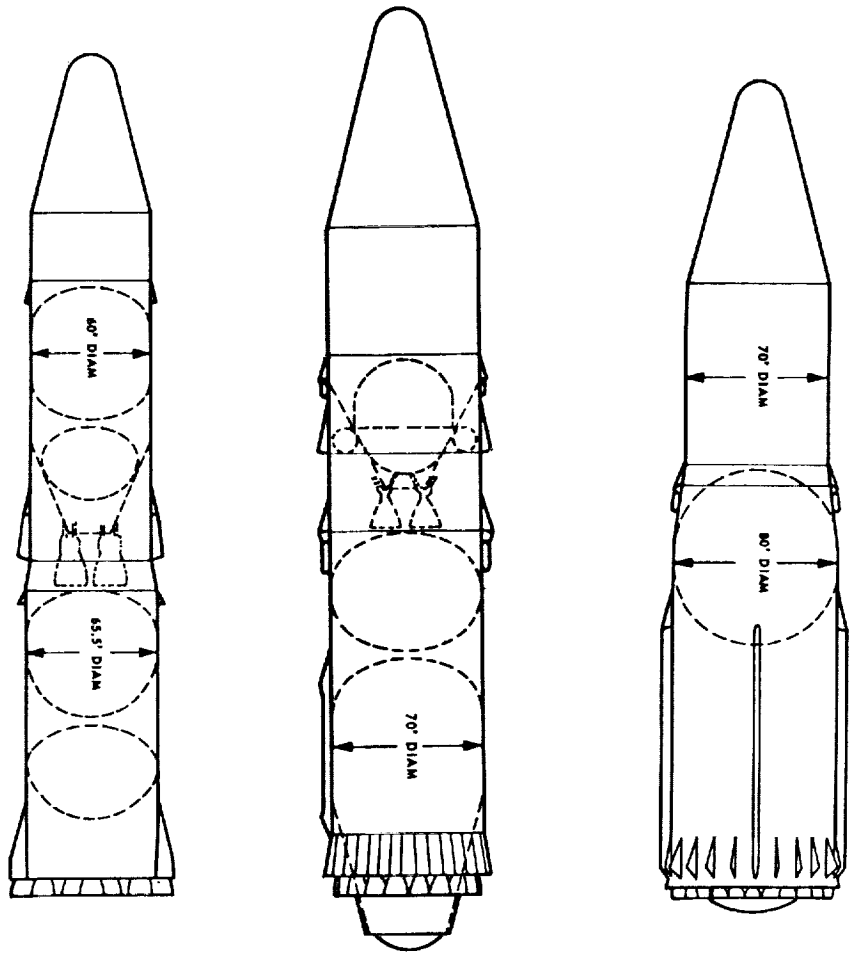
SECTION 2

APPROACH

This study may be easily visualized as a parametric analysis in two dimensions. The primary interest was in the effects of variations in design parameters and techniques on structural weight. Evaluation of the influence of vehicle technology—number of stages, type of propulsion, etc.—on weight was also desired and formed the second dimension. It was the objective in both dimensions not to stop at variations activating state-of-the-art limits but to extend beyond them and explore the areas requiring technology advancements. In this way, structural weight sensitivities were derived which would be of use not only for near-term design efforts, but also for directing structural research activities accounting for the effects of simultaneously advancing vehicle technology.

The first task in the study was to establish the range of vehicle technology to be considered. This was done by reviewing a number of configurations and finally selecting the three illustrated in Figure 2-1. These three were studied by the Martin Company in a total system framework (References 1 and 2) and were chosen because their structural designs were based on sound methods and current, practical design criteria. Furthermore, they were considered typical of three technology areas: Near Technology (Vehicle 101), Advanced Technology (Vehicle 201) and Very Advanced Technology (Vehicle 301). Thus the configurations selected represent a spread of vehicle technology, yet are based on sound, practical structural engineering practices.

These vehicles were used as base hardware examples to provide a foundation for evaluating the structural technologies analyzed. Accordingly, the structural weights shown in Figure 2-1 were calculated as part of this study, using the same tools and methods employed in the sensitivity analyses, to assure that all nominal and perturbed weights were computed on exactly the same basis. For this reason, these nominal structural weight values differ slightly from those to be found in References 1 and 2. The nominal values used for the major parameters, when calculating these base structural weights, are presented in Table 2-1.



	101	201	301
L/O Weight—lbs.	20.1M	14.4M	24.0M
L/O Thrust—lbs.	25.2M	18.0M	30.0M
Length—ft.	415	423	402
Diameter—ft.	65.5	70	80
L/V Structures—lbs.	756,305	690,822	641,320
Nominal Payload—lbs.	< 1M	~ 1M	> 1M

Figure 2-1. Baseline Configurations and Descriptive Data

Table 2-1

Nominal Design Parameter Values

Parameter	Nominal Value
Prelaunch winds	99.9 percent
Inflight winds	95.0 percent
Maximum acceleration	
101 Vehicle	4.80g's
200 Series Vehicles	5.55g's
301 Vehicle	2.50g's
Tanks	Pressurized
Nozzle	Gimbaled bell
101 Vehicle	Plug
200 Series Vehicles	Plug
301 Vehicle	
Material	2219-T87 Aluminum
Construction	
Heads	Monocoque
Walls	Integrally stiffened skin

The study was primarily concerned with the effects on structural weight of variations in the items shown in Table 2-2. All parameters were varied singly and in different combinations while such things as analysis techniques and design constraints were studied on an individual basis. In every case, the objective was the evaluation of the increase or decrease in structural weight for variations about the nominal levels of the listed design parameters and techniques.

Variations of two factors, fineness ratio and payload density, were studied by the analysis of four new vehicle configurations. Designated as Vehicles 202, 203, 204, and 205, they are derivatives of the 201 Vehicle and are illustrated in Figure 2-2. Vehicles 202 and 203 represent fineness ratio variations on either side of the 201 Vehicle. They have the same payload density and tank volumes as the parent vehicle. The 204 and 205 Vehicles are identical to the 201 with the exception of the payload section which was varied in length to obtain different payload densities. Both of these vehicles have higher payload densities than the nominal value as the latter was considered to be essentially a lower bound.

Table 2-2

Parameters Considered in Structural Weight Sensitivity Study

Design Criteria	Unique Design Approaches	Material and Fabrication	Structural Analysis Techniques
Prelaunch Winds Inflight Winds Maximum Boost Acceleration Tank Pressures Vehicle Type Factor of Safety	Propulsion (Engine) Type Front-End Steering Payload Density Fineness Ratio (L/D) Strap-on Auxiliary Propulsion Systems (Attach Structure)	Type of Metals (Isotropic) Types of Laminates (Anisotropic) Types of Wall Construction Construction Factors	Failure Criteria for Biaxial Stress Fields Pressure Coupling Buckling Coefficients

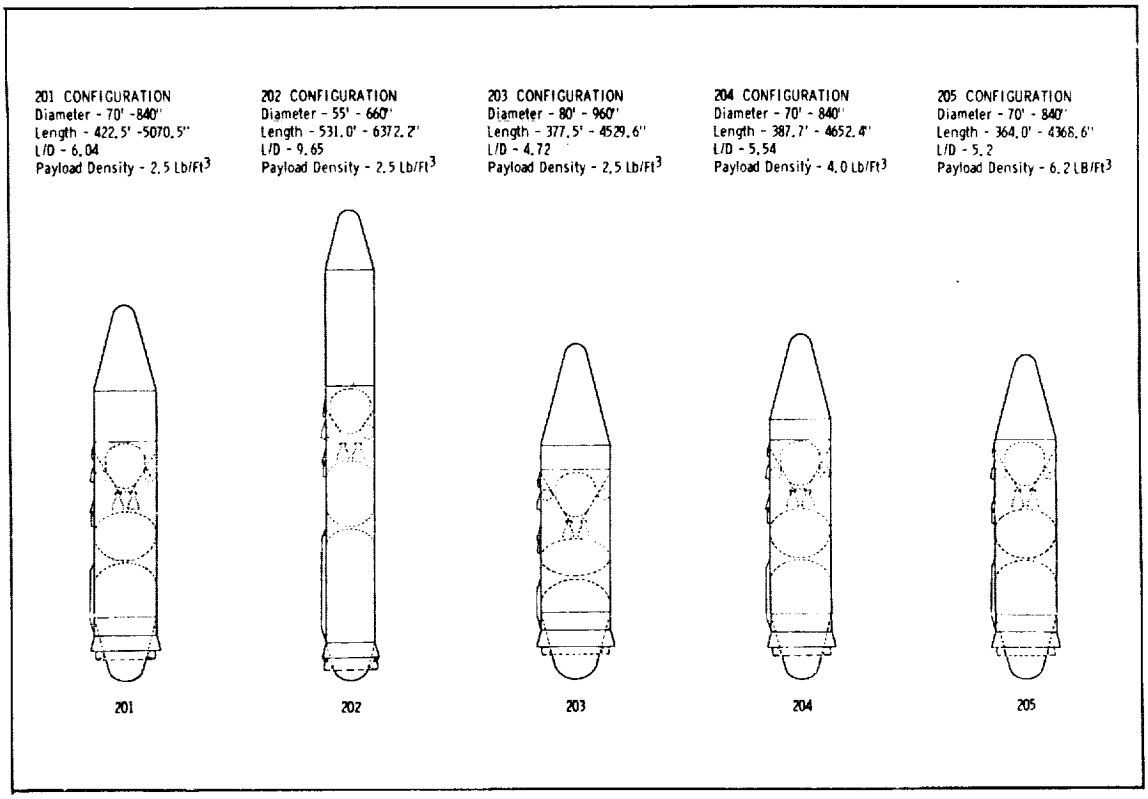


Figure 2-2. Variations of 201 Configuration

A fifth version of the 201 Vehicle was designed as part of the front-end steering analysis. Designated 202RT, it was identical to Vehicle 202 except that the first stage LO_2 and LH_2 propellant tanks were interchanged. The front-end steering analyses included evaluating the effect of vehicle mass distribution on steering requirements.

Thus, the parametric analysis involved variations about nominal design values for the three baseline vehicles, as well as the five additional configurations just described.

The vehicles were assessed at the following five design points which were identified as critical and served as the analysis points for obtaining all sensitivity data:

a. Prelaunch unpressurized, exposed to 99.9 percent winds.
b. Prelaunch pressurized, exposed to 99.9 percent winds.
c. Maximum product of dynamic pressure and angle of attack.
d. Maximum pressure on the bottom heads of propellant tanks.
e. Maximum boost acceleration.

In order to keep the study effort within tolerable limits, careful attention was given to the establishment of a system of ground rules and assumptions. These were of such a nature that they did not compromise the objectives and usefulness of the study, but they did restrict the depth and to some extent the complexity of the analyses.

The principal ground rules employed were:

a. Except for some special studies, (e.g., pressure coupling) the additional weight resulting from structural discontinuities was assumed to be small in comparison with the total structural weight.
b. Changes in the structural configuration were assumed to have a minimal influence on inertial loads.
c. The weights of slosh baffles and insulation were assumed to be constant for each vehicle throughout the study.
d. Fabrication factors were used to account for noncalculable structural weight (weld lands, doublers, etc.).
e. A fixed rate-displacement control system configuration was used for stabilization and control of all vehicles.
f. The structural weight necessary to prevent buckling in a partially-filled lower-tank head were assumed to have a negligible effect on total vehicle weight sensitivities.

Even with these restrictions, the number of study combinations (see Table 2-2) considered was equivalent to the analysis of tens of thousands of vehicles, each comprised of up to twenty major structural elements. This immense computational and data handling problem was solved, as will now be described, by a combination of engineering analysis and machine computation and a novel approach to the utilization of the latter.

The topics investigated during the study were divided into two groups; those amenable to direct application of a system of computer programs and those requiring specialized studies. The latter group was further divided into special studies requiring rigorous analytical efforts and supporting studies, conducted continuously, to provide basic data for the parametric studies. Figure 2-3 illustrates the organization of the study, based on this three-way division.

The specialized analytical studies, just referred to, were accomplished manually and, when appropriate, through the use of small, special purpose computer programs written by the investigators. The specific studies in this category consisted of:

a. Failure criteria for biaxial stress fields.
b. Pressure coupling.
c. Buckling criteria.
d. Thrust structure and advanced propulsion.
e. Front-end steering system equipment weights.
f. Attach structure for strap-on solid propellant motors and liquid propellant tanks.

Those topics studied with the aid of the computer system employed the system of computational modules illustrated in Figure 2-4. The GASP module generated rigid-body vehicle trajectories in the pitch plane. These provided the response of the vehicle to various loading conditions—winds, maximum boost acceleration, etc. The LASS-1 Program combined these responses with the stiffness and mass distributions, and distributed aerodynamic coefficients to produce the corresponding axial forces and bending moments. These, together with fabrication factors, material properties, etc., were used to develop optimal structural weights for both isotropic and anisotropic materials. Details of all modules are found in Appendices A and B in Volume 2.

A very important aspect of the study, one which largely alleviated the data handling problem, was the procedure used in applying the above computer programs. This procedure, involving the concept of Generalized Weight/Loads Matrices, is explained

in detail in Volume 2, Section 2. The use of these matrices and the described computer programs combined to form a very powerful parametric analysis tool.

The efficiency of the study was enhanced by organizing it in three phases. The first phase was a broad, single-variable analysis to establish the relative magnitude of the influence of the parameters of interest. The Phase II effort was a multiple-parameter analysis of those areas identified in Phase I as having the greatest influence on total vehicle structural weight or those variations which may be of lesser impact but are of interest due to potential ease of incorporation. The third phase was devoted to an in-depth analysis of the interaction effects.

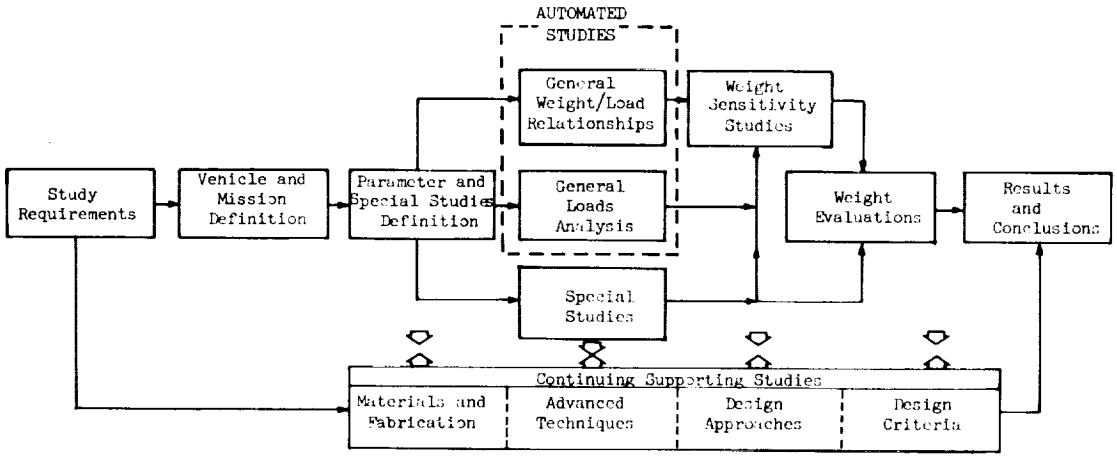


Figure 2-3. Study Work Flow

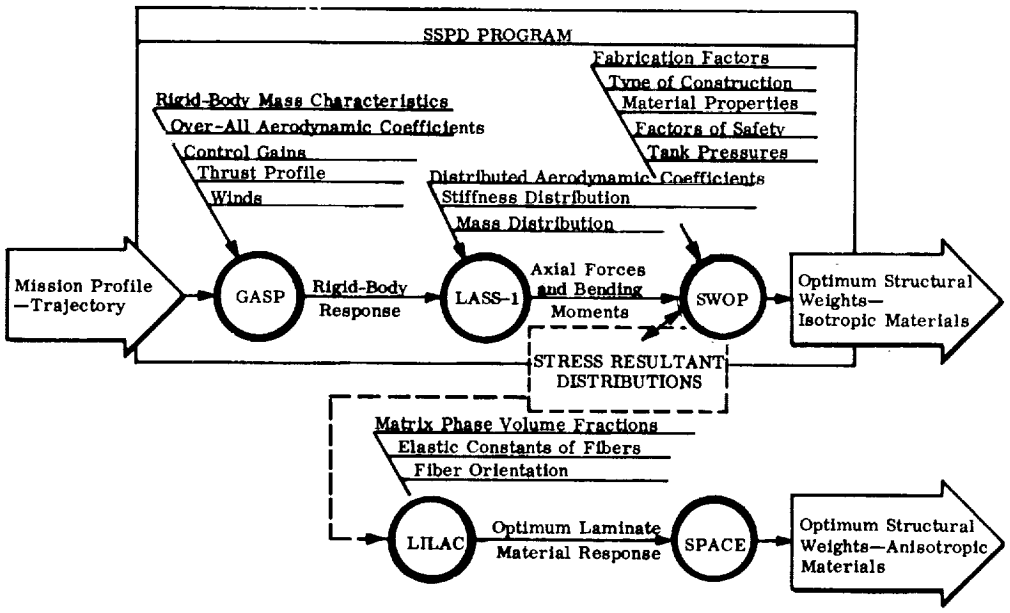


Figure 2-4. Structural Weight Optimization Computer Programs

SECTION 3

SUMMARY OF RESULTS AND CONCLUSIONS

3.1 SUMMARY OF STRUCTURAL WEIGHT SENSITIVITIES

This section presents a top-level summary of the structural weight sensitivities generated in this study. Detailed results and in-depth discussions of their sources and impact are included throughout Volume 2.

In general, the results are presented here as percent decreases in structural weight for favorable changes from the nominal values of one or more indicated variables. In many cases, specific results are noted for each of the five vehicles; 101, 201, 202, 203 and 301. Where possible, the range of excursion of the indicated variables is displayed with the results. This section discusses first the effects of varying single parameters and then the results of simultaneously varying combinations of these parameters through the same ranges.

The data presented are considered valid for the indicated ranges but care should be observed in the application of specific results. The weight sensitivities are generally nonlinear, particularly with respect to loads criteria. And, although the effects of a given parameter variation generally differed little among the three base vehicles, the study was constrained to the million-pound-payload class of vehicles. Application of results presented here to smaller or larger vehicles may not be valid; appropriate scaling laws were not devised.

Figure 3-1 indicates the maximum structural weight reduction obtained within each category of variables. These results reflect single parameter variations through appropriate ranges and illustrate the predominant importance of advances in materials and fabrication techniques. Note that, as in all results presented in this section, only variations in vehicle structural weight are reflected; i.e., attendant changes in the weights of other systems are not presented.

Significant differences were found when several factors which create vehicle loads were varied simultaneously. Similarly, significant interactions were noted when both structural materials and fabrication types were varied simultaneously. Summary results of the multi-variable analysis are represented in Figure 3-2.

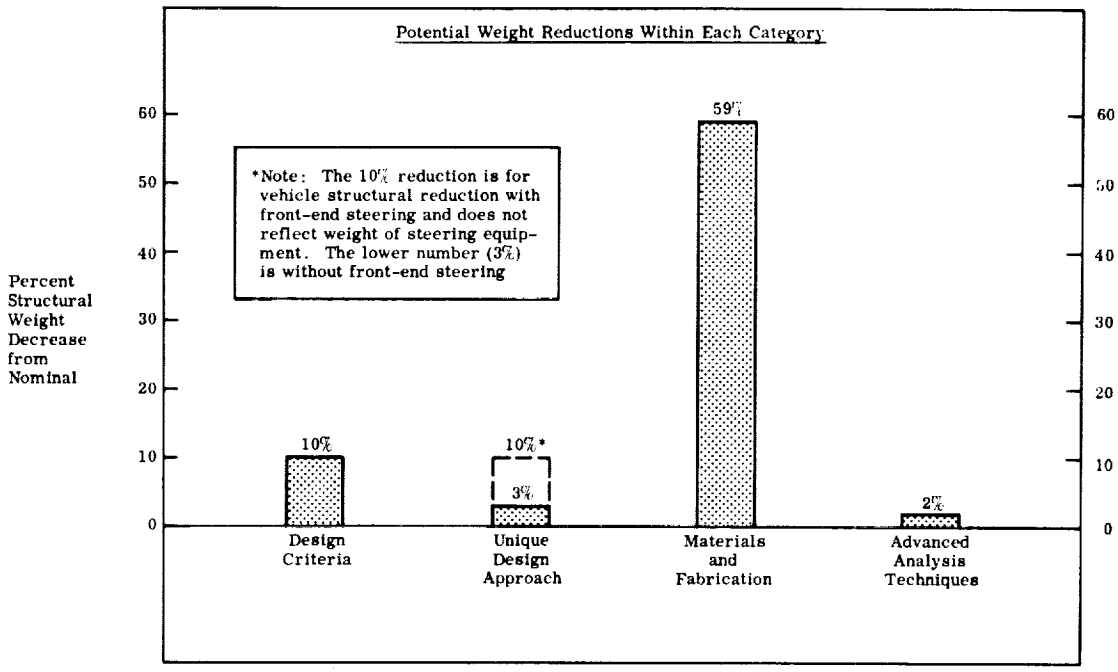


Figure 3-1. Largest Weight Reductions for Single-Parameter Variations within Each Category

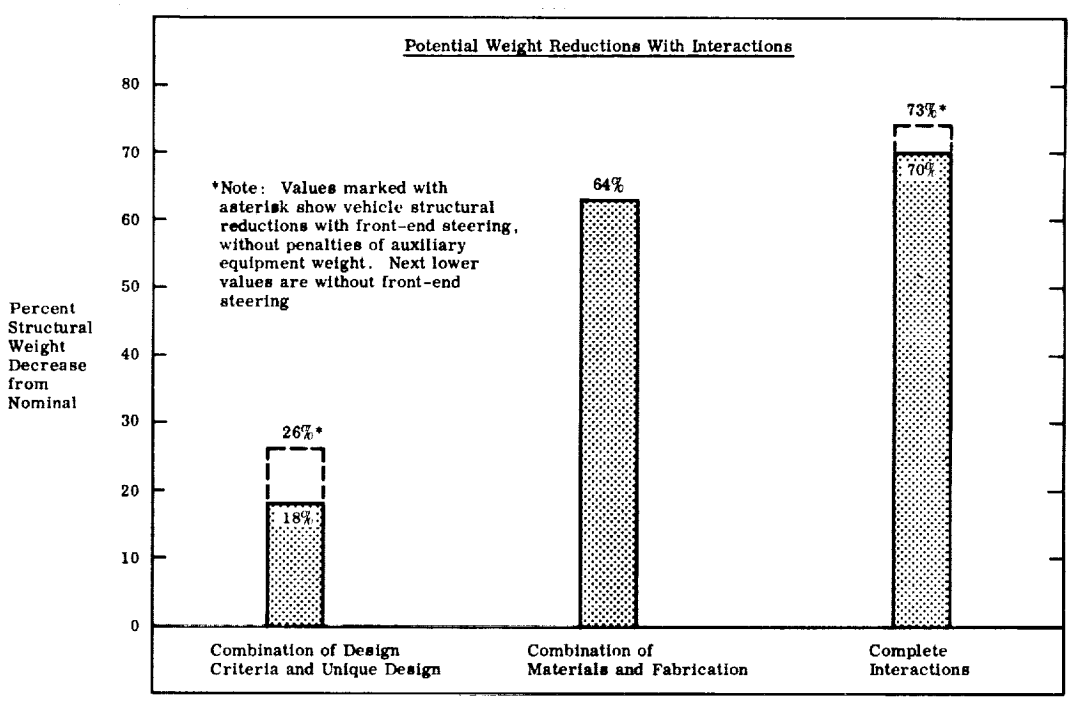


Figure 3-2. Largest Weight Reduction for Simultaneous Variation of Several Parameters

3.2 STRUCTURAL WEIGHT SENSITIVITIES FOR VARIATION IN DESIGN CRITERIA

Variations in design criteria, when considered one-at-a-time produce the changes in structural weight illustrated in Figure 3-3 for the five representative vehicles.

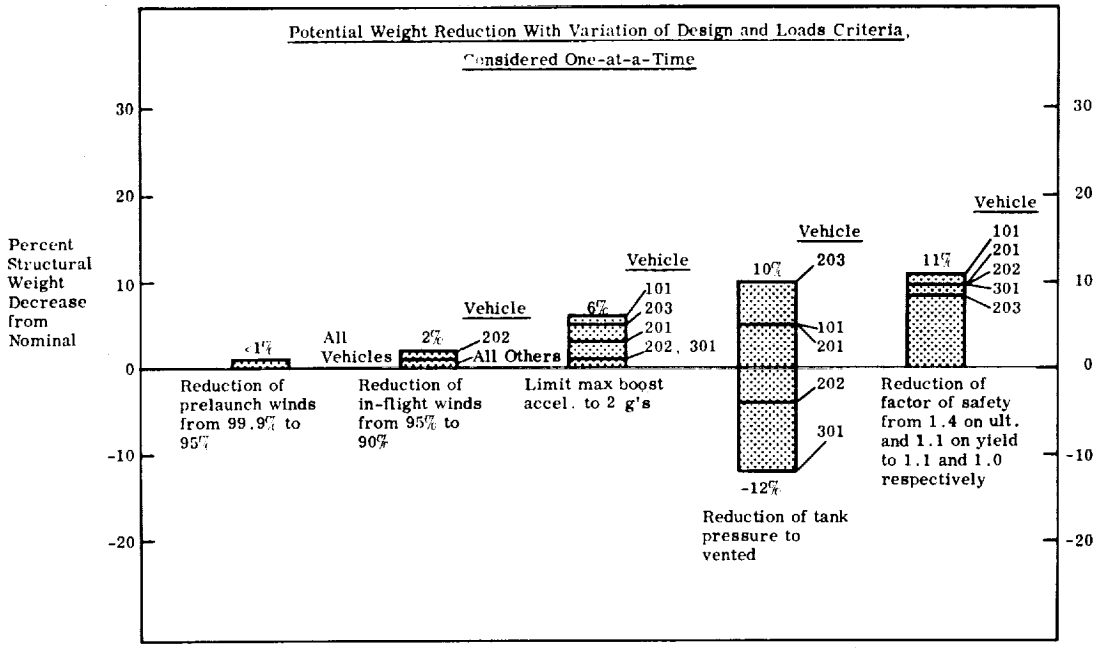


Figure 3-3. Variation of Design and Loads Criteria

Variation of prelaunch surface wind velocity profiles from the design value of 99.9 percent probability of occurrence winds down to 95 percent probability of occurrence winds during the windiest month at Cape Kennedy, Florida, produces little change in structural weight. This is true regardless of whether the vehicle is pressurized or unpressurized, and is largely a result of the low L/D and large diameter of the base vehicle used for this study

Variation of inflight wind profiles from the design value of 95 percent probability of occurrence to 90 percent probability of occurrence during the windiest month at Cape Kennedy, Florida, results in a similarly small structural weight reduction of less than 2 percent when winds are varied as a single variable. Synthetic wind profiles, which included a 9-meter per second gust, were shifted in altitude to produce the highest loads in each case.

Limiting the maximum acceleration to a low value such as 2 g's reduces structural weight by as much as 6 percent when considered as a single variable. This results primarily from reduced propellant head within tanks and reduced axial loads in interstages.

Reduction in tank pressures to a fully vented condition results in structural weight reductions of up to 10 percent, but these results are greatly influenced by the propellant tank configurations. As pressure is reduced, the loads on the tank heads are decreased and the loads on the tank cylinders are increased. The weight savings available, therefore depend upon how the total structural weight is divided between tank heads and tank cylinders. Tanks with long cylindrical sections such as the 202 and 301 Configurations show increases in weight as the pressure is reduced (see Volume 2). Conversely, a vehicle such as 203 which is primarily composed of heads benefits from reduced pressure. The pressure reduction was assumed to be achieveable in the limit by improved pumps with reduced NPSH requirements.

The impact of the factor of safety on structural weight, indicated in Figure 3-3, was a reduction of about 10 percent. It is not implied that such a reduction would be warranted for either manned or unmanned vehicles. However, these results do illustrate the sensitivity of structural weight to variations in factors of safety.

3.3 STRUCTURAL WEIGHT SENSITIVITIES TO DESIGN APPROACHES

Results for variations in design and steering methods, are summarized in Figure 3-4. A special study was also carried out to estimate the weight of local attach structure required for strap-on propulsion systems.

Use of gimballed bell nozzles results in a structural weight decrease (on the order of 3 percent) over that for plug-nozzle engines. This results from the reduced bending moment in comparison with that accompanying the use of differential throttling for thrust-vector control in a plug-nozzle design. If secondary injection is used to obtain the required steering moment rather than differential throttling, the structural weight associated with a plug-nozzle design would be closer but still greater than that of a gimbaled bell-nozzle design.

The use of front-end steering significantly decreased the bending moments applied to the vehicle structure as a result of inflight wind disturbances. This reduction in

bending moment is accompanied by a significant decrease in required structural weight which in the cases analyzed here is as high as 10 percent. These results apply equally for either side-thrusting rocket engines or movable aerodynamic surfaces located in the vicinity of the center of pressure as illustrated in Figure 3-5. However, this structural weight reduction will be reduced by the weight penalty which is imposed by the front-end steering system. Weight estimates of the required front-end steering systems were made and are covered in detail in Volume 2. Comparing the structural weight reductions due to reduced bending with the front-end steering equipment weight estimates suggest that no advantage is available when front-end steering is evaluated as a single variable. This conclusion will be modified by the results of the interaction study presented later in this section.

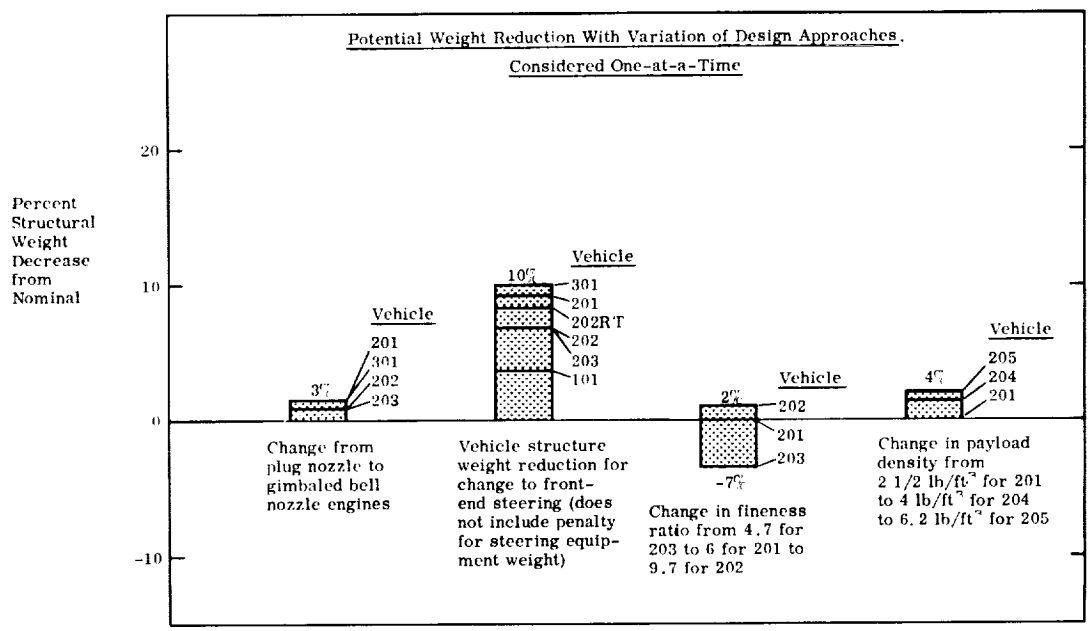


Figure 3-4. Unique Design Approaches

Variations in fineness ratio from the 201 Vehicle (L/D = 6.04) as a reference to the 202 Vehicle (L/D = 9.65) and the 203 Vehicle (L/D = 4.72) indicated that structural weight is relatively insensitive to variations in fineness ratio.

Variations in payload density from the 2.5 lb./ft.^{3} in the 201 Vehicle to 4.0 lbs./ft.^{3} and 6.2 lbs./ft.^{3} for the 204 and 205 Vehicles respectively reduce the structural weight on the order of 4 percent or less as shown in Figure 3-4. The low sensitivity to variations in payload density may be the result of the assumption of a constant diameter vehicle where the nose cap is moved back relative to the remainder of the vehicle.

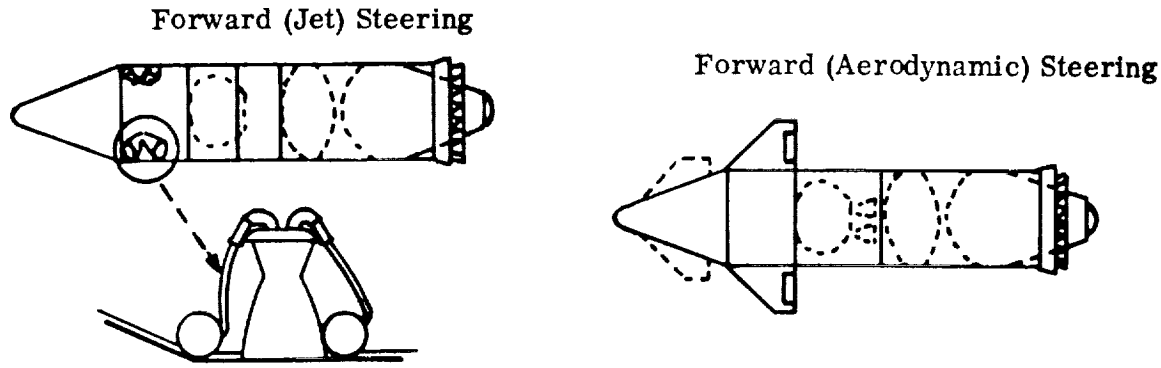


Figure 3-5. Schematic Illustrations of Front-End Steering

The attach structure weight for eight 260-inch solid motors is tabulated in Table 3-1 for the additional local structure necessary to transmit the thrust between the strap-on propulsion systems and the core 201 Vehicle. The attach structure is considered in three parts:

a. The additional local weight added to the core vehicle
b. The thrust collar and local structure added to the auxiliary propulsion system
c. The structure which connects the auxiliary propulsion system to the core vehicle

The increases in core vehicle structure necessary to sustain the increased loads of greater payloads and larger thrust loads were not considered in this study.

Table 3-1
Weight Of Attach Structures

	Core	Attachments	SRM	Total
8 Solid Rocket Motors (Forward or Aft Attached)	169,188 lb.	9,924 lb.	559,408 lb.	738,520 lb.
8 Solid Rocket Motors (4 Aft Attached, 4 Forward Attached)	265,932 lb.	9,924 lb.	559,408 lb.	835,264 lb.

The motors were assumed to be connected at two longitudinal locations and to fire as a zeroth stage. In either case, the attach structure penalties are quite significant and exceed the weight of the 201 Core Vehicle structure.

Consideration was also given to strap on tanks. This is covered in Volume 2, paragraph 6.7.

3.4 STRUCTURAL WEIGHT SENSITIVITIES TO VARIATIONS IN MATERIALS AND FABRICATION

The structural weight sensitivities to materials and types of construction were established by the variations shown in Figure 3-6 and Table 3-2. Using the nominal vehicle configuration as a base, Figure 3-7 illustrates the very strong sensitivity of structural weight to changes in isotropic materials or types of construction when varied one-at-a-time. An interaction analysis of materials and types of construction is presented in Paragraph 3.7. Filamentary composite materials were also evaluated during the course of the study. These were not treated as one-at-a-time variations, however, and are presented with the interaction analysis results in Paragraph 3.8.

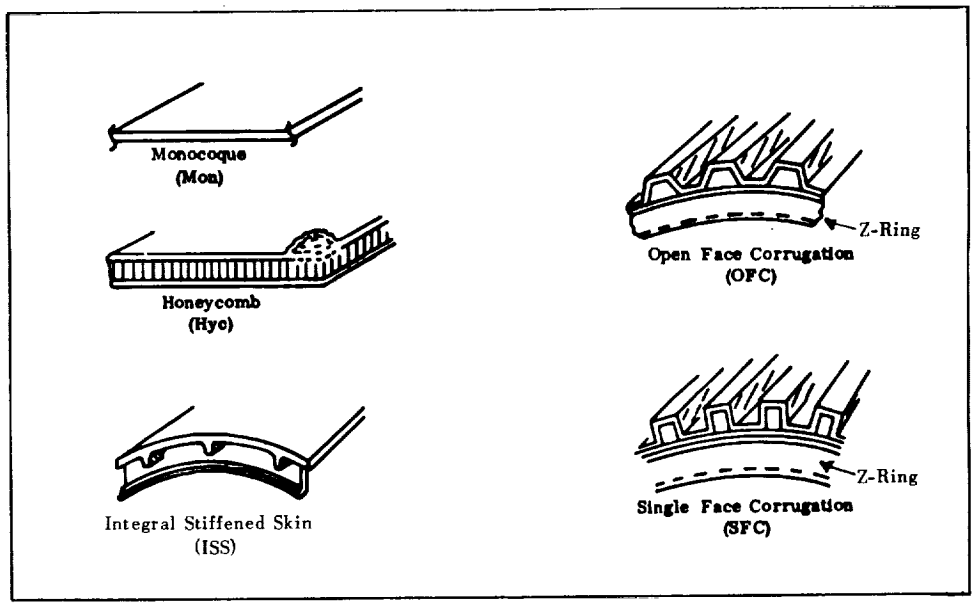


Figure 3-6. Types of Construction—Metals

When beryllium is used instead of aluminum, the structural weights of all the vehicle configurations are reduced on the order of 50 to 60 percent of the nominal vehicle

structural weight. The high modulus-to-density ratio of beryllium is very efficient in resisting buckling failures and accounts for the large weight sensitivity illustrated. The relatively low fracture toughness nature of beryllium was not considered in this analysis since the goal was to obtain structural weight sensitivities. However, the low fracture toughness of beryllium and the problems associated with fabricating this material would be important considerations in any practical design application.

Table 3-2

Material Properties

	E PSI	ρ PCI	σ_{yield} KSI	σ_{ult} KSI	$\frac{E}{\rho}$
Aluminum 2219-T87	10.4×10^6	0.100	50.0	62.0	104×10^6
Beryllium	42.0×10^6	0.06655	64.5	75.0	631×10^6
Titanium 6A1-4V	16.0×10^6	0.1597	126.0	130.0	100.1×10^6

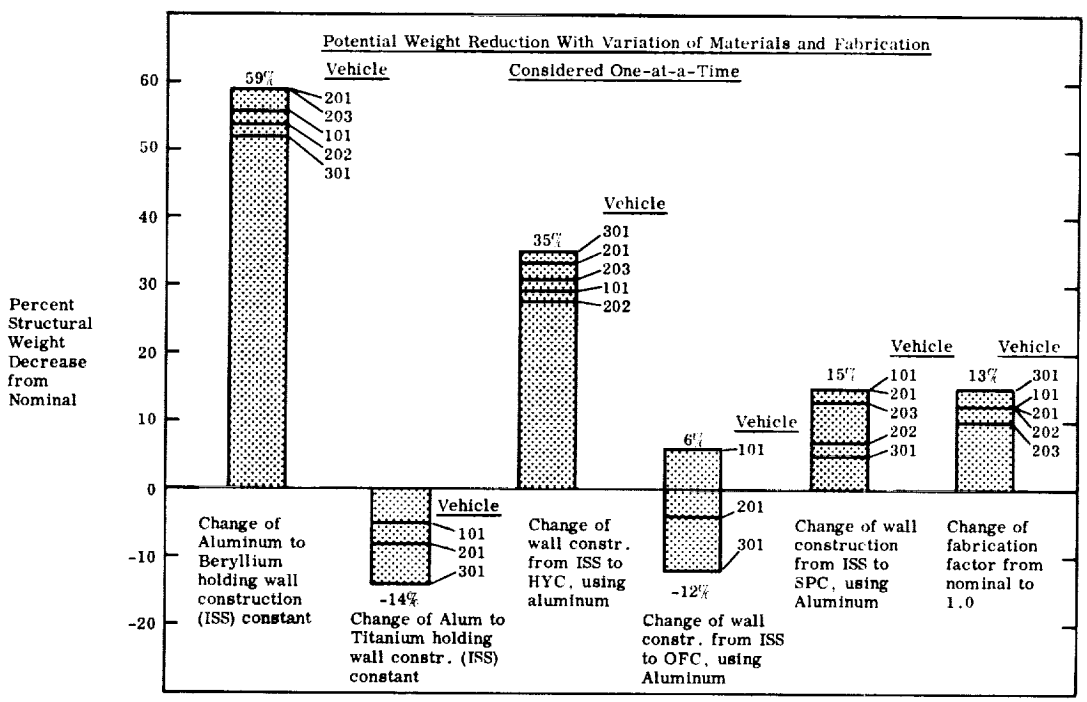


Figure 3-7. Materials and Fabrication

When titanium is used instead of the nominal aluminum material, the structural weight of the vehicles is increased 5 to 14 percent over the nominal vehicles structural weight. This is primarily due to the slightly lower modulus-to-density ratio of titanium which results in increased structural weight for structures loaded in compression. Weights of structural elements subjected only to tensile loads (such as tank heads) can take advantage of the greater strength of the titanium. The tank heads, in general, are lighter when they are made of titanium than when they are made of either aluminum or berryllium.

The net effect when titanium is used for the entire vehicle, however, is to increase structural weight. The high temperature characteristics of titanium could be an important consideration in some design applications even though it might produce slightly higher structural weights.

The use of honeycomb sandwich construction produces reductions of up to 35 percent over the less efficient integral-stiffened skin of the nominal configurations. The analysis assumed a very low density core and ignored the problems of joining and edge effects which would be of paramount importance in a practical design. The large sensitivity of structural weight does, however, demonstrate the benefits to be obtained by overcoming these practical limitations.

Using open-face corrugation in unpressurized cylinders, the effect on structural weight is varied. The nominal weight of the 101 Vehicle is reduced 6 percent while the 201 and 301 Vehicles experience increases in structural weight of 4 percent and 12 percent respectively. In general, the weight sensitivity is small compared to that of the honeycomb sandwich construction.

Using single-face corrugation construction in unpressurized cylinders reduces the nominal structural weight from 5 percent to 15 percent. Although this type of construction appears to be more efficient than the open-face corrugation, the structural weight sensitivity is also less than that for the honeycomb sandwich construction.

Fabrication factors which were used in the analysis to account for non-calculable structure, such as welds, doublers, etc., vary with the type of construction as shown in Table 3-3.

Table 3-3
Fabrication Factors

Type of Construction	Fabrication Factor
Monocoque	1.05
Integral Stiffened Skin	1.20
Honeycomb Sandwich	1.25
Open-Face Corrugation	1.20
Single-Face Corrugation	1.20

The sensitivity of the total structural weight to this factor was evaluated by reducing these factors to unity. The structural weight decreased between 11 and 13 percent as shown in Figure 3-7.

3.5 SENSITIVITY OF STRUCTURAL WEIGHT TO METHODS OF ANALYSIS

The structural weight sensitivities to variations in methods of analysis are moderate when compared to advanced materials and construction methods. In the case of single-stage-to-orbit types of launch vehicles, however, they are of considerable interest due to the extreme sensitivity to mass fractions of these vehicles. Two analytical techniques were considered during this study, pressure coupling and biaxial stress failure theories. Buckling coefficient sensitivities were also examined. The relative sensitivities of these are represented in Figure 3-8.

Pressure coupling is the effect of the meridional stress resultant on discontinuity stresses that occurs with a change in geometry in a pressure vessel. For the representative vehicles considered in this study, the inclusion of pressure coupling reduced the structural weight less than 1 percent from the nominal. The pressure coupling effects would be greater (perhaps as large as 5 percent) for highly pressurized thin-walled cylinders which are typical of baloon tank designs.

The use of an advanced biaxial stress-failure theory to account for the increased biaxial strength exhibited by certain materials had a small effect on structural weight. Use of Hill's failure theory and a plastic Poisson's ratio of $\mu_p = 0.7$, such as observed with textured titanium alloys, resulted in a 2 percent decrease in structural weight. The nominal vehicle was designed using the Huber-Hencky - von Mises

failure theory which, as noted in Figure 3-9, corresponds to a plastic Poisson's ratio of 0.5. On the other hand, if the maximum shear stress or maximum principal stress theories of failure were used, the nominal structural weight would increase about 1 percent.

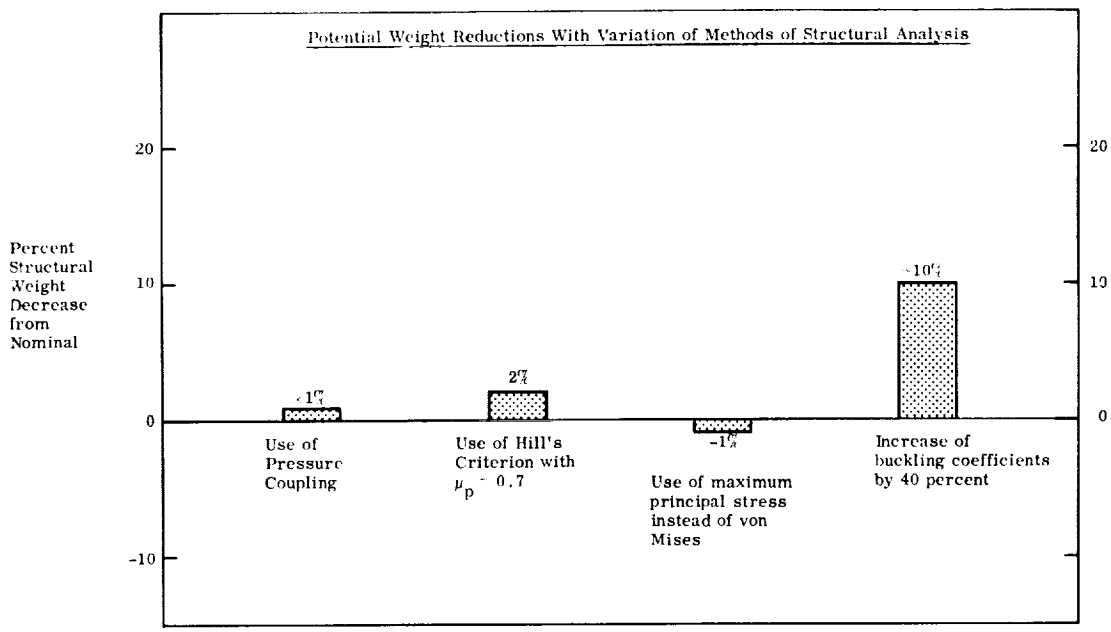


Figure 3-8. Method of Analysis

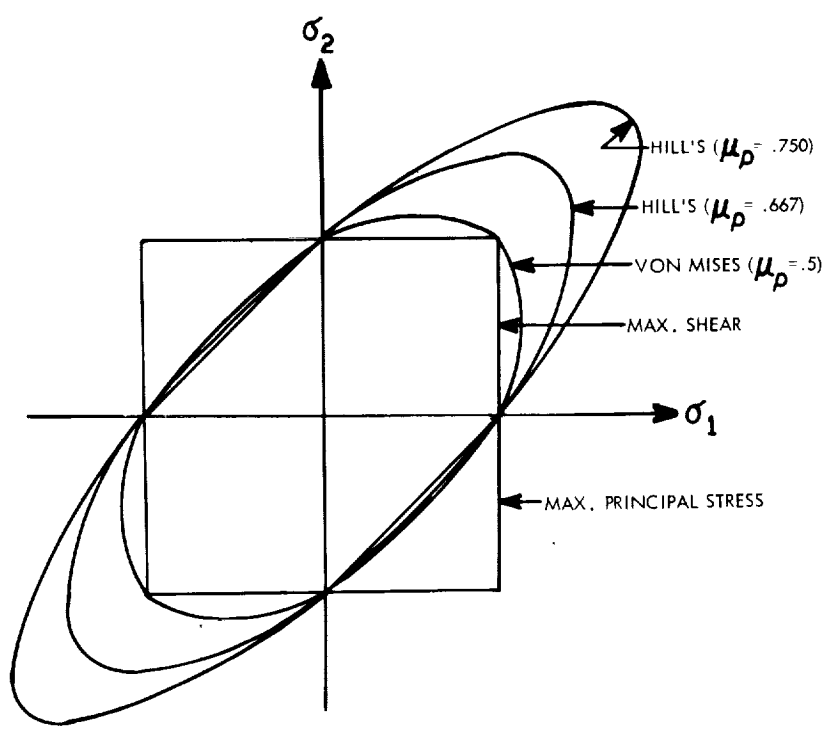


Figure 3-9. Strength Failure Criteria

Variation of buckling coefficients, the "knock-down" factors which are used to correlate theoretical shell stability analyses with test results, produces a structural weight decrease of about 1/4 percent for each 1 percent increase in buckling coefficient. There are slight variations in the structural weight sensitivities for different types of construction as shown in Figure 3-10. Recent experiments with near perfect cylinders have proved that large increases in buckling coefficients will depend on improvements in manufacturing techniques for future launch vehicles. If the imperfections of shell structures can be reduced for practical designs, the resulting reductions in structural weight are very attractive.

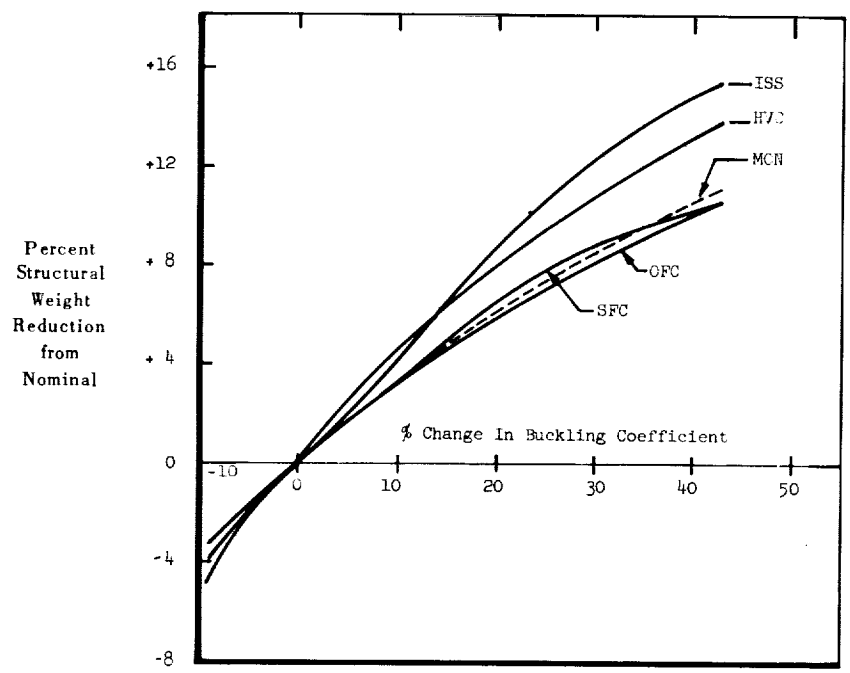


Figure 3-10. Influence of Variations in Buckling Coefficients

3.6 INTERACTION OF DESIGN CRITERIA AND OTHER DESIGN VARIABLES

Results to this point have been concerned with decreases in structural weight for large favorable variations in design parameters when considered one at a time. Simultaneous variation of the design criteria as shown in Figure 3-3 (but with fixed factor of safety) produced the results shown in Figure 3-11. Results are indicated for a plug-nozzle design (PN), a gimbaled-nozzle design (GBN) and a front-end steering design (FES) for five vehicle configurations. Clearly, results with several simultaneous variations (Figure 3-11) are not the accumulated changes with one-at-a-time variations (Figure 3-3), since the criteria influences through loads have considerable interdependence effects. The critical loads profile is a combination of bending moments,

axial forces and pressure resultants which are in turn strongly influenced by design criteria. Relaxing several criteria simultaneously has a strongly non-linear effect on loads and hence structural weight. Numerous results of the interactions analysis are contained in Section 6 of Volume 2; methods and working charts for determining results for other combinations of variables are included in the same volume.

Impact of front-end steering is more significant with simultaneous variations of criteria as shown in Figure 3-11, than with the single variation in Figure 3-4. In both figures, the weight of steering equipment (calculated in Section 6, Volume 2 as 9 percent or more of the structural weight) is not included. When this equipment penalty is compared with the potential improvements from a 3 percent base to 20 percent for the 202 and 202RT Vehicles, front-end steering may have a beneficial effect of conceivably as much as 8 percent. However, these results presume that the vehicle is designed specifically for front-end steering and a more thorough investigation is warranted prior to making any general conclusions.

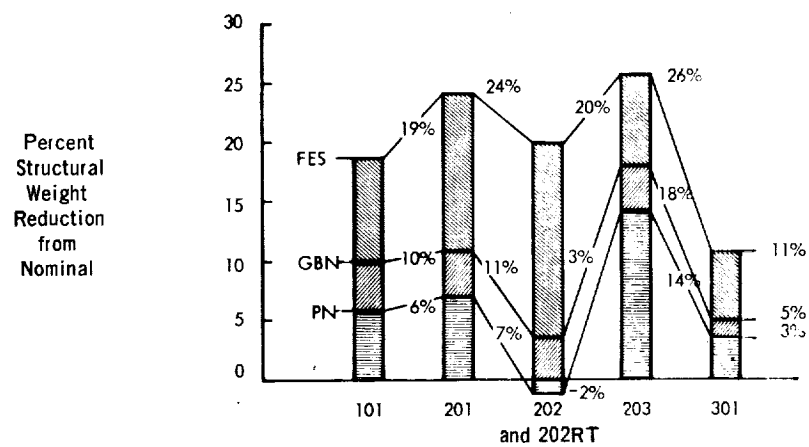


Figure 3-11. Influence of Design and Load Criteria Interaction

Variation of fineness ratio has a relatively small effect (less than 10 percent) on structural weight even when interactions are considered. The upper curve (A) in Figure 3-12 shows variation of structural weight for nominal conditions and construction for the 201, 202 and 203 Vehicles. Reducing the loads criteria to the low values of Figure 3-11 produces curve (B); changing materials and wall construction but keeping loads criteria the same as nominal yields curve (C). Combining the changes to best materials and reduction of loads criteria results in the structural weight of curve (D). As seen in all cases, structural weight is insensitive to a reasonable range of vehicle fineness ratio (4.72 to 9.65)

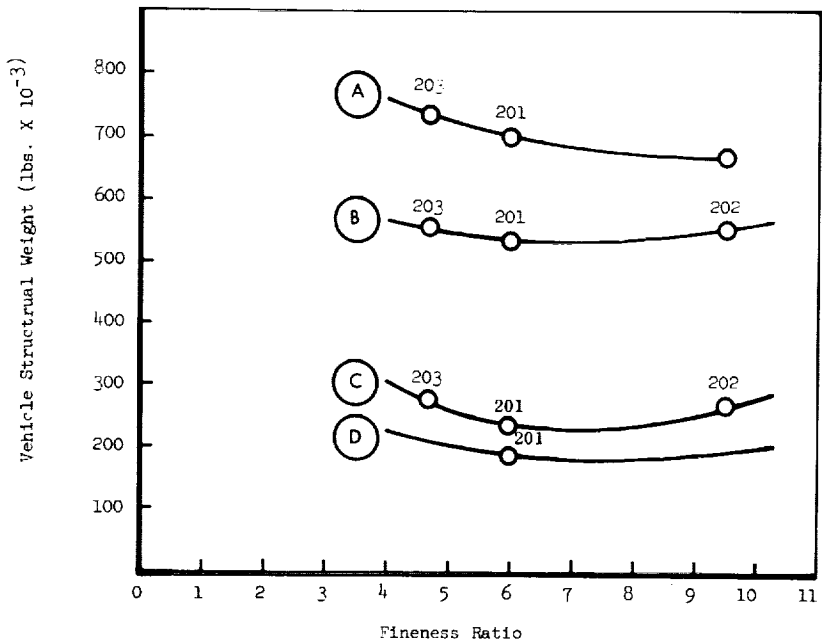


Figure 3-12. Effect of Fineness Ratio on Structural Weight

3.7 INTERACTION OF MATERIALS AND FABRICATION TECHNIQUES—ISOTROPIC MATERIALS

The structural weight sensitivities were presented in Section 3-4 for one-at-a-time variations of the materials listed in Table 3-2 and the types of construction illustrated in Figure 3-6. Weight sensitivities corresponding to combinations of these parameters are presented in Figures 3-13 and 3-14. In Figure 3-13 the percent structural weight reductions from nominal are shown for the three different metals where the type of construction is selected for each section along the vehicle to give the lowest structural weight. Using beryllium, with its high E/ρ and the type of construction that gives the lowest weight, the weight reductions reach 58 to 64 percent for the five vehicles analyzed. For titanium, which is considered typical of higher-strength alloys, the weight reductions are between 44 and 47 percent (titanium was not used for the 202 and 203 Vehicles). Aluminum structure shows weight reductions between 31 and 35 percent. With few exceptions, the honeycomb sandwich construction was the most efficient construction for all materials.

Figure 3-14 shows that the percent structural-weight reductions from nominal for three types of construction where the materials are selected for each section along the vehicle to give the lowest structural weight, (except for the monocoque tank heads), combined with the material that gives the lowest weight, the weight reductions are between 57 and 63 percent. At the other extreme, if the entire vehicle uses monocoque construction, the weight reductions vary between 20 and 33 percent using the lightest

material. The other types of construction fall between these two extremes as demonstrated by the integral stiffened-skin construction. With very few exceptions, titanium is the lightest material in the tank heads and beryllium is the lightest material for the remainder of the vehicle structures.

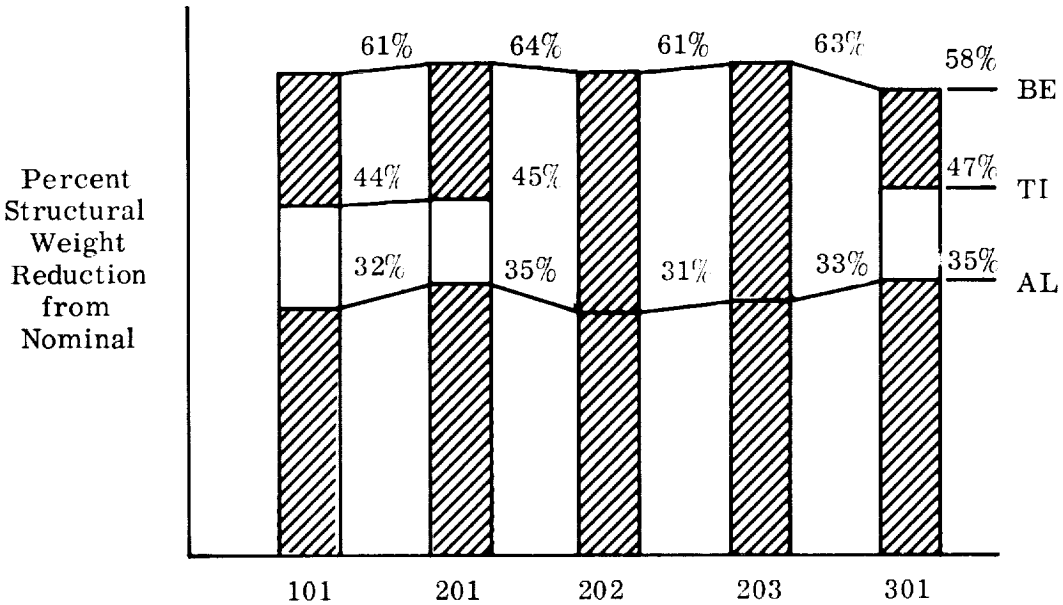


Figure 3-13. Weight Reduction for Most Efficient Structure with Various Materials

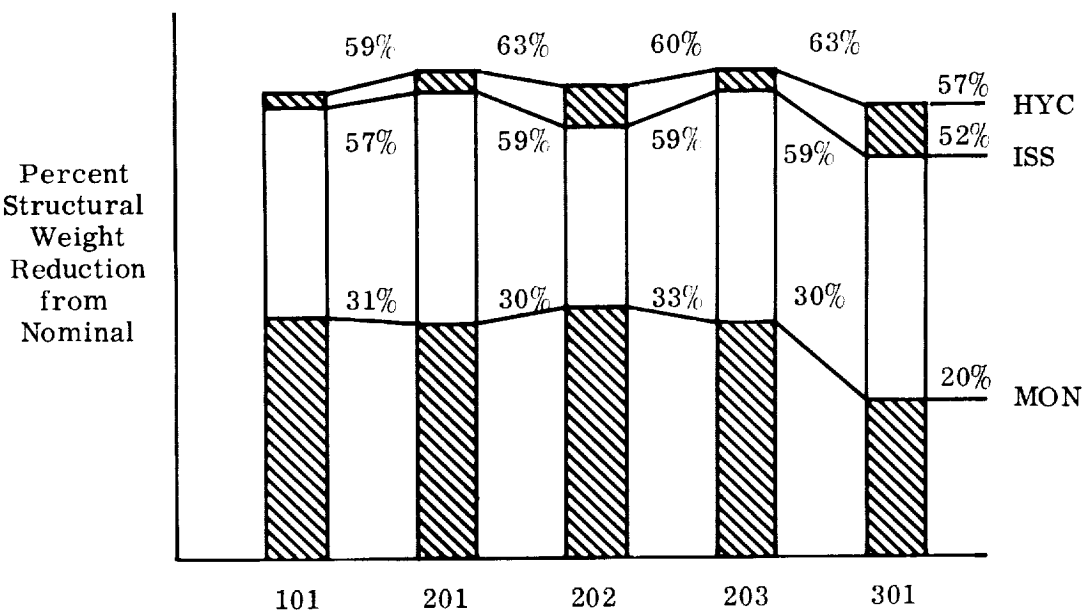


Figure 3-14. Weight Reduction for Lightest Metals with Various Types of Construction

3.8 INTERACTION OF MATERIALS AND FABRICATION TECHNIQUES—COMPOSITE MATERIALS

Three different combinations of filaments and binders were considered in this study:

- Glass filaments in an epoxy binder.
- Boron filaments in an epoxy binder.
- Carbon filaments in an aluminum binder.

The binder occupies 30 percent of the total volume in all composites. Each of the composite materials was considered with both isotropic windings and orthotropic windings. The material properties of the composites constituents are those shown in Table 3-4.

Table 3-4
Material Properties of Constituents

MATERIAL	ELASTIC MODULUS (PSI)	POISSON'S RATIO	DENSITY (PCI)
FILAMENTS			
GLASS	16.0×10^6	0.20	.0194
BORON	60.0×10^6	0.20	.0830
CARBON	60.0×10^6	0.18	.0720
BINDERS			
EPOXY	0.5×10^6	0.350	.050
ALUMINUM	10.7×10^6	0.315	.100

The isotropic composites have three equal thickness lamina where the filaments are oriented at -60, 0, and 60 degrees as shown in Figure 3-15. The orthotropic composites have two unequal thickness-lamina where the filaments are oriented at 0 and 90 degrees as shown in Figure 3-15. These composite materials were evaluated for monocoque construction as well as for sandwich constructions, such as shown in Figure 3-6, with core densities of 0.001 lbs./in.^{3} and 0.005 lbs./in.^{3}.

The structural weight sensitivities are shown in Figure 3-16 for various combinations of materials and types of construction. The winding pattern varies from section-to-section to get the lowest weight structure. The results shown reflect the weight of a 0.002 inch aluminum liner for the propellant tanks.

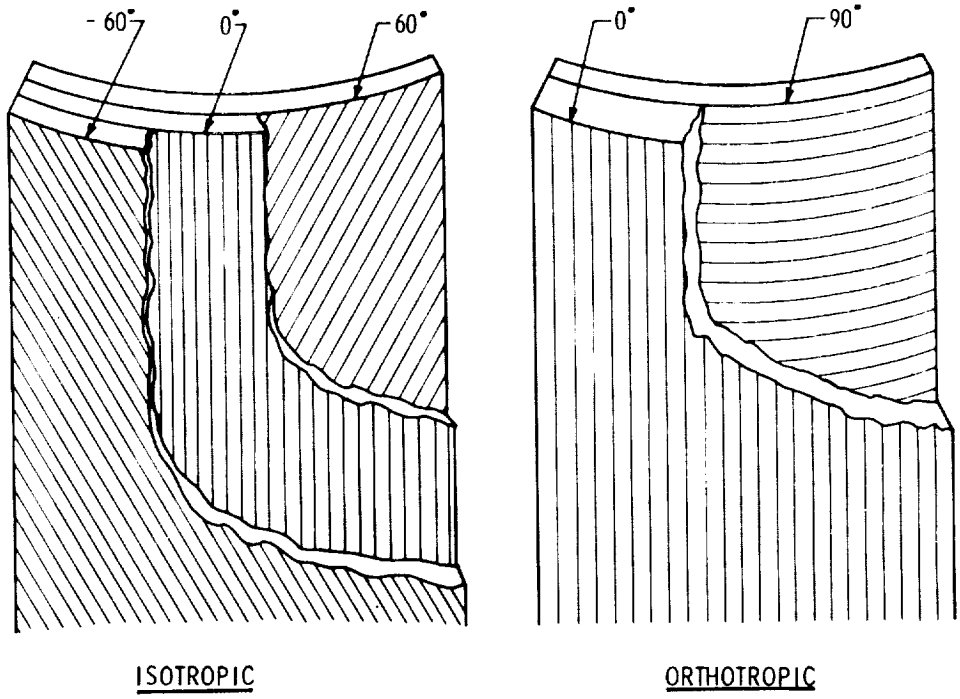


Figure 3-15. Composite Winding Patterns

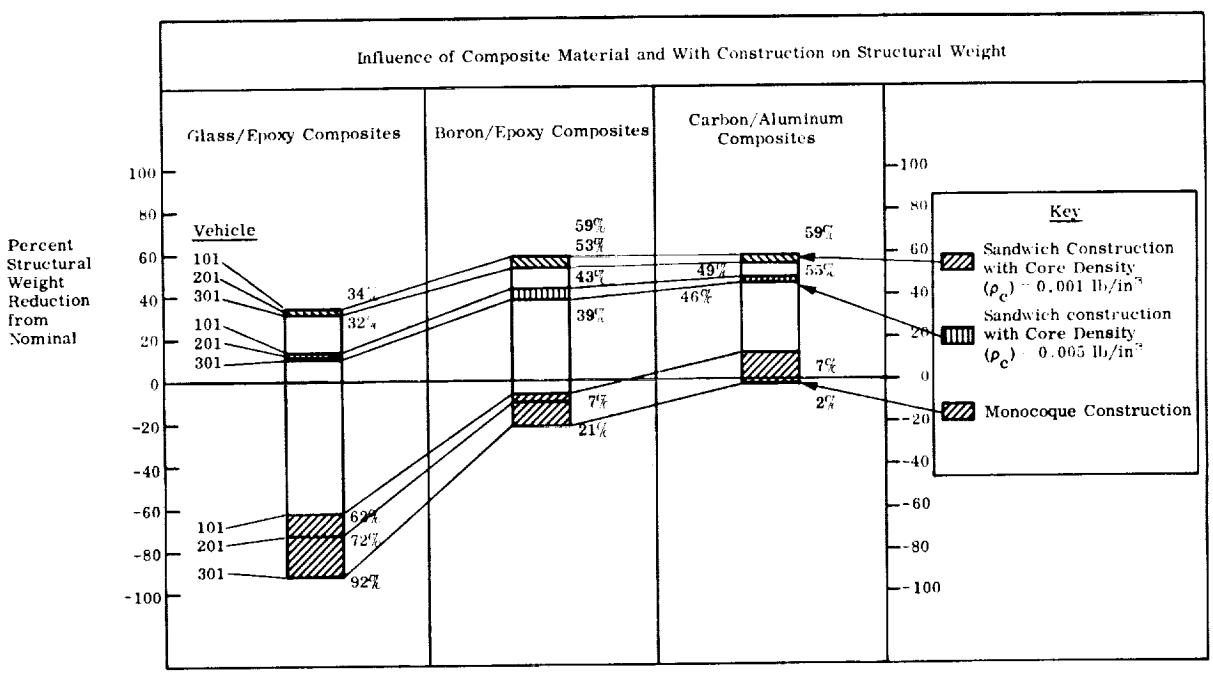


Figure 3-16. Weight Sensitivities Associated with Filamentary Composite Materials

Glass/epoxy composites, representing today's state of the art for pressure vessels, produce approximately the same results as aluminum. With glass/eposy and a light weight core (ρ_c = 0.001 lb./in.^{3}), weight savings ranged from 32 to 34 percent as against 31 to 35 percent for aluminum honeycomb.

The boron/epoxy composites represent today's advanced technology and appear to have good potential for structural weight reduction. The sandwich versions compare favorably with advanced metals, with weight savings of from 53 to 59 percent which are nearly as high as those achieved with beryllium.

The use of carbon filaments in an aluminum matrix is indicative of future technology and looks quite attractive for future investigations. Carbon/aluminum composites show equal or slightly better performance than the boron/epoxy composites and could conceivably be less difficult and expensive to fabricate and use. However, considerable research and development will be required before the practicability of composites such as carbon/aluminum is known.

3.9 IMPACT OF STRUCTURAL WEIGHT REDUCTIONS

An arrangement of the results of this study by difficulty of incorporation and, by inference, state of the art advancements, is shown in Figure 3-17.

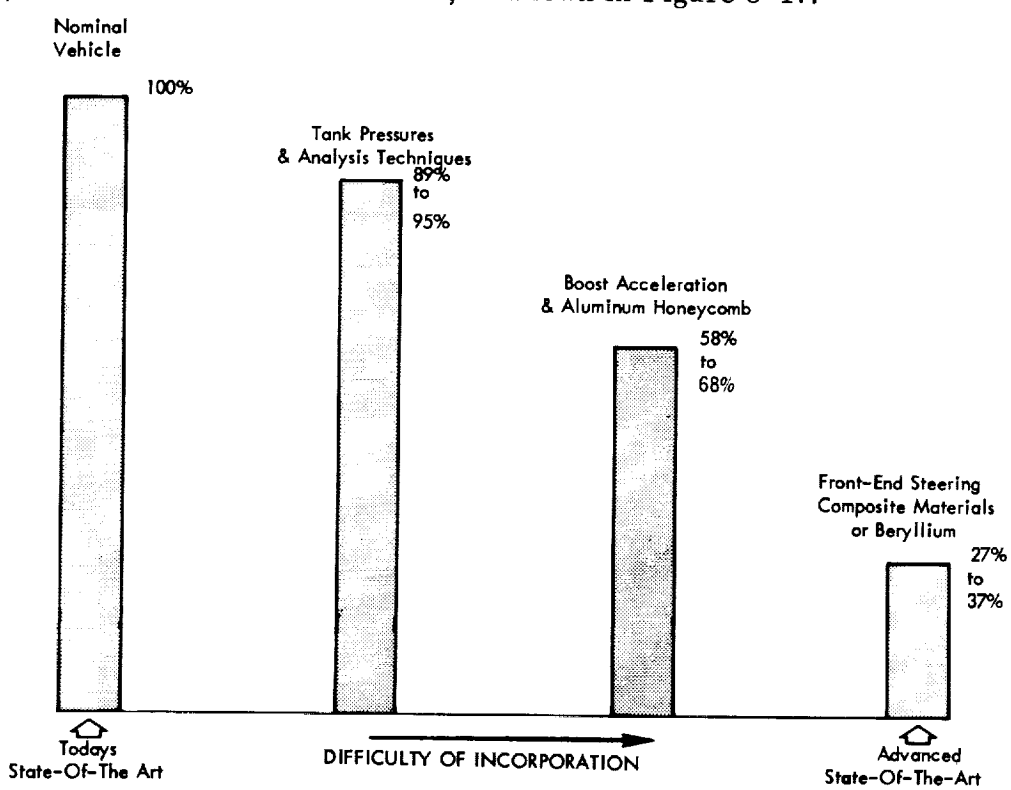


Figure 3-17. Reduction of Structural Weight with Advancement in State of the Art

Weight reductions range from the near future where weight reductions might be on the order of 5 to 11 percent to advanced designs with limited boost accelerations and aluminum honeycomb construction where structural weight reductions might be as high as 42 percent. For the very advanced designs, assuming the use of composite materials or beryllium, structural weight reductions of 63 to 73 percent are conceivable.

The significant finding of this study is that structural weight reductions of well over 50 percent are indicated with the use of advanced materials and fabrication methods.

Throughout this study, changes in structural weight were assumed to be reflected in higher energy missions since the payload and propellant loadings were held constant. However, such large reductions would permit a payload increase of 250,000 pounds to 350,000 pounds in these one-million-pound-to-orbit vehicles, or alternatively, would provide significant increases in margin of safety and hence cost-effectiveness.

3.10 SUGGESTIONS FOR FUTURE WORK

This study has identified and ranked, according to their potential, the areas of structural technology which can lead to lighter structures and increased cost-effectiveness for future launch vehicles. It is recommended that the following areas be pursued in future research and development programs:

- Development of honeycomb and other advanced wall construction methods should be intensified for specific applications in future vehicles.
- Methods for the use of metals with high modulus-to-density ratios, such as beryllium should be developed. Means of circumventing their inherent fabrication, brittleness and compatability problems should be pursued.
- Current research and development of filamentary composites, such as boron/epoxy and carbon in an aluminum matrix should be intensified for sandwich, as well as for monocoque constructions. Fabrication of such composites into integral stiffeners should also be investigated.
- A structural design optimization study should be conducted for the installation and attach structure of strap-on solid propellant motors to minimize the weight penalties incurred.

The following areas showed more moderate savings in structural weight. However, they are significant enough to warrant serious attention in future study efforts:

- Improved definition and potential reduction of design criteria, such as wind criteria, acceleration limits, and tank pressure requirements, would be beneficial.
- Improved structural analysis techniques, such as pressure coupling offer small but worthwhile reductions.
- Improved knowledge of buckling coefficients ("knock-down factors") is warranted, particularly for complex wall constructions and large diameter tanks.
- Front-end steering should be considered from an overall systems approach, considering both design and performance effects and using sub-optimized vehicle controls and engine systems.

In addition, while this study was confined to analyses of large launch vehicles, the question arises regarding applicability of these structural weight sensitivities to medium and small size launch vehicles, and to those with different propellants. Therefore, it is suggested that these analyses be extended into these areas to develop families of weight sensitivities of broad applicability to launch-vehicle design.

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