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STUDY OF TECHNOLOGY REQUIREMENTS FOR STRUCTURES OF LARGE LAUNCH VEHICLES

FINAL REPORT
VOLUME 2 OF 3

ANALYSIS OF TECHNICAL AND ECONOMIC IMPACT

1 JULY 1969

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GENERAL ELECTRIC COMPANY
DAYTONA BEACH, FLORIDA 32015

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FOREWORD

This report presents the results of the Phase II study of technical and economic impact of advanced materials technologies on launch vehicle structural weight and cost. The study is being performed for the National Aeronautics and Space Administration under Contract NAS2-5047, monitored by Mr. Kenji Nishioka and Mr. Harry Hornby of the Mission Analysis Division of the Office of Advanced Research and Technology.

Individuals from several locations at the General Electric Company have made significant contribution to this volume of the final report. These include Neil Munch, William Metzger, Jim Upp, Harold Odgers and Jack Beharrell of the Apollo Systems Department, Bill Postelnek of Re-Entry Systems and Dr. Larry Shu, Dr. Will Sutton and Roger Snyder of the Space Sciences Laboratory. In addition, consultation and guidance was provided by Dr. Jack Burns of the University of Florida and numerous other individuals within the General Electric Company.

We wish to acknowledge many organizations and individuals who provided us with data pertinent to this study. A list of these organizations and individuals is included at the end of this report.

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SUMMARY

This is Volume 2 of a three volume series of the final report summarizing the results of the study entitled, "Study of The Technology Requirements for Structures of Large Launch Vehicles." Selected structural technological areas were examined to determine current status. Economic and technical feasibility of selected technology areas spanning the range from current to future state-of-the art in structural designs was analyzed. The methods and results of these analyses are described in Volume 2. A survey of advanced structures technologies is described in Volume 3.

Of the advanced structural constructions studied, aluminum honeycomb offers both a cost reduction (15 percent) and a structural weight reduction (45 percent) compared with present technology. Present technology in this study is represented by aluminum integrally stiffened skin construction. Use of advanced filamentary composite materails, such as carbon/epoxy honeycomb, results in reductions in structural component weight of up to 80 percent of that from present technologies, and with only a slight increase in cost.

Trade-off studies of increased vehicle costs against the payload value gained with this reduced weight show that significant economic benefits can result from the use of advanced materials. In addition, reductions in cost are achieved for some materials through increased structural safety factor and the accompanying overdesign or design simplification. Aluminum honeycomb, for example, shows a 28% cost reduction when the safety factor is doubled.

A design study of a future launch vehicle using weight saving construction and simplified design with ruggedness achieved through elevated safety factors is recommended. Aluminum honeycomb (or fiber-glass honeycomb) appears attractive for the initial design with a growth potential designed into the vehicle which will take advantage of advanced composites, such as carbon or boron/epoxy honeycomb in the unpressurized sections, as these materials are more thoroughly developed and become available.

NOMENCLATURE

Symbols or abbreviations are listed in order of appearance

Al ISS	Aluminum Integrally Stiffened Skin
Al Hyc	Aluminum Honeycomb
Be Hyc	Beryllium Honeycomb
Be SS	Beryllium Stiffened Skin
B/Ep Hyc	Boron Filament, Epoxy Matrix Honeycomb
C/Ep Hyc	Carbon Filament, Epoxy Matrix Honeycomb
B/Ep Stiff	Boron Filament, Epoxy Matrix Unidirectional Stiffeners on Aluminum Monocoque Shell
B/Al Hyc	Boron Filament, Aluminum Matrix Honeycomb
Al Mono	Aluminum Monocoque Head
Ti Mono	Titanium Monocoque Head
B/Al Mono	Boron Filament, Aluminum Matrix Monocoque Head
$F_S/F_{S_{Nom}}$	Ratio of Investigated Safety to Nominal Design Safety Factor (Often Referred to as Relative Factor of Safety)
P	Representative Pressurized Tank Structural Section
U	Representative Unpressurized Structural Section
Fixed Vehicle Config	Vehicle Configuration and Propellant Loading Fixed but With Variable Payload Weight
Fixed Payload Config	Vehicle Configuration and Propellant Loading Variable but With Fixed Payload Weight
SWOP	Structural Weight Optimization Program
HOBE	Honeycomb Before Expanding
TIG	Tungsten Inert Gas
M, F, I	Materials, Fabrication, Inspection
(I)	Isotropic
(O)	Orthotropic
N_x	Highest Calculated Value for the Axial (or Meridional) Stress Resultant
N_o	Highest Calculated Value for the Equivalent Uniaxial Stress Resultant
ρ	Density
ν	Poisson's Ratio
E_{Tan}	Young's Modulus (Tangential)

E_{Long}	Young's Modulus (Longitudinal)
$\overline{E}$	Effective Stiffness $= \left(\frac{E_{Long} \times E_{Tan}}{1 - \nu_{LT} \nu_{TL}} \right)^{\frac{1}{2}}$
S	Strength
M_S	Mean Strength
σ_S	Standard Deviation of the Strength Distribution
R	Reliability
L	Load
M_L	Mean Load
σ_L	Standard Deviation of Load Distribution

SECTION 1

INTRODUCTION

1.1 BACKGROUND

Previous studies have shown that significant reductions in structural weight can be achieved with the use of advanced materials in future large launch vehicles. The General Electric Company, under a prior contract, NAS2-3811,[1]* has shown that structural weight reductions of 60 to 70 percent can be realized in large launch vehicles with substitution of advanced materials such as beryllium or boron/epoxy in place of the conventional aluminum construction. This weight reduction is significant in improving launch vehicle performance, particularly in single-stage-to-orbit concepts. Technological areas which offered substantial weight saving in the above study, have been evaluated parametrically for technical feasibility and economic characteristics in this study.

Other studies presently in progress for NASA Office of Advanced Research and Technology will complement this study. Boeing Aircraft is engaged in a detailed cost study of large launch vehicles which provides a range of payload capability under Contract NAS2-5056, "Cost Studies of Multipurpose Large Launch Vehicles." McDonnell-Douglas Aircraft Corporation is developing a cost model and is studying costs of spacecraft, under Contract NAS2-5022, "Study of Optimized Cost/Performance Design Methodology for Orbital Transportation Systems." North American-Rockwell has studied the costs of a spectrum of launch vehicles from performance and cost viewpoints, under Contract NAS7-368, "Influence of Structure and Material Research on Advanced Launch Systems' Weight, Performance and Cost."

1.2 ECONOMIC CONSIDERATIONS

The successful achievement of larger launch vehicles, such as Saturn IB, Saturn V, and Titan III, have not brought the expected reduction in delivery costs of payload into orbit. Earlier estimates[5] of cost/lb of payload reduction to the $100/lb range or less have not been achieved. Instead, these multi-billion dollar launch vehicle developments have produced launch vehicles of unprecedented success and reliability. The importance of

* Superscripts refer to references which are included at the end of Volume 3 of this report.

achieving safe and successful flights has dominated the development cycle; launch costs remain at the $500/lb to $1,000/lb level.

In order to achieve a balanced and vigorous future space program, it is essential that costs of launches be minimized. Many concepts[6,7,8] have been advanced. Goals now range around the $10/lb level for earth orbit—a reduction of two orders of magnitude from today's costs. Conversely, with such future vehicles, 100 times the weight of today's payloads must be launched for equivalent cost.

The primary impact of such cost reduction will be to foster and promote those space efforts such as space manufacturing, earth resources exploitation, and orbiting laboratory projects not feasible from a dollars and cents viewpoint. Commercial exploitation of space can be expected to follow reductions in launch costs reduced to a viable level for acceptance by the free enterprise system.

Thus, the keystone to the exploitation of space by mankind lies in reduced launch systems costs. This study is directed toward exploring potential cost reductions for launch vehicle structures—one of the major elements of launch vehicle costs—by evaluating some advanced technologies and concepts.

SECTION 2

STUDY APPROACH

2.1 INTRODUCTION

This study has been accomplished in two phases as indicated in the following table.

Table 2-1
Study Approach

Phase I--Technical Feasibility Analysis
a. Selection of promising investigation areas
b. Survey and evaluation of these areas
c. Selection of specific, detail technologies for Phase II Study
Phase II—Technical and Economic Feasibility Analysis
a. Detailed definition design and costing of specific technologies
b. Overdesign/Design Specification Analysis
c. Trade-off Studies and Interaction Analysis

This study has evaluated the technical and economic impact of advanced structures technologies. The results from the study entitled "Study of Structural Weight Sensitivities for Large Rocket Systems" performed by the General Electric Company under Contract NAS2-3811 formed the basis of this study. The Phase I activities spanned a 3-month period and were addressed toward the obtaining of technical and economic data including future trends and their examination to determine areas of interest and technical status in detail. Volume 3 describes the Phase I activities in detail.

Phase II activities were primarily concerned with the analysis of economic and technical feasibility of the technology areas. These materials and wall constructions were selected from the Phase I results and span the range from current to future state-of-the-art in structural designs. The methods and results of these analyses are described in this volume.

2.2 SCOPE

Materials and constructions selected for this study included eight combinations which are listed in Table 2-2. The first configuration, aluminum Integrally Stiffened Skin (ISS) wall construction with an aluminum monocoque head, is representative of current construction techniques and is utilized as a comparison baseline for the other materials and constructions.

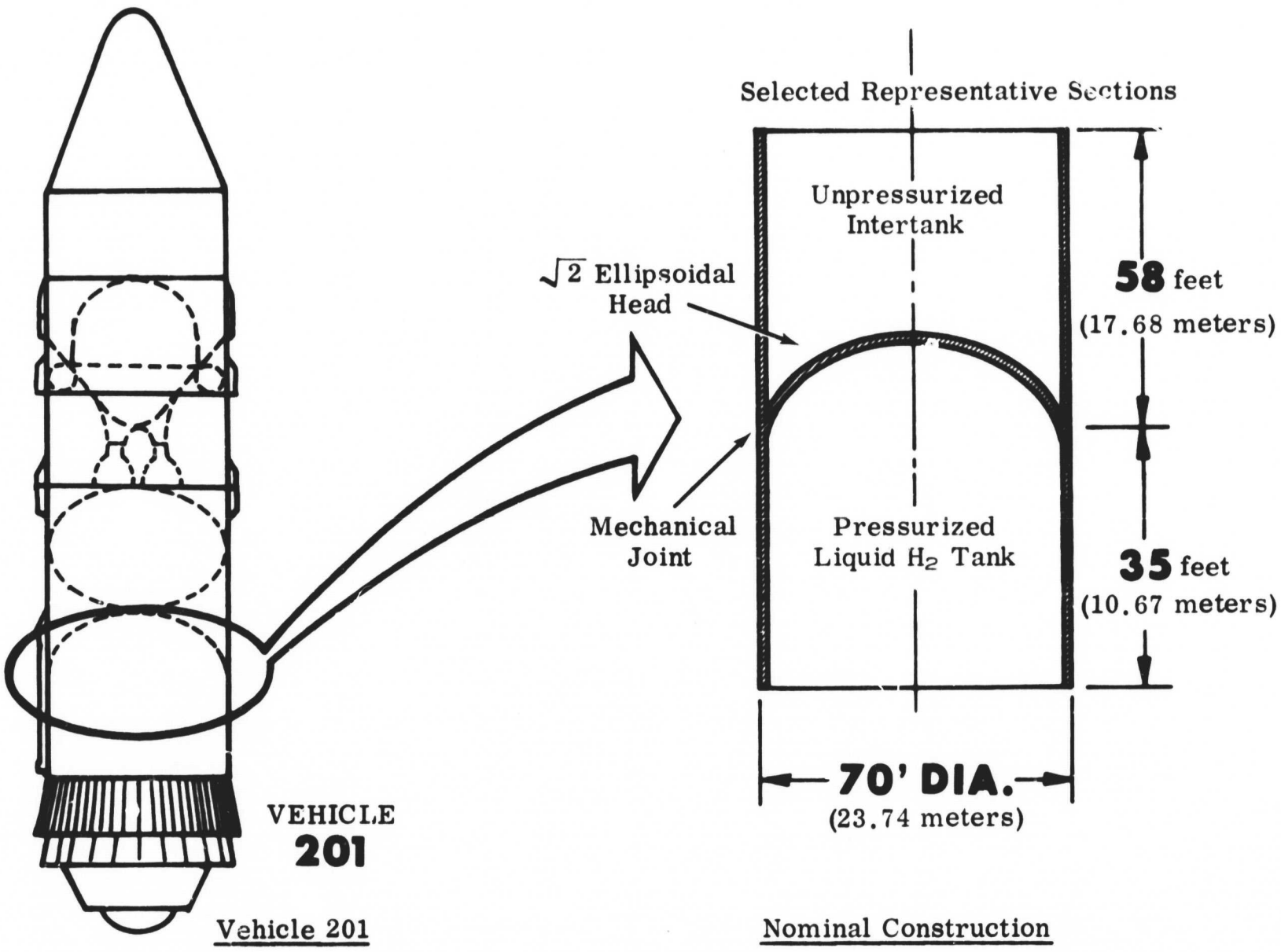
Table 2-2

Materials and Structural Configurations Selected for Detailed Study in Phase II

Unpressurized Shell		Pressurized Shell	
1.	Aluminum Integrally Stiffened Skin (Al ISS) Walls	9.	Aluminum Integrally Stiffened Skin (Al ISS) Walls Aluminum Monocoque (Al Mono) Head
2.	Aluminum Honeycomb (Al Hyc) Walls	10.	Aluminum Honeycomb (Al Hyc) Walls Aluminum Monocoque (Al Mono) Head
3.	Beryllium Honeycomb (Be Hyc) Walls with Aluminum Core	11.	Titanium Honeycomb (Ti Hyc) Walls Titanium Monocoque (Ti Mono) Head
4.	Beryllium Integrally Stiffened Skin (Be ISS) Walls		
5.	Boron Epoxy Honeycomb (B/EP Hyc)		
6.	*Carbon Epoxy Honeycomb (C/EP Hyc)		
7.	Boron/Epoxy Stiffeners on Aluminum Monocoque Shell	12.	Boron/Epoxy Stiffeners on Aluminum Monocoque Walls and Head
8.	Boron/Aluminum Composite Honeycomb (B/Al Hyc) Walls	13.	Boron/Aluminum Composite Honeycomb (B/Al Hyc) Walls Boron/Aluminum Composite (B/Al Mono) Monocoque Head

* The terms, carbon and graphite, are used interchangeably in this report to refer to the graphitic carbon fibers currently being developed under trade names such as Thornel.

The large launch vehicles, which formed the basis of the earlier study, were the same ones studied by the Martin Company in the Nova Study[6,7]. One of these vehicles, noted in Reference 8 as Vehicle 201, was selected as the baseline design vehicle for this study. Typical pressurized and unpressurized sections used as a baseline for comparative analysis are illustrated in Figure 2-1. This study was oriented toward technology investigation, rather than a vehicle design study. Accordingly, the analyses were developed as sensitivity studies about this baseline with emphasis placed on determination of sensitivity of excursion from this nominal design.



Vehicle 201

Total Structural Wt 690,822 lb
(313,357 kg)

Factors of Safety:
Yield Factor of Safety = 1.1
Ultimate Factor of Safety = 1.4

Payload to Orbit = 1,019,000 lb
(462,218 kg)

Nominal Construction

Aluminum Integrally Stiffened Skin Pressurized Cylinder	63,411 lb (28,763 kg)
Aluminum Monocoque Head	15,935 lb (7,228 kg)
Aluminum Integrally Stiffened Skin Unpressurized Cylinder	156,026 lb (70,773 kg)
Total	235,372 lb (106,765 kg)

Figure 2-1. Representative Sections Selected For Study

The study of technological feasibility and cost was limited to the areas illustrated on Figure 2-2, i.e., materials, fabrication, inspection, and structural test. It is recognized that there are numerous other areas such as illustrated in Figure 2-2 which influence costs, but these four specific areas are the primary parameters having first-order effects on the various structural technologies.

To facilitate comparative costing of different structural technologies, emphasis was placed on the determination of the recurring cost elements of materials, fabrication, inspection, and test. Non-recurring costs, such as tooling, fixtures, machines, facilities, and other one-time cost elements were noted as initial investments, but these were not evaluated in this study.

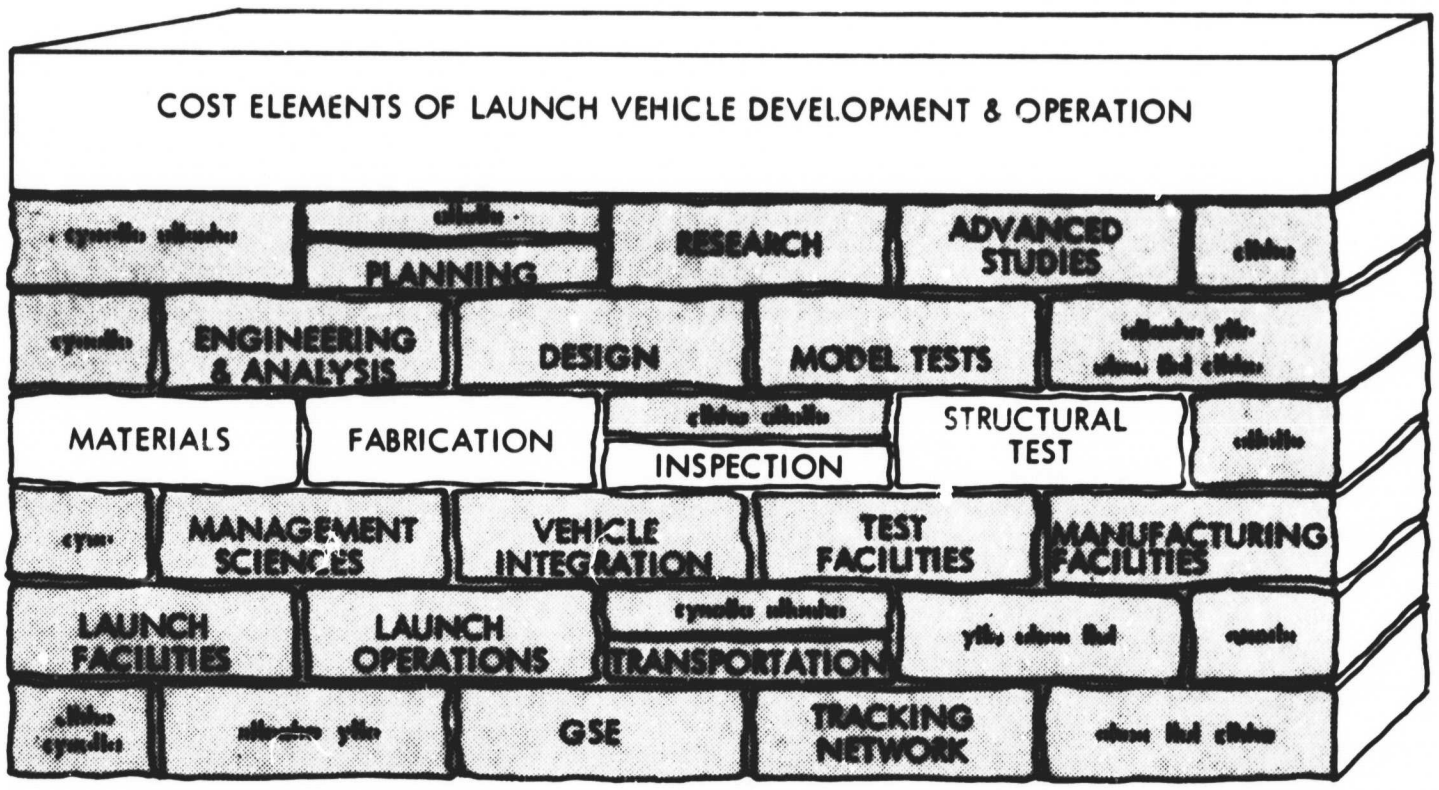
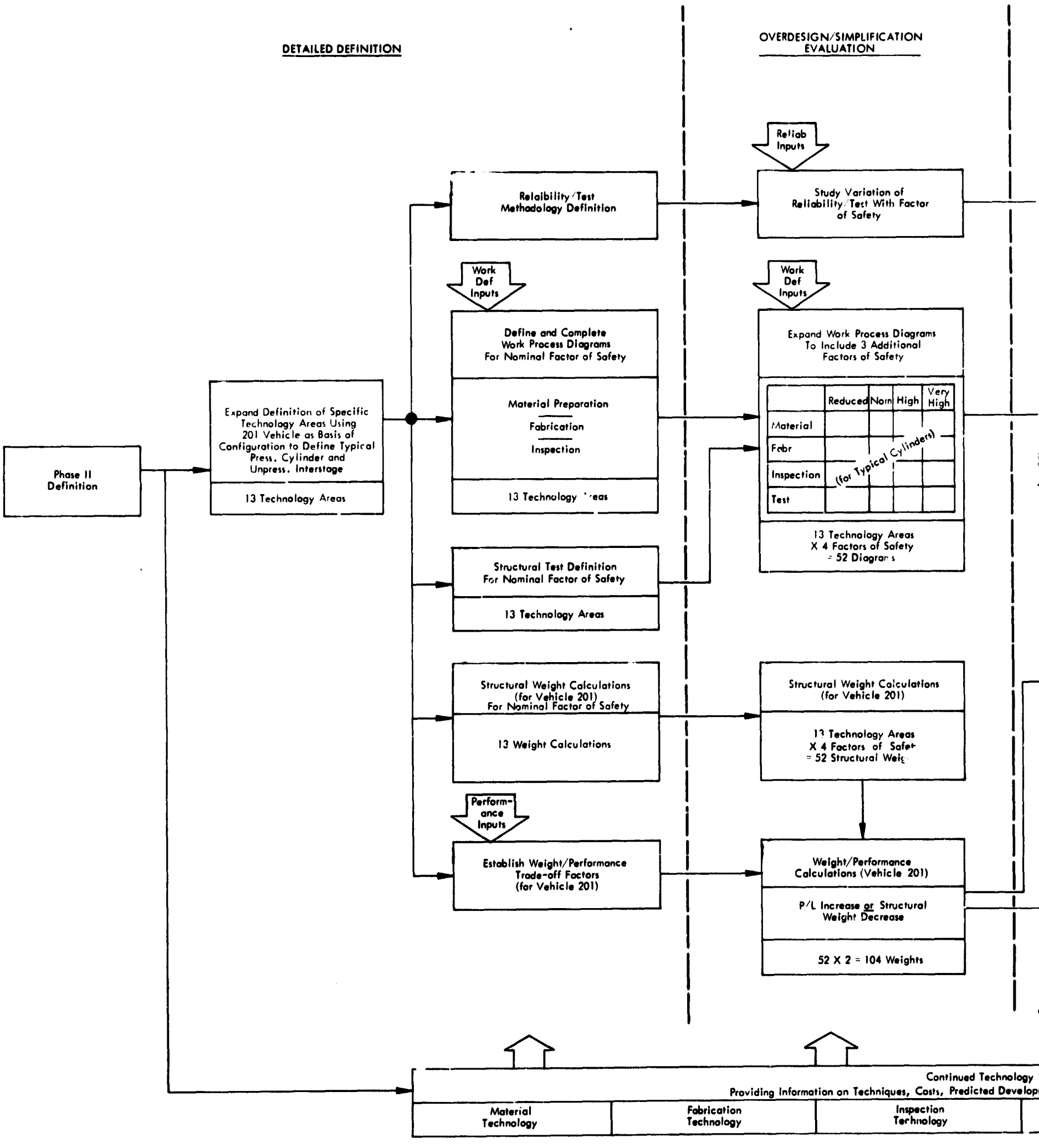


Figure 2-2. Elements—Recurring Costs

2.3 WORK ELEMENTS

The work elements for the Phase II portion of this study are shown in Figure 2-3. Materials requirements, described in general in Volume 3, were analyzed for each of the above constructions, and unique differences from general practice were noted as part of the manufacturing flow diagrams for the components. The manufacturing process diagram focused primarily on the fabrication and inspection to determine specific requirements for individual component/technology. Specific technology requirements were identified as part of this analysis.



FOLDOUT FRAME 1

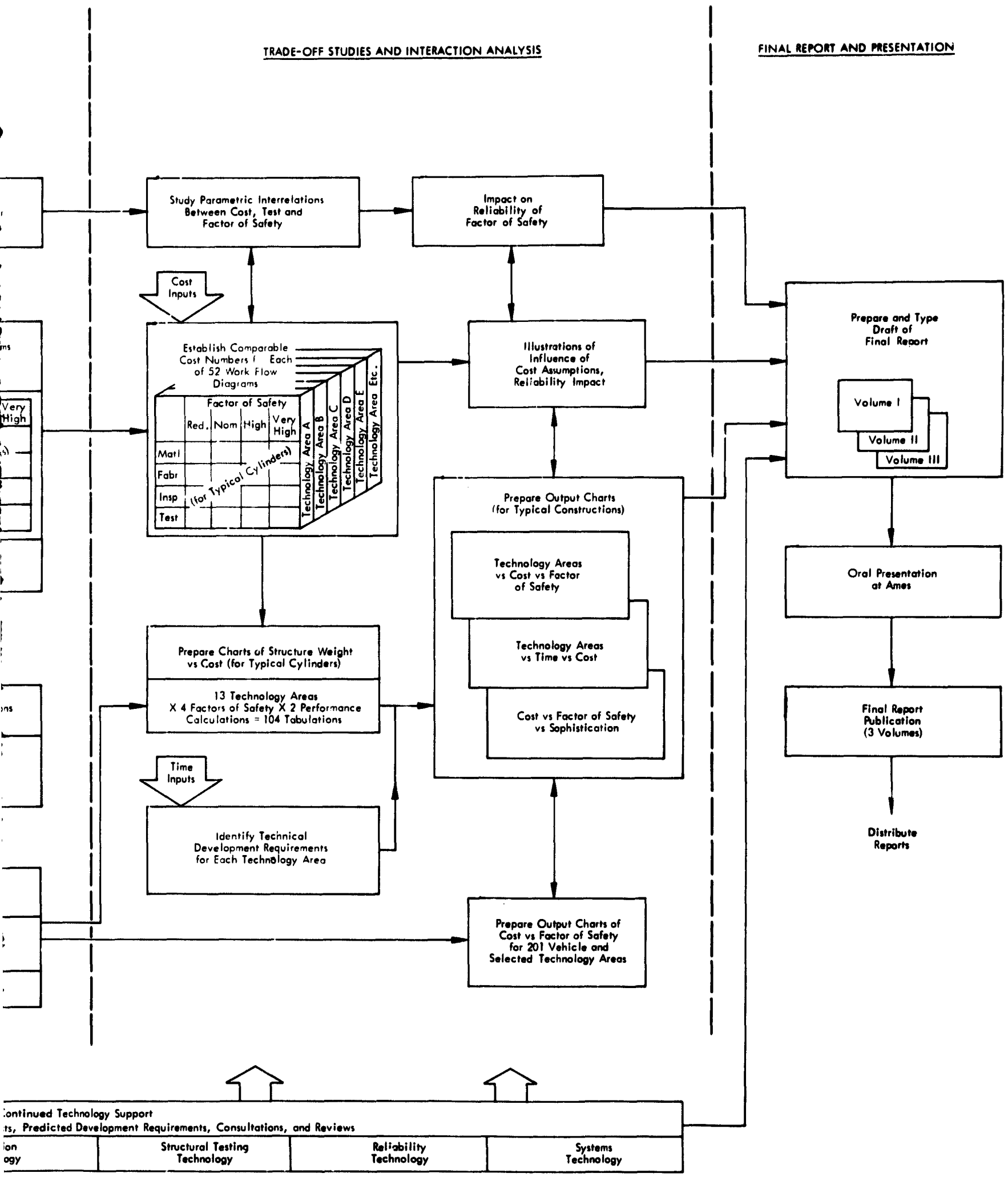


Figure 2-3. Phase II Work Flow

FOLDOUT FRAME 2

Test requirements, related primarily to quality control for these large structures, were investigated briefly, and specific requirements were noted for the typical structures selected.

Structural weights were determined for the optimized configuration during the calculation of the specific design configurations for each material/technology. Appropriate analytical methods were employed for determining specific configurations and weights for isotropic and anisotropic materials as described in References 1 and 2. For the isotropic materials, such as metals, the dimensions and weights are determined by a Structural Weight Optimization Computer Program (SWOP), as discussed in Section 4-2. Also, a netting analysis was used as described in Section 4-2 for anisotropic materials. The weights were calculated for each particular orientation and thickness of fibrous layers.

The cost and technical feasibility analyses were performed by initially evaluating, in detail, the constituent processes and materials required to produce a cylinder of the design used in the 201 vehicle. Then, changes in cost and processes for alternate materials and design philosophy were evaluated as sensitivity factors which identify variations in cost for changing to advanced materials and methods from conventional construction. Potential methods for reducing costs such as design simplification and overdesign were evaluated, as well as impact of quality and reliability factors.

Recurring costs for manufacturing were computed for each material and design criteria; however, for the structural test, the recurring costs were assumed to be independent of materials and a function only of design criteria. That is, acceptance tests such as pressure and leakage tests will be performed in an equivalent manner, regardless of materials, although a certain portion of the processes such as referee fluid may be altered. Such costs are assumed to be independent of materials.

Costs were not determined for those elements of the structure which were not primary load carrying members. Thus, the costs determined in this study do not reflect the costs of items such as piping, wiring harnesses, insulation, paint, slosh baffles, external attachments, access doors, etc. The costs studied here for the technologies have all been computed using common ground rules; therefore, they are valid for comparison between the various technologies.

The impact of these materials and structural arrangements as illustrated in Table 2-3 on costs were determined. Each of these variables is, in turn, divided into a number

of independent variables. Combinations of the variables resulted in literally thousands of structural design and cost calculations which were made for the determination of the economic merit of the various structural technologies. To facilitate the handling and assessment of data, a small "time-sharing" desk-side computer system was used to store and display computed results.

Table 2-3

Study Variables

Study Variables	No. of Variations Studied
STRUCTURAL TECHNOLOGIES a. Metals 1. Aluminum 2. Beryllium 3. Titanium b. Composites 1. Boron/Epoxy 2. Carbon/Epoxy 3. Boron/Aluminum 4. Unidirectional Stiff. on Aluminum c. Wall Configuration 1. Integrally Stiffened Skin 2. Honeycomb	8
TYPE OF STRUCTURAL SECTION STUDIED a. Unpressurized Cylinder b. Pressurized Cylinder 1. Cylinder Walls } Press. 2. Head c. 201 Vehicle (Total)	3
RECURRING COSTS a. Material b. Fabrication } Manufacturing c. Inspection d. Test	4
OVERDESIGN/DESIGN SIMPLIFICATION a. Factor of Safety/Factor of Safety (Nominal) 1. 0.7 2. 1.0 3. 1.4 4. 2.0	4
PERFORMANCE CRITERIA a. Constant Vehicle Configuration, Variable Payload b. Constant Vehicle Payload	2
QUALITY CONTROL VARIATIONS a. Fixed Quality Control (unchanging with factor of safety) b. Fixed Reliability (Quality Control relaxed as factor of safety is increased, but without degrading reliability	2

As noted in Table 2-3, there were eight combinations of materials and wall configurations which were considered in typical pressurized and unpressurized sections (as well as the total vehicle for some cases). For each of these arrangements, calculations were made for recurring costs for materials, fabrication, inspection, and test for each of the four indicated factors of safety. These combinations were also subjected to variations of quality control factors and performance criteria.

Study results were compiled, summarized, and cross-plotted. They are presented in Section 3 of this report. The influence of study assumptions were examined as to their influence on the results. Trade-off studies to evaluate cross-relationships between variables, such as weight and cost, to determine breakeven points were made. Conclusions and recommendations from this study are presented in Section 3.

SECTION 3

RESULTS AND CONCLUSIONS

3.1 INTRODUCTION

Results of this study determining the impact of various factors and technologies on the cost and weight of launch vehicles structures are presented in this section. Study conclusions drawn from the results are then presented. Areas for future research and development are identified, and potential application of advanced technologies are recommended.

3.2 TECHNOLOGY IMPACT

Of primary importance to this study was the identification of those technologies and areas which result in the optimum reduction in vehicle weight and cost. The following paragraphs summarize the various factors within the technologies considered and the impact on vehicle cost and weight.

3.2.1 ADVANCED MATERIALS

Advanced materials offer a great potential for reduction in large launch vehicle weights but usually at high cost. In this study, analytical evaluations of the technological feasibility/cost relationships have been completed using the existing structural technology as typified by Aluminum Integrally Stiffened Skin (ALISS).

The high modulus materials such as boron, carbon, or beryllium offer the greatest weight saving possibilities. All advanced material technologies studied yielded some weight savings. Costs of the various alternatives vary considerably with carbon/epoxy honeycomb showing the lowest cost among the low weight constructions. These high modulus composites, such as boron/epoxy, produce the lowest weights (less than 20 percent of the nominal design), but at costs slightly higher than aluminum. The selection of the best materials will be a function of cost tr de-off between factors involving launch vehicle, payload weight, and cost.

3.2.2 IMPROVED TYPES OF CONSTRUCTION

In this study, honeycomb was used as representative of good advanced construction practices. Experience with honeycomb does show excellent performance, with all materials considered. Its use should be actively pursued for future use in launch vehicle structures.

Aluminum honeycomb construction, while in common use for many years, is considered here in the category of advanced materials, principally because continued development is required before confidence can be gained in its use as primary structure. Aluminum honeycomb was found to be the most suitable material for construction of "new" vehicles in terms of optimized cost-weight considerations. Aluminum honeycomb construction was noted to have the lowest cost of all constructions considered.

Honeycomb construction, Figure 3-1, was consistently superior in performance to other types of wall construction considered both for reduced cost and best overall performance. Other constructions, such as integrally stiffened skin, Figure 3-2, resulted in lower costs but in higher weights than the honeycomb construction.

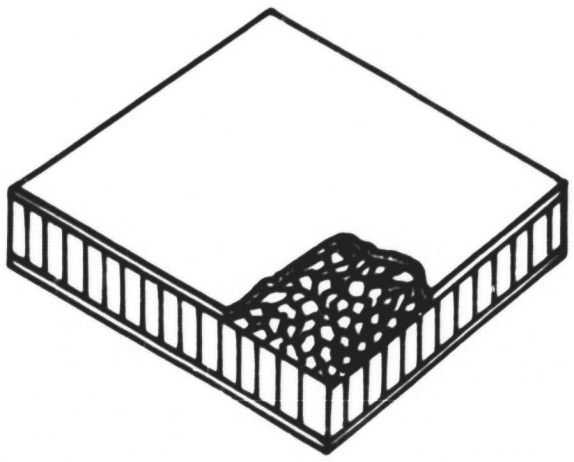


Figure 3-1. Typical Honeycomb Section

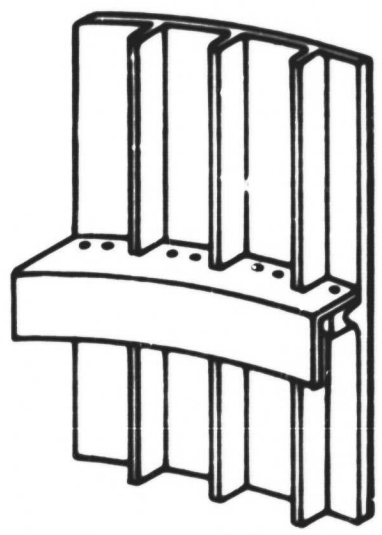


Figure 3-2. Typical Integrally Stiffened Skin Section With Ring Frame Section

3.2.3 IMPROVED MANUFACTURING, QUALITY CONTROL, AND TEST PROCESSES

In the manufacturing and quality control areas, methods of achieving significant reductions of weight or cost could not be identified for fixed design criteria. Rather, manufacturing and quality control processes in use today and those projected to the 1975 time period appear reasonably effective in terms of cost reduction, efficiency, and performance. Some reductions in test costs appear to be possible as additional experience is gained in the planning and execution of test programs of large vehicles.

3.2.4 OVERDESIGN/DESIGN SIMPLIFICATION

Increasing design criteria to facilitate overdesign ruggedness coupled with design simplification produced significant reductions in cost. Weight of structure, however, increases almost linearly as factor of safety is increased, as well as in proportion to design simplification.

For conventional materials and construction, the largest elements of cost are those other than material costs. Cost savings can be brought about by simplification of the test procedures, component handling, design simplification, and reduction of test and inspection requirements. Cost is also reduced where manufacturing and quality control processes are also reduced and simplified. These reductions can more than offset increased material costs. Aluminum honeycomb was an exception, and its costs were insensitive to structural safety factors over the range considered.

These effects suggest that approaches incorporating increased structural factor of safety and design simplification are beneficial for future launch vehicles where advanced materials are used in strategic locations. They have the potential of producing lighter, stronger, and less costly vehicles.

3.2.5 TIME PERIOD

The time period used in establishing cost of materials is 1975. Variations in material costs are shown in Figure 3-8 of Volume 3. Little variation in the recurring costs of the structural technologies is anticipated for the baseline time period (1975) with the exception of the advanced materials where an order of magnitude decrease in costs is expected in the 1970 decade.

3.2.6 PRODUCTION RATE

The variations in recurring costs with number of vehicles produced is primarily a function of recurring investment and secondarily for learning curves for cost improvements. Since the primary objective of this study did not include the evaluation of non-recurring costs, the effect of number of vehicles on cost is limited to recurring costs which do not vary greatly for the limited production expected for these large (million-lbs-to-orbit) vehicles.

3.3 COMPARATIVE WEIGHTS AND COSTS FOR MANUFACTURING OF REPRESENTATIVE SECTIONS

Table 3-1 presents an overall comparison of the weight and manufacturing cost of representative pressurized and unpressurized launch vehicle structural components for the materials listed. The comparisons in this table are separately made for pressurized or unpressurized sections using equivalently designed sections of Aluminum Integrally Stiffened Skin (ALISS). For example, if carbon/epoxy honeycomb was used for the unpressurized vehicle sections instead of aluminum integrally stiffened skin, the result is a reduction in weight of the unpressurized vehicle sections by 81 percent but at a cost increase of 8 percent. Similarly, if aluminum honeycomb is substituted for the pressurized and unpressurized sections of the aluminum integrally stiffened skin, a vehicle structural weight savings of 45 percent and a cost reduction of 29 percent result. The table points out the highly favorable results achieved with aluminum honeycomb, carbon/epoxy and boron/epoxy. Excellent weight savings can also be achieved with beryllium, either honeycomb or sheet stringer, but a high cost penalty was computed.

Table 3-1 portrays the results of calculations based on a fixed vehicle configuration. The qualitative results when payload is fixed are similar, and they are shown in Table 3-2. The fixed vehicle configuration was picked for the detailed study in the remainder of the study.

3.4 SUMMARY OF RESULTS FOR REPRESENTATIVE SECTIONS

The results when combinations of materials are used for the pressurized and unpressurized sections of a large launch vehicle are shown in Figure 3-3. The results for nominal design, as well as the impact of overdesign/design simplification, are shown. A tabulation of these results is shown in Table 3-3. Summarized are the structure weights and costs for the eight selected materials and for four values of relative design factor of safety. The relative factor of safety (FS) is the ratio of actual factor of safety to nominal factor of safety. Thus, when relative FS is multiplied by the nominal design factor of safety, the result is the actual factor of safety. Four values of related FS are used: 0.7, 1.0, 1.4, and 2.0. Since ultimate factors of safety (1.4) dominate the design selection process for most of the materials studied, these relative FS values correspond to ultimate (actual) factors of safety of 0.98, 1.4, 1.96, and 2.8, respectively.

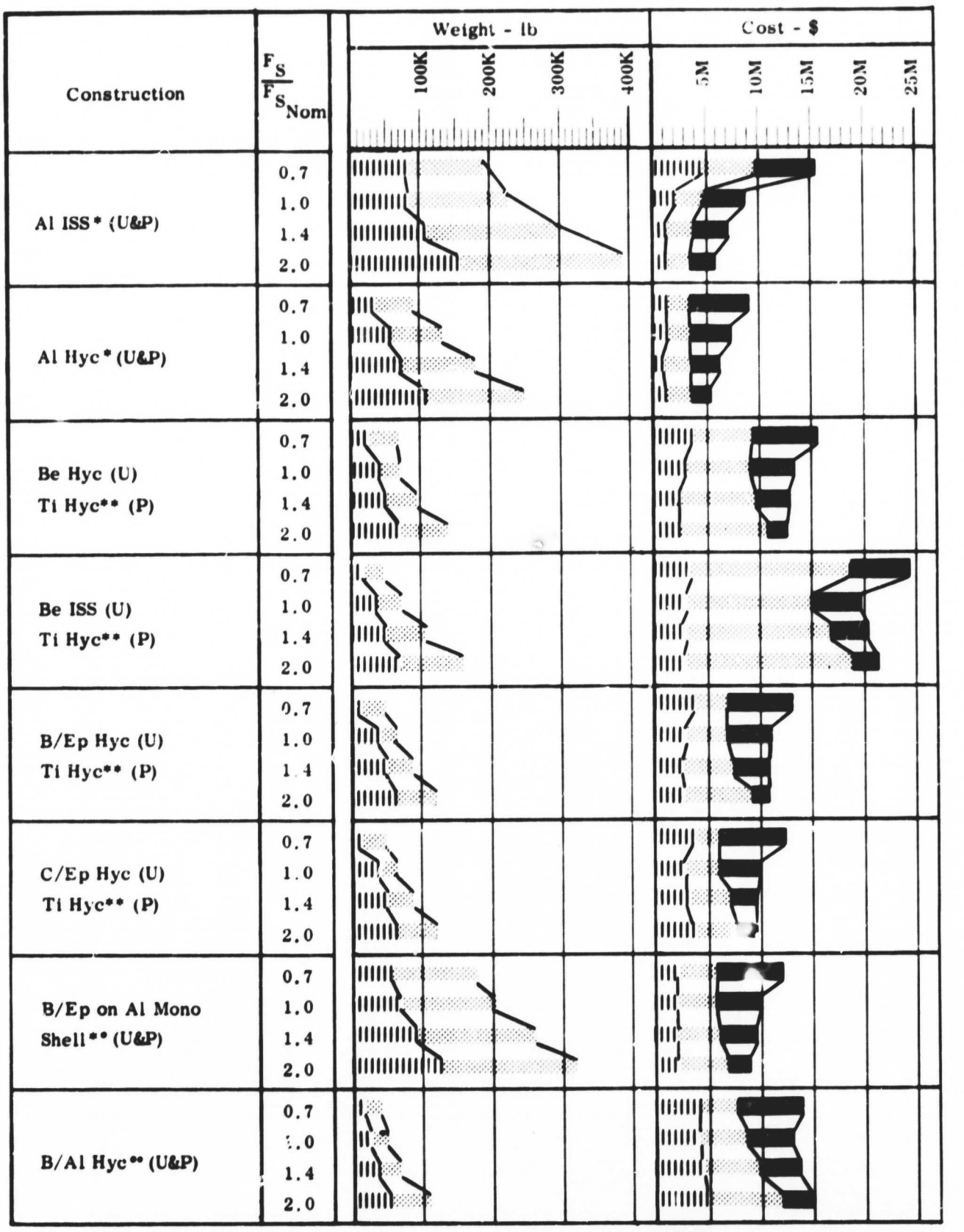
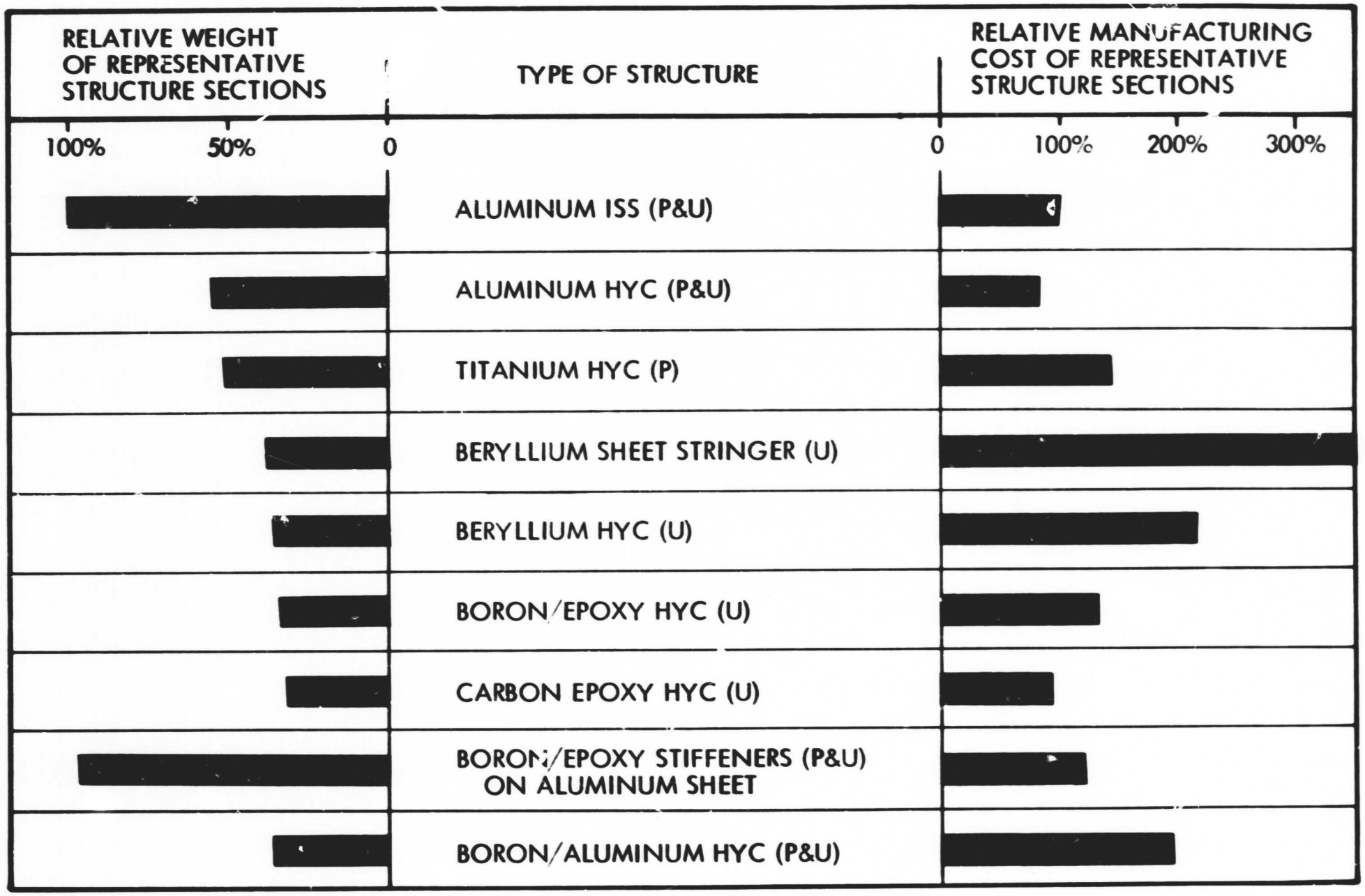


Figure 3-3. Structural Weights and Costs for Various Factors of Safety

Table 3-1

Overall Comparative Results for Representative Structural Section Weights and Manufacturing Costs



P - PRESSURIZED SECTIONS
U - UNPRESSURIZED SECTIONS

Table 3-2

Comparison Between Fixed Vehicle and Fixed Payload Calculations of Relative Structure Weights and Costs for Representative Sections

Relative Weights of Representative Structure (Percent)		Type of Structure (Nominal Case)	Relative Costs of Representative Structure (Percent)	
Fixed Vehicle	Fixed Payload		Fixed Vehicle	Fixed Payload
100	100	Aluminum ISS (P&U)	100	100
55	50	Aluminum Hyc (P&U)	71	65
51	46	Titanium Hyc (P)	143	128
26	23	Beryllium Sheet Stringer (U)	507	442
24	21	Beryllium Hyc (U)	236	204
20	17	Boron/Epoxy Hyc (U)	140	120
19	1[illegible]	Carbon/Epoxy Hyc (U)	108	92
90	88	Boron/Epoxy Stiffeners on Aluminum Shell (P&U)	126	123
30	21	Boron/Aluminum Hyc (P&U)	182	156

These results were calculated assuming that the maximum advantage was taken of increased safety factor to reduce costs. This assumed that quality control and costs were reduced to the maximum extent without degrading reliability. Results for other philosophies of varying quality control with factor of safety are discussed in Section 4.6.

The manufacturing costs, reported herein, include the recurring costs for all material, fabrication, and inspection required for manufacturing the selected sections of the 201 launch vehicle. Such costs do not include recurring costs of attachments, "Y" rings, insulation, wiring, piping, paint, or other external attachments which are considered to be costs independent of the material and wall configuration selected for the primary structure. Also, the costs herein do not include non-recurring costs such as fixtures, holding devices, clamps, machines, tooling, or other non-expendable equipment or facilities. Test costs are computed and shown as a part of the total structural costs.

The weights as shown in Figure 3-4 vary almost linearly with factor of safety as was expected for efficient structures, while the costs-factor of safety curves vary in different patterns with material choice (Figure 3-5). The constructions with inexpensive materials, such as aluminum, showed marked decrease with increased safety factor. Other construction, such as boron/epoxy, carbon/epoxy, and beryllium honeycomb, shows a very slight decrease cost with factor of safety. The other constructions show minimum cost near the nominal factor of safety.

The results show that for low-cost materials, the manufacturing and testing parameters dominate cost, whereas for high-cost materials, the exchange or trade-off in weight savings and factor of safety is about even. As expected for the very high cost materials, its cost dominates the cost of the component. Thus, in general, reduced costs appear obtainable at higher safety factor than those in use today.

The curves of Figure 3-6 can be used to compare constructions on an equal performance basis. On this plot of cost versus weight, a vertical line for a fixed weight is a valid comparison at constant performance between materials. Aluminum honeycomb is superior to other constructions down to weights near 125,000 pounds. Below these weights, carbon/epoxy and boron/epoxy are preferred. Thus, if a significant weight reduction is indicated, one of these composites appears to be the most attractive.

Table 3-3

Weights, Manufacturing Costs and Test Costs for
for Representative Structures, Fixed Vehicle Config

Category			$FS/FS_{Nom} = 0.7$							
No.	Unpress (U)	Press (P)	Weight - lb			Manufacturing Cost - $			Test Cost $	Total Cost $
			U	P	T	U	P	T		
1	Al ISS	Al ISS	115,361 (74%)	70,908 (89%)	186,269 (79%)	5,318,000 (209%)	4,155,370 (196%)	9,473,370 (203%)	6,400,000 (145%)	15,873,3 (175%)
2	Al Hyc	Al Hyc	53,173	39,674	92,847	1,631,940	1,931,600	3,563,540	6,400,000	9,963,
3	Be Hyc	Ti Hyc	27,251	29,812	57,063	5,946,310	3,656,590	9,602,900	6,400,000	16,002,
4	Be SS	Ti Hyc	34,416	29,812	64,228	14,673,600	3,656,590	18,330,190	6,400,000	24,730,
5	B/Ep Hyc	Ti Hyc	25,648	29,812	55,460	3,081,550	3,656,590	6,738,140	6,400,000	13,138,
6	C/Ep Hyc	Ti Hyc	24,092	29,812	53,904	2,407,440	3,656,590	6,064,030	6,400,000	12,464,
7	B/Ep Unid S on Al	B/Ep Unid S on Al	109,347	62,229	171,576	3,267,460	2,671,430	5,938,890	6,400,000	12,338,
8	B/Al Hyc	B/Al Hyc	23,223	23,031	46,254	3,828,500	4,145,716	7,374,210	6,400,000	14,374,
			$FS/FS_{Nom} = 1.4$							
1	Al ISS	Al ISS	187,918 (120%)	109,601 (138%)	297,519 (126%)	1,952,000 (77%)	1,842,300 (87%)	3,794,300 (81%)	3,600,000 (82%)	7,394, (82%)
2	Al Hyc	Al Hyc	102,400	78,354	180,754	1,525,710	1,685,150	3,210,860	3,600,000	6,810,
3	Be Hyc	Ti Hyc	51,061	54,646	105,707	6,636,410	2,837,980	9,474,390	3,600,000	13,074,
4	Be SS	Ti Hyc	54,895	54,646	109,541	13,989,900	2,837,980	16,827,880	3,600,000	20,427,
5	B/Ep Hyc	Ti Hyc	40,242	54,646	94,888	4,506,250	2,837,980	7,344,230	3,600,000	10,944,
6	C/Ep Hyc	Ti Hyc	37,479	54,646	92,125	3,432,050	2,837,980	6,270,030	3,600,000	9,870,
7	B/Ep Unid S on Al	B/Ep Unid S on Al	161,671	97,305	258,976	3,565,060	2,673,490	6,238,550	3,600,000	9,838,
8	B/Al Hyc	B/Al Hyc	38,969	44,506	83,475	4,872,090	5,062,660	9,934,750	3,600,000	13,534,

FOLDOUT FRAME /

Table 3-3

Test Costs for Various Values of FS/FS_{Nom}
Vehicle Configuration, and Constant Reliability

st st $	Total Cost $	FS/FS_{Nom} = 1.0							
		Weight - lb			Manufacturing Cost - $			Test Cost $	Total Cost $
		U	P	T	U	P	T		
,000 %)	15,873,370 (175%)	156,026 (100%)	79,346 (100%)	235,372 (100%)	2,544,900 (100%)	2,118,800 (100%)	4,663,700 (100%)	4,400,000 (100%)	9,063,000 (100%)
,000	9,963,540	73,784 (47%)	56,216 (71%)	130,000 (55%)	1,566,500 (62%)	1,750,000 (83%)	3,316,500 (71%)	4,400,000 (100%)	7,716,500 (85%)
,000	16,002,900	36,965 (24%)	40,457 (51%)	77,422 (33%)	6,011,090 (236%)	3,025,980 (143%)	9,037,070 (194%)	4,400,000 (100%)	13,437,070 (148%)
,000	24,730,190	40,825 (26%)	40,457 (51%)	81,282 (34%)	12,909,500 (507%)	3,025,980 (143%)	15,935,480 (342%)	4,400,000 (100%)	20,335,480 (225%)
,000	13,138,140	31,902 (20%)	40,457 (51%)	72,359 (31%)	3,562,140 (140%)	3,025,980 (143%)	6,588,120 (141%)	4,400,000 (100%)	10,988,120 (121%)
,000	12,464,030	29,929 (19%)	40,457 (51%)	70,386 (30%)	2,751,200 (108%)	3,025,980 (143%)	5,777,180 (124%)	4,400,000 (100%)	10,177,180 (112%)
,000	12,338,890	133,350 (85%)	78,001 (98%)	211,351 (90%)	3,300,310 (130%)	2,573,550 (121%)	5,873,860 (126%)	4,400,000 (100%)	10,273,860 (114%)
,000	14,374,210	29,971 (19%)	32,183 (41%)	62,154 (30%)	4,150,920 (163%)	4,352,520 (205%)	8,503,440 (182%)	4,400,000 (100%)	12,903,440 (143%)
		FS/FS_{Nom} = 2.0							
,000 %)	7,394,300 (82%)	235,756 (151%)	154,984 (195%)	390,740 (166%)	1,756,370 (69%)	1,765,440 (83%)	3,521,810 (75%)	2,400,000 (54%)	5,921,810 (65%)
,000	6,810,860	145,323	111,562	256,885	1,497,640	1,648,440	3,146,080	2,400,000	5,546,080
,000	13,074,390	72,205	75,930	148,135	7,724,290	2,745,160	10,467,450	2,400,000	12,860,450
,000	20,427,880	76,000	75,930	151,930	16,536,100	2,745,160	19,281,260	2,400,000	21,681,260
,000	10,944,230	52,751	75,930	128,681	5,967,690	2,745,160	8,712,850	2,400,000	11,112,850
,000	9,870,030	48,804	75,930	124,734	4,487,550	2,745,160	7,232,710	2,400,000	9,632,710
,000	9,838,550	198,374	123,675	322,049	4,088,570	2,847,560	6,936,130	2,400,000	9,336,130
,000	13,534,750	52,465	62,806	115,271	6,103,090	6,243,460	12,346,550	2,400,000	14,746,550

POOR QUALITY FRAME 2

No.	Unpress	Press
1	Al ISS	Al ISS
2	Al Hyc	Al Hyc
3	Be Hyc	Ti Hyc
4	Be SS	Ti Hyc
5	B/Ep Hyc	Ti Hyc
6	C/Ep Hyc	Ti Hyc
7	B/Ep Unid	B/Ep Unid
8	B/Al Hyc	B/Al Hyc

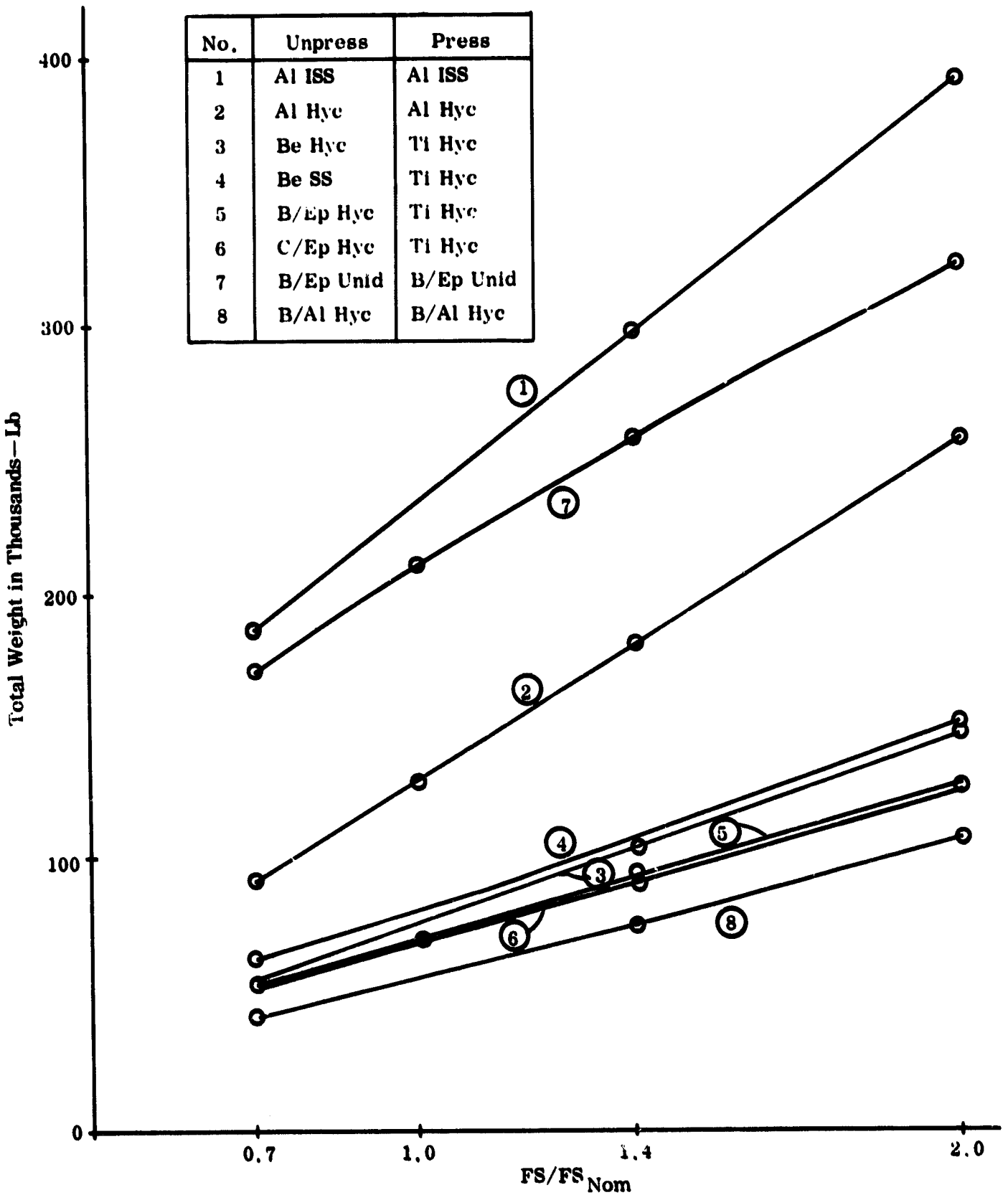
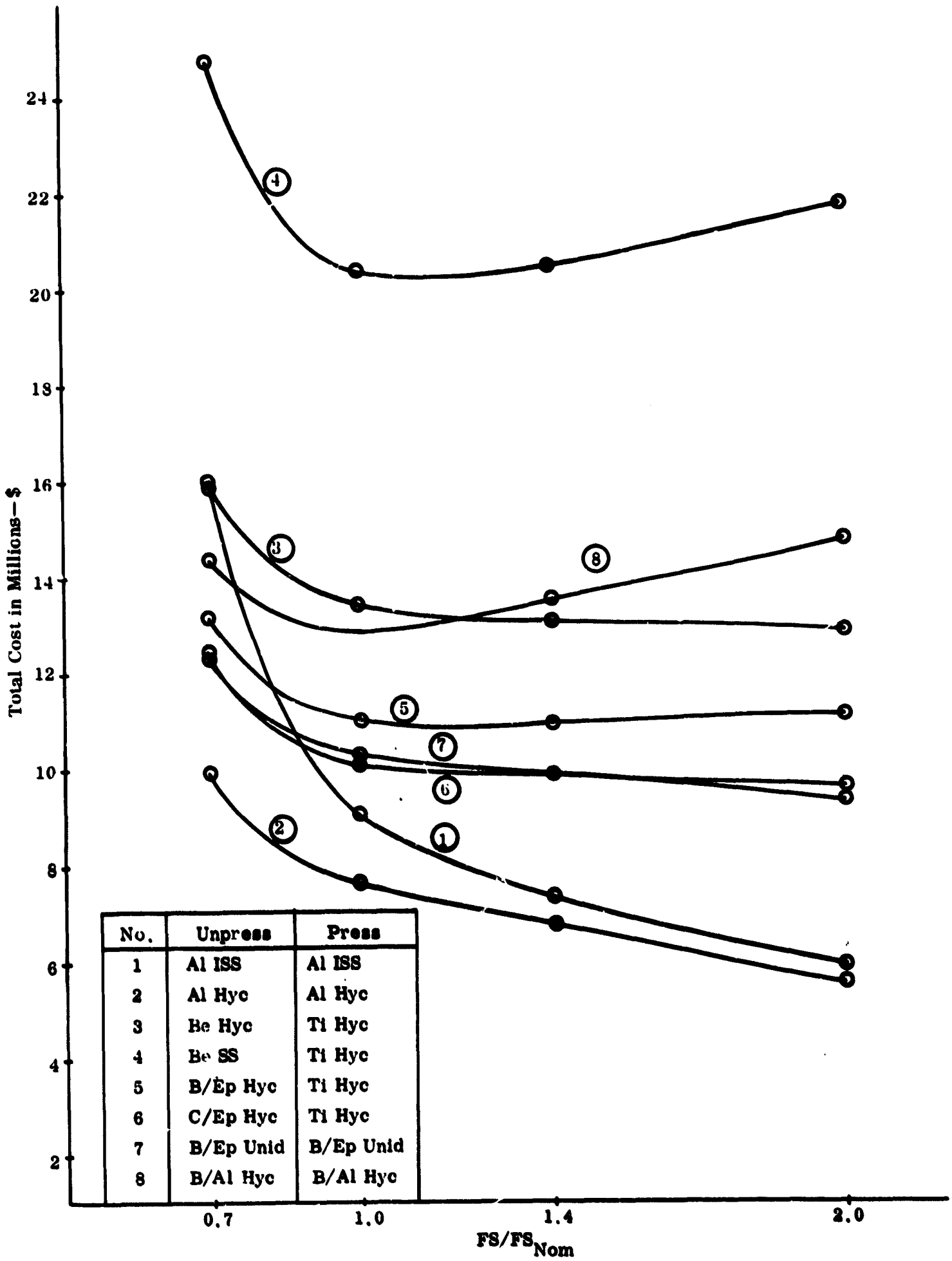
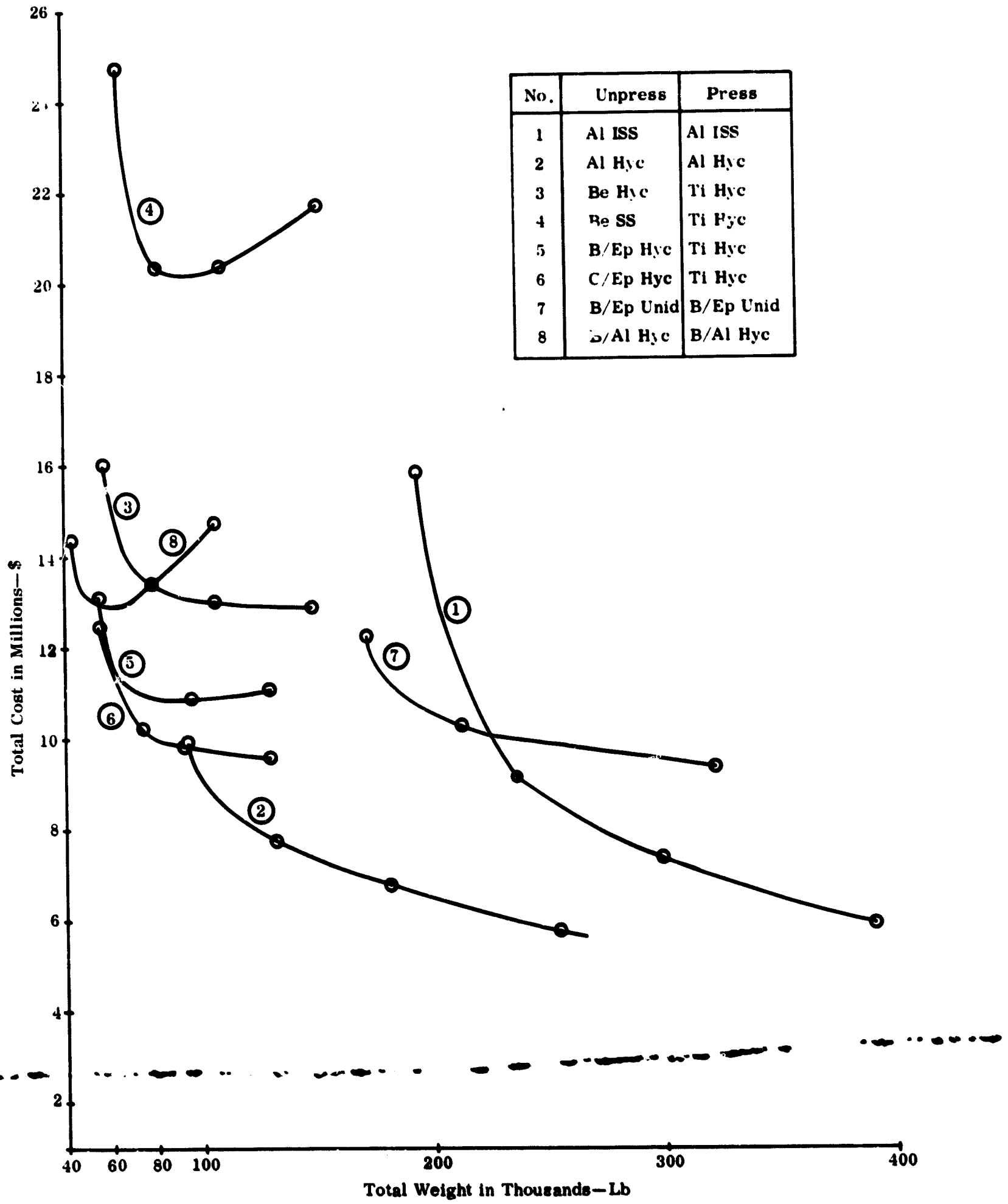


Figure 3-4. Total Weight vs FS/FS_{Nom}



No.	Unpress	Press
1	Al ISS	Al ISS
2	Al Hyc	Al Hyc
3	Be Hyc	Ti Hyc
4	Be SS	Ti Hyc
5	B/Ep Hyc	Ti Hyc
6	C/Ep Hyc	Ti Hyc
7	B/Ep Unid	B/Ep Unid
8	B/Al Hyc	B/Al Hyc

Figure 3-5. Total Cost vs FS/ FS$_{Nom}$



No.	Unpress	Press
1	Al ISS	Al ISS
2	Al Hyc	Al Hyc
3	Be Hyc	Ti Hyc
4	Be SS	Ti Hyc
5	B/Ep Hyc	Ti Hyc
6	C/Ep Hyc	Ti Hyc
7	B/Ep Unid	B/Ep Unid
8	B/Al Hyc	B/Al Hyc

Figure 3-6. Total Weight vs Total Cost for Values of FS/FS_{Nom}

The true influence of test costs on the foregoing results is somewhat questionable since the recurring costs for tests were assumed to be a function of safety factor only. The costs of manufacturing processes above, including materials, fabrication, and inspection costs but excluding test costs, produced the curves on Figures 3-7 and 3-8. These curves are a result of cross-plotting the results of weight versus safety factor and cost versus safety factor to produce cost versus weight for the unpressurized and pressurized sections. The curves for manufacturing cost alone show a different character than the equivalent curves for total cost, but the qualitative results remain the same. Aluminum honeycomb remains superior for moderate weight reductions, and the filamentary composites are superior for producing extremely lightweight structures.

Factor of safety influence on manufacturing cost is more significant for those constructions using expensive materials. For aluminum honeycomb there is little variation in manufacturing costs with safety factor. For the aluminum integrally stiffened skin construction, it is seen that there is only a slight advantage (for both pressurized and unpressurized sections) in <u>increasing</u> safety factor by 40 percent.

For the fibrous composites, the carbon/epoxy honeycomb cylinder configuration for the lowest safety factor resulted in the lowest cost. Costs were only slightly higher than that for the aluminum integral stiffened skin construction, but the weights are significantly reduced.

The cost variations between the various design points are significant, and some conclusions may be drawn from these results; however, a much more detailed investigation is required to determine costs precisely for any specific design.

3.5 SUMMARY OF RESULTS FOR OVERALL VEHICLE

These results were expanded to include the entire vehicle structure for three of the promising material combinations. These results are presented in Figure 3-9 for fixed vehicle configuration, nominal design. As with the results for typical structural sections, the aluminum honeycomb offers both a cost and weight reduction. Substitution of carbon/epoxy composite honeycomb for the unpressurized section yields substantial reductions in weight with costs little greater than the conventional aluminum structure. Detailed data supporting these results is given in Section 4.6.7 of this report.

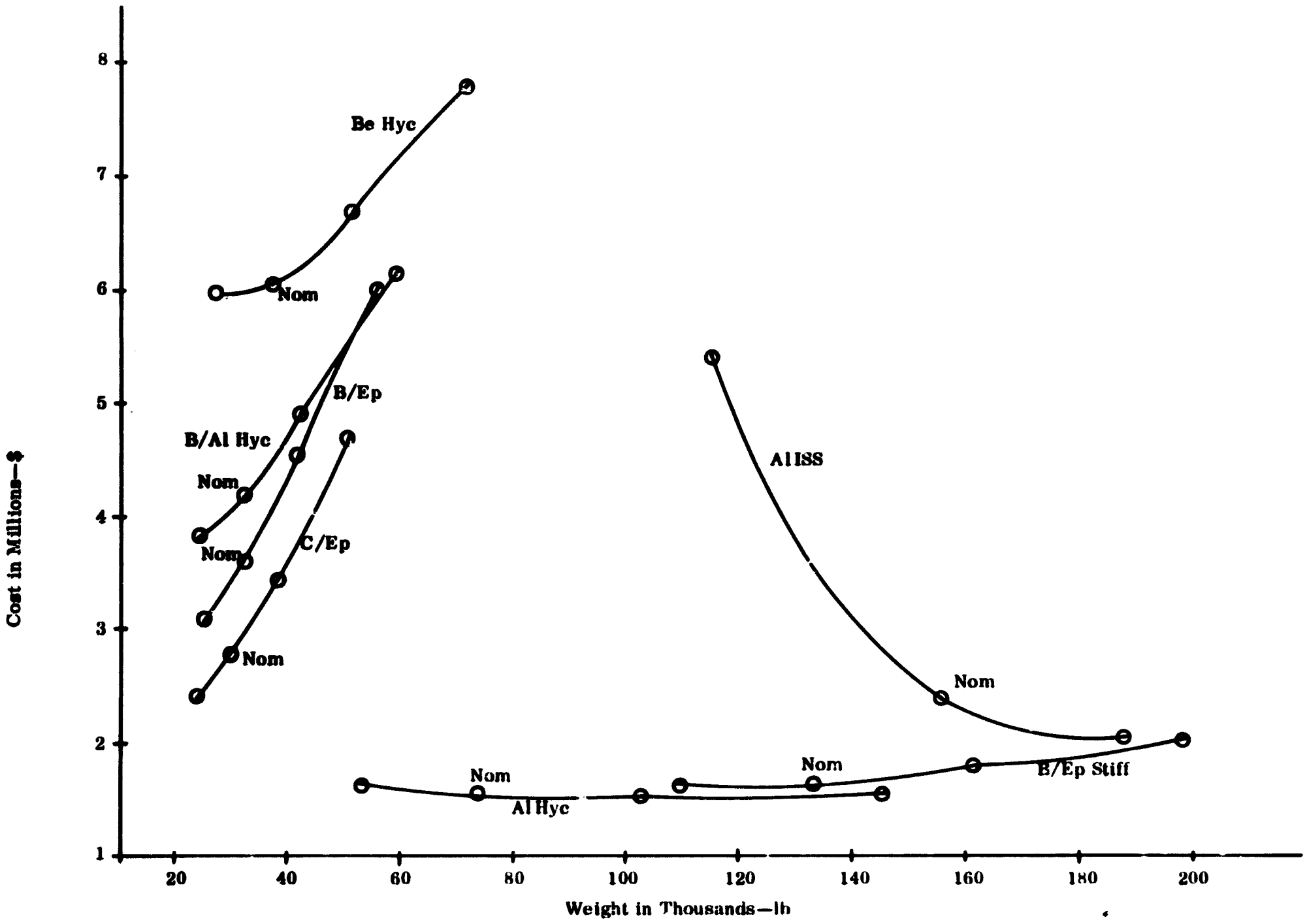


Figure 3-7. Manufacturing Unpressurized Cylinder Costs for Fixed Vehicle Configuration

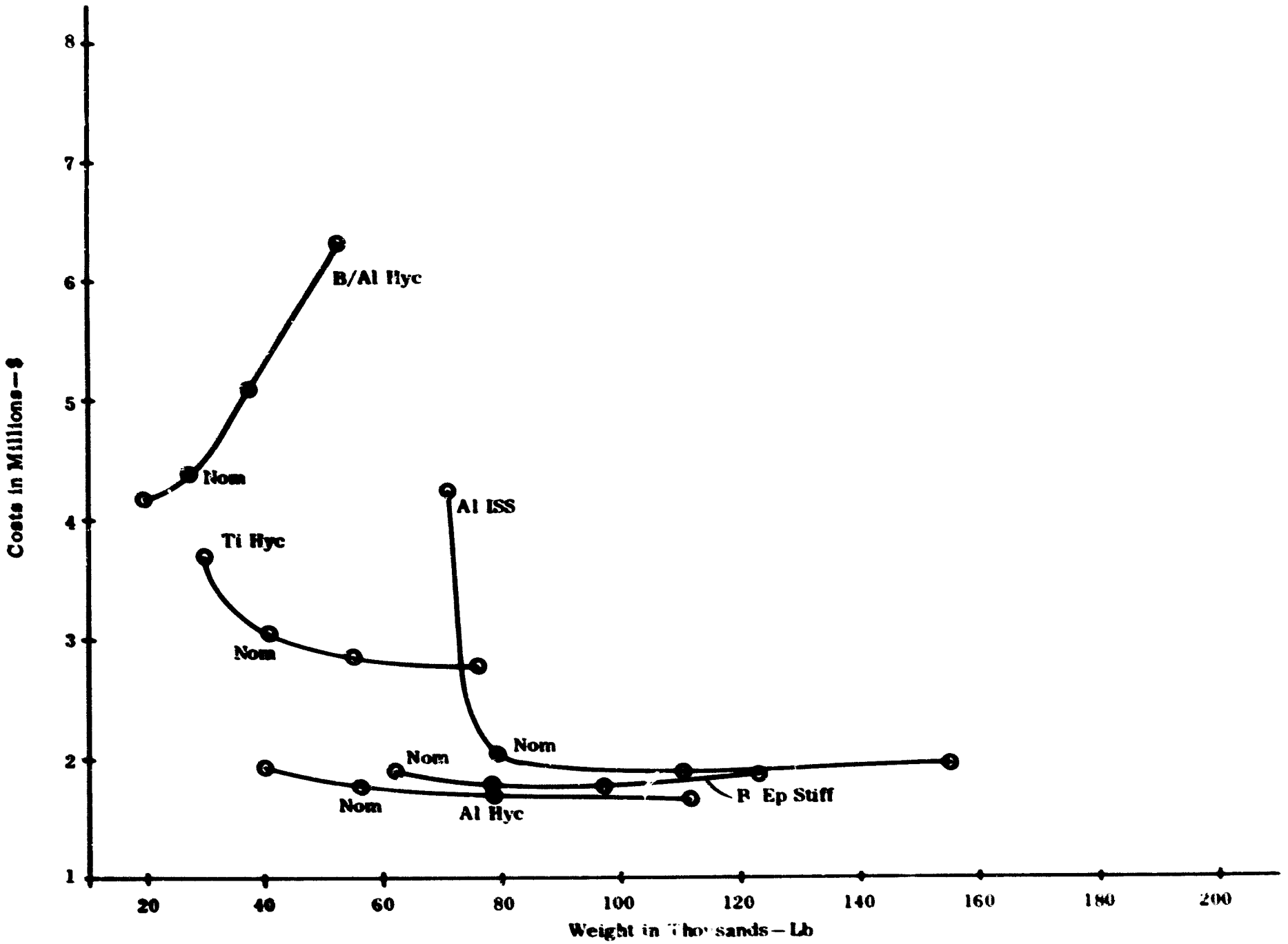


Figure 3-8. Manufacturing Pressurized Cylinder Costs for Fixed Vehicle Configuration

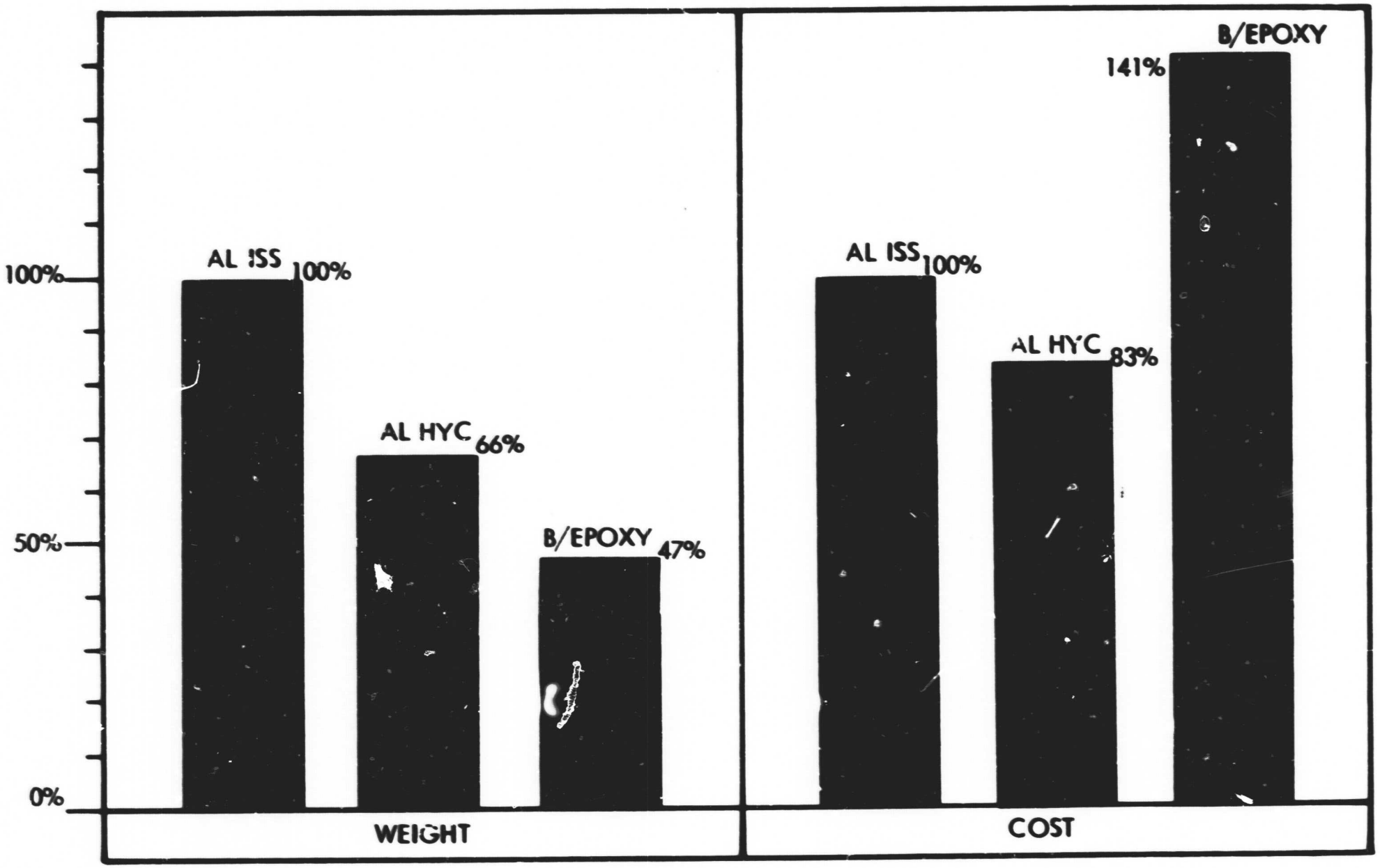


Figure 3-9. Total Vehicle Structural Weight and Cost Comparison

3.6 PAYLOAD TRADE-OFF

The cost of substitution of advanced materials results in reduced vehicle structural weights which in turn provides payload capability. This then can be traded-off against the cost of substituting advanced materials for weight reductions using the net value of the payload as the basis.

The economic value of a payload may be established in a number of ways. For payloads, such as communication satellites, the value can be established directly from increased revenues which can be realized from expanded operation. A second method used would be a comparison with alternate (non-space) methods of accomplishing the payload function. This method could be applied to payloads whose functions are communication, surveillance, or space laboratories. A third method of establishing payload value is to use the cost of putting the payload into orbit. In each of these methods, the value must take into account the cost of the payload so that the value chosen as the comparative basis is essentially a net figure. Values of $200 to $1,000 per pound are taken as representative for payloads whose purpose ranges from commercial, such as communications, to scientific.

Table 3-4 summarizes the results of the payload trade-off studies for the eight selected material combinations based on the nominal design. In this table, the cost per pound of weight saved was determined from the ratio of the change in cost of the launch vehicle to the change in launch vehicle structural weight, based on the results when the given construction is used instead of the baseline construction. The cost per pound of payload gain is also indicated. This value is computed from the launch vehicle structure cost change and the resulting payload capability gain and payload value. The breakeven point is reached when the value of the payload (dollar per pound) exceeds the cost per pound of payload capability gain.

Figure 3-10 shows a plot of payload trade-off for selected material combinations. The savings, shown in this plot, represent the difference between the payload value gained by increasing the payload capability through use of the various materials and the cost of using that material. Again, aluminum integrally stiffened skin is used as the basis for comparison. Aluminum honeycomb construction which is less expensive than aluminum integrally stiffened skin represents the most attractive selection for payload values up to approximately $150/lb. Beyond this point carbon or boron/epoxy honeycomb represents the optimum selection. For extremely high values of payload, boron aluminum construction is the most attractive.

Table 3-4

Payload Trade-off Summary for Substitution of Advanced Materials in Typical Sections

Technology	Weight (Pounds)	Cost ($)	Cost Per Pound of Weight Reduction ($/lb)	Payload Breakeven Cost Point ($/lb) (1)	Cost Savings If Payload Is Worth $1000/lb ($)	Cost Savings If Payload Is Worth $200/lb ($)
Al ISS Walls Al Mono Head	235,372	9,063,000	-	-	-	-
Al Hyc Walls Al Mono Head	130,000	7,716,500	Note 2	Note 2	32,958,100	6,668,820
Be Hyc Walls w/Al Core T Hyc Walls T Mono Head	77,422	13,437,070	27.7	92	43,010,930	5,102,930
Be ISS Walls T Hyc Walls T Mono Head	81,282	20,335,480	73.2	244	34,954,600	-2,027,080
B/Ep Hyc T Hyc Walls T Mono Head	72,359	10,988,120	11.8	40	46,978,780	7,855,660
C/Ep Hyc T Hyc Walls T Mono Head	70,386	10,177,180	6.7	22	48,381,620	8,784,980
B/Ep Stiffners on Al Mono Shell, Walls , and Head	211,351	10,273,860	50.4	168	5,995,440	230,400
B/Al Hyc Walls B/Al Mono Head	62,154	12,303,440	22.2	74	48,124,960	6,552,640

Notes: 1. Payload increase was computed as 0.3 times structural weight reduction.
2. The breakeven point for Al Hyc is not included since its cost is lower than for Al ISS.

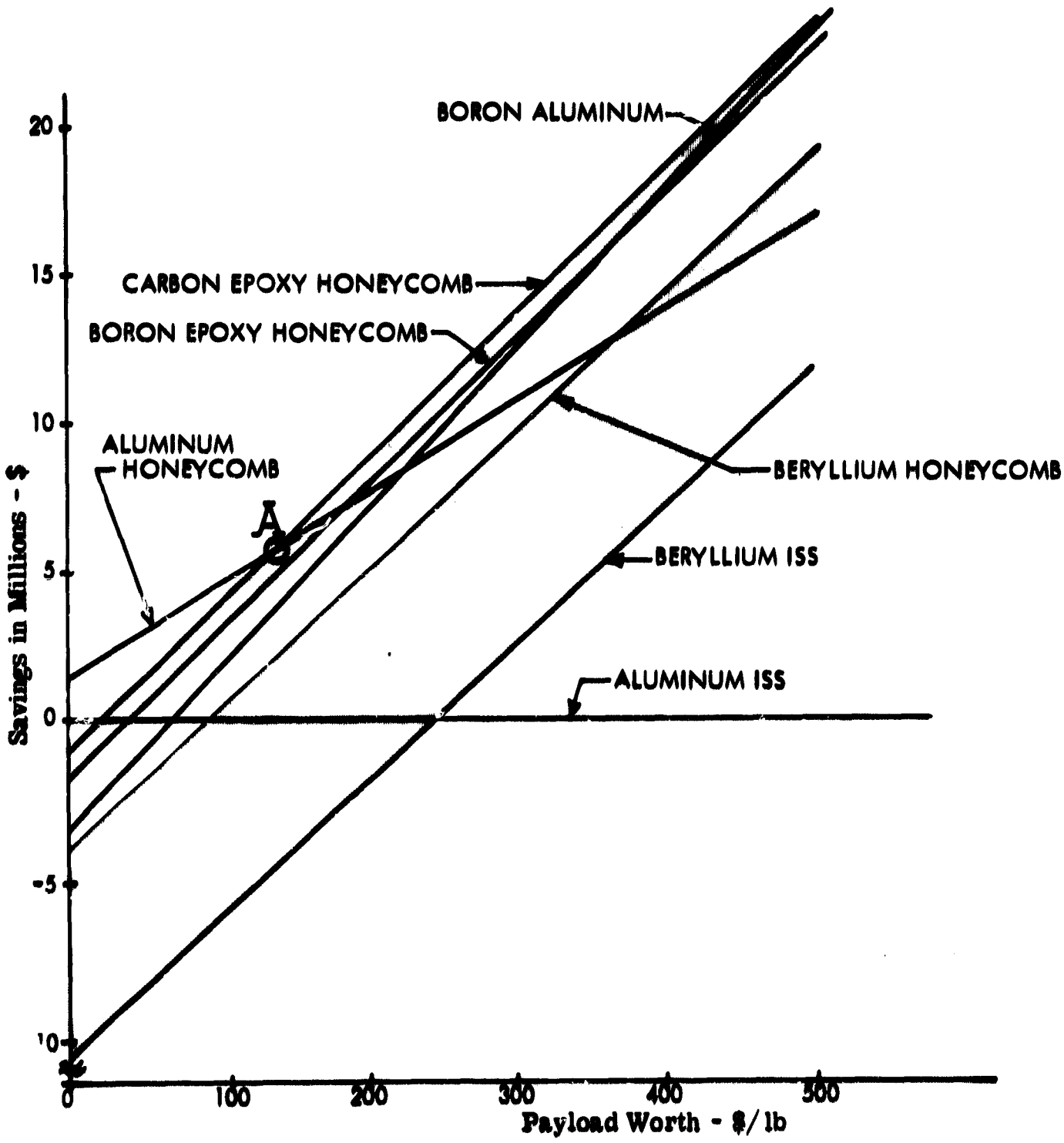


Figure 3-10. Payload Value—Cost Savings

3.7 STRUCTURAL TECHNOLOGY AREAS REQUIRING FURTHER RESEARCH AND DEVELOPMENT

3.7.1 INTRODUCTION

A number of areas have been identified for the selected technologies where current knowledge is insufficient and further research is required prior to use. Methods for solutions of these problems are advanced wherever possible.

In general, these areas requiring further research in connection with the development and design of large launch vehicles can be categorized into two areas:

a. The development problems associated with the manufacturing of large launch vehicles and the application of advanced materials to these vehicles.

b. The analysis problems associated with the design of the large launch vehicles.

These two areas are discussed separately below.

3.7.2 THE DEVELOPMENT PROBLEMS

Many technology areas considered in this study are still in the developmental stage. The basis of consideration is the improvement of the end products from both safety and economic viewpoints. Problem areas listed below have been categorized according to the materials used in the construction. The problems shown for aluminum honeycomb are generally applicable to and typical of many honeycomb structures.

a. Aluminum Honeycomb Construction

(1) The differences in the thermal expansion coefficients of aluminum skin and the adhesive resin used to fabricate the honeycomb may induce high stresses at liquid H_2 temperatures and could cause debonding or failure of the resin itself. Adhesive resins and bonding methods should be studied to develop a solution to this problem of thermal expansion mismatch. This problem is common to all bonded honeycomb construction.

(2) Optimum techniques of joining sandwich panels should be studied. For instance, bonded skins with weld lands should be compared to bonded edge attachments for butt joining. The design of joints should be analyzed for stress at the transition between honeycomb panels.

(3) The adhesive used for bonding requires improvement so that it could be cured at temperatures lower than 325°F and at atmospheric

pressure with a longer room-temperature shelf-life. Radiation curing of adhesives requires further development.

(4) Welding of 2219 aluminum with post-welding heat treatment results in low weld strength of about 40 ksi. Study of techniques to improve weld strength of this alloy and other high strength aluminum alloys is required.

(5) Development of better methods of non-destructive testing is recommended.

b. B/Al Honeycomb Construction

(1) In the creep-forming of B/Al face sheet to the specified curvature, development of better dies and other tooling are needed.

(2) More efficient non-destructive testing is required for this particular type of construction.

(3) The joining of B/Al sheets should be studied. Continuous spot welding and bonded doubler joints are the present state-of-the-art, but they are not suitable for pressure vessel applications. For pressure vessel applications, this is especially critical in joining gore sections to form bulkheads.

(4) Performance of honeycomb structures under dynamic loads, including shock loads, should be further studied.

c. B/Epoxy and Graphite/Epoxy Honeycomb Construction

(1) Development work is required for resin and adhesive formulation so that curing at temperatures lower than 325°F can be accomplished. Furthermore, room temperature shelf life should be more increased to allow more flexible manufacturing schedules.

(2) More efficient non-destructive testing techniques are needed.

(3) Design of attachments, joints, and cut-outs should be investigated. This problem should be integrated into research efforts of stress analysis and micro-mechanics of composite materials.

(4) There is a lack of comprehensive design data on advanced composite materials similar to that for metals in MIL-H-5.

(5) Development is required for mono-filament graphite fiber as opposed to the yarns and tows which are now available. This type of fiber would provide for better utilization of graphite fiber properties and simplify fabrication.

(6) Design and development is required for large filament winding machinery to wind structures of the size studied in this program.

d. Ti Honeycomb Construction

(1) The all-titanium honeycomb made by the Stressskin process of diffusion bonding should be evaluated by extensive testing before being accepted for application.

(2) Improvement in TIG (Tungsten-inert gas) welding techniques for Ti-6Al-4V ELI would allow for its application in pressurized cylinder construction with a 10 percent increase in strength and fracture toughness over Ti-Al-2.5 Sn ELI which is recommended because of its ease of welding.

(3) Titanium weldments are normally stress relieved by heat treatment between 900°F and 1200°F. Compressive residual stresses, due to forming, have been relieved by shot peening or cold rolling. However, the effect of shot peening on stress relief of weldments has not been fully investigated. Since it is not practical to subject large welded structures to heat treatment, mechanical stress relief such as shot peening would be useful if more information were available.

(4) More efficient non-destructive testing techniques are needed.

e. Be Sheet Stringer Construction

(1) A sheet rolling program is required to produce 48-inch cross-rolled sheets with more uniform properties than are presently available. This also requires development of larger billets as rolling stock.

(2) Development of new processes for winning Be from ore should be considered in order to reduce the ultimate price of sheet products.

3.7.3 ANALYSIS PROBLEMS

Research areas are identified for advanced materials and constructions so that they may be used to obtain better designs for large launch vehicles. They are:

a. A detailed stress analysis should be conducted on the honeycomb construction and its associated attachments and joints. The analysis is even more necessary if fiber-reinforced composites are used as the construction materials.

b. The study funds did not allow a complete analysis of composite stiffened metal skin structures. It did not determine optimized structure, nor did it establish the effectiveness of this kind of construction as being more attractive so far as cost is concerned. For example, the pattern of stiffening, spacing of stiffeners, and fiber-volume fractions of stiffening composites should be optimized to obtain the comparative cost. Local

buckling of stiffening stringers should be studied to determine the proper design for stiffening rings.

c. A better definition of yield criteria should be developed for fiber-reinforced composite laminates. The application of composites might then be even more attractive in large launch vehicles.

d. Based on the current yield criterion used, an optimization process should be made in studying the structural weight/strength as a function of fiber-volume fractions in honeycomb as well as in monocoque constructions.

e. In composite materials, the difference of thermal properties of the constituting fibers and matrix materials may induce thermal stresses. Certain parts of a vehicle in flight may then be subjected to high thermal stresses that can cause excessive deformation or failure. Therefore, the study of thermal stress effects in composites should be considered a significant future research area.

f. Dynamic effects are not considered in the current study of launch vehicles. The inclusion of dynamic effects may be necessary for components of the structure during certain portions of the course of flight.

g. The inclusion of viscoelastic effects on the behavior of vehicle structure may be necessary. This is justified if the structure, composed of metal, is subjected to elevated temperature; on the other hand, creep deformation of the composite structures at the bond lines due to dead weight may exceed tolerable limits while the vehicle is at rest on the launch pad. Furthermore, for composite materials, the resins exhibit strong time-dependent behavior even at room temperature.

h. Prestressed structural applications have not been given much consideration in launch vehicle design. It may be feasible to use prestressed members, metal, or composites to stiffen primary structural components.

i. In the reliability study, both the statistical distributions of the strength of the structure and of the applied load are assumed to be normal. In reality, this may not be true. An extensive survey of existing experimental data should be conducted to see whether this assumption is within allowable error. So far as strength distribution is concerned, another approach it to investigate the possibility of obtaining analytically the statistical nature of the strength of the structure as a whole in terms of the known or more easily accessible distributions of its components.

j. In the present reliability study, the element of time is not considered as a variable. If prelaunch period is long and if the condition during this

period is such that critical loading may be present, then the entire history of the launch vehicle may be long enough to consider statistically time dependent loading.

3.8 CONCLUSIONS

Areas were identified where the application of advanced technologies could yield substantial improvement toward the reduction of weight and cost in launch vehicles, but it is significant that no areas have been identified as leading to order of magnitude reduction in the cost of launch vehicles. This conclusion indicates that present technology and design are well balanced and does not afford drastic cost reductions. More important is the implication that other areas more basic such as design guidelines and specifications must be changed to obtain the desired, often talked about reduction in cost.

It was noted that the use of advanced materials does result in significant structural weight savings and consequent payload gains, which in turn has further implications for cost savings. Proper selection of the materials yielded substantial economic benefits for uses where the payload value was high.

Of the advanced materials technologies studied, aluminum honeycomb alone offers improvement over aluminum integrally stiffened skin in both weight and cost for fixed vehicle configuration and for fixed payload requirement. For fixed vehicle applications, use of carbon/epoxy or boron/epoxy offers great potential for weight reduction at a nominal increase in vehicle cost. For payload values over $150/lb, carbon/epoxy or boron/epoxy fibrous composites are superior.

One advanced material which compares poorly is beryllium. The results of its high raw material cost and fabrication complexities cannot be offset by its superior weight savings potential. Reduction of berylliun. materials costs and improved manufacturing processes are areas where future development are required before its weight saving potential can be economically exploited.

A further area studied was the potential benefits offered by overdesign or design simplification. In the case of some of the materials, total vehicle structural costs are reduced significantly with increased factor of safety. These results showed a favorable

balance between increasing material costs and decreasing fabrication, inspection, and test costs. Aluminum honeycomb, for example, shows a reduction of 15 percent when structural safety factors are doubled.

All materials studied exhibited overall structural costs which are sensitive to factor of safety. In most cases, the lowest cost occurs for safety factors higher than the nominal values currently in use.

It is concluded that any launch vehicle designed for use in the intermediate time span take advantage of the potential offered by the technologies of simplified design; the use of aluminum honeycomb results in a rugged high-safety factor launch vehicle. This vehicle could also be designed to be capable of exploiting the considerable growth potential offered by the substitution of advanced composites, such as carbon or boron/epoxy honeycomb in the unpressurized sections, as these materials are more thoroughly developed and become available.

3.9 RECOMMENDATIONS

Based on the foregoing results and conclusions, the following recommendations are made:

a. Potential areas benefiting from the use of aluminum honeycomb should be identified and explored further, required developments should be identified, and where necessary they should be carried out to allow complete freedom of use on future launch vehicle structures. Prior work[141] should form a basis for this research, and resolution of the problems encountered in that work be the topic of future continued development necessary to provide data to gain confidence and experience for using aluminum honeycomb in primary structures.

b. Fiber-glass epoxy, though not analyzed specifically in this study, should be followed since it has the potential (low material cost) of providing the same benefits as aluminum honeycomb and may provide a valuable alternate design choice.

c. Research and development of advanced composites such as carbon/epoxy and boron/epoxy should be actively pursued to produce the necessary competence and design data required so that it can be utilized on advanced launch vehicle structures. These advanced composites showed the greatest potential for reducing weight without a significant increase in cost. These materials appear particularly attractive in honeycomb construction; however, further research and development are necessary to verify buckling and thermal behavior under simulated environment.

d. Future design should include concepts of overdesign in the design trade-off studies. Increased factor of safety appears to have a significant influence on reducing costs for conventional materials. This influence may be significantly greater where other cost elements of production of launch vehicles are considered. Such considerations include engineering, design, and development all of which should show reduced costs for elevated factors of safety.

e. The numerous areas identified in Section 3.7 should be considered for future research and development. Of particular interest is improved configurations using combinations of metals and composites. Prestressing to facilitate load carrying capability is a distinct possibility.

f. The results of this study should be applied to a broader study of economics of launch vehicles to consider potential cost reduction of all aspects of the design and development cycle.

SECTION 4

ANALYSIS

4.1 GENERAL APPROACH

4.1.1 INTRODUCTION

The technology and economic analysis of large launch vehicle structures was performed by establishing a point baseline and then evaluating the advanced structures technologies against that baseline. The baseline structural components were taken as the pressurized and unpressurized sections of the million-pound payload-to-orbit vehicle (vehicle 201), as illustrated in Figure 4-1, between Stations 960 and 2073 inches. This includes the pressurized cylinder and head for a liquid H_2 tank (-420°F) and an unpressurized intertank section from Station 1380 inches to 2073 inches. The nominal construction was assumed to be 2219-T87 aluminum with integrally stiffened skin (ISS) in the cylinder walls and 2219-T87 aluminum monocoque head.

To allow for use of dissimilar materials in the pressurized and unpressurized section, a mechanically fastened joint between these sections was designed. The "Y" ring between the pressurized cylinder and this mechanical joint was constructed of the same materials as the pressurized section. The "Y" ring is required regardless of the designs, thus the cost and weight penalties for the "Y" ring were assumed to be constant and not considered further in the cost and weight analyses.

The analysis for the evaluation of technical and economic feasibility of advanced structural technologies was performed using the above sections to compare the cost and feasibility of each technology against the baseline components of aluminum ISS. The overall vehicle was then considered grossly to evaluate the overall influence of advanced technologies on a total vehicle scale.

The vehicle selected for this study is non-recoverable. Since the requirements imposed on skin temperatures and g loads on a recoverable booster are probably more severe, the results of this study do not necessarily apply to recoverable boosters.

A unique objective of this study was the broad economic study of the potential use of advanced materials so that cost saving through methods such as design simplification

VEHICLE DATA

Gross Weight at Liftoff	14,400,000 lbs	(6,531,840 Kg)
Thrust		
At Liftoff	16,000,000 lbs	(80,064,000 N)
Nominal (Vacuum)	21,651,000 lbs	(97,193,248 N)
Vehicle Reference Diameter	70 ft. (21.34 m)	
Aerodynamic Reference Area	3,848.45 sq. ft. (357.52 sq. m)	
Vehicle Length	422.5 ft. (128.78 m)	
Effective Nozzle Exit Area	262,044 sq. in. (169.02 sq. m)	
Propellant Weight Flow Rate	47,452 lb/sec (21,524 Kg/sec)	
Propellant Mixture Ratio		
N-1 (LOX/LH_2)	6.5	
N-11 (LOX/LH_2)	6.5	
Number of Engines	16/2 High Pressure	
Nominal Vehicle Structural Weight		
Second Stage Structure	123,429 lbs	(55,987 Kg)
First Stage Structure	567,393 lbs	(257,369 Kg)
Total Vehicle Structure	690,822 lbs	(313,356 Kg)
Nominal Payload	1,019,000 lbs	(462,218 Kg)

Safety Factors:

Yield Safety Factor	1.1
Ultimate Safety Factor	1.4

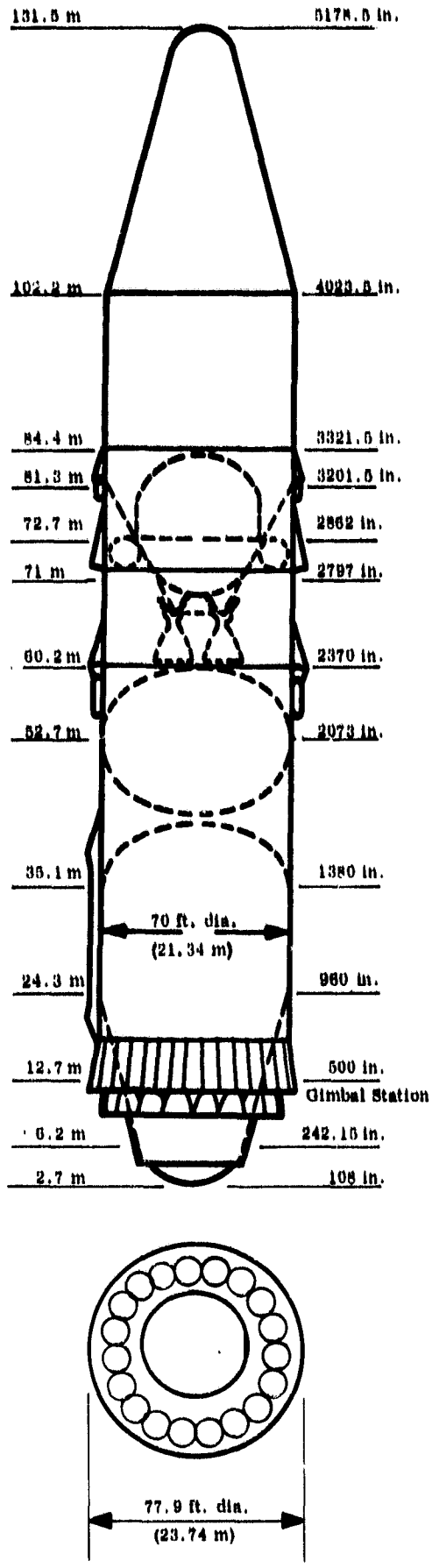


Figure 4-1. Vehicle 201 Configuration

or over design could be realized without any weight increase because of their excellent strength properties. The question was "Can advanced materials be used to reduce costs through utilization of the increased strength and low weight of such materials to permit increased factors of safety and design simplification?" Or, more simply, "Can we cut costs by using better materials to simplify design, manufacturing, and test?" In this study, the increased design strength was studied by varying factor of safety and evaluating changes in complexity and cost. Costs were determined for nominal designs and for off-nominal design points. Variations in total costs were then determined to trade-off cost savings versus weight savings. The impact of proposed changes in quality and safety factor on structural reliability was considered, and the feasibility of changes in design factors was determined.

The detailed steps in these evaluations are discussed in the following sections.

4.1.2 SELECTION OF MATERIAL TECHNOLOGIES

4.1.2.1 Summary

The advanced structural technologies selected for in depth comparison with the aluminum integrally stiffened skin include the following:

a. 2219-T87 aluminum honeycomb walls, and 2219-T87 monocoque heads.
b. Honeycomb walls of beryllium skins with aluminum core in unpressurized vehicle sections, titanium honeycomb walls in pressurized tanks, and titanium monocoque heads.
c. Beryllium stiffened skin walls in unpressurized sections with titanium in pressurized sections as in "b" above.
d. Honeycomb walls of boron/epoxy skins with aluminum core in unpressurized vehicle sections, titanium honeycomb walls in pressurized tanks, and titanium monoque heads.
e. Honeycomb walls of carbon/epoxy skins with aluminum core in unpressurized vehicle sections, titanium honeycomb walls in pressurized tanks, and titanium monocoque heads.
f. Unidirectional stiffeners of boron/epoxy on aluminum monocoque walls for both pressurized and unpressurized sections, and aluminum monocoque heads.
g. Honeycomb of boron/aluminum composites skins with aluminum core in pressurized and unpressurized walls, boron/aluminum composite monocoque heads.

Factors considered in selecting these technology areas include:

a. Technologies which were representative of near-time and future advancements which would be applicable to large launch vehicle structures.
b. Sufficient data was available to allow a meaningful analysis to be made. (Very advanced technologies which are in the experimental stage with insufficient data have not been included).

Background information and criteria used in selecting these materials are provided in the following paragraphs. Specific details on selected materials, including advantages and disadvantages of each, are contained in Appendix C.

4.1.2.2 Selection of Materials

The representative materials were selected to span a range of structures technology which extends from today's state of the art to near technology time periods and to advanced (1980's) technologies. Very advanced technologies, such as the use of whiskers, were not included because insufficient data is available to form a meaningful basis for determining economic factors and for completing a comprehensive analysis.

Materials selected for studies included both metals and composites. Advanced metals were typified by the new titanium alloys in high-strength areas and beryllium for high-modulus applications. Excellent resinous composites with filaments ranging from steel to boron are approaching state-of-the-art. Advanced filaments of beryllium and carbon appear to be the next generation of fibers for high-strength composites. Metal-matrix composites are perhaps the most spectacular of new technologies; boron filaments in aluminum or titanium metal matrices appear to have great potential. Carbon in aluminum composites have been disappointing to date and were not included in this study.

4.1.2.3 The Major Problems To Be Overcome

Structural requirements indicate the need for tailor-made materials to fit local load and environmental requirements. Pressurized tanks must retain corrosive liquids without leakage, usually at temperatures near absolute zero. Severe environmental demands of shock, vibration, and acoustic noise must be satisfied. Materials must not only meet the demands of strength and buckling resistance, but must also have sufficient ductility to prevent brittle fractures, crack propagation, or fatigue failures.

Manufacturing technology for utilizing these materials efficiently must be determined. Joining and repairing technology for efficient fabrication by welding, bonding, or other techniques must be developed. For some of the materials, toxicity is a problem requiring definition of precise safety requirements, and the procedures to keep the fabrication practices within these requirements must be developed. Inspection and testing techniques which are unique to composites must be defined, and state-of-the-art techniques must be adapted, or advanced techniques must be developed. Finally, cost must be minimized, and cost-effectiveness of these materials must be demonstrated.

4.1.2.4 Structural Considerations

Application of advanced materials to light-weight pressure vessels presents some significant problems. Leakage and permeability are some potential problem areas for these advanced materials, and corrosivity is an ever present problem. For epoxy laminates, a 4-mil inner liner of aluminum was included in our earlier work to reduce tank leakage. Weight studies summarized in Appendix D indicate that titanium honeycomb will be competitive with the best of the other materials for the pressurized tanks. In fact, performance data available and the state of current technology for titanium suggest that a reasonable approach to the solution of some of the problems of large launch vehicle structures would be the use of titanium honeycomb for pressurized tank walls. The more advanced and sophisticated composite materials would be used in unpressurized sections of the vehicle structure. Aluminum honeycomb walls appear advantageous, but have greater structural weight than those of titanium.

4.2 ANALYTICAL METHODS AND ASSUMPTIONS

4.2.1 STRUCTURAL DESIGN ANALYSIS

4.2.1.1 General

The representative sections described earlier and shown in Figure 2-1 were designed for the nominal construction and the advanced materials using automated methods[2]. The resultant design configurations and costs, determined in this analysis, are considered sufficiently valid to permit comparative cost analyses. Structural costs were determined for each of the parametric design points by a detailed, step-by-step study of the required operations and materials required for fabrication, inspection, and test of the structures under study. Labor, material, and costs were determined by in-house General Electric Company evaluation and analysis of each step of the process was confirmed by consulations with individuals from industry, Government, and universities. Study results are expressed in absolute numbers in this report and are intended for use in a relative or comparative sense. Detailed future studies exploring those areas shown to be profitable during this comparative analysis would be desirable.

4.2.1.2 Loads Analysis

The major structural elements of a launch vehicle were represented as thin shells of revolution. It was further assumed that all structural loads were axisymmetric.

The detail methods of loads determinations are discussed in Appendix F. The resultant critical loads envelope is shown in summary form in Figure 4-2, where,

N_x is the highest calculated value for the axial (or meridional) stress resultant.

N_o is the highest calculated value for the equivalent uniaxial stress resultant.

The design conditions for which the maximum values of N_x and N_o are indicated on Figure 4-2; it is noted that they may occur at different times in the mission.

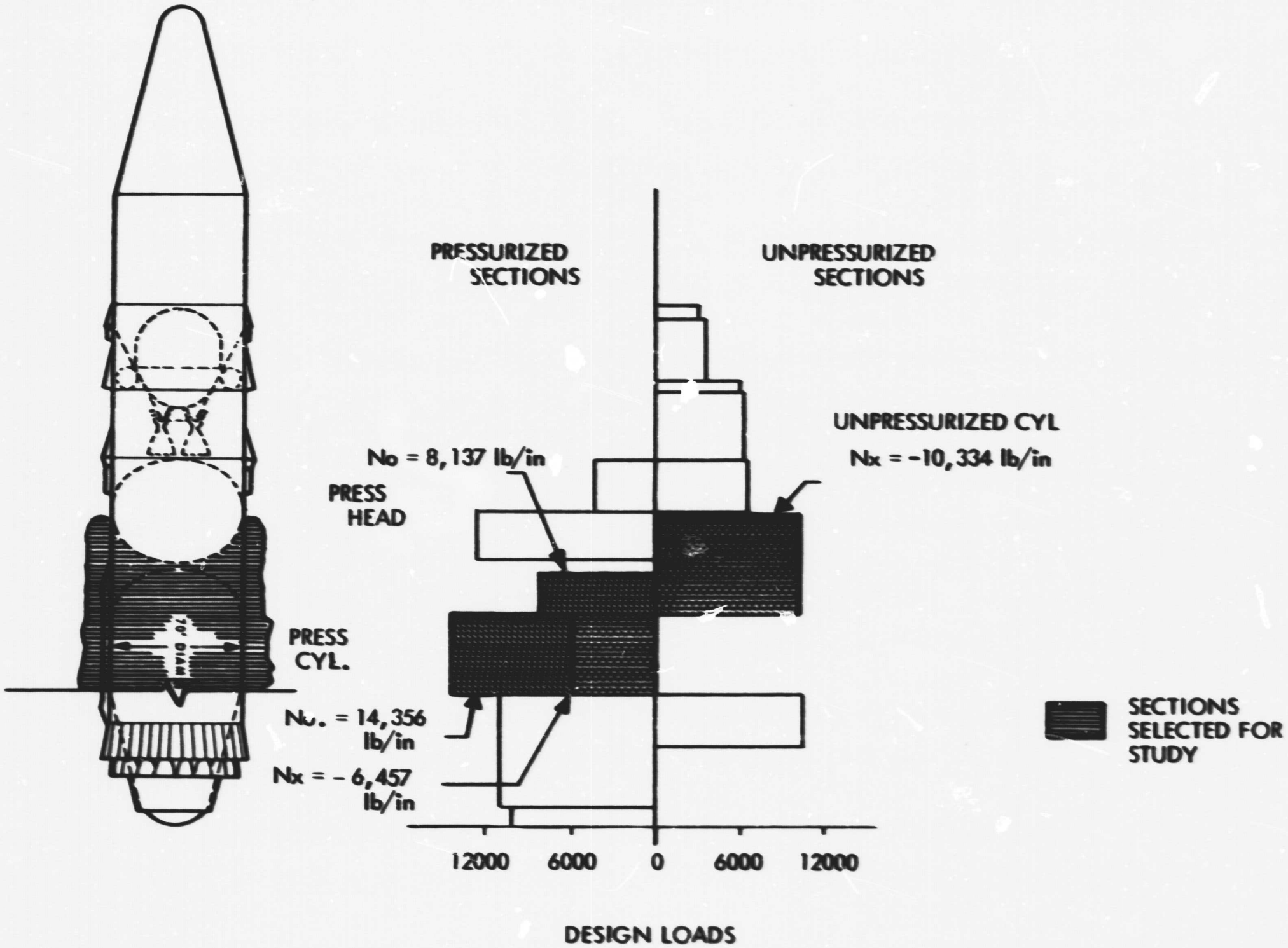


Figure 4-2. Loads Envelope for the 201 Configuration

The average loads of primary interest to this study are shown by the horizontal stripped sections. These are:

a. $N_x = -6457$ lb/in for pressurized H tank walls
   $N_o = 14,356$ lb/in
b $N_o = 8137$ lb/in for the H top head
c. $N_x = -10,334$ for the unpressurized intertank

Those sections picked for study are in lower locations in a relatively highly loaded area. Other sections, higher in the vehicle would have lighter loads, but the more heavily loaded lower sections are considered to be reasonably typical of launch vehicle structures.

Loads were assumed fixed at the above values for the remainder of the analysis. The only variability encountered is the strength of the structures which is assumed to vary in some distribution about the mean strength values.

4.2.1.3 Metal Structures Design Analysis

Based on the results of prior studies[2], the types of constructions considered in this study were narrowed to honeycomb, integrally stiffened skin, and monoque (for the heads). This was done to limit the scope of this study which permitted more detailed analysis of the configurations. These configurations were considered representative of possible structural designs. The metals included in the study were 2219-T87 aluminum, 6-Al-4V titanium, and a high strength beryllium. The properties used for these metals are given in Table 4-1.

The analysis of specific designs was performed by the Structural Weight Optimization Program (SWOP)[2]. This program was used to determine the optimized configuration for each of several factors of safety. Specific dimensions and weights are determined in the following manner for the critical loads illustrated in Figure 4-2.

The launch vehicle is divided into basic geometric shapes, elliptical or conical. The SWOP program which performed the required analysis is made up of several subprograms controlled by an executive control program as shown in Figure 4-3. One of the subprograms which is of primary importance in SWOP is the STRESS subprogram. STRESS calculates the hydrostatic, hydrodynamic, and ullage pressure loadings in the propellant tanks and combines the pressure loads with the force and moment distributions. These total loads are then resolved into orthogonal stress resultants in the

Table 4-1
Material Properties versus Temperature for 2219-T87 Aluminum

Temp (°F)	Percent σ_y at Room Temp	Percent σ_{ult} at Room Temp	σ_y (x10³ psi)	σ_{ult} (x10³ psi)	σ_o (x10³ psi)	$\sigma_{o,ss}$ (x10³ psi)	Percent E_c at Room Temp	E_c (x10⁶ psi)	ρ (lbs/ft³)	μ
Room	100	100	60	62	52	50	100	10.4	172.8	0.30
0	102	102	61	63.25	52.25	51	100.5	10.45	172.8	0.30
-50	104	104	62	64.5	52.5	52	101	10.5	172.8	0.30
-100	105	106	62.5	65.6	53	52.5	102	10.6	172.8	0.30
-150	107	107	63.5	66.3	55	53.5	103	10.7	172.8	0.30
-200	110	110	65	68.1	57	55	104	10.8	172.8	0.30
-250	113	114	66.5	70.6	59	56.5	106	11.0	172.8	0.30
-300	117	120	68.5	74.4	62	58.5	107	11.1	172.8	0.30

Material Properties versus Temperature for 6A1-4V Titanium

Temp (°F)	Percent σ_y at Room Temp	Percent σ_{ult} at Room Temp	σ_y (x10³ psi)	σ_{ult} (x10³ psi)	σ_o* (x10³ psi)	$\sigma_{o,ss}$* (x10³ psi)	Percent E_c at Room Temp	E_c (x10⁶ psi)	ρ (lbs/ft³)	μ
Room	100	100	126	130	128	124	100	16	276	0.3
0	106	106	133.5	137.5	135.5	128	101	16.15	276	0.3
-50	112	112	141	146	143.5	132.5	102	16.3	276	0.3
-100	117	118	148	154	151	146	103	16.5	276	0.3
-150	123	123	155	160	157.5	152.5	103.5	16.6	276	0.3
-200	128	128	162	166	164	158.5	104	16.65	276	0.3
-250	135	135	170	175	173	167.5	105	16.8	276	0.3
-300	144	144	182	187	184.5	178.5	107.5	17.2	276	0.3

*The same percent increases that were used for yield and ultimate were used for the secant yield stresses at 70 percent and 85 percent.

Material Properties versus Temperature for Y5804, QMV-5 Beryllium*

Temp (°F)	Percent σ_y at Room Temp	Percent σ_{ult} at Room Temp	σ_y (x10³ psi)	σ_{ult} (x10³ psi)	σ_o (x10³ psi)	$\sigma_{o,ss}$ (x10³ psi)	Percent E_c at Room Temp	E_c (x10⁶ psi)	ρ (lbs/ft³)	μ
Room	100	100	64.5	75	54	43.5	100	42	115	
-300									↓	

*Use room temperatures properties of beryllium from -50° to -300°F since applicable data is not available at this time.

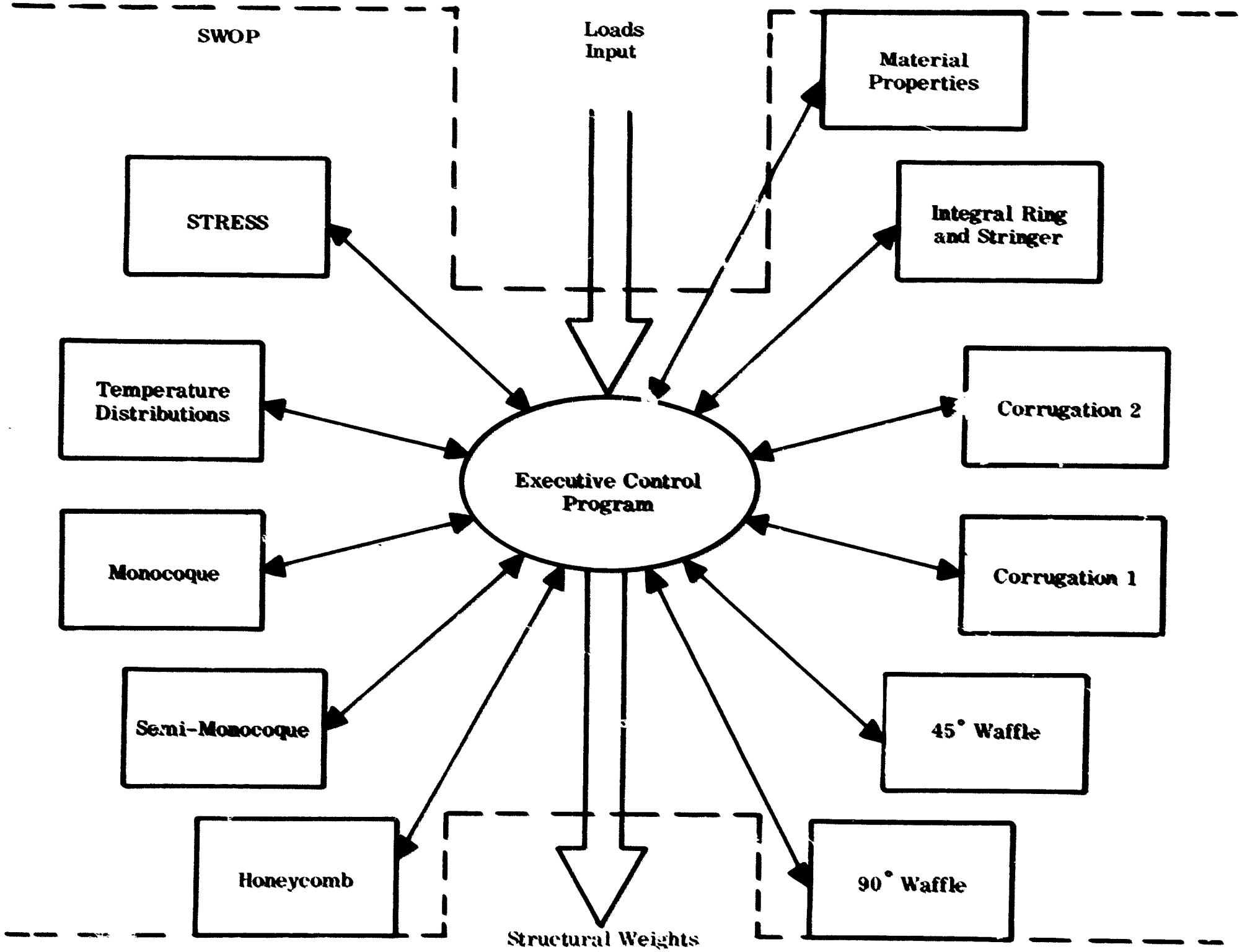


Figure 4-3. Organization of SWOP

plane of the structural components. This procedure of load calculation is repeated for every time point in the mission selected for investigation. The other subprograms can then use the stress resultants from STRESS to calculate the resultant structural weight for several different types of construction as listed in Figure 4-3. The optimal structure required to withstand this "time" catalog of stress resultants is then determined by optimization analyses for each type of construction. The minimum weight configuration for each type of construction can be compared, showing the relative advantages between different types of construction for the given application.

4.2.1.4 Composite Structures Design Analysis

The advantages in weight savings by using advanced fiber-reinforced composites in primary structures of large launch vehicles are explored in References 1 and 2. The analytical methods used for a quantitative assessment of weight savings of composites are essentially the methods of efficiency analysis developed in References 40 and 41. The minimum structural weight is evaluated as a function of a structural index characterizing the design load and the structural geometry. By varying the design load corresponding to varying factors of safety, the structural configuration and weights of sections of a vehicle can be determined for different types of composite materials and different lamination patterns.

4.2.2 ANALYSIS OF MANUFACTURING PROCESSES

4.2.2.1 General

The detailed processes involved in obtaining materials, fabrication, assembly, and inspection were analyzed in a step-by-step approach for each material and construction type. The specific designs, with the dimensions developed in the design analyses, discussed above, were assigned quality control limits, tolerances, fabrication requirements, and other specific constraints which were necessary to permit determination of the detailed requirements. Manufacturing processes required to construct these designs to those requirements were then evolved by a series of analytical iterations. Due to limitations of time and funds for this study, no attempt was made to determine the optimal methods of manufacturing; rather, a sound manufacturing procedure was obtained, typical of the construction processes for each material. These detailed processes were than tabulated in step-by-step flow charts, with quantities, sizes, and assembly requirements noted.

Specific details of these processes are discussed under each of the indicated materials and wall construction combinations in Sections 4.3 and 4.4 for metals and composites, respectively. Some of the specific assumptions and constraints are listed below.

4.2.2.2 Materials

Materials used in this study are generally those well understood and in (at least) limited use today. The advanced materials center around the high modulus metals (beryllium) and filaments (boron and carbon). The status and description of these materials are documented in Volume 3 of this report.

The assumptions on general availability for these materials was that they would be available in the 1975 time period. The aluminum plate is received in the 2219 pre-processed condition and is processed to 2219-T87 after being machined to integrally stiffened skin. The beryllium is IS400 cross-rolled from high-quality, low-impurity powder to sheet and plate of high quality. A lower quality material was assumed for the stringers and rings of stiffened skin construction.

The aluminum honeycomb core used was material of current commercial quality with densities between 1.8 to 3.0 pounds per cubic foot depending on design optimization calculations.

The boron filaments were assumed to be similar to currently available 5-mil-diameter continuous filaments, but of projected substrateless quality rather than the current tungsten substrate. The carbon filaments were assumed to be high modulus (60×10^6 psi) with a strength of 200,000 psi. For both the boron/epoxy and carbon/epoxy materials it was assumed that preimpregnated tapes four inches wide and of approximately 0.005 inch thick were used. With the use of these tapes, which facilitated manufacture, the maximum composition of filament was assumed to be limited to 60 percent by volume. Structures with higher percent of filament have been made but not with the "pre-preg" tapes.

The volume percent fraction of boron filament in aluminum was limited to 50 percent since this is the maximum successfully formed to date. (This reduced percentage actually showed lower weight than the higher percent filament composites since present analytical techniques for determining the traverse strength of the composite assumes that the strength is independent of fiber volume fraction as described in Section 4.4.)

The adhesive used in bonding the honeycomb core to face sheets was assumed to be standard commercial quality adhesive sheets. Fiber-glass scrim cloth was used to increase the bond strength. Although this adhesive requires both pressure and temperature for curing, it was selected to assure bond strength and integrity. It is quite conceivable that improved adhesives which bond at ambient pressure may be developed by the 1975 period, but the adhesives used in this study were limited to those in which there are proven performance and confidence.

4.2.2.3 Fabrication

Construction of 70-foot-diameter cylinders and heads proved to be an interesting challenge, nevertheless, one that appears feasible within today's state-of-the-art. The limitations in size of today's autoclaves (maximum of 28 feet by 55 feet) were no problem for the metallic honeycomb where the vehicle is constructed of panels which are sized to fit in today's autoclaves. The problems of assemblying and inspecting the large cylinders, appear little different though somewhat more complex than the problems associated with constructing the Lockheed C-5A or the Boeing 747. The total structure could be assembled at the launch site or be shipped from assembly to launch site; either method is feasible for a 70-foot-diameter cylinder. Repair and refurbishment seem quite feasible with removal and replacement of defective areas by cutting and welding or bonding.

The composite honeycomb proved too large for today's autoclaves. Construction by panels did not appear attractive in view of the loss of strength and integrity at the joints. Accordingly, the boron/epoxy and carbon/epoxy honeycomb cylinders were constructed by building up the total cylinders on a vertical mandrel and by using curing blankets to provide heat and vacuum bags to provide 15-psi pressure. This method is similar to the construction of composite/honeycomb in the Syncomm satellite[142], manufactured by Hughes, who has successfully cured these laminates with heating blankets and 15-psi pressure.

The unidirectional stiffened aluminum shell was constructed in long segments with boron/epoxy stiffeners and ring segments formed separately and bonded to the shell segments. The segments were sized to fit within available autoclaves. Completion of the structure was made by welding and bonding with low temperature and pressure curing adhesives.

Several alternative methods of welding were considered for the metal structures. After in-house analysis and consultation with industry, TIG (tungsten inert gas) welding was selected over EB (electron beam) welding as less sensitive to potential problems, using simpler facilities, and generally acceptable on an all-around basis. In future weldments, EB welding may emerge with wider acceptance and lower costs, and this would then be the obvious choice; but at this time TIG welding appears preferable and is used throughout the study.

4.2.2.4 Quality Control and Inspection

For the nominal constructions (those constructions at nominal factors of safety), complete quality control of fabricated sections is planned. This is in keeping with today's inspection practices of space vehicle structures, where 100 percent inspection is maintained for every fabricated part and assembly.

The proposed honeycomb constructions are inspected 100 percent by both X-ray and ultrasonic inspection. The inspection for surface defects is performed on all constructions by penetrants or other visual means. Stiffened skin welds and other welded areas are checked by X-ray and surface checks. Rivets and fasteners are inspected by appearance and surface checks. Manufacturing and assembly tolerances are checked in a similar manner to current practices in inspection.

Other inspections such as dynamic, shock, vibration, and acoustic checks would be required, but have been considered to be performed as a part of the non-recurring qualification testing and were not included in the recurring inspection costs.

4.2.3 COST ANALYSIS

4.2.3.1 General

Recurring costs were determined for the specific steps for manufacturing and test and are included in the following sections for metals and composites. Numerous detailed assumptions were made in these calculations which are tabulated in this section so that the reader may evaluate the results in light of these assumptions. These assumptions have been checked against industry, Government, and consultant experiences, as well as by a sensitivity study to evaluate the impact of these assumptions on results.

As a general note, the costs of structures quoted in this section are based only on estimated materials and labor costs and do not include such non-recurring elements as engineering development, drawings, tooling, machines, and fixtures.

Material costs for common materials are based on current market prices which assume these prices will be valid in the 1975 time period. The more exotic material costs were estimated forecasts for the same time period. Labor costs are based on 1969 rates.

Labor costs include only the fabrication and inspection costs directly associated with the production of the structure. These were derived from data obtained from the aerospace industry and Government sources for processes comparable to those under consideration in this study.

4.2.3.2 Material Costs Assumptions

The following criteria and source data form the basis for material cost assumptions used in this study:

a. Aluminum—Current market price, not expected to change appreciably.
b. Titanium Honeycomb (Stressskin)—Forecast by Stressskin in quantities appropriate to the vehicle under consideration.
c. Beryllium—Forecast in MAB study[8]; see cost curve in Volume 3.
d. Carbon Epoxy and Boron Epoxy—Based on 60 percent by volume tape, $100.00 per pound fiber as forecast by current trends.
e. Aluminum Core and Adhesive—Current market price, not expected to change appreciably.

4.2.3.3 Labor Costs Assumptions

The following criteria and source data form the basis for labor cost assumptions:

a. Beryllium Forming—Based on survey of Lockheed, Douglas, and Solar, but modified to include only recurring cost (without cost of dies and development).
b. TIG Welding—Cost based on survey of industry and data obtained from Defense Metals Information Center.
c. Aluminum Machining—Based on information furnished by Air Force Machinability Data Center and Defense Metals Information Center.
d. Adhesively Bonded Honeycomb Sandwich Fabrication—Estimate of man-hours by Hexcel Corporation.

e. Non-Destructive Testing—Estimate of manhours required per square foot or linear foot for both ultrasonic and X-ray inspection. Exotic fixturing not included.

f. Filament Winding—Based on manhour estimates from industry experience in filament winding of advanced composites and fiberglass structures.

g. Other Labor Costs—Other processes were based on labor cost at $15.00 per hour. Such processes include raw material inspection, quality assurance, and acceptance testing, machining, and assembly operations.

4.2.3.4 Manufacturing Cost Assumptions

Table 4-2 summarizes specific cost figures used to arrive at an estimate of materials, fabrication, and inspection for the nominal construction in this study.

Table 4-2

Manufacturing Cost Assumptions

MATERIAL COSTS	
Aluminum sheet for honeycomb skin (face sheets) and monocoque	$ 0.68/lb
Aluminum core	15.00/ft^3
Adhesive for bonding	1.00/ft^2
Boron/epoxy tape	100.00/lb
Carbon/epoxy tape	100.00/lb
Boron/aluminum sheet	100.00/lb
Titanium sheet	10.50/lb
Titanium honeycomb (Stressskin)	180.00/ft^2
Beryllium sheet for honeycomb face sheets	100.00/lb
Beryllium sheet for stringers and rings	80.00/lb
FABRICATION COSTS	
Metal removal costs: Numerically controlled machining 80% (at .50/lb) Chemmill 20% (at 5.50/lb)	1.50/lb
TIG welding	7.00/ft
Forming of beryllium panels	75.00/lb
Forming of beryllium stringers and rings	115.00/lb
INSPECTION COSTS	
X-ray and ultrasonic inspection	5.50/ft^2

4.3 METAL CONSTRUCTIONS—DESCRIPTION AND ANALYSIS

4.3.1 INTRODUCTION

This section presents a detailed description and the results of the detailed calculations for each of the following five metal configurations analyzed:

a. Aluminum integrally stiffened skin.
b. Aluminum honeycomb.
c. Beryllium honeycomb.
d. Beryllium stiffened sheet construction.
e. Titanium honeycomb.

Data pertinent to this report has been gathered together for both the pressurized cylinders and non-pressurized cylinders in each section. Costs are recurring costs; non-recurring items are noted in several of the sections, but the analysis is primarily for recurring costs.

4.3.2 ALUMINUM INTEGRALLY STIFFENED SKIN CONSTRUCTION (ALISS)

4.3.2.1 General Description and Analysis

4.3.2.1.1 Pressurized Cylinder and Unpressurized Interstage

Aluminum skin integrally stiffened with rings and stringers is selected as illustrative of conventional technology in the design and construction of large launch vehicles. This technology has been used in several studies of advanced launch vehicles, either as a baseline for comparison in optimization studies (1, 2, 7, 8), or as a basis for vehicle design (5, 6, 9). To provide a baseline for comparison in this study, various details of fabrication, structural weights, and costs of Aluminum Integrally Stiffened Skin (ALISS) construction are presented first for a pressurized cylinder with an aluminum monocoque (ALMONO) head and an unpressurized interstage.

The construction of the interstage and pressurized tank is similar. The shell is made up of plates which are machined to form rectangular section stiffeners and circumferential ribs, and then contour formed in a fixture and aged at 500°F. Next, the plates are welded together at their radial edges to form individual 70-foot-diameter rings, and the rings are then assembled and welded circumferentially using a holding attachment. "L" section rings are fabricated by rolling and forming to the cylinder radius.

After aging, they are machined, slotted, and drilled for rivet attachment to the integral circumferential ribs.

4.3.2.1.2 Aluminum Monocoque Head

The aluminum monocoque head is used with the ALISS construction. The head is made up of a series of trapezoidal-shaped plates of tapered thickness and with a circular cap. The plates are machined to the proper outline, correct thickness taper and edge preparation. They are then formed and aged in a holding fixture and welded together. Finally, the head and cylinders are welded to a common circular "Y" section adapter to which the unpressurized intertank cylinder can be bolted.

4.3.2.2 Manufacturing Processes—Materials, Fabrication, and Inspection

4.3.2.2.1 Production Process

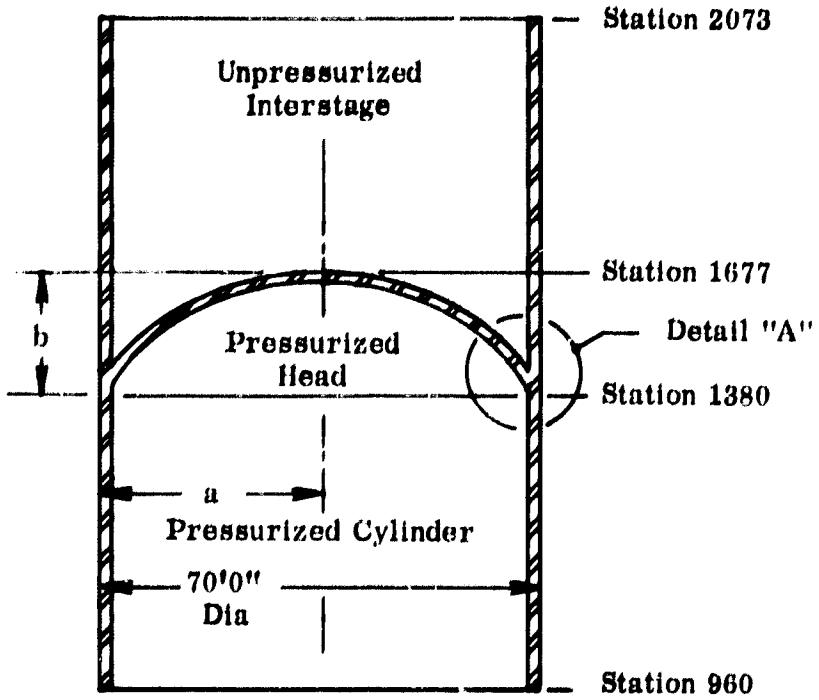
The production processes for aluminum integrally stiffened unpressurized cylinder, pressurized cylinder, and aluminum monocoque head are outlined in Tables 4-3 and 4-4. These flow process charts describe, in sequence, the operations required to fabricate, inspect, and assemble the three major subassemblies; the cylinder, stiffening rings, and head.

4.3.2.2.2 Cylinder Fabrication

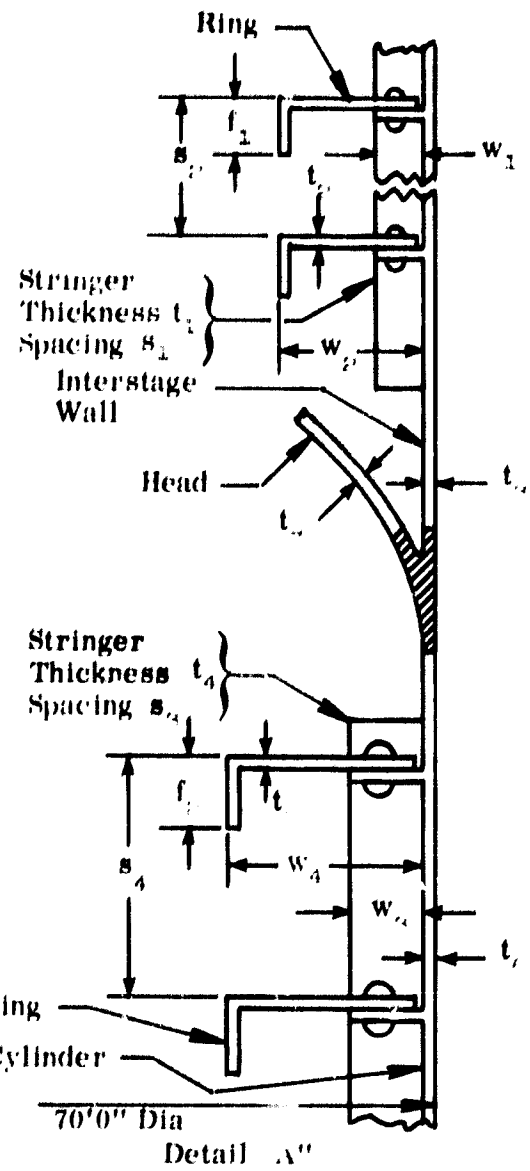
Figure 4-5 illustrates the aluminum cylinder wall segments trimmed to size, Tables 4-3, 4-4 (steps 1 and 2).* and Figure 4-6 show the plate after numerically controlled (N/C) machining and chemmilling (steps 3 and 4). Figure 4-7 illustrates the contour forming of the plate to a 35-foot radius, where it is clamped to a contour fixture and aged at 500°F (steps 5 through 8). (Steps 9 and 10) of the flow process chart show the aluminum sheet for the rings cut to size in Figure 4-8, after which it is roll formed, slot machined, drilled and aged; Figure 4-9 (steps 11 through 14). Figures 4-10 and 4-11 show the assembly, first of a typical panel where the ring segments are riveted to the integral circumferential ribs and then welded, using a holding fixture, to form ring sections. Finally, the ring sections are welded together in a holding attachment to form the completed cylinder. All operations in Figures 4-10 and 4-11 are included in (step 15) of the flow process chart.

* ( ) indicate process steps in tables.

Construction Details and Typical Dimensions for Various FS/FS_{Nom} Values



Note: Station Numbers Are in Inches.
Head is Elliptical, $a = \sqrt{2}\ b$



FS/FS_{Nom}	Unpressurized Interstage									Head	
	w_1	w_2	t_1	t_2	t_3	f_1	s_1	s_2	Weight	t_w	Weight
0.7	3.985	9.963	0.299	0.299	0.319	3.985	11.816	45.000	115361	0.140	11154
1.0 Nom	4.670	11.675	0.467	0.467	0.280	4.670	9.231	45.000	156026	0.200	15935
1.4	5.252	13.129	0.525	0.525	0.340	5.252	10.379	45.000	187918	0.280	22309
2.0	6.125	15.311	0.612	0.612	0.429	6.125	12.102	45.000	235756	0.400	31869

FS/FS_{Nom}	Pressurized Cylinder									Total Weight
	w_3	w_4	t_4	t_5	t_6	f_2	s_3	s_4	Weight	
0.7	4.312	10.780	0.323	0.323	0.216	4.312	8.573	74.000	59754	186269
1.0 Nom	3.848	9.620	0.289	0.289	0.231	3.848	7.493	40.000	63411	235372
1.4	4.884	12.211	0.431	0.431	0.293	4.884	9.615	53.600	87292	297519
2.0	6.439	16.097	0.644	0.644	0.386	6.439	12.797	74.000	123115	390740

Dimensions are in inches, weights in pounds.

Figure 4-4. Aluminum Integrally Stiffened Skin Construction—Pressurized Cylinder, Monocoque Head and Unpressurized Interstage

Table 4-3

Flow Process Charts—Manufacture of Aluminum ISS Cylinder and Monocoque Head--Pressurized

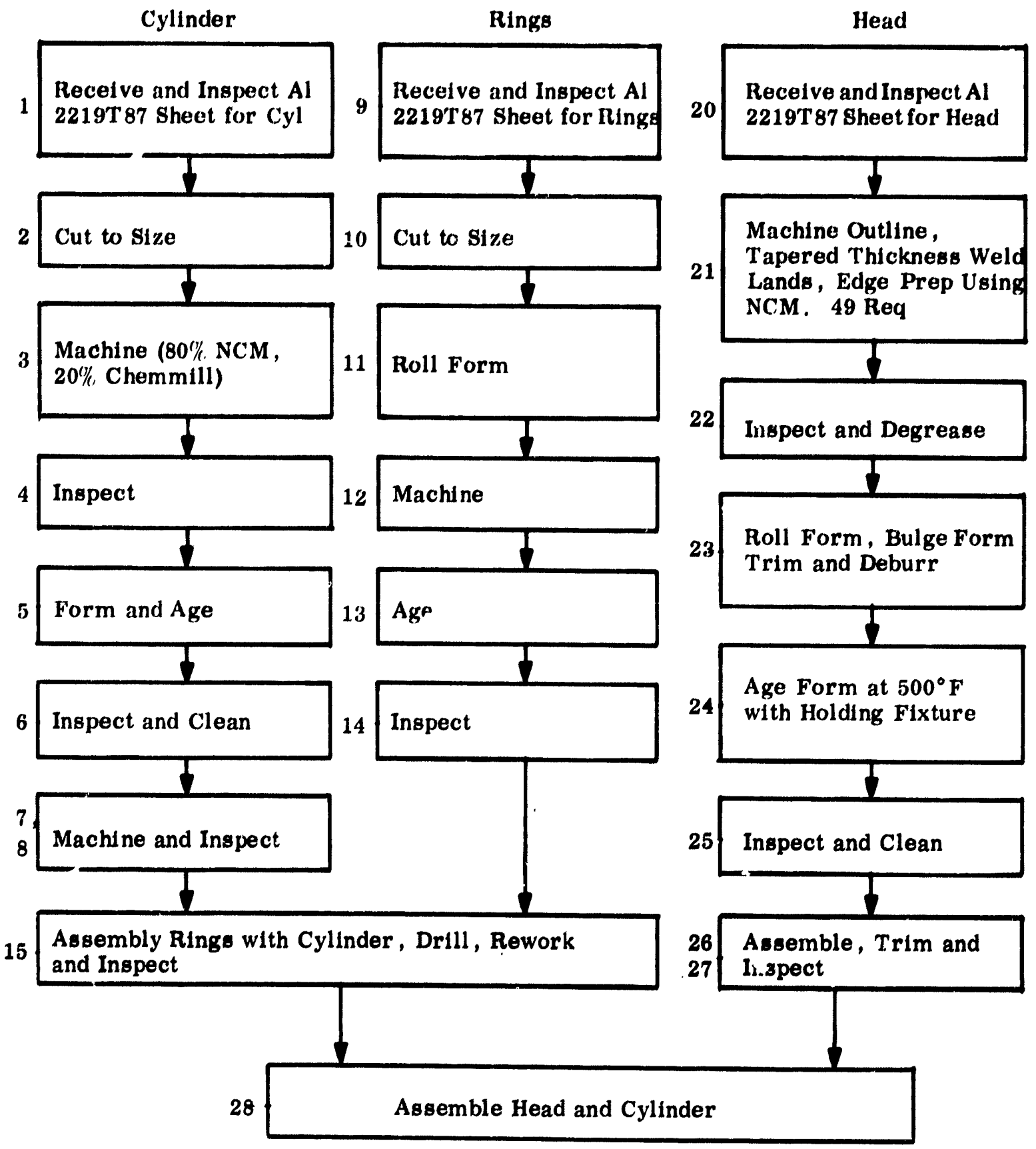
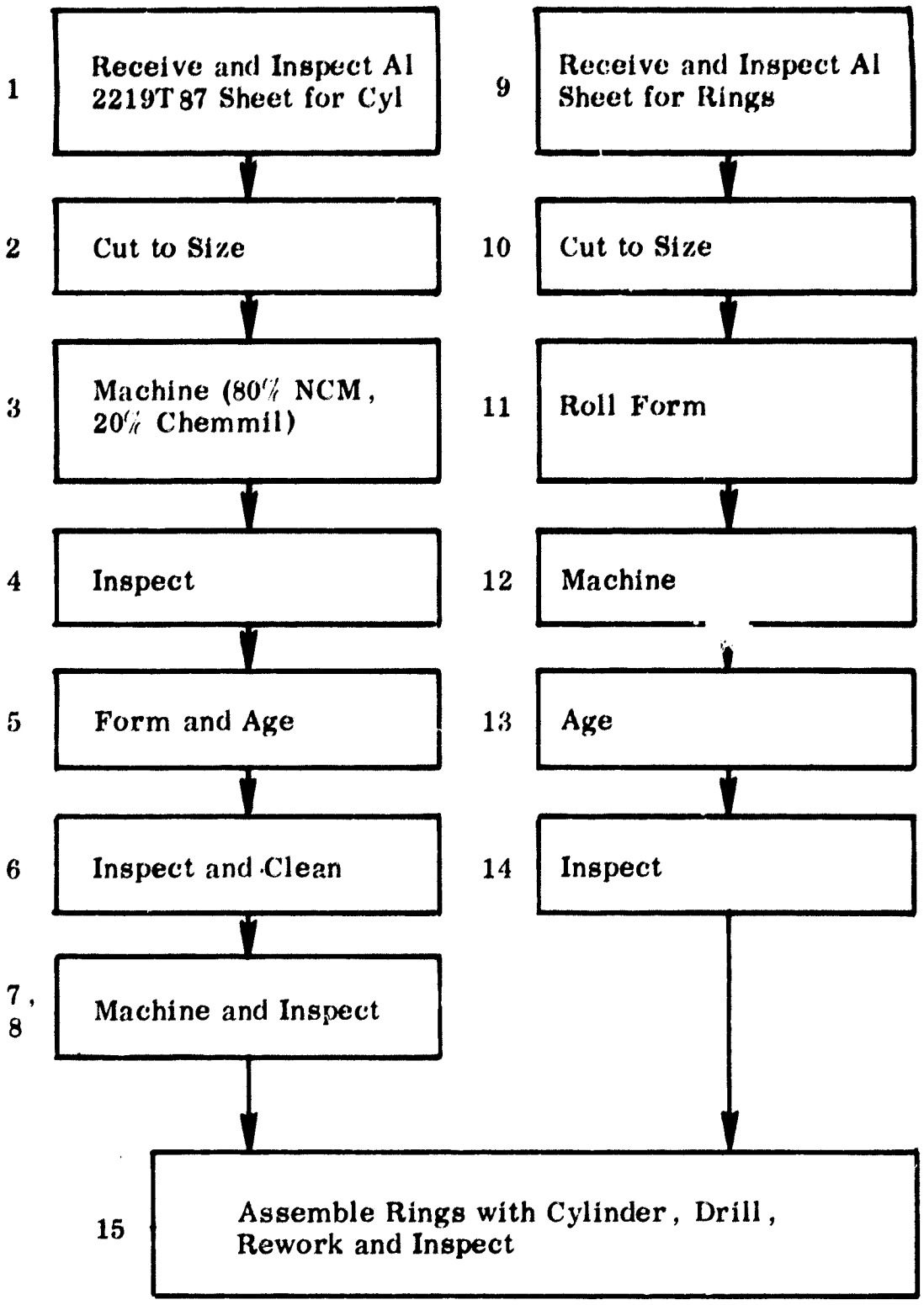


Table 4-4

Flow Process Charts—Manufacture of Aluminum ISS Interstage—Unpressurized



Steps 1, 2
Plate Trimmed to Size
60 Required

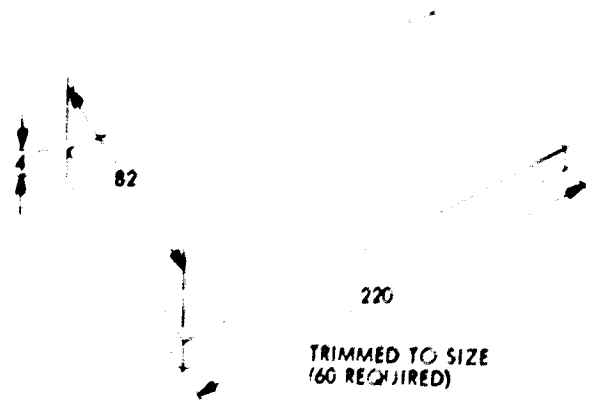


Figure 4-5. Aluminum ISS Cylinder Panels
Plate Trimmed to Size

Steps 3, 4
Plate Machined
(80% NCM, 20% Chemmill)

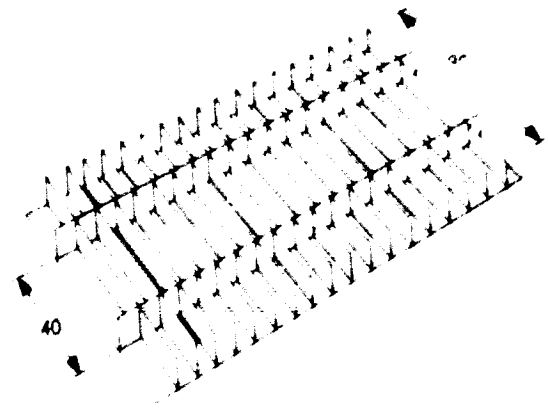


Figure 4-6. Aluminum ISS Cylinder Panels
Plate Machined

Steps 5, 6, 7, 8
Plate Formed on Contour Machine
Using Fixture. Clamp in Fixture
and Age at 500° F.

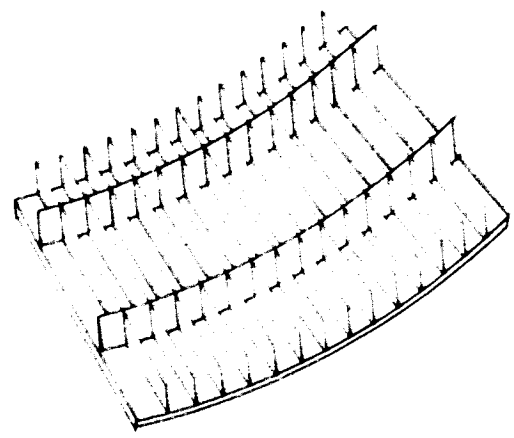


Figure 4-7. Aluminum ISS Cylinder Panels
Plate Formed

4.3.2.2.3 Head Fabrication

Figure 4-12 represents (steps 20 through 27) of the flow process chart, Table 4-3, and shows the fabrication techniques required to produce the aluminum monocoque head. The head material is cut to size and is machined for outline, tapered thickness, and edge preparation for the gore segments and cap (steps 20 and 21). After inspection and degreasing, the gore segments and cap are roll formed and bulge formed to the required contour and aged at 500°F in a holding fixture (steps 22 through 25). The head segments are then TIG welded together, trimmed, and inspected.

4.3.2.2.4 Assembly of Cylinder and Head

Figure 4-13 illustrates the assembly of the cylinder and head showing the "Y" ring to which both are attached (steps 26 and 27).

Steps 9, 10
Plates Cut to Size
120 Required

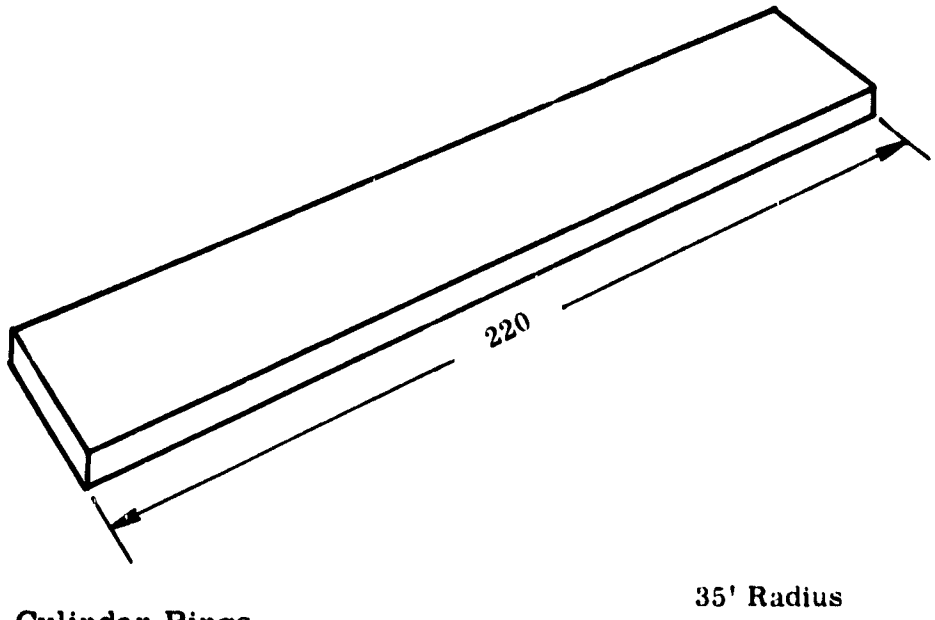


Figure 4-8. Aluminum Cylinder Rings
Plates Cut to Size

Steps 11, 12, 13, 14
"L" Ring After Rolling
Stretch Forming, Slots
Machined and Drilled

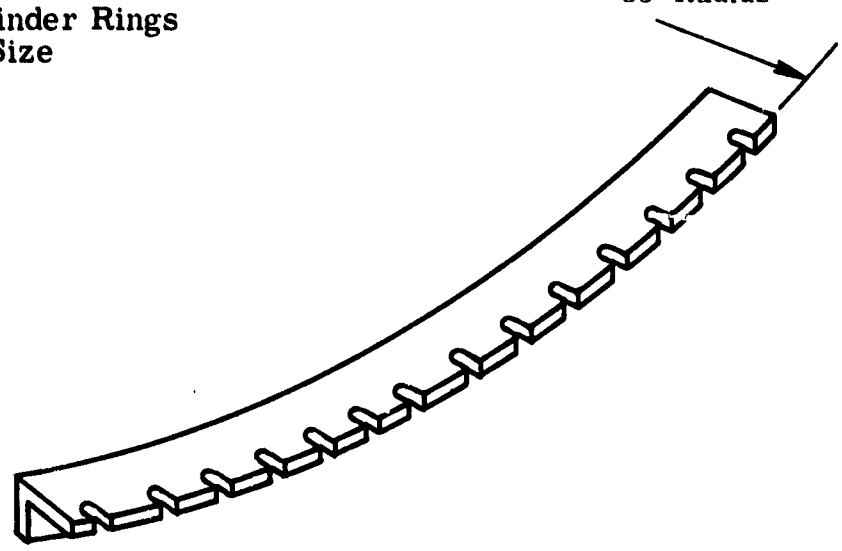


Figure 4-9. Aluminum Cylinder Rings
"L" Ring

Step 15
Typical Panel With
"L" Ring Riveted to
Integral Circumferential Ribs

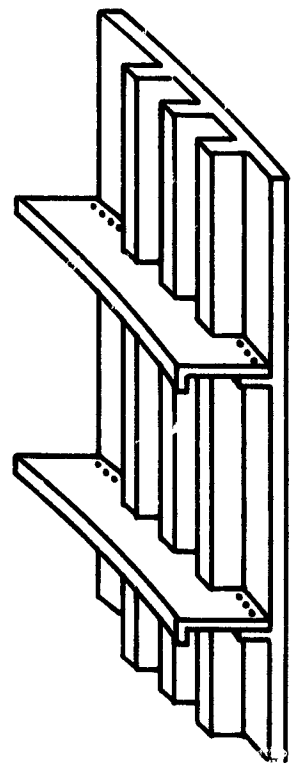
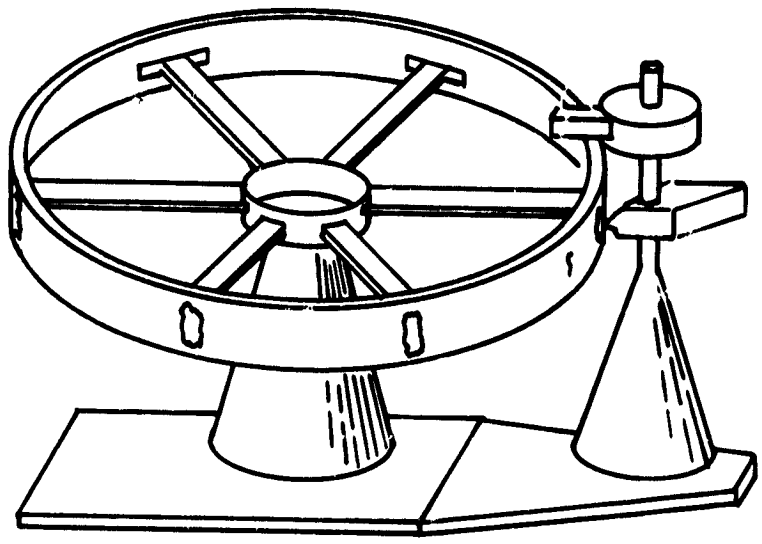


Figure 4-10. Aluminum Cylinder Rings
Typical Panel



Step 15
12 Cylinder Panels Assembled on Holding Fixture and Welded to Form a Ring 80" High × 70'0" Diameter

5 Rings Plus One 20" Y Ring Welded together in Assembly Attachment to Form Cylinder

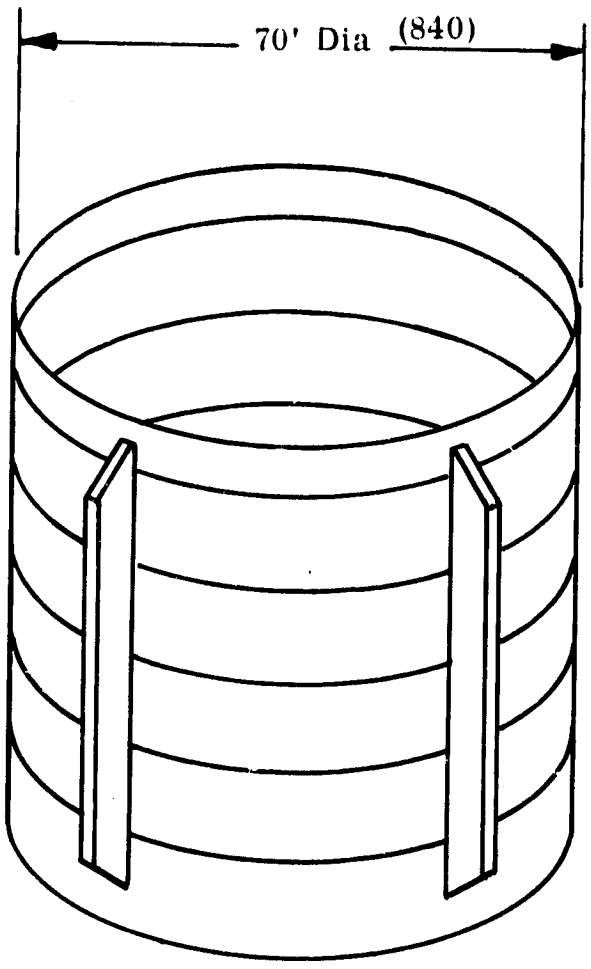
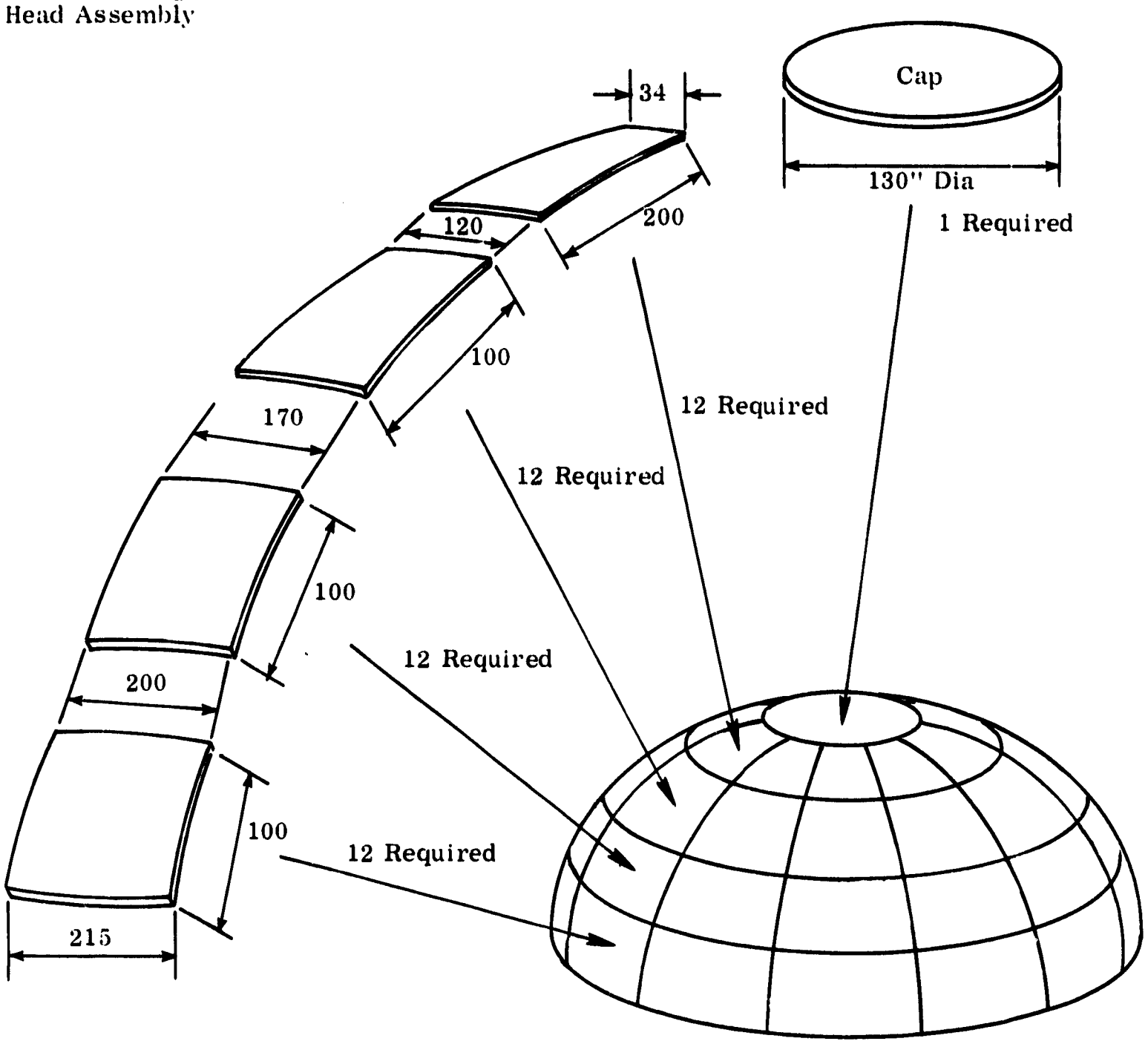


Figure 4-11. Aluminum ISS Cylinder Assembly

Formed Gore Segments Before Assembly (40 Required)

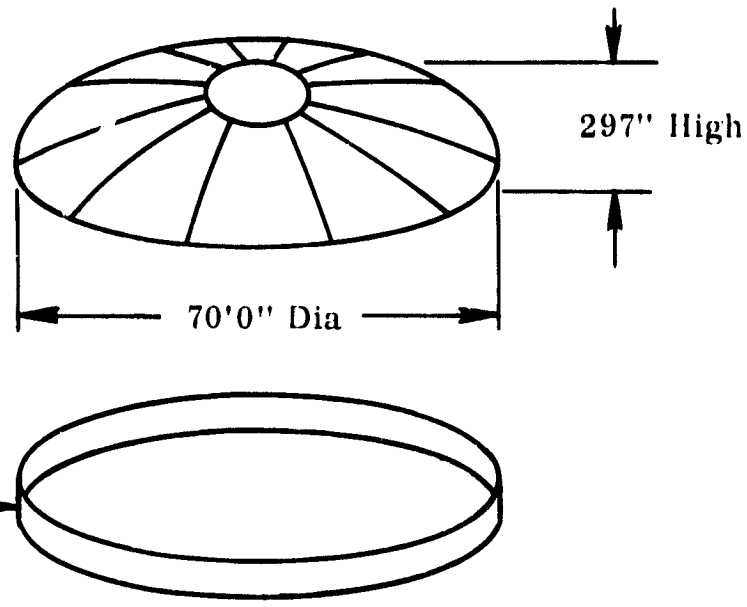
Line 20 through 27
Head Assembly



Approximate Weight 200 to 400 lbs Each
Thickness Tapers from 0.1 inch at Outer Segments to 0.2 at the Cap.

All Dimensions are Approximate.

Figure 4-12. Nominal Aluminum Monocoque Head



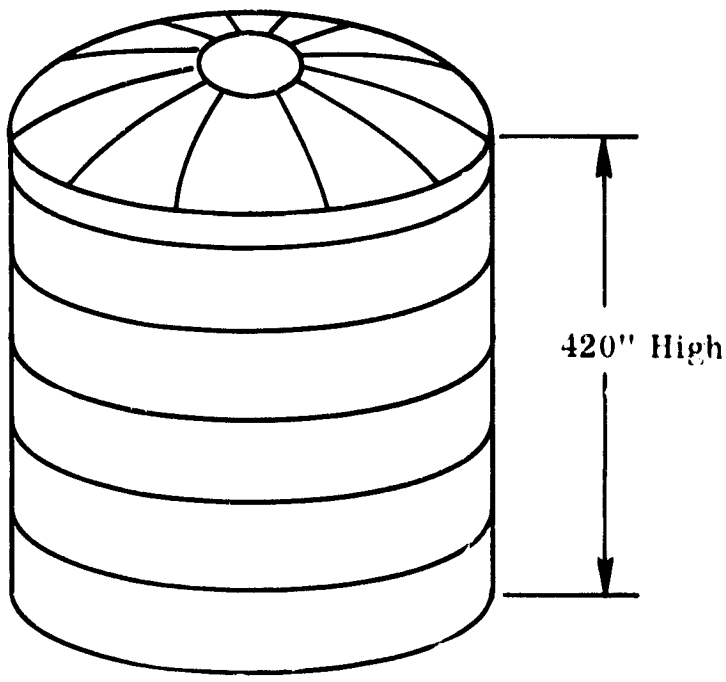


Figure 4-13. Nominal Aluminum Monocoque Head and ISS Cylinder Shell

4.3.2.3 Recurring Costs for Manufacturing Processes

The following pages give a breakdown of the recurring costs associated with the production of a pressurized cylinder and head, and an unpressurized interstage. Tables 4-5, 4-6, and 4-7 show materials (M), fabrication (F), and inspection (I) costs for each step of the applicable flow process chart for the pressurized cylinder, head, and unpressurized interstage.

Table 4-5

Recurring Costs for Manufacturing Processes—
Aluminum ISS Cylinder—Pressurized

Sequence Number	Cost Item	Thousands of Dollars FS/FS$_{Nom}$ = 1.0 M	F	I
	Cylinder			
1	Receive and Inspect	319.6		
2	Trim		30.0	
3,7	Machine (80% NC, 20% Chemmill)		627.0	
4	Inspect			20.0
5	Form and AGE		65.0	
6	Inspect and Clean			15.0
8	Inspect			20.0
		(319.6)	(722.0)	(55.0)
	Rings			
9	Receive and Inspect	8.2		
10	Cut to size		3.0	
11	Roll Form		62.0	
12	Machine		34.0	
13	AGE		23.0	
14	Inspect			17.0
		(8.2)	(122.0)	(17.0)
	Assembly Rings/Cylinder			
15	Assemble, Drill, Rework,		113.0	30.0
	Cylinder Subtotals	(327.8)	(957.0)	(102.0)
	Cylinder Total		(1386.8)	
	Head Assembly			
	Head Subtotals*	(22.0)	(645.0)	(65.0)
	Head Total		(732.0)	
	Cylinder and Head Subtotals	(349.8)	(1602.0)	(167.0)
	Cylinder and Head Total		(2118.8)	
	Subtotal Percent of Total	16.5%	75.6%	7.9%
	Total Weight (Cylinder 63411 + Head 15935)—lb		79346 lb 35991 kg	

* From Table 4-6

Table 4-6

Recurring Costs for Manufacturing Processes—
Aluminum Monocoque Head

Sequence Number	Cost Item	Thousands of Dollars		
		$FS/FS_{Nom} = 1.0$		
		M	F	I
Head Segments				
20	Receive and Inspect	22.0		
21	Machine		185.0	
22	Inspect			18 0
23	Form		155.0	
24	AGE		30.0	
25	Inspect			15.0
Head Assembly				
26	Assemble		190.0	
27	Trim and Inspect			17.0
Assembly Head/Cylinder				
28	Assemble, Weld, Trim, Inspect		85.0	15.0
	Head Subtotals	(22.0)	(645.0)	(65.0)
	Head Total		(732.0)	

Table 4-7

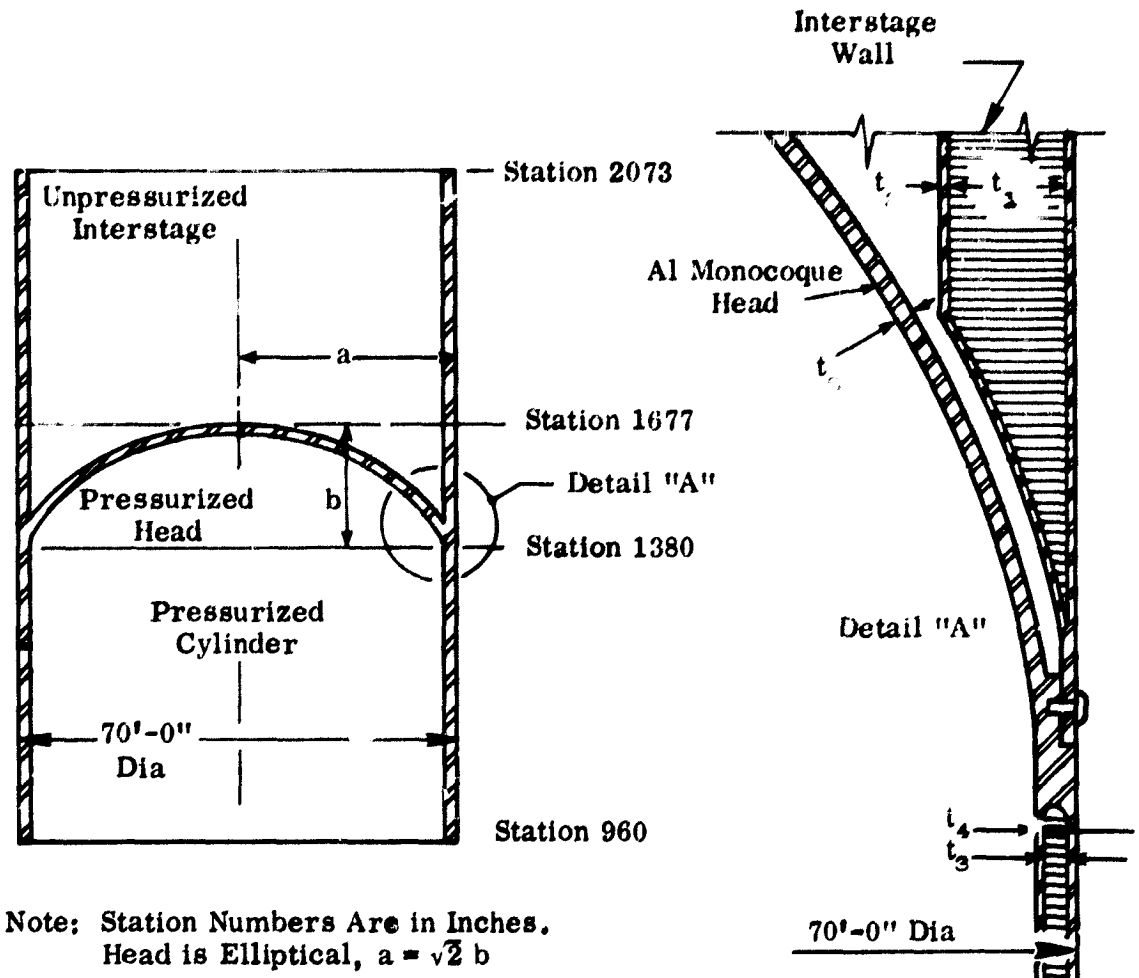
Recurring Costs for Manufacturing Processes—
Aluminum ISS Cylinder—Unpressurized

Sequence Number	Cost Item	Thousands of Dollars FS/FS$_{Nom}$ = 1.0		
		M	F	I
	Cylinder			
1	Receive and Inspect	652.8		
2	Trim		30.0	
2,7	Machine (80% NC, 20% Chemill)		1240.5	
4	Inspect			20.0
5	Form		98.0	
6	Inspect and clean			15.0
8	Machine and Inspect			20.0
		(652.8)	(1368.5)	(55.0)
	Rings			
9	Receive and Inspect	20.6		
10	Cut to Size		5.0	
11	Roll Form		100.0	
12	Machine		55.0	
13	AGE		40.0	
14	Inspect			30.0
		(20.6)	(200.0)	(30.0)
	Assembly Rings/Cylinder			
15	Assemble, Drill, Rework, Inspect		188.0	30.0
	Cylinder Subtotals	(673.4)	(1756.5)	(115.0)
	Cylinder Total		(2544.9)	
	Subtotal Percent of Total	26.5%	69.0%	4.5%
	Total Weight, Cylinder		156,026 lb 70,773 kg	

4.3.3 ALUMINUM HONEYCOMB CONSTRUCTION (ALHYC)

4.3.3.1 General Description and Analysis

Aluminum honeycomb construction technology has been developed to a point where it is possible to fabricate large and complex honeycomb sandwich structures. The cylinders under study were assumed to be welded together to form the cylindrical configuration. Figure 4-14 shows the construction details and typical dimensions for the aluminum honeycomb cylinders and aluminum monocoque head.



Note: Station Numbers Are in Inches.
Head is Elliptical, $a = \sqrt{2}\, b$

FS/FS_{Nom}	Unpressurized Interstage				Head	
	t_1	t_2	d*	Weight	t	Weight
0 7	3.920	0.105	3.217	53173	0.140	11154
1.0 Nom	5.058	0.147	4.284	73784	0.200	15935
1.4	5.430	0.204	5.824	102400	0.280	22308
2.0	5.989	0.290	8.130	145323	0.400	31869

FS/FS_{Nom}	Pressurized Cylinder				Total Weight
	t_3	t_4	d*	Weight	
0.7	1.281	0.100	4.402	28520	92847
1.0 Nom	1.288	0.142	6.288	40281	130000
1.4	1.291	0.199	8.803	56046	180754
2.0	1.295	0.286	12.576	79693	256885

*Maximum Allowable Core Cell Diameter, Inches.

Dimensions are in inches, weights in pounds.

Figure 4-14. Aluminum Honeycomb Construction for Pressurized Cylinder, Monocoque Head and Unpressurized Interstage Construction Details and Typical Dimensions for Various FS/FS_{Nom} Values

4.3.3.2 Manufacturing Processes--Materials, Fabrication, and Inspection

Manufacturing processes associated with the construction of an aluminum honeycomb configuration are shown in Tables 4-8 and 4-9.

The honeycomb core material is received, and the HOBE is expanded. The face plate material, 2219-T87 aluminum, is cut to panel size and rolled to the required radius of curvature. Panels are cleaned, etched, adhesively bonded to the core material over tooling, and cured at 30 psi and 250°F (steps 1 through 5). The panels are then ultrasonically inspected and trimmed to size (step 6). Aluminum sheets for edge attachments are cut to size (steps 10, 11, and 12) and bonded to the honeycomb panels at 30 psi and 325° F leaving a 2-inch overlap along each edge for panel joints (step 7). The The honeycomb panels are TIG welded together on both sides along the edge attachments; welds are subject to x-ray and ultrasonic inspection, and assembly is completed (steps 8, 9, 13, 14) Figure 4-15.

Table 4-8

Flow Process Chart--Manufacture of Aluminum Honeycomb—Pressurized

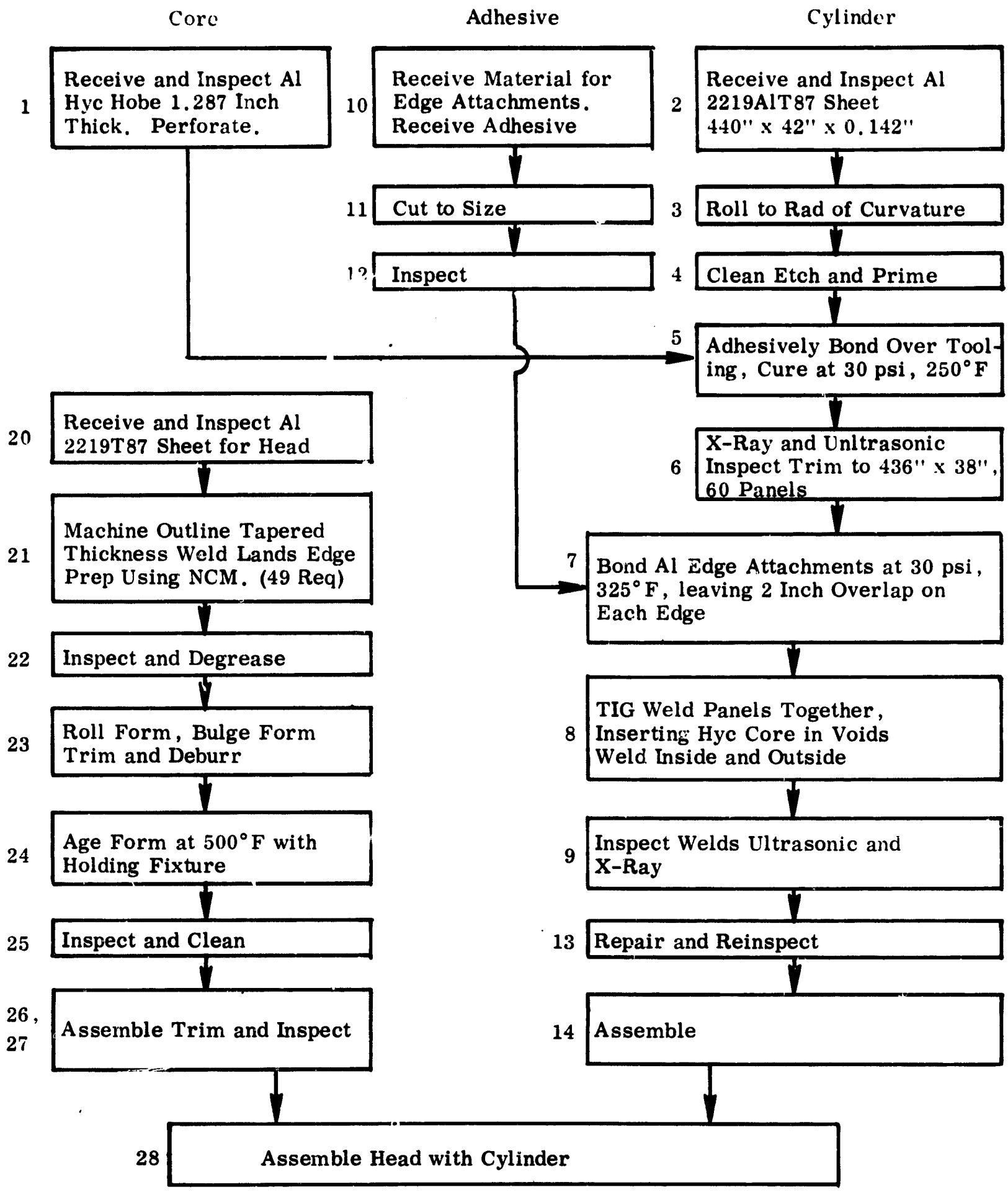
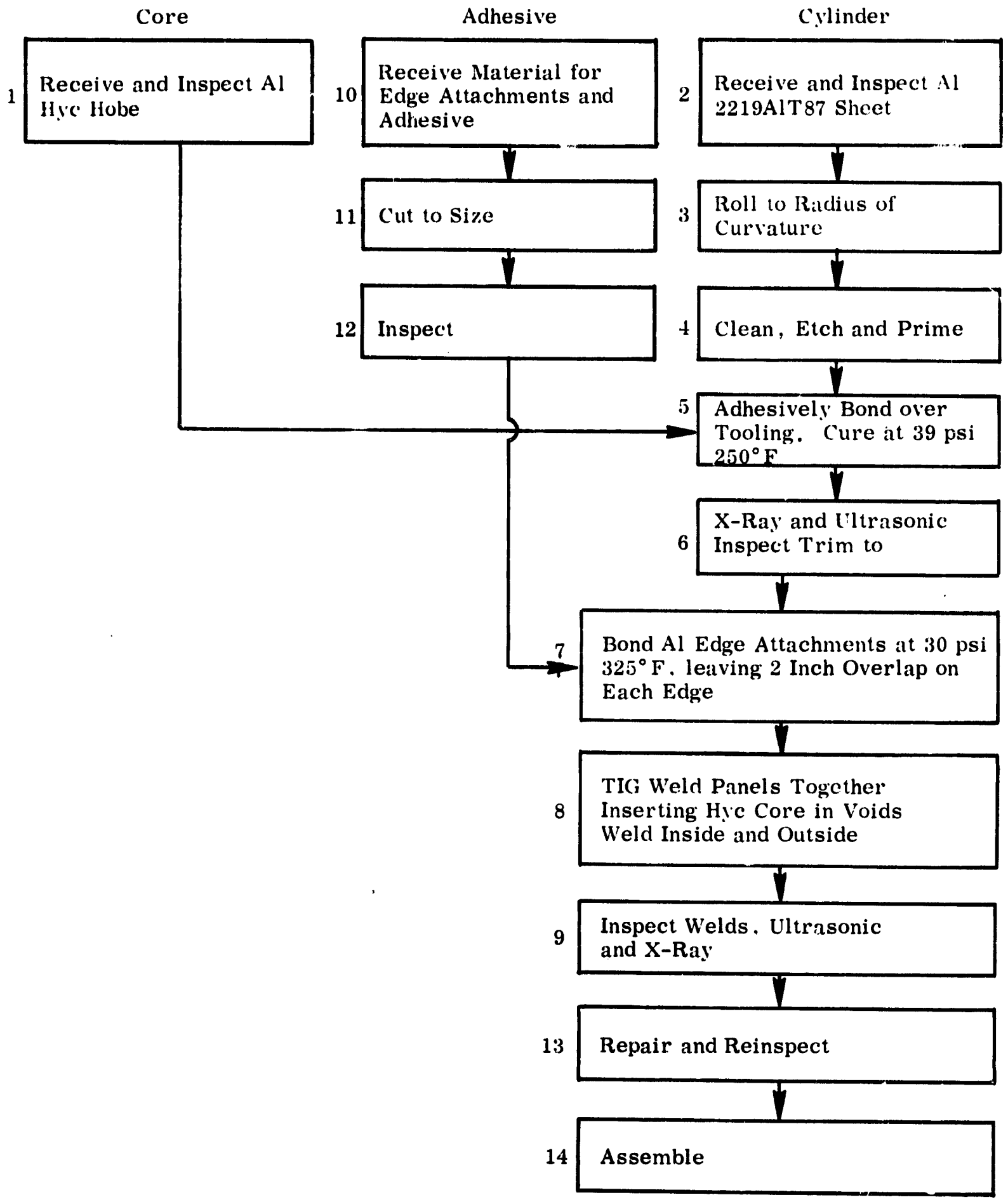
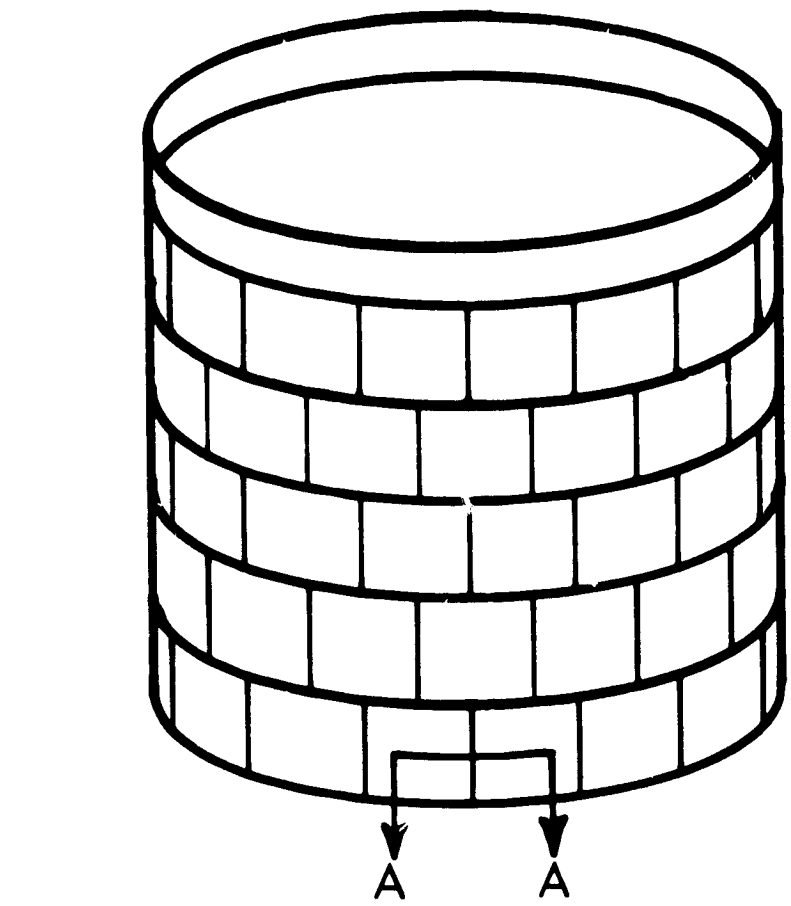
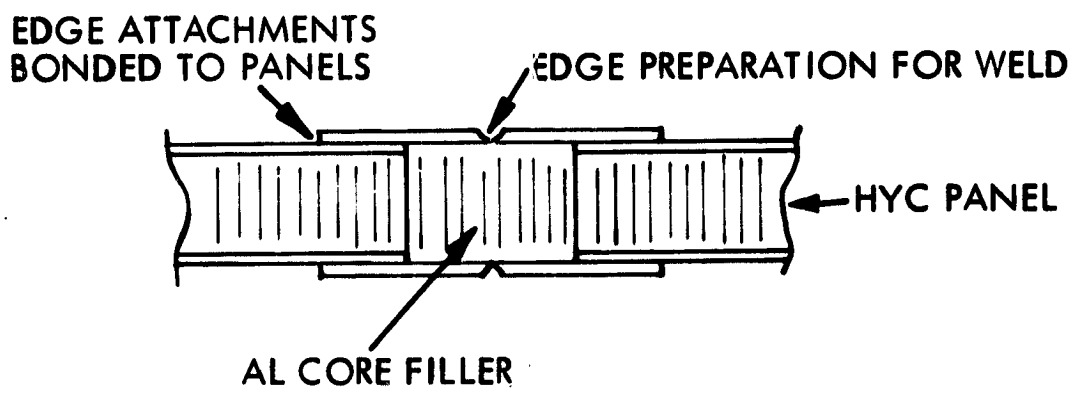


Table 4-9

Flow Process Chart—Manufacture of Aluminum Honeycomb—Unpressurized







ENLARGED SECTION A-A

Figure 4-15. Aluminum Honeycomb Construction

4.3.3.3 Recurring Costs for Manufacturing Processes

Recurring costs associated with the manufacture of an aluminum honeycomb structure are shown in Tables 4-10, 4-11 and 4-12 for the materials (M), fabrication (F), and inspection (I) costs for each step of the flow process chart.

Table 4-10

Recurring Costs for Manufacturing Processes—Aluminum Hyc Cylinder—Pressurized

Sequence Number	Cost Item	Thousands of Dollars		
		$FS/FS_{nom} = 1$		
		M	F	I
Cylinder				
1	Receive and Inspect Core	15.5		
2	Receive and Inspect Sheet	27.0		5.0
3	Roll		25.0	
4,5	Clean and Bond		288.0	
6	Machine and Inspect		100.0	44.0
7	Bond Edge Attachments		83.0	
8	Weld Panels		77.0	
9	Inspect Weld			60.5
10	Receive Edge Attach and Adhesive	50.0		
11	Machine Edge Attachments		25.0	
12	Quality Control			25.0
13	Repair Honeycomb		50.0	
14	Assembly		113.0	30.0
	Cylinder Subtotals	(92.5)	(761.0)	(164.5)
	Cylinder Total		(1018.0)	
Head Assembly				
	Head Subtotals*	(22.0)	(645.0)	(65.0)
	Head Total		(732.0)	
Cylinder and Head Subtotals		(114.5)	(1406.0)	(229.5)
	Cylinder and Head Total		(1750.0)	
	Subtotal Percent of Total	6.5%	80.3%	13.2%
	Total Weight (Cylinder 40281 + Head 15935)—lb		56,216 lb 25,500 kg	

*From Table 4-11.

Table 4-11

Recurring Costs for Manufacturing Processes—Aluminum Monocoque Head

Sequence Number	Cost Item	Thousands of Dollars		
		$FS/FS_{nom} = 1.0$		
		M	F	I
Head Segments				
20	Receive and Inspect	22.0		
21	Machine		185.0	
22	Inspect			18.0
23	Form		155.0	
24	Age		30.0	
25	Inspect			15.0
Head Assembly				
26	Assemble		190.0	
27	Trim and Inspect		17.0	
Assembly Head/Cylinder				
28	Assemble, Weld, Trim, Inspect		85.0	15.0
	Head Subtotals	(22.0)	(645.0)	(65.0)
	Head Total		(732.0)	

Table 4-12

Recurring Costs for Manufacturing Processes–Aluminum Hyc Cylinder–Unpressurized

Sequence Number	Cost Item	Thousands of Dollars		
		$FS/FS_{nom} = 1.0$		
		M	F	I
Cylinder				
1	Receive and Inspect Core	110.0		
2	Receive and Inspect Sheet	44.0		
3	Roll		40.0	
4,5	Clean and Bond		460.0	
6	Machine and Inspect		150.0	84.0
7	Bond Edge Attachments		120.0	
8	Weld Panels		112.0	
9	Inspect Weld			88.0
10	Receive Edge Attach and Adhesive	78.5		
11	Machine Edge Attachments		50.0	
12	Quality Control			50.0
13	Repair Honeycomb		80.0	
14	Assembly		100.0	
	Cylinder Subtotals	(232.5)	(1112.0)	(222.0)
	Cylinder Total		(1566.5)	
	Subtotal Percent of Total	14.8%	71.0%	14.2%
	Cylinder Weight		73,784 lb 33,509 kg	

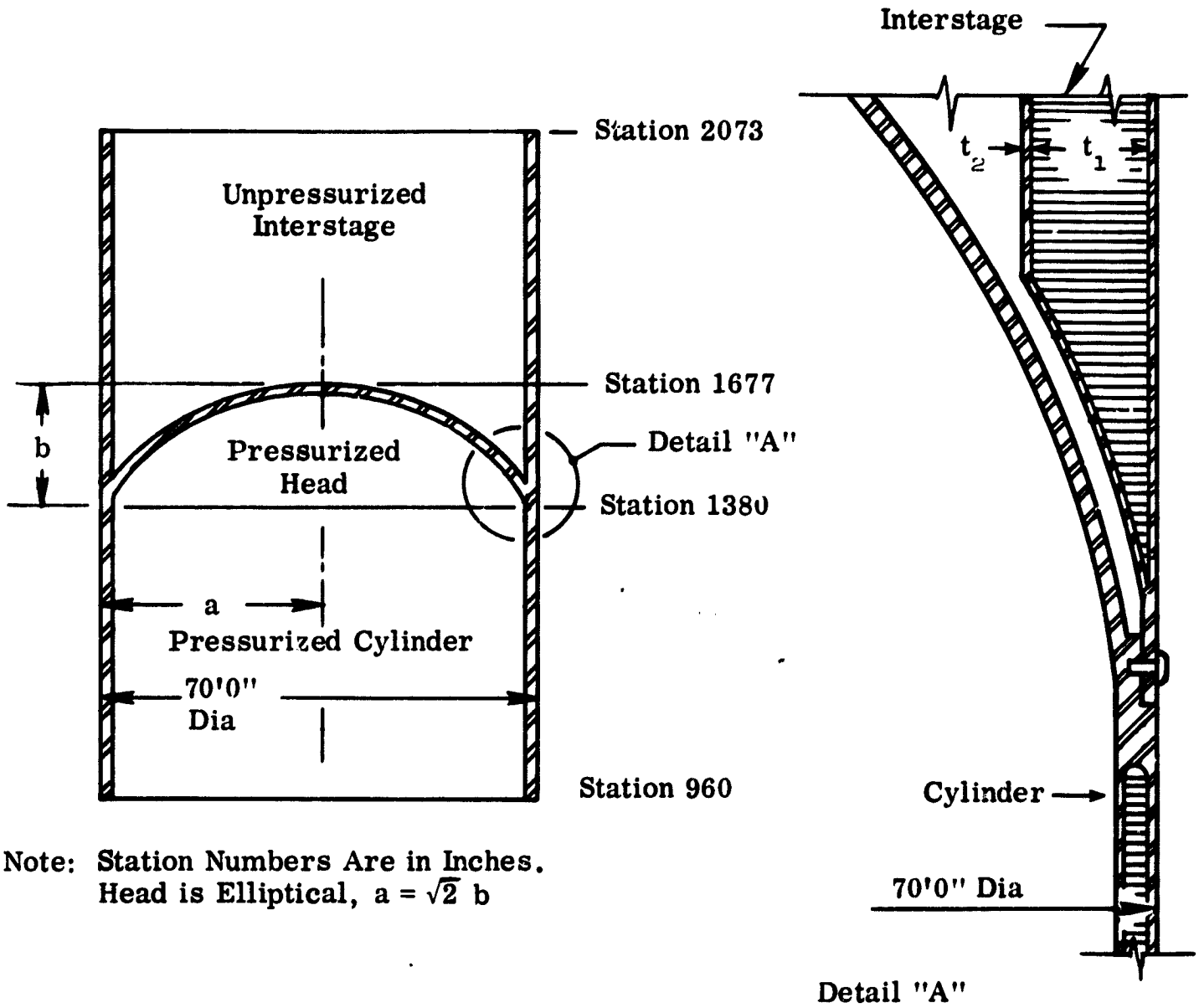
4.3.4 BERYLLIUM HONEYCOMB CONSTRUCTION (BEHYC)

4.3.4.1 General Description and Analysis

The use of beryllium for primary load carrying structures is controversial, but there is general agreement that its unique mechanical properties make it a prime candidate for rigid, lightweight structures where buckling is the primary mode of failure. Its disadvantages are: brittleness, toxicity, fabrication difficulties, and cost. Substantial experience, however, has been gained over the past decade in fabricating and handling beryllium. Its properties and fabrication problems are discussed in Volume 3.

This study considers the materials and fabrication of a honeycomb structure using IS400* powder sheet beryllium face plates and an aluminum core. The design configuration and weights were determined[7] and are tabulated in Figure 4-16.

*The properties of IS400 sheet are assumed to be equivalent to those shown in Table 4-1 for QMV beryllium.



Note: Station Numbers Are in Inches.
Head is Elliptical, $a = \sqrt{2}\ b$

FS/FS_{Nom}	Unpressurized Interstage			
	t_1	t_2	d*	Weight
0.7	4.756	0.068	2.195	27251
1.0 Nom	5.398	0.097	3.135	36965
1.4	5.588	0.136	4.389	51061
2.0	5.872	0.195	6.271	72205

*Maximum Allowable Core Cell Diameter, Inches.

Dimensions are in inches, weights in pounds.

Figure 4-16. Beryllium Honeycomb Construction for Unpressurized Interstage Construction Details and Typical Dimensions for Various FS/FS_{Nom} Values

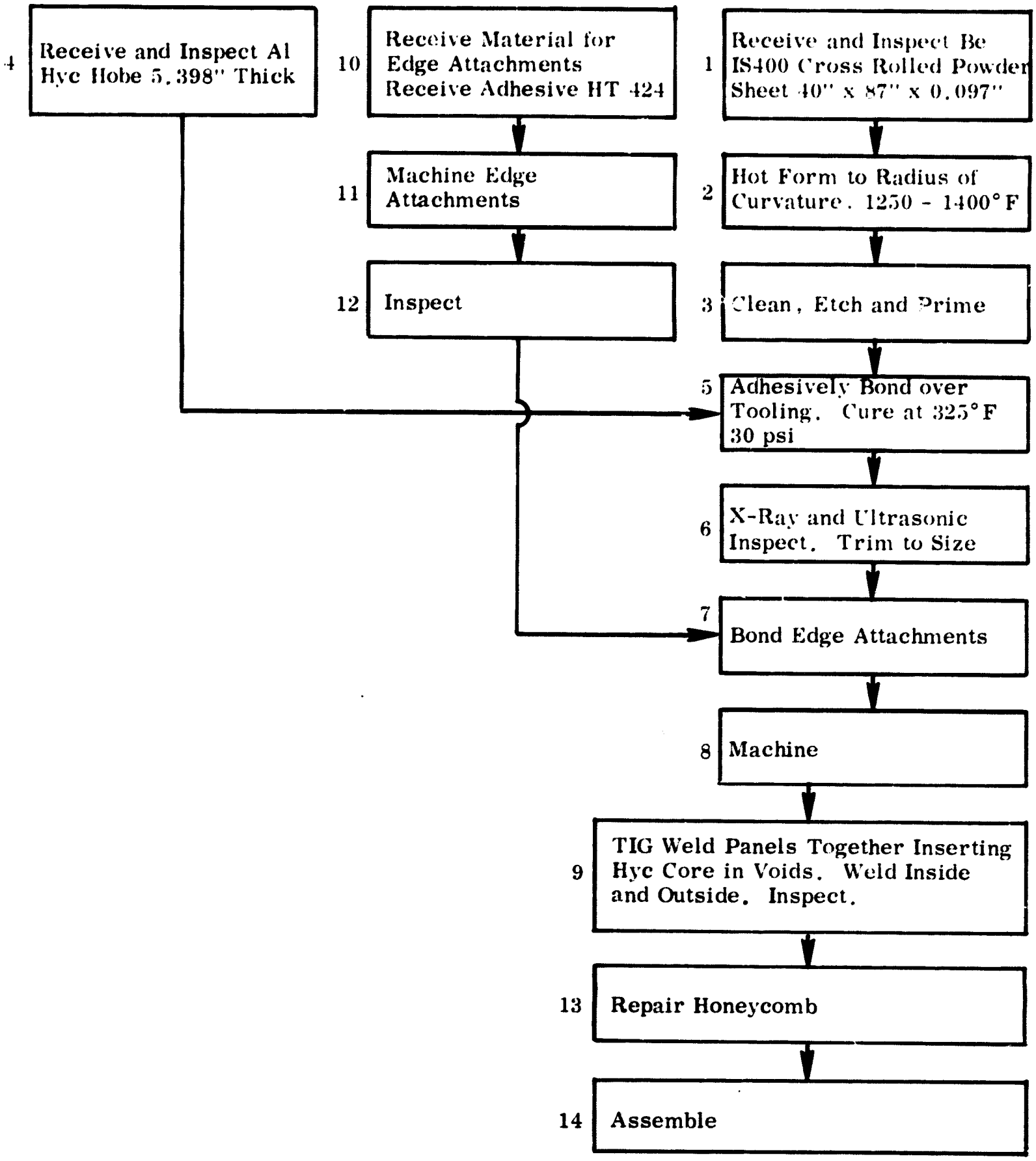
4.3.4.2 Manufacturing Processes—Materials, Fabrication, and Inspection

Manufacturing processes required for the construction of a honeycomb structure which uses an aluminum core and beryllium face plates are shown in Table 4-13.

The steps parallel those used for aluminum honeycomb except that the beryllium sheets are cut to size, hot formed to the radius of curvature at 1250 to 1400° F, and cleaned etched, and primed (steps 1, 2, and 3). The aluminum HOBE is expanded and adhesively bonded over tooling to the beryllium face plates and cured at 30 psi and 325°F. It is then subjected to x-ray and ultrasonic inspection and trimmed to size (steps 4, 5, and 6). Aluminum edge attachments are machined to size and adhesively bonded to the beryllium face plates leaving a two-inch overlap along each edge and then machined for size and edge preparation (steps 10, 11, 12, 7, and 8). Panels are TIG welded together, inserting strips of the core material in the voids between edge attachments. Necessary honeycomb repairs are made, and assembly is completed (steps 9, 13, and 14).

Table 4-13

Flow Process Chart—Manufacture Be/Al Hyc Cylinder—Unpressurized



4.3.4.3 Recurring Costs for Manufacturing Processes

Table 4-14 gives a breakdown of the recurring costs for the unpressurized beryllium/aluminum honeycomb interstage for materials (M), fabrication (F), and inspection (I) costs for each step of the flow process chart.

Table 4-14

Recurring Costs for Manufacturing Processes—
Beryllium/Aluminum Hyc—Unpressurized

Sequence Number	Cost Item	Thousands of Dollars		
		$FS/FS_{Nom} = 1$		
		M	F	I
Cylinder				
1	Receive and Inspect Sheet	2376.5		
2	Hot Form		1810.0	
3,5	Clean, Etch and Bond		460.0	
4	Receive and Inspect Core	103.0		
6	X-Ray and Ultrasonic Inspect			84.0
7	Bond Edge Attachments, Inspect		195.0	138.0
8	Machine		200.0	
9	TIG Weld Panels and Inspect		138.0	176.0
10	Receive Edge Attachments and Adhesive	50.5		
11	Machine Edge Attachments		50.0	
12	Quality Control			50.0
13	Repair Honeycomb		80.0	
14	Assemble		100.0	
	Cylinder Subtotals	(2530.0)	(3033.0)	(448.0)
	Cylinder Total		(6011.0)	
	Subtotal Percent of Total	42.1%	50.5%	7.4%
	Cylinder Weight		36965 lb 16767 kg	

4.3.5 BERYLLIUM STIFFENED SKIN CONSTRUCTION

4.3.5.1 General Description and Analysis

Beryllium stiffened skin construction was included in this study to allow the determination of comparative costs for a more conventional type of construction. Integrally stiffened skin, such as used for aluminum, was investigated for beryllium, but the costs of such a structure were prohibitive due to large amounts of beryllium wasted in the construction. Therefore, the design dimensions were determined for beryllium skin, stiffened internally with channel section rings and externally with hat section stringers. The configuration and dimensions are shown in Figure 4-17. Squeeze rivets are used in structural assembly.

4.3.5.2 Manufacturing Processes—Materials, Fabrication, and Inspection

4.3.5.2.1 Cylinder Walls

Manufacturing processes for beryllium stiffened skin construction are outlined in Table 4-15 which show the sequence of operations required for the beryllium sheet cylinder walls, stringers, and rings. The material under consideration is powder sheet, cross-rolled IS 400 or equivalent. Cylinder wall segments are roll formed at 1250°F to 1400°F to required radius and placed in a transite cooling box (steps 12, 13). They are then machined, drilled, and etched for assembly with the rings and stringers (step 14).

4.3.5.2.2 Rings

Ring material is cut to size (steps 1 and 2), hot formed to a channel section at 1250°F to 1400°F, and then placed in a transite cooling box (steps 3 and 4). The rings are then trimmed, and holes for assembly are machined and etched (steps 5 and 6).

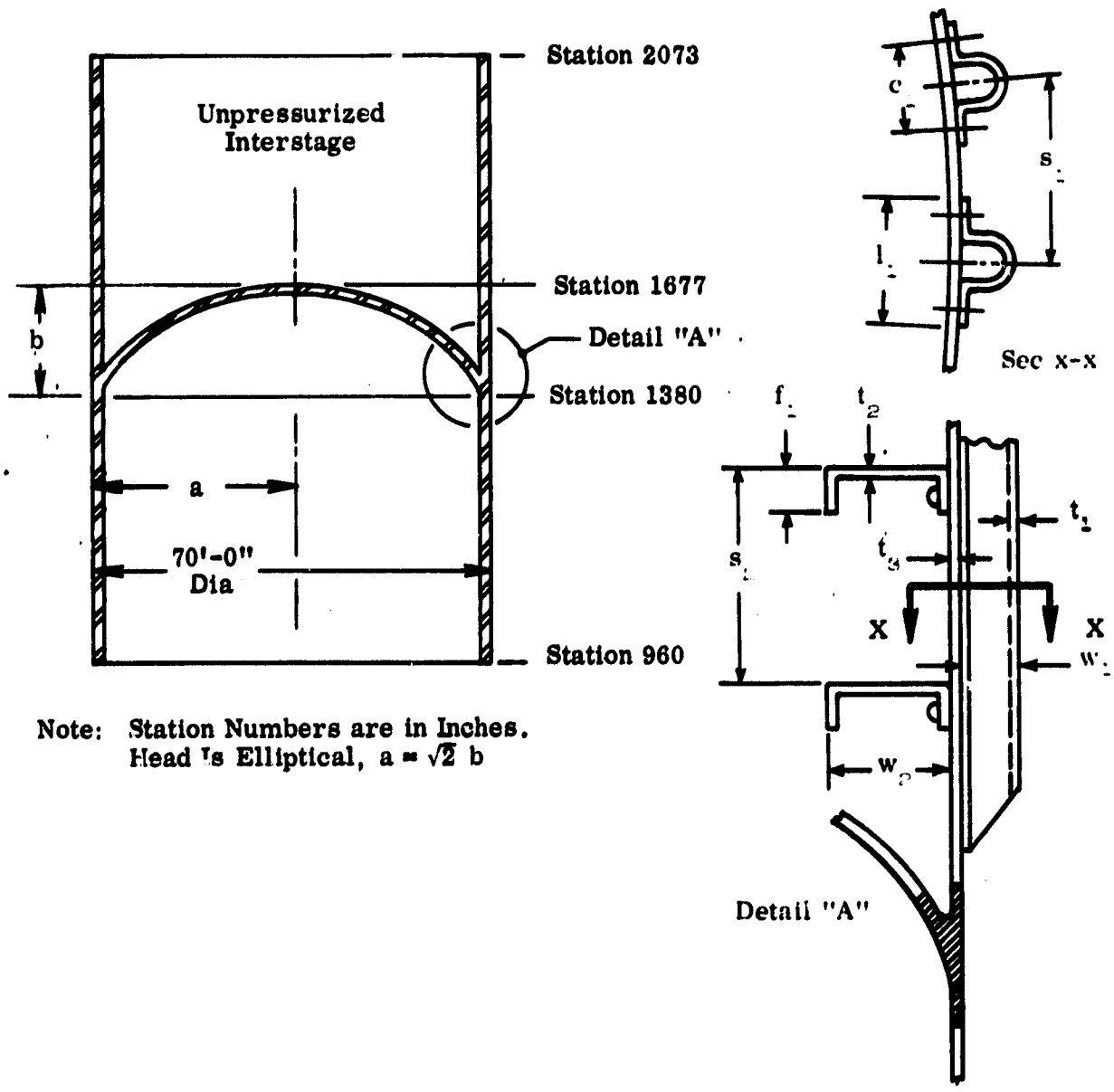
4.3.5.2.3 Stringers

Stringer material is cut to size and hot formed at 1250°F to 1400°F to hat section members (steps 7 and 8). Next, they are removed from the die and placed in a transite cooling box (steps 8 and 9). They are then trimmed and holes are machined and etched for assembly (steps 10 and 11).

4.3.5.2.4 Assembly

Step 15 consists of the assembly of sheets, rings, and stringers using titanium squeeze rivets on threaded fasteners, and step 16 consists of inspection with dye penetrant of stress areas around fastener holes.

Construction Details and Typical Dimensions for Various FS/FS_{Nom} Values



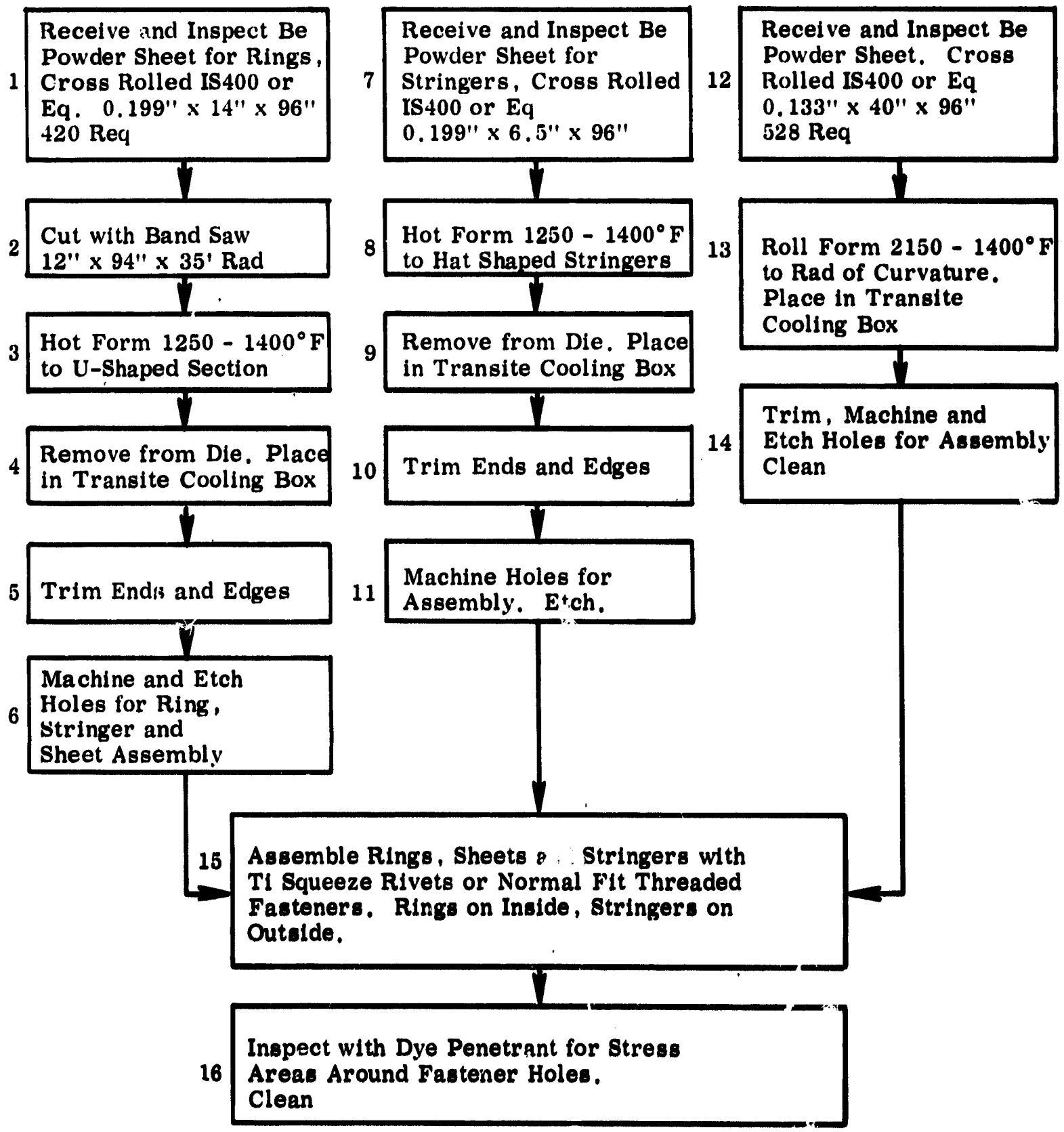
FS/FS Nom	Unpressurized Interstage										
	w_1	w_2	t_1	t_2	t_3	f_1	s_1	s_2	c_1	l_1	Weight
0.7	2.810	5.719	0.100	0.172	0.133	2.289	13.673	30.00	3.200	4.200	34416
0.1 Nom	2.810	6.633	0.100	0.199	0.133	2.654	7.997	45.00	3.200	4.200	40825
1.4	2.810	8.427	0.100	0.253	0.133	3.372	6.239	45.00	3.200	4.200	54895
2.0	2.810	11.119	0.100	0.334	0.133	4.448	4.704	45.00	3.200	4.200	76000

Dimensions are in inches, weights in pounds.

Figure 4-17. Beryllium Stiffened Skin Construction—Unpressurized Interstage

Table 4-15

Flow Process Chart—Manufacture of Beryllium SS—Unpressurized



4.3.5.3 Recurring Costs for Manufacturing Processes

Table 4-16 gives a breakdown of recurring costs associated with the production of an unpressurized beryllium stiffened skin interstage. It shows materials (M), fabrication (F), and inspection (I) costs for each step of this construction.

Table 4-16

Recurring Costs for Manufacturing Processes—
Beryllium SS Cylinder—Unpressurized

Sequence Number	Cost Item	Thousands of Dollars FS/FS$_{Nom}$ = 1		
		M	F	I
Rings				
1	Receive and Inspect Rings	515.0		
2	Machine and Inspect		50.0	20.0
3,4,5	Hot Form, Cool and Trim		868.0	80.0
6	Machine Holes		100.0	
		(515.0)	(1018.0)	(100.0)
Stringers				
7	Receive and Inspect Stringers	1170.0		
8,9,10	Hot Form, Cool and Trim		1656.5	100.0
11	Machine Holes		1000.0	
		(1170.0)	(2656.5)	(100.0)
Skin				
12	Receive and Inspec. Sheet	1550.0		
13	Roll Form, Cool		1100.0	100.0
14	Trim, Machine Holes		1100.0	
		(1550.0)	(2200.0)	(100.0)
Assembly				
15	Receive Fasteners, Assemble	300.0	2900.0	
16	Dye Penetrant Inspect			300.0
		(300.0)	(2900.0)	(300.0)
	Cylinder Subtotals	(3535.0)	(8774.5)	(600.0)
	Cylinder Total		(12909.5)	
	Subtotal Percent of Total	26.9%	68.0%	4.6%
	Total Weight, Cylinder		40825 lb 18518 kg	

4.3.6 TITANIUM HONEYCOMB CONSTRUCTION (TIHYC)

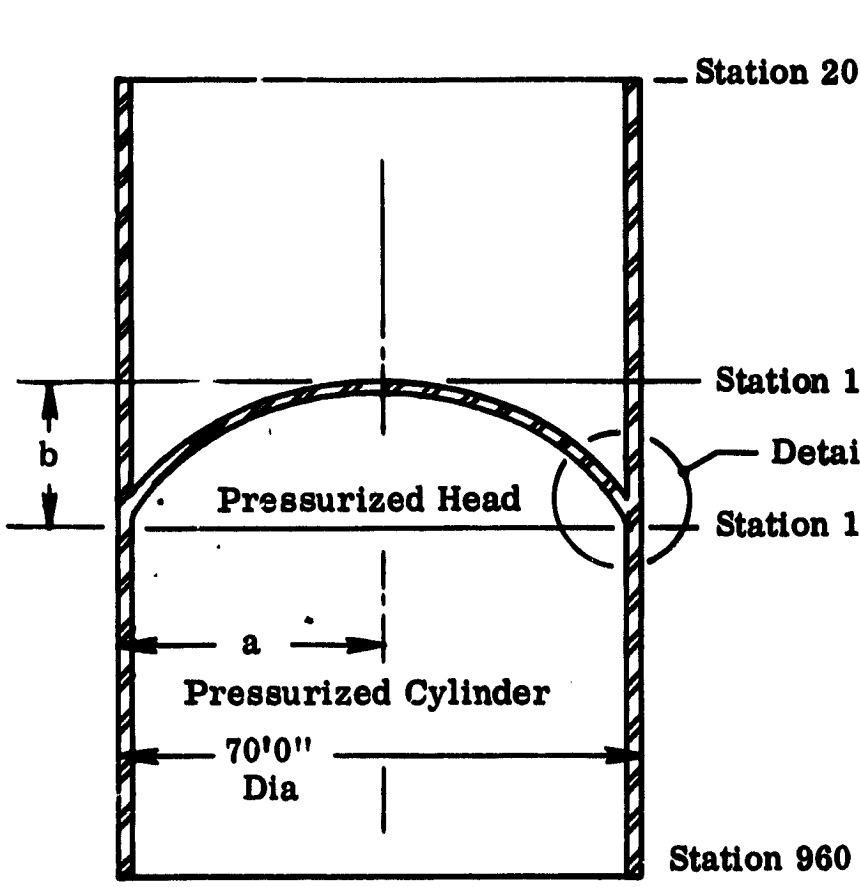
4.3.6.1 General Description and Analysis

Several difficulties still exist in the use of titanium, particularly in the machining, joining, and forming of the metal, but suitable techniques have emerged as a result of contracts by the U.S. Government for titanium development so that there is general acceptance of the material in the aerospace industry. The following pages describe the materials, fabrication processes, and costs associated with the construction of a large pressurized titanium honeycomb cylinder and a titanium monocoque head. Dimensions were determined by methods given in Reference 7.

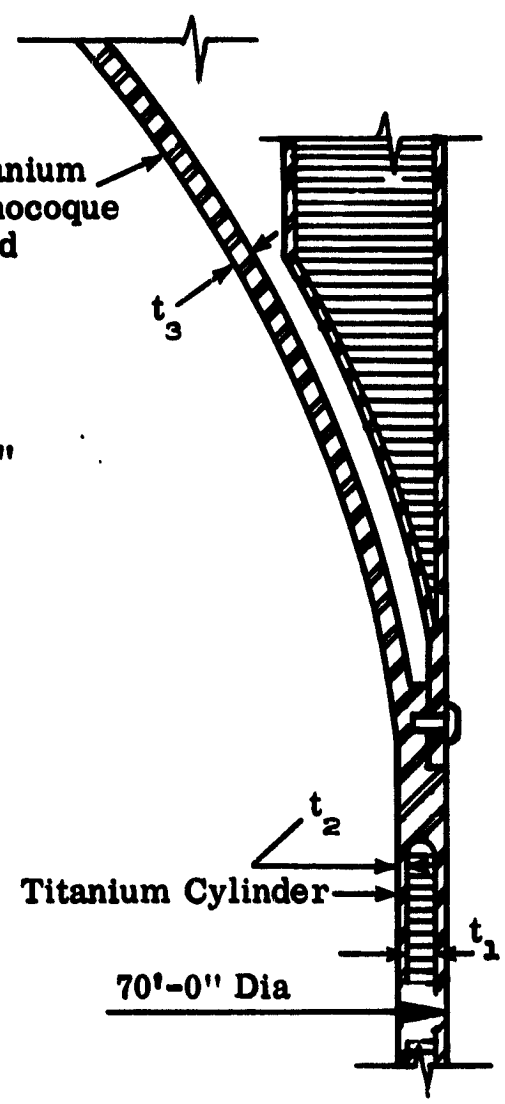
The honeycomb construction selected for this design was "stresskin", a process developed by Stresskin Products Division of Tool Research and Engineering Corporation. In this process, attachment of the core ribbons to each other and to the face sheets is obtained by resistance spot welding, progressively, as the panel is assembled. Panels are then diffusion bonded in a vacuum autoclave. A more conventional honeycomb construction was also considered, as a basis of comparison, but the stresskin construction appeared preferable for ease of fabrication and assurance of quality.

Construction details and typical dimensions for the titanium honeycomb pressurized cylinder and titanium monocoque head are shown in Figure 4-18.

Construction Details and Typical Dimensions for Various FS/FS_{Nom} Values



Note: Station Numbers Are in Inches.
Head Is Elliptical, $a = \sqrt{2}\ b$



Detail "A"

FS/FS_{Nom}	Pressurized Cylinder				Head		Total Weight
	t_1	t_2	d*	Weight	t_3	Weight	
0.7	2.060	0.040	1.286	22625	0.057	7187	29812
1.0 Nom	2.061	0.057	1.837	30189	0.081	10268	40457
1.4	2.062	0.080	2.572	40271	0.113	14375	54646
2.0	2.063	0.115	3.674	55394	0.162	20536	75930

d* = Maximum Allowable Core Cell Diameter, Inches.

Dimensions are in inches, weights in pounds.

Figure 4-18. Titanium Honeycomb (Stresskin) Construction—Pressurized Cylinder and Titanium Monocoque Head

4.3.6.2 Manufacturing Processes—Materials, Fabrication, and Inspection

4.3.6.2.1 General

Table 4-17 outlines the manufacturing processes required for the construction of a titanium honeycomb pressurized cylinder and a titanium monocoque head. A brief description of these processes follows:

4.3.6.2.2 Cylinder Walls

Cylinder material 5AL-2.5 SN ELI titanium is cut to size. C.P. titanium ribbon is fed through a forming machine to obtain cores in strip form. The core strips are resistance welded at nodes and welded to the face sheets to form honeycomb panels (steps 1, 2, 3, and 4). The panels are diffusion bonded in a vacuum furnace at 1600° F over ceramic tooling where they are formed to the required radius of curvature and trimmed to size (steps 5 and 6). After 100 percent x-ray inspection of the bond, mechanical properties tests are performed on trimmings, and the panels are TIG welded (steps 7 and 8). The welded joints are then mechanically stress relieved and submitted to Quality Control for inspection.

4.3.6.2.3 Head

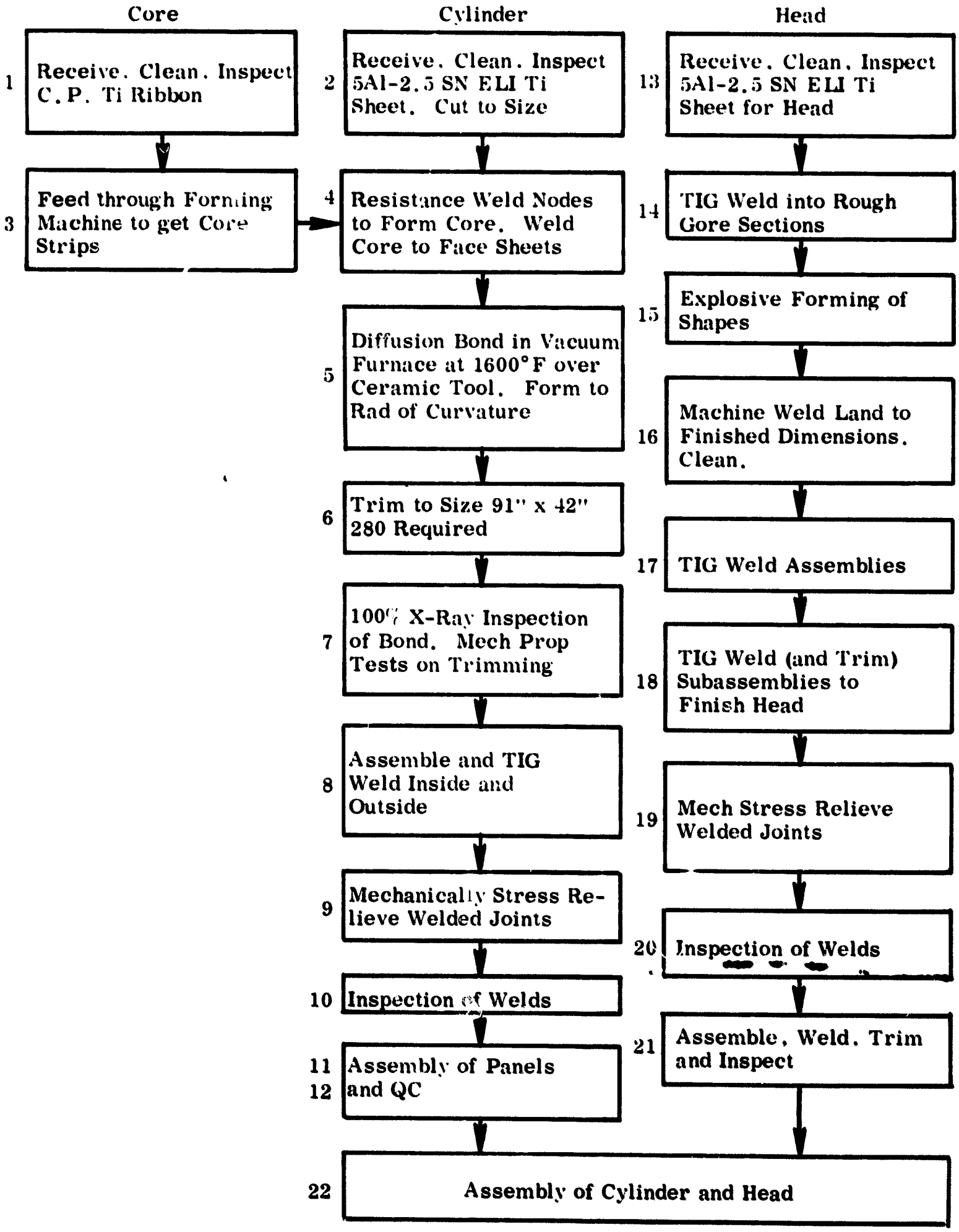
Head material 5AL-2.5 SN ELI titanium is cut and TIG welded into rough gore sections (steps 13 and 14). Segments are subjected to explosive forming and machined to finished dimensions (steps 15 and 16). Subassemblies are then TIG welded together, the joints are mechanically stress relieved and assemblies are trimmed and inspected (steps 17 through 21).

4.3.6.2.4 Assembly

The cylinder assembly and head assembly are TIG welded or mechanically attached to the "Y" ring adapter (step 22).

Table 4-17

Flow Process Chart—Manufacture of Titanium Hyc Cylinder and Monocoque Head—Pressurized



4.3.6.3 Recurring Costs for Manufacturing Processes

Recurring costs for the manufacture of a titanium pressurized cylinder and titanium monocoque head are tabulated on the following pages in Tables 4-18 and 4-19 for materials (M), fabrication (F), and inspection (I).

Table 4-18

**Recurring Costs for Manufacturing Processes--
Titanium Hyc Cylinder—Pressurized**

Sequence Number	Cost Item	Thousands of Dollars $FS/FS_{Nom} = 1$		
		M	F	I
Cylinder				
1, 2, 3, 4, 5, 6	Receive and Inspect Ribbon, Sheet, Form Stressskin Panels, Diffusion Bond	300.0	1213.0	100.0
7	and Inspect			
8	TIG Weld		94.0	
9	Stress Relieve		75.0	
10	X-Ray and Ultrasonic Inspect			74.0
11	Assembly of Panels		100.0	
12	Quality Control			25.0
22	Assemble With Head		113.0	30.0
	Cylinder Subtotals	(300.0)	(1595.0	(229.0)
	Cylinder Total		(2124.0)	
	Head Subtotals*	(144.0)	(678.0)	(80.0)
	Head Total		(902.0)	
	Total Cylinder and Head		(3026.0)	
	Cylinder and Head Subtotals	(444.0)	(2273.0)	(309.0)
	Subtotal Percent of Total	14.7%	75.1%	10.2%
	Total Weight (Cylinder 30189 + Head 10268)—lb		40457 lb 18351 kg	

Table 4-19

Recurring Costs for Manufacturing Processes—
Titanium Monocoque Head

Sequence Number	Cost Item	Thousands of Dollars $FS/FS_{Nom} = 1$		
		M	F	I
<u>Head</u>				
13	Receive and Inspect Segments	144.0		
14, 17, 18	Weld		18.0	
15	Form Gores		275.0	25.0
16	Machine Gores		275.0	25.0
19	Mech. Stress Relieve		25.0	
20	Quality Control			15.0
<u>Assembly</u>				
21	Assemble, Weld, Trim and Inspect		85.0	15.0
	Head Subtotals	(144.0)	(678.0)	(80.0)
	Head Total		(902)	

4.4 COMPOSITE CONSTRUCTION—DESCRIPTION AND ANALYSIS

4.4.1 GENERAL DISCUSSION

4.4.1.1 Background and Scope

4.4.1.1.1 Introduction

An area of substantial promise for an increase in launch vehicle payload capacity is the use of advanced materials in the primary structure. Of particular interest are the composite materials available today because of their capability of being "tailor made" with the desired combination of properties to fit the application which is not available in any single material. Previous work[135] has indicated the efficiency of filament wound composites for cylinders under axial compression because of just such a combination of properties. The combination of the high tensile strength and modulus of elasticity of the various fibers combined with the low density of available matrix materials results in particularly high strength-to-density and modulus-to-density ratios for the resulting composites. More recent advances in strength and modulus of filamentary materials have enhanced their potential use in filament composite wound pressure vessels such as propellant tanks.

Because the advent of fibrous composites into the field of major structural components is a relatively recent development, many unforeseen problems could be encountered in their use. An example of specific problems which may be encountered are chemical reactions between the fibers and matrix materials at elevated temperatures, insufficient bonding of the fibers to the matrix material, and difficulty in aligning the fibers in the matrix as desired. There is also a need to develop more adequate techniques for joining fabricated sections of fibrous composites and testing them nondestructively. It is clear that much research will be necessary to develop these materials to the point where they are competitive with more conventional materials for general widespread use. However, because of their obvious potential, a large number of research programs, sponsored by both Government and private enterprise, are currently in progress, and the technology is expanding rapidly.

Development necessary for these materials to be seriously considered in studies of major space hardware structural components has been attained. This current study endeavors to remain within presently available and near future state-of-the-art techniques. The intended purpose of the study to evaluate an optimum combination of

minimum structural weight and comparative costs of stiffened fibrous composite shells as a function of design load and overall structural geometry will also be pursued for these composite materials.

4.4.1.1.2 Configuration Selection

Two principal structural configurations in Section 4.3 were selected for the composite unpressurized cylindrical shell sections, honeycomb and stiffened metallic shell. The fibrous composite honeycomb shell with an aluminum core was selected to represent the general case of efficient construction for each of the composite materials selected. The core was assumed to have adequate stiffness to stabilize the face sheets but carried no load. A pseudo-isotropic (+60°, 0°, -60°) laminate winding pattern was selected for the face sheets, as illustrated in Figure 4-19. Previous studies have indicated that this isotropic pattern is most efficient when elastic stability is the governing design criterion and in regions where axial compression is combined with internal pressure loading of the cylinders.

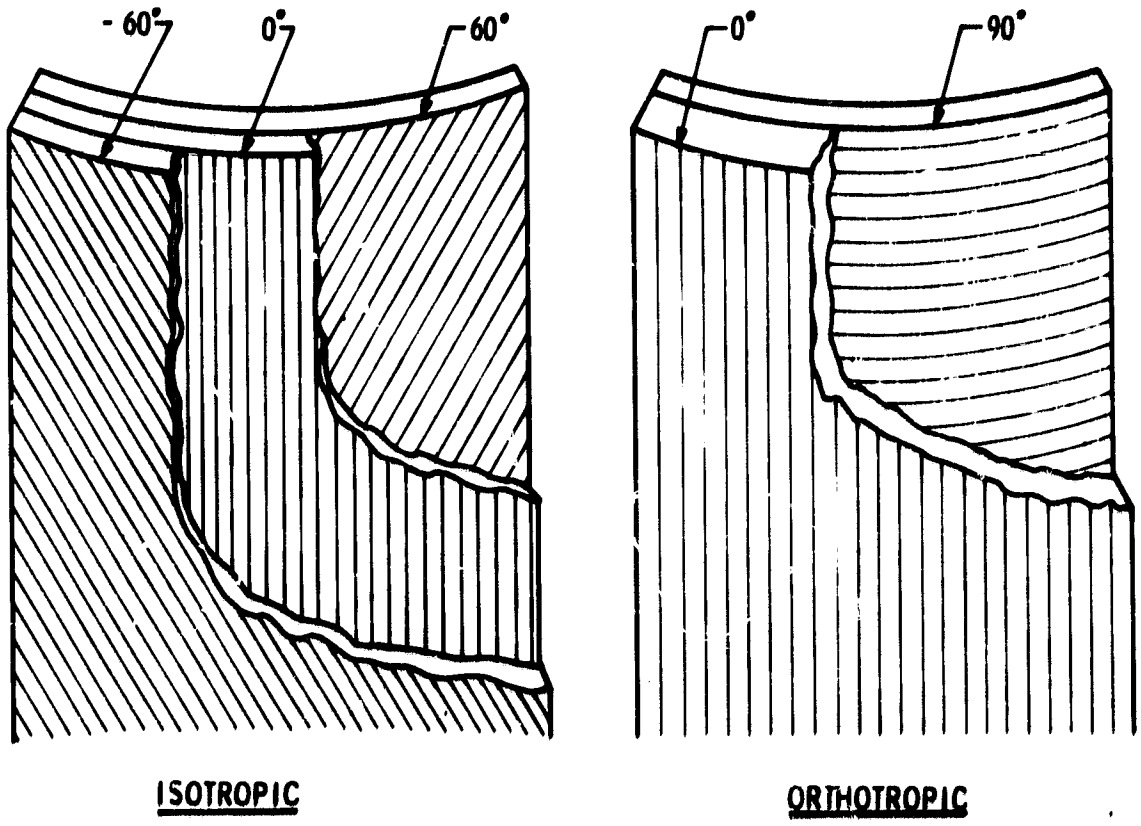


Figure 4-19. Typical Composite Winding Patterns

For high axial loads where strength is the governing criterion, a 0°-90° laminate with most of the fibers in the direction of the load is more efficient; however, for simplicity this study was limited to the single pattern most efficient in the broadest range of

loading modes. Table 4-20 presents the structural weight parameter for stability and the axial yield strength (in compression) of various laminate winding patterns. This subject is covered in more detail in the discussion of the interaction curves and efficiency curves in the next section.

Of the composites selected, only boron/aluminum was considered practical for the pressurized cylindrical honeycomb shell. Leakage of propellants becomes a problem with the epoxy binder used in the other two composite materials.

The second structural configuration selected as a reference point for comparison was a combination of boron/epoxy stiffeners on an aluminum monocoque shell. This configuration was considered in both the pressurized and unpressurized cylindrical shell section as well as the pressurized head. This combination of a fibrous composite with a metallic shell appears to provide some of the more desirable properties of each. Specifically, it reduces the problems inherent in the fabrication and assembly of a honeycomb cylindrical structure of large dimensions. It also eliminates the leakage problem mentioned earlier with fiber/epoxy composites. A typical arrangement of these stiffeners on the metal is shown in Figure 4-20.

4.4.1.1.3 Summary

In summary, the following material and configuration combinations were selected for Phase II of this study in the area of composite fibrous materials:

a. Boron/epoxy honeycomb walls with aluminum core in unpressurized vehicle sections, titanium honeycomb walls in pressurized tanks, and titanium monocoque heads.
b. Carbon/epoxy honeycomb walls with aluminum core in unpressurized vehicle sections, titanium honeycomb walls in pressurized tanks, and titanium monocoque heads.
c. Unidirectional stiffeners of boron/epoxy on aluminum monocoque walls and heads for both pressurized and unpressurized sections.
d. Boron/aluminum composite honeycomb with aluminum core in pressurized and unpressurized walls, boron/aluminum composite monocoque heads.

These combinations seem to be most representative of present and near future advancements which could find application in large launch vehicles. Sufficient data exist in each of the technologies selected to allow a meaningful analysis to be made. Very

Table 4-20
Properties of 0°-90° and "Isotropic" Laminates

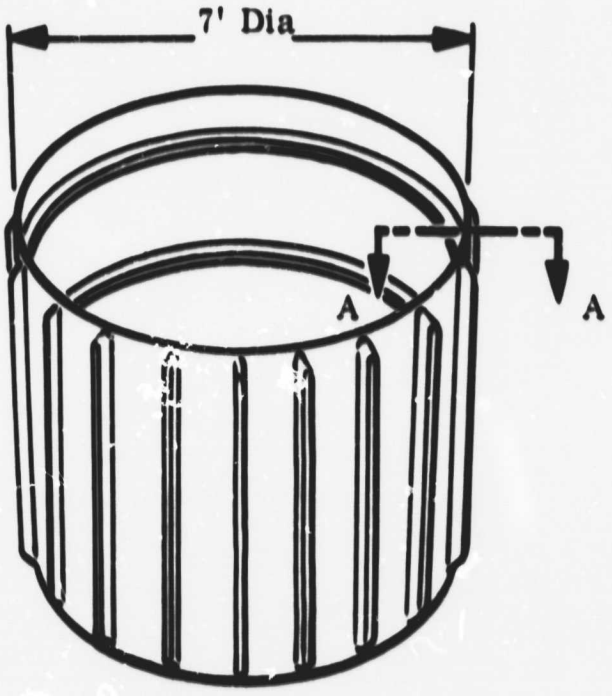
Laminate Configuration	Glass/Epoxy		Boron/Epoxy		Boron/Aluminum	
	σ_y, psi	f, $(lb)^{1/2}/(ft)^2$	σ_y, psi	f, $(lb)^{1/2}/(ft)^2$	σ_y, psi	f, $(lb)^{1/2}/(ft)^2$
0°-.7 t	$35.1x10^3$	0.00781	$107x10^3$	0 00538	$93.5x10^3$	0.00262
0°-.75t	$36.9x10^3$	0.00784	$114x10^3$	0.00543	$95.0x10^3$	0.00262
0°-.8 t	$38.7x10^3$	0.00789	$121x10^3$	0.00550	$96.5x10^3$	0.00262
0°-.85t	$40.6x10^3$	0.00795	$128x10^3$	0.00560	$98.2x10^3$	0.00262
0°-.9 t	$42.7x10^3$	0.00802	$136x10^3$	0.00574	$100x10^3$	0.00262
0°-.95t	$44.6x10^3$	0.00811	$144x10^3$	0.00594	$102x10^3$	0.00262
0°-t	$46.9x10^{3*}$	0.00822	$155x10^{3*}$	0.00628	$103x10^{3*}$	0.00262
Isotropic	$37.8x10^3$	0.00632	$81.4x10^3$	0.00339	$93.0x10^3$	0.00252

*Limiting Value as $t_{90°} \rightarrow 0$

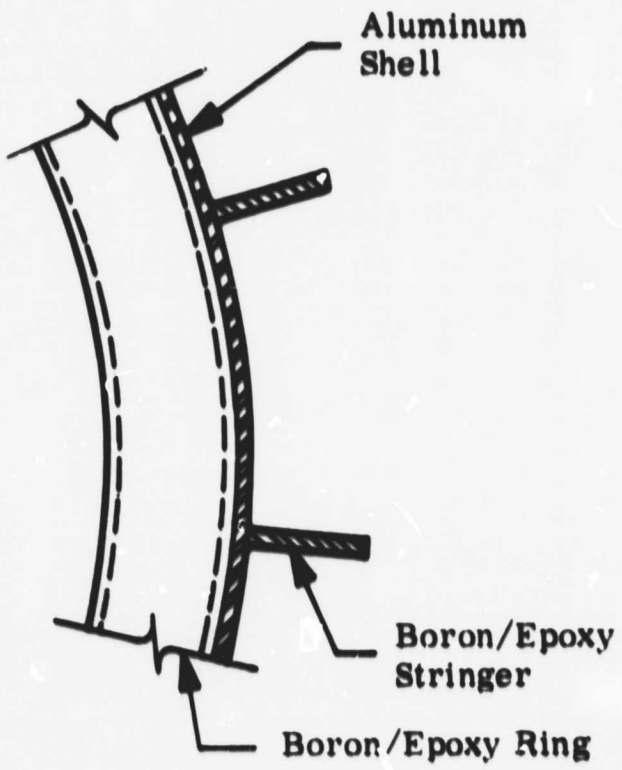
For Monocoque Shells $\frac{W}{R} = f\frac{N_x^{1/2}}{R}$

σ_y = yield stress in compression

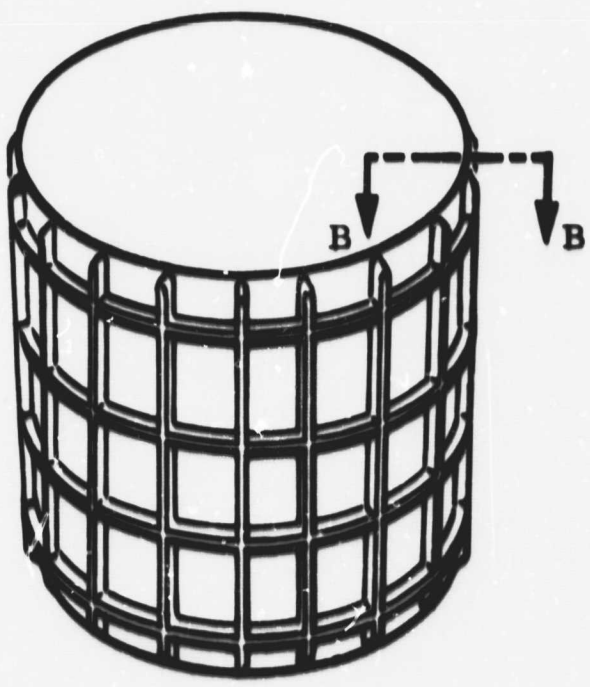
t = thickness of 0° laminate



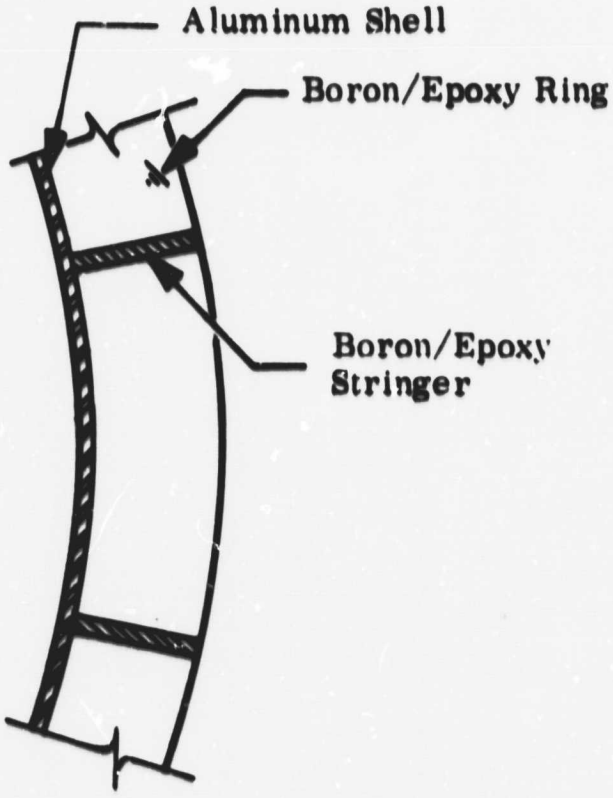
Internal Rings



Section A-A



External Rings



Section B-B

Figure 4-20. Boron/Epoxy Stiffeners on an Aluminum Shell

advanced technologies, such as the use of whiskers, are not included because sufficient data are not available to form a meaningful basis for determining economic factors and for completing a comprehensive analysis.

4.4.1.2 Material Properties

4.4.1.2.1 Introduction

Material properties are calculated for the fibrous composites for each specific installation to take maximum advantage of their unique properties. In general, these composite materials are extremely efficient in terms of strength and stiffness per unit weight under tensile or compressive loads applied parallel to the fiber direction. Since those materials exhibit maximum strength and stiffness along the direction of the fiber length, a truly tailor-made material can be obtained by aligning the fiber to satisfy specific design requirements. A wide range of directional properties is possible, depending upon fiber direction and concentration and, of course, upon the properties of the fiber and matrix material.

Efficient application of composite materials to a specific structure requires proper selection of both pattern and material. In previous studies[41], the effects on the structural efficiency of boost vehicle shells were investigated. The materials selected for this study are based primarily upon conclusions of that study. A summary of the material technology areas selected, along with the advantages and disadvantages of each, is presented in Appendix C.

4.4.1.2.2 Materials Selected

The composites chosen for consideration in this program are: carbon fibers in an epoxy binder, a representative, present-day material that has already been used for similar applications; boron fiber/epoxy composite which represents the stiffest continuous fiber available and a matrix which can be readily fabricated into composite; and finally, a boron filament/aluminum composite which represents an advanced composite now available and a matrix which can be readily fabricated into composite; and finally, a boron filament/aluminum composite which represents an advanced composite now available in laboratory form. These materials were chosen to represent the spectrum of properties readily foreseeable for future use. Properties of the above constituents are present in Table 4-21. The composites formed by arranging a parallel set of fibers in the matrix (a uniaxial composite) are transversely isotropic and have five independent elastic moduli. These are evaluated by previously mentioned methods[136]. The average

of the upper and lower bounds of the elastic moduli in that reference are used, and the results are presented in Table 4-22. These are the properties of the individual lamina used to construct the various laminates studied during this program. The strengths of these laminates are also presented in Table 4-22. Shear and transverse composite strengths were assumed to be equal to the matrix strengths[137]. Longitudinal tensile strengths were based on experimental data[138] and longitudinal compressive strengths were computed.

For the present compression application, the important properties are the elastic stiffnesses and the compressive strengths. These properties are governed primarily by fiber modulus, binder moduli, and binder yield strength[136,138]. Since the boron and and carbon fibers are very close in stiffness to other available high modulus fibers and whiskers, the results for carbon/epoxy, boron/epoxy, and boron/aluminum composites can be considered representative of other composites having the given matrix material.

4.4.2 TECHNICAL APPROACH

4.4.2.1 General

The analytical techniques used in determining the foregoing material properties and the application of those materials in composite structures are detailed in Reference 1 and Appendix E. A brief summary of the computational methods and approach is provided in this section. Specific results using this analysis are collected and presented for each material in the following sections.

4.4.2.2 Summary of Analysis Procedure for Composite Honeycomb Shells

The analysis procedure for composite honeycomb shells includes a series of calculations which first characterized the material and then determined the specific design configuration and weight. These steps include the following activities:

a. Specific structural components for study were selected, specifying shape, loads, pressures, and other constraints.
b. Constituent material properties were selected from Phase I study.
c. Physical characteristics of the most promising composite laminates were determined.
d. Winding patterns were investigated and selected.
e. Yield surfaces were determined for selected materials and patterns.

f. Efficiency curves were constructed for selected materials.
g. Weights were tabulated, manufacturing processes were determined and costed.
h. Final characteristics were compared and tabulated to obtain vehicle costs.

The specific structural configuration best suited for the loads characterized the material requirements for each application. Determination of this configuration involved, first, the investigation of alternate winding methods, fiber orientation, materials, and other design constraints. For each material with a selected volume percent of filament and winding pattern, a yield surface is determined. One such yield surface is shown in Figure 4-21 for boron/epoxy for combined tension and compression loads. These yield curves can be used to generate some of the material properties such as shown in Tables 4-21 and 4-22. Computer programs[1] were used to determine the efficiency curves for the selected filamentary composite material. An example of these efficiency curves is shown in Figure 4-22 for boron/epoxy composite with isotropic winding. These efficiency curves were established through parametric relationships between the stress resultants and the critical loads envelope. The value for N_x/t of 79,000 psi, identified on Figure 4-21, is the value entered and identified in Table 4-22 for an interaction yield for an unpressurized cylinder of 60/40 boron/epoxy.

Figure 4-22 is concerned with the composite material boron/epoxy with an isotropic (-60°, 0°, 60°) winding pattern. Curves were plotted for monocoque construction as well as for honeycomb sandwich construction with a core density of 0.001 pounds per cubic inch and 0.005 pounds per cubic inch. Various ratios of N_y and N_x are examined in order to obtain the structural weights of pressurized cylinders.

From these efficiency curves and dimensions, weights were readily determined for each section. Wall configuration dimensions were similarly determined during the above calculations. The manufacturing processes were then defined in consultation with manufacturing personnel and consultants. Manufacturing and material costs were determined then inspection and test requirements were evaluated and costed. The final results including weight and costs, were compared with other materials to evaluate the technical and economic feasibility of composites in relation to other materials.

The specific details for each of the materials considered in this study are included in the following sections.

Table 4-21

Properties of Fibers and Matrix Materials

Property	Boron	Glass	Carbon	Aluminum	Epoxy	Thornel 50 (Carbon)
Density (ρ), lb/in^3	0.083	0.0914	0.072	0.100	0.05	0.072
Poisson's Ratio (ν)	0.20	0.20	0.18	0.315	0.35	0.18
Youngs Modulus (E), psi	60×10^6	16×10^6	60×10^6	10.7×10^6	0.5×10^6	50×10^6
Shear Modulus (G), psi	2.5×10^7	-	-	4.05×10^6	-	-

Table 4-22

Properties of Fibrous Composite Materials

Property		Boron/ Aluminum 50/50 (I) *	Boron/ Aluminum 50/50 (O)	Carbon/ Epoxy 60/40 (O)	Carbon/ Epoxy 60/40 (I) *	Boron/ Epoxy 60/40 (O)	Boron/ Epoxy 60/40 (I) *	Thornel/ Epoxy 60/40 (O)	Thornel/ Epoxy 60/40 (I)
Density (ρ), lb/in^3		0.0915	0.0915	0.0632	0.0632	0.0698	0.0698	0.0632	0.0632
Poisson's Ratio	(ν_{LT})	0.2750	0.1715	0.0166	0.326	0.01755	0.327	0.0198	0.296
	(ν_{TL})	0 2750	0.2408	0.0960	0.326	0.1013	0.327	0.0168	0.324
Youngs Modulus, psi	(E_{Tan})	2.654×10^7	2.432×10^7	5.697×10^6	13.4×10^6	5.697×10^6	13.39×10^6	5.08×10^6	10.39×10^6
	(E_{Long})	2.654×10^7	3.415×10^7	32.87×10^6	13.4×10^6	32.88×10^6	13.39×10^6	27.47×10^6	11.39×10^6
Shear Modulus (G) psi		10.41×10^6	8.62×10^6	0.72×10^6	5.05×10^6	0.72×10^6	5.05×10^6	0.72×10^6	3.88×10^6
Effect Stiffness ($\overline{E}$) psi		27.6×10^6	29.43×10^6	13.70×10^6	14.17×10^6	13.7×10^6	14.17×10^6	11.83×10^6	11.44×10^6
Interaction Yield, psi Unpressurized		96,000	105,000	146,000	79,000	146,000	79,000**	124,000	68,000

$$\overline{E} = \left(\frac{E_{Long} \times E_{Tan}}{1 - \nu_{LT} \nu_{TL}} \right)^{\frac{1}{2}}$$

(I) = Isotropic

(O) = Orthotropic

* Composites Analyzed in the Final Cost Study

** Value Obtained from Figure 4-21

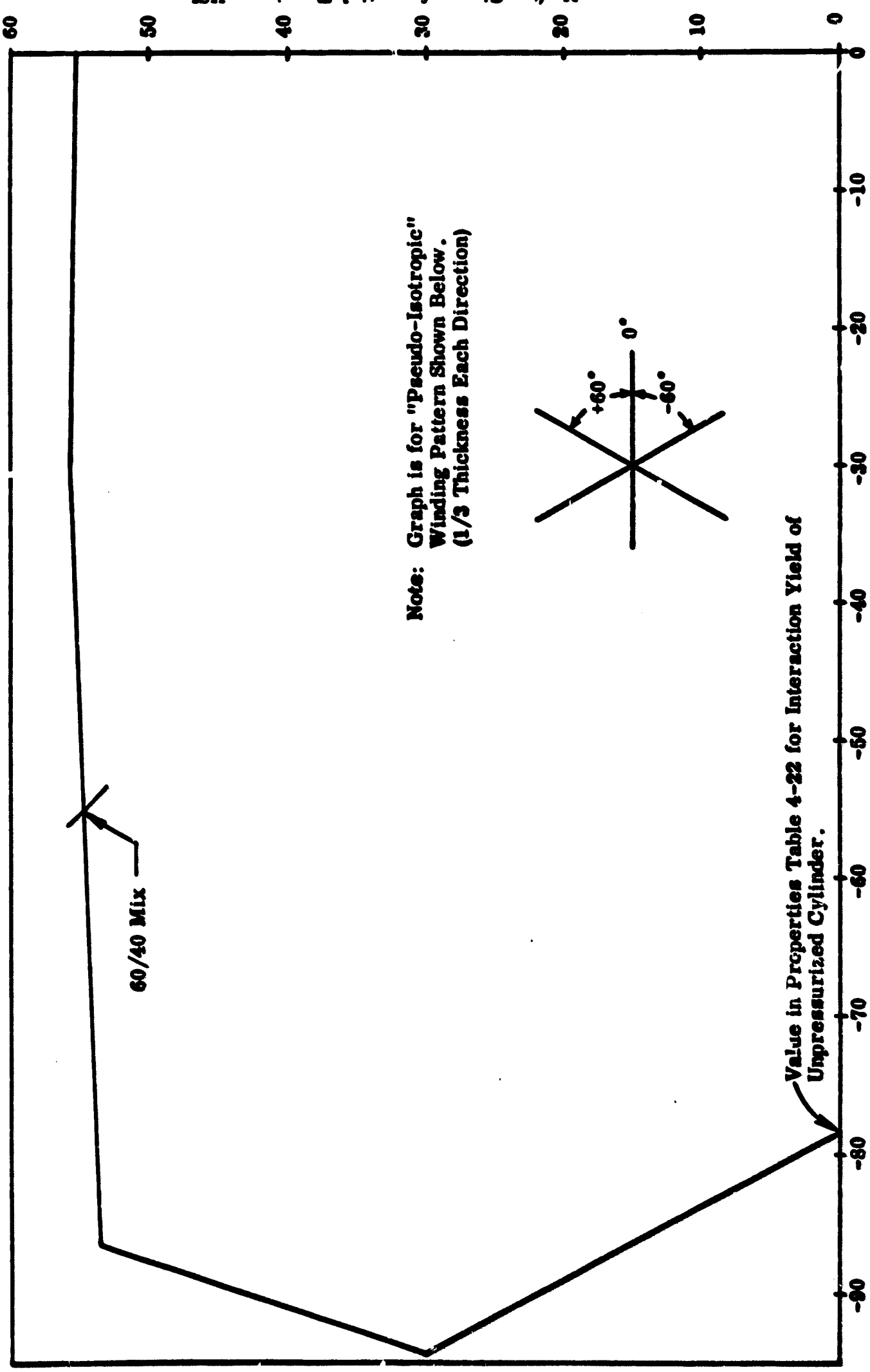


Figure 4-21. Interaction Curves (Yield Surfaces) for Boron/Epoxy Composite Laminates

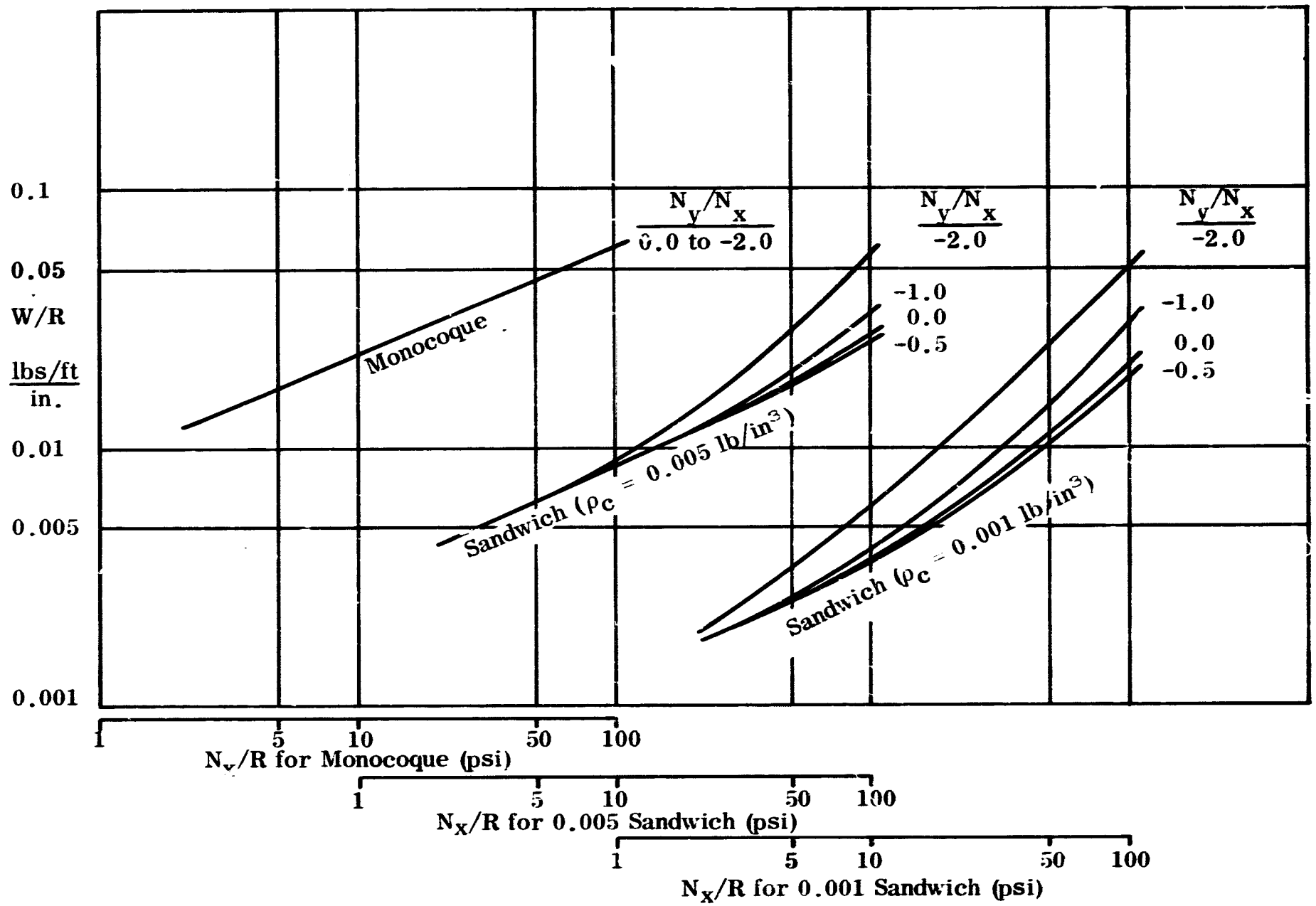


Figure 4-22. Weight/Load Relationship, Boron/Epoxy with Isotropic Winding

4.4.3 BORON/EPOXY FILAMENTARY COMPOSITE HONEYCOMB CONSTRUCTION

4.4.3.1 General Description and Analysis

As in the metallic structures section of this report, the typical 201 launch vehicle component sections were taken as the baseline for a comparative study of boron/epoxy fibrous composite as a structural material.

Boron/epoxy honeycomb was utilized in this study for the unpressurized section only. This was due to potential environmental and leakage problems associated with epoxy in pressurized tanks. Instead, for the pressurized sections, titanium honeycomb was used in the cylindrical walls along with a titanium monocoque tank head.

4.4.3.2 Manufacturing Processes

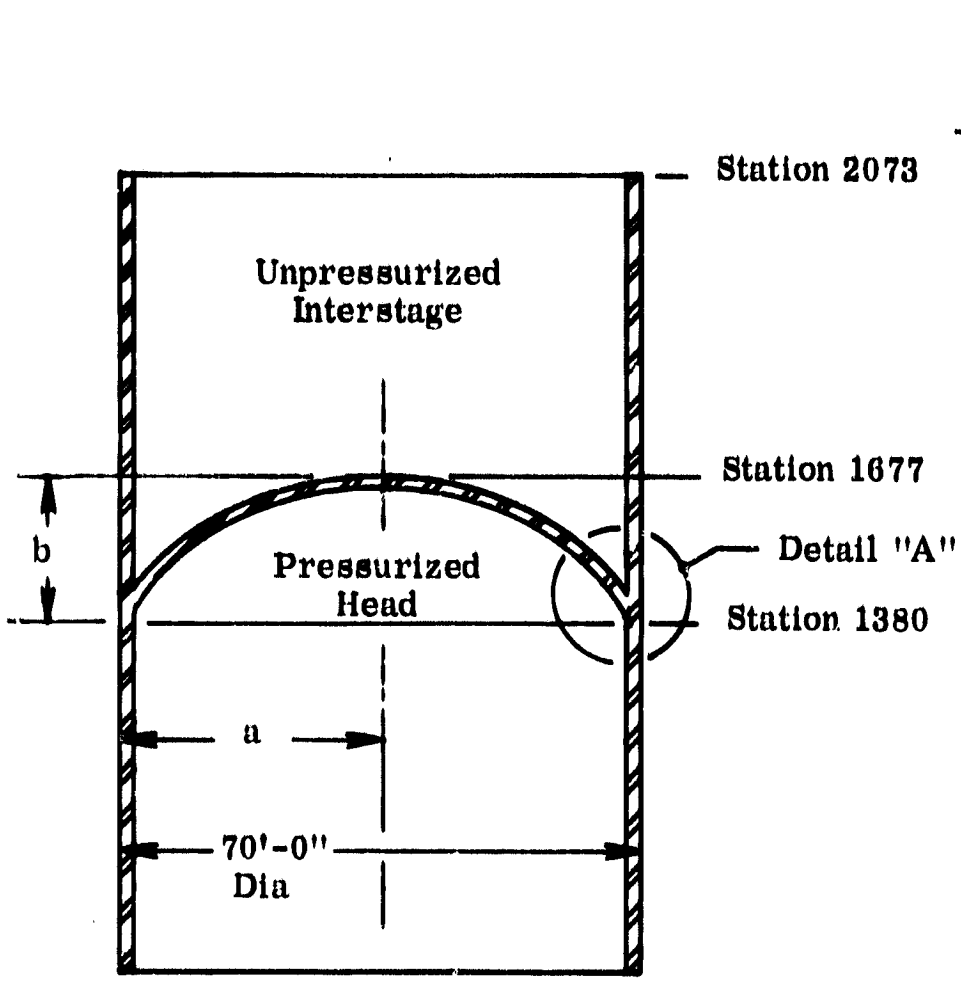
The boron/epoxy fiber is used in 4-inch wide impregnated tape form. Although structure of the size of the one in question have not yet been fabricated from this material, it appears to be practical in every respect. The following manufacturing process forms the basis for this portion of the study (see also Table 4-23).

The inner honeycomb shell is formed by winding the pre-impregnated tape on a steel mandrel to the desired thickness, curing, and covering with an adhesive film. The expanded aluminum honeycomb core is put in place over this inner skin and is covered with adhesive. Finally, the outer skin of boron/epoxy tape is wound over the core, and the entire assembly is placed in a vacuum bag and again cured at 325° F. The steel mandrel is then dismantled and removed from the shell. Inspection is accomplished by non-destructive x-ray and ultrasonic techniques.

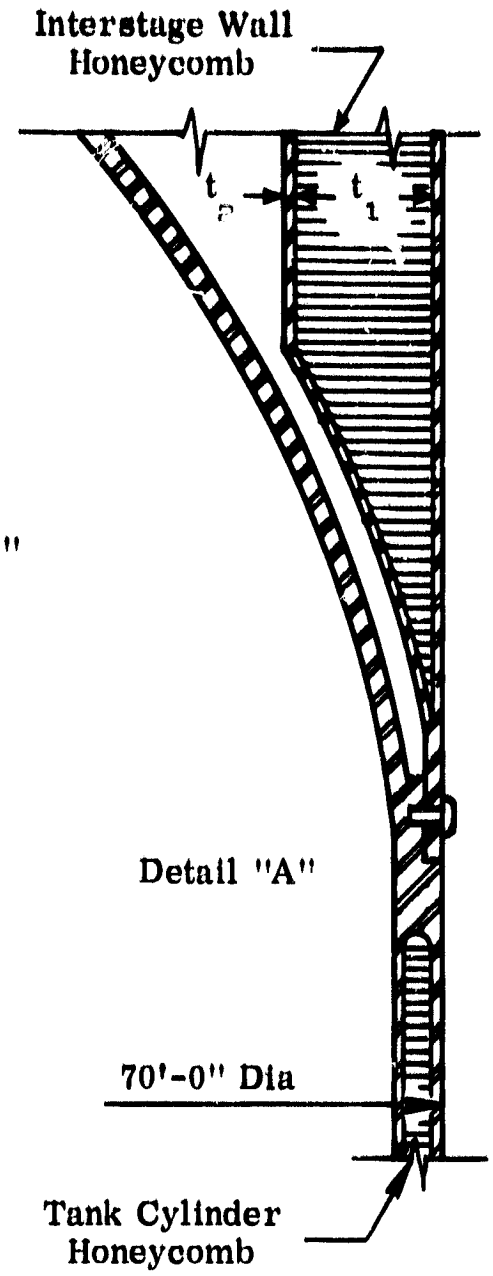
Considerations which underlie this manufacturing process include the following:

a. The materials are those expected to be available in 1971-73 period.
b. 60 volume percent of 5-mil boron in the composite is the upper practical limit. Development work is required to extend shelf life of resin at room temperature.
c. Vacuum bags of a size to cover the mandrel have not been built, but this is within state-of-art.

Construction Details and Typical Dimensions for Various FS/FS_{Nom} Values



Note: Station Numbers Are in Inches.
Head Is Elliptical, $a = \sqrt{2}\ b$



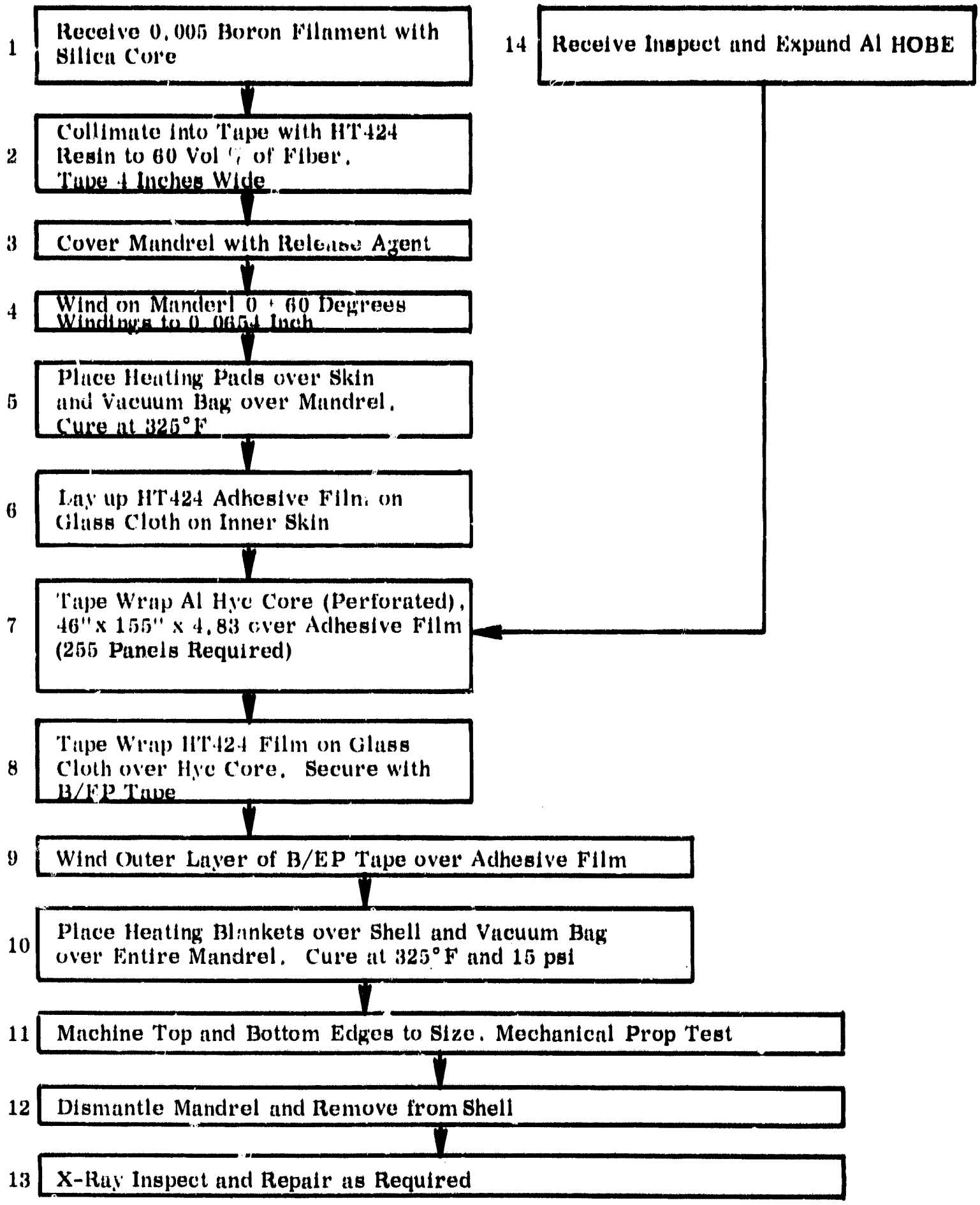
FS/FS_{Nom}	Unpressurized Interstage		
	t_1	t_2	Weight
0.7	4.83	0.0458	25648
1.0 Nom	4.83	0.0654	31902
1.4	4.82	0.0916	40242
2.0	4.81	0.1308	52751

Dimensions are in inches, weights in pounds

Figure 4-23. Boron/Epoxy Honeycomb Construction Unpressurized Interstage

Table 4-23

Flow Process Chart—Manufacture of Boron/Epoxy Hyc Cylinder—Unpressurized



d. Development work is required on adhesives to extend shelf life to several months at room temperature before cure takes place.
e. It may be necessary to lay up individually and cure honeycomb panels, singly.
f. Although 30 to 40 psi is required for good honeycomb sandwich bond, compression from windings should allow cure even at ambient pressure. Development work is required for lower temperature curing resins.
g. Repair of voids can be made by trepanning out sections of skin, replacing with new skin, and curing locally.

One possible arrangement of the filament winding equipment is shown in Figure 4-24. In this installation, two traveling winders are used to wrap tapes successively on the mandrel at ±60° and 0° orientation. The tape is attached at top and bottom of the cylinder by clamping lugs. Control of the winding apparatus is achieved with a numerical control computer. Monitoring of the wrapping process is achieved with closed circuit television monitors. Inspection and repair is accomplished with the mobile inspection towers.

As the composite cylinder is built up, metallic skins are interleaved with the filament layers at the top and bottom of the cylinder. After completion of the winding and curing, the cylinder is trimmed to size, and the composite laminate with interleaved metal is drilled and prepared for attachment to adjacent cylinders.

4.4.3.3 Recurring Costs For Manufacturing Processes

Associated with each step of the flow process chart in Table 4-23, is a breakdown summary of the material, fabrication, and inspection costs as given in Table 4-24.

4.4.4 CARBON/EPOXY FIBROUS COMPOSITE HONEYCOMB CONSTRUCTION

4.4.4.1 General Description and Analysis

For the requirements of this study, carbon/epoxy was assumed to be almost identical in structural properties to the boron/epoxy discussed in Section 4.4.3, and the manufacturing techniques are similar. The same typical launch vehicle components are used for carbon/epoxy as are used throughout this study in order to provide a meaningful basis for comparison. As with boron/epoxy and, indeed, with all epoxy matrix com-

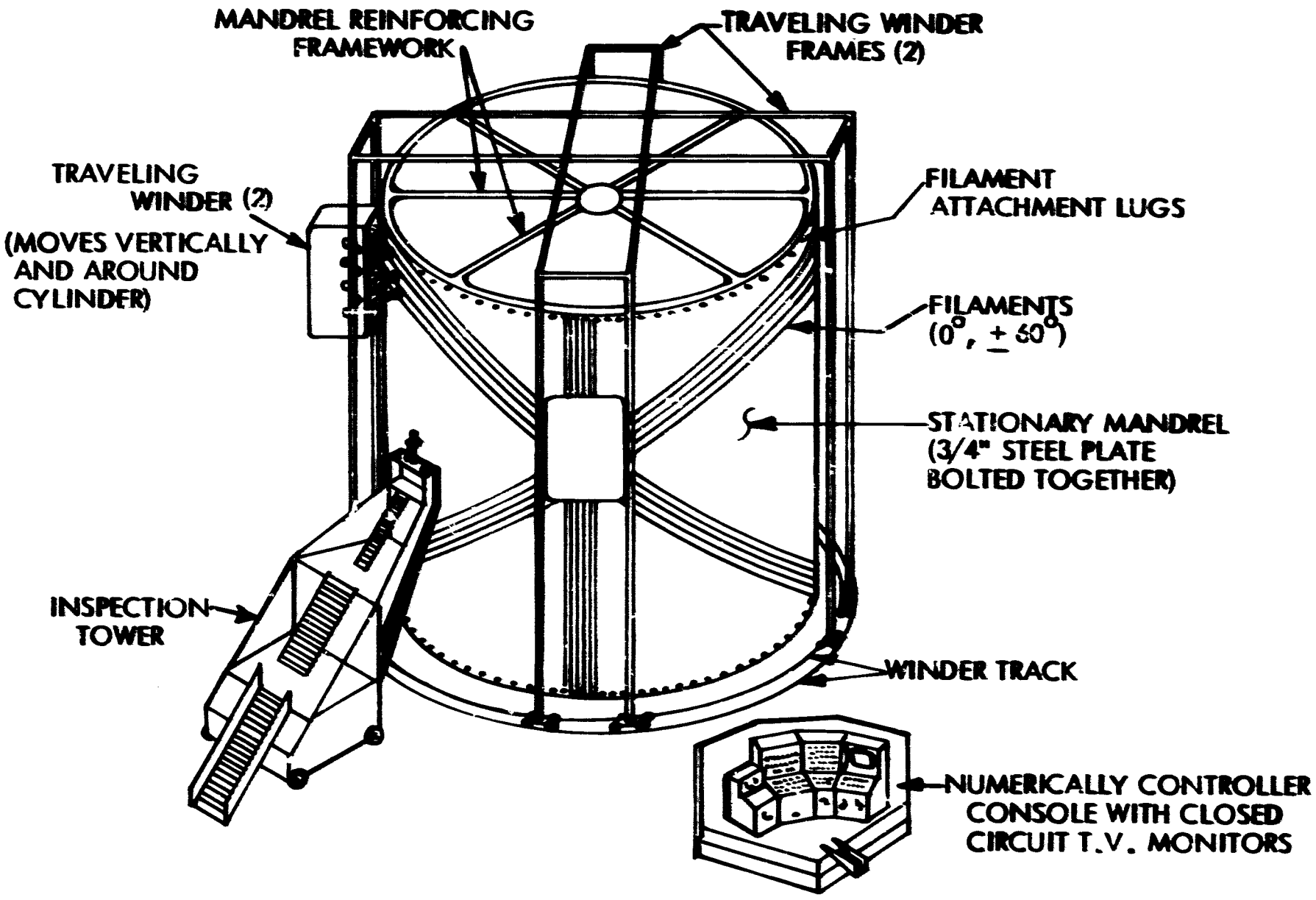


Figure 4-24. Numerically Controlled Filament Winding Equipment

Table 4-24

Recurring Costs for Manufacturing Processes—
Boron/Epoxy Hyc Cylinder--Unpressurized

Seq No.	Cost Item	Thousands of Dollars FS/FS$_{Nom}$ = 1		
		M	F	I
1, 2	Receive Tape	2729.0		
3	Set Up Mandrel and Rel Agent		50.0	
4,9	Winding		205.0	
6,8	Adhesive Film	30.5		
7	Cure Inner Skin		75.0	
10	Bonding Core		288.0	
11	Machining and Mechenical Prop Tests		7.5	15.0
12	Dismantle Mandrel		25.0	
13	X-Ray and Ultrasonic Inspect; Repairs		15.0	44.0
14	Receive Core	78.0		
	Cylinder Subtotal.	(2837.5)	(665.5)	(59.0)
	Cylinder Total		(3562.0)	
	Subtotal Percent of Total	79.7%	18.7%	1.6%
	Total Wt of Cylinder		31902 lb 14471 kg	

posites, carbon/epoxy is not considered practical for the pressurized sections. Again, to provide a basis for comparison for the total cost of the components under study, the cost and weight of using titanium pressurized sections are included in the summary.

4.4.4.2 Manufacturing Processes

For the carbon/epoxy unpressurized cylinder, wall thickness, core thickness, and weights of the honeycomb sandwich were determined by the previously mentioned methods[1] for each of the relative factors of safety (0.7, 1.0, 1.4, 2.0) used as a basis for the study. Although the structural properties of the carbon and boron/epoxy composites are almost identical, carbon exhibits a slight weight advantage because of its lower density (see Table 4-22 for properties).

The manufacturing process is presented in the flow chart in Table 4-25. Briefly, the process consists of winding and curing carbon fiber impregnated tape over a steel mandrel. The proposed manufacturing process, inspection, and winding apparatus are exactly as presented in Section 4.4.3.3 and in Figure 4-25 for boron/epoxy and will not be repeated here. Considerations underlying the manufacturing process, other than those in Section 4.4.3.3, include the following:

a. Either Thornel yarn or Cortoulds or Morganite tow can be used, depending upon developments. In the time period 1972-75, graphite fiber with $E = 1 \times 10^{7}$ psi and $\sigma = 500{,}000$ psi will be available. Thinner shells based on these properties can be used thus reducing weight, materials cost, and fabrication time.
b. 60 volume percent of graphite fibers is the upper practical limit. Development work required to extend shelf life of resin at room temperature is required.

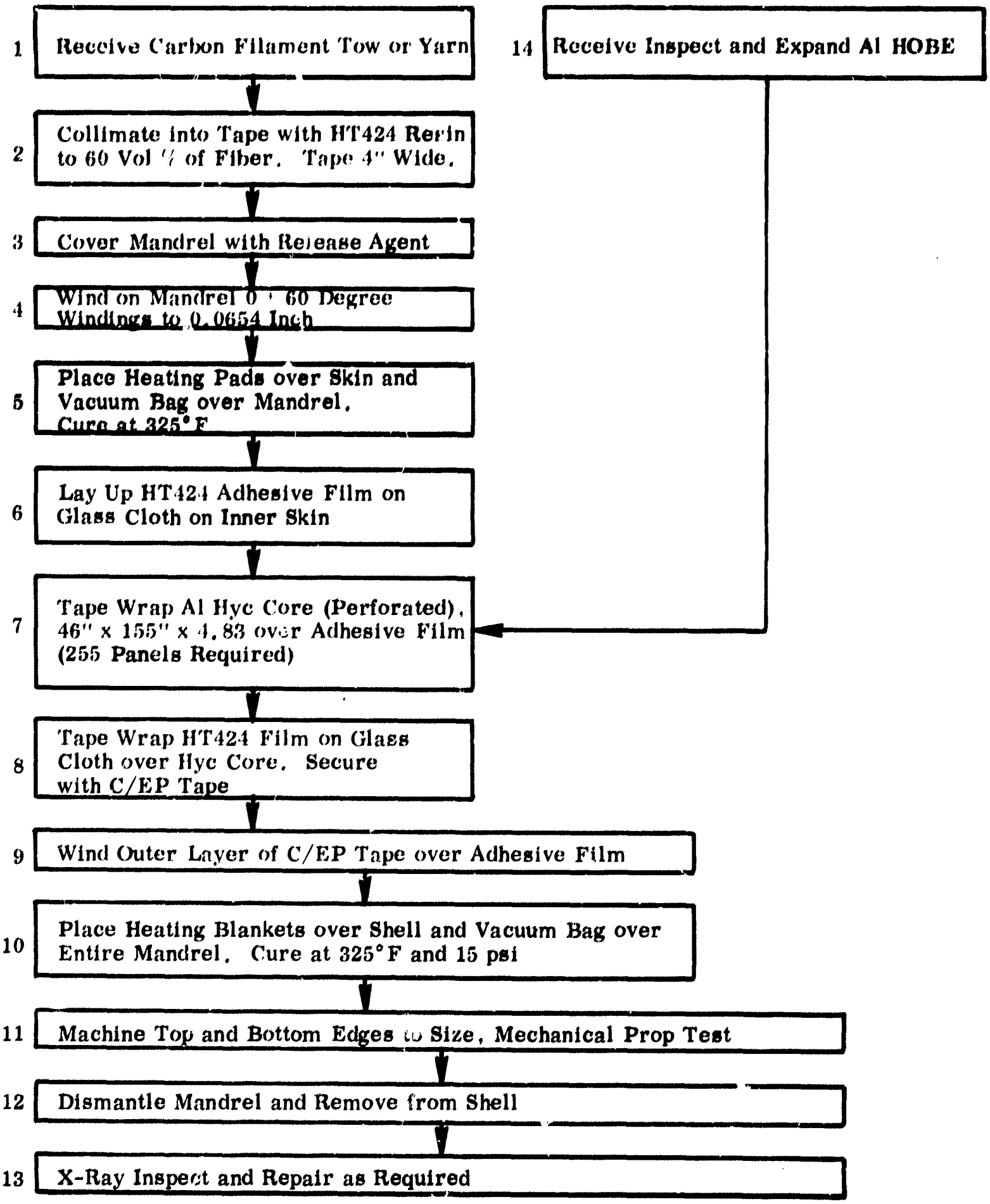
Carbon/epoxy, in addition to the weight advantage over boron/epoxy, appears to have a cost advantage as well. The cost summary breakdown is given in Table 4-26.

4.4.4.3 Recurring Costs for Manufacturing Processes

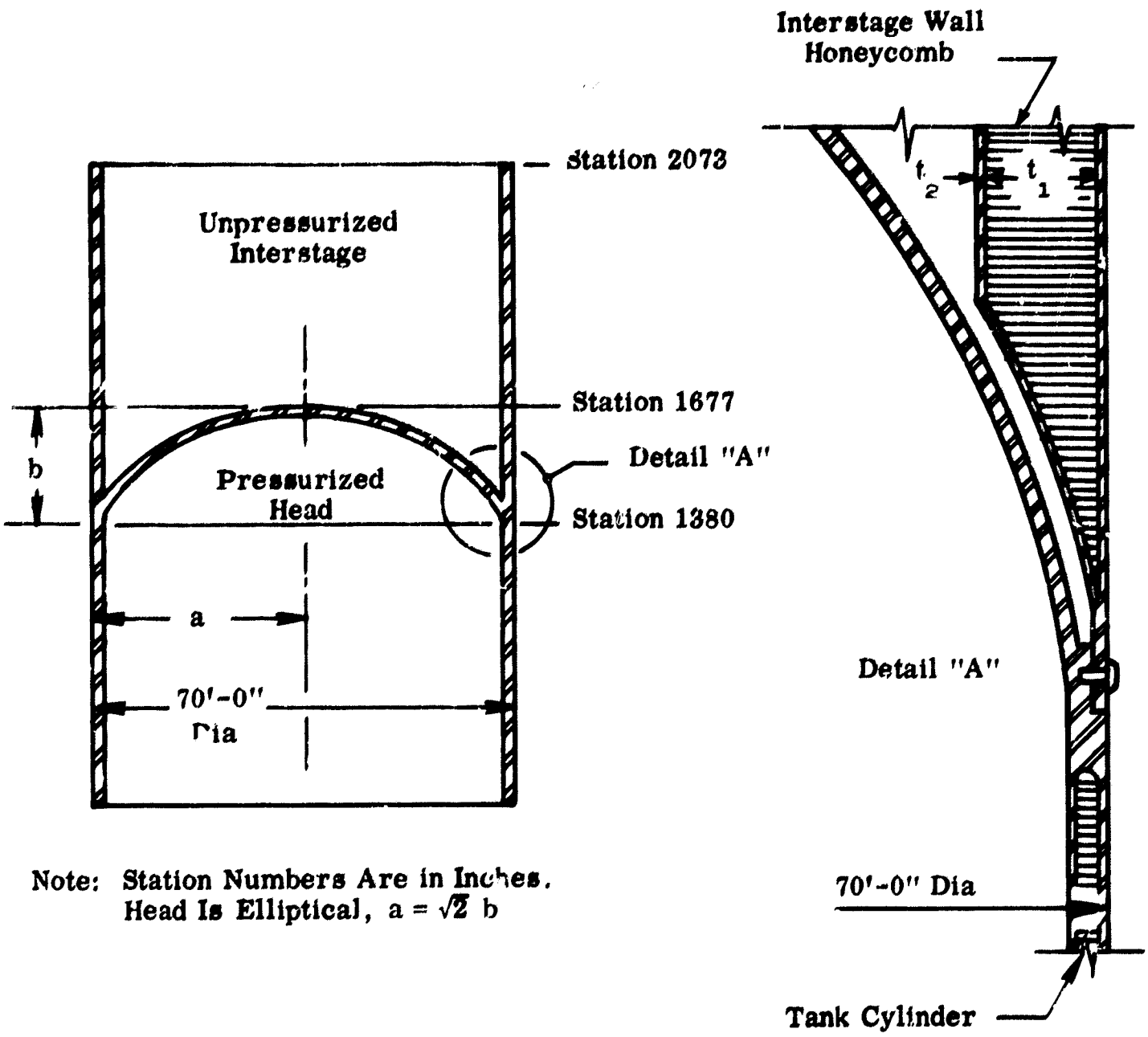
Table 4-26 shows a breakdown summarizing the material, fabrication, and inspection costs corresponding to each step in the flow process chart, Table 4-25.

Table 4-25

Flow Process Chart—Manufacture of Carbon/Epoxy Hyc Cylinder—Unpressurized



Construction Details and Typical Dimensions for Various FS/FS_{Nom} Values



Note: Station Numbers Are in Inches.
Head Is Elliptical, $a = \sqrt{2}\ b$

FS/FS_{Nom}	Unpressurized Interstage		
	t_1	t_2	Weight
0.7	4.75	0.0458	24092
1.0 Nom	4.83	0.0654	29929
1.4	4.82	0.0916	37479
2.0	4.81	0.1308	48804

Dimensions are in inches, weights in pounds.

Figure 4-25. Carbon/Epoxy Honeycomb Construction—Unpressurized Interstage

Table 4-26

Recurring Costs for Manufacturing Processes—
Carbon/Epoxy Hyc Cylinder—Unpressurized

Seq No.	Cost Item	Thousands of Dollars $FS/FS_{Nom} = 1.0$		
		M	F	I
1	Receive Carbon/Epoxy	1975.0		
2	Setup Mandrel and Rel Agent		50.0	
3	Winding		148.0	
4	Adhesive Film (Receive)	30.5		
5	Cure Inner Skin		75.0	
6	Bonding Core		288.0	
7	Machine and Mechanical Prop Tests		7.5	15.0
8	Dismantle Mandrel		25.0	
9	X-Ray and Ultrasonic Inspect; Repairs		15.0	44.0
10	Receive Core	78.0		
	Cylinder Subtotals	(2083.5)	(608.5)	(59.0)
	Cylinder Total		(2751.0)	
	Subtotal Percent of Total	75.8%	22.1%	2.1%
	Total Wt of Cylinder		29929 lb 13576 kg	

4.4.5 BORON/EPOXY STIFFENERS ON ALUMINUM MONOCOQUE SKIN

4.4.5.1 General Description and Analysis

An alternate approach to honeycomb sandwich construction for composite materials is the use of composite stiffeners for conventional metallic structures in configurations such as the cylindrical shells under consideration here. The use of an isotropic material, such as aluminum, for the face sheets avoids the problem of premature failure transverse to the fiber direction in a comparable composite face sheet. The use of fibrous composites as stiffeners for the aluminum sheets then provides the efficient stiffening necessary for cylindrical shell structures under axial load. Stiffener constructed with fibrous composites provides the additional advantage of being particularly amenable to having the fiber orientation in the load direction. In the case of epoxy matrix composites, the isotropic metal shell also eliminates the problem of diffusion leakage in pressurized tanks.

Thus, the utilization of composite stiffened isotropic skin, at least in theory, takes full advantage of the anisotropic features of composites while avoiding the inherent weaknesses. It would seem that the best features of conventional construction are combined with the exceptional strength qualities of the advanced materials. Unfortunately, at the present state of technology development, fabrication problems prevent the full realization of these advantages. Specifically, the difficulty in bonding the stiffener to the metallic shell and the loss of strength due to discontinuity of fibers at stiffener intersections are areas of research which have not been fully explored. Further, time restrictions did not permit the determination of an optimum structural configuration. It is expected that further analysis would have produced structures of greater efficiency and low weight.

4.4.5.2 Manufacturing Processes

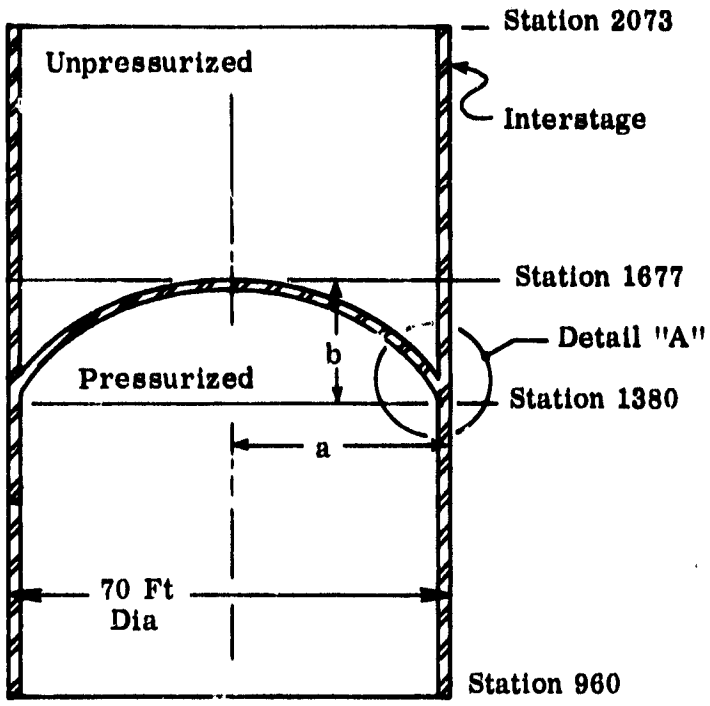
Summaries of shell and stiffener dimensions along with total weight for various factors of safety are given in Figures 4-26 and 4-27 for both the pressurized and unpressurized components. A sketch of construction details is also presented in these figures. A typical configuration sketch can be found in Figure 4-28.

A detailed description of the methods of analysis and construction, as well as the advantages and disadvantages of each, can be found in Appendix E.

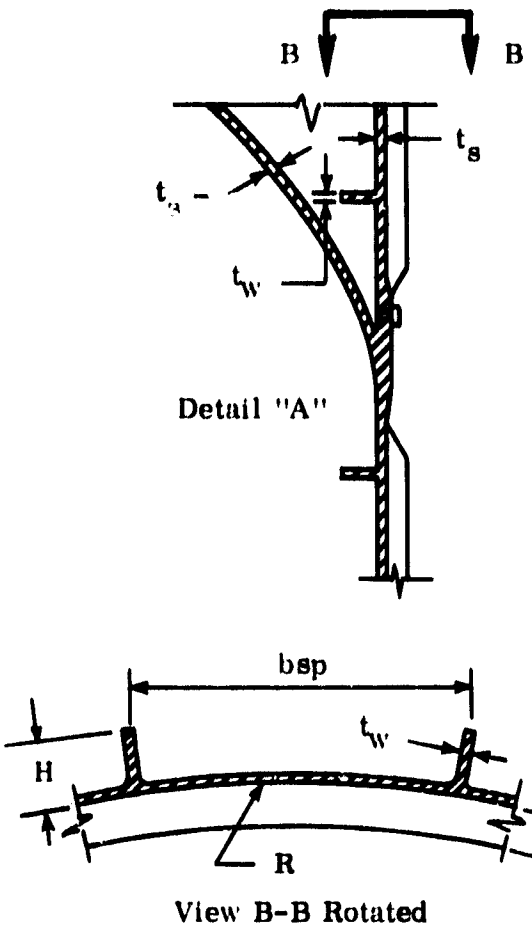
4.4.5.3 Recurring Cost for Manufacturing Processes

The major manufacturing processes required for fabricating the integrally stiffened sections are outlined step-by-step in Table 4-27. The costs associated with each step of the fabrication procedures are summarized in Table 4-28 for the unpressurized section and in Table 4-29 for the pressurized section.

Construction Details for Various Factors of Safety



Note: Station Numbers Are in Inches.
Tank Head Is Elliptical in Shape,
Where $a = \sqrt{2}\ b$



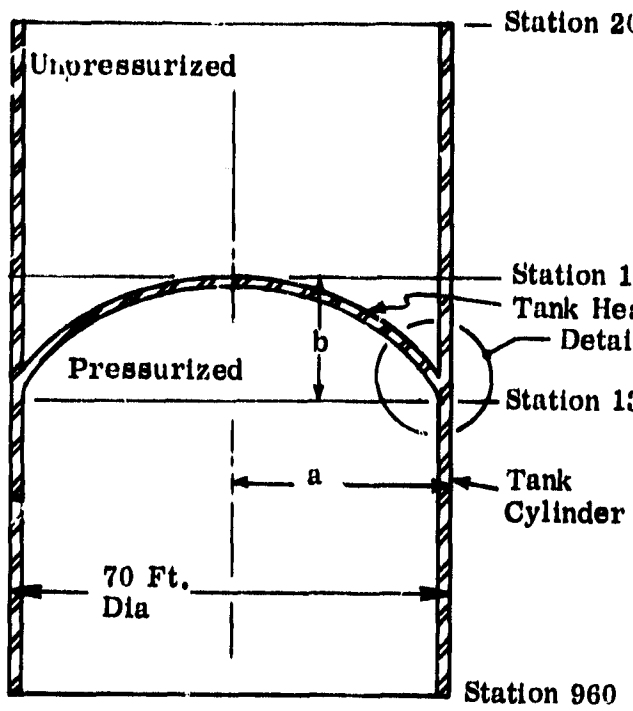
View B-B Rotated

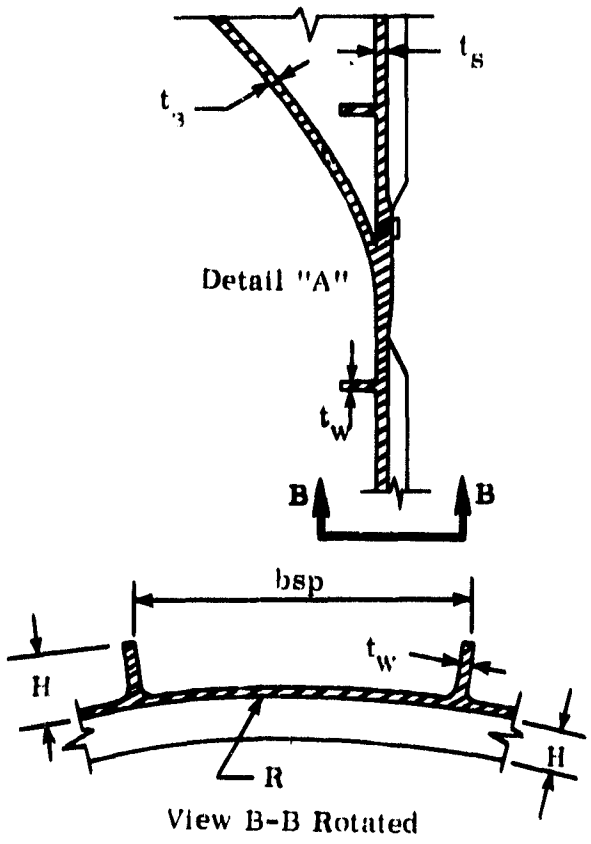
Material	Relative Factor of Safety (FS/FS_{Nom})	Unpressurized				
		t_s, in	t_w, in	H, in	bsp, in	Weight lb
Unidirect. Boron/ Epoxy Stiffened Aluminum Shell	0.7	0.286	0.572	4.573	45.73	109,347
	1.0	0.349	0.697	5.578	55.78	133,350
	1.4	0.423	0.845	6.762	67.62	161,671
	2.0	0.519	1.037	8.296	82.96	198,374

Dimensions are in inches, weights in pounds.

Figure 4-26. Unidirectionally (Fibrous Composite) SS—Unpressurized

Construction Details for Various Factors of Safety





Note: Station Numbers Are in Inches.
Tank Head Is Elliptical in Shape,
Where a = $\sqrt{2}$ b

Material	Relative Factor of Safety $(FS/FS)_{Nom}$	Pressurized						
		Aluminum Head		Tank Cylinder				
		t_3 in	Weight lb	t_s in	t_w in	H, in	bsp in	Weight lb
Unidirect. Boron/ Epoxy Stiffened Aluminum Shell	0.7	0.140	11,154	0.220	0.440	3.525	35.25	51,075
	1.0	0.200	15,935	0.268	0.535	4.284	42.84	62,066
	1.4	0.280	22,309	0.324	0.647	5.176	51.76	74,996
	2.0	0.400	31,869	0.396	0.792	6.336	63.36	91,806

Dimensions are in inches, weights in pounds.

Figure 4-27. Unidirectionally (Fibrous Composite) SS—Pressurized

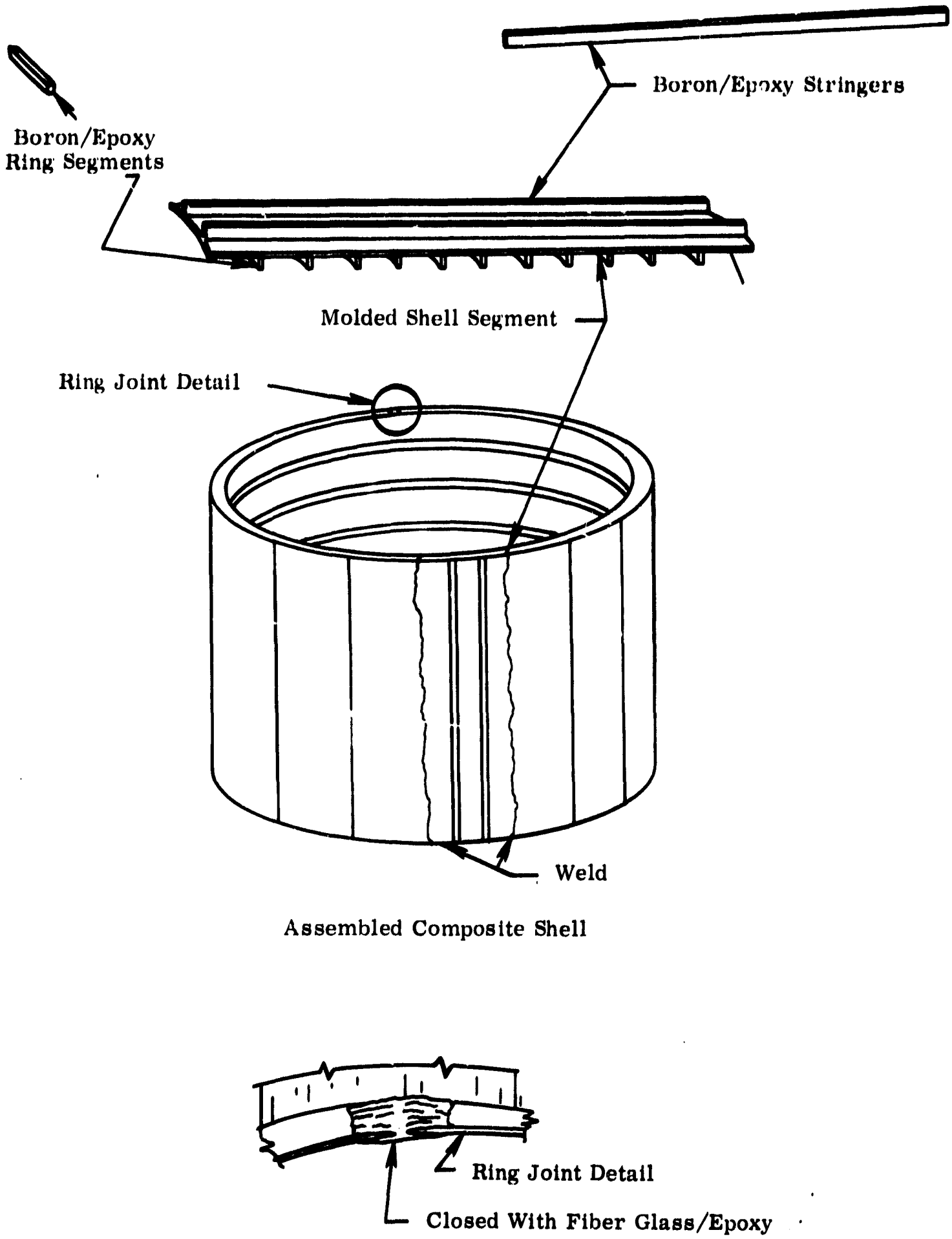


Figure 4-28. Fabrication of Boron/Epoxy Stiffened Aluminum Shell

Table 4-27

Flow Process Chart--Manufacture of Boron/Epoxy Stiffeners--Unpressurized

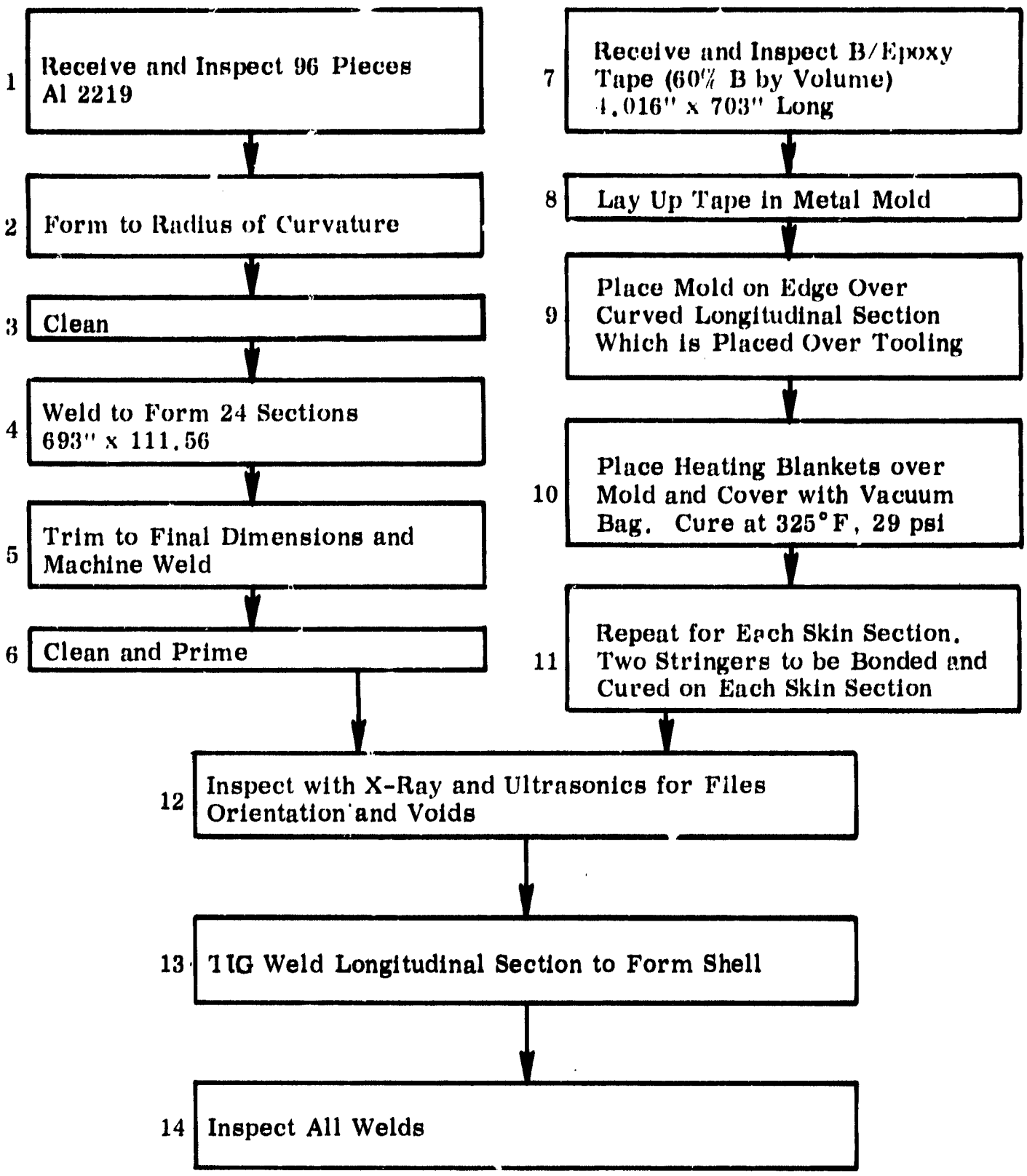


Table 4-28

Recurring Costs for Manufacturing Processes—Boron/Epoxy Stiffener On Aluminum Shell (Unpressurized)

Seq No.	Cost Item	Thousands of Dollars $FS/FS_{Nom} = 1.0$		
		M	F	I
Cylinder		52.0		
1	Receive		62.0	
2,3	Form and Clean		4.5	
4	Weld			11.0
4a, 14	Inspect		22.5	
5	Trim		44.0	
6,9,10, 11	Clean, Mold, Bond, Cure, Etc.	1.0		
7	Receive Tape	1017.0		
8	Tape Layup		235.0	
12	X-ray, Inspect, Mechanical Prop. Test			40.0
13	Weld Section		111.0	
Rings				
	Receive Tape	1200.0		
	Tape Layup		360.0	
	Bonding Ring to Skin		30.0	
	X-ray and Ultrasonic Inspection			30.0
	Fiber Glass Attach Between Segments		50.0	
	Bonding Inspection			30.0
	Cylinder and Ring Subtotals	2270.0	919.0	111.0
	Totals		3300.0	
	Subtotals as Percent of Total	68.8%	27.8%	3.4%
	Total Weight, Cylinder		133,350 lb 60,488 kg	

Table 4-29

Recurring Costs for Manufacturing Processes—Boron/Epoxy Stiffeners On Al Shell (Pressurized)

Seq No.	Cost Item	Thousands of Dollars $FS/FS_{Nom} = 1.0$		
		M	F	I
Cylinder				
1	Receive Al 2219 Sheet	25.0		
2,3	Form and Clean		60.0	
4	Weld and Inspect		6.0	11.0
5	Trim		15.0	
6,9, 10,11	Clean, Mold, Bond, Cure, etc.	1.0	30.0	
7	Receive B/Ep Tape	468.0		
8	Tape Laying		140.0	
12	X-ray Inspect, Mechanical Prop. Test			27.0
13	TIG Weld Sections		108.0	
Rings				
15	Receive Tape	571.0		
16	Tape Laying		170.0	
17	Bond to Skin		15.0	
18	X-ray, Ultrasonic Inspection			15.0
19	Fiber Glass Attach Between Segments		22.0	
20	Bonding Inspection			15.0
Assembly				
14	Assemble and Inspect		113.0	30.0
	Cylinder and Rings Subtotals	(1065.0)	(679.0)	(98.0)
	Total Cylinder and Rings		(1842.0)	
Head Al Mono				
	Head Subtotals*	(22.0)	(645.0)	(65.0)
	Head Total		(732.0)	
	Total Cylinder, Rings and Head		(2574.0)	
	Subtotal Percent of Total	42.2%	51.5%	6.3%
	Total Weight (62006 + 15935)		78001 lb 35381 kg	

* From Table 4-7

4.4.6 BORON/ALUMINUM FILAMENTARY COMPOSITE HONEYCOMB CONSTRUCTION

4.4.6.1 General Description and Analysis

While the technology of composite materials is still in its infancy, the field of metal-matrix composites is in an even earlier stage of development. So much so, that their potential in future applications relies heavily upon major improvement in such areas as methods of fabrication and optimization of material constituent combinations.

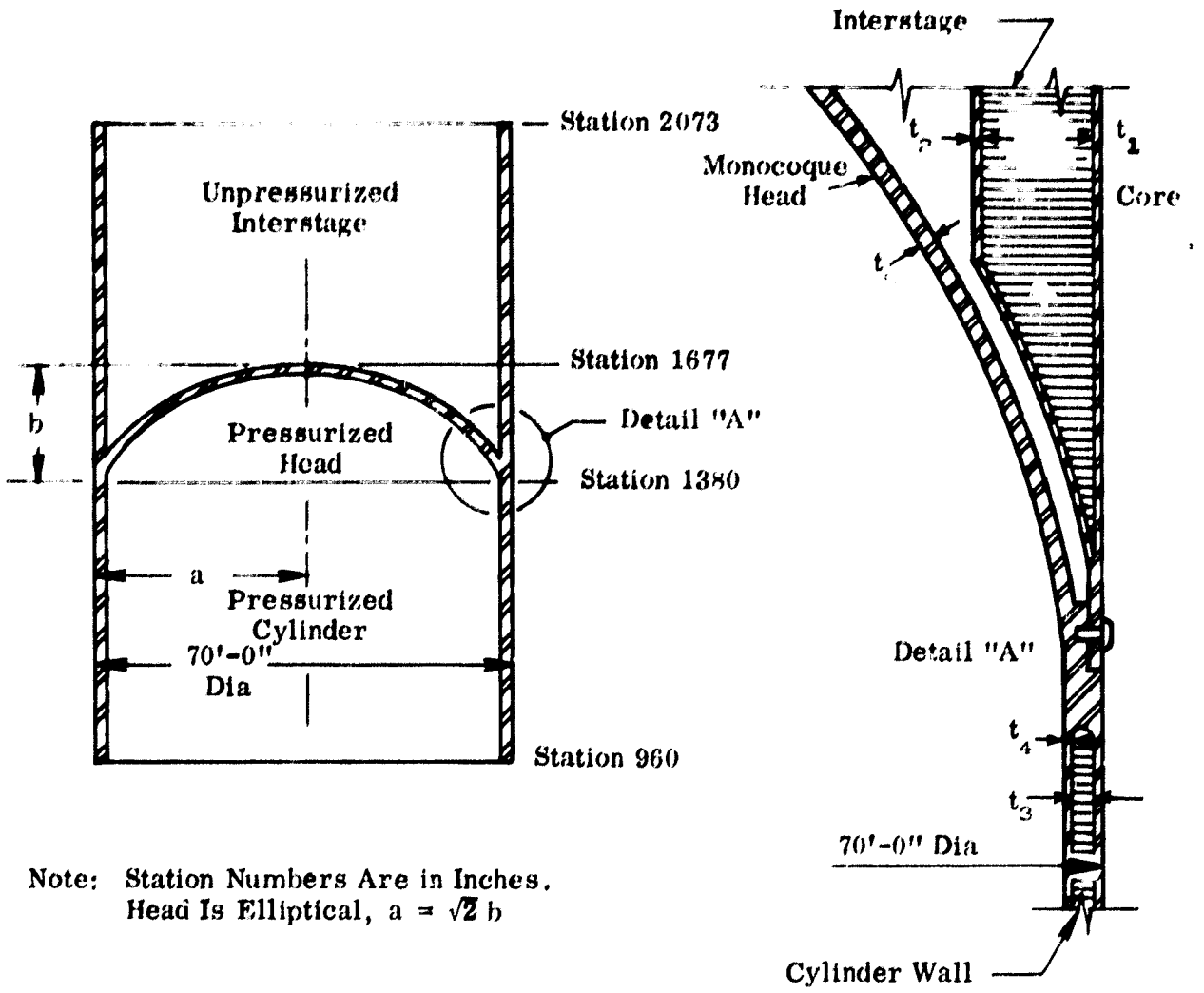
Boron/aluminum, a metal matrix composite, was included in this study because it is in the most advanced stage of development for this class of composite. Production is rising steadily, and relatively large sheets of this material have been produced making its consideration feasible in large structural components. However, it should be emphasized that many areas of research and development must be explored before the full potential of metal-matrix composites can be realized.

4.4.6.2 Manufacturing Processes

The methods considered for fabrication of this aluminum matrix composite differs considerably from those used with the epoxy matrix composite discussed elsewhere in this study. The process that seems to have achieved the greatest success is the diffusion bonding of alternate layers of boron filaments and aluminum foil. This method allows excellent control over fiber packing and spacing and has been produced in relatively large specimens. Diffusion bonding at moderate temperature and pressures over a fairly long period of time reduces fiber degradation to a minimum. The face sheets of predetermined thickness are then adhesively bonded to the aluminum honeycomb core, inspected, and trimmed into preformed sections for fabrication into the final product.

It might be well to again emphasize that the above methods will require much research to develop them to a point of feasible use in large structural components.

Construction Details and Typical Dimensions for Various FS/FS_{Nom} Values



Note: Station Numbers Are in Inches.
Head Is Elliptical, $a = \sqrt{2}\,b$

FS/FS_{Nom}	Unpressurized Interstage			Head	
	t_1	t_2	Weight	t_5	Weight
0.7	3.260	0.0377	23223	0.050	3623
1.0 Nom	3.260	0.0538	29971	0.071	5176
1.4	3.260	0.0754	38969	0.099	7247
2.0	3.250	0.1076	52465	0.142	10352

FS/FS_{Nom}	Pressurized Cylinder			Total Weight
	t_3	t_4	Weight	
0.7	1.107	0.0704	19408	46254
1.0 Nom	1.102	0.1006	27007	62154
1.4	1.090	0.1408	37259	83475
2.0	1.078	0.2012	52454	115271

Dimensions are in inches, weights in pounds.

Figure 4-29. Boron/Aluminum Honeycomb Construction Pressurized Cylinder, Monocoque Head and Unpressurized Interstage

4.4.6.3 Recurring Costs for Manufacturing Processes

Flow process charts for boron/aluminum honeycomb sandwich components in both the pressurized and unpressurized cylinders and for the monocoque head are presented in Tables 4-30, and 4-31, respectively. Costs for each process are summarized in Tables 4-32, 4-33, and 4-34.

Table 4-30

Flow Process Chart—Manufacture of Boron/Aluminum Honeycomb Sandwich—Pressurized and Unpressurized

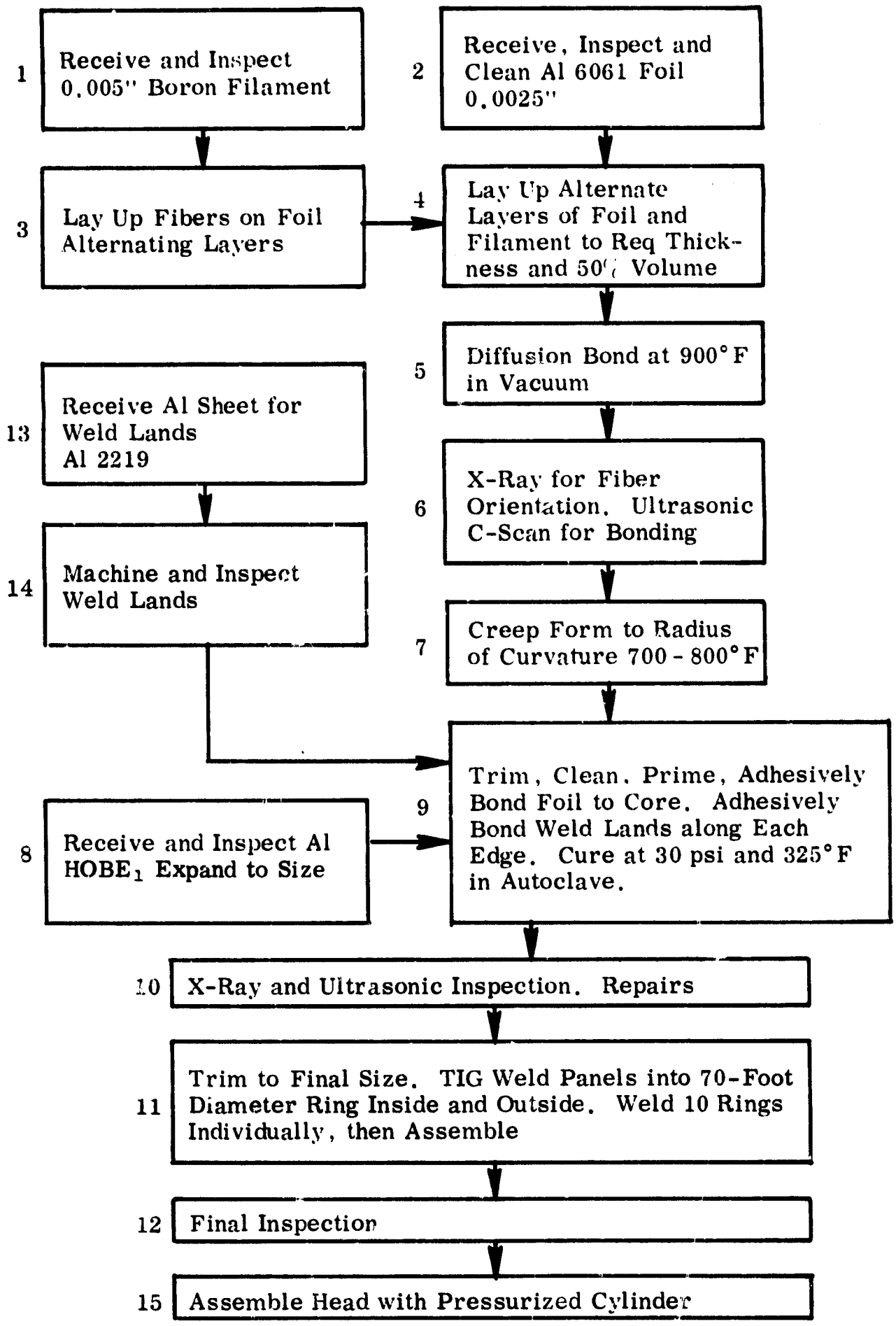


Table 4-31

Flow Process Chart—Manufacture of Boron/Aluminum Monocoque Head

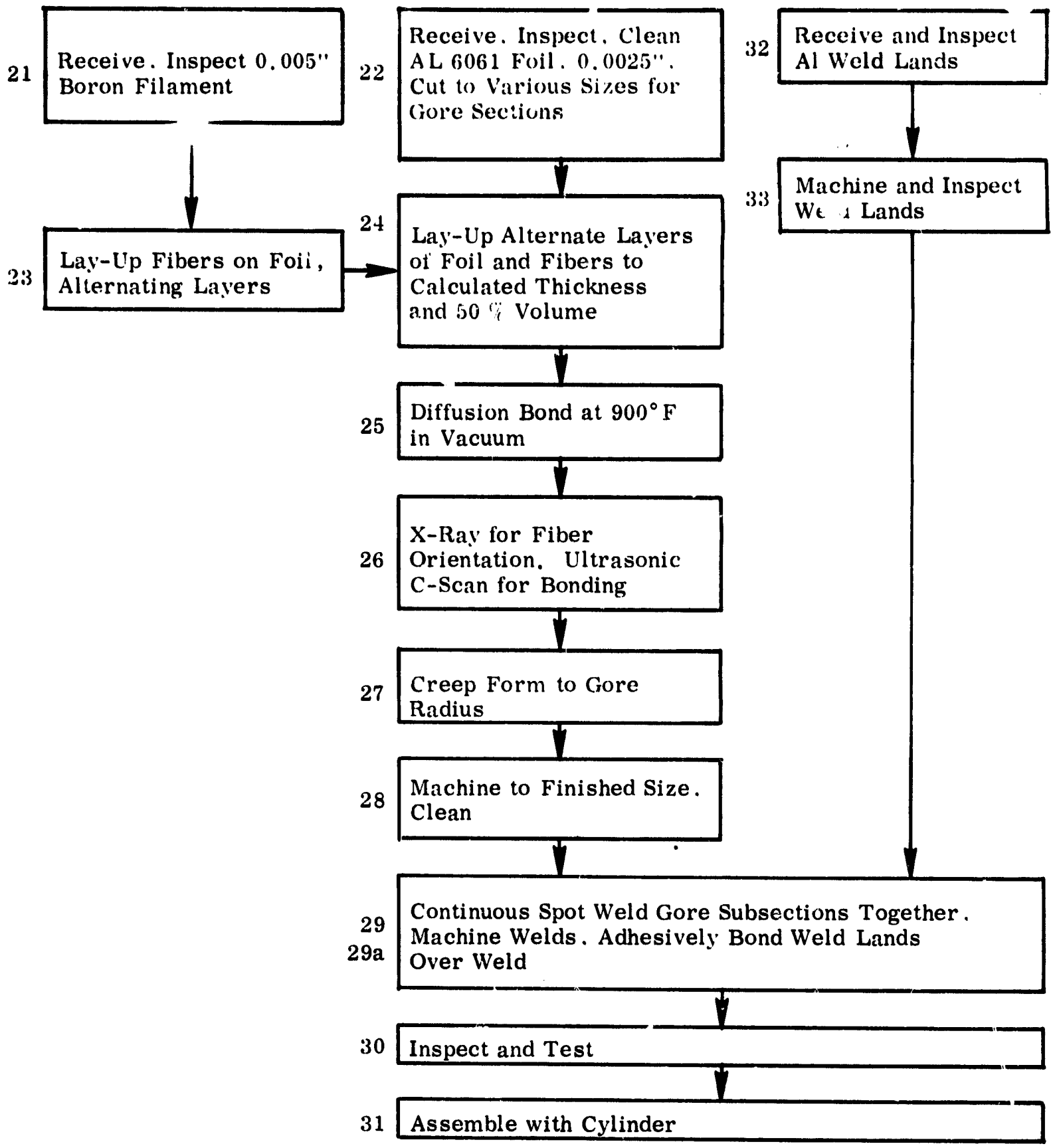


Table 4-32

Recurring Costs for Manufacturing Processes—
Boron/Aluminum Honeycomb—Unpressurized

Seq No.	Cost Item	Thousands of Dollars $FS/FS_{Nom} = 1.0$		
		M	F	I
1,2 3,4 5,6	Receive Boron Filaments, Lay-up Fibers Receive Al Foil, Lay-up Layers of Foil and Fibers, Diffusion Bond, X-ray, Quality Control	1800.0	800.0	300.0
7	Creep Forming of Panels		42.0	
8	Receive Al Hyc Core	42.0		
9	Trim, Bond, Cure	34.0	537.0	
10	X-ray, Quality Control			84.0
11	TIG Weld		84.0	
11a	Al Weld Lands	37.0	50.0	
12	Inspect Welds			66.0
12a	Quality Control			50.0
13	Machining		150.0	
14	Repair Hyc		75.0	
	Subtotals	(1913.0)	(1738.0)	(500.0)
	Total		(4151.0)	
	Subtotal Percent of Total	46.0%	42.0%	12.0%
	Total Weight		29971 lb 13595 kg	

Table 4-33

Recurring Costs for Manufacturing Processes—
Boron/Aluminum Honeycomb—Pressurized

Seq No.	Cost Item	Thousands of Dollars FS/FS$_{Nom}$ = 1.0		
		M	F	I
1,2 3,4 5,6	Receive Boron Filaments, Lay-up Fibers, Receive Al Foil, Lay-up Layers of Foil and Fibers, Diffusion Bond, X-ray, Quality Control	1600.0	680.0	200.0
7	Creep Forming of Panels		28.0	
8	Receive Al Hyc Core	11.0		
9	Trim, Bond, Cure	19.0	386.0	
10	X-ray, Quality Control			44.0
10a	Repairs		50.0	
11	Trim and Weld		155.0	
12	Inspect, Quality Control			69.0
13	Receive Weld Lands	25.0		
14	Machine Weld Lands and Inspect		20.0	5.0
Assembly				
15	Assemble Cylinder and Head, Trim, Inspect		113.0	30.0
	Cylinder Subtotals	(1655.0)	(1433.0)	(348.0)
	Cylinder Total		(3435.0)	
	Head Subtotals*	(250.0)	(568.0)	(100.0)
	Head Total		(918.0)	
	Total Cylinder and Head		(4353.0)	
	Subtotals Percent of Total	43.7%	46.0%	10.3%
	Total Weight (27007 + 5176)—Lb		32183 lb 14598 kg	

*From Table 4-34

Table 4-34

Recurring Costs for Manufacturing Processes—
Boron/Aluminum Monocoque Head

Seq No.	Cost Item	Thousands of Dollars $FS/FS_{Nom} = 1.0$		
		M	F	I
21,22 23,24 25,26	Receive Boron Filiments, Lay-up Fibers Receive Al Foil, Lay-up Layers of Foil and Fibers, Diffusion Bond, X-ray, Quality Control	200.0	200.0	40.0
32,33	Receive Weld Land, Machine, Inspect	50.0	43.0	10.0
27	Forming		60.0	
28	Machining		60.0	
29	Bonding and Welding		25.0	
29a	Assembly		100.0	
30	Inspect and Test			30.0
31	Assemble Cylinder with Head		80.0	20.0
	Head Subtotals	(250.0)	(568.0)	(100.0)
	Head Total		(918.0)	

4.5 ANALYSIS OF IMPACT OF STRUCTURAL INSPECTION AND TESTING

4.5.1 INTRODUCTION

The inspection and testing methods for advanced materials have a significant influence on the quality and cost of structural components. The following sections discuss the impact of these techniques on advanced structures, particularly with respect to technology requirements and cost.

4.5.2 NON-DESTRUCTIVE TEST REQUIREMENTS FOR LARGE LAUNCH VEHICLE FABRICATION

4.5.2.1 General Remarks

The non-destructive test (NDT) methods described in Appendix B are applicable for use in quality assurance of large launch vehicle tankage and interstage structures fabricated from the materials systems considered in this study; however, each of the NDT methods has advantages and limitations. NDT inspection of very large structural elements introduces related problems of fixturing, setting up of equipment, recording devices, etc. Certain techniques which are in daily use for inspection of welds, adhesive bonds, etc., would, of necessity, require recalibration in order to inspect thicker and larger sections of the sizes of interest to this study. New standards need to be established in terms of the number, sizes, and kinds of defects which can be tolerated and what effect these factors will have on the structural integrity of the booster components. The current and future NDT requirements are tabulated in Table 4-35 and discussed in the following paragraphs.

Development of new NDT methods, refinement of present methods, and application of these methods as quality control instruments in aerospace manufacturing are proceeding at a very rapid rate. A DOD Information Center on NDT methods has been established at Watertown Arsenal, Massachusetts. Advanced planners in the USAF are considering establishing requirements that a new materials system will be acceptable as part of the inventory only when complete manufacturing and NDT methods have been developed as part of the system.

The following discussion describes the problems that are most likely to occur in manufacturing large boosters, by the methods described in the flow charts, which can be pin-pointed by NDT for composite materials, honeycomb sandwich structures, welded joints, and riveted joints. In each section, NDT requirements are discussed together with an indication of availability of methods and suggested improvements.

4.5.2.2 Composite Materials

For composite materials of interest, boron/epoxy, graphite/epoxy, and boron/aluminum, the physical and mechanical properties are notably affected by structural anomalies which can occur. For example, inclusions in the matrix or fibers tend to reduce strength by introducing stress concentrations. Porosity or voids reduce strength and stiffness. Incorrect fiber orientation and spacing will result in variation in strength and stiffness from the original design. Mechanical strengths and stiffness are frequently noted to be dependent on material density even when the changes are the result of porosity or molecular structure. Also, mechanical strength and stiffness, particularly in shear, are highly dependent on the degree and quality of matrix-fiber bonding.

These, then, are the problems which dictate the requirements for NDT for composite materials. Also, these methods must be low cost. The inspection of composite materials should thus identify fiber orientation discontinuities, voids, and poor fiber-matrix bonding. The present production methods for inspection are ultrasonic and x-ray techniques. Thermal or sonic techniques, and possibly microwave techniques, are in development at the present time; however, further development and definition of standards are required before these techniques can be considered production methods. Another NDT method under development which appears suitable for composites is acousto-optical imaging. This method enables one to obtain a visual image of defects in the interior of a solid, such as voids, inclusions, cracks, debonding, etc., with good resolution.

4.5.2.3 Honeycomb Sandwich Structures

Honeycomb sandwich structures considered in this study are: all aluminum, boron/epoxy face sheets with aluminum core, graphite/epoxy face sheets with aluminum core, beryllium face sheets with aluminum core, boron/aluminum face sheets with aluminum core, and all titanium honeycomb sandwich.

The problems associated with honeycomb sandwich fabrication are generally concerned with the quality of the bond between the face sheet and the core. The bonding of the nodes of the honeycomb core also requires inspection, especially in the case of the diffusion bonded titanium honeycomb.

Poor bonding of the core to face sheets or lack of bonding resulting in voids which can cause catastrophic failure of primary load bearing honeycomb sandwich structures. When

Table 4-35

Summary of NDT Inspection Requirements for Large Launch Vehicles

	Materials System	NDT Inspection Required	Present Standard NDT Techniques	Advanced NDT Techniques To Be Adapted	Engineering Development Requirement
1.1 1.2	Al ISS	(Welded areas—) (Inclusions and) (contaminants)	X-ray, ultrasonics	Continuous radiography improved ultrasonics, acousto-optical imaging	Fixturing and standards permanent recording fixturing and standards
1.3		(Welded areas—) (Cracks and) (microcracks)	Dye penetrants	Hy-Rez dye penetrants	Fixturing and standards
2.1	Al Hyc	Honeycomb core nodes	X-ray	Continuous radiography	
2.2		Face sheet-core bond voids, debonding	Ultrasonics	Sonic, microwaves, thermal, improved ultrasonics	Fixturing and standards permanent recording
2.3		Bonded edge attachments	See 2.2 above.	Sonic, microwaves, thermal, improved ultrasonics	Fixturing and standards permanent recording
3.1	Be Hyc	Honeycomb core nodes	See 2.1 above		
3.2		Face sheet-core bond voids, debonding	See 2.2 above		
3.3		Bonded doublers—voids, debonding	See 2.2 above		
4.1	Be S.S.	Riveted joints-cracks (area around rivet)	See 1.3 above		
4.2		Riveted joints-cracks (area beneath rivet heads)	Sonic	Sonic improvements	Fixturing and standards permanent recording

Table 4-35

Summary of NDT Inspection Requirements for Large Launch Vehicles (Cont.)

	Materials System	NDT Inspection Required	Present Standard NDT Techniques	Advanced NDT Techniques To Be Adapted	Engineering Development Requirement
5.1	Be/Epoxy Hyc	Fiber orientation, alignment Spacing, voids, fiber-matrix bonding	X-ray, ultrasonic	Thermal, sonic, micro-waves acousto-optical imaging	Fixturing and standards permanent recording
5.2		Face sheet to core bonding	See 2.2 above		
5.3		Honeycomb core nodes	See 2.1 above		
5.4		Surface defects of composites	See 1.3 above		
6.1	C/Epoxy Hyc	See 5.1 - 5.4			
7.1	Be/Epoxy Stiffened Al	Welded areas Be/epoxy stiffeners Bonding of stiffeners to skin	See 1.1, 1.2 and 1.3 above See 5.1 above See 2.2 above		
8.1	Be/Al Hyc	See 5.1 - 5.4 Welded Al edge attachments	See 1.1, 1.2, and 1.3 above		
9.1	Ti Hyc	Honeycomb core nodes Diffusion bonding of core to face sheet welded areas	See 2.1 above X-ray ultrasonic See 1.1, 1.2 and 1.3 above	Sonic, thermal, micro-waves, acousto-optical imaging	Fixturing and standards permanent recording

detected, these voids can be trepanned and repaired. When honeycomb panels are joined with adhesively bonded doublers, these bonded joints also require inspection.

Ultrasonic and x-ray inspection of honeycomb sandwich panels are the production techniques presently employed. Newer methods such as continuous motion radiography can be applied to core inspection of honeycomb panels. For inspection of face sheet bonding on larger sections such as the all-aluminum honeycomb or the composite face sheet honeycomb, sonic techniques are applicable.

Sonic inspection can cover approximately one square foot per minute and can cover both sides of a sandwich simultaneously. The sonic method requires further development in the areas of application to varying thickness of face sheets, non-metallic face sheets, recording and fixturing devices, especially as pertaining to large launch vehicle sizes and materials.

For titanium honeycomb where the face sheet is diffusion bonded to the core, a strippable thermographic method is potentially applicable. A strippable tape is applied to the sandwich surface and heated to 130°F. A permanent image is developed and then stripped off. This method shows areas of no bonding, but still requires further development for large booster applications.

To inspect bonded doublers or honeycomb sandwich panels, present ultrasonic techniques are applicable for external doublers, but development is required for inspection of internal doublers, possibly by sonic techniques.

4.5.2.4 Welded Joints

In welding segments of aluminum sheet, honeycomb sandwich panels, titanium honeycomb panels, as well as ring and stringer sections to form large structures, localized shrinkage occurs. The shrinkage can be dimensionally compensated for by proper design; however, weld shrinkage inevitably leaves residual stresses in fusion type weldments. In general, these residual stresses can result in brittle fracture, stress corrosion cracking, fatigue fracture, or buckling failure although the cause and effect relationship is not clear. Stress relieving can be accomplished by heat treatment or mechanical means, as peening or cold working. For large structures such as those being considered, thermal treatment is not practical, but shot peening may be feasible. Ultrasonic and x-ray techniques are used to inspect weldments for flaws, cracks, and contaminants. In the case of titanium, no suitable NDT method is available for the

detection of weld contaminants, although ultrasonic delta techniques are in the development stages for detection of such internal flaws.

Microcracks and other surface defects are discernable by fluorescent dye penetrants. Permanent records can be obtained with the use of such penetrant systems as Hy-Rez.

4.5.2.5 Riveted Joints

Sheet stringer assembly of aluminum and beryllium interstages using mechanical fasteners can result in severe local stress concentrations in the area of the fastener. The problem can be especially acute in the case of beryllium, where microcracks can form, even when squeeze rivets are used. Dye penetrants are the usual method of detecting this type of flaw. The Hy-Rez process is applicable for surface defects around riveted joints, but for inspection of areas beneath rivets, sonic techniques are being developed for this purpose.

4.5.3 STRUCTURAL TESTING CONSIDERATIONS

4.5.3.1 Introduction

Because testing represents a significant part of launch vehicle programs, particular interest exists in the relationship of test costs to design factors such as factor of safety. In this section, factors are identified which influence test costs, and an analysis of the test program is performed to assess the magnitude of the variation of test costs with factor of safety.

4.5.3.2 Approach

The approach followed in the investigation incorporates the following steps:

a. An investigation of current test program documentation was performed to identify those requirements in test documents which explicitly relate test requirements to materials selection or design factors such as factor of safety.

b. The organization of a test program is delineated to provide a basis for analysis of factors affecting test costs. Test program categories and verification methods are those currently being used in test planning in the Apollo Applications Program. This definition is generally compatible with the NOVA study data.

c. Factors which have potential impact on test program costs were identified. These factors have a potential direct effect on test costs achieved through reduction of test requirements, or an indirect effect on the test program achieved through simplification of test methods, or vehicle handling.
d. An analysis is conducted to assess the extent to which the factors impact the test requirements. Primary emphasis is on recurring test costs.

The results of this analysis are utilized to help draw basic conclusions concerning relationships between test costs, materials, and design factors. A relationship is established, based on the analyses, on the variation of recurring test cost with design factor of safety, and material selection.

4.5.3.3 Test Program Definition

The influence of factors on test cost varies with the type and method of testing. Listed below are the various test types and methods utilized in large launch vehicle programs. These types as defined by existing test requirements documentation currently in use by NASA include:

a. Development.
b. Qualification.
c. Reliability.
d. Acceptance.
e. Integrated System.
f. Prelaunch Checkout.
g. Flight Verification.
h. Post Flight.

Methods established for meeting test requirements include:

a. Test (exercise of the equipment).
b. Assessment.
   (1) Similarity.
   (2) Analysis.
   (3) Inspection.
   (4) Demonstration.
   (5) Validation of Records.

For each type of test, objectives and requirements are delineated based on the Apollo Applications Test Requirements Document. The objectives and requirements in this document are currently being used as test planning functions and are included in Appendix B.

4.5.3.4 Identification of Cost Influence Factors

4.5.3.4.1 General

Selection of materials and design factors of safety may impact test costs either through a direct reduction of test requirements or indirectly through changes which simplify test methods or procedures which result in lower costs.

The principal factors which may result from increasing the design factor of safety include:

a. Test Requirements Reduction

Test requirements may be eliminated or reduced.

b. Test Hardware Reduction

Fewer test articles may be required for increased design margins.

Other factors which influence overall test costs include:

a. Test Methods Simplification

Simulation of the operating environment may be cruder, tending to reduce test costs. Test procedures may also be simplified because of increased vehicle ruggedness.

b. Vehicle Weight Increase

With increasing factor of safety, weight increases in the vehicle will tend to increase vehicle handling costs associated with tests.

c. Vehicle Ruggedness Increase

With increasing factor of safety, vehicle ruggedness will increase and tend to reduce vehicle handling costs associated with tests.

4.5.3.4.2 Scrappage

In some installations, particularly with the fibrous composites, there is expected to be a relatively high scrappage rate. Since the material costs are high for these composites, another method of reducing costs with relaxed quality processes is to reduce the scrappage. Estimated scrappage costs are expected to vary from 9 percent decrease for relaxed quality measures to 5 percent increase for tightened quality control.

4.5.3.4.3 Repair

Repair costs were assumed to vary in the same proportion as inspection costs, from a possible 10 percent increase to a 50 percent decrease for various safety factor requirements.

4.5.3.4.5 Structural Test

Structural cost variations with quality control factors are limited to proof testing. Costs for proof testing are largely influenced by the need for testing these large tanks in pressures which simulate expected pressure loadings. A silo arrangement is used to limit the maximum hydrostatic pressure resulting from use of water at a density of 62.4 pounds per cubic foot rather than liquid hydrogen at a density of 4 pounds per cubic foot. Increased factors of safety permit the hydro testing of the cylinders without the silo. The overall cost variations are from 45 percent increase to 55 percent decrease over the range of quality control variations as discussed in Section 4.5.3.5.

The details of the interrelationship studies, using these assumptions are discussed in the following section.

4.5.3.5 Analysis

4.5.3.5.1 Approach

In assessing the impact of the factors of the various categories of testing, cost elements of the test program have been defined as follows:

a. Facilities.
b. Test Equipment.
c. Instruments.
d. Test Hardware.
e. Labor.

The distinction between recurring test costs and non-recurring test costs is made on the basis of test category. Development, qualification, and reliability testing represent that portion of the test program associated with non-recurring costs, while the acceptance, integrated system, prelaunch checkout, flight, and post flight represent recurring costs. Of the last group, only acceptance testing is sensitive to changes in design factor of safety since the primary objectives and requirements of the other categories of test are based on test requirements other than structural requirements. In general, these tests would still have to be performed if structural requirements were reduced or eliminated.

Using the test program definitions of Appendix B, the variations in elements of test program costs caused by the factors were identified. A typical NOVA test program is also defined in Appendix B, as well as the test programs for the S-II and S-IVB which were used as complementary information for the test program definition.

4.5.3.5.2 Assumptions

Specific assumptions made in assessment of test cost variation include the following:

a. Weight of the ALISS structure is 235,372 pounds.
b. Test costs do not vary with type of materials (for those materials and constructions considered in this study).
c. Recurring test costs for the representative sections are obtained on a weight percentage basis of the fuel tank test costs.
d. Silo tests are required for pressure tests for values of factors of safety of 0.7 and 1.0, only partially for 1.4, and not at all for 2.0.
e. Environmental and cryogenic leak test costs are independent of safety factors.

4.5.3.5.3 Acceptance Test Analysis

The results of a detailed cost analysis of steps required in the vehicle structural acceptance tests are tabulated in Table 4-36. These results show variations in total costs for various factors of safety. The results of this analysis are reflected in the general results of Section 4.6.5.

Table 4-36

Recurring Test Costs (Acceptance Test)

Test Type	Cost in Thousands			
	FS/FS_{Nom}			
	0.7	1.0	1.4	2.0
1. LH_2 Cold Soak, Pressure Test				
a. Move vessel, instrumentation into place	200	100	80	80
b. Clean inspect add pressure gauges, strain gauges	240	200	160	120
c. Fill with liquid hydrogen	200	200	200	200
d. Pressurize	150	70	50	50
e. Monitor pressure rates, heat loss, boil-off rates, etc.	150	70	50	50
f. Leakage check; cycle pressure	-	-	-	-
g. Empty Vehicle	120	100	100	100
h. Repair	300	250	220	200
i. Retest	350	250	220	200
j. Secure test area	100	100	100	100
k. Clean, ship cylinder	250	150	100	100
Subtotal	$2,050	$1,490	$1,280	$1,150

Table 4-36

Recurring Test Costs (Acceptance Test) (Cont.)

Test Type	Cost in Thousands			
	FS/FS_{Nom}			
	0.7	1.0	1.4	2.0
2. Proof Test—H_2 Cylinder				
a. Move vessel into proof test facility	200	100	80	80
b. Clean, inspect	20	20	20	20
c. Add instrumentation	400	300	200	100
d. Fill with water and/or referee fluids	400	200	100	50
e. Fill Silo (if used)	300	200	170	0
f. Pressurize	-	-	-	-
g. Monitor, visual checks	500	320	250	100
h. Remove pressure, inspect and x-ray	300	160	130	100
i. Reduce data, interpret	300	200	200	100
j. Repeat test, cycle pressure	500	400	350	-
k. Clean, ship cylinder	250	150	120	50
l. Secure test area	100	100	100	100
Subtotal	$3,270	$2,050	$1,720	$ 700

Table 4-36

Recurring Test Costs (Acceptance Test) (Cont.)

Test Type	Cost in Thousands			
	FS/FS_{Nom}			
	0.7	1.0	1.4	2.0
3. Other Structural Tests and Related Activities				
a. Check, monitor related test programs	130	100	100	100
b. Test auxiliary tank fittings, etc.	400	250	200	150
c. Structural adequacy of intertank through NDT methods	400	410	300	200
d. Other factors	150	100	100	100
Subtotal	$1,080	$ 860	$ 700	$ 550
TOTAL	$6,400	$4,400	$3,600	$2,400

4.6 INTERACTION ANALYSIS

4.6.1 GENERAL SCOPE

The cost analyses were extended to include those designs beyond the nominal design points to determine the influence of overdesign and/or design simplification on reducing costs. Interaction of these cost results including other launch vehicle variables was then analyzed. Such analyses rapidly expand the number of tabulated results by several orders of magnitudes since the numbers of variables are large. These variables include the following factors which vary with factors of safety:

a. Quality control exercised at higher factors of safety (Can inspection costs be reduced?)
b. Design simplification (Can designs be simplified by cutting out operations, using cheaper construction?)
c. Reduction in quality requirements for materials; machining tolerances; manufacturing processes
d. Interrelationship with weight of structures
e. Interrelationship with expected structural reliability
f. Requirements for NDT, structural test
g. Facilities cost
h. Handling and transportation costs

The approach to the interaction analyses which interrelate many of the variables is described in detail in Appendix A and were in two steps:

a. Analysis to determine cost variation with changes in factor of safety while holding quality control factors constant. This is accompanied by a significant increase in structural reliability as safety factor is increased.
b. Analysis of the effect on cost when factors of safety and quality control are simultaneously allowed to vary.

The results presented in the earlier sections of this report were for a particular type of variation in the second case above where the maximum variation of cost with factor of safety was determined while the structural reliability was held constant. Quality control measures were reduced to decrease cost as strength was increased. This takes advantage of the lighter weights of the advanced materials to reduce costs through relaxed quality control and test measures, but without reducing structural effectiveness.

The particular methods of achieving this variation are to first evaluate those elements of construction that are functions of the two independent variables:

a. Factor of Safety
b. Quality Control and Test

If one looks at aluminum honeycomb as an example, increase in factor of safety will change parameters such as dimensions, skin thickness, core thickness, core minimum cell diameter, and of course, weight. Quality control reductions will permit reductions in the time and cost of inspection, cost of repairs, reduction in scrappage rate, reduction in a few of the manufacturing and assembly operations, reduction in material costs, and reduction in structural test costs. Furthermore, quality control and factor of safety are independent of each other, i.e., one may be increased while the other is decreased. Structural reliability, however, is dependent on the variation of both of these variables, increasing with factor of safety and quality control and test effectiveness.

4.6.2 VARIATIONS WITH FACTOR OF SAFETY

The dimensions and weights for each construction and each material were computed. The cost variations were determined as sensitivity factors by comparing resultant configurations against the nominal configurations about the nominal construction. In general, cost rates changed only slightly with geometric or weight changes associated with different factors of safety. In one or two cases, such as titanium honeycomb, the change in factor of safety was attended by a very small change in total cost; the rates in dollars/pound varied essentially in inverse proportion to weight but produced only a relatively small change in total cost. The principal change in the cost of aluminum core was due to variations associated with minimum cell size; the core cost varied from $18 per cubic foot down to $14 per cubic foot as cell diameter increased. Other cost rates remained relatively independent of the changes in weight or size.

4.6.3 VARIATION WITH QUALITY CONTROL FACTORS

The cost rates were found to be strongly dependent on quality control practices. Expressing quality control in terms of the allowed variability in strength, cost relationships were developed for cost rates versus relative standard deviation of strength. The variation of expected strengths about the mean strength (M_s) were assumed to be normally distributed with some standard deviations (σ_s). The allowable design

strength (S) was set at some (arbitrary) number of standard deviations (N_s) below the mean strength (M_s) by the equation,

$$S = M_s - N_s \sigma_s \tag{4-1}$$

Dividing by mean strength (M_s), we have

$$\frac{S}{M_s} = 1 - N_s \left(\frac{\sigma_s}{M_s} \right) \tag{4-2}$$

Relative standard deviation is directly related to manufacturing tolerances and quality factors; thus, cost rates were assumed to vary with relative standard deviation (σ_s/M_s). These relationships were used to determine the relative cost variations about the nominal design points as quality control factors* are varied. Costs estimated in this manner have limited value on an absolute scale, but they are considered to be a valid representation of cost sensitivity to quality control variations. The variations in quality control cost rates used in these calculations are summarized below.

4.6.3.1 Inspection

Inspection costs for the processes directly associated with strength variability varied from 10 percent increase for increased quality control factors to a 50 percent reduction for decrease in quality control factor. That is, cost would be reduced by as much as 50 percent for relaxed quality control procedures which would be associated with overdesigned structures.

4.6.3.2 Machining

Machining costs, particularly costs for finish machining, could be reduced with relaxed quality control factors. In the case of chemmilling versus numerically controlled (NC) machining of integrally stiffened skin structures, 80 percent of the metal was removed for the nominal construction by NC machining and the last 20 percent by chemmilling to produce the desired finish and tolerance. Relaxed quality control procedures would allow the entire machining to be accomplished by NC machining, a reduction from $1.50 to $0.50 per pound of metal removed. Conversely, tightening tolerances would increase costs to as much as $5.50 per pound of metal removed.

*Quality control factors as referred to herein are factors which include those elements influencing strength variability (σ_s/M_s), such as material variability, machining tolerances, etc. For example, increased material variability and machining tolerances increase σ_s/M_s which may in turn reduce costs

4.6.3.3 Metal Skin

The cost of metal skins varied as the inverse of the allowable standard deviation of strength varied. Relaxing quality requirements for a metal with a given M_s allows a lower value of N_s and higher value of S, as per Equation 4-1. The lower cost of metal skins results in as much as a 9 percent reduction in cost; increased quality control factors increase cost by as much as 6 percent.

Starting from an arbitrary point, with σ_s/M_s in Equation 4-2 equal to 0.15 and $M_s = 2$, Table 4-37 of reliability and quality control factors is obtained. Figure 4-30 depicts the interrelationships of σ_s/M_s, M_s/M_L, and reliability as determined by the methods described in Appendix A. Values shown in Table 4-37 were computed using these methods.

Table 4-37
Reliability and Quality Factors

	Factor	Factors of Safety/Factor of Safety, Nominal			
		0.7	1.0	1.4	2.0
Constant Quality (Curve I On Figure 4-30)	σ_s/M_s	0.15	0.15	0.15	0.15
	M_s/M_L	1.4	2.0	2.8	4.0
	Reliability	0.96	0.9995	0.99999	0.999999
Variable Relative Quality (Constant (Reliability) (Curve II On Figure 4-30)	σ_s/M_s	NA	0.15	0.21	0.255
	M_s/M_L	NA	2.0	3.38	5.7
	Reliability	NA	0.9995	0.9995	0.9995

NOTE: NA = Not Applicable, Discontinuous Function at FS/FS Nom = 0.7

These figures illustrate the large relative increase in structural reliability if factor of safety is increased and quality control measures are held constant.

To check the sensitivity of the results to assumptions, the cost rates were varied. In a like manner, the sensitivity of results to the initial starting values of σ_s/M_s was checked. In each case, no significant changes on the overall relative results were observed. The absolute value of the results changed with the varied assumptions, but the overall trends of the resulting curves remained unchanged. The best performance

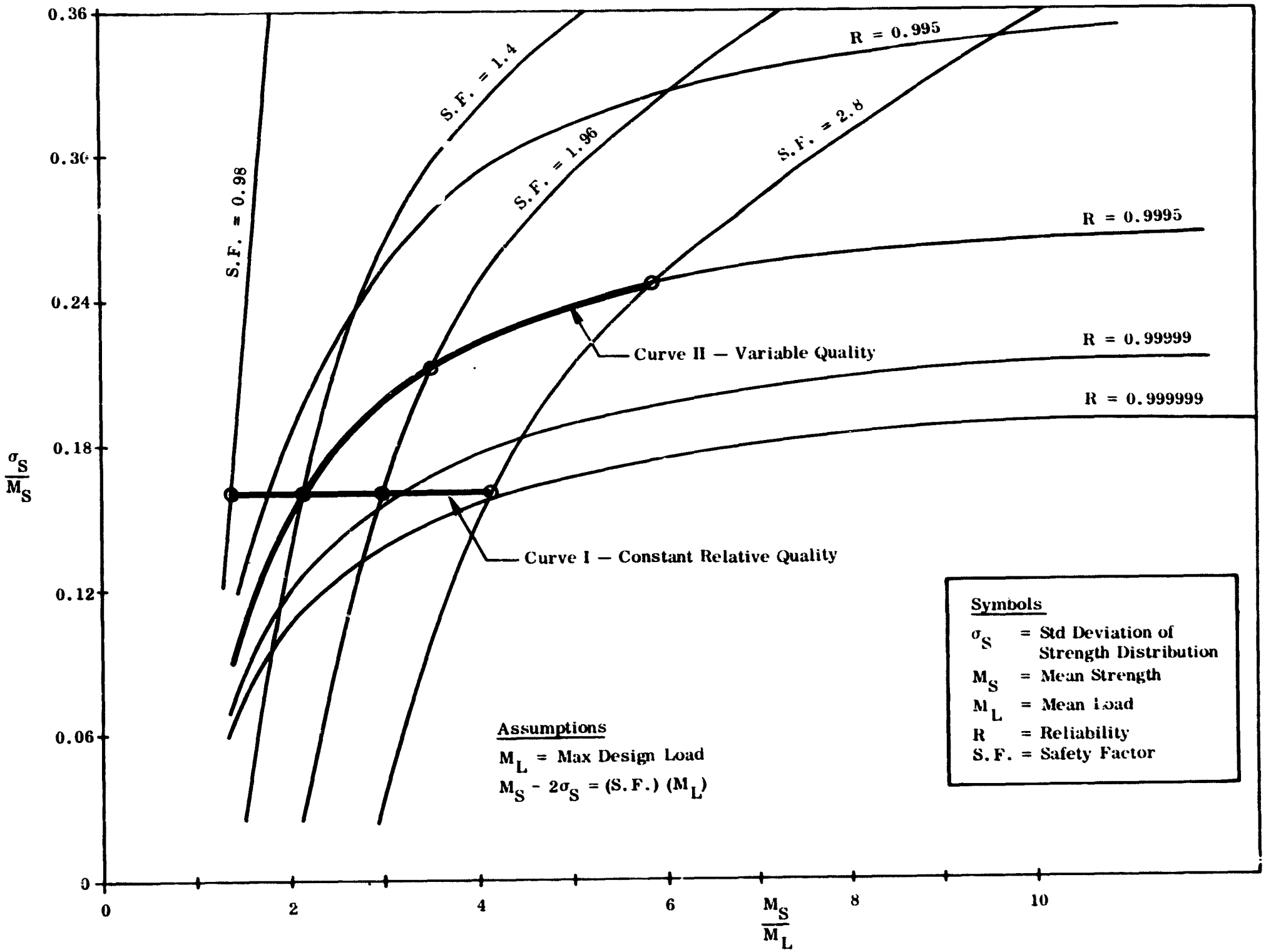


Figure 4-30. Schematic Representation of Interrelationships of Reliability, Safety Factor, Strength Ratios, and Quality Control Factors

for the inexpensive materials occurred for safety factors higher than the nominal factors of safety; the best results for the more expensive materials occurred at lower factors of safety.

4.6.4 INTERACTION OF RECURRING MANUFACTURING COSTS AND SAFETY FACTOR

The results of two types of variation in quality control on manufacturing costs are tabulated in Table 4-38 and illustrated for several materials on Figures 4-31 and 4-32. The variations that were considered here are:

a. Quality control requirements are held constant so that the only changes in cost are due to variations attributable to factor of safety. This corresponds to Curve I of Figure 4-30.

b. Quality control is allowed to decrease with increase in factor of safety in such a way as not to degrade reliability. This constant reliability case represents the maximum cost reduction that is achievable without reducing structural effectiveness, and is illustrated by Curve II of Figure 4-30.

For Al ISS, there is a strong dependence of cost on the assumed variation of quality with factor of safety. For the other materials, sensitivity of costs with assumed quality variation was smaller. For the honeycomb constructions, the influence of quality variations was masked by the strong dependence of cost on shell area. For the more costly materials, such as boron, carbon, or beryllium, the influence of the assumptions has much less effect than the increased weight of materials required for the higher factor of safety. The best manufacturing performance for cost is achieved at the lowest possible safety factor for these higher cost materials.

Table 4-38

Summary of Structural Costs for Constant and Variable Quality
Representative Structures

Structure	Cost in Thousands							
	Factor of Safety/Nominal Factor of Safety							
	0.7		1.0		1.4		2.0	
	Constant Quality I*	Variable Quality II	Constant Quality I	Variable Quality II	Constant Quality I	Variable Quality II	Constant Quality I	Variable Quality II
Al ISS (P)	2177.6	4155.4	2118.8	2118.8	2360.1	1842.3	2715.8	1765.4
Al ISS (U)	2312.7	5318.0	2544.9	2544.9	2782.2	1952.0	3138.2	1756.4
Al Hyc (P)	1735.9	1931.6	1750.0	1750.0	1770.7	1685.2	1802.8	1648.4
Al Hyc (U)	1534.3	1631.9	1566.6	1566.6	1581.3	1525.7	1602.7	1497.6
Be Hyc (U)	5284.9	5946.3	6011.1	6011.1	6968.9	6636.4	8418.5	7724.3
Ti Hyc (Stresskin) (P)	3058.9	3656.6	3026.0	3026.0	3007.3	2838.0	3018.9	2745.2
Be SS (U)	12095.4	14673.6	12909.5	12909.5	15227.4	13989.9	19019.8	16536.1
B/Ep Hyc (U)	2683.6	3081.6	3562.1	3562.1	4739.1	4506.3	6500.4	5967.7
C/Ep Hyc (U)	2115.5	2407.4	2751.2	2751.2	3602.9	3432.1	4877.3	4487.6
B/Ep Unid S On Al (P)	2356.8	2671.4	2573.6	2573.6	2805.8	2673.5	3094.5	2847.6
B/Ep Unid S On Al (U)	2893.7	3267.5	3300.3	3300.3	3725.9	3565.1	4411.4	4088.6
B/Al Hyc (P)	3594.6	4145.7	4352.5	4352.5	5361.5	5062.7	6880.8	6243.5
B/Al Hyc (U)	3350.9	3828.5	4150.9	4150.9	5150.7	4872.1	6710.4	6103.1

*The Notation I and II refer to the curves on Figure 4-30.

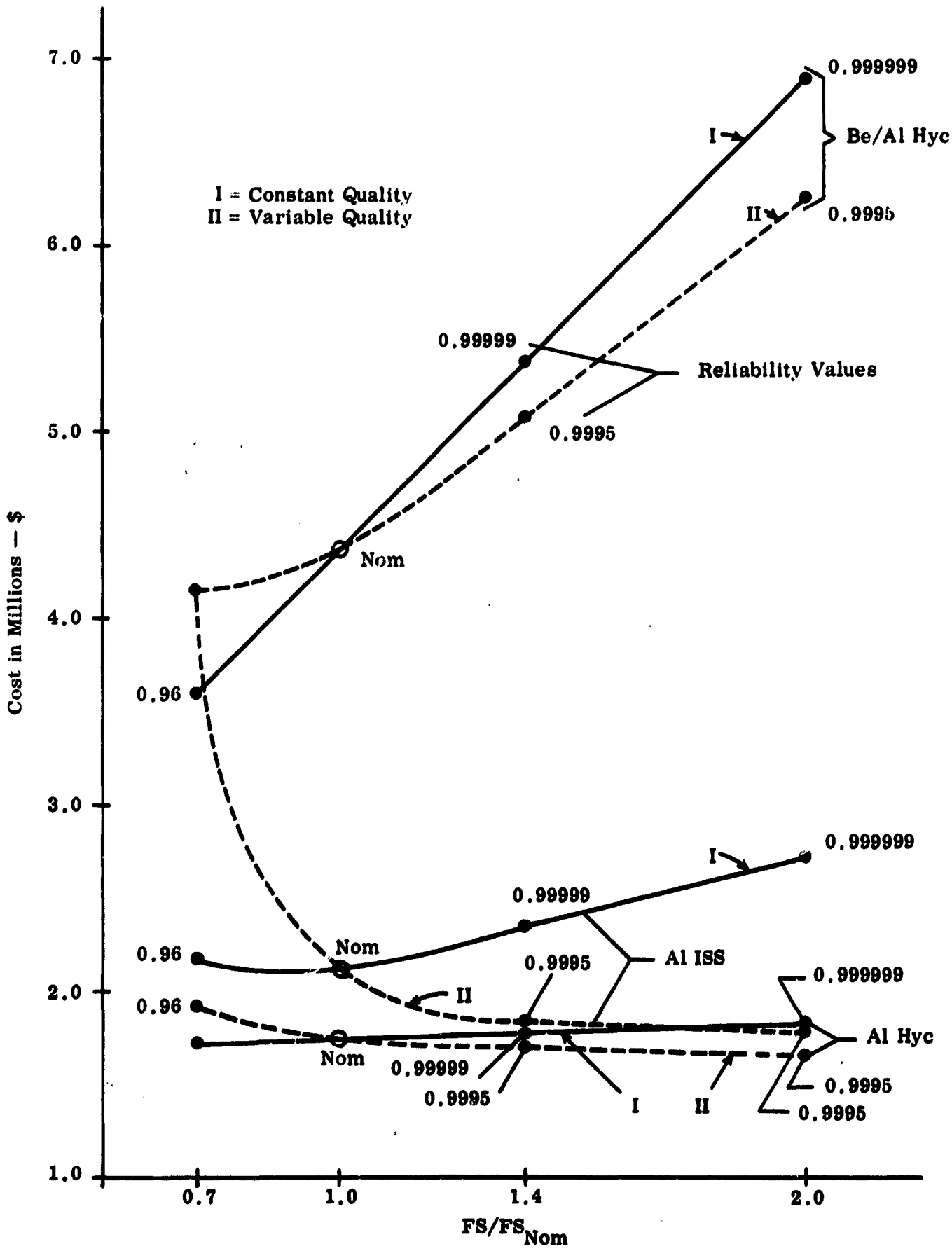


Figure 4-31. Pressurized Cylinder Costs versus Relative Factor of Safety (FS/FS Nom) For Various Materials and Quality Control Factors (Assuming Fixed Vehicle Configuration)

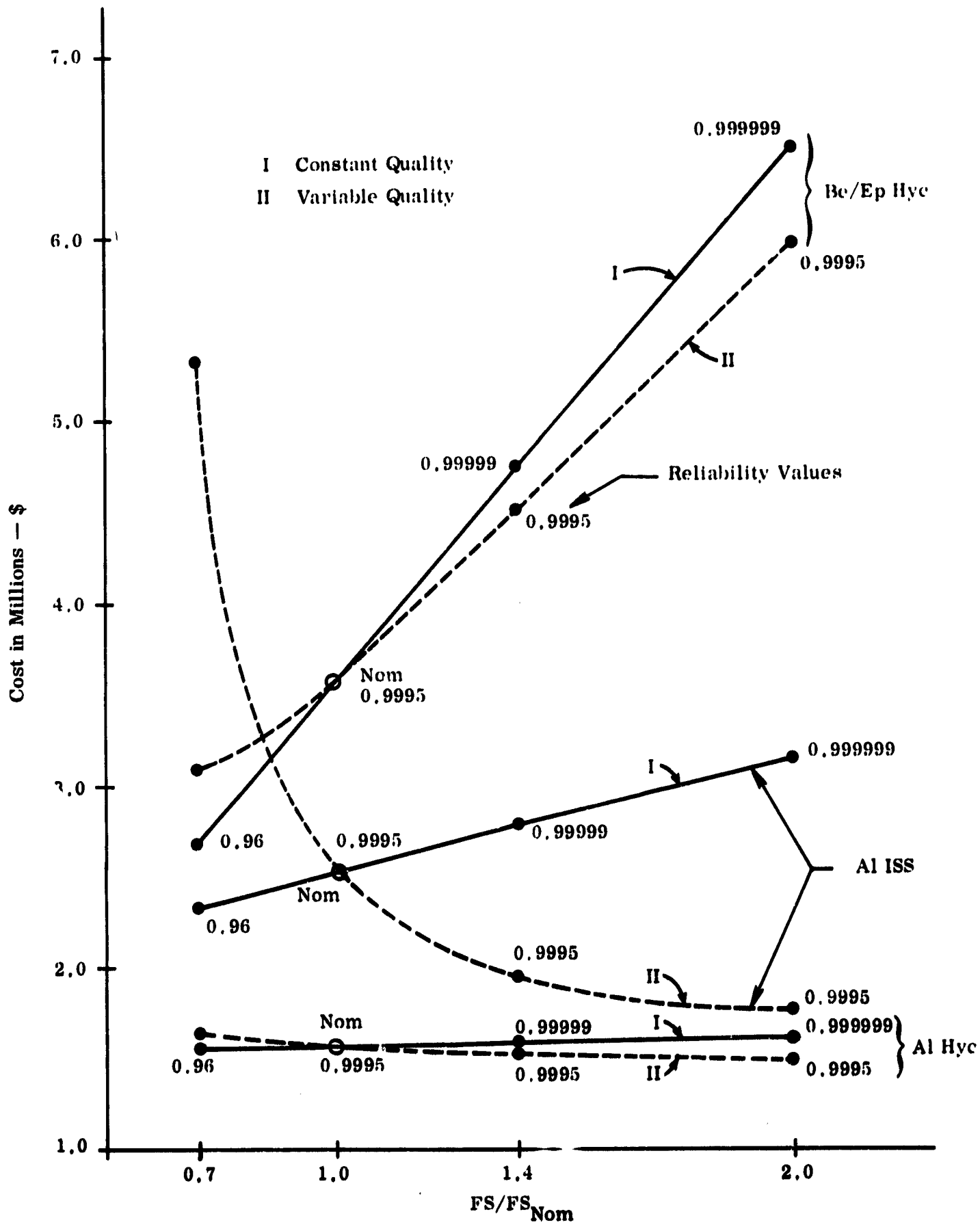


Figure 4-32. Unpressurized Cylinder Costs versus Relative Factor of Safety (FS/ FS Nom) For Various Materials and Quality Control Factors (Assuming Fixed Vehicle Configuration)

4.6.5 INTERACTION OF STRUCTURAL TEST COSTS AND SAFETY FACTOR

Table 4-39 shows the recurring cost variations in the test program cost as a result of varying the relative factors of safety. The data shows the changes in recurring test costs as a function of changes in factor of safety. This analysis, which correlates with the data in Table 4-36, shows how various factors influence test costs. The data shows a test cost variation between $\$2.4 \times 10^6$ and $\$6.6 \times 10^6$ as the factor of safety multiplier ranges between 0.7 and 2.0. These results are used in the analyses of vehicle comparative costs. The test analysis revealed that while increasing the factor of safety would result in a gradual decreasing of test costs, the biggest single impact would be in simplification of the silo tests. Present test practices require the application of referee fluids outside the vehicle and pressurization under strict test procedures. As vehicle ruggedness is increased, these procedures can be simplified, and finally, a state would be reached where the silo could be eliminated.

4.6.6 VEHICLE PERFORMANCE SENSITIVITIES (FIXED CONFIGURATION VERSUS FIXED PAYLOAD)

4.6.6.1 Introduction

The performance improvement with advanced materials can be utilized in two ways:

a. Increased payload—assume that the vehicle size and configuration remains the same with constant propellant loading and thrust.

b. Reduced vehicle size—the required payload remains the same and the propellants, configuration, and thrust are all reduced as a function of the reduced structural weight.

The foregoing analyses have dealt primarily with the first case (a) above. This is analogous to the situation where improved materials might be substituted in an existing vehicle to increase payload capability.

An analysis summarized in this section evaluates the impact of (b) above—the reduction of vehicle size permitted by the use of advanced materials. In this case, the vehicle is considered to be "rubberized" to maintain a constant payload. Such a "rubberized" vehicle concept is rarely practical since in the design cycle a number of fixed constraints usually emerge which constrain a design and invalidate the concept of shrinking or expanding the vehicle dimensions. However, it is interesting from an academic viewpoint to compare the relative merits of the various construction technologies for a fixed payload.

Table 4-39

Recurring Test Costs/Vehicle
(Cost in Millions)

	FS/FS_{NOM}			
	0.7	1.0	1.4	2.0
Base Cost (for Factor of Safety = 1)	$4.4	$4.4	$4.4	$4.4
Changes With Increased Safety Factor				
Requirements Reduction	0	0	0	0
Hardware Reduction	0	0	0	0
Test Methods Simplification	+2.0	0	-0.8	-2.0
Weight Increase	-0.4	0	+0.16	+0.4
Ruggedness Increase	+0.4	0	-0.16	-0.4
Cost	$6.4	$4.4	$3.6	$2.4

4.6.6.2 Analysis

The factors used to adjust structural size have been determined by assuming constant mass ratios for the fixed configuration and fixed payload vehicles for each particular material and construction combination.

$$\frac{W_i}{W_o} = e^{\left(\frac{\Delta v}{I_{sp}g}\right)} = \text{Mass Ratio} = \text{Constant} \qquad (4\text{-}3)$$

where:

W_i = Initial mass of a stage, lb

W_o = Final (burnout) mass of a stage, lb

Δv = Incremental velocity achieved by a stage, ft/sec

$I_{sp}g$ = Engine exhaust velocity, ft/sec

This assumption of a fixed mass ratio implies that the structural weights can be varied, along with other weights, but only in proportion so that a constant ratio is maintained. Thus, as structural weights are decreased with the use of improved materials, the overall vehicle weight decreases, then the propellant requirements decrease. This now, results in a slight size reduction but still with the same payload.

The results of the analysis for the fixed configuration vehicles are shown in the upper portions of Tables 4-40 and 4-41. Included in the upper portion of the table are the weights for each structural section of the 201 vehicle. Payload of the nominal vehicle is 1,019,000 pounds. Calculations for other materials and other factors of safety provide different structural weights and hence different payload. For example, the payload is 1,118,358 for aluminum honeycomb with nominal safety factor and 1,021,516 for aluminum honeycomb with factors of safety twice nominal.

The lower portion of Tables 4-40 and 4-41 shows the results of correcting the structural weights by the correction factors for the fixed payload of 1,019,000 pounds.

The structural reduction factors, i.e., those factors which indicate the reduction necessary for constant payload, are plotted in Figure 4-33 and found to be a linear function with weight for the unpressurized sections. Structure reduction factors in Table 4-42, were obtained by using this curve and the weights from Sections 4.3 and 4.4 of this report. The structural weight for the fixed configuration vehicle were then multiplied by these factors to obtain an approximation of weights for the fixed payload case.

For purposes of this sensitivity study, it was assumed as a first approximation that costs vary in direct proportion to the weight changes for a "rubberized" vehicle. A more thorough analysis, requiring a considerable amount of design and engineering, would be required to produce more accurate results. However, for the purposes of these trade-off studies, the linear approximation is considered sufficiently accurate to reveal gross cost trends.

Table 4-40

Performance/Weight Analysis Results Sho

Section	Construction	Nominal Weight	Alumin Factor of Safe	
			0.7	1.(
Fixed Vehicle Configuration				
IU and Fwd Skirt	Al ISS/Hyc	13004	10120	13(
LH_2 Tank and Thrust Structure*	Al	39323	39323	39
Intertank	Al ISS/Hyc	38963	31434	38
Baffles and Insulation*	Fixed	12900	12900	12
LOX Tank*	Al Mono	8850	8850	8
Aft-skirt	Al ISS/Hyc	10389	8283	10
2nd Stage Total—lb		123429	110910	123
2nd Stage Total—kg		(55987)	(50309)	(55
Interstage	Al ISS/Hyc	65266	52056	65
Fwd Skirt	Al ISS/Hyc	46882	36603	46
LOX Tank Top Head	Al Mono	8746	6122	8
LOX Tank Bottom Head	Al Mono	19318	13523	19
Intertank	Al ISS/Hyc	156026	115361	156
LH_2 Tank Top Head	Al Mono	15935	11154	15
LH_2 Tank Cylinder	Al ISS/Hyc	63411	59754	63
LH_2 Tank Bottom Head	Al Mono	35330	24731	35
Thrust Take Out	Al ISS/Hyc	53698	39517	53
Thrust Structure*	Al	82741	82741	82
Baffles and Insulation*	Fixed	20040	20040	(20
1st Stage Total—lb		567393	461602	567
1st Stage Total—kg		(257369)	(209383)	(257
Vehicle Total—lb		690822	572512	690
Vehicle Total—kg		(313356)	(259692)	(313
Payload Increase from Nominal**		-	44256	
Percent Total Change in Payload		-	6.406	
Payload		1019000	1063256	1019
Standard Reduction Factor for Fixed Payload at 1,019,000 lb		1.0	1.043	
Fixed Payload of 1,019,000 lb				
Intertank		156026	110605	156
LH_2 Tank Top Head		15935	10694	15
LH_2 Tank Cylinder		63411	57290	63
Total of Above Sections, lb		235372	178589	235
kg		(106765)	(81008)	(106

*Assumed Constant Values

**Total Difference in Stage 2 Plus 0.3 × Total Difference in Stage 1 (Reference 6)

READOUT FRAME

Table 4-40

lysis Results Showing Structure Weights

Aluminum ISS Factor of Safety Multiplier			Aluminum Hyc Factor of Safety Multiplier		
	1.0	2.0	0.7	1.0	2.0
20	13004	19819	3176	4292	7781
23	39323	39323	39323	39323	39323
34	38963	60925	10860	14795	27604
00	12900	12900	12900	12900	12900
50	8850	8850	8850	8850	8850
83	10389	14792	2064	2941	5866
10	123429	156609	77173	83101	102324
09)	(55987)	(71038)	(35006)	(37695)	(46414)
56	65266	111595	20880	28746	54401
03	46882	76751	15208	20950	39845
22	8746	17492	6122	8746	17492
23	19318	38636	13523	19318	38636
61	156026	235756	53173	73784	145323
54	15935	31870	11154	15935	31870
54	63411	123115	28520	40281	79693
31	35330	70660	24731	35330	70660
17	53698	81339	17842	24754	48656
41	82741	82741	82741	82741	82741
40)	(20040)	20040	20040	20040	20040
02	567393	889989	293934	370625	629357
83)	(257369)	403699	(133328)	(168116)	(285476)
12	690822	1046598	371107	453726	731681
92)	(313356)	(474737)	(168334)	(205811)	(331890)
56	0	96779	128294	99358	2516
06	0	14.009	18.571	14.382	0.036
56	1019000	922221	1147294	1118358	1021516
43	1.0	0.905	1.126	1.098	1.002
05	156026	260504	47223	67199	145033
94	15935	35215	9906	14513	31806
90	63411	136039	25329	36686	79534
89	235372	431758	82458	118398	256373
08)	(106765)	(195845)	(37403)	(53705)	(116291)

POUR FRAME 2

Table 4-41

Performance/Weight Analysis Results Show

Section	Construction	Nominal Weight	Beryllium/T Factor of Safe	
			0.7	1.
Fixed Vehicle Configuration				
IU and Forward Skirt	Be ISS/Hyc	13004	2922	33
LH_2 Tank and Thrust Structure*	Ti	39323	38742	387
Intertank	Be ISS/Hyc	38963	8769	106
Baffles and Insulation*	Fixed	12900	12900	129
LOX Tank*	Ti Mono	8850	6523	65
Aft-skirt	Be ISS/Hyc	10389	2217	29
2nd Stage Total—lb		123429	72073	750
2nd Stage Total—kg		(55987)	(32692)	(340
Interstage	Be ISS/Hyc	65266	14535	190
Fwd Skirt	Be ISS/Hyc	46882	10548	137
LOX Tank Top Head	Ti Mono	8746	4011	51
LOX Tank Bottom Head	Ti Mono	19318	8616	123
Intertank	Be ISS/Hyc	156026	34416	408
LH_2 Tank Top Head	Ti Mono	15935	7187	102
LH_2 Tank Cylinder	Ti Hyc	63411	22625	301
LH_2 Tank Bottom Head	Ti Mono	35330	15760	225
Thrust Take Out	Be ISS/Hyc	53698	11747	139
Thrust Structure*	Be ISS/Hyc	82741	36105	361
Baffles and Insulation*	Fixed	20040	20040	206
1st Stage Total—lb		567393	185590	2247
1st Stage Total—kg		(257369)	(84184)	(1019
Vehicle Total—lb		690822	257663	2997
Vehicle Total—kg		(313356)	(116876)	(1359
Payload Increase from Nominal**		-	165897	151
Percent Total Change in Payload		-	24.014	21.8
Payload		1019000	1184897	1170
Structural Reduction Factor for Fixed Payload at 1,019,000 lb		1.0	1.163	1.1
Fixed Payload of 1,019,000 lb				
Intertank		156026	29592	355
LH_2 Tank Top Head		15935	6180	89
LH_2 Tank Cylinder		63411	19454	262
Total of Above Sections, lb		235372	55226	708
Total of Above Sections, kg		(106765)	(25051)	(321

*Assumed Constant Values

**Total Difference in Stage 2 Plus 0.3 × Total Difference in Stage 1 (Reference 6)

FOLDOUT FRAME

Table 4-41

ysis Results Showing Structure Weights

	Beryllium/Titanium ISS Factor of Safety Multiplier		Beryllium/Titanium Hyc Factor of Safety Mu'tiplier		
	1.0	2.0	0.7	1.0	2.0
	3313	5549	1763	2354	3851
	38742	38742	38742	38742	38742
	10630	16867	6073	8123	14192
	12900	12900	12900	12900	12900
	6523	6523	6523	6523	6523
	2931	4522	1143	1626	3235
3	75039	85103	67144	70268	79443
2)	(34038)	(38603)	(30457)	(31874)	(36035)
5	19063	28623	11258	14956	27197
8	13706	19960	8252	10863	19889
1	5731	11462	4011	5731	11462
6	12309	24618	8616	12309	24618
6	40825	76000	27251	36965	72205
7	10268	20536	7187	10268	20536
5	30189	55394	22625	30189	55394
0	22514	45028	15760	22514	45028
7	13953	25835	9156	12404	24200
5	36105	36105	36105	36105	36105
0	20040	20040	20040	20040	20040
0	224703	363601	170261	212344	356674
4)	(101925)	(164929)	(77230)	(96319)	(161787)
3	299742	448704	237405	282612	436117
6)	(135963)	(203532)	(107687)	(128193)	(197822)
7	151197	99464	175425	159676	107202
4	21.887	14.398	25.394	23.114	15.518
7	1170197	1118464	1194425	1178676	1126202
3	1.148	1.098	1.172	1.157	1.105
2	35562	69217	23257	31949	65344
0	8944	18703	6132	8875	18585
4	26297	50450	19305	26092	50130
6	70803	138370	48694	66916	134059
1)	(32116)	(62765)	(22088)	(30353)	(60809)

WAITING FRAME 2

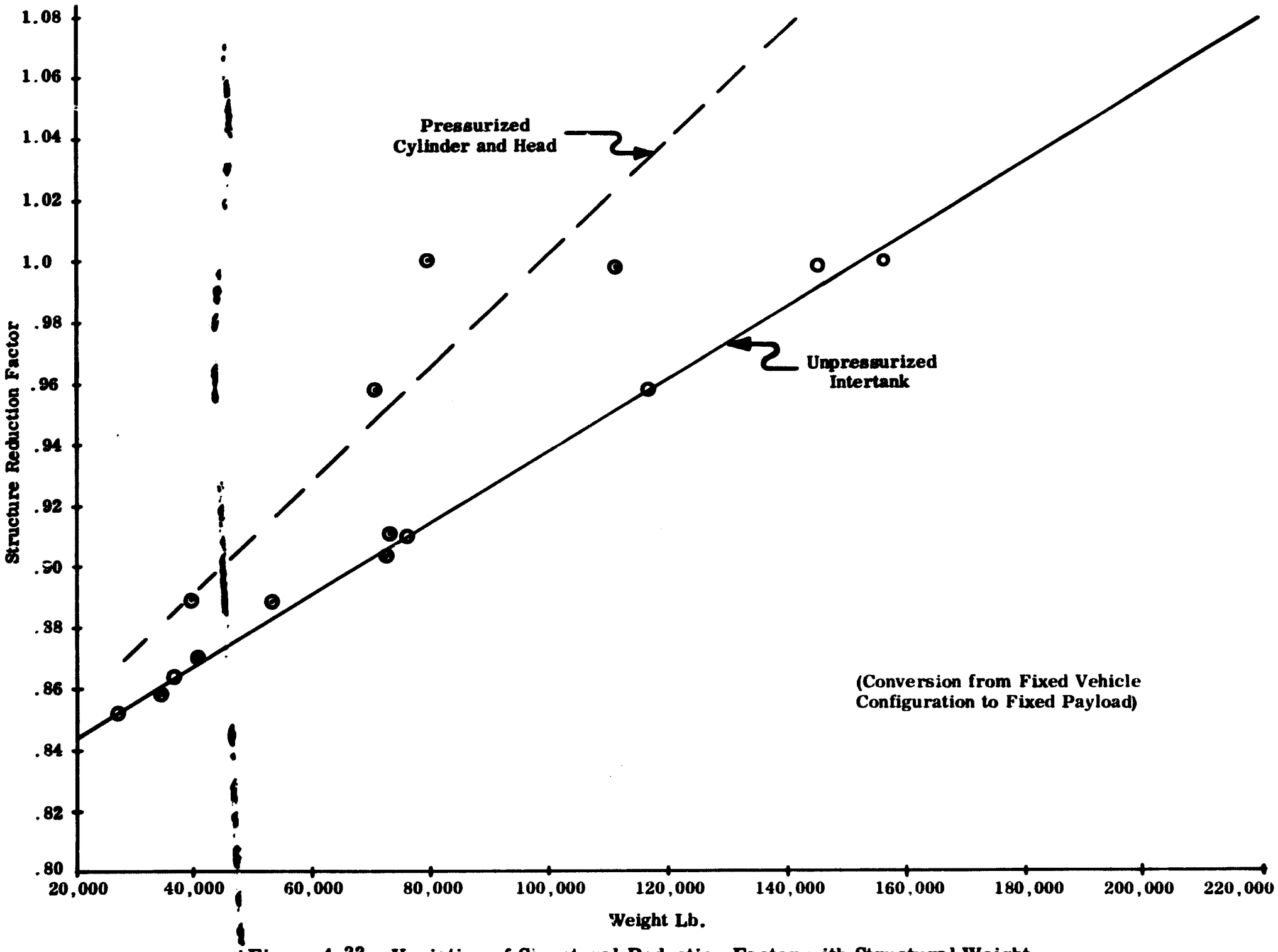


Figure 4-33. Variation of Structural Reduction Factor with Structural Weight

Table 4-42

Structure Reduction Factor for Fixed Payload

Material Combination	Safety Factor/Nominal Safety Factor			
	0.7	1.0	1.4	2.0
Al ISS	$\frac{1}{1.043} = 0.958$	1.0	1.042*	$\frac{1}{0.905} = 1.105$
Al Hyc	$\frac{1}{1.126} = 0.888$	$\frac{1}{1.098} = 0.91$	0.9405*	$\frac{1}{1.002} = 0.998$
Be Hyc	$\frac{1}{1.172} = 0.852$	$\frac{1}{1.157} = 0.864$	0.881*	$\frac{1}{1.105} = 0.904$
Be SS	$\frac{1}{1.163} = 0.859$	$\frac{1}{1.148} = 0.870$	0.885*	$\frac{1}{1.098} = 0.91$
Be/Ep Hyc	0.850*	0.858*	0.870*	0.8865*
C/Ep Hyc	0.848*	0.855*	0.8655*	0.880*
B/Unid Stiff Al	0.949*	0.9775*	1.011*	1.055*
B/Al Hyc	0.849*	0.858*	0.872	0.890*
Ti Hyc	~ 0.871*	~ 0.892*	~ 0.908*	~ 0.957*

*Values interpolated from curve.

In Figure 4-34 and 4-35 the structural materials and wall configurations can be compared on an equal weight basis. The lowest cost construction for fixed payload is aluminum honeycomb as similarly determined for fixed configuration vehicles earlier. Again, variations with factor of safety become more significant for those constructions with higher priced materials. For aluminum honeycomb, there is little variation in cost with safety factor. For the aluminum integrally stiffened skin construction, it is seen that there is a slight advantage (for both pressurized and unpressurized sections) in increasing the safety factor by 40 percent. For the composite materials considered, the lowest costs are seen to occur at the lowest factors of safety.

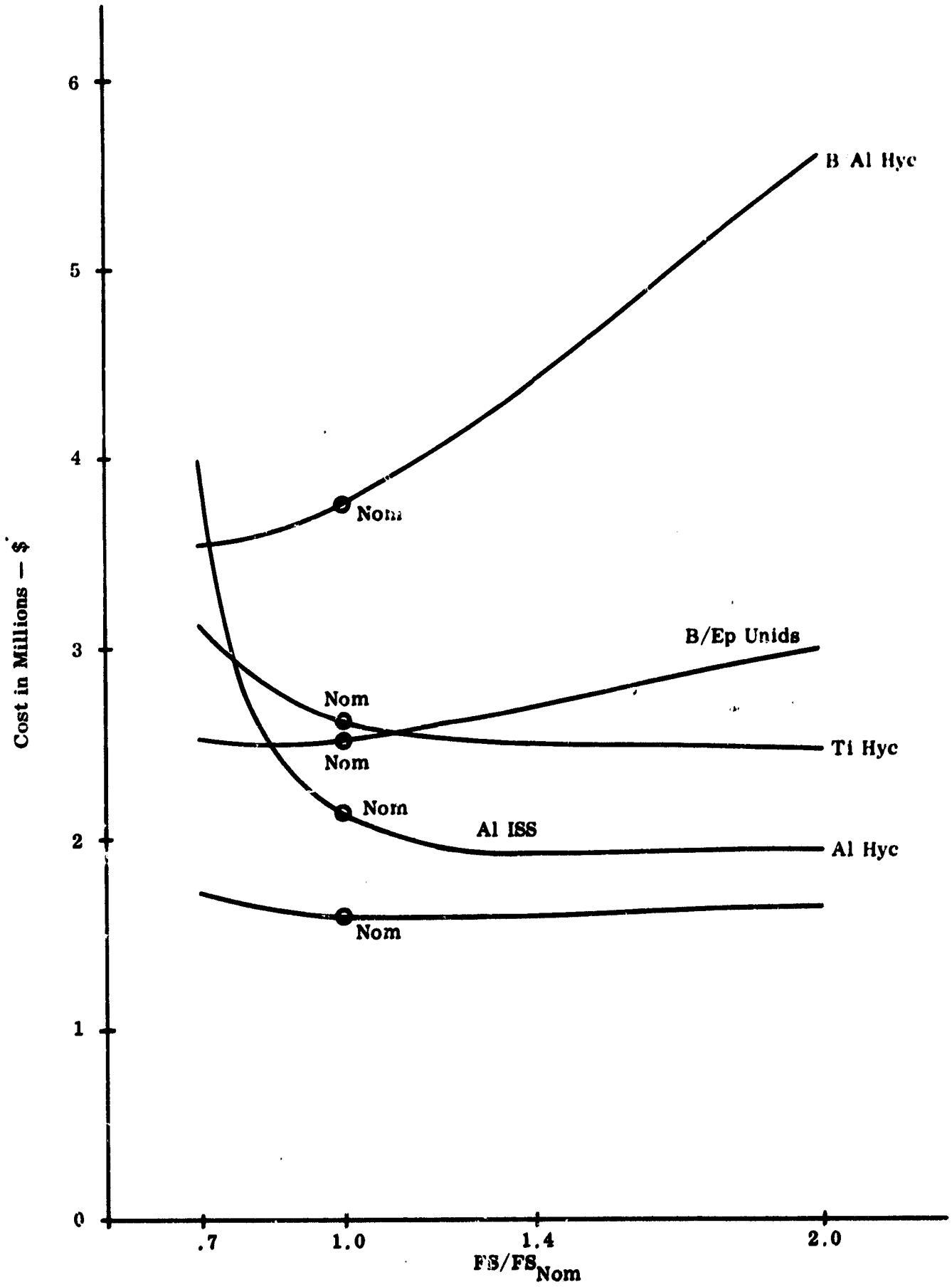


Figure 4-34. Manufacturing Cost versus Relative Factor of Safety (FS/FS_{Nom}) For Fixed Payload Pressurized Cylinder

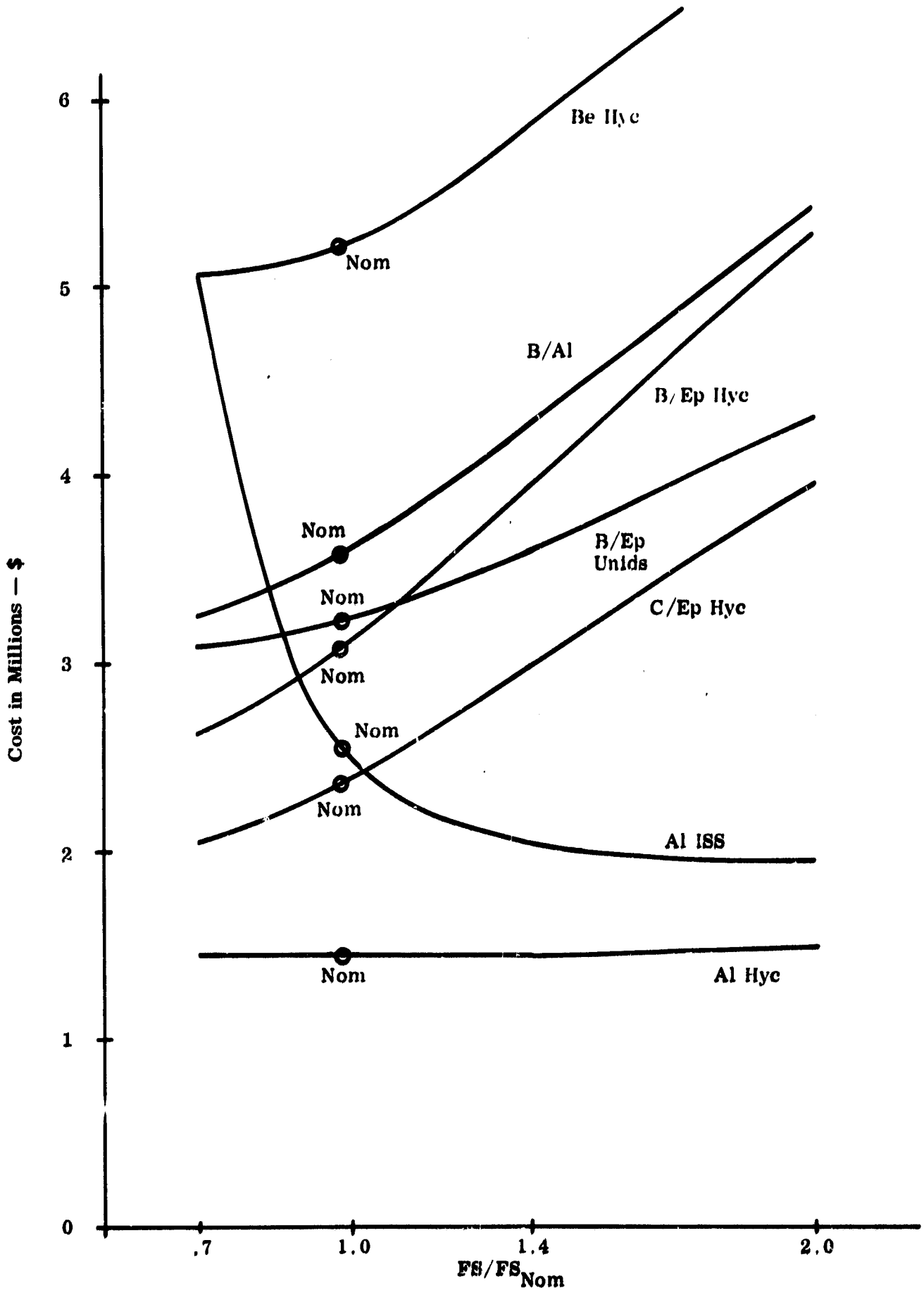


Figure 4-35. Manufacturing Cost versus Relative Factor of Safety (FS/FS_{Nom}) For Fixed Payload Unpressurized Cylinder

4.6.7 IMPACT ON TOTAL VEHICLE STRUCTURAL COST

The influence of the improved structures technology on the total vehicle was analyzed. As indicated in Appendix D, there are advantages in both design and economics by selecting the optimum materials for different components of the vehicle. Three vehicles that were selected for study are illustrated in Table 4-43. The investigation was limited to the case of recurring material fabrication and test costs for nominal factor of safety and for similar vehicle configurations.

The aluminum integrally stiffened skin vehicle which served as the basis for comparison has an estimated manufacturing cost of $11,527,000. This cost was determined through use of cost ratios expressed in dollars per pound, which were representative of each of the sections.

The tank heads for the aluminum honeycomb vehicle were of monocoque construction. Total cost for this vehicle was determined similarly to the aluminum integrally stiffened skin vehicles. Cost per pound ratios were determined for the three representative sections and then applied to the total vehicle. The expected manufacturing costs for the same sections as computed for the aluminum integrally stiffened skin totaled $8,745,000 or a 24 percent reduction from the base vehicle for the aluminum honeycomb vehicle. This was achieved concurrently with an overall 34 percent reduction in vehicle weight. These results indicate that aluminum honeycomb is a very attractive material for large launch vehicles.

The third vehicle in Table 4-43 uses boron/epoxy honeycomb in the unpressurized cylindrical sections and titanium honeycomb in the pressurized cylindrical sections. The pressurized heads are of titanium monocoque construction. As with the first two vehicles, the costs were computed using cost values determined for the representative sections of the vehicle used in this study and appropriately extended to other equivalent sections. The total cost for this vehicle was $13,783,000 which is an increase of 41 percent over the baseline vehicle. This increase in cost was accompanied by a 53 percent reduction in weight.

In general, the cost results are similar to those determined for the representative sections. Table 4-43 illustrates the relative magnitude of total costs which may be associated with the introduction of advanced materials and technology along with the potential benefit of weight savings.

Table 4-43

201 Vehicle—Weight/Cost Analysis—$FS/FS_{Nom} = 1.0$

Section	Al ISS				Al Hyc				B/Epoxy (0.001 lb/in^3 Core)				
	Weight (lb) (kg)	Fixed Cost (Thous)	Variable* Cost (Thous)	Cost/ lb $	Weight (lb) (kg)	Fixed Cost (Thous)	Variable* Cost (Thous)	Cost/ lb $	Material	Weight (lb) (kg)	Fixed Cost (Thous)	Variable* Cost (Thous)	Cost/ lb $
IU and Fwd Skirt	13004		225	17.31	4292		91	21.24	B/Ep	2759		308	111.65
LH_2 Tank and Thrust Str	39323		-	-	39323		-	-	-	39323		-	-
Intertank	38963		674	17.31	14795		314	21.24	B/Ep	8663		967	111.65
Baffles and Insulation	12900		-	-	12900		-	-	-	12900		-	-
LOX Tank	8850		-	-	8850		-	-	-	8850		-	-
Aft Skirt	10389		180	17.31	2941		62	21.24	B/Ep	2122		237	111.65
2nd Stage Total	(123429) (55987)		(1079)		(83101) (37695)		(467)			(74617) (33846)		(1512)	
Interstage	65266		1130	17.31	28746		611	21.24	B/Ep	14294		1596	111.65
Fwd Skirt	46882		812	17.31	20950		445	21.24	B/Ep	10251		1145	111.65
LOX Tank Top Head	8746		402	45.94	8746		402	45.94	Ti	5731		503	87.84
LOX Tank Bottom Head	19318		887	45.94	19318		887	45.94	Ti	12309		1081	87.84
Intertank	156026		2545	17.31	73784		1567	21.24	B/Ep	31902		3562	111.65
LH_2 Tank Top Head	15935		732	45.94	15935		732	45.94	Ti	10268		902	87.84
LH_2 Tank Cylinder	63411		1387	21.87	40281		1018	25.27	Ti	30189		2124	70.35
LH_2 Tank Bottom Head	35330		1623	45.94	35330		1623	45.94	Ti	22514		1584	70.35
Thrust Take Out	53698		930	17.31	24754		526	21.24	B/Ep	11514		1286	111.65
Thrust Structure	82741		-	-	82741		-	-	-	82741		-	-
Baffles and Insulation	20040		-	-	20040		-	-	-	20040		-	-
1st Stage Total	(567393) (257369)		(10448)		(370625) (168116)		(8278)			(251753) (114195)		(13783)	
Total Vehicle	(690822) (313356)		(11527)		(453726) (205811)		(8745)			(326370) (148041)		(15295)	
Percent of Al ISS	100		100		66		76			47		141	

(Not Determined)

*This is the recurring cost only, reflecting the costs for material fabrication and tests.

APPENDIX A

THE RELATION BETWEEN STRUCTURAL SAFETY FACTOR, RELIABILITY AND QUALITY CONTROL FACTOR

APPENDIX A

THE RELATION BETWEEN STRUCTURAL SAFETY FACTOR, RELIABILITY AND QUALITY CONTROL FACTOR

The basic concept of reliability is the prediction that a given part with certain physical properties, which if exceeded, will result in failure of that part. These properties are known only to the extent that they belong to a population and provides a base for determining statistically those expected physical properties. For a structural element, this population is composed of elements such as basic material properties as well as design parameters such as thickness, cross-sectional area, etc. The equations of stress analysis supply the relations which relate these parameters, resulting in a quantity known as the strength of the part. A structural element will have several different strengths depending upon the type of loading expected and the criteria for defining the failure. For example, in some environments fatigue life may be the limiting factor, while in other cases static rupture of a pressure vessel may be the only significant failure mode. Only the latter or equivalent type of failure will be considered here.

Strength of a part is defined as that load which the structure can carry without catastrophic failure or rupture which would prevent the structure from fulfilling its normal functions. This failure strength is a function of the basic material properties and the geometrical design parameters. Variations in the strength about the design value will depend on variations of material properties, on manufacturing tolerances, etc. The influence of the variation of a particular parameter on the overall strength of the part can be determined from the design equations.

To determine the expected variation in strength of a group of nominally identical parts, a great many must be tested to failure to attain high confidence in the result. This frequently is not economically feasible, especially for large structures where measuring reliability is usually not justified, and simplifying approximations are therefore made. Also, costs would be prohibitive. The simplest type of distribution to treat mathematically is the Gaussian distribution (normal distribution). This approximation will be used in the analysis of this portion of the study.

The probability of failure depends upon the variability of strength, and on the external load (and so on the stress level). Although it is known that the spectrum of stresses

due to certain types of applied loads may depart significantly from the normal distribution (e.g., wind loads are better represented by a log-normal distribution), it is doubtful if the small amount of available data justifies the use of any distribution other than normal. The launch vehicle design criteria is expressed as a deterministic synthetic wind profile.

Calculations of stresses for wind loadings are based on the assumption that the vehicle will encounter this wind profile. As a basis for developing the mathematical relations, it is assumed here that loads are normally distributed. The case for known fixed loads is analyzed by setting the standard deviation of the load distribution equal to zero. The loads, like the strengths, are treated here as having an experimentally determined normal distribution of known mean and standard deviation. The relation between the load and strength distributions is shown in Figure A-1.

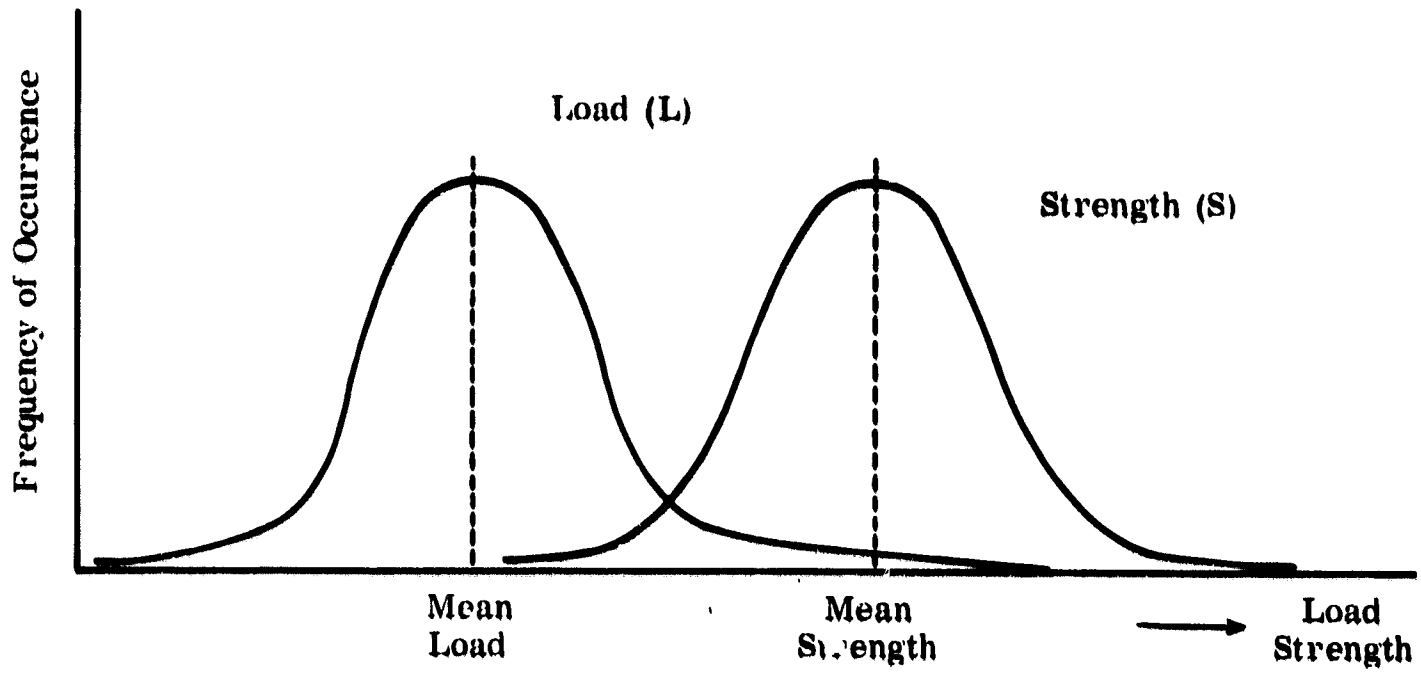


Figure A-1. Load and Strength Relationship

Strength (S) and Load (L) as defined above are random normally distributed variables. For static loads, failure occurs when L > S for any members of the S and L populations chosen at random. A new normally distributed random variable Z, where Z = S - L, is utilized to evaluate the probability that S - L > 0.

If the random variables S and L have means M_S and M_L and standard deviations σ_S and σ_L, respectively, then the distribution function for the variable Z has M and σ given by:

$$M_Z = M_S - M_L$$

$$\sigma_Z^2 = \sigma_S^2 - \sigma_L^2 \qquad \text{(A-1)}$$

Reliability is defined as the probability that the strength is greater than the applied load. Therefore,

$$\text{Reliability (R)} = \text{Prob}(S > L) = \text{Prob}(Z > 0)$$

Since Z is also normally distributed, by definition,

$$\text{Prob}(a < Z < b) = \int_a^b \frac{1}{\sigma_Z \sqrt{2\pi}} e^{-\frac{(Z - M_Z)^2}{2\sigma_Z^2}} dZ \qquad \text{(A-2)}$$

where a and b are any two real numbers.

The probability that $Z > 0$ is then

$$R = \text{Prob}(0 < Z < \infty) = \frac{1}{\sigma_Z \sqrt{2\pi}} \int_0^\infty e^{-\frac{(Z - M_Z)^2}{2\sigma_Z^2}} dZ \qquad \text{(A-3)}$$

Since we wish to evaluate the integral from normal distribution tables, which are based on a random variable having zero mean and unity standard deviation, we introduce a variable Y having these properties:

$$Y = \frac{Z - M_Z}{\sigma_Z} \qquad \text{(A-4)}$$

Then

$$R = \frac{1}{\sqrt{2\pi}} \int_{-\frac{M_Z}{\sigma_Z}}^\infty e^{-\frac{Y^2}{2}} dY \qquad \text{(A-5)}$$

Figure A-2 shows this integral graphically.

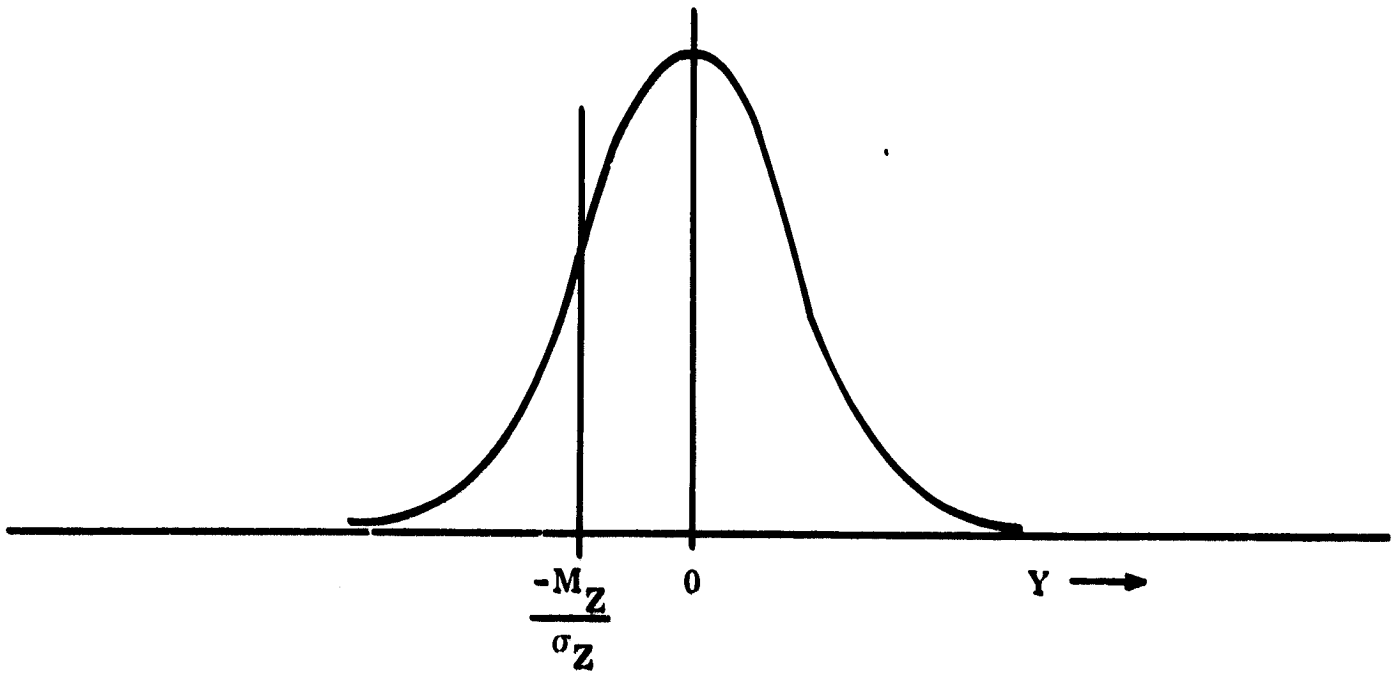


Figure A-2. Distribution of a Y Variable

Since the distribution of Y is symmetrical about zero, it is apparent that the reliability R is also given by

$$R = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\frac{M_Z}{\sigma_Z}} e^{-\frac{Y^2}{2}} dY \qquad \text{(A-6)}$$

which is in a more convenient form for evaluation from Gaussian distribution tables.

In terms of strength and load parameters

$$R = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\frac{M_S - M_L}{(\sigma_S^2 + \sigma_L^2)^{\frac{1}{2}}}} e^{-\frac{Y^2}{2}} dY \qquad \text{(A-7)}$$

For normally distributed S and L, the reliability depends only on the quantity represented by the upper limit of the integral in Equation A-7.

To determine the effect of changes in the shapes of strength and load distribution and of the spacing of the means M_S and M_L, the quantity X is treated as a variable.

$$X = \frac{M_S - M_L}{(\sigma_S^2 + \sigma_L^2)^{\frac{1}{2}}} \qquad \text{(A-8)}$$

For a given value of X (and therefore of R), the relation between the ratio of mean strength to mean load and the quantity σ_S/M_S can easily be found from Equation A-8 as:

$$\left(\frac{\sigma_S}{M_S}\right)^2 = \frac{1}{X^2}\left\{\left[1 - \frac{1}{M_S/M_L}\right]^2 - \left(\frac{\sigma_L}{M_L}\right)^2\left(\frac{1}{M_S/M_L}\right)^2 X^2\right\} \qquad \text{(A-9)}$$

For the case where the load is assumed to be a constant, ($\sigma_L = 0$), this reduces to

$$\frac{\sigma_S}{M_S} = \frac{1}{X}\left[1 - \frac{1}{M_S/M_L}\right] \qquad \text{(A-10)}$$

In order to relate the probabilistic reliability parameter (R) to the usual deterministic structural safety factor, the quantities N_S and N_L (Figure A-3) are introduced. The safety factor is defined as

$$\text{S.F.} \equiv \frac{S}{L} \qquad \text{(A-11)}$$

The quantity N_S is the number of standard deviations that the design strength is set below the mean strength, and N_L is the number of standard deviations that the design load is placed above the mean load. Thus

$$L = M_L + N_L \sigma_L$$

$$S = M_S - N_S \sigma_S$$

and

$$\text{S.F.} = \frac{M_S - N_S \sigma_S}{M_L + N_L \sigma_L} \qquad \text{(A-12)}$$

or in terms of the ratio of strength standard deviation to mean strength,

$$\frac{\sigma_S}{M_S} = \frac{1}{N_S}\left[1 - \left(1 + N_L \frac{\sigma_L}{M_L}\right) S.F.\left(\frac{1}{M_S/M_L}\right)\right] \qquad \text{(A-13)}$$

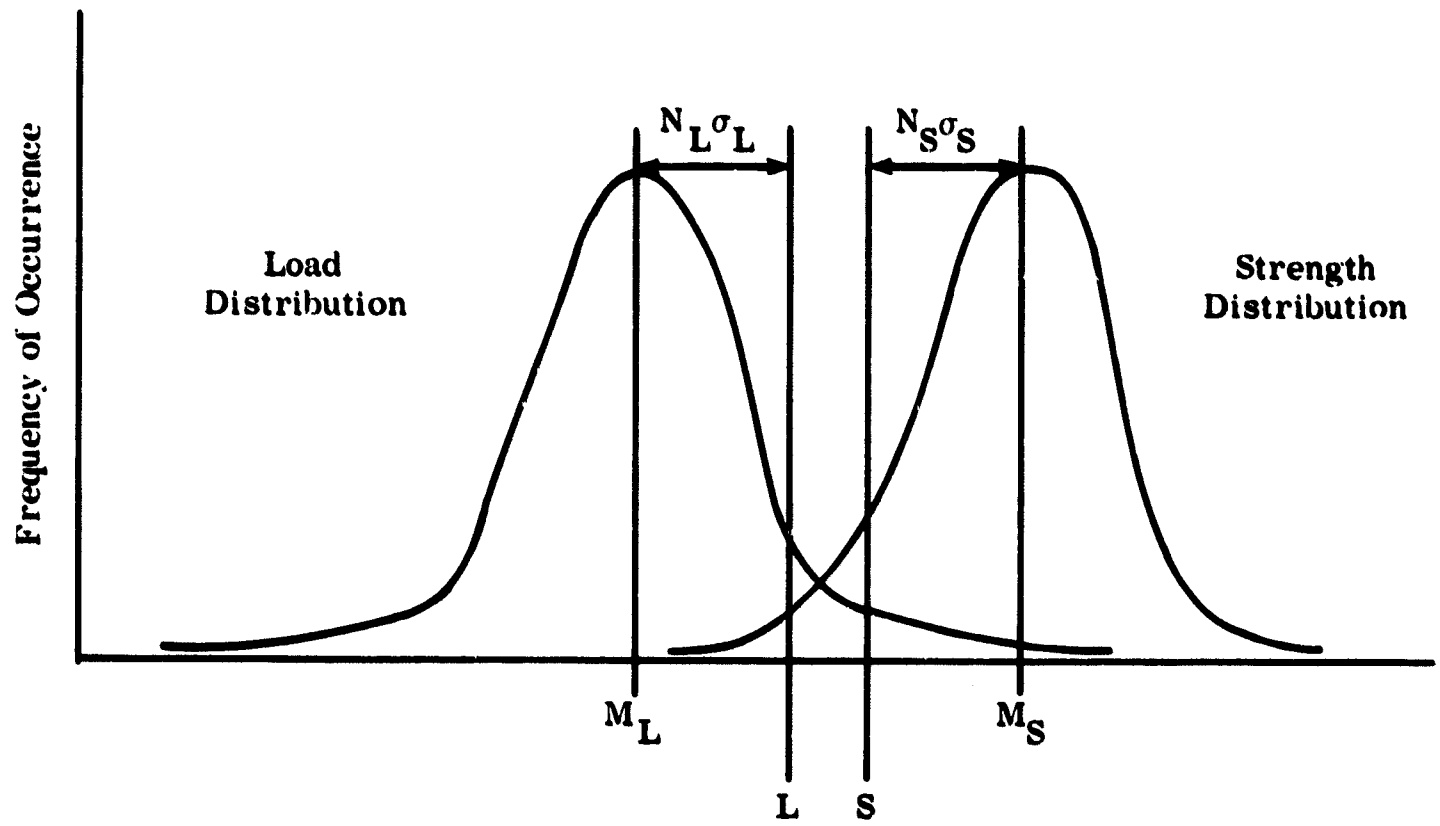


Figure A-3. Load and Strength Distribution

From Equations A-9 and A-13, graphs of σ_S/M_S versus M_S/M_L are plotted for particular values of N_L, N_S, and σ_L/M_L using constant values of R and S.F. as parameters.

Similarly, the dimensionless parameter M_S/M_L can be eliminated to obtain a relationship between R and S.F. for various values of σ_S/M_S. Reliability from Equation A-7 is plotted against S.F. in Figure A-4 for various values of σ_S/M_S.

These graphs establish the relation between R and S.F. when the load and strength distributions and the design points are specified. The curves in Figures A-5 through A-8 are plotted from these equations for the combinations of values of $N_L = 0, 3$, and $N_S = 2, 3$. Plotting both R and S.F. as functions of σ_S/M_S and M_S/M_L allows the evaluation of situations where S.F. is varied for fixed values of R, or where R is varied for fixed values of S.F.

The relationships developed can also be used to relate R and S.F. for various ratios of mean strength to mean load as plotted in Figure A-9. This relationship is derived

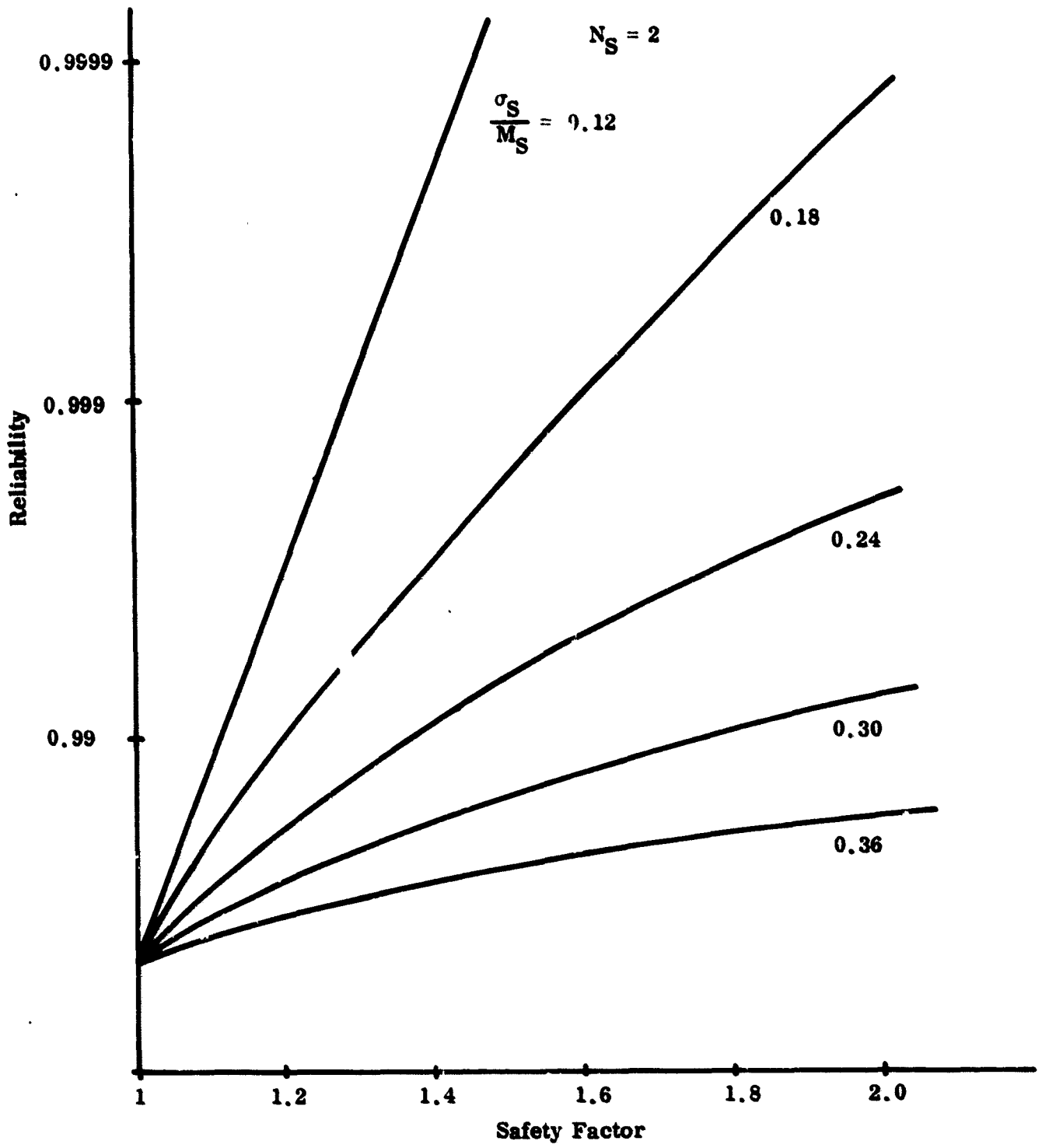


Figure A-4. Relationship of Reliability and Factor of Safety Non-Statistical Loads

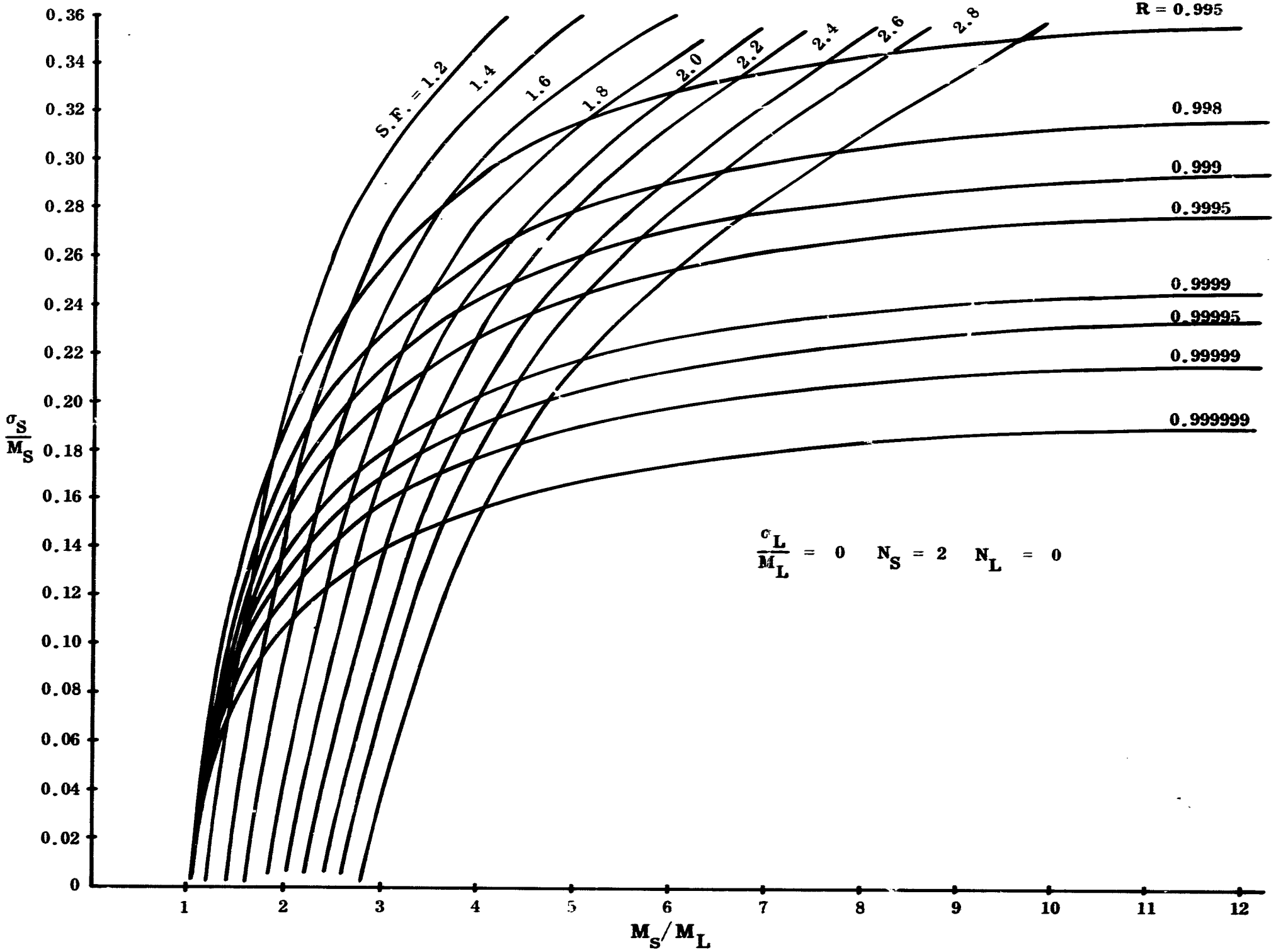


Figure A-5. Reliability and Safety Factor Relationship

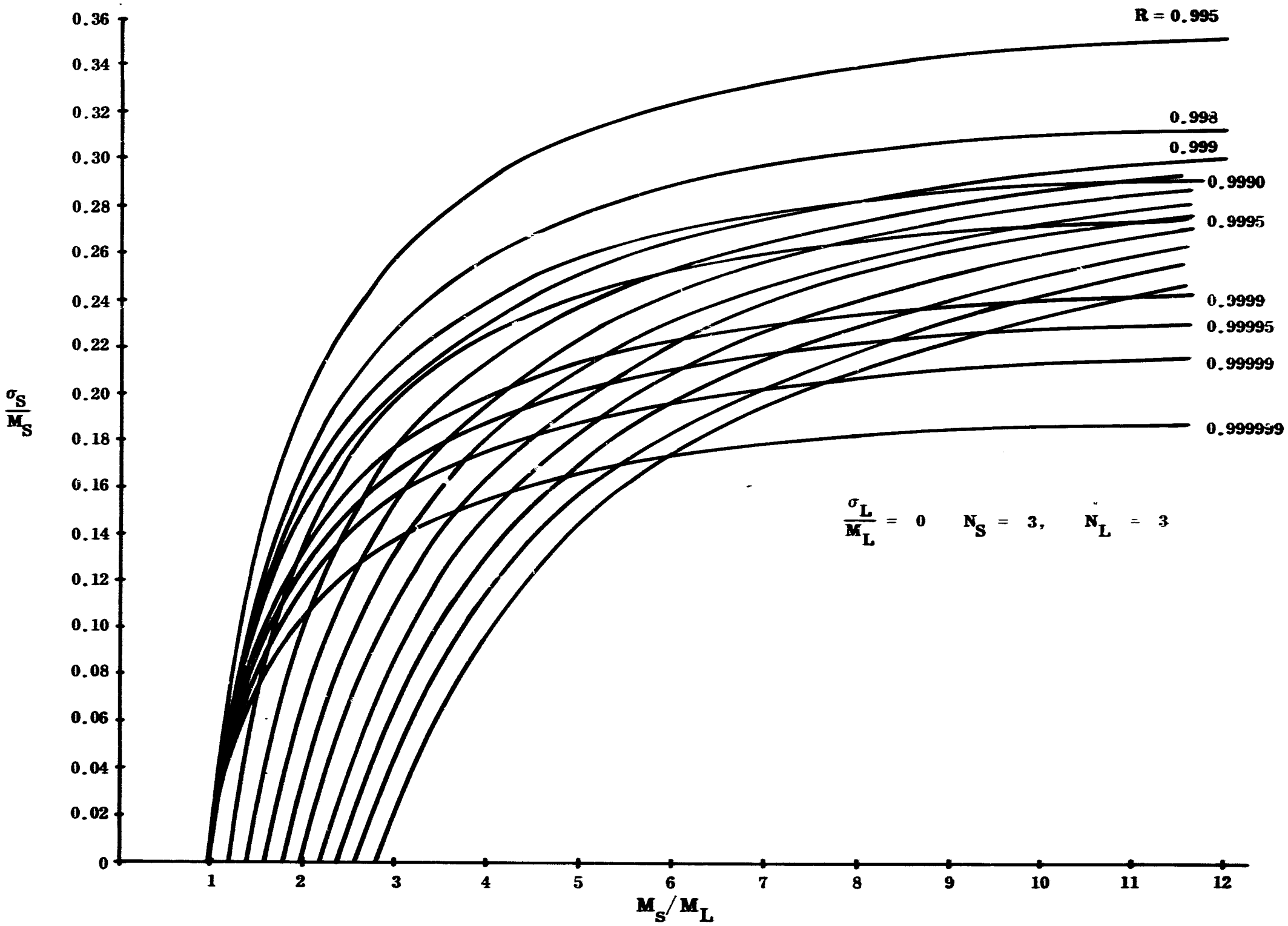


Figure A-6. Reliability and Safety Factor Relationship

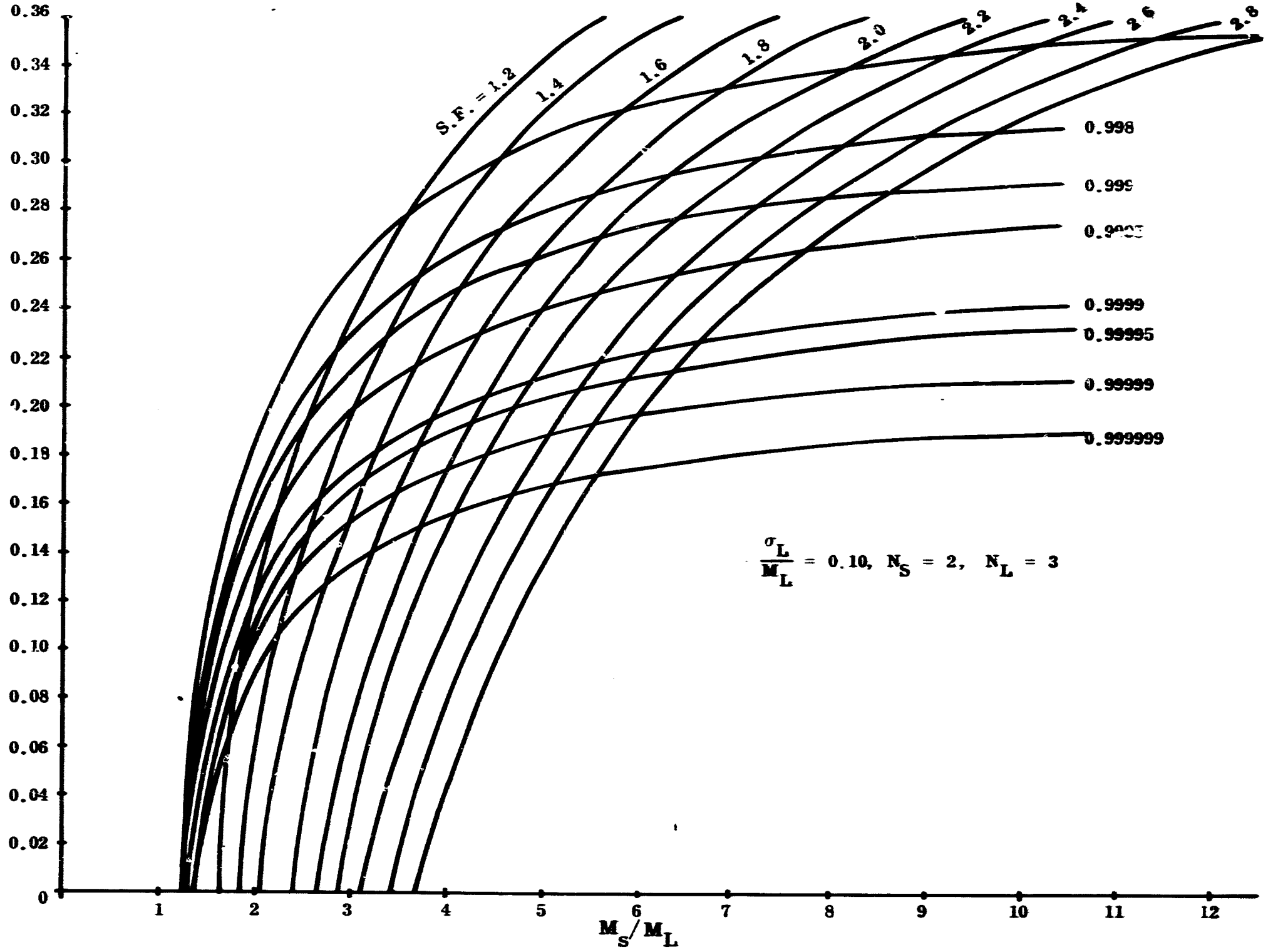


Figure A-7. Reliability and Safety Factor Relationships for $\sigma_L/M_L = 0.10$, $N_S = 2$ and $N_L = 3$

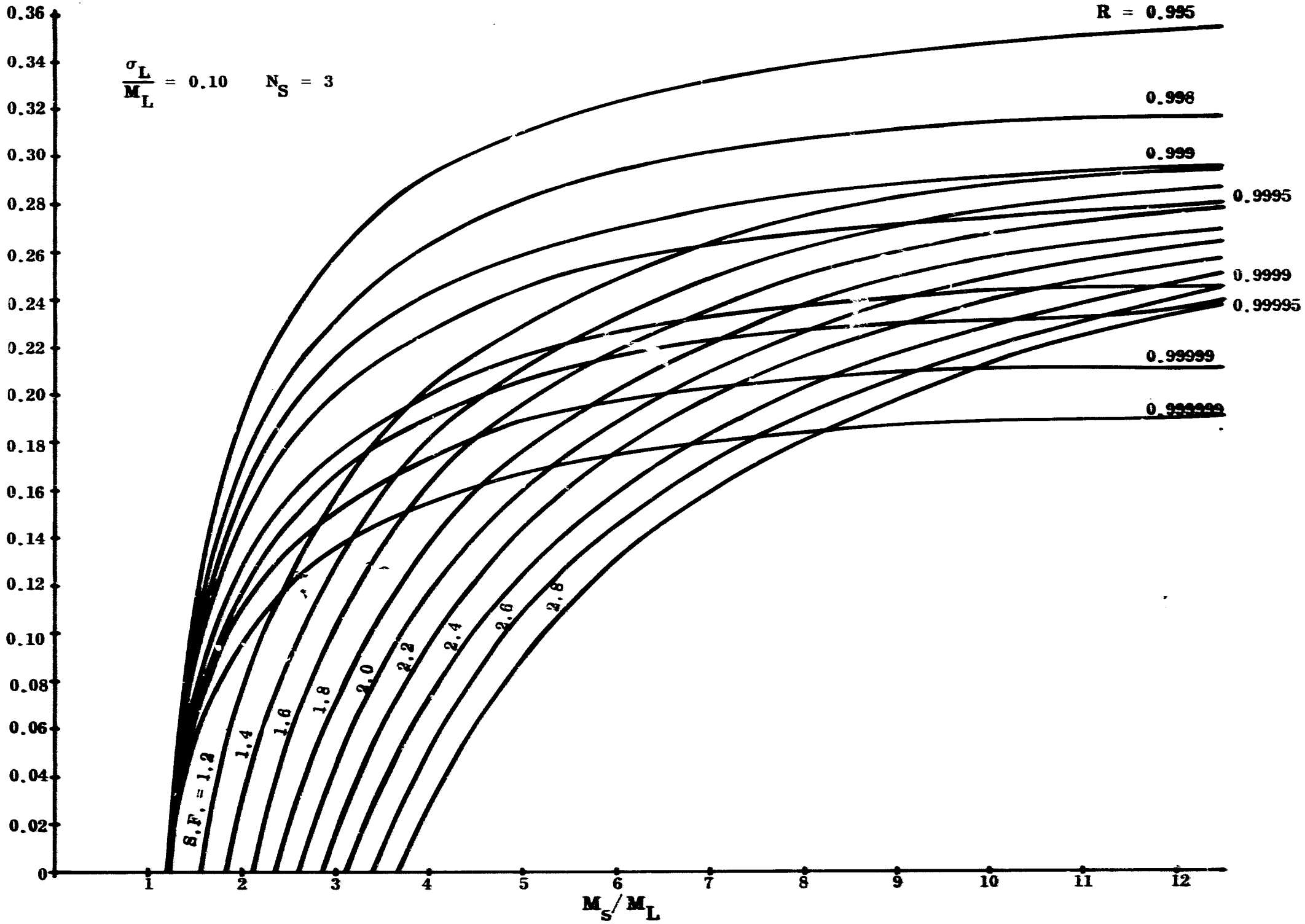


Figure A-8. Reliability and Safety Factor Relationship for $\sigma_L/M_L = 0.10$ and $N_S = N_L = 3$

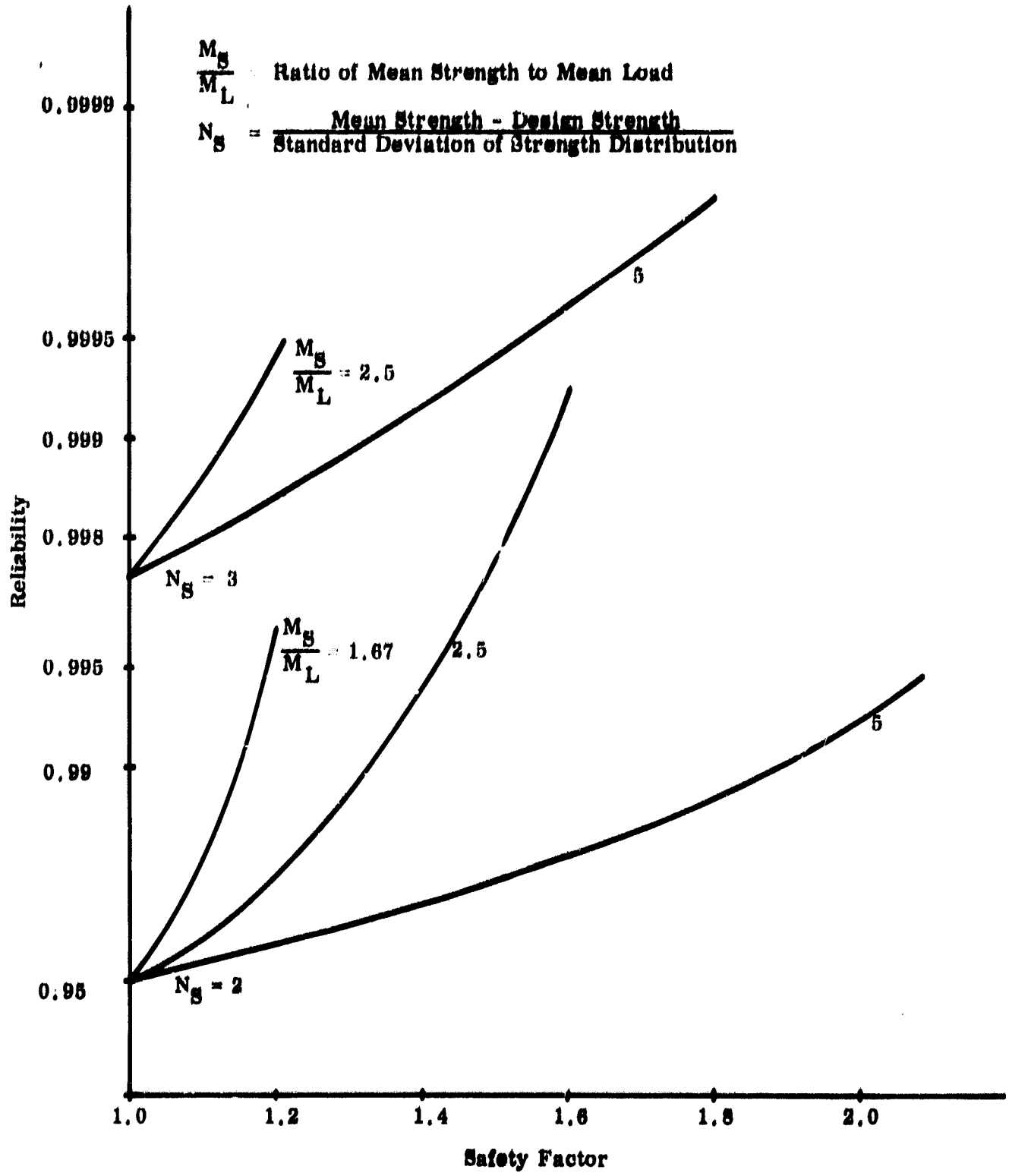


Figure A-9. Relationship of Reliability and Safety Factor Non-Statistical Loads

directly from the Equations A-7 and A-13 by eliminating σ_S/M_S and considering only non-statistical loads ($\sigma_L = 0$).

Nomenclature for these equations is repeated below:

M_L = Mean Load, lb

M_S = Mean Strength, lb

S = Design Strength, lb

σ_S = Standard Deviation of Strength Distribution

N_S = Number of standard deviations that the design strength is set below the mean strength

S.F. = Safety Factor = S/L

N_L = Number of standard deviations that the design load is placed above the mean load.

DISCUSSION OF RELATIONSHIPS

Figure A-5 has been replotted as shown in Figure A-10 to illustrate relationships of these variables to increases in the values of M_S/M_L. For example, increasing M_S/M_L from a value of 2 to a value of 3 and holding R fixed at 0.9995 would allow σ_S/M_S to increase from 0.15 to 0.21 (or 35 percent). This is equivalent to an increase in M_S/M_L of 50 percent such as might be achieved through the use of better materials (such as beryllium rather than aluminum or better wall construction such as honeycomb instead of integrally stiffened skin). The 35 percent increase in σ_S/M_S could be used to permit relaxation of manufacturing tolerances, or use of a cheaper grade of beryllium, or reduction in the number and type of structural tests. These changes all tend toward reducing the costs.

Alternatively, the retention of the same value of σ_S/M_S in the above example of 0.15, accompanied by an increase in M_S/M_L from 2 to 3, indicated an increase in safety factor from 1.4 to 2.1 and a simultaneous increase in reliability from 0.9995 to 0.999995. These in turn may reduce program costs due to the reduced probability of structural failures. These examples illustrate several alternate approaches used to vary these variables for the purposes of this study.

In this investigation, several different approaches to quality control philosophy were considered in the determination of manufacturing costs versus factor of safety and

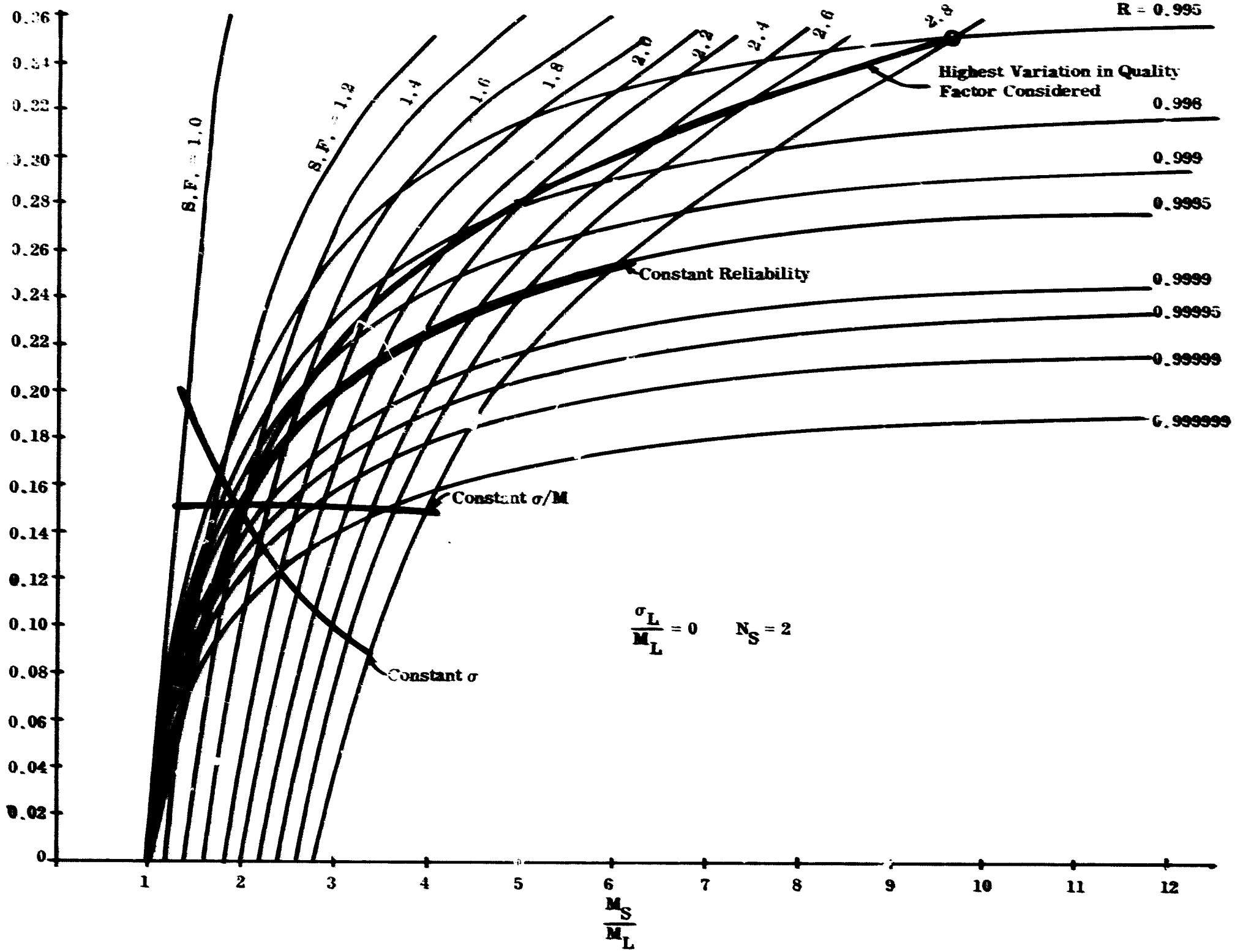


Figure A-10. Reliability and Safety Factor Relationship

reliability. These philosophies of quality control are illustrated on Figure A-10 for four different approaches as follows:

1. Constant Standard Deviation (σ_S)—where manufacturing tolerances and strength variability are assumed to be fixed at a preselected value, and hence, independent of size and mean strength of the structure.
2. Constant Relative Standard Deviation (σ_S/M_S)—where variability of materials and structural strength vary in proportion to the mean strength and size of the structure. In this case, the manufacturing tolerances are proportionate to the size of the material, and structural strength variability increases in proportion to the size of the structure. This situation is considered the most representative of what would occur for actual cases where normal increases in size and strength of structures would be accompanied by increased manufacturing tolerances as section dimensions are increased.
3. Constant Reliability—where structural design and strength are varied in a particular way such that the probability of failure remains constant. This permits taking maximum advantage of increases in factors of safety to reduce cost without degrading reliability.
4. Highest Increase in Relative Standard Deviation (σ_S/M_S)—where a higher variation than achieved with constant reliability was studied to determine potential cost reductions when reliability was allowed to degrade as factor of safety was increased.

The processes associated with material preparation, fabrication, and inspection are related to cost through both factor of safety and relative standard deviation (σ_S/M_S). The costs were found to be related to factor of safety through structural elements which were a function of the specific designs associated with each factor of safety, i.e., the honeycomb core maximum cell diameter is a function of design associated with each factor of safety and this, in turn, can be directly related to honeycomb core costs. Structural costs are directly related to the relative standard deviation (σ_S/M_S) through relationships with the underlying processes which result in the relative standard deviation values. In this latter case, it is more difficult to establish cost relationships, and thus, a range of these relationships is considered to determine the impact of these assumptions.

For clarity of presentation, the results presented throughout the main text of this report are shown for the case where reliability is held constant for varying safety factor. This allows maximum reduction of cost with increasing safety factor while it maintains reliability.

APPENDIX B

STRUCTURAL RELIABILITY,

INSPECTION AND TEST CONSIDERATIONS

APPENDIX B

STRUCTURAL RELIABILITY, INSPECTION AND TEST CONSIDERATIONS

B.1 INTRODUCTION

One of the concerns of this study is to evaluate the effects on structural test requirements in response to variations in design factors, materials, or reliability. A change in design safety factors has shown a significant interplay with test demonstration of structural capability. In this section, methods of non-destructive testing (NDT) for inspection of large launch vehicle structures are described. These NDT techniques will play a major role in assuring the integrity of structures fabricated using new materials. This appendix contains information which deals with NDT and structural test requirements.

B.2 APPLICATION OF NON-DESTRUCTIVE TEST METHODS FOR INSPECTION OF LARGE LAUNCH VEHICLE STRUCTURES

B.2.1 INTRODUCTION

A major problem for future large launch vehicles, regardless of material, will be the inspection of the very large structures in the field, that is, the adaption of methods developed for smaller items and/or laboratory use to field installations. The major potential problem areas will be the inspection of honeycomb, bonded joints, and welded structures. These problems are further complicated by the size of the large launch vehicle structures.

A number of previously developed and new NDT methods are available to meet the inspection requirements of both conventional and new materials. These NDT methods, which are basically adequate for most of the foreseeable problems, include the following:

a. Coin-tapping.
b. X-Ray (Qualitative and Quantitative)
c. Ultrasonic
d. Sonic
e. Eddy Current
f. Penetrant
g. Magnetic Particle
h. Microwave

i. Infrared/Thermal
j. Liquid Crystals
k. Optical/Holographic
l. Mechanical Signature Analysis (MSA)
m. Dielectric Constant
n. Electrical and Magnetic
o. Acousto-Optical Imaging

These will be discussed individually in the following paragraphs; then, the most appropriate NDT methods to meet the specific needs of large launch vehicle structures will be discussed in paragraph B.2.3.

B.2.2 DETAILED REVIEW OF NDT METHODS

Individual NDT methods are discussed in the following paragraphs.

B.2.2.1 Coin-Tapping

This is an easy, quick and on-the-site method of testing structures, but it is not sufficiently accurate and therefore of limited usefulness.

B.2.2.2 X-Ray

Radiography is widely used for a variety of inspections for all of the major structural items. In current industry, it is the major technique for weld inspection and bond-void detection and, although much work has been done to develop ultrasonic techniques for this purpose, it still remains the most likely candidate for field inspection problems. For this purpose there are available a wide variety of portable and specialty items (such as strip film). In addition, the literature describes many special techniques for radiography such as 3D, color, neutrography, and digital techniques which offer unique advantages for service in this area.

In addition to the purely pictorial aspects of portraying material defects, several radiation techniques lend themselves to other purposes as well. Thus backscatter techniques can be used for surface chemistry and corrosion depth. Transmission techniques can monitor density of numerous materials such as polymers, graphite, and metals.

B.2.2.3 Ultrasonics

The use of high frequency (> 1 MHz) sound waves in NDT has made great strides in recent years for material and bond inspection. Reference 123 provides an excellent appraisal of this technology and is recommended as a source of detailed information. Figures B-1, B-2, B-3 and B-4 are extracted from Reference 123 and illustrate the relationships of parameters, techniques, and applications. The modes of vibration of ultrasonic energy are listed in Figure B-2; waveforms and frequency ranges are outlined in Figure B-3. Ultrasonic techniques are summarized in Figure B-4.

Ultrasonic test equipment, in the hands of a trained operator, permits quick and easy non-destructive testing. However, these tests suffer from a lack of permanent records (except for scope photographs) when used in portable facilities and/or handscanning operations. Also, specific standards are required to evaluate the significance of the responses in the various materials tested. Neither of these problems has proven to be a serious handicap in the widespread use of this method for advanced flaw detection, and none is anticipated here.

In addition to pure flaw detection, techniques based on the measurement of ultrasonic velocity, attenuation, and mode conversion are finding increasing use for the dynamic measurement of material properties, and it is expected that they will find similar applications with highly stressed components and materials subject to environmentally induced degradation.

B.2.2.4 Sonic

The use of sonic methods for honeycomb and bond inspection has made great strides in recent years. Tests working in this frequency range have also shown promise for measuring cohesive bond in many adhesive-bonded assemblies. Thus they can be expected to be of considerable value for many of the structures envisioned.

Like the higher-frequency ultrasonic tests, there is a problem with permanent records and particular standards, but the increasingly wide use of these devices indicates that these are not major impediments.

B.2.2.5 Eddy Current

Eddy current techniques are limited to conductive materials where they find use in measuring plating and coating thickness and flaw detection. Many sophisticated devices

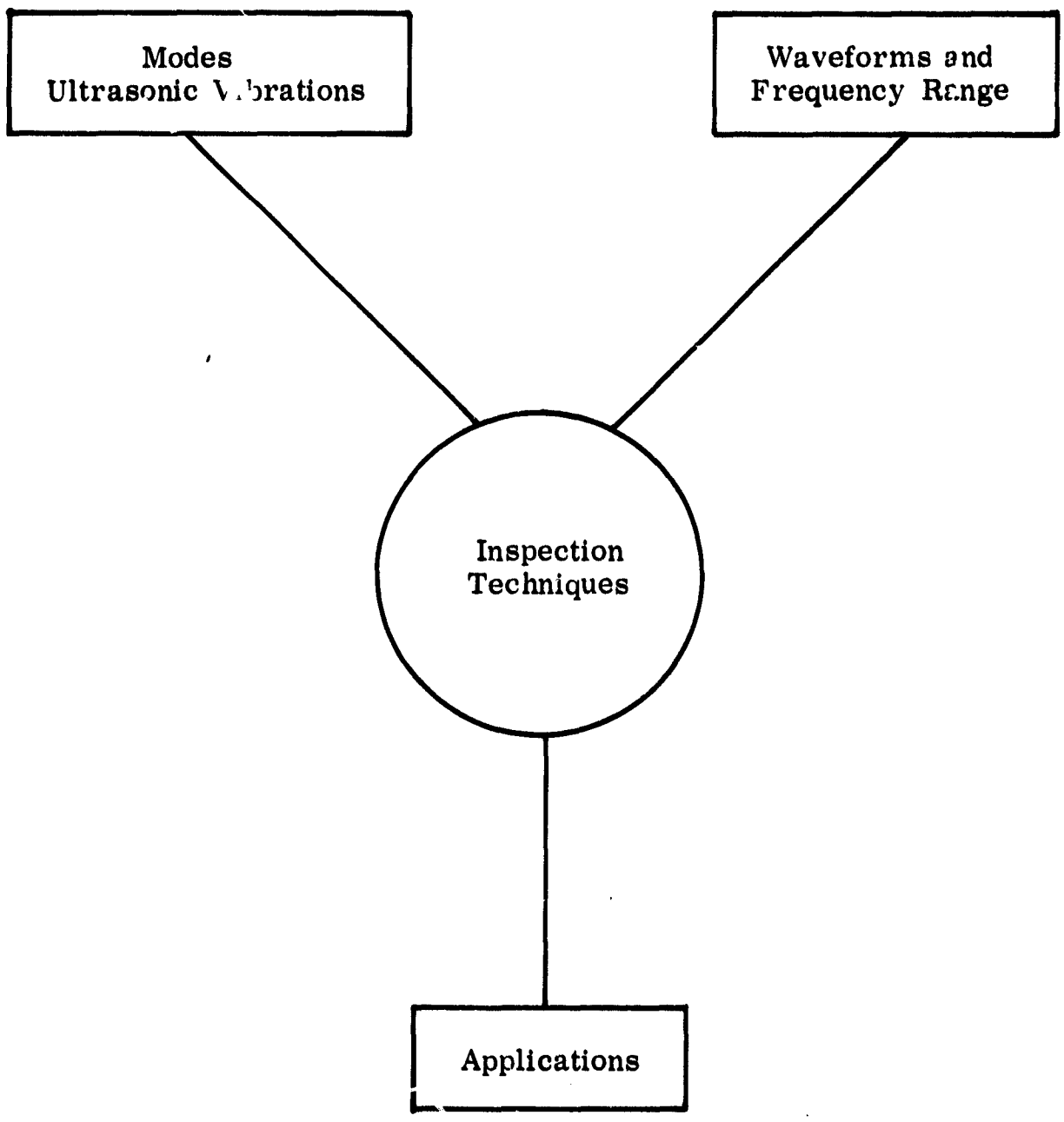


Figure B-1. Relationship of Ultrasonic Parameters, Non-Destructive Inspection Techniques, and Applications

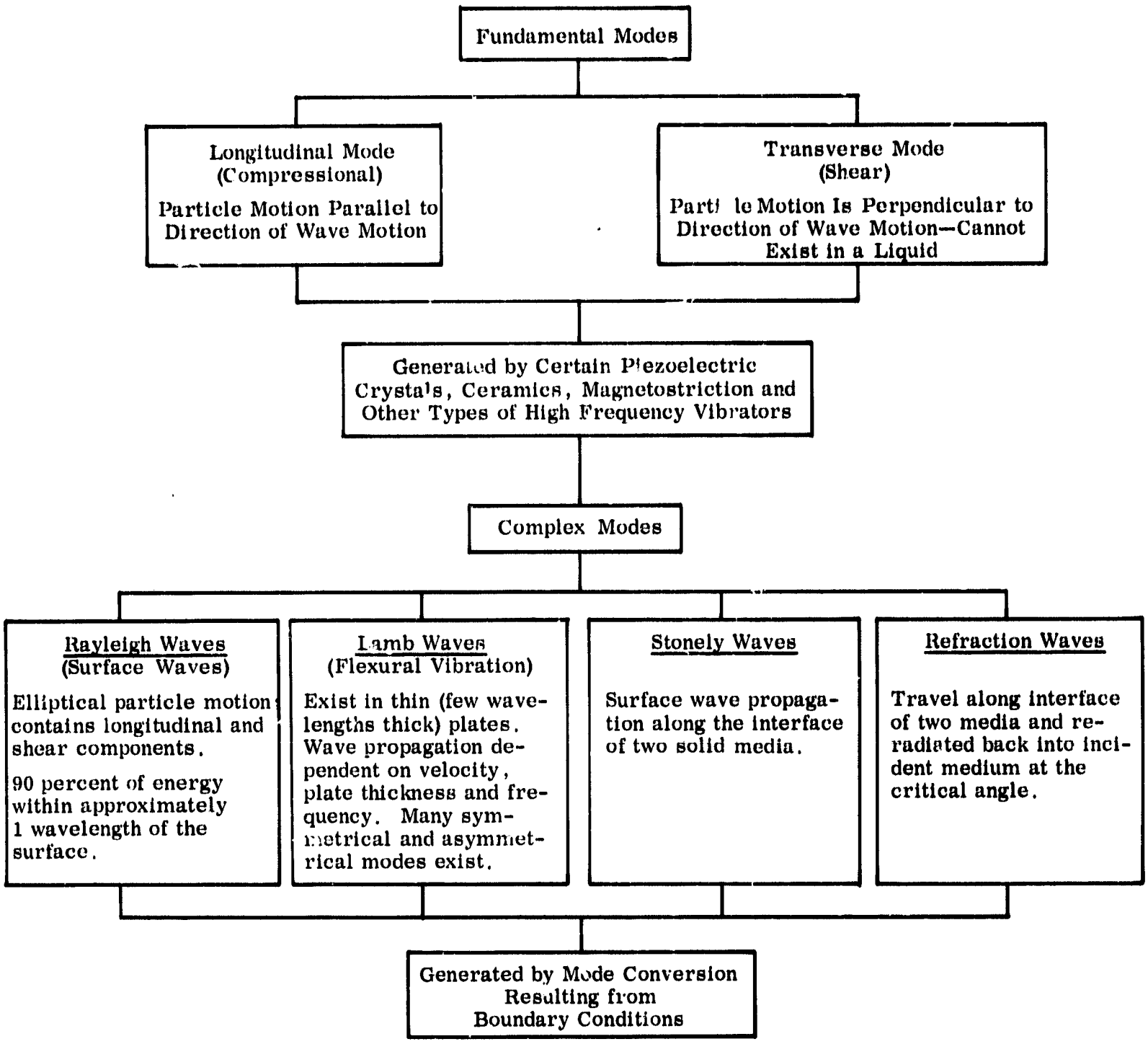


Figure B-2. Modes of Vibration of Ultrasonic Energy

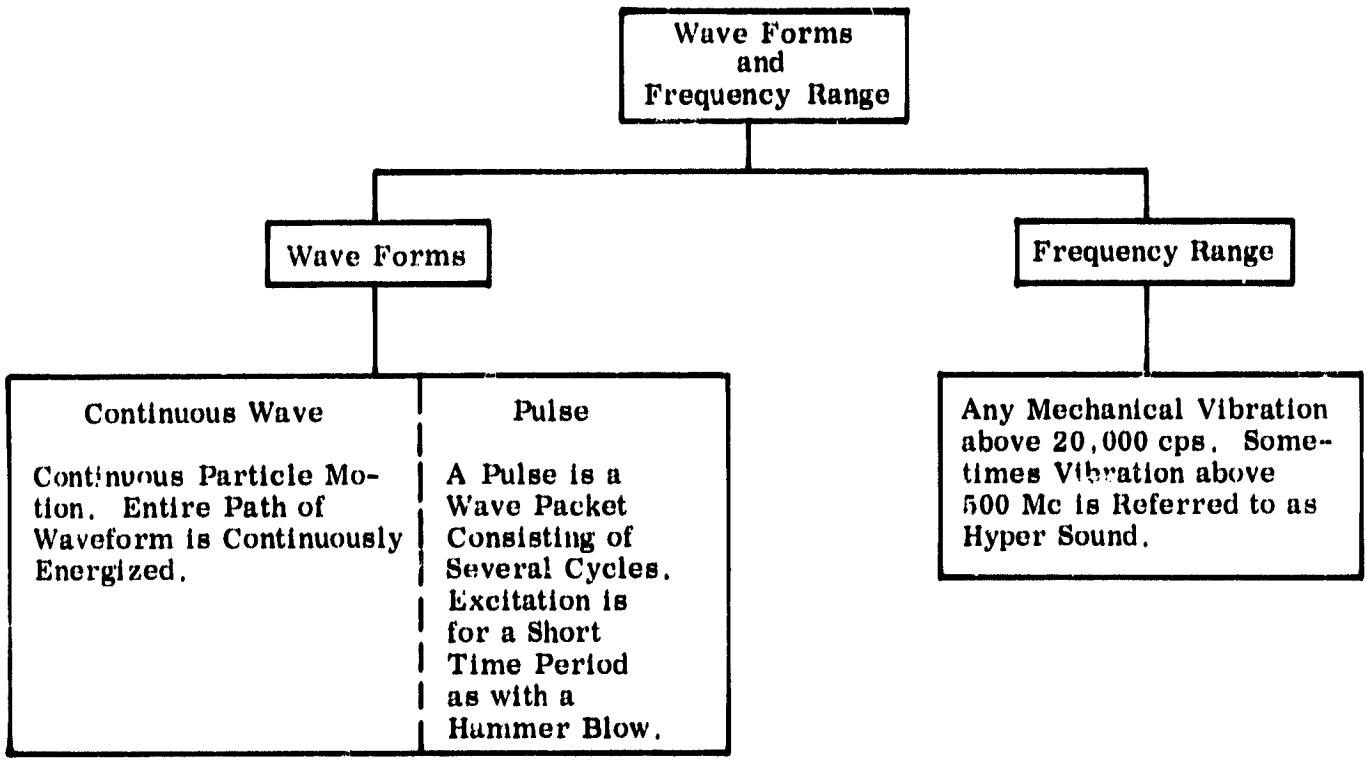
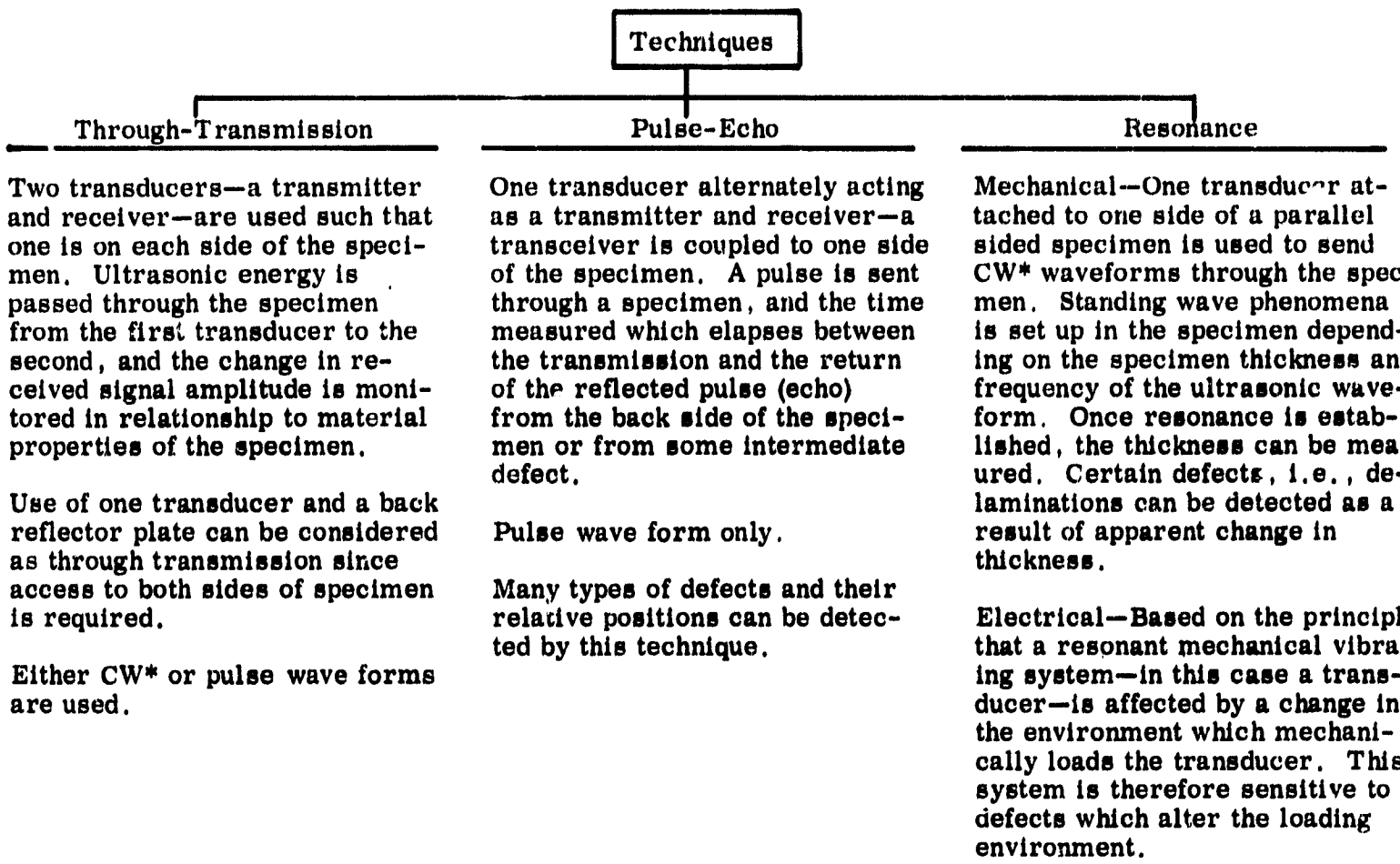


Figure B-3. Ultrasonic Wave Forms and Frequency Ranges



*Continuous Wave

Figure B-4. Ultrasonic Non-Destructive Testing Techniques

and methods utilizing these techniques are in use today. Although automated inspection is best suited to eddy currents, manual inspection can be used. Data are in the form of a meter readout which is recordable.

B.2.2.6 Penetrant and Magnetic Particle

These are older methods for detecting surface flaws in all non-porous materials (penetrant) and subsurface flaws on magnetic materials (magnetic particle). They are inexpensive to perform and relatively easy to use. Recently, techniques for producing permanent records have been developed.

B.2.2.7 Microwaves

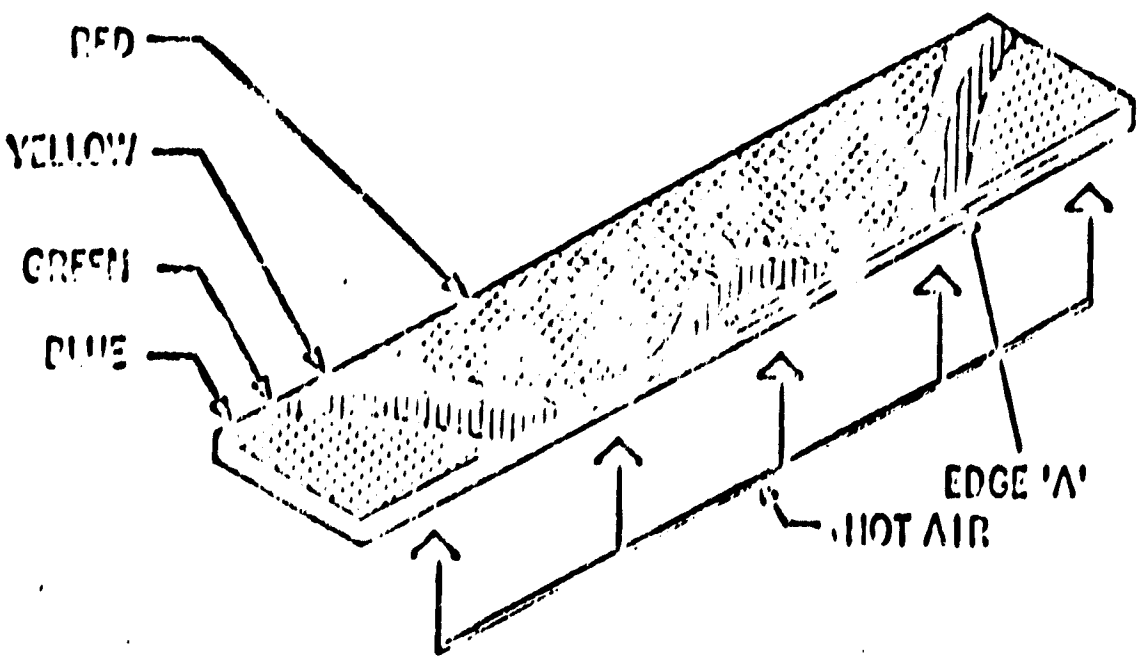
This is one of the newer methods which is finding use for a variety of bond inspection and flaw detection problems with non-conductive materials. Based on radar techniques, this method can be used in many applications where sonic techniques fail. While there are problems in applying the technique to large structures, the state of the art in producing smaller, more portable test equipment is advancing so rapidly that most of the difficulties are expected to disappear by the time these techniques are needed.

B.2.2.8 Infrared

This is another new method which is finding use on bond inspection and the inspection of electronic components. The method works well only with relatively good thermal conductors or emitters, but the sensitivity of the detectors is steadily improving. Again, applying the technique to large structures in the field is a problem which will need considerable work to solve.

B.2.2.9 Liquid Crystals

The use of liquid crystals in a similar thermal-gradient technique has been proposed in Reference 124. The liquid crystals would be used to coat the external surfaces and any discontinuities to heat flow would be readily discernible from colors of coating. Figures B-5, B-6, B-7, and B-8 from Reference 124 illustrate how flaws, voids, or delaminations might be detected. This technique is still in the conceptual stage, however, and there remains a considerable amount of development work prior to general usage of this technique.



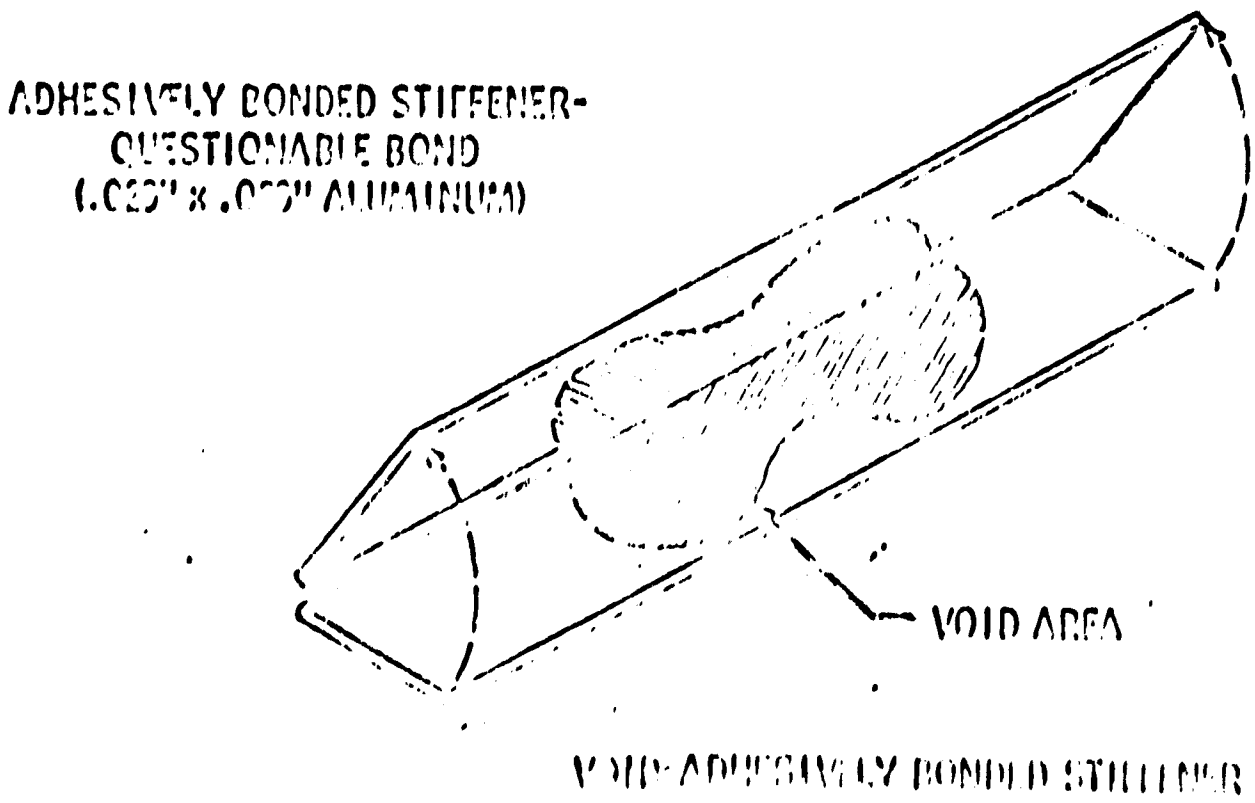


Figure B-5. Void Detection in Adhesively Bonded Aluminum Stiffeners (Schematic)

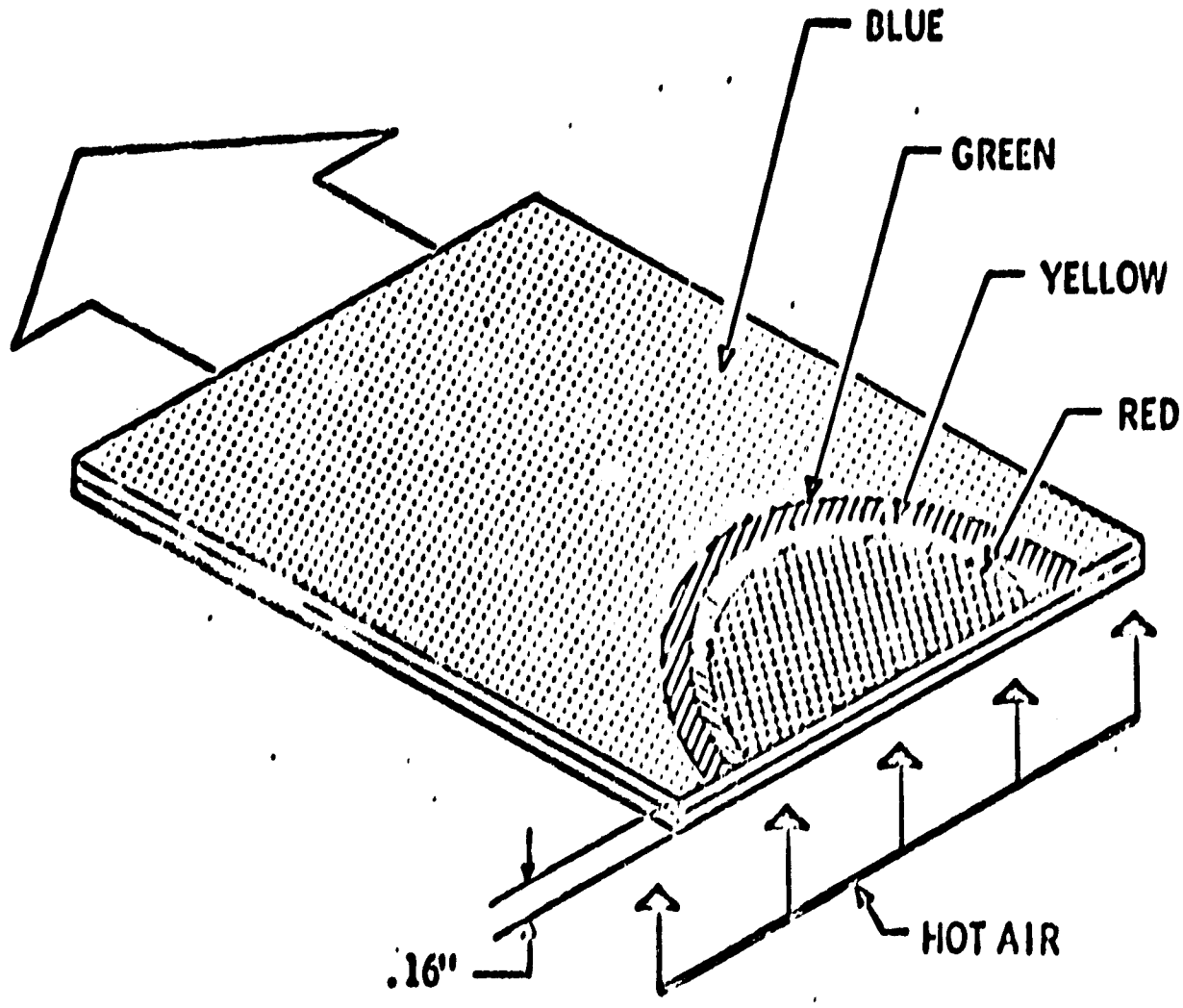


Figure B-6. Detection of Fiberglas Delamination (Schematic)

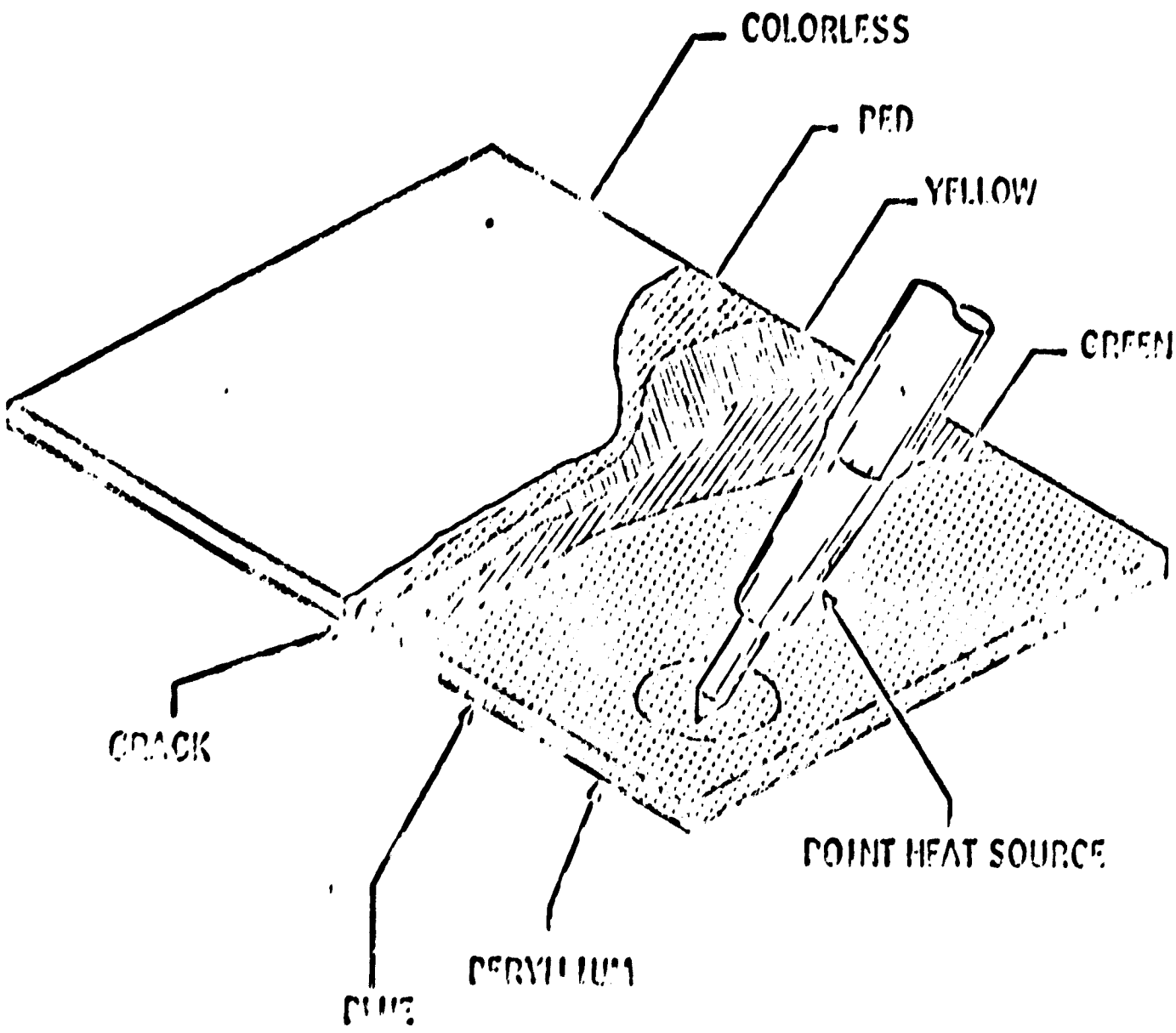


Figure B-7. Crack Detection with Liquid Crystals (Schematic)

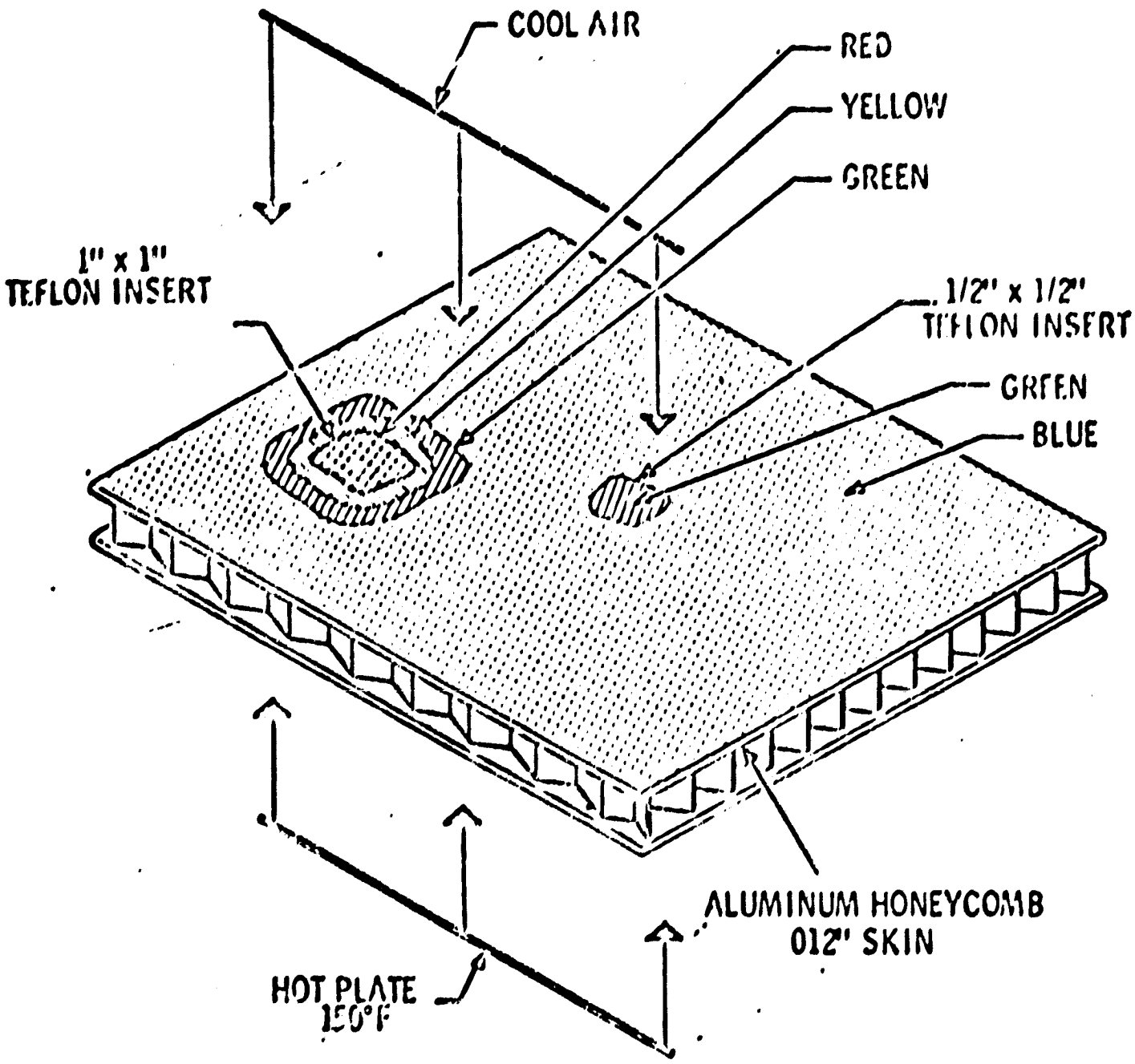


Figure B-8. Visualization of Teflon Inserts in Aluminum Honeycomb (Schematic)

B.2.2.10 Optical/Holographic

Optical techniques have been used for a long time to check alignment. Most recently laser photography has been applied to this problem and improvements of several orders of magnitude obtained. In addition, laser photographs of vibrating assemblies have been used to show structural anomalies, and work is under way to use it to detect internal defects in vibrating structures. This technique is so new that its full capabilities have not yet been defined but it is expected that it will find considerable use on structures having large working distances.

B.2.2.11 MSA (Mechanical Signature Analysis)

This is a technique being developed at General Electric for the dynamic analysis of complex structures for anomalies. It is highly sophisticated and utilizes computer analysis for establishing the presence and level of conditions sought. For large vehicles it offers a way of inspecting major portions of the structure all at one time. It is appreciated that this would not be easy to do but the consequent savings in test time and expense would be substantial.

B.2.2.12 Dielectric Constant

These techniques are used to establish levels of various properties (and therefore the degree of degradation) in non-conductive materials. Recent work with one-sided probes has greatly extended the range of utility of these methods. New equipment is portable and digital readouts are available.

B 2.2.13 Electrical and Magnetic

Tests based on these phenomena encompass a wide variety of techniques for particular purposes. Many of them are portable and would find a variety of uses depending on particular needs.

These are the current methods available for use on this program. As noted above, they cover a wide enough area that it is felt that they or tests derived from them will be applicable to most of the needs of this program. New tests would have to be based on other physical phenomena and, while many are potentially available, only a few have shown much promise. These are in the field of nuclear resonance effects and preliminary experiments show potential applicability to problems of stress analysis. Another approach is the tying together of NDT, pattern recognition, and computer analyses into an integrated test regime to monitor the total adequacy of structures,

components and materials. Only preliminary work has been done on this approach which, if successful, would create vast new opportunities for the useful application of NDT.

B.2.2.14 Acousto-Optical Imaging

Acousto-optical imaging is a technique which enables one to obtain a visual image of defects in the interior of liquids or solids. The method is based on the fact that light and sound interact as was first postulated by Brillouin in 1922 and was experimentally established by Debye and Sears in 1932. The actual imaging of a solid using the principle, however, was not achieved until most recently, following the rapid development of the laser technology and new acoustic techniques. The feasibility of using acousto-optical imaging as an effective nondestructive testing tool was demonstrated through several experiments performed on solids (metals, plastics, composites). The method is shown to be capable of obtaining visual images of interior defects such as voids, inclusions, cracks, and debonding in these solids with good resolution.

B.2.3 APPLICATION TO LARGE LAUNCH VEHICLE STRUCTURES

B.2.3.1 General

The previous section has briefly discussed a number of nondestructive test methods and their current status of development. Which of these techniques should be applied to NDT analysis of large launch vehicles will depend to a large extent on future development programs accomplished on alternative NDT methods; however, there is a sufficient number of methods available today to permit comprehensive testing of metal and composite structures.

B.2.3.2 Composite Structures

The primary NDT methods applicable to NDT testing of composites are as follows:

a. Radiography
b. Ultrasonic
c. Sonic
d. Penetrants

An example of using these methods with resin-matrix composites is summarized in Table B-1. Metal-matrix composites could be tested in much the same way. In addition, until more comprehensive NDT methods (such as listed in paragraph B.2.2) are

Table B-1

Summary of NDT Techniques Used with Resin-Matrix Composites (Reference 11)

TESTING OF FIBER REINFORCEMENTS
Fiber Breakage
Conventional X-ray methods are the most suited of the methods investigated for locating broken fibers. This technique has limited capabilities which makes it impossible to determine fibers which are broken, but not separated or misaligned. Also, fibers not located in the outer surface plies cannot be detected unless they form an area of 1 inch by 1/8-inch minimum.
Fiber Alignment
Misaligned fibers are the most readily detected defects. A fiber which deviates from the orientation of the rest of the fibers in the laminate will show clearly on an X-ray picture and it is easily recognized. Furthermore, voids are often trapped around a misaligned fiber because of the distortion of the adjacent plies. Such lines of voids can be detected with the ultrasonic reflector plate techniques.
TESTING OF RESIN MATRIX
Delaminations
When delaminations between plies are of a nature where the surfaces are separated by even a minute gap they are readily detected by the ultrasonic reflector plate method. When the delaminated surfaces are in intimate contact, there is no means of detection. Any detectable delamination will block the sound in succeeding layers.
Voids in Resin
Concentrations of voids in the resin matrix can be detected by the ultrasonic reflector plate method. The concentration of blocked out sound signal gives a quantitative impression of the accumulated void content in the test area. There is no way to differentiate between a heavily accumulated effect of voids in different layers and a disbond. Also, no method has been developed to determine the depth of the recorded defects in the laminate.
Resin Crazing and Surface Defects
The "Penestrip" method will readily expose even very minute surface cracks. This method is especially sensitive when using fluorescent dye and black light. Most ultrasonic recordings are affected by the surface irregularities of the test panel. Very heavy surface defects will block the sound and appear as a delamination or void.
TESTING OF HONEYCOMB PANELS
Face Sheets
The boron/epoxy face sheets should be inspected prior to bonding to the honeycomb core by the ultrasonic reflector plate method. Any defects introduced during bonding to the core cannot be distinguished from the defects in the face sheets.
Honeycomb Core
The core is readily inspected with conventional X-ray techniques. Fractured walls and crushed or deformed core can be detected.
Adhesive Bond
Disbonds between face sheet and adhesive and between adhesive and core can be detected with the ultrasonic through transmission where the disbond is greater than 1/4 by 1/4-inch. Major disbonds can also be detected with the sonic resonator. In this case the inspection can also be performed where there is access to only one surface. Secondary bonding of ribs or spars to one face sheet may be inspected with the sonic resonator, but only major disbonds can be detected in this manner.
TESTING OF ATTACHMENT JOINTS
The inspection of a metal to plastic joint proved very difficult. None of the ultrasonic test methods produced reliable data when used on the fabricated test specimens. The tapered joint design for the wing box was even harder to inspect because of resonant and antiresonant areas as progress is made along the taper distorted the recordings. The sonic resonator may offer some solution in this area as this test showed no disbonds of a joint which in a later destructive test showed a good bond in the antiresonant areas.
If we have the above noted method of inspection and they are in turn efficient enough to locate defects, then there will always have to be a Go/No-Go set of limits. These limits will have to be determined by the engineering and materials departments because many of them will be load-oriented. The following is a typical example of some of the allowable defects found on parts/components fabricated of boron:
Except as otherwise specified, the fabricated parts shall be free from defects. Any part in which the laminate contains more than the maximum allowable defects in nature, size or extent shall be rejected unless repaired. Any sandwich part in which the core material is crushed, split, etc., or contains more than the maximum allowable defects in nature, size of extent shall be withheld for rejection or rework.

developed, destructive tests will be required to establish structural adequacy and to assure reliable and predictable performance in service.

B.2.3.3 Advanced Metallic Structures

Nondestructive and destructive tests will be similar to those outlined above, plus the addition of the following:

a. Magnetic particles.

b. Eddy current.

In general, the testing of honeycomb sections would be accomplished in much the same way as with composite structures, shown on Table B-1.

B.3 POST-SATURN STRUCTURAL TEST PLANS

The Post-Saturn studies at Martin [125] and General Dynamics [126] in the 1963-1964 time period have yielded a substantial compilation of data documenting test plans. Since the Post-Saturn Program has not been implemented, these test descriptions remain largely unverified. But the test data have been sufficiently worked out to provide insight into typical details for a program for the size of vehicles with which this study is concerned.

Figure B-9, extracted from Reference 125, indicates the breadth of test plans anticipated for vehicles of the million-pound-to-orbit category. Of the 52 types of ground tests listed here, there are approximately 21 (or 40 percent) which relate in some way to structural tests. Thus it can be seen that structural tests play a major role in test and demonstration programs which are in turn a major factor in program costs. If the required number of tests could be reduced due to increased safety factors, then there may be a significant potential for reducing program costs.

B.4 APOLLO/SATURN STRUCTURAL TEST DATA

The Apollo/Saturn components, stages, and vehicles have probably been the most thoroughly evaluated, tested, and checked out vehicle in the history of space flight.

The Saturn V Test Plan and Status Summary [127] has tabulated over a hundred major tests of the Saturn V vehicle before flight. An example of the specific tests and the verification status for each requirement is given for the AS-501 launch vehicle [128]. Looking at just one stage, the S-II stage of the AS-501, there are six major tests related to structural verification as noted in Table B-2 [128]. These tests are each a

major program element, representing a significant expenditure of time and resources to verify structural adequacy prior to launch. In at least one of these tests, there was a catastrophic failure which increased program costs and delayed development time.

In other tests, cracks and weld failures on the flight stages necessitated a supplementary program to verify the adequacy of modifications and repairs. The specific details of one of these S-II tests[129] are considered typical of test specifications and are utilized in the test program analysis.

B.5 TEST PROGRAM REQUIREMENTS

Test program requirements were based on the experience gained during the development of the Saturn/Apollo vehicles test requirements and test plans for vehicles of the Apollo Applications Program.

The following paragraphs which are extracted from those references, describe the objectives and requirements of a major test program. These requirements are utilized in combination with the NOVA data to define a test program which can be used to determine the variations of the test program when the design factor of safety is changed.

B.5.1 DEVELOPMENT TESTS

B.5.1.1 Objectives

Development tests verify the feasibility of the design approach and provide confidence in the ability of the hardware to pass qualification tests. Tests are performed primarily to acquire data to support the design and development process. (Development hardware is representative of, but not necessarily identical to, flight hardware or operational GSE.)

B.5.1.2 Requirements

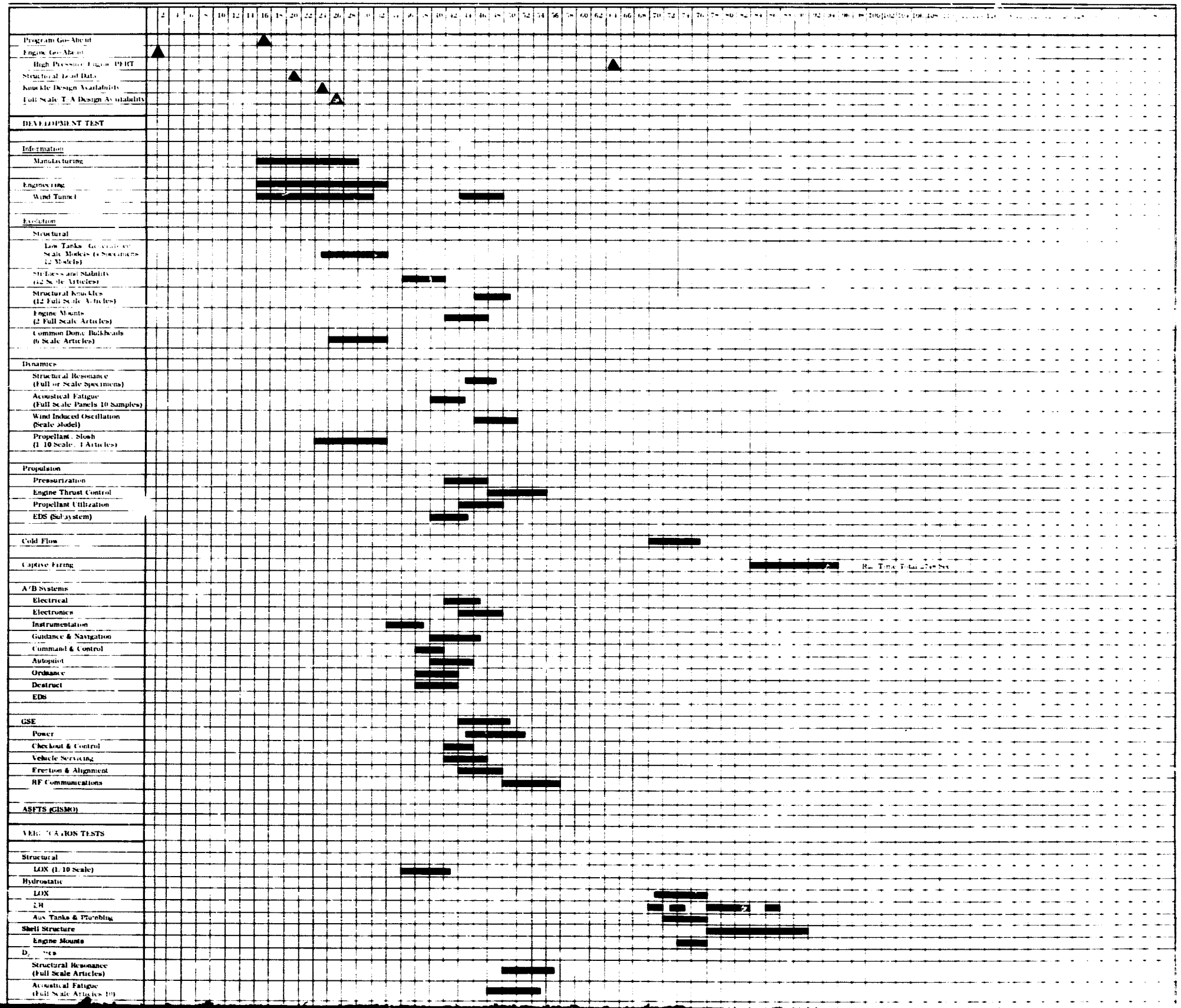
The following requirements apply to all hardware generation levels and are designed to determine:

a. Adequacy and optimization of design margins.
b. Significant failure modes and effects.
c. The effects of varied stress levels.

FOLDOUT FRAME 1

NOVA TEST SCHEDULE (Prelim)

Configuration 33



Figure

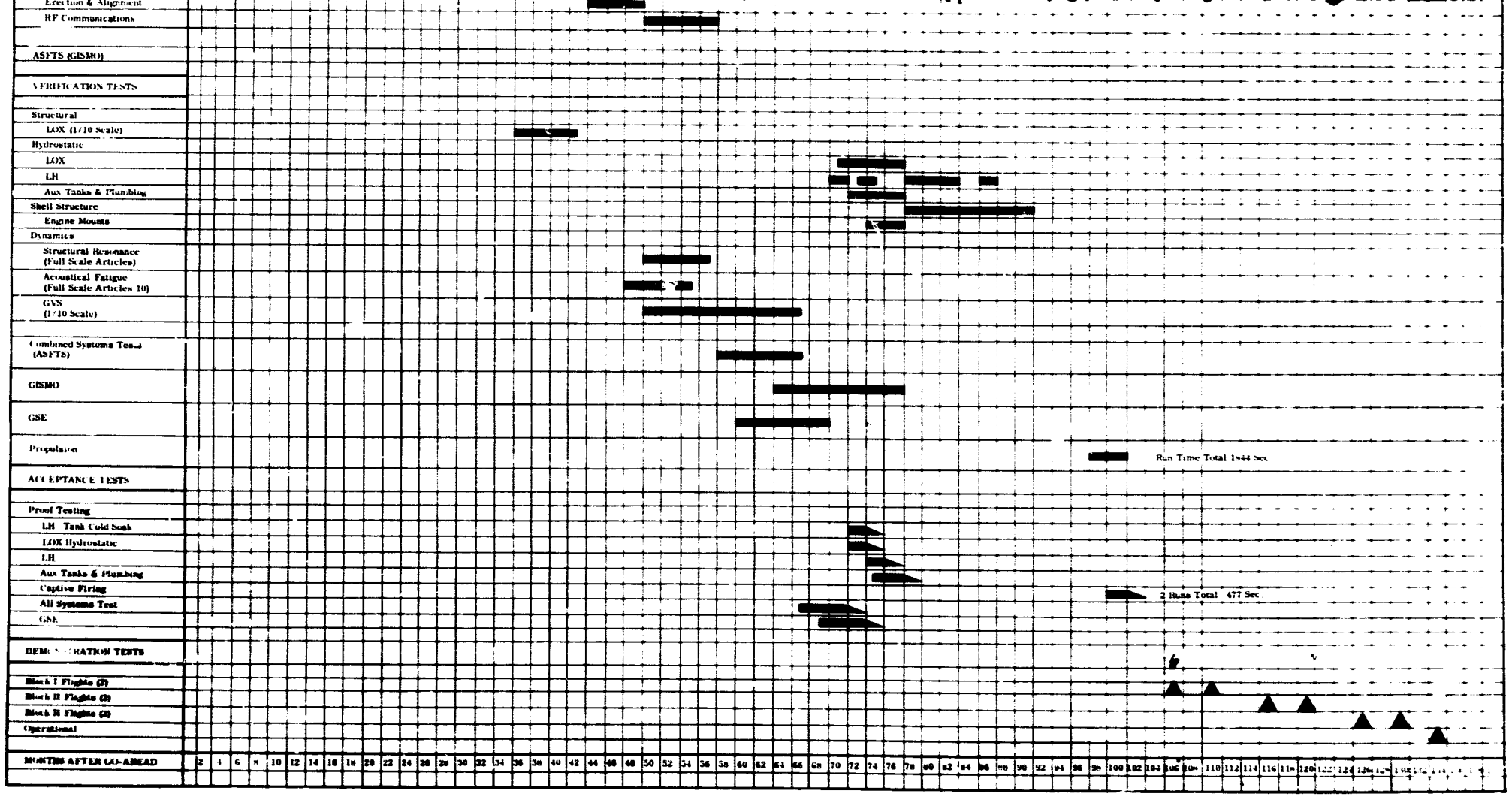


Figure B-9. NOVA Test Schedule

ROLLOUT FILE COPY

Table B-2

Structural Test Requirements for a Large Hydrogen Oxygen Stage, Using the S-II Stage for the AS-501 Vehicle as an Example

Test Title	Test Configuration
S-II Battleship Program	The battleship stage is a heavy duty, non-flyable propulsion development stage, permanently assembled in a static test stand. The propulsion subsystems are functionally similar to the flight subsystems and utilize development and prototype hardware. The tanks are of chambered construction to permit simulation of various degrees of flight-weight tank insulation by regulating the contained gas pressure.
S-II-T All Systems Program	Prior to completion of the all systems program, the S-II-T stage suffered a catastrophic failure which was unrelated to the mission requirements of the stage. Completion of the all systems program is an objective for the AS-501 flight stage. Flight hardware not installed on the S-II-T stage includes elements of the pressurization system, elements of the propellant feed system, elements of the recirculation system, and the propellant utilization electronics package. The stage was otherwise basically identical to the flight stage except for lighter gage skin on the forward skirt and the LH_2 tank, and use of 0.8-inch LH insulation rather than 1.6-inch flight insulation.
S-II-S Stage Structural Program	The S-II-S structural static test stage was the first S-II production article, similar to the S-II-1 flight stage. In general, structural components not required to carry loads or to stabilize the primary load-carrying structure are not installed. These include the systems tunnel, heat shield and support, tank insulation, and some bracketry. The LH_2 tank wall and forward skirt skin are of lighter-gage aluminum. Flight temperatures are not simulated. Water is used in place of cryogenic propellants. Applied structural loads are adjusted to partially simulate cryogenic temperature effects. Tank pressurizing load conditions were eliminated due to scheduling problems. Hydraulic struts are used to simulate engine, lateral inertial, and aerodynamic loads.
S-II High Force Test Program (HFTP)	The test specimens are: Foward Skirt Assembly — S-II station 818 to 995 Thrust Complex Assembly — S-II station 112 to 284 Interstage Assembly — S-II station -23 to 196 The forward skirt and thrust structure will have simulated structural interfaces. No interface is identified for the interstage assembly. Each assembly to be tested will be fitted with actual or dummy components to provide dynamic similarity to an actual vehicle. Dummy components include J-2 engines, ullage rocket motors, batteries, and feed lines.
S-II Hydrostatic Program	The hydrostatic program includes the Common Bulkhead Program (CBTT), and the Aft LOX Bulkhead test. Common Bulkhead Program—The test specimen includes the forward LH_2 bulkhead, a foreshortened section of the LH_2 tank cylinder, a common bulkhead, and a simulated LOX tank. The specimen is supported on a section of the aft skirt. Aft LOX Bulkhead—The aft bulkhead is tested as a separate component in the hydrostatic test facilities. Test conditions include the critical design loading condition representative of maximum longitudinal acceleration prior to shutdown of S-IC engines and maximum burst pressure.
SA-500-D Dynamics	The test objectives for the SA-500D dynamic test program are: a. Obtain elastic body data through dynamic testing to verify structural dynamic response predictions. b. Explore thrust structure compliance under dynamic conditions and obtain experimental thrust transfer functions for the Saturn V control system. c. Assess the compatibility of the S-IC/S-II/S-IVB mechanical interfaces.

B.5.1.3 Additional Requirements

The following additional development test requirements apply only to major experiment, stage, and/or module level of hardware.

a. Structural tests are conducted to evaluate structural integrity at critical loading, e.g., aerodynamic, cryogenic, winds, thrust, etc., and to verify that the structure will withstand design limit loads without permanent deformation.

b. Dynamic tests are conducted to determine characteristics under conditions simulating flight dynamics insofar as practicable.

c. Thermal vacuum tests are conducted at the highest hardware level practicable for the selected environmental facility, to:

(1) Demonstrate space hardware operation and man/machine performance under normal and emergency modes during simulated phases of the space mission, such as earth orbital, translunar or lunar surface operations.

(2) Determine thermal modes and provide baseline data for hardware development.

(3) Determine the thermal response and performance characteristics of structures, systems, and subsystems in a simulated space environment.

d. Compatibility tests are conducted to demonstrate the physical, functional, and operational interfaces of mating hardware. When new major end items are involved, test articles or their equivalent shall be utilized where possible to demonstrate compatibility with:

(1) Ground equipment at the VAB and launch facility during checkout operations.

(2) Other flight equipment with which it interfaces physically and/or functionally.

B.5.2 QUALIFICATION TESTS

B.5.2.1 Objectives

Qualification tests verify that flight-type hardware, and GSE, meet the performance and design requirements under anticipated operational environments as defined in applicable specifications. Tests shall be conducted as a formal demonstration of performance and design adequacy. (Flight-type hardware is used for ground testing and is identical in performance, configuration, and fabrication to the space vehicle flight hardware.)

B.5.2.2 Requirements

a. Qualification tests are conducted on parts, components, subassemblies, and higher levels of assembly at the highest practical level. Prior to qualification testing, all hardware shall be subjected to testing identical to the acceptance which would be performed on operational flight and GSE hardware. The number of test units required for qualification shall be determined by the Center considering previous testing of development and flight-type hardware.

b. Tests are designed to verify, as a minimum:

(1) The effects of combinations of tolerances and drift of design parameters.

(2) The effects of combinations and sequences of environments and stress levels. The limits for environmental tests, e.g., vibration, thermal, vacuum, electromagnetic radiation, etc., shall reflect the severest anticipated mission environment.

(3) Electromagnetic compatibility. (MIL-STD-460, -462, -463, -464 shall be used as applicable.)

c. Hardware is requalified when:

(1) Manufacturing source has changed.

(2) A more severe environment or operating condition exists than that to which the hardware was originally qualified, e.g., Apollo, Gemini, etc. Where practical, only the delta between the original and the new requirement shall be tested.

(3) Design or manufacturing process has changed. As in subparagraph (2) above, only the delta shall be tested.

(4) A number of a previously qualified configuration has been produced and the cognizant Center desires assurance that the qualification status is maintained.

Center approval is required prior to initiation of contractor requalification tests.

d. Engineering critical components contained within an end-item are individually qualified.

e. Qualification tests are performed under strict control of environment and procedures. Revisions to procedures, adjustments, or tuning are not permissible during the course of the test unless it is normal to in-service operation. If such action becomes necessary, the test specimen shall be disqualified pending corrective action. A record of total

accumulated operational and nonoperational test time shall be maintained on qualification hardware.

f. Failure of the hardware during the course of the test disqualifies all hardware made to the same specifications and intended for the same application as the hardware undergoing test. When a failure occurs, hardware or procedural changes are made, and the qualification test is reinitiated. Qualification testing may be reinitiated at the point where failure occurred, provided that new parts are subjected to the total time/cycles at the stress levels required by the specification at the completion of the test.

g. Post-test inspections are performed on disassembled qualification test hardware to locate potential failure modes (partially broken leads, damaged piece-parts, etc.) which may be undetectable during normal functional tests.

h. New or modified GSE is required to support missions that undergo qualification tests, generally at the part or component level.

i. Development test results may be used in lieu of Qualification at all levels of hardware when they are intended to be the only source of data to satisfy qualification requirements as specified in the applicable specification. When Development Tests are not conducted at major experiment, stage, and/or module levels of hardware, the requirements of these paragraphs shall become requirements for qualification.

j. Materials compatibility is verified at the systems level when lower level test results do not meet the qualification requirements of end-item specifications. Tests shall be conducted in the flight configuration, but not necessarily on flight hardware.

B.5.2.3 Constraints

a. Hardware which has been subjected to environmental qualification tests is normally utilized as flight or backup hardware. If such hardware is utilized, it is essential that:

(1) Crew safety is not compromised.

(2) The hardware is recertified to meet the performance and test requirements of the CEI specification by replacing those components whose performance may have been degraded by environmental testing.

b. Qualification tests are completed and documented in test reports and MTCR's prior to initiation of factory checkout of major pieces of flight hardware, e.g., stage, module.

B.5.3 RELIABILITY TESTS

B.5.3.1 Objectives

Reliability tests are performed to establish a significant level of engineering confidence in Category 1 and selected Category 2 flight-type hardware and selected Categories A and B, GSE, to perform their intended function in order to improve the probability of mission success.

B.5.3.2 Requirements

Reliability tests include, as a minimum, the following:

a. Tests conducted at the lowest practical hardware generation level for those items identified, by one or more of the following methods, as "critical hardware" (see NHB 5300.5, paragraph 2.5):
   (1) Failure Modes and Effects Analysis
   (2) Criticality Analysis
   (3) Single Failure Point Analysis
   (4) Mission Reliability Analysis
   (5) Test Failure

   This hardware is subjected to acceptance test prior to reliability tests.
b. Tests are conducted only when analyses of Apollo and other program reliability tests are considered inadequate for the appropriate hardware.
c. Testing in simulated mission environments normally is performed as a continuation of Qualification Testing to verify useful life requirements for the mission profile, with the addition of overstress and off-limits tests, as necessary, to determine failure modes and safety margins.
d. Modification of procedures, adjustment or tuning is not permitted during the course of the test unless it is normal to the in-service operation. If such action becomes necessary, the hardware, by definition, fails.
e. Failures do not necessarily disqualify the hardware from further reliability testing. When repairs, adjustment, etc., have been made, the hardware is resubjected to acceptance tests prior to further reliability testing.

f. Test-to-failure is conducted where test history or analysis indicates that the item is a single failure point or may have trouble meeting mission requirements. Where such testing is planned, prime emphasis is placed on failure mode and causes as determined by FMEA, using single failure point analysis, and/or previous test history.

g. Tests/assessment for GSE shall be required for all hardware utilized in support of the AAP space vehicle checkout from the time of launch vehicle fueling to liftoff.

B.5.3.3 Constraints

a. Hardware subjected to reliability testing is to be used as flight or back-up hardware.

b. Reliability tests are not conducted specifically for obtaining MTBF and MTTR data.

B.5.4 ACCEPTANCE TESTS

B.5.4.1 Objectives

Acceptance tests are performed to verify that the end-item hardware conforms to the applicable specifications for performance as a basis for acceptance. Testing confirms that the end-item performance and configuration are equivalent to the previously qualified end-item.

B.5.4.2 Requirements

Acceptance test requirements include, as a minimum:

a. Receiving Tests/Inspection which:

(1) Is conducted on all levels of hardware upon receipt at the manufacturer's plant or using site.

(2) Is nondestructive.

(3) Verifies conformance with end-item specifications.

(4) Includes dimensional, weight, configuration tests, and inspections.

(5) Verifies no shipping or transportation damage has occurred to the hardware.

(6) Normally is conducted at existing ambient conditions.

(7) Is conducted by contractors in conformance with Center approved applicable requirements of NPC 200-2, paragraph 5.6, in addition to the above requirements.

b. In-Process Tests/Inspection, which:

(1) Is performed at points of assembly where further assembly will reduce the capability to perform a complete functional test/inspection of the specific item.

(2) Screens the hardware, employing nondestructive mechanical or electrical stresses during the manufacturing cycle. Unsatisfactory conditions in the parts, components, and subassemblies are identified prior to committing the hardware to assembly or installation in higher generation level hardware.

(3) Normally is conducted at ambient conditions. Other environmental conditions shall be in accordance with subparagraph c.

(4) Is conducted by contractors in conformance with the Center approved applicable test requirements of NPC 200-2, paragraph 7.4.1 in addition to the above requirements.

c. Environmental Test, which:

(1) Is conducted on flight hardware and GSE for acceptance under environmental rigors other than ambient for the prime purpose of verifying the quality of the hardware.

(2) Is of sufficient severity, e.g., time/cycle and levels, to uncover latent quality defects but not severe enough to cause damage or fatigue the hardware.

(3) Includes combinations and sequences of environments.

d. Manufacturing Checkout Test, which:

(1) Is successfully completed prior to assembly into higher hardware generation level at another contractor's plant or NASA installation site.

(2) Includes testing in environments other than ambient under conditions of subparagraph c. where applicable.

(3) Verifies functional operation of all redundant components/systems.

(4) Verifies that the end-item meets the performance/design requirements of the CEI Specification, including physical and functional mating compatibility with flight and ground support equipment, as applicable.

(5) Is conducted by the contractor with Center approved applicable test requirements of NPC 200-2, paragraphs 7.3 and 7.4.

e. Final acceptance of new and modified GSE, which is: accomplished where possible after the GSE has been mated with the appropriate stage,

module, experiment, system, subsystem, or component; compatibility tests have been performed to assure that all functional and physical interfaces are operational; and the GSE is able to perform its required function.

B.5.4.3 Constraints

a. Where practical, hardware is accepted at the manufacturing facility to eliminate duplicate testing and associated resources at the follow-on sites, e.g., PIC and KSC, representatives of the receiving organization, participate in the acceptance of stages/modules at the manufacturing facility of Center in order to ensure continuity of data during all subsequent test activities.
b. Static firing test of Saturn IB and V stages and modules procured for AAP is not conducted unless authorized by the Apollo Applications Director.

B.5.5 INTEGRATED SYSTEMS TESTS

B.5.5.1 Objectives

Integrated Systems Tests verify that all flight systems will meet mission performance requirements as an integrated "system" and are physically, functionally, and operationally compatible with mating hardware systems and ground support systems.

B.5.5.2 Requirements

Integrated Systems Tests are used for acceptance at higher levels of assembled hardware, e.g., stages, major experiments, integrated payload modules, space vehicles, and launch vehicles. Test/assessment is conducted to verify that the assembled hardware satisfies integrated system performance/design requirements of the specifications, including:

a. Interface performance/design requirements which cannot be verified at the level of the individual end-item. Interface requirements may be satisfied by means of simulation or functional prototype when a mating end-item of hardware is not available.
b. Integrated performance within specification limits after being subjected to the transportation and handling environment.

c. Requirements for selective environmental stresses at the integrated systems level, singly or in combination, e.g., dynamic/vibration, thermal, and vacuum/pressure stresses.
d. The interchangeability and maintainability requirements of the system in the configuration that will be operational in space.
e. On-board checkout systems, when applicable.

B.5.5.3 Constraints

a. Hardware acceptance at the Integrated Systems level normally is preceded by acceptance at lower levels, DD Form 250 sign-off and COFW sign-off.
b. Testing previously conducted at a lower hardware level is not duplicated unnecessarily by Integrated Systems Tests.
c. End-item hardware is inspected to determine that no damage resulted from transportation or handling.
d. Pre-use checkout and verification tests are conducted on new, refurbished or modified GSE or interfacing hardware prior to Integrated Systems Testing.

B.5.6 PRELAUNCH CHECKOUT

B.5.6.1 Objectives

Prelaunch checkout tests verify that the integrated space vehicle is ready for launch and that the ground support equipment is ready to support the launch.

B.5.6.2 Requirements

Prelaunch checkout tests include, as a minimum:

a. Complete visual receiving inspection to ensure satisfactory physical condition of the hardware.
b. A functional pre-use checkout and verification test on all subsystems and systems of the total space vehicle and mission essential GSE, including test facilities and instrumentation, e.g., calibration, etc. The tests exercise the GSE in normal operating modes and under simulated mission environments for periods sufficient to verify mission capabilities.
c. Electromagnetic interference tests.
d. Simulated flight tests.

e. Verification, to the maximum extent practical, of functional operation of all redundant subsystems and their elements prior to launch. The verification is limited to flight hardware and mission-essential GSE.

B.5.6.3 Constraints

Testing previously conducted on space vehicle hardware is to be duplicated at the launch site except as cited in subparagraphs under B.5.6 above.

B.5.7 FLIGHT VERIFICATION TESTS

B.5.7.1 Objectives

Flight Verification Tests are performed on Categories 1 and 2 hardware only to verify those requirements which cannot be verified by ground test.

B.5.7.2 Requirements

Flight Verification Tests are conducted on selected new systems, advanced systems, and new experiments to form a test base for the following flights leading to the capability for long-duration missions. Prior to flight verification testing, planned ground tests are successfully completed, and the COFW's are signed off. Typical testing shall include:

a. Existing Apollo systems, modified or unmodified, when necessary to determine extended mission capability.
b. Unmanned flight verification tests of spacecraft systems affecting crew safety.
c. Manned flight verification tests to verify procedures, develop crew experience and refine the skills necessary to carry out AAP mission objectives.
d. Demonstration of the adequacy of an in-flight spares and maintenance plan for follow-on AAP missions.
e. Major AAP-peculiar hardware that cannot be verified by ground test.

B.5.7.3 Constraints

a. Flight verification, where possible, is conducted simultaneously with other flight mission objectives.
b. Flight test specifically for flight verification is conducted only with the concurrence of the AAP Director.

B.5.8 POSTFLIGHT TESTS

B.5.8.1 Objectives

Postflight tests are performed to determine the effect of:

a. Space flight operation on performance and construction of recovered equipment.

b. Launch damage on the launch site GSE.

B.5.8.2 Requirements

Postflight test requirements include, as a minimum:

a. Tests of hardware with an identified flight anomaly or on hardware intended for reuse.

b. Center identification of tests to be conducted, including the number, type, location, and procedure.

c. GSE testing to assess damage to launch equipment after the launch and to establish flight hardware operating conditions at launch.

d. Test reports for feedback to Design, Reliability, Test and other related organizations to ensure that:

   (1) Corrective measures are taken to preclude recurrence of the failure.

   (2) Performance may be enhanced on subsequent flights.

APPENDIX C

MATERIALS AND STRUCTURAL TECHNOLOGY AREAS SELECTED FOR DETAILED STUDY

APPENDIX C

MATERIALS AND STRUCTURAL TECHNOLOGY AREAS SELECTED FOR DETAILED STUDY

C.1 SELECTED STRUCTURAL TECHNOLOGY AREAS FOR DETAILED STUDY

The selected technology areas, together with a summary of advantages and disadvantages of each technology, are tabulated in Table C-1.

In addition to the nominal construction of aluminum integrally stiffened skin, the following types of materials were studied for preferred types of construction:

a. Metals.
b. Resinous composites.
c. Combined metals and composites.

Metals technology was studied using aluminum honeycomb and beryllium honeycomb as illustrative of near-time and future technology. Resin-based composites were studied using both boron and carbon filaments with an epoxy matrix, and are used as the face sheets in the honeycomb wall construction. The honeycomb core in each case was aluminum.

The combination of metals and filamentary composites provided one of the more interesting areas for the Phase II studies. Potentially, combining the strong points of the various technologies, the combination of metals and boron filaments in epoxy matrices appears attractive from both the technical feasibility and economic aspects of this study, though this particular combination was not selected for detailed study.

C.2 SOME CANDIDATE MATERIALS NOT SELECTED FOR DETAILED STUDY

In the process of selecting a limited number of technology areas to study in depth, many materials were considered. The materials which were not selected are listed in Table C-2. They were not necessarily inadequate or unattractive. In some cases they were not included due to their similarity to those materials that were selected for study, and in other cases the data available was not sufficient to permit a proper evaluation.

Table C-1

Selected Structural Technology Areas for
Detailed Study for Application to Future Large Launch Vehicles

Selection	Technology Area	Advantages	Disadvantages
A (Basis for Comparison)	2219-T87 aluminum integrally stiffened skin in vehicle walls, 2219-T87 monocoque heads	1. Basis of good, current state-of-the art; 2. Substantial experience in fabrication and handling; 3. Metal working industry and techniques are developed; 4. Known methods of analysis and testing; 5. Excellent corrosion resistance; 6. Propellant compatibility; 7. Preliminary design available from Martin studies; 8. Universally accepted technology.	1. Heavier than advanced construction; 2. Weld cracking still persists; 3. Complex construction and tooling.
B	2219-T87 aluminum honeycomb walls and 2219-T87 monocoque heads	1. Lightest weight aluminum structure; 2. Honeycomb is now accepted by metal working industry; 3. Flight experience in Apollo/ Saturn common bulkheads; 4. This material has all the benefits of aluminum in corrosion protection and propellant compatibility; 5. Now produced in sizes up to 96" × 144".	1. Little experience in primary load carrying structures of launch vehicles; 2. Bonding and fabrication unknowns; 3. Inspection and repair technology still is not sufficiently developed; 4. Joints to adjacent structure and to other honeycomb structures are problem areas; 5. Current adhesives require large autoclave facilities.

Table C-1

Selected Structural Technology Areas for
Detailed Study for Application to Future Large Launch Vehicles (Cont.)

Selection	Technology Area	Advantages	Disadvantages
C	UNPRESSURIZED: Beryllium honeycomb walls with aluminum core in unpressurized vehicle sections	1. Lightest weight structure; 2. Beryllium now proven in some flight applications; 3. Fabrication of honeycomb demonstrated on experimental basis by practically every aerospace company; 4. Satisfactory experience in drilling and forming; 5. Can be roll-diffusion bonded, brazed, glued, spot welded. (Other welds including fusion are being done on an experimental basis.)	1. Controversial among manufacturing research people; 2. Not accepted by many experienced structural engineers; 3. Toxic properties; 4. Cracking and low ductility; 5. Limited production and small size sheets (less than 40" × 100"); 6. Lack of adequate manufacturing control produces variable properties within sheet; 7. Differential thermal expansion; 8. Very expensive; 9. Joining limited to mechanical fastening, bonding, or brazing; 10. Special machine tooling required; 11. Subject to corrosion and oxidation by propellants; 12. May be adversely affected by noise, vibration; 13. Requires special design at joints to prevent crack propagation.

Table C-1

Selected Structural Technology Areas for
Detailed Study for Application to Future Large Launch Vehicles (Cont.)

Selection	Technology Area	Advantages	Disadvantages
C (Cont.)	PRESSURIZED: Titanium honeycomb walls in pressurized walls, titanium monocoque heads	1. Excellent strength to weight properties produce lightweight structures; 2. Generally accepted for pressure vessels (85% of pressure vessels in space program are titanium); 3. Good compatibility with most propellants; 4. Joints can be made by welding, brazing, gluing, mechanical fasteners, and metalurgical bonding; 5. Roll-bonding and "stressskin" applications appear attractive.	1. Unproven as primary shell structures for launch vehicle; 2. Requires extensive tooling and manufacturing facilities; 3. Moderately expensive (compared with aluminum); 4. Occasional stress corrosion problems.
D	UNPRESSURIZED: Beryllium integrally stiffened skin in unpressurized vehicle sections PRESSURIZED: (Same as C)	1. Conventional construction; 2. Lightweight, similar to beryllium honeycomb weights; 3. Fabrication of beryllium now demonstrated with sheet stringer construction (similar to Be ISS); 4. Can be mechanically fastened or riveted using today's technology. 5. Circumvents potential troubles in fabricating beryllium honeycomb.	1. Similar to beryllium honeycomb—Selection C above.

Table C-1

Selected Structural Technology Areas for
Detailed Study for Application to Future Large Launch Vehicles (Cont.)

Selection	Technology Area	Advantages	Disadvantages
E	UNPRESSURIZED: Boron/Epoxy honeycomb with aluminum core in unpressurized vehicle sections PRESSURIZED: (Same as C)	1. Lightweight advanced structure; 2. Utilizes available processes and newly developed boron filaments, integral stiffeners and bonded core possible; 3. Can be "tailor-made" to provide exact requirements; 4. Minimum waste of material	1. Relatively new and still in experimental stage; 2. No experience with effects of brittleness on fracture, fatigue; 3. Requires thermal conditioning of filaments; 4. Filaments still expensive; 5. Sandwich structure requires lightweight, hard to fabricate cores.
F	UNPRESSURIZED: Carbon/Epoxy honeycomb with aluminum core in unpressurized vehicle sections PRESSURIZED: (Same as C)	1. Carbon filaments appear to have excellent potential of modulus greater than 100×10^6 psi, strength of 500,000 psi, and cost approaching $100/lb.; 2. In epoxy binder, carbon filament should out perform boron (above) at lower cost.	1. New and unexplored material; 2. Unknown material properties and fabrication techniques; 3. Carbon may deteriorate with environment or abrasive conditions; 4. Joints have not been developed; 5. Sandwich structure requires low density, hard to fabricate cores.

Table C-1

Selected Structural Technology Areas for
Detailed Study for Application to Future Large Launch Vehicles (Cont.)

Selection	Technology Area	Advantages	Disadvantages
G	Unidirectional stiffeners of Boron/Epoxy on aluminum monocoque walls and heads for both pressurized and unpressurized sections	1. Combines the load carrying capability of composites with the ease of fabrication of aluminum shells; 2. Stiffeners can be placed where required in compressive sections and shells joined by conventional means. Load carrying efficiency nearly that of honeycomb without the concern for lightweight cores or internal bonding; 3. Stiffeners can be replaced with improved materials when developed.	1. Conceptual stage only; 2. Little research or development to date on unidirectional stiffened shells; 3. No knowledge of fabrication or analytical techniques; 4. Bond strength of stiffener to the shell is unknown; 5. Best orientation and spacing of stiffeners must be determined; 6. Inspection techniques not developed.
H	Boron/Aluminum composite honeycomb with aluminum core, in pressurized and unpressurized walls with monocoque heads	1. Another method of potentially combining the load carrying capability of composites with the ease of fabrication of metal shells; 2. Filaments can be placed where required; 3. Good tank sealing and compatibility with propellants; 4. Use of tapes may provide desired section shapes in fabrication.	1. New technology, not fully developed or evaluated; 2. Fabrication techniques and cost are still largely unknown; low weight cores are required; 3. Core to skin bonding may be a problem; 4. Boron filaments expensive; 5. Inspection techniques unproven.

Table C-2

Some Candidate Structural Materials Not Selected for Detailed Study

Material	Properties	Reason for Not Selecting for Study
Carbon/Aluminum Composite	1. Lightweight potential, low cost composite which offers hope of a solution to joining and fabrication problems. 2. Presently fabrication of high modulus graphite fibers is limited due to small diameter (0.0003 in.) which limits usefulness in metal matrices.	1. Insufficient demonstration of ability to fabricate carbon in an aluminum matrix producing required strengths; (the advent of larger diameter, perhaps coated, graphite filaments could make this a much more desirable composite). 2. Limited information on material properties and analysis method.
Glass/Epoxy Composite	1. Modest Weight savings. 2. State-of-the-art fabrication technology. 3. Low cost composite.	1. Improvements are insufficient to show gains over aluminum honeycomb construction. 2. Performance should be approximately the same as aluminum honeycomb. 3. The oldest of the fibrous composite technologies.
Carbon/Titanium Composite	1. Good high-temperature strength. 2. Good strength/weight and modulus/weight ratios. 3. Could be joined readily, yet retains structural efficiency. 4. Low cost.	1. Difficult to manufacture carbon in titanium matrix (see Section 3). 2. Experience with assembly and test is extremely limited. 3. Limited information on material properties and analysis methods.

Table C-2

Some Candidate Structural Materials Not Selected for Detailed Study (Cont.)

Material	Properties	Reason for Not Selecting for Study
Boron/Titanium Composite	1. Similar to Carbon/Titanium above.	1. Difficult to manufacture. 2. Boron filaments are expensive. 3. Thermal treatment of the boron required. 4. Fabrication from tapes is not applicable to large structures.
Beryllium Wire/Aluminum Composite	1. Strong, lightweight, high modulus composite. 2. Potentially competitive with boron/aluminum costs. 3. Should be capable of simplifying construction, joints, and assembly of components.	1. High cost of beryllium wire to date. 2. Little experience with wires and this matrix. 3. Limited information on material properties and analysis methods.
Beryllium Wire/Titanium Composite	1. Same as for Beryllium Wire/Aluminum composite plus good high temperature properties for high heating applications.	1. Little experience. 2. Very high cost. 3. Limited information on material properties and analysis methods.

Table C-2

Some Candidate Structural Materials Not Selected for Detailed Study (Cont.)

Material	Properties	Reason for Not Selecting for Study
Whiskers	1. Ultra-high strength producing light-weight structures. 2. Use with resin or metal matrix should improve capability of structural configurations.	1. Very limited experience, no knowledge of material properties or fabricating techniques. 2. Very high costs. 3. Unsolved manufacturing problems. 4. Too far in future.
Titanium Face, Beryllium Core Honeycomb	1. Easier to fabricate and join to neighboring sheets. 2. Titanium has the corrosion resistance and inertness to fuels to protect the beryllium core. 3. Beryllium in the core provides the benefits of high modulus to minimize core weight.	1. Limited knowledge of properties, analysis methods, and test experience of this type of honeycomb. 2. Possible bonding problems between Ti and Be.

APPENDIX D

CONSIDERATION OF WEIGHT RELATIONSHIPS FOR SELECTIVELY MIXED ADVANCED AND CONVENTIONAL CONSTRUCTIONS AND MATERIALS ON REPRESENTATIVE VEHICLES

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CONSIDERATION OF WEIGHT RELATIONSHIPS FOR SELECTIVELY MIXED ADVANCED AND CONVENTIONAL CONSTRUCTIONS AND MATERIALS ON REPRESENTATIVE VEHICLES

D.1 INTRODUCTION

Review of the technologies for this study (Contract NAS2-5047) indicate that there may be serious difficulties in fabricating and using pressurized tanks made of advanced materials. Beryllium is difficult to fabricate and seal against leakage of gas and liquid propellants. Advanced composites also must be designed to minimize leakage, while carrying the biaxial tensile and compressive loads.

A combination of advanced and conventional construction methods was considered briefly in order to establish the feasibility of using advanced materials and constructions in unpressurized sections only. Weights using a mixture of materials were compared with conventional construction weights and the weights of vehicles using totally advanced construction.

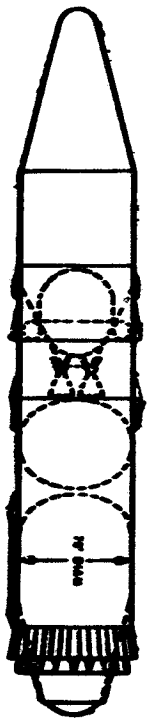
D.2 METHOD

The data from Contract NAS2-3811, Final Report[1,2], was used as a starting point. In the first case, all pressurized tanks were assumed to be of aluminum honeycomb construction, with advanced construction, such as berrylium honeycomb, used in all unpressurized sections. In the second case, the pressurized tanks were assumed to be made of titanium honeycomb, with beryllium honeycomb elsewhere.

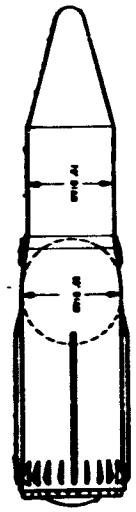
The weights were assembled from charts in the final reports of Contract NAS2-3811 and produced the results summarized in Figure D-1. Figures D-2 and D-3 show the detailed weight calculations for the 2 vehicle. Figure D-4 shows the detailed weight calculations for the 301 vehicle—a vehicle with a higher percentage of its weight in pressurized tanks than the 201 vehicle.

D.3 DISCUSSION OF RESULTS

The results shown in Figure D-1 illustrate the effectiveness of using different materials throughout the vehicle. The lowest weight structure, which uses beryllium in both pressurized and unpressurized areas, shows reductions of 57.7 percent and

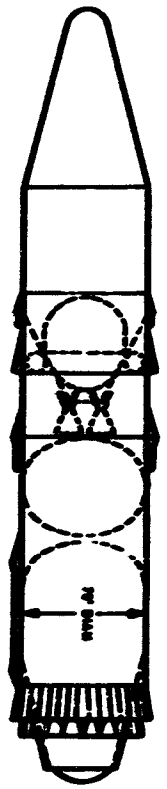


Configuration	201 Vehicle		301 Vehicle	
	Structural Weight (lb)	Percent Weight Savings	Structural Weight (lb)	Percent Weight Savings
(Nominal Construction) 1. (Alum ISS Walls,) (Alum Mono Heads)	690,822	-	641.320	-
2. (Alum Hyc Walls) (Alum Mono Heads)	453,726	34.3	418,609	34.7
3. (Be Hyc Walls) (Ti Mono Heads)	250,919	63.7	271,480	57.7
4. (Ti Hyc Walls) (Ti Mono Heads)	382,146	44.7	342,764	46.6
5. (Alum Hyc Walls in)* (Pressurized Tank) (Alum Mono Heads) (Be Hyc Walls in) (Unpressurized Sections)	369,043	46.6	358,714	44.1
6. (Ti Hyc Walls in)* (Pressurized Tanks) (Ti Mono Heads) (Be Hyc Walls in) (Unpressurized Sections)	277,536	59.8	296,443	53.8



*These constructions are considered typical of designs where the use of the best constructions is confined to unpressurized sections. While these results were determined specifically for Beryllium Honeycomb in the unpressurized walls, the results are considered typical of what might be also achieved with other materials, such as advanced fibrous composites in the unpressurized walls.

Figure D-1. Summary of Calculations for Selective Mix of Advanced Metals

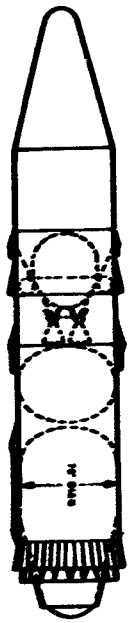


Section	Al in all Press. Tanks, Be Elsewhere
Inst Unit and Forward Skirt	2,354
LH_2 Tank and Thrust Str.	39,323
Intertank	8,123
Baffles and Insulation	12,900
LOX Tank	8,850
Aft Skirt	1,037
Second Stage Total in lbs	72,587
(Second Stage Total in kg)	32,925
Interstage	14,956
Forward Skirt	10,863
LOX Tank Top Head	8,746
LOX Tank Bottom Head	19,318
Intertank	33,565
LH_2 Tank Top Head	15,935
LH_2 Tank Cylinder	40,281
LH_2 Bottom Head	35,330
Thrust Take Out	11,317
Thrust Structure	36,105
Baffles and Insulation	70,040
First Stage Total in lbs	296,456
(First Stage Total in kg)	134,472
Vehicle Total in lbs	369,043
(Vehicle Total in kg)	167,398
Difference from Nominal	-321,779
Percent Weight Saving	46.58

NOTE: For clarity, only stage and vehicle total weights are expressed in kilograms within brackets.

Data extracted from References 1 and 2.

Figure D-2. 201 Vehicle Configuration Variation of Vehicle Structural Weight with Changes in Materials and Types of Construction Exposed to Nominal Loading Conditions

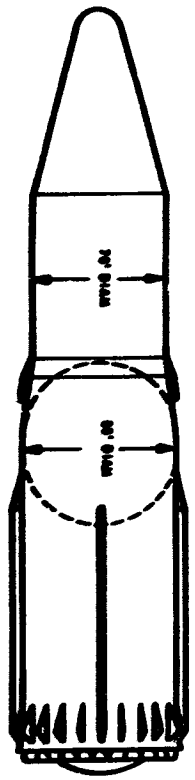


Section	Nominal Construction		Weight Variation Using Lightest Wall Construction for Each Material								Ti in All Press. Tanks, Be Elsewhere
	Aluminum		Aluminum		Titanium		Beryllium		Lightest Metal Lightest Wall Cons.		
	Wall Cons		Wall Cons		Wall Cons		Wall Cons		Wall Cons		
Inst Unit and Forward Skirt	ISS	13,004	Hyc	4,292	Hyc	3,800	Hyc	2,354	Hyc	2,354	2,354
LH_2 Tank and Thrust Str	--	39,323	--	39,323	--	38,742	--	18,511	--	18,511	38,742
Intertank	ISS	38,963	Hyc	14,795	Hyc	12,563	Hyc	8,123	Hyc	8,123	8,123
Baffles and Insulation	--	*12,900	--	*12,900	--	*12,900	--	*12,900	--	*12,900	12,900
LOX Tank	--	8,850	--	8,850	--	6,523	--	4,840	--	4,840	6,523
Aft Skirt	ISS	10,389	Hyc	2,941	Hyc	2,244	OFC	1,037	OFC	1,037	1,037
Second Stage Total in lbs		123,429		83,101		76,772		47,765		47,765	69,679
(Second Stage Total in kg)		(55,987)		(37,695)		(34,824)		(21,666)		(21,666)	31,606
Interstage	ISS	65,266	Hyc	28,746	Hyc	22,804	Hyc	14,956	Hyc	14,956	14,956
Forward Skirt	ISS	46,882	Hyc	20,950	Hyc	16,521	Hyc	10,863	Hyc	10,863	10,863
LOX Tank Top Head	Mono	8,746	Mono	8,746	Mono	5,731	Mono	5,284	Mono	5,284	5,731
LOX Tank Bottom Head	Mono	19,318	Mono	19,318	Mono	12,309	Mono	12,623	Mono	12,309	12,309
Intertank	ISS	156,026	Hyc	73,784	Hyc	55,682	SFC	33,565	SFC	33,565	33,565
LH_2 Tank Top Head	Mono	15,935	Mono	15,935	Mono	10,268	Mono	9,982	Mono	9,982	10,268
LH_2 Tank Cylinder	ISS	63,411	Hyc	40,281	Hyc	30,189	Hyc	25,161	Hyc	25,161	30,189
LH_2 Bottom Head	Mono	35,330	Mono	35,330	Hyc	22,514	Mono	23,258	Mono	22,514	22,514
Thrust Takeout	ISS	53,698	Hyc	24,754	Hyc	18,715	SFC	11,317	SFC	11,317	11,317
Thrust Structure	--	82,741	--	82,741	--	90,601	--	36,105	--	36,105	36,105
Baffles and Insulation	--	*20,040	--	*20,040	--	*20,040	--	*20,040	--	*20,040	20,040
First Stage Total in lbs		567,393		370,625		305,374		203,154		202,096	207,857
(First Stage Total in kg)		(257,369)		(168,116)		(138,518)		(92,151)		(91,671)	94,284
Vehicle Total in lbs		690,822		452,726		382,146		250,919		249,861	277,536
(Vehicle Total in kg)		(313,356)		(205,811)		(173,342)		(113,817)		(113,337)	125,890
Difference from Nominal				-237,096		-308,676		-439,903		-440,961	-413,286
Percent Weight Saving				34.32		44.68		63.68		63.83	59.83

NOTE: For clarity, only stage and vehicle total weights are expressed in kilograms within brackets.

Data Extracted from References 1 and 2.

Figure D-3. 20[illegible] Vehicle Configuration Variation of Vehicle Structural Weight with Changes in Materials and Types of Construction Exposed to Nominal Loading Conditions



Section	Al in All Press. Tanks, Be Elsewhere	Nominal Construction		Weight Variation Using Lightest Wall Construction for Each Material								Ti in All Press. Tanks, Be Elsewhere
		Aluminum		Aluminum		Titanium		Beryllium		Lightest Metal and Wall Cons.		
		Wall Cons	Weight	Wall Cons	Weight	Wall Cons	Weight	Wall Cons	Weight	Wall Cons	Weight	
Instrument Unit	2,815	ISS	13,647	Hyc	5,258	Hyc	4,519	Hyc	2,815	Hyc	2,815	2,815
Forward Skirt	10,570	ISS	52,748	Hyc	19,355	Hyc	16,830	Hyc	10,570	Hyc	10,570	10,570
LOX Tank Top Head	14,489	Mono	14,489	Mono	14,489	Mono	9,403	Mono	9,003	Mono	9,003	9,403
LOX Tank Cylinder	3,821	ISS	5,189	Hyc	3,821	Hyc	2,458	Hyc	2,501	Hyc	2,458	2,458
Common Bulkhead	63,425	Hyc	63,425	Hyc	63,425	Hyc	51,310	Hyc	52,110	Hyc	51,310	51,310
LH_2 Tank Cylinder	175,098	ISS	316,615	Hyc	175,098	Hyc	139,515	Hyc	113,558	Hyc	113,558	139,515
LH_2 Tank Bottom Head	22,287	Mono	22,287	Mono	22,287	Mono	14,163	Mono	14,714	Mono	14,163	14,163
Thrust Takeout	17,779	ISS	78,745	Hyc	40,701	Hyc	30,391	SFC	17,779	SFC	17,779	17,779
Thrust Structure	30,430		56,175		56,175		56,175		30,430		30,430	30,430
Insulation	18,000		*18,000		*18,000		*18,000		*18,000		*18,000	18,000
Vehicle Total in lbs	358,714		641,320		418,609		342,764		271,460		270,086	296,443
(Vehicle Total in kg)			(290,903)		(189,881)		(155,478)		(123,143)		(122,511)	134,467
Difference from Nominal	-282,606				-222,711		-298,556		-369,840		-371,234	-344,877
Percent Weight Savings	44.07				34.73		46.55		57.67		57.89	53.78

NOTE: For clarity, only stage and vehicle total weights are expressed in kilograms within brackets.

Data Extracted from References 1 and 2.

Figure D-4. 301 Vehicle Configuration Variation of Vehicle Structural Weight with Changes in Materials and Types of Construction Exposed to Nominal Loading Conditions

63.7 percent for the 301 vehicle and the 201 vehicle, respectively. However, of greater significance is the fact that, even if more conventional metals such as titanium or aluminum are used for the structures in the pressurized areas and beryllium honeycomb in the unpressurized areas, weight savings in the range from 44 to 59.8 percent are still available.

As summarized in Figure D-1, the judicious mix of aluminum or titanium in the pressurized tanks and advanced materials such as beryllium or advanced composites elsewhere results in a vehicle with significant weight savings. These weight reductions are less than 4 to 17 percent than the maximum achievable with the best beryllium and titanium construction. But the mixed material structures should be more readily fabricated and tested than those constructed of a single metal or composite.

APPENDIX E

UNIDIRECTIONAL COMPOSITE STIFFENING OF METALLIC STRUCTURE

APPENDIX E

UNIDIRECTIONAL COMPOSITE STIFFENING OF METALLIC STRUCTURE

E.1 GENERAL

The results of structural efficiency studies as reported by Rosen, Snyder, and Dow [40] indicated that composite materials (i.e., boron/epoxy and carbon/aluminum) become competitive weight-wise with light-metallic construction (in particular, beryllium construction) only when efficiently stiffened. This conclusion was reached by studying various honeycomb-sandwich shell type constructions. For the region of the structural loading intensities of interest, the shell weight was determined by equating elastic buckling strength to ultimate strength in compression, resulting in a fairly small core to face sheet thickness ratio. This was primarily due to low transverse strength in the face sheets.

The resultant core to face sheet thickness ratios were so low as to render their fabrication and assembly extremely difficult. As an alternative to this type of construction, the use of integral stiffners is proposed. The application of uni-axial stiffeners is proposed. The application of uni-axial stiffeners to tube-columns of isotropic metals (notably aluminum and beryllium) was studied by Rosen and Dow [41]. Their results indicate that with the proper combination of materials, it is possible to achieve a significant weight savings (as much as 40 percent), over the unstiffened configuration. The use of an isotropic material as the skin eliminates the problem of premature transverse failure in the face sheet. These results are shown in Figure E-1 [41].

An extreme example of the possibilities is shown in Figure E-2 [41]. Here are plotted several efficiency curves, all for boron/epoxy composites. A "skelton shell" (a 0 degree-, ±60 degree-waffle with zero thickness skin) is also shown on the plot. While substantially lighter than monocoque construction, it is slightly heavier than sandwich construction. However, it is probably much easier to construct. A more important advantage of this type of construction is that the use of metallic skin makes possible the use of conventional metallic joining techniques, thus leading to a more reliable structure.

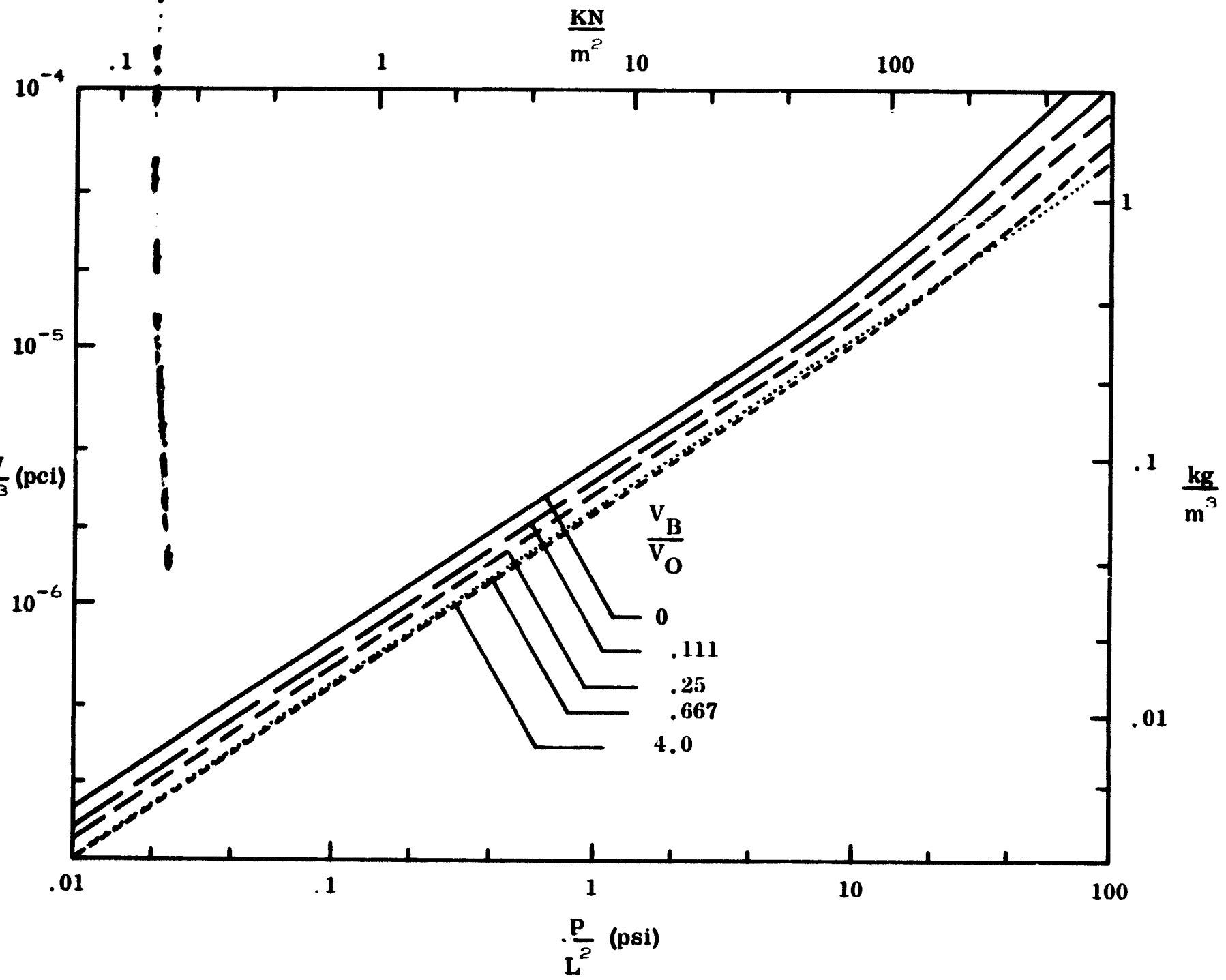


Figure E-1. Efficiencies of Round 7075-T6 Aluminum Alloy Tube-Columns Reinforced at Three Points by Unidirectional Boron/Epoxy Stiffeners

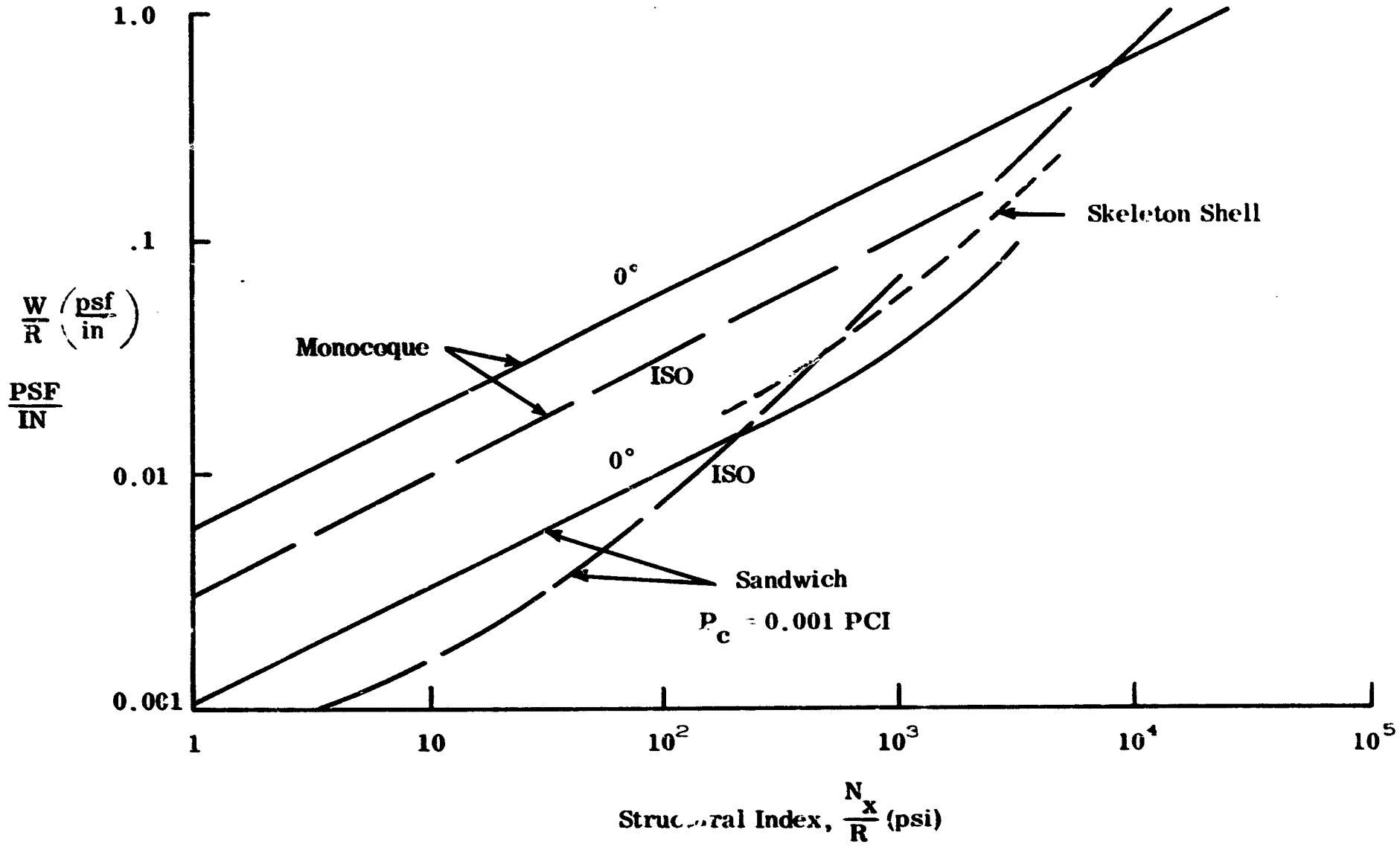


Figure E-2. Efficiency of Boron/Epoxy Cylinders of Various Constructions, Subjected to Axial Compression

E.2 DETERMINATION OF EFFICIENCY CURVES

Integrally stiffened cylindrical shells were studied by constructing laminates with properties analogous to the stiffened shell. The arrangement and dimensions for a typical stiffener pattern are shown in Figure E-3. For each rib pattern, six layers are needed for the analogous laminate.

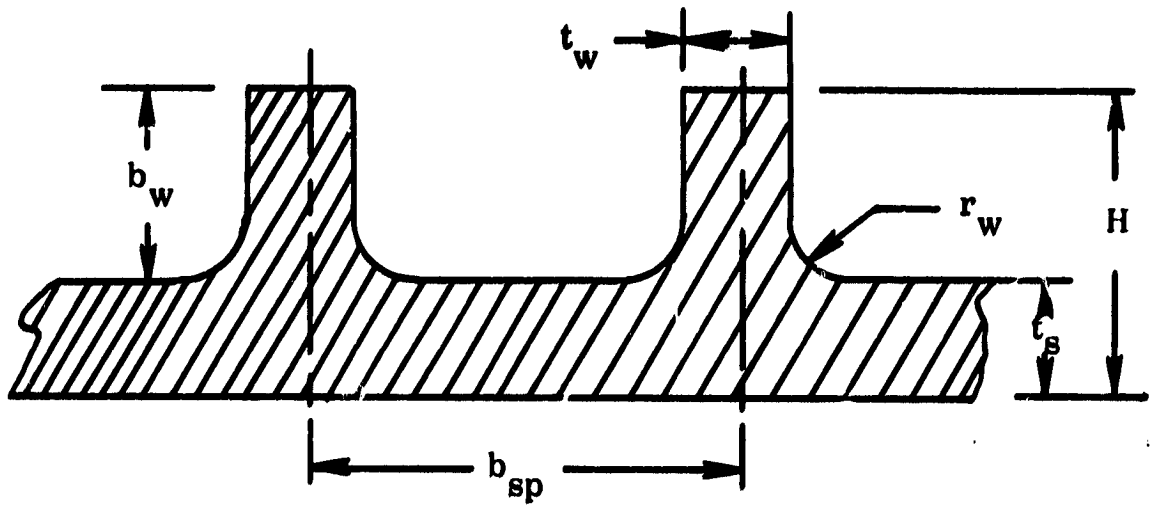


Figure E-3. Typical Stiffener Pattern

The stability of the resulting cylinder is determined using small-deflection theory for orthotropic-cylinder buckling. The efficiency curves for two sets of cylinders are shown in Figure E-4. For comparison purposes, the same material properties reported earlier [40] were used. One set of curves refers to a beryllium cylinder with axial boron/epoxy stiffeners, the second set refers to an aluminum cylinder (7075-T6 alloy) with axial boron/epoxy stiffeners. Several combinations of stiffener dimensions were used as noted on the figure. The case of equal rib height and skin thickness was also computed ($t_s/H = .5$) but the results were almost identical to the case of $t_s/H = .25$ and are not shown on the graph.

No attempt was made to optimize the rib pattern. A stringer spacing of 20 inches was arbitrarily selected. In order to check the reasonableness of this assumption, the panels were assumed to buckle as simply supported plates. The resulting efficiency curves as reported by Dow, Rosen, and Kingsbury [42], are shown in Figure E-5. These results are converted to the form of the cylinder efficiency curves for the thin ribs.

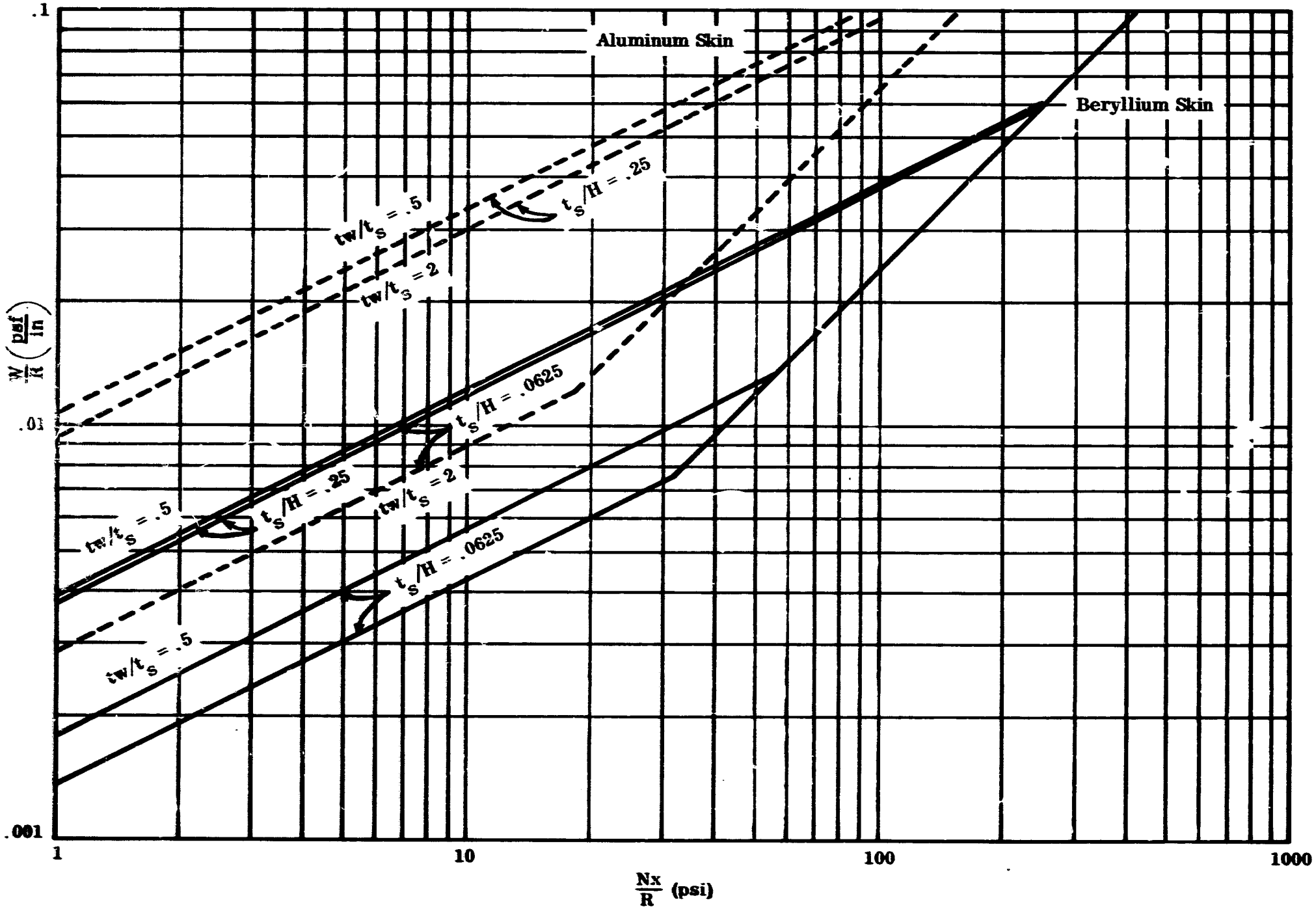
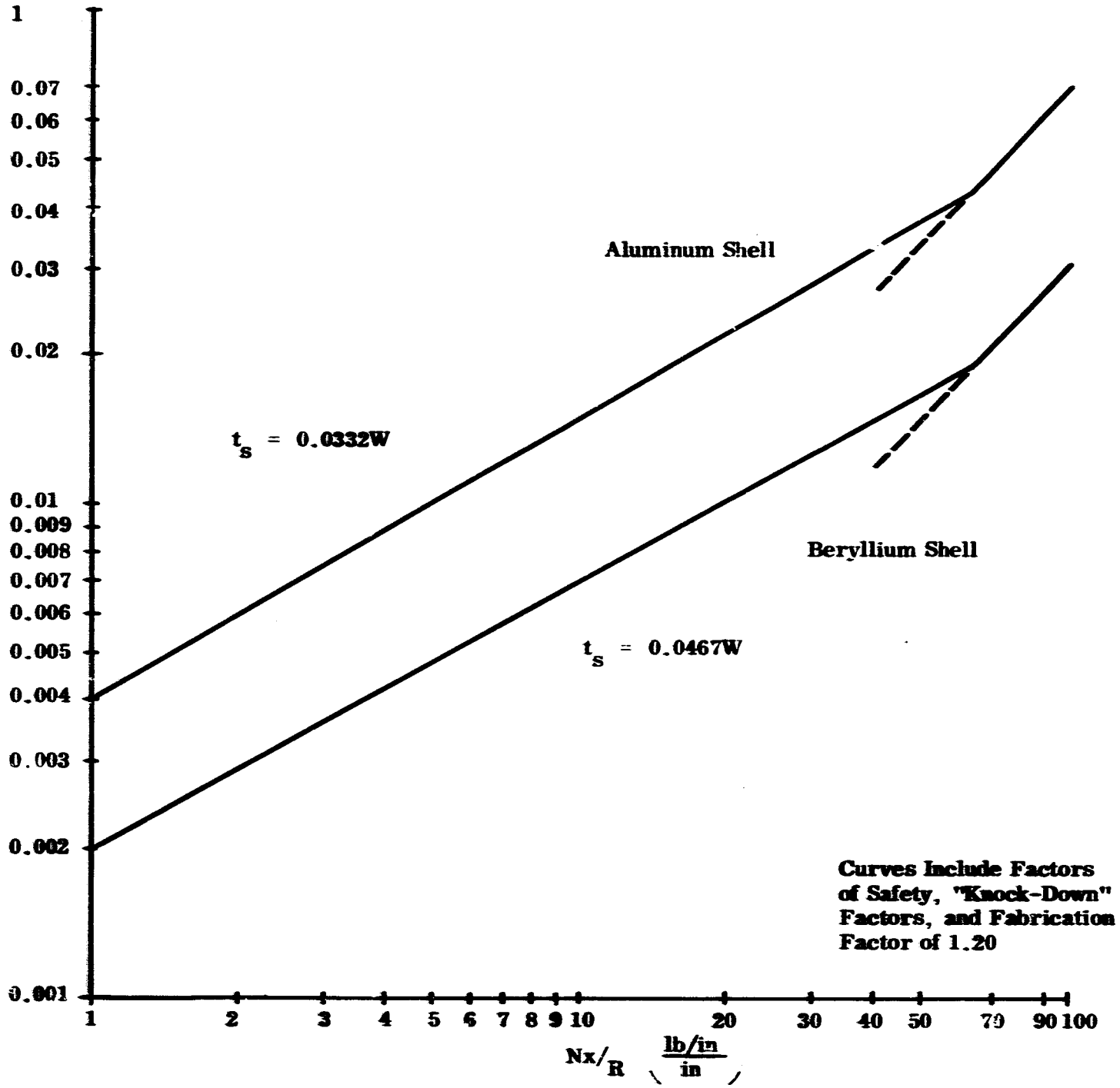
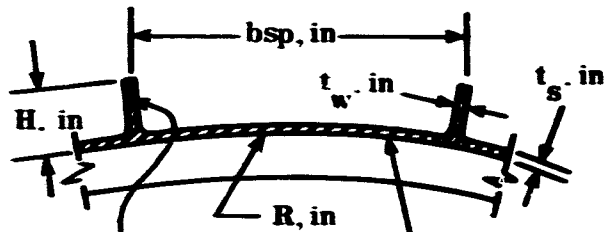


Figure E-4. Efficiencies of Isotropic Cylinders Reinforced With Boron/Epoxy Stringers



Symbols



t_w/t_s = 2

bsp/H = 10

t_s/H = 0.0625

Figure E-5. Efficiency Curves for Thin Ribs

No attempt was made to optimize the rib pattern. A stringer spacing of 20 inches was arbitrarily selected. The actual curves used in this analysis are shown in Figure E-5. Stringer spacing was varied as a parameter ($b_{SP/H}$). Structural "knock-down" and fabrication factors were included so that the results were on a comparable basis as the metallic structures. The nomenclature and assumptions are indicated on Figure E-5.

Due to limited time and effort permitted this study, the complete optimization of this structure was not attempted. It is apparent that more efficient structural designs can be evolved with stringer more closely spaced; however, for purposes of this study, the dimensions indicated were used in the cost analysis.

E.3 MATERIALS AND FABRICATION

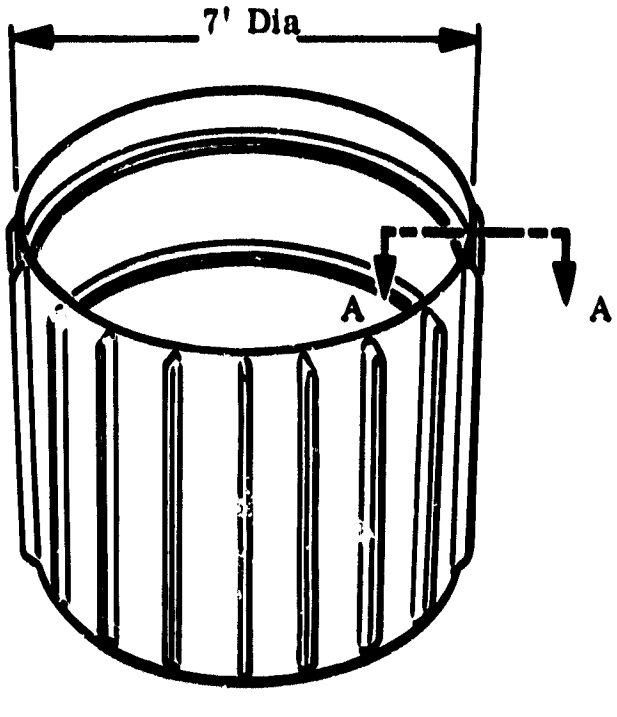
The metallic shell can be any of the structural metals which are compatible with launch vehicle requirements. Data is given in Figure E-5 for aluminum and beryllium shells; however, in view of the difficulty in using beryllium to contain pressurized propellants, this discussion will be confined to aluminum shells.

The inner shell could be designed and fabricated to carry the internal pressure with tank cylinders and heads constructed as monocoque shells without stiffeners. The resultant tanks would be reasonably low cost, yet practical, containers for the propellants.

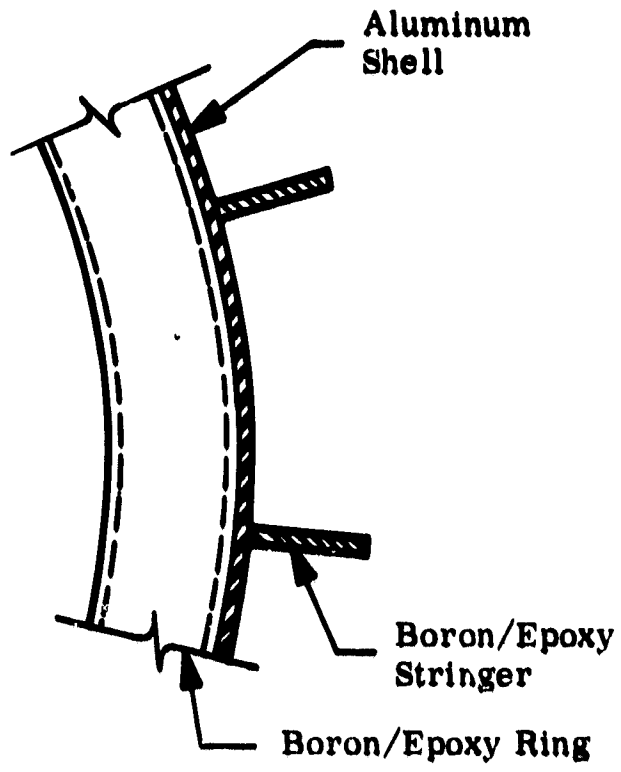
The unidirectional stiffeners constructed of composite materials could be bonded onto the pre-constructed metal monocoque shells on either the inner or outer surfaces. For purposes of simplified construction, the unidirectional stiffeners are shown in Figure E-6 on the exterior surfaces of the pressurized cylindrical tank and unpressurized inter-tank walls, but not across the elliptical head due to the difficulty in attaching the stringers.

The ring frames, also constructed of composite materials, can be installed either on the inner or outer surfaces of the shell. Advantages of each location are as follows:

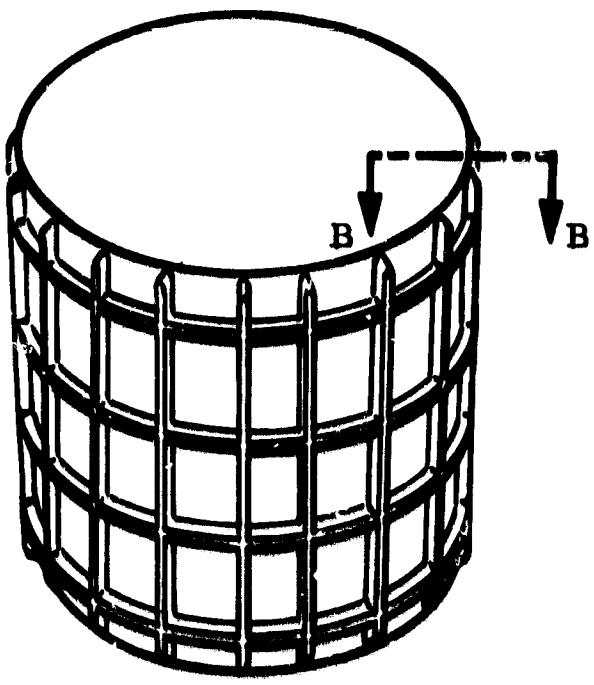
Location	Advantage
a. Inner Surface Attachment of Ring Frames	1) Easier fabrication and installation of individual frames. 2) Convenient attachment points for slosh baffles.



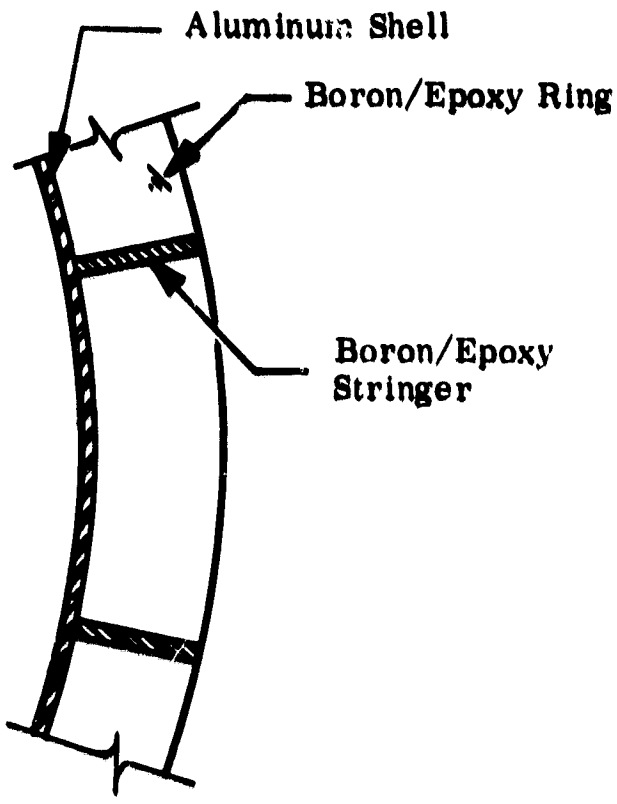
Internal Rings



Section A-A



External Rings



Section B-B

Figure E-6. Unidirectionally-Stiffened Metal Shells

Location	Advantage
	3) Spacing of frames independent of stringer construction.
	4) Smoother aerodynamic shape than for external frames.
b. Outer Surface Attachment of Ring Frames	1) Fabrication possible by jointly winding stringers and ring frames.
	2) Easier design of fixtures for autoclave.
	3) Stronger attachment of stringers to frames.

The analysis of this study was based on the first case above, as shown in Section A-A on Figure E-6.

The materials for the unidirectional stiffeners can be any of the conventional fibrous composites, such as,

Boron/Epoxy
Glass/Epoxy
Carbon/Epoxy
Boron/Aluminum
Carbon/Aluminum

These composites are discussed in Volume 3 of this report. The shape of the stiffeners is originally considered to be rectangular to facilitate calculations. More efficient shapes such as hat sections, "Z" sections, or "T" sections would probably be more attractive from a weight reduction viewpoint, but these types of stiffeners have not yet been analyzed.

In addition to the resin and metallic matrix composites, a high modulus metal such as beryllium might be used to stiffen the aluminum shell. Attachment, as above, could be by adhesive bonding and the resultant structural weight would probably be comparable to the fibrous composites, but have not been analyzed in this study. Analysis of Beryllium - 38 percent Aluminum (Lockalloy) stringers on an aluminum skin in Reference 121 showed weight savings approximately one half of the weight savings for an all beryllium construction in a representative cylinder 200 inches in diameter and 36 inches long; but with limited value from a cost-effectiveness viewpoint.

E.4 CONCLUSIONS

A brief look indicates that unidirectional stiffening of metallic shells is sufficiently attractive to warrant future optimization study of placement of stringers and rings. In addition, the use of more efficient stiffener shapes, such as for hat sections, should be investigated further. These two studies should permit a much more complete appraisal of the worth of unidirectional stiffeners.

APPENDIX F

LOADS DETERMINATION FOR VEHICLE 201

APPENDIX F

LOADS DETERMINATION FOR VEHICLE 201

LOAD ANALYSIS

Loads calculations summarized in Reference 1 were performed in the following manner.

The axial force transmitted along the vehicle axis was derived from three sources:

a. The axial thrust loads.
b. The bending moment.
c. The tank pressure.

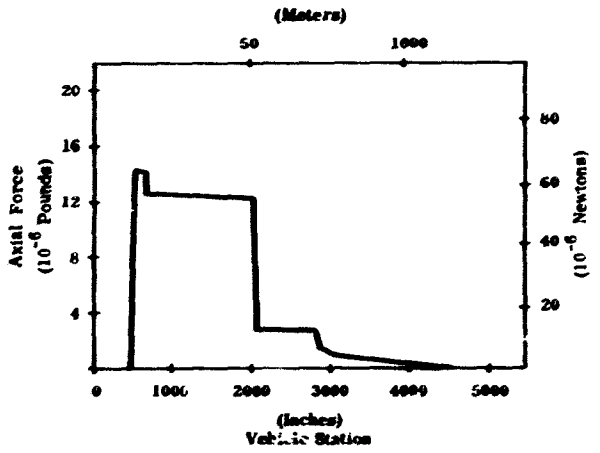
The magnitudes of these three loads were considered to be dependent upon the location along the vehicle axis and on the time of flight. The total equivalent axial force at a distance "x" along the vehicle axis for an arbitrary flight time "t", is expressed by Equation F-1.

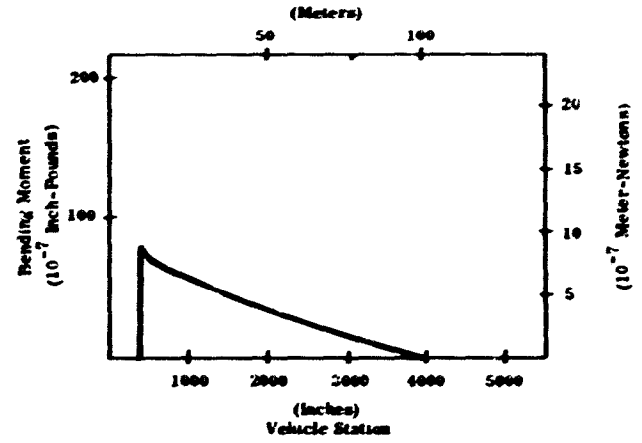
$$F(x,t) = -T(x,t) \pm \frac{2M(x,t)}{R(x)} + R^2(x)\, P(x,t) \qquad (F\text{-}1)$$

where:

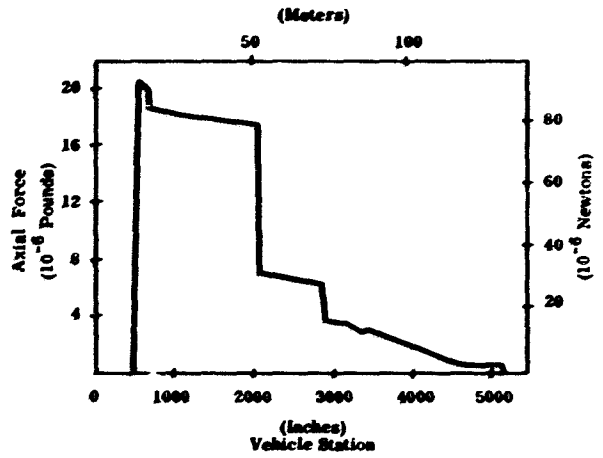
F is the total axial force.
M is the bending moment.
T is the axial force resulting from the thrust load.
P is the local pressure (gauge) in the propellant tank.
R is the local radius of the vehicle structure.

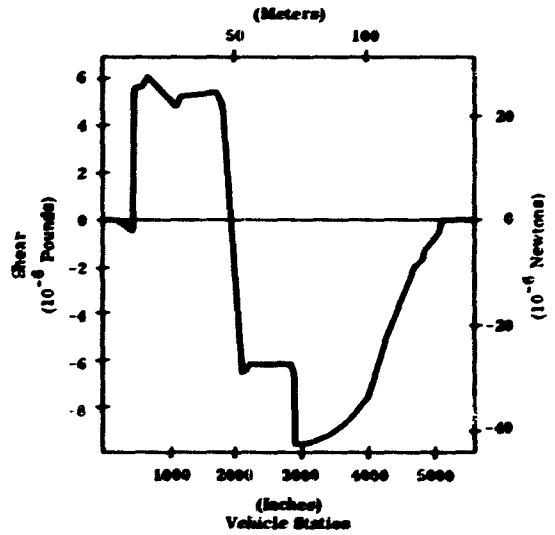
In the above equation, the minus sign signifies compression and the plus sign signifies tension. The plus or minus sign on the bending moment term results from the non-axisymmetry of the bending load. Since there is no preferential direction for the bending moment to act, either the plus or minus sign was chosen to produce the most severe load. The thrust loads are compressive and the pressure loads are tensile. In performing a buckling analysis on a shell, the terms of Equation F-1 were chosen such that the maximum compressive load was developed. Thus, the minus sign was used for the bending moment term which would add to the compressive thrust load. The pressure load, on the other hand, has a positive sign and tends to relieve the compressive loads. The nominal load distributions for the 201 vehicle are shown in Figure F-1.

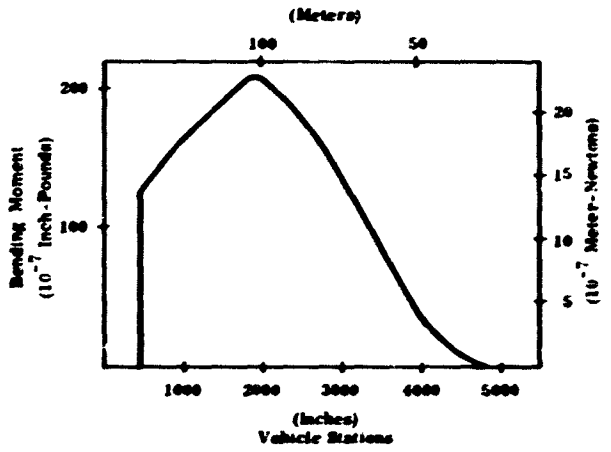




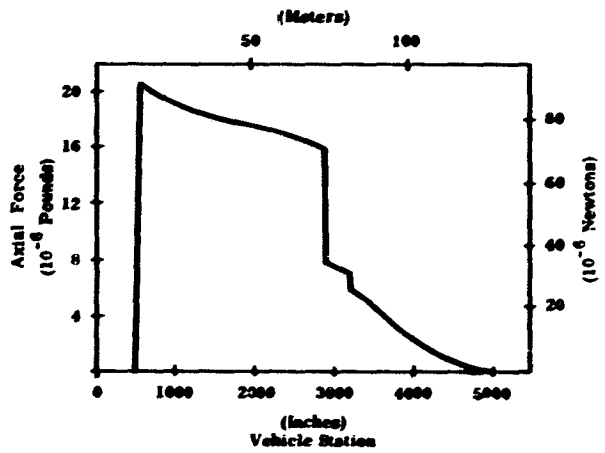
(a) PRELAUNCH







(b) MAXIMUM qα



(c) MAXIMUM ACCELERATION

Figure F-1. Nominal Load Distributions For the 201 Vehicle Configuration

Design loads are obtained by increasing the limit loads by the factors of safety with the exception that pressure relieving loads are left unchanged. Hence, the first two terms of Equation F-1 were multiplied by the factor of safety to obtain the design load, and the pressure term added directly to the design load without increase. The nominal factor of safety used in this analysis,

Yield Factor of Safety = 1.1

Ultimate Factor of Safety = 1.4

For convenience, the load defined by Equation F-1 was divided by the local circumference of the shell to yield a stress resultant (or load intensity) N_x as shown by Equation F-2.

$$N_x(x,t) = \frac{-T(x,t)}{2\pi R(x)} \pm \frac{M(x,t)}{\pi R^2(x)} + \frac{P(x,t)\, R(x)}{2} \qquad (F-2)$$

In a similar manner, the hoop loads due to the tank pressures were divided by the local circumference of the shell to obtain the stress resultant N_y given by Equation F-3.

$$N_y = R(x)\, P(x,t) + \beta(t)\gamma\, d(x)\, R(x) \qquad (F-3)$$

where:

P is the local pressure (guage) in the propellant tank.

R is the local radius of the vehicle structure.

β is the instantaneous acceleration in g's.

γ is the specific weight of the propellant in the tanks.

d is the distance of station "x" below the level of the propellant.

The relative directions of N_x and N_y are shown on typical shell elements in Figure F-2.

All possible failure modes were considered in applying these loads to the analysis of the vehicle structure. In general, all failure modes were classified in two categories—stability failures and strength failures. The buckling modes of failure were considered to be sensitive only to the compressive axial loads, whereas, the strength modes of failure are dependent upon both the axial and hoop loads.

For isotropic materials, the Hencky-von Mises theory of failure was used to combine the biaxial components of load. The resulting equivalent stress resultant was used in the analysis of strength failures, based on the uniaxial strength properties of the

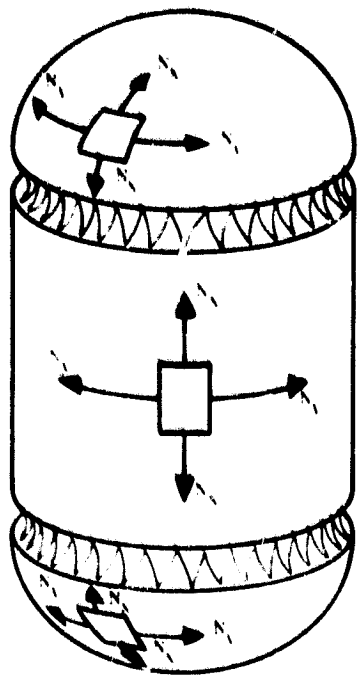


Figure F-2. Representation of Stress Resultants on Typical Shells

structural materials evaluated. In terms of the biaxial stress resultants, N_x and N_y, the equivalent uniaxial stress resultant N_o is expressed by Equation F-4.

$$N_o = (N_x^2 - N_x N_y + N_y^2)^{1/2} \qquad \text{(F-4)}$$

where:

N_x is the axial (or meridional) stress resultant.

N_y is the hoop (or circumferential) stress resultant.

N_o is the equivalent uniaxial stress resultant.

For anisotropic materials, such as filamentary composites, the methods of combining N_y to N_x to predict strength failures were more complex. The variety of winding patterns, filament materials, and binder materials precludes generalizations about the interactions of stress components. For this reason, the relationship between loads and structural weight are treated differently than for isotropic materials as discussed in Section 4.4.

For isotropic materials, the stress resultants N_x and N_o completely characterize the loading of a structural element at any particular instant of time. Stability or buckling analyses are dependent on N_x, and the strength analyses are dependent on N_x and N_o.

The procedures for determining the critical values (i.e., the largest) of N_x and N_o were based on comparative selection from the loads at the five design points, as follows:

a. Prelaunch unpressurized.
b. Prelaunch pressurized.
c. Maximum $q\alpha$ product.
d. Maximum pressure on propellant tank bottom beads.
e. Maximum acceleration.

The critical loads envelope for the 201 vehicle was then determined by identifying the largest N_x and N_o for each section considering each of the five design points.