Advanced

Vehicles

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Systems Integration and Demonstration of Advanced Reusable Structure for ALS

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FOREWORD

Systems Integration and Demonstration of Advanced Allowable Structures for Advanced Launch System (SIDARS) program (Contract No. NAS1-18560, Task Assignment 7) was performed by the Boeing Defense & Space Group, Aerospace & Electronics Division for the Langley Research Center, NASA, Hampton Virginia, under ALS Advanced Development Program (ADP) 3201 Materials for Propulsion/Avionics Modules. Mr. Dick Royster from Langley Research Center (LaRC) was the NASA Contract Monitor. Mr. Allen Taylor was the ALS ADP 3201 Task Manager, and Mr. Thomas Bales was the Structures and Materials Area ADP Manager, both from LaRC.

Mr. Curt. C. Chenoweth was the program manager and Mr. John H. Laakso was the task manager. Peter Rimbos and Martin Gibbins were the principal investigators. Bill Westre was the structural designer. The following organizations also provided significant contributions: BP Chemicals (HITCO), Inc.; Rohr Industries, Inc; the ASTECH Division of Alcoa/TRE; and Aeronca, Inc.

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FIGURES

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Nomenclature

Al	Aluminum
Al-Li	Aluminum Lithium
ALS	Advanced Launch System
ANSYS	A structural finite element code
BMI	Bismaleimide matrix material or adhesive
C-C	Carbon-Carbon
dSiC	discontinuous silicon carbide
DB	Diffusion Bond
DDT&E	Design, Development, Test & Evaluation
FEM	Finite Element Model
Gr/Ep	Graphite/Epoxy composite material
Gr/PI	Graphite/Polyimide composite material
H/C	Honeycomb
HSA	Standard Oil registered trademark for ceramic fiber paper insulation
HTA	High Temperature Aluminum
LaRC	Langley Research Center
LCC	Life Cycle Cost
LID	Liquid Interface Diffusion
MMC	Metal Matrix Composite
NC	Numerically Controlled
OMS	Orbital Maneuvering System
P/A	Propulsion/Avionics
PDT	Product Development Team
PI	Polyimide
PT	Polymer Triazine
QA	Quality Assurance

Nomenclature (Continued)

RCS	Reaction Control System
SCS/Al	Silicon Carbide/Aluminum
TDP	Technology Development Plan
TFU	Theoretical First Unit
Tg	Glass Transition Temperature
Ti	Titanium
TPS	Thermal Protection System

SUMMARY

This report covers Phase I of Contract NAS1-18560, Task Assignment 7. Objectives were to investigate the potential of advanced materials to achieve life cycle cost benefits for reusable structure on the advanced launch system. Three structural elements were investigated-all components of a reusable propulsion/avionics module: (1) aeroshell, (2) thrust structure, and (3) aft bulkhead. Structural concept definitions were prepared using a variety of configurations and materials. Preliminary analysis indicated the most promising concepts for further analysis. Manufacturing cost estimates, weight statements, and life cycle cost estimates were prepared for each of these concepts. Based on the concepts showing the greatest benefits, a technology development plan was prepared to validate the applicable structural technology.

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1.0 INTRODUCTION

The U.S. Advanced Launch System (ALS) targets routine access to space at improved launch cost effectiveness over current systems. One method to keep system launch costs (life cycle cost) to a minimum is recovering and reusing the higher-cost launch vehicle hardware such as the main engines and avionics hardware. This is especially important if main engine costs remain a high percentage of the total vehicle cost, as is the case in current launch systems. One approach to accomplishing this is with a propulsion/avionics (P/A) module.

The baseline ALS vehicle configuration for this study is shown in figure 1.0-1. The expendable structure represents the majority of the launch vehicle structural weight. The P/A modules represent the structure that would be reused. These modules contain the highest cost-per-unit mass items: the main engines and the avionics hardware. This baseline ALS vehicle configuration represents a relatively high level of reusability; however, other configurations are possible. One variation involves replacing the liquid fuel booster and its two booster P/A modules with solid-rocket boosters. P/A module structural technology is still applicable to the remaining core P/A module. In this way the P/A module concept investigated herein represents and supports a family of launch vehicles.

Two types of P/A modules are included in the baseline vehicle: the core elements and the booster elements. The missions for these modules are illustrated in figure 1.0-2. Some minutes after launch, the six engines contained in the two booster P/A modules exhaust their fuel supply. The booster element is jettisoned and the booster P/A modules (1) fly a suborbital, low-velocity reentry profile; (2) deploy parachutes; and (3) splash down for recovery. The core P/A module continues to orbit, deploys the payload, and reenters at high velocity from an optimum orbital position to either splashdown or land by parachutes. Landing attenuation is provided by air bags for both the water and land operation.

This study examines advanced materials in the structure of a reusable P/A module on a baseline ALS vehicle, and evaluates usage on the basis of system life cycle cost (LCC) benefit.

By exploiting new lightweight, high-strength materials and efficient manufacturing processes, P/A module structural performance and cost effectiveness are maximized. Nevertheless, development is required to apply these materials in the P/A module structure. Only a limited database and experience base on advanced materials performance and applications are available, and the raw material costs are

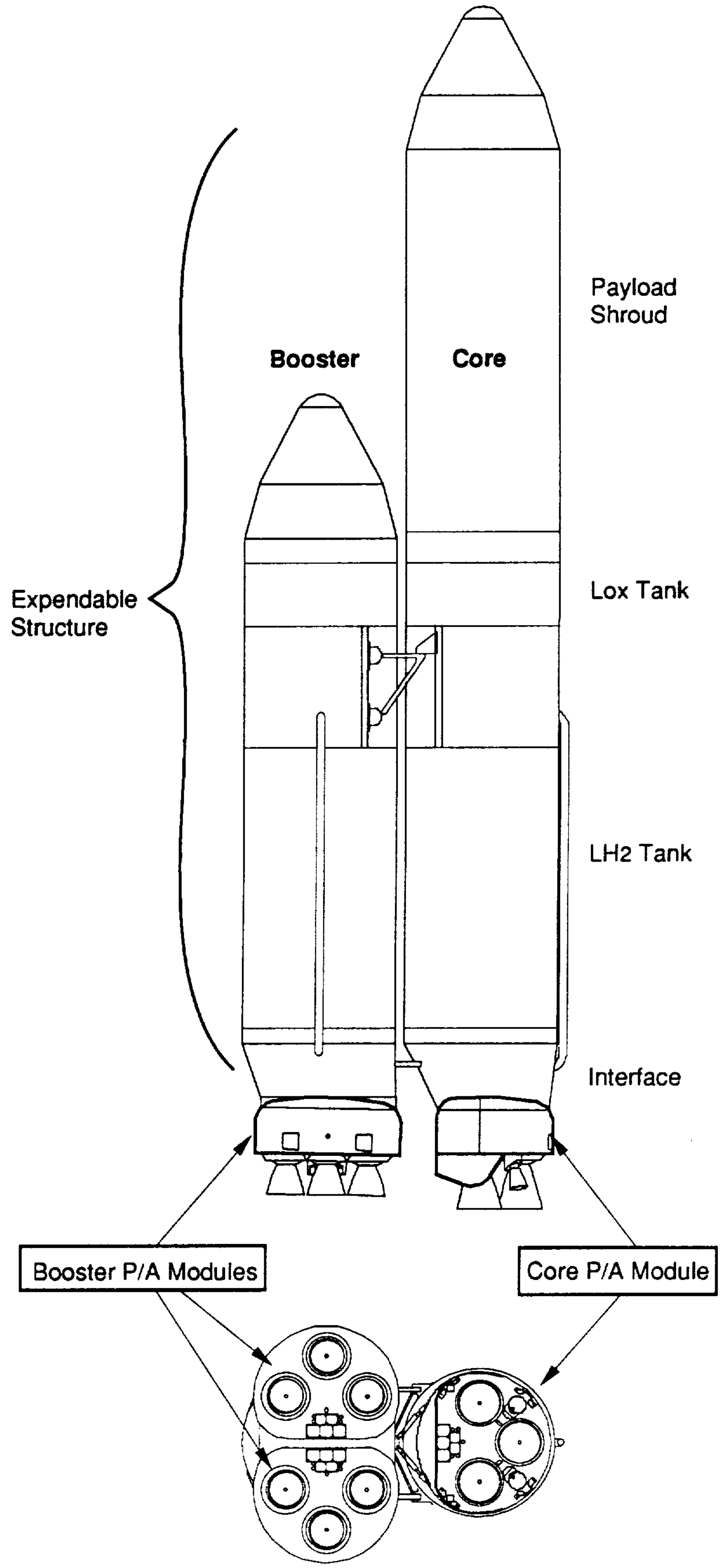

Figure 1.0-1. ALS Liquid Booster Configuration Incorporating Three Common P/A Module Structural Systems; ≈ 150,000 lb to LEO.

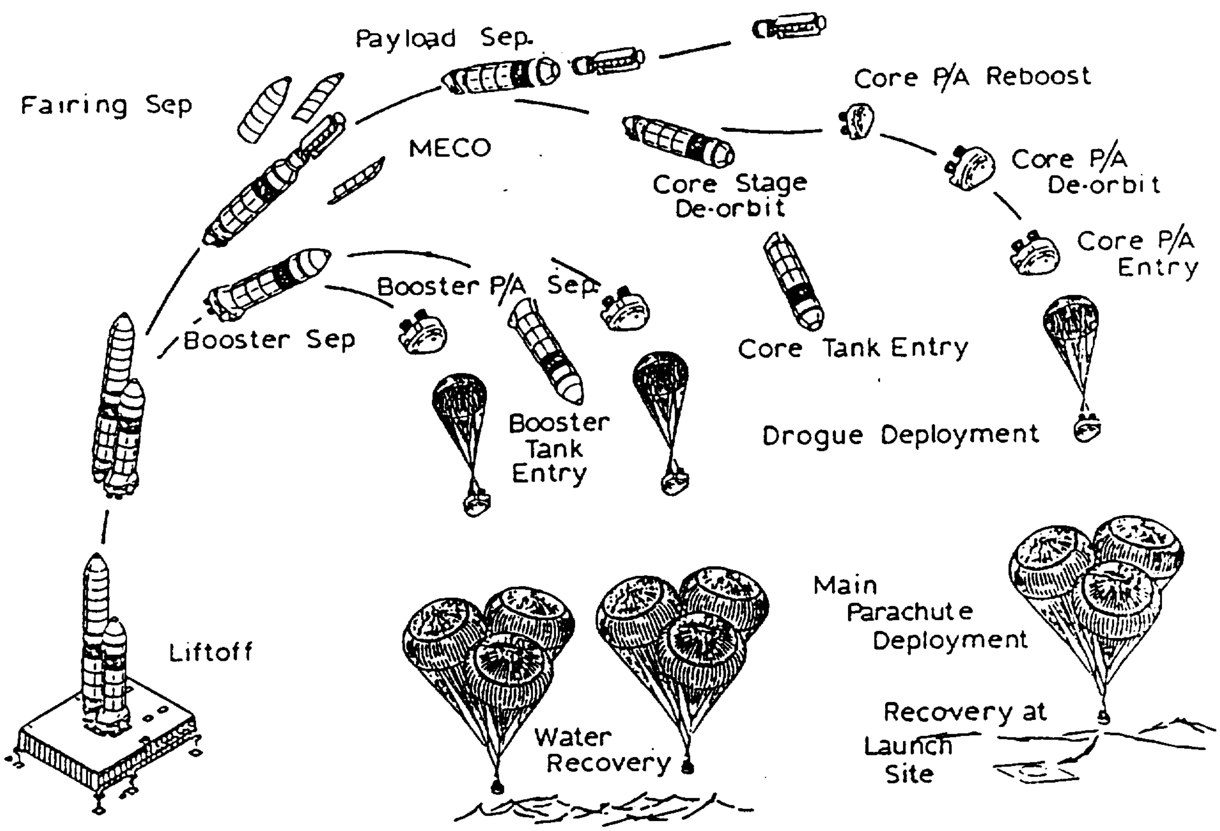

Figure 1.0-2. ALS Mission Profile.

currently high because of the relatively recent emergence of these materials for use in primary structures. Technology development priorities depend on system evolution timing, necessity to resolve critical issues, and ultimate life cycle cost (LCC) payoffs and objectives. Several commonalties exist between respective types of system components that affect cost and weight. Consequently, technology development efforts in one area can benefit another area, if properly planned. This program applies appropriate structural design and analysis techniques to the most promising materials for application on the ALS P/A module.

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2.0 OBJECTIVES

The objective of this program is to identify and demonstrate the potential of advanced materials and processes, internal insulation, and thermal protection systems for cost-effective, reusable structures for an ALS reusable element such as the P/A module. The major premise of the P/A module is that the main engines and avionics computers are valuable enough that reusing them reduces overall launch system costs. The specific objective for Phase I is a structural concept design and analysis study on a selected ALS recoverable P/A module system. Whenever possible, system definition for this study relied on a systems study performed under contract to NASA Marshall Space Flight Center (ref. 1). The primary output of Phase I is a technology development plan to guide technology validation and demonstration in Phases II and III.

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3.0 PROGRAM PLAN

The overall program is divided into three phases: Phase I: System Design Study, Phase II: Technology Validation, and Phase III: Hardware Demonstration.

During the Phase I System Design Study, preliminary structural designs for the ALS recoverable P/A module structural elements were developed and evaluated, and a technology development plan was prepared. The major P/A module system components (shown in figure 3.0-1), which represent the baseline P/A module system design. The four primary structural components are: aeroshell dome, aeroshell sidewall, thrust structure, and bulkhead.

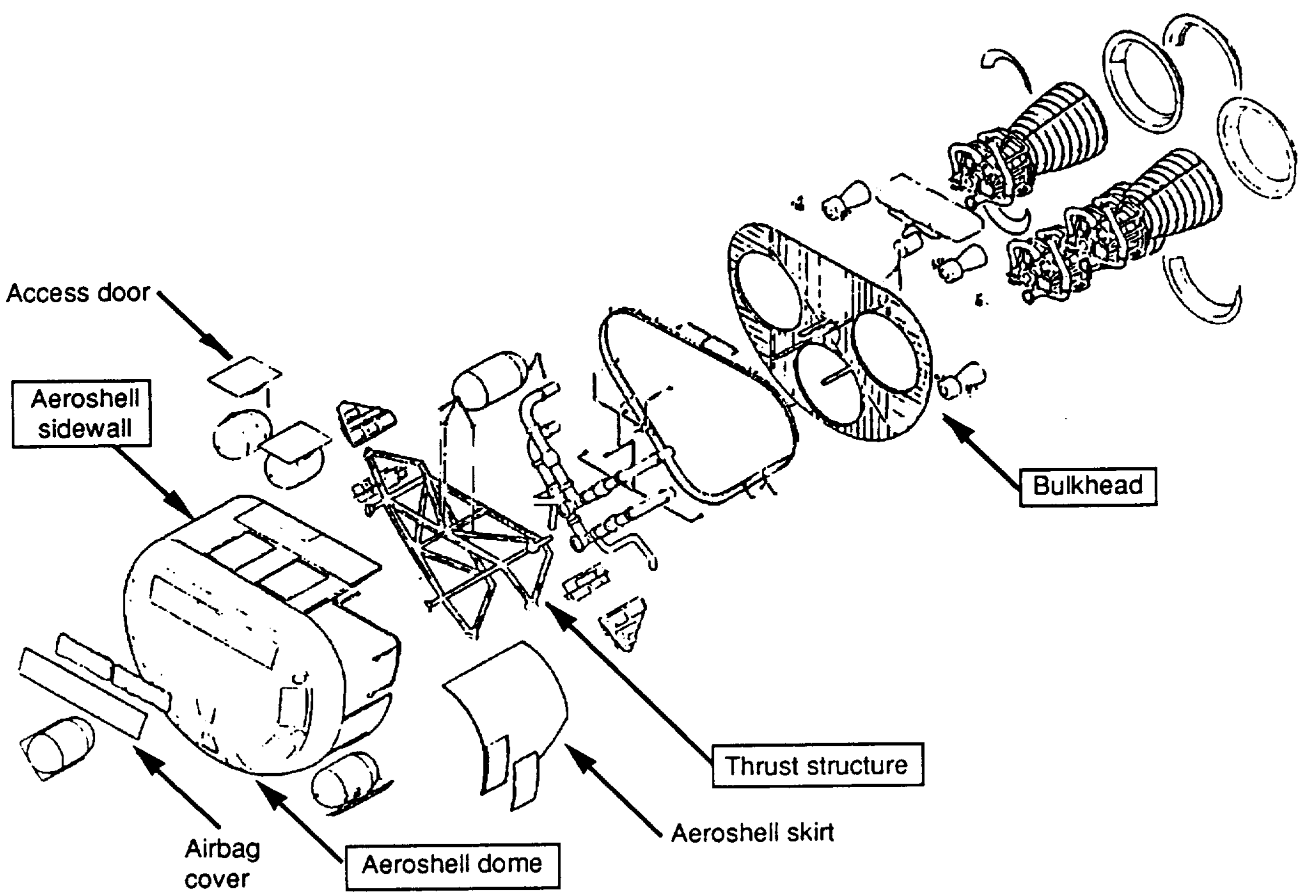

Figure 3.0-1. Propulsion/Avionics Module System Components; Primary Structural Members Are Identified

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Three major tasks were performed in the first phase. These are:

Task 1. Concept Development: (1) defined a candidate structural system; (2) identified system and structural requirements that guide structural concept definition; and (3) identified a policy for ensuring the design concepts are compatible with system recovery.

Task 2. Concept Definition and Evaluation: (1) prepared a variety of design concept options for the key structural components; (2) evaluated those concepts for structural efficiency and manufacturability; (3) conducted LCC analysis of the structural concepts; and (4) identified the most promising structural concepts for planning the technology validation and hardware demonstration tasks in phases II and III.

Task 3. Technology Development Plan: (1) prepared technology development plans leading to technology validation and hardware demonstration during phases II and III, respectively; (2) identified and prioritized materials, processes, and manufacturing for further development that would enhance reusable structural design and provide significant cost benefits; (3) prepared cost estimates and schedules for phase II and III implementation, which include the required structural and material allowable data, manufacturing development tasks, structural element tests, and demonstration tests.

4.0 TECHNICAL DISCUSSION

This section describes the entire phase I effort. Structural concept development and evaluation, including material evaluation, generally followed the flow chart shown in figure 4.0-1. The numbers

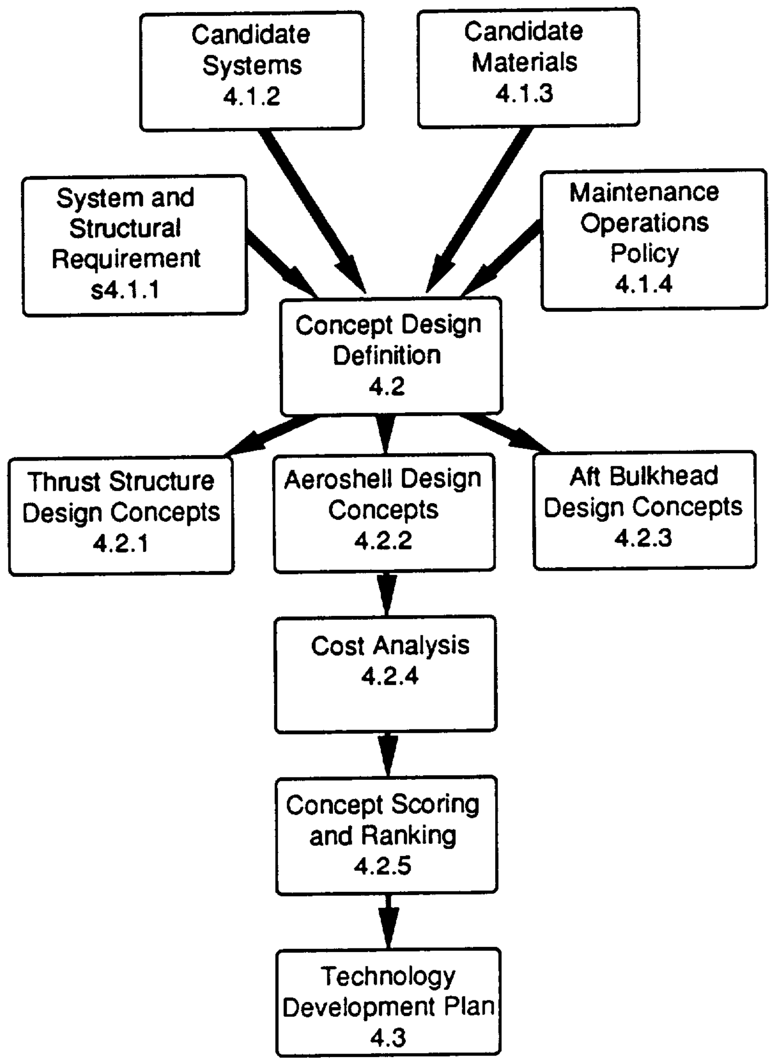


Figure 4.0-1. Concept Development and Evaluation Procedure

included in each box represent the report section describing the box activity. Some reevaluation and iteration through this procedure occurred as we increased our understanding of the structural requirements and material limitations. Design, analysis, manufacturing, quality control, and cost analysis personnel from the Boeing ALS program provided support to maintain consistency with the ALS system model.

4.1 TASK 1 - CONCEPT DEVELOPMENT

ALS cost and operability goals suggest the benefits in using structure common for both the core and the booster P/A module vehicles. Common structure reduces the cost of engineering development, tooling, inventories, and speeds progress down the manufacturing learning curve. Our structural concepts have been developed to accommodate both P/A module vehicles, i.e., a common P/A module.

4.1.1 System and Structural Requirements

ALS system requirements serve as a basis to ensure that structural concept development fully supports ALS goals. Strategies for achieving low cost by reusing main engines and avionics hardware which affect the structure are listed as requirements in figure 4.1-1. These requirements ensure system operability. The P/A module mission defined in figure 1.0-2 implies additional structural requirements; for example, the structure must provide strength for main-engine thrust, Orbital Maneuvering System (OMS) thrust, reentry aerodynamic pressures and accelerations, parachute deployment, and landing impact. Various structural elements must support all the subsystems. The aeroshell dome, sidewall, and bulkhead must maintain acceptable internal temperatures during main-engine burn and reentry heating. External environments include lightning strike during pad operations and flight, thrust plume-induced heating from the main engines, heating on the external structure during reentry, salt water effects from splashdown, and the effects of impact during landing.

Requirement	Approach
Structure must support the P/A module role of returning the high cost components for reuse.	Provide volume and support for main engines and avionics hardware.
Structure must be applicable to a family of launch vehicles of varying payload capacities.	Common interfaces to core and booster expendable elements.
Structure must reliably perform up to 50 flights.	Structurally robust. Corrosion resistant.
Structure must not hinder quick system recycling after each flight to ensure system availability (provide ready access to subsystems during all preparation phases so repairs and checkout can be quickly made).	Doors in aeroshell sidewall permit access during all operations phases.
Maximize commonality between booster and core structure to enhance system cost effectiveness.	Accommodate airbags to permit both splashdown and landing.

Figure 4.1-1. Strategies For Low-Cost Structure On The ALS P/A Module.

The reentry trajectories for the booster and core P/A modules, diagrammed in figure 4.1-2, define the aeroheating environment on the aeroshell. The booster P/A module reentry trajectory begins at booster separation, about 300,000-ft altitude. The booster P/A modules accelerate as they fall toward Earth, but aerodynamic friction begins slowing them below 200,000-ft altitude. The core P/A module trajectory begins as the module passes through 400,000-ft altitude after the deorbit engine burn. A depressed trajectory is illustrated which provides enhanced targeting capability for a possible landing near the launch site, but also increases surface temperatures. Conversely, a lofted trajectory would reduce external temperatures, but decrease targeting accuracy. These trajectories are used directly in calculating structural temperatures as described in following sections.

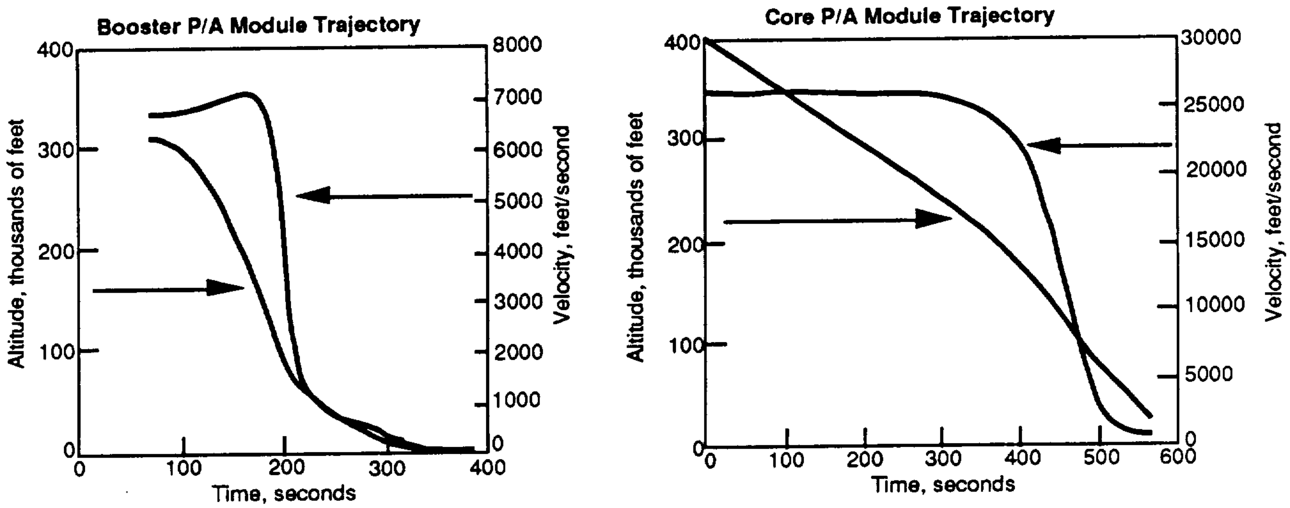


Figure 4.1-2. Trajectories of the ALS P/A Modules During Atmospheric Reentry.

The loads that drive the structural design include main-engine thrust, aerodynamic reentry, parachute deployment, water impact, and landing impact (if this recovery option is used). The magnitudes for these loads are consistent with the P/A Module Definition Study (ref. 1). This external load environment has been used with detailed finite element models (FEM) of major structural components to determine load distribution throughout the P/A module structure.

The primary design requirements for the thrust structure include react main-engine thrust loads, access subsystems during maintenance operations, and provide attachments and access for subsystems (fig. 4.1-3) Parachute loads and water/land impact loads are not critical and are secondary design influences. The interface fittings are considered expendable hardware (they are exposed to the reentry environment); therefore, for these, only attachment provisions were accounted for.

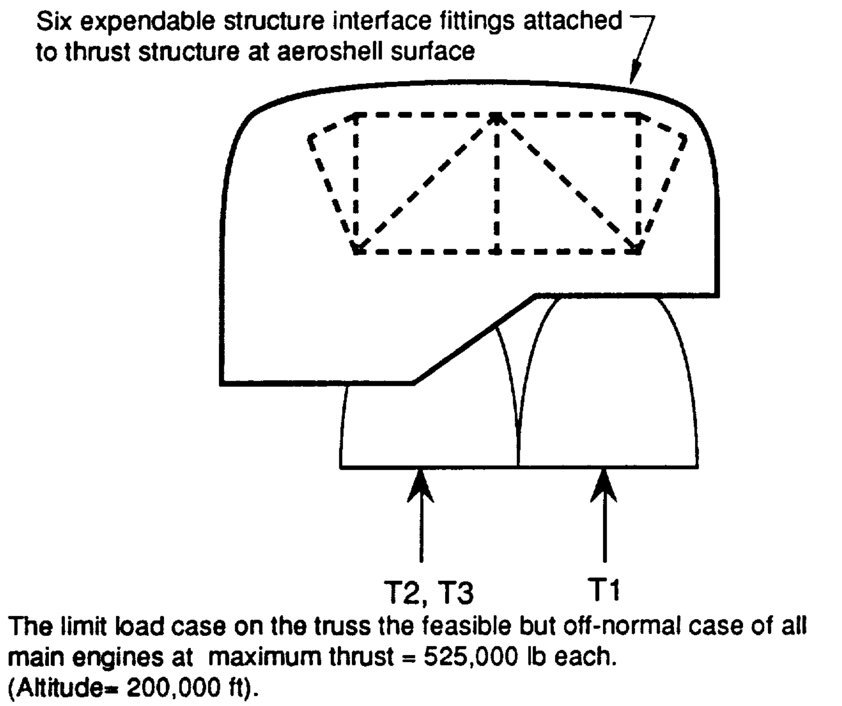


Figure 4.1-3. Thrust Structure Critical Loads –Main Engine Maximum Thrust.

The most severe aeroshell structure loading condition is water impact after one of the three main parachutes fail, and with a drift velocity due to high winds as shown in figure 4.1-4. Pitch angle varies somewhat randomly with wave orientation and parachute swing amplitude. Roll angle can also vary. (Roll is defined by the flight direction axis of the entire launch vehicle.) Nominal values were used to define the aeroshell critical loads.

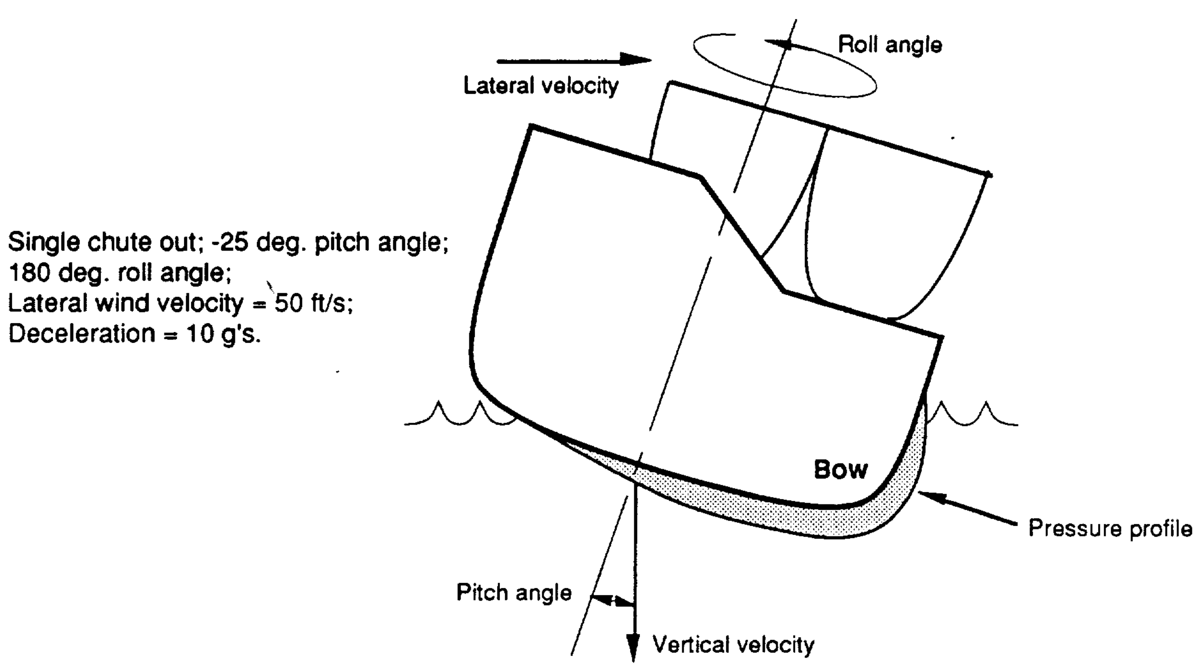
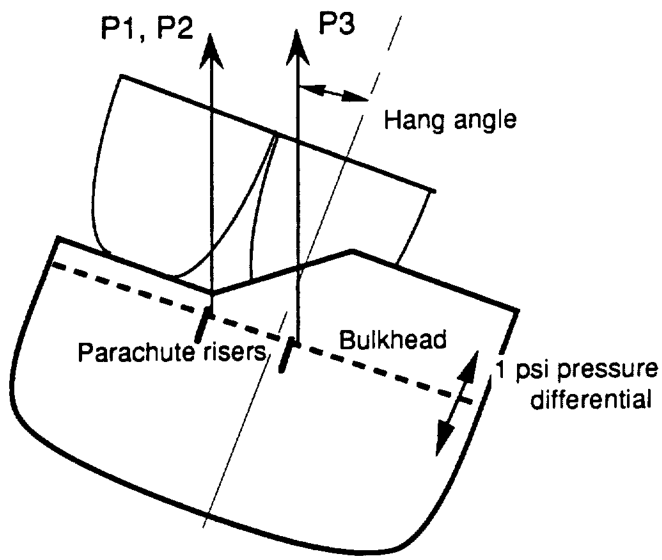


Figure 4.1-4. Aeroshell Critical Load Case—Water Impact.

Nominal parachute deployment (three good chutes) applies a 3g load to the bulkhead beams at three attachment points (fig. 4.1-5). This load is primarily reacted by the parachute risers (attached to the thrust structure), but the bulkhead must resist the resulting shear load. Pressure loads across the bulkhead during altitude change and main engine start are 1 to 3 psi. The bulkhead and support beams must also support the OMS engines, however these loads do not drive the design.



Triple chute, 37 deg. hanging angle, deceleration= 3g's

Figure 4.1-5. Bulkhead Critical Loads Parachute Deployment and Pressure Differential

The above described requirements, loads, and environments are sufficient to proceed with identification of candidate P/A module structural systems and assessments of preliminary concept designs for LCC assessment.

4.1.2 Candidate Systems

The structural elements shown in figure 3.0-1 representing the baseline structural definition are described below. The thrust structure provides the primary load path from the main engines through to the expendable upper stages of the launch vehicle. It also provides for subsystem mounting locations and support to the aeroshell during landing operations. Both truss and shear-panel designs were evaluated. Due to the large thrust structure loads, joints and fittings generally dominate truss weight. Structural concept development addressed joint size and weight to minimize overall thrust structure cost, complexity, and weight.

The aeroshell dome takes the primary reentry heating and the landing loads on both the core and booster P/A modules. The aeroshell dome contains covers for the airbag landing attenuation system. The dome shape accommodates a volume for landing bag stowage, and accommodates access and propellant line doors. The sidewall provides an aerodynamic surface during reentry and protects interior components from heat. Access doors are required in the sidewall for subsystem access during launch preparation. Additional doors may be required for a flotation collar system. A combined dome and sidewall structure has been considered and may be integrated or may be separately joined elements depending on the fabrication approach.

The bulkhead protects internal subsystems from the plume heating environment and supports external subsystems such as orbital maneuvering system engines and parachutes. This structure is initially defined as a stiffened panel with additional beams for the point loads. The structure must be either thermally resistant or insulated from the plume heating environment.

4.1.3 Candidate Materials and Materials Selection

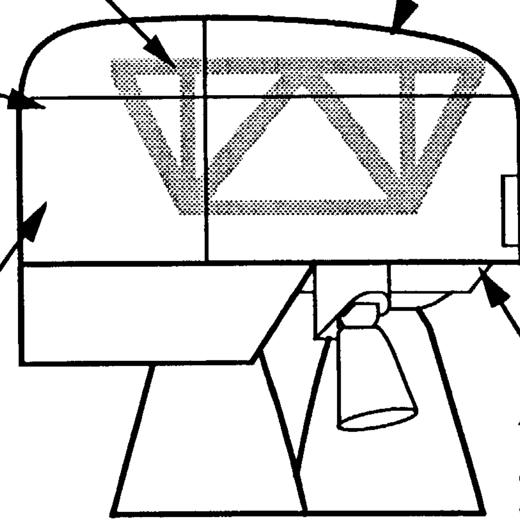
The high performance usually required of launch vehicle structure leads to materials balancing structural efficiency with reasonable fabrication cost. Candidate material types as they apply to the identified structural elements are listed in figure 4.1-6. A detailed mechanical and physical property database across appropriate operating temperatures was compiled and is included in Appendix A. Graphite/epoxy (Gr/Ep) was specified by the ALS reference P/A module configuration (ref. 1). Specific material formulations, alloys, and heat treatments are selected to the level the design detail requires. During full-scale development, material specifications would be selected including strengthening treatments, precise fiber and matrix, and reinforcement fractions.

Because the main engines produce high loads in the thrust structure, candidate materials should have high specific compressive strength and stiffness. Since it is in a moderate thermal environment, high-temperature strength is not a benefit to thrust structure materials. If the access requirements are reduced and shear web structure is feasible, materials with high specific shear stiffness and strength are beneficial to reducing weight.

Thrust Structure
(reacts engine thrust and parachute loads)
- Tubular element truss structure
- Point of departure
  Gr/Ep tubes
- Alternatives
  - Shell type thrust structure
  - Metals: High-temperature aluminum
    Al-Li, Titanium
  - MMC: dSiC/Al, SCS/Al, SCS/Ti

Outer aeroshell dome
(reacts reentry and landing loads)
- Stiffened skin with rings
- Point of departure
  Gr/Ep
- Alternatives
  - Honeycomb sandwich, isogrid, corrugation
  - Metals: High-temperature aluminum
    Al-Li, Titanium
  - MMC: dSiC/Al

Outer aeroshell TPS
(protects against reentry temperatures)
- ablative, nonreusable insulation
- Point of departure
  1.00 in. phenolic cork
- Alternatives
  - Evacuated honeycomb sandwich, foam, multiwall
  - Metals: High-temperature aluminum
    Al-Li, Titanium
  - MMC: dSiC/Al
  - C-C



Aeroshell sidewall
(reacts reentry and landing loads)
- Stiffened skin with rings
- Point of departure
  Gr/Ep
- Alternatives
  - Honeycomb sandwich, isogrid, corrugation
  - Metals: High-temperature aluminum
    Al-Li, Titanium
  - MMC: dSiC/Al

Aft Bulkhead
(reacts reentry and parachute loads)
- Skin stringer construction
- Point of departure
  Gr/Ep
- Alternatives
  - Honeycomb sandwich, isogrid
  - Metals: High-temperature aluminum,
    Al-Li, Titanium
  - MMC: dSiC/Al

Figure 4.1-6. Candidate P/A Module Materials And Structures For Evaluation And Trade Study.

The aeroshell dome is subject to high bending and compression loads from splashdown, therefore a highly stiffened shell structure is beneficial. Materials should have high specific stiffness and moderate temperature capability. The aeroshell sidewall experiences less severe loading and temperatures, therefore lower cost materials and structures may be viable there.

A qualitative assessment of candidate materials for application on the aeroshell and bulkhead structure is displayed in figure 4.1-7. Typical aerospace fabrication methods are listed for 2024, 7075, and 2219 aluminums to cover the low-cost and low-risk spectrum of concepts. In this context, risk is proportional to the cost of fully developing a concept for flight hardware. Aluminum-lithium (Al-Li) is included as a less developed but potentially higher performance material. A common drawback of these materials is the requirement of applying a thermal protection system (TPS) to the external surface to survive the reentry environment for the aeroshell and the main engine plume heating environment for the bulkhead. A list of candidate TPS materials with quantitative and qualitative attributes is included in Appendix A.

Titanium can potentially perform under the heating environment indicated by preliminary thermal analysis, and is considered a robust material, which is an important attribute for reusable structure with a mission profile that includes launch and recovery. Graphite/polyimide (Gr/PI) composite materials are resistant to the temperatures indicated by the preliminary thermal analyses for the booster P/A module, and can be laid up and cured in the desired aeroshell dome compound curvature. Potentially, large structural members are feasible, thereby requiring few structural splices, although process and structural development would be needed. Graphite/epoxy was specified by the Boeing ALS program as the baseline material for the aeroshell and bulkhead, and can also be laid up in the required complex contours. The Inconel alloys are robust, have greater high-temperature resistance than Ti, and can be fabricated in similar ways to Ti, but have comparatively low specific properties. The high-temperature aluminum (HTA) alloys have potential in hot area applications, but are relatively undeveloped, as are the discontinuous silicon carbide-reinforced aluminum (dSiC/Al) MMCs. Silicon carbide-fiber-reinforced metals (titanium or aluminum) were considered only for the thrust structure tubes due to their high compressive strength and stiffness and limited level of development for large sheets.

Material	Fabrication Candidates	Potential Payoff	Risks/Disadvantages	Winning Strategy
Aluminum 2024 7075	• Sandwich - bonded • Stringer stiffened - fastened	• Low cost • Mature materials	• TPS required on booster at additional cost & weight	• Inexpensive materials • Known fab techniques
Aluminum 2219	• Machined and welded built-up structure	• Temp. stability (50% of RT Fty @ 500°F) • Weldability	• TPS required on booster at additional cost & weight	• Inexpensive materials • Known fab techniques
AL-Li 2090	• Laser VPPA welding • Super plastic forming (SPF)	• Higher specific strength stiffness than conventional aluminum alloys	• TPS required on booster • Less mature aluminum alloy	• High specific strength and stiffness
Weldalite	• Laser VPPA welding • Super plastic forming (SPF)	• Higher specific strength than 2090	• TPS required on booster • Less mature aluminum alloy	• High specific strength and stiffness
Titanium	• Welding, LID bonding, brazing, DB, SPF	• Short exposure temp capability up to 1000°F • Mature materials & fab • Corrosion performance	• High fabrication costs for large structure	• Low risk design & fab • Fab options
Gr/PI	• Sandwich - large structure co-cured • Skin stringer	• Short exposure temp capability up to 900°F • Conform to complex contour	• Fabrication scaleup • Damage/defect potential • Processing sensitivity • Incorporating fasteners • Material cost	• Low LCC potential for aero-shell • Low weight potential
Gr/Ep	• Filament winding • Sandwich co-cured • Skin-stringer	• Lower risk than Gr/PI • High specific properties	• TPS required on booster at additional cost & weight • Material cost	• Baseline ALS material
Super-Alloy Inconel 625	• Brazing • Welded built-up structure • Explosive bonding (with Ti)	• High temperature capability and stability	• Low specific properties (relative to other materials) at aeroshell temperatures	• Robust structure for aero-shell
High Temp Al Allied 8-12 Allied 12-12 Alcoa CU78 Alcoa CZ42	• High temp bond • Fastening • Machining • Forging	• Higher stiffness than Al • Short exposure temp capability up to 800 °F and possibly higher[1] • Corrosion performance	• No aerospace service experience • Few low-cost fabrication approaches • Material availability, cost	• Potential to combine low cost features of Ti and Gr/PI concepts
dSiCp/Al	• Fastening, bonding	• High specific stiffness and strength	• Material cost and availability	

Reference:
(1) Rapidity Solidified Aluminum Transition Metal Alloys for Aerospace Applications, P.S. Gilman, et.al. AIAA 88-4444

Figure 4.1-7 SIDARS Structural Materials Screening

Preliminary thermal analyses of the reentry profiles, summarized in figure 4.1-8, indicate that aeroshell surface temperatures for the core P/A module reach temperatures too high for the candidate materials, even for carbon-carbon. An expanded egg crate structural concept using Incoloy MA 956 high-temperature steel on the outer surface (ref. 2) was inadequate without active cooling. Therefore, reasonable aeroshell structural materials must be protected (with a TPS) from the temperatures experienced during atmospheric reentry upon return from orbit.

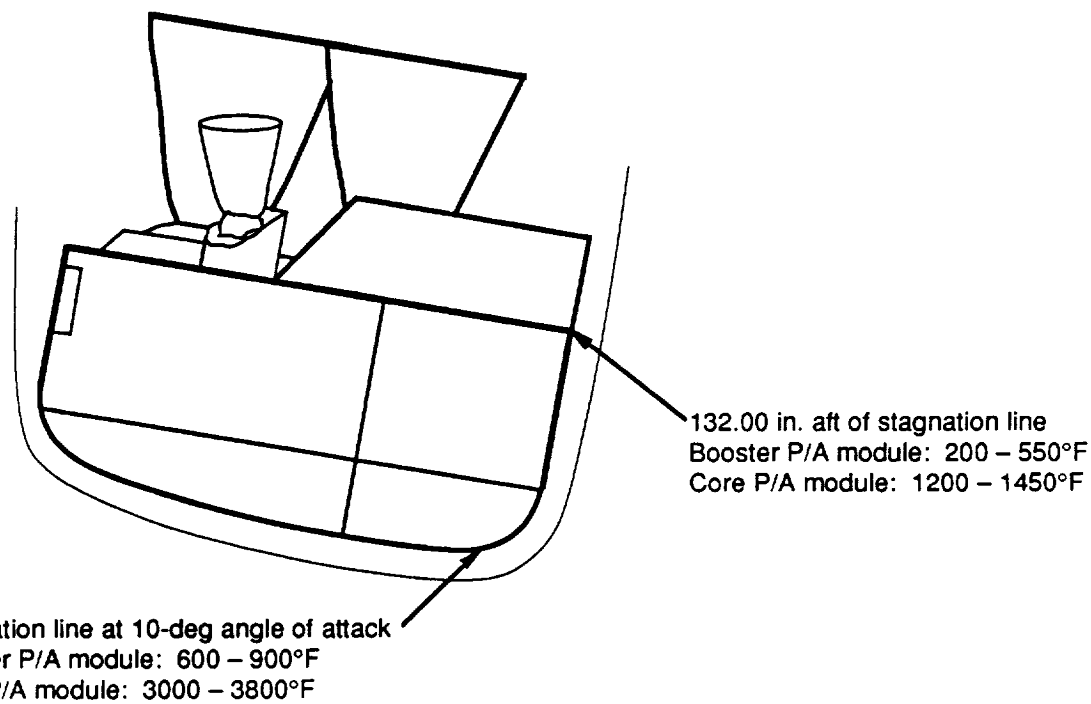


Figure 4.1-8. Maximum Surface Temperatures During P/A Module Reentry at Two Aeroshell Locations.

Temperature performance of materials influenced material selection. Specific strength properties of selected materials are plotted against temperature in figure 4.1-9. These properties were drawn from the materials database in Appendix A. On this basis the most attractive aeroshell materials were Gr/PI (Celion 6000/PMR-15) and Ti (Ti-6-4). The HTA alloy 8009 is also attractive based on its specific compression yield strength. The Gr/PI and HTAs have sparse data in the maximum temperature range, however these maximum temperatures are experienced for under 2 min each flight and do not occur during maximum loads which occur at splashdown.

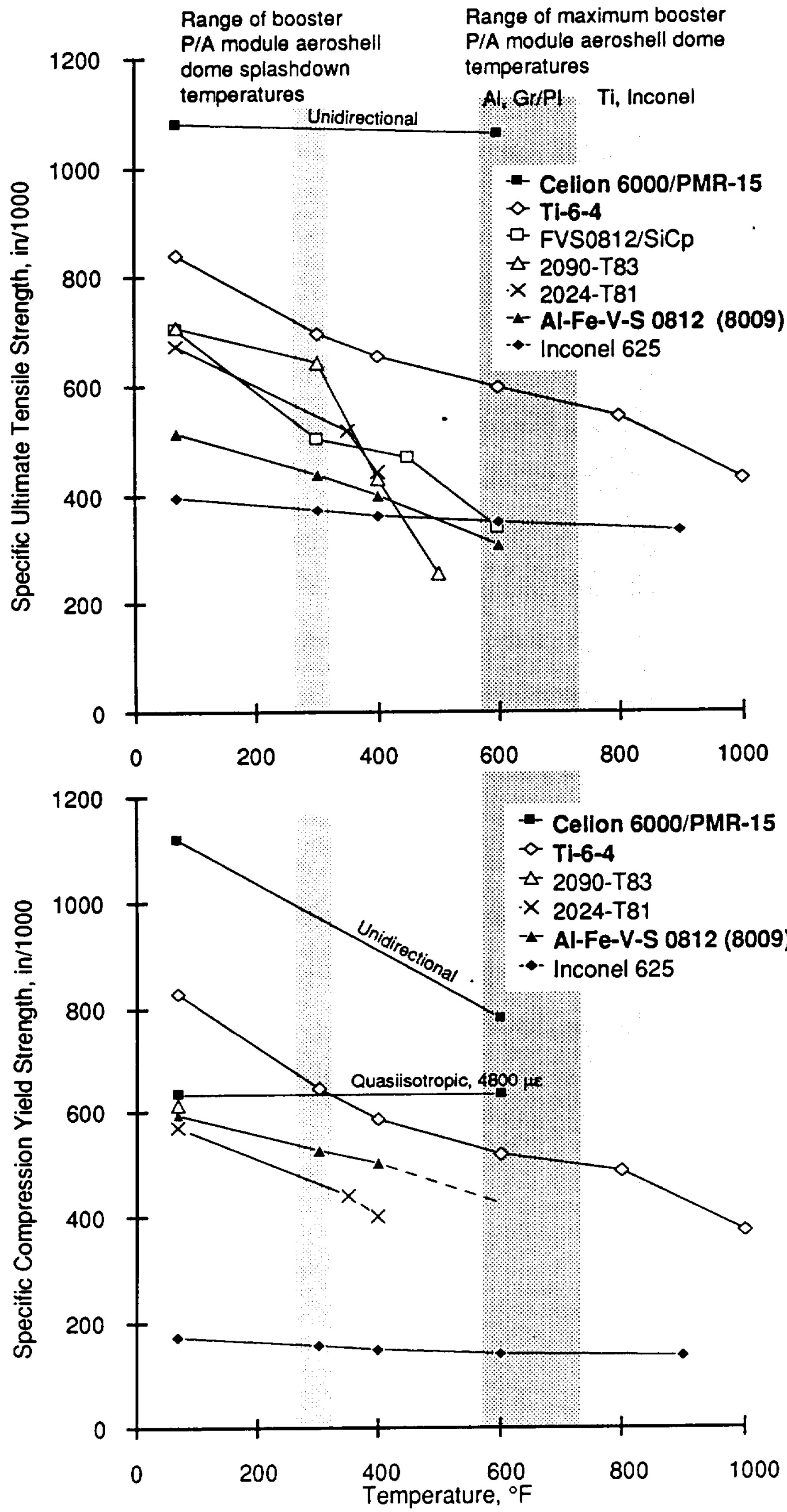


Figure 4.1-9. Specific Properties Comparison For Candidate Aeroshell Materials.

The above review demonstrates that a good range of candidate materials applicable to the P/A module environment are available for structural concept development. Precise specification of alloy heat treatments and reinforcement material identification await full-scale development when all system issues can be thoroughly considered.

4.1.4 Maintenance Operations Policy

A low-cost, routine launch system requires structure that is maintainable, reliable, and operable as described in figure 4.1-1. Our designs reflect this policy. For instance, the aeroshell contains three large doors for launch pad access to the internal subsystems, such as avionics computers. In other cases direct adherence to these requirements is difficult because design concepts and procedures are not well enough developed. Other system details and procedures enhancing operability may not be well defined and therefore cannot be incorporated into structural concept definition.

Because the thrust structure is completely encapsulated within the P/A module, inspection between flights is difficult at best without disassembly. Consequently, our design approach emphasizes a robust structure.

The most extensive of maintenance operations involves the TPS. Upon reentry from orbit, the core P/A module flight profile is depressed for targeting accuracy increasing temperatures on the aeroshell surface. The extremely high temperatures near the stagnation point (fig. 4.1-8) drives the configuration toward an ablative layer in that region. This ablator must be replaced often and perhaps for each mission. Conversely, for the booster P/A module, system operability is enhanced by eliminating the TPS because temperatures are less and can be resisted by high-temperature materials.

4.2 TASK 2: CONCEPT DEFINITION AND EVALUATION

A multidiscipline product development team (PDT) approach was used so that involved personnel would be cooperatively familiar with details of the design prior to conducting analyses (e.g., structural, manufacturing, QA, cost). Concepts were then effectively defined to the extent required for equivalent structural, manufacturing, and cost analysis. Appendix B contains summaries of all structural concepts defined and discussed in the PDT. The leading concepts, based on qualitative assessment by the PDT, were provided with additional design and analysis definition.

All flight trajectories, loads, and design criteria were obtained from the Boeing ALS program. After evaluating the overall P/A module load and thermal environment, critical design conditions were selected for each major structural component as summarized in figure 4.2-1. Only the bulkhead endures maximum loading (main engine acoustic environment) at maximum temperatures (plume heating), requiring the use of a TPS for all concepts—on the booster as well as the core P/A modules.

Structural Component	Thermal ① Environment	Structural Loads ①
Aeroshell	Reentry	Water impact upon splashdown
Thrust structure	Reentry	Launch loads (main engine start)
Bulkheads	Plume heating	Parachute deployment
		Pressure (altitude and main engine start)

① Do not occur simultaneously

Figure 4.2-1. Critical Design Conditions

For the structural materials considered, a set of design criteria consistent with ALS program philosophy and common aerospace practice was used, as shown in figure 4.2-2.

	Metals	Composites
Factor of safety	1.25	1.40
Failure criteria, tension	ultimate	ultimate
Failure criteria, compression	yield	4800$\mu\varepsilon$

Figure 4.2-2. Structural Materials Design Criteria

4.2.1 Thrust Structure Design Concepts

Primary emphasis was given to a truss design approach that would (1) spread the high main engine loads relatively far apart (to the expendable structure interface points) and (2) maintain good access (for operations and maintenance) to subsystems. Bolted joints provided capability of disassembly and individual strut replacement, as required. The thrust structure truss configuration is shown in figure 4.2-3. The outboard thrust wing members are most highly loaded. The geometry is defined by the aeroshell shape and the interface point locations.

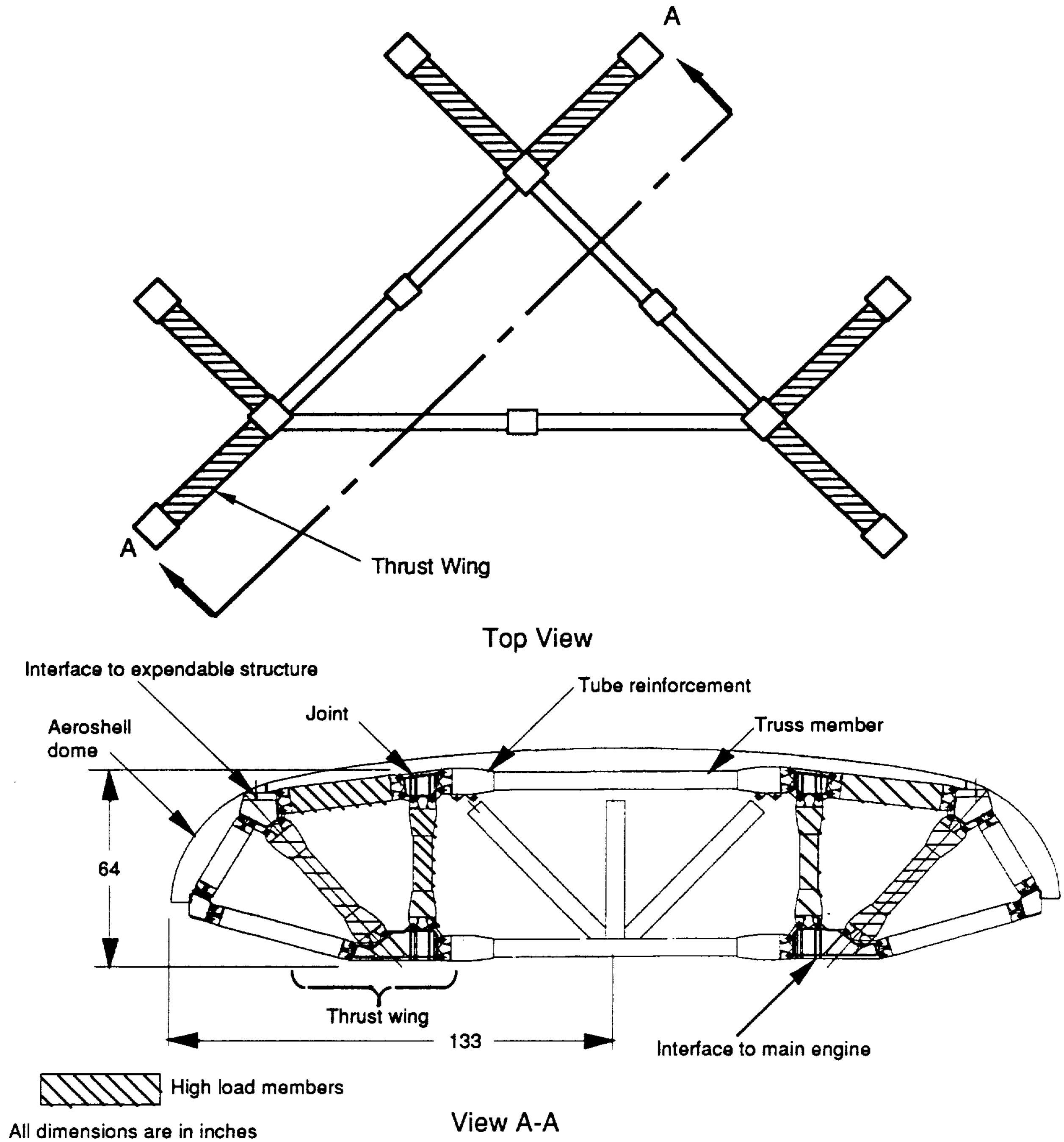


Figure 4.2-3. Thrust Structure Truss Configuration

Initial truss concept definitions using various materials are qualitatively evaluated in figure 4.2-4. Filament-wound Gr/Ep tubes with titanium end fittings are lightweight but may be sensitive to impact damage. An all-welded titanium truss is low risk, but would weigh more than the Gr/Ep concept. An all-aluminum truss is also low risk, but is sensitive to corrosion in salt water. Metal-matrix composite (MMC) tube concepts are quite structurally efficient, but are higher risk and also are corrosion sensitive.

Strut Material	Joint Material	Relative Cost	Relative Weight	Relative Risk
Gr/Ep	Ti	med	low	med
Ti	Ti	low	med	low
7075-T6	7075-T6	low	high	low
dSiC/Al	dSiC/Al	med	med	high
SCS/Al	Ti	high	low	high
Al-Li	7075-T6	med	med	med

Figure 4.2-4. Thrust Structure Truss Concepts Qualitative Analysis

Shear web thrust structure concepts were later added to the trade study for completeness including integrally stiffened (shear resistant and diagonal tension) and sandwich structure. Shear web concepts were not originally included because the point-to-point load paths seemed to favor truss concepts, and a P/A module systems analysis report (ref 1) indicated a preference for truss thrust structure for subsystem accessibility. For initial screening structural weights were estimated and compared for a single thrust wing as shown in figure 4.2-5. The only concept competitive with the truss concepts was a sandwich with high-shear-strength Ti facesheets and low-density Al honeycomb core (H/C).

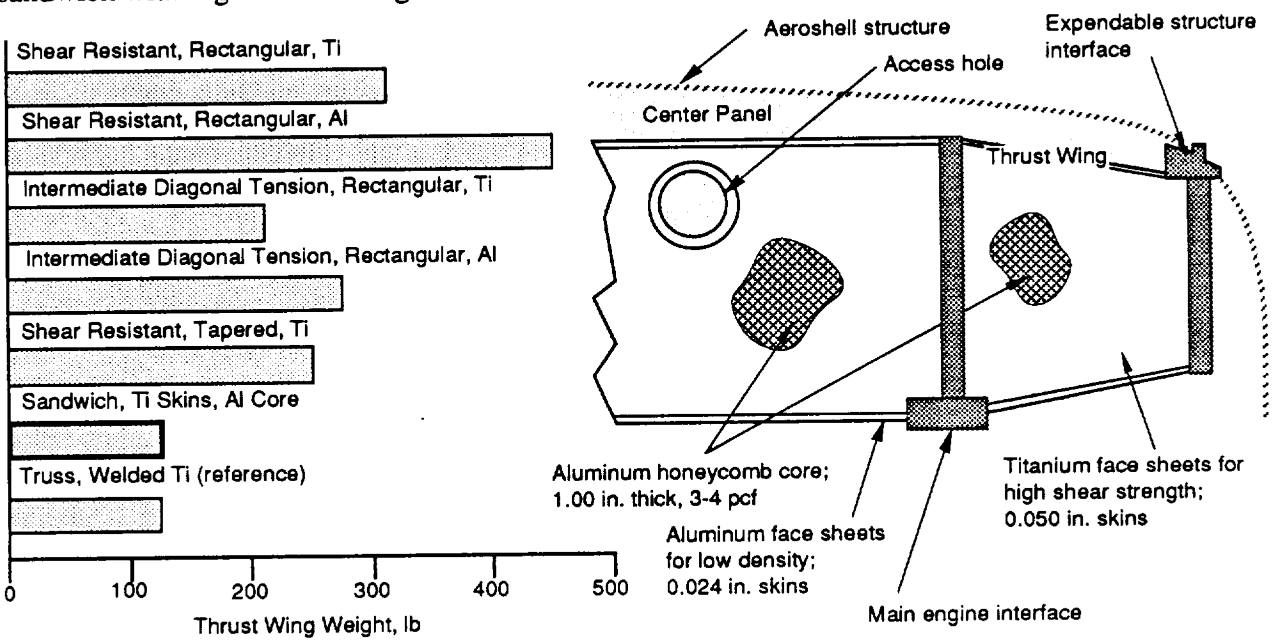


Figure 4.2-5. Relative Weight Comparison for Shear-Panel Thrust Structure Concepts

The key detail of our Gr/Ep tube concept is the tube end fitting attachment concept shown in figure 4.2-6. The tube end attachment uses two-piece titanium fittings integrally wound onto the Gr/Ep tube for low cost and structural efficiency. The tube ends consist of two identical Ti investment castings terminating in a bolted interface. The two-piece construction was chosen to allow the halves to conform with the Gr/Ep. The spacing of the lugs and bolt holes would be controlled during winding or machined after curing.

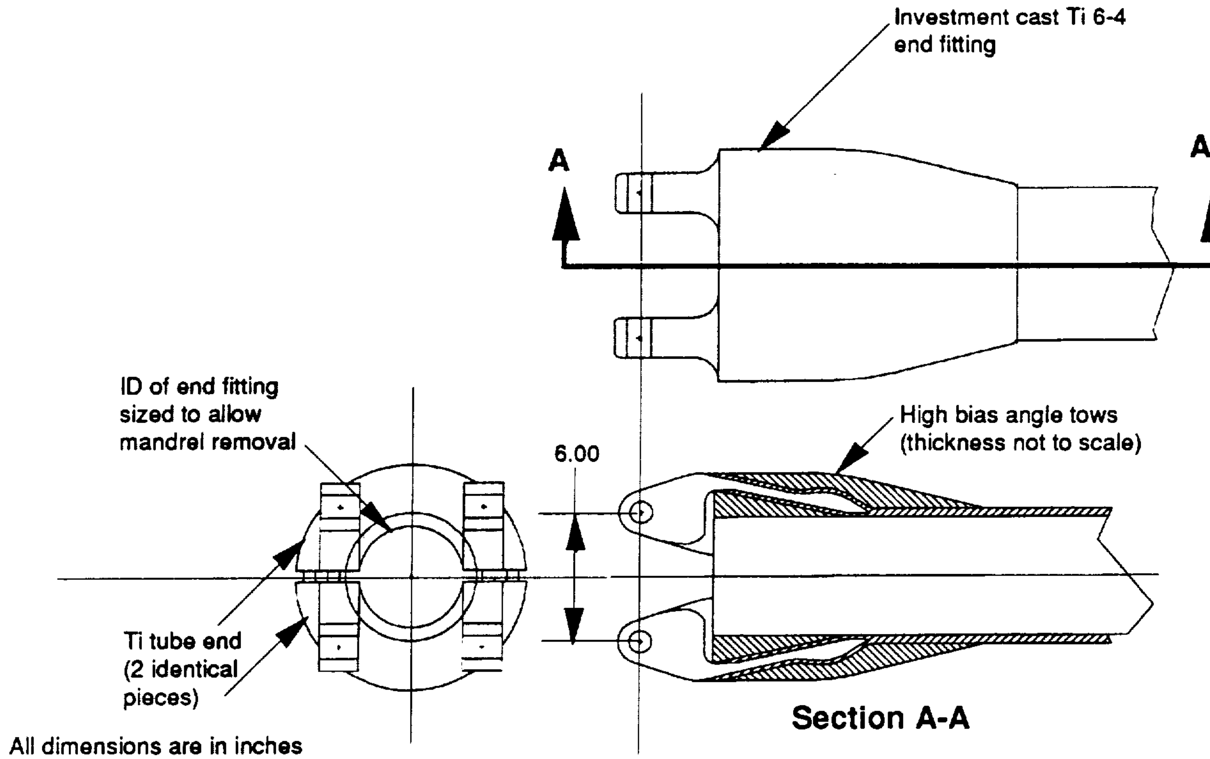


Figure 4.2-6. Tube End Attachment (2-piece Ti ends integrally wound onto Gr/Ep tube)

A potentially low-risk option is an all-welded Ti truss. Conventional Ti tubing is used for struts or tapered struts superplasticity formed (SPF) from a smaller-diameter, thick-walled tube. SPF tubes provide the option of integral longitudinal stiffening. All struts are assembled to high-strength Ti 15-3-3-3 cast nodal fittings with matching circular flanges. Center line congruence is maintained at the nodal points to minimize local moments. Strut-to-fitting joints are automatically welded with tube welders that reduce stress and distortion. Stress relief is accomplished locally at the nodal points in ceramic holders with embedded nichrome heating elements. Positive pressure argon gas is pumped through the holder and down the length of the strut. An internal passage in the cast fittings supplies argon to the entire inside diameter of the assembly. Excess material is left on the surfaces at the interfaces. Light machining, using a laser reference system for location, completes the assembly.

A stress analysis was performed to size the truss tube members. The thrust structure was modeled as a space frame to determine load distribution in truss tube members. Detailed joint FEMs were not constructed and must be considered in any future truss definition. An optimization routine was coupled with ANSYS to reduce member weight where practical. Calculated weights for the thrust structure concepts are listed in section 4.2.4, because they are incorporated into the trade study through LCC analysis.

Using Gr/Ep, Ti, or SCS/Al tube members in the baseline truss structure configuration is a feasible approach to thrust structure design. Time limitations prevented full consideration of shear web thrust structure, which, in the highly loaded areas, may have cost benefits due to simpler construction.

4.2.2 Aeroshell Design Concepts

A potential LCC reduction stems from using common dome structure for both the core and booster P/A modules. For a common aeroshell scheme, the core module requires an ablative TPS to resist the high temperatures encountered during reentry from orbit, while passive approaches are feasible on the booster P/A module since the temperatures are lower. An aeroshell concept was defined to withstand the booster trajectory temperatures, but incorporate structural features permitting attachment of an ablative TPS for flight as a core P/A module aeroshell. This provides a common aeroshell structure between core and booster modules leading to lower fabrication and maintenance costs.

The aeroshell primary structural elements are shown in figure 4.2-7. Sandwich structure is an attractive approach due to the pressure loads encountered during reentry and especially splashdown. As a point of reference, sandwich structure was used to support the heat shield of the Apollo capsule (ref 3). Outer surface elements, the dome, and the sidewall have somewhat different environments. The dome is exposed to the highest temperatures during reentry and to the highest loads during landing or splashdown. Three access doors in the sidewall permit efficient servicing of the internal systems. The propellant line doors are required to permit routing the fuel lines efficiently from the tanks to the main engines. Attachments to

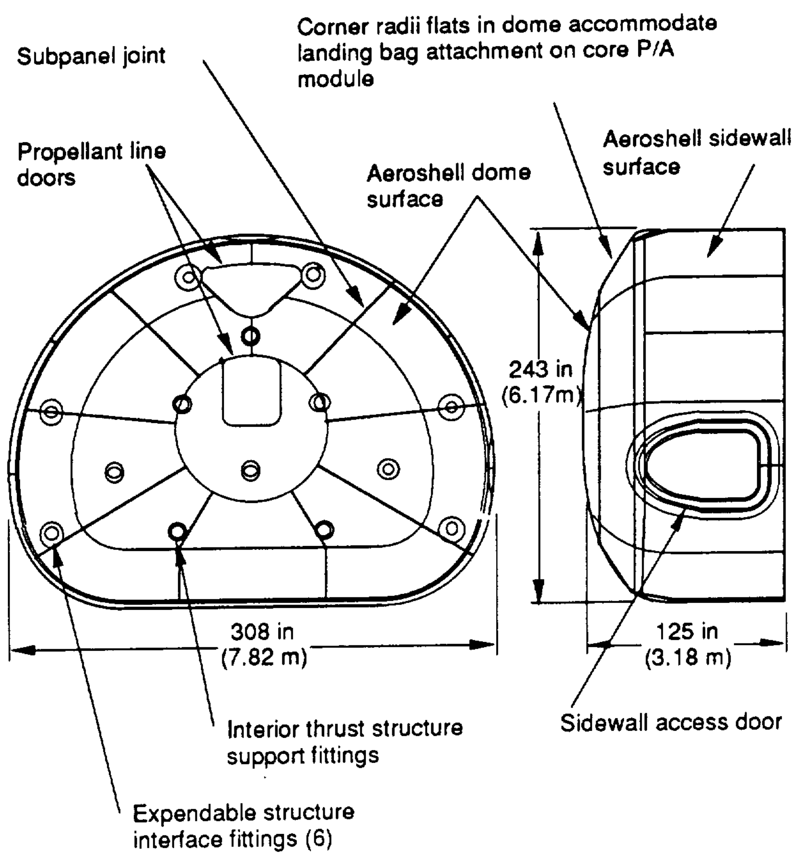


Figure 4.2-7. Overall Aeroshell Configuration, Elements, and Features

the aeroshell dome are designed to prevent water ingress. The interface between the expendable tank module structure and reusable P/A module occurs at six expendable fittings integral with the P/A module thrust structure and attach to hard points in the aeroshell. These exposed fittings are degraded during reentry and are replaced between flights. The thrust structure also is fastened to the aeroshell at eight interior fittings. There is no penetration of the sandwich in these locations. For non-water landings, airbags are incorporated between the structural shell and the TPS, which separates after reentry, eliminating the need for airbag doors in both the shell and TPS. Corner radii flats in the dome provide the volume required.

Graphite/Epoxy Aeroshell. The baseline aeroshell concept selected by the ALS project used Gr/Ep sandwich construction. Fabricating with Gr/Ep is well suited to conforming to the complex shape of the dome structure, and an experience base exists for building large structural components. Nevertheless, Gr/Ep cannot endure even the booster module reentry profile, and therefore requires a TPS on both booster and core modules. A preliminary assumption is that fabricating and replacing TPS shields contributes significantly to life cycle cost as well as increases system weight.

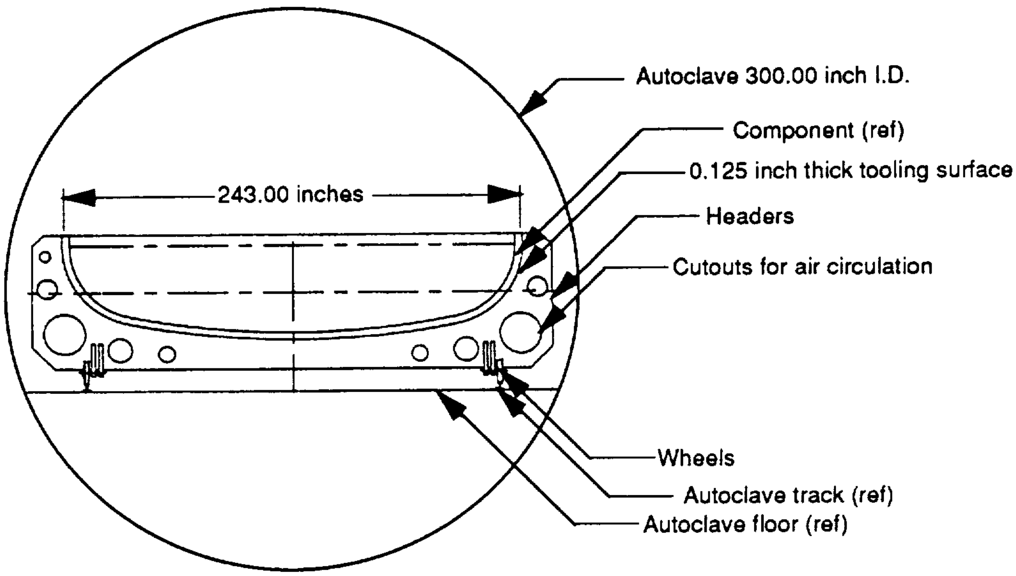
Graphite/Polyimide Aeroshell. The Gr/PI H/C sandwich concept is similar to the Gr/Ep approach, but requires no TPS to endure the booster reentry trajectory environment due to the high temperature capability of polyimide. This feature potentially lowers the operations cost because removal of the used TPS shell and replacement with a new one would not be required. The Gr/PI concept is illustrated in figure 4.2-8. The moderate heat conduction rate of the composite sandwich means that only the outer surface must have high temperature capability. Therefore, the inner surface is Gr/Ep for reduced fabrication cost and risk. It is bonded in place after the Gr/PI has been cured. Titanium honeycomb core is employed for durability over composite core material and to avoid corrosion between aluminum core and the graphite fibers. Blind inserts installed in a closed-cell foam-filled box stiffener provide triple-redundant protection against water ingestion into or through the sandwich.

Titanium Aeroshell. The titanium sandwich concept (fig. 4.2-12) features welded frame inserts with tapped holes at attachment locations for the external airbags. Circular inserts are embedded at the truss interface attachment locations. The access doors have the same stiffness as the shell and transfer pressure loads through structural panel fasteners on the outer face sheet. These fasteners are locked through small Allen-wrench holes in the TPS (see the section on Thermal Protection System below). The door is sealed with redundant pressurized bulb seals. A door frame limits deflections from splashdown around the door periphery. Similar seals can be applied to the doors in other aeroshell concepts.

The Gr/PI fabrication sequence is listed in figure 4.2-9 steps for inspection and panel joining have been included. Figure 4.2-10 shows a concept of the aeroshell dome tool and part in a 25-ft diameter autoclave demonstrating the feasibility of curing the dome in one piece if desired. Such facilities are available at Boeing. Candidate materials are listed in figure 4.2-11. New formulations of high temperature resin matrix composites continue being developed and evaluated such as PMR-II (ref. 7), and may provide better performance.

1. Layup exterior face sheet in female mold — dome, sidewall panels.
2. Bag and cure in autoclave: 200 psi max, 550–600°F max.
3. Post cure in oven to 650–700°F.
4. Inspect face sheet for delaminations, porosity.
5. Apply high-temperature film adhesive to face sheet.
6. Lay in honeycomb core segments; apply foaming adhesive at splices.
7. Apply upper caul plate, bag, and cure at 600°F.
8. Layup interior Gr/Ep face sheets over core.
9. Bag and cure in autoclave at 50 psi, 350°F.
10. Inspect bond lines.
11. Join panels together mechanically and join to thrust structure.

Figure 4.2-9. Fabrication Scenerio for Gr/PI Honeycomb Sandwich P/A Module Aeroshell Structure.



SECTION VIEW AUTOCLAVE

Figure 4.2-10. Aeroshell Dome Bond Tool

Structural Component	Material	Supplier
Exterior face sheet	Celion 6000/PMR 15	BASF American Cyanamid Ferro
Honeycomb core	Ti, 0.003 foil, 0.375 cell, 4 pcf Glass/PI, 4 pcf	Hexcel, Rohr Hexcel
Bonding adhesive	FM 35 FM 680 PT Resin	American Cyanamid American Cyanamid Allied-Signal / YLA
Interior face sheet	IM6/3501-6	
PI structural foam	Under development Fluorocore 3A3	Imi-Tech/ Ethyl Corp. Furon – Aerospace Comp. Div.
PI foaming adhesive	HT 424 Type II Phenolic Epoxy FM 30 Modified Polyimide	American Cyanamid American Cyanamid

Figure 4.2-11. Materials Available for Gr/PI Aeroshell.

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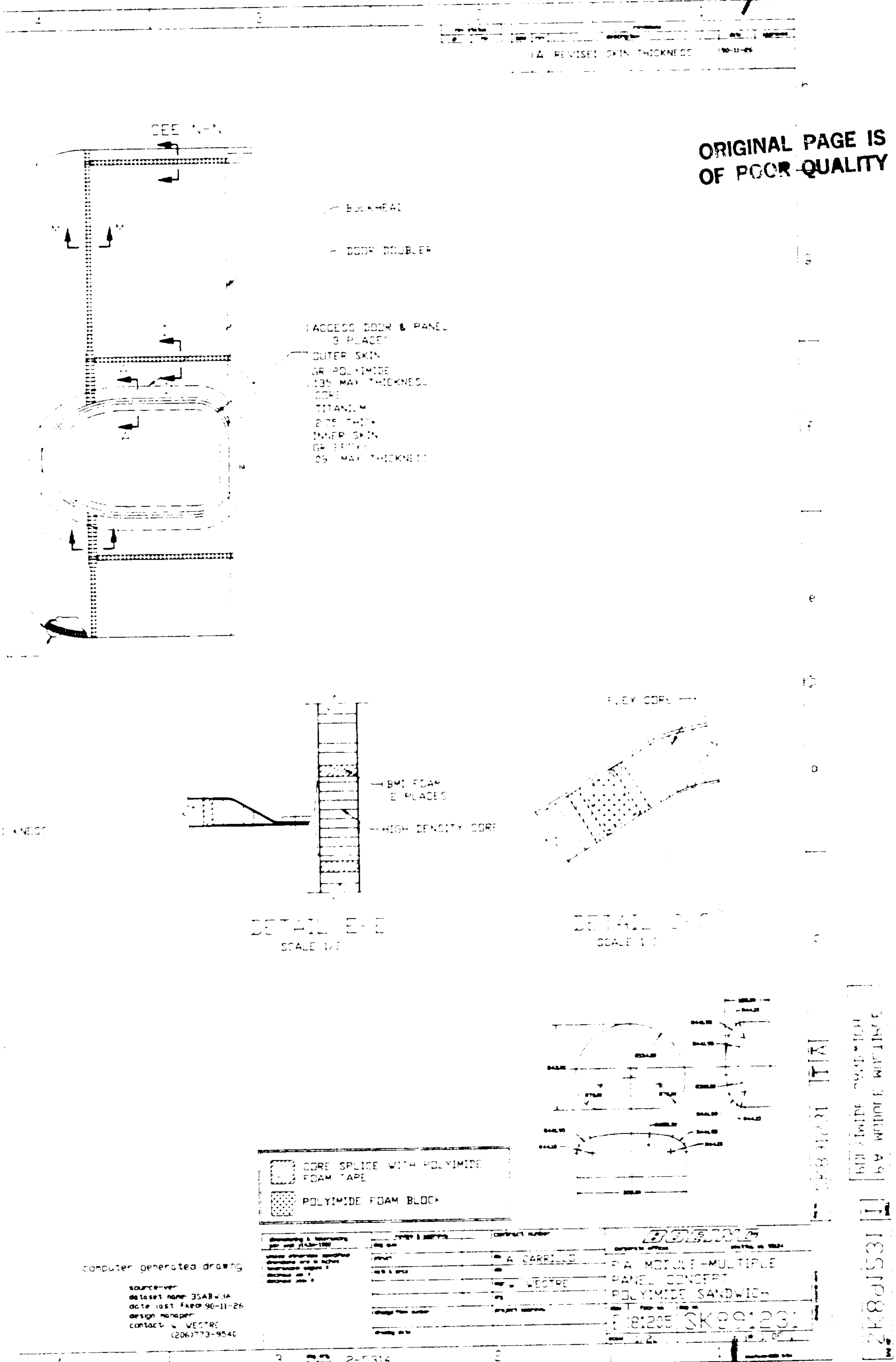
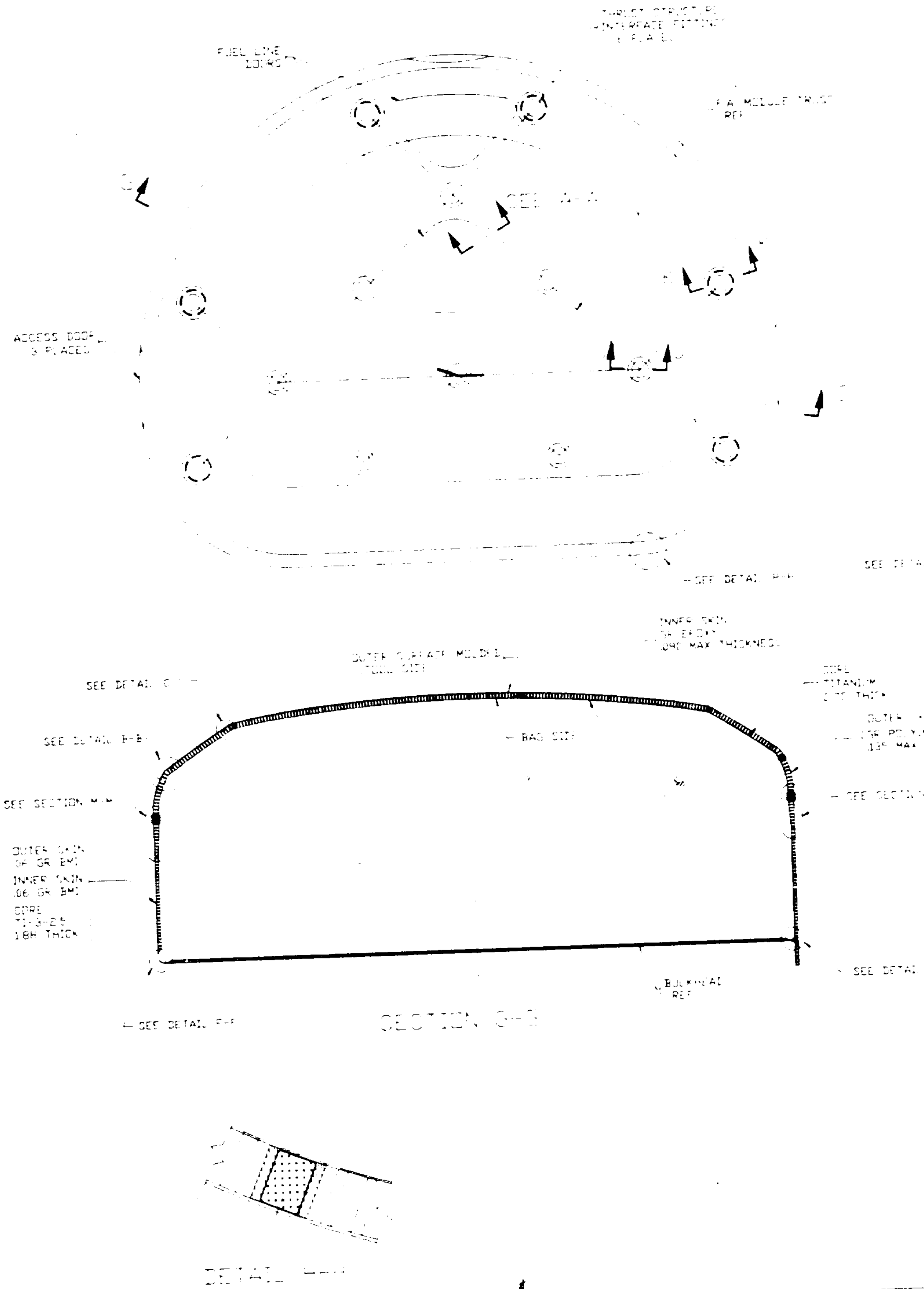


Figure 4.2-8. Graphite/Polyimide Aeroshell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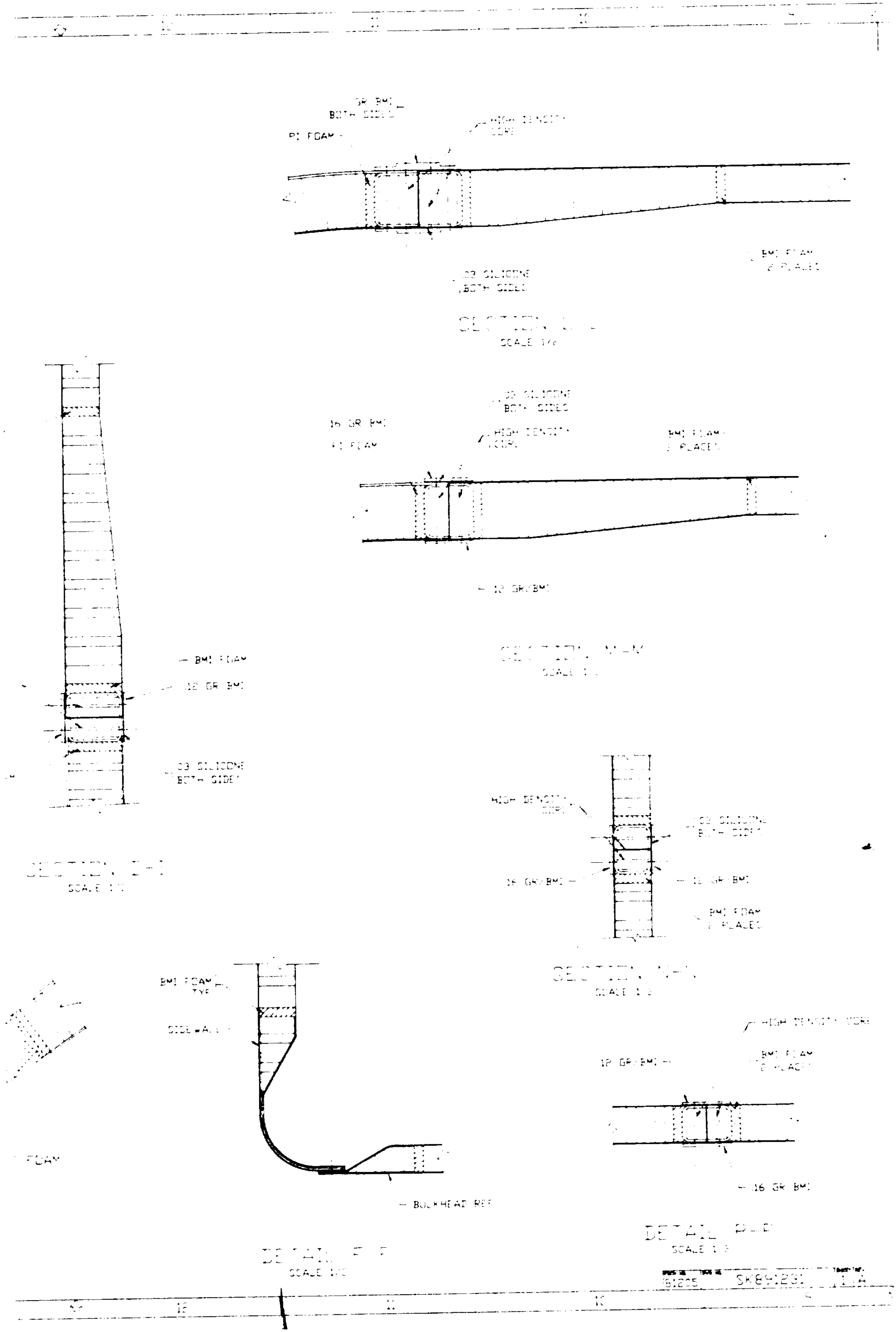

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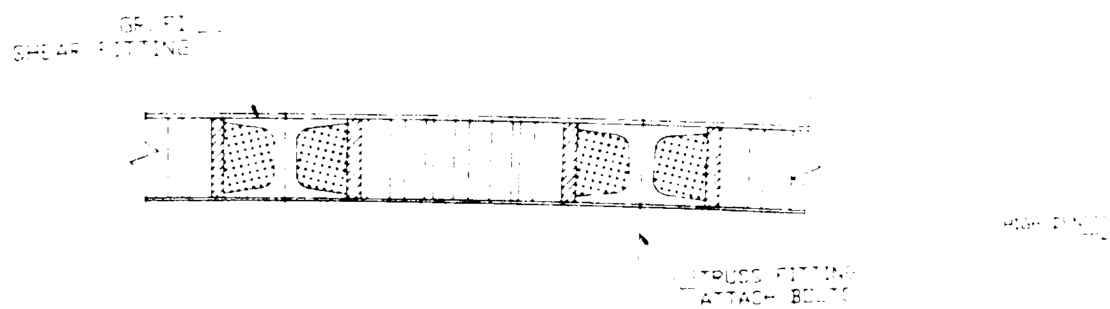

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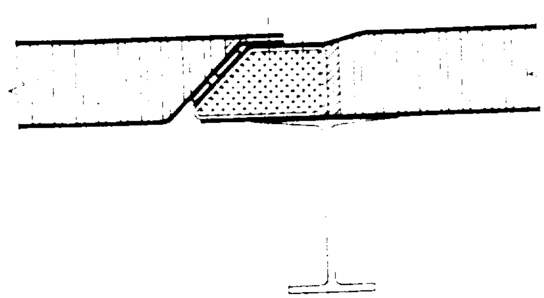

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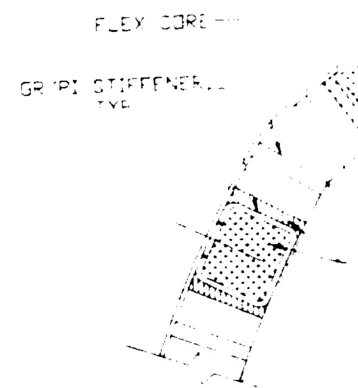

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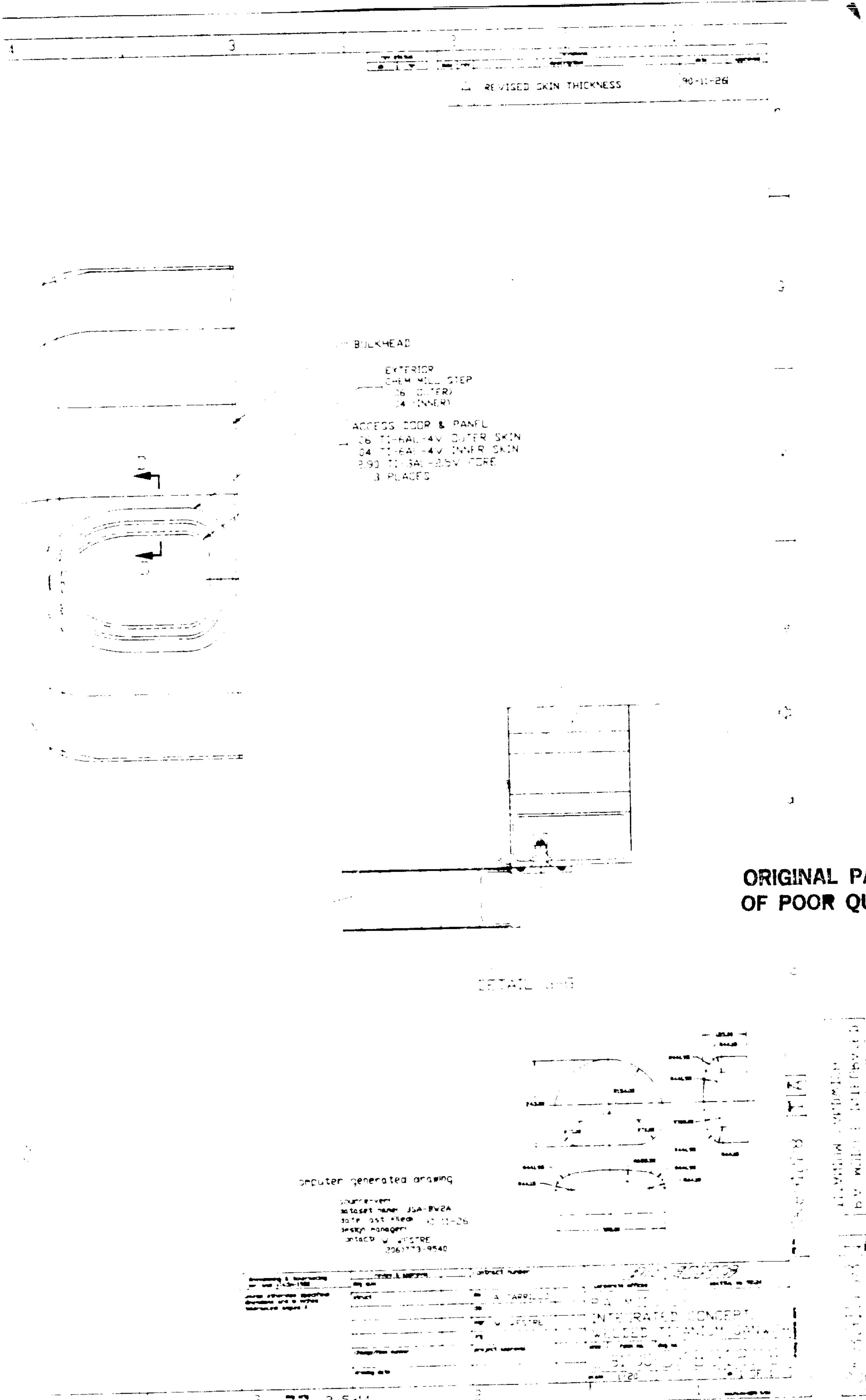

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Figure 4.2-12. Titanium Aeroshell

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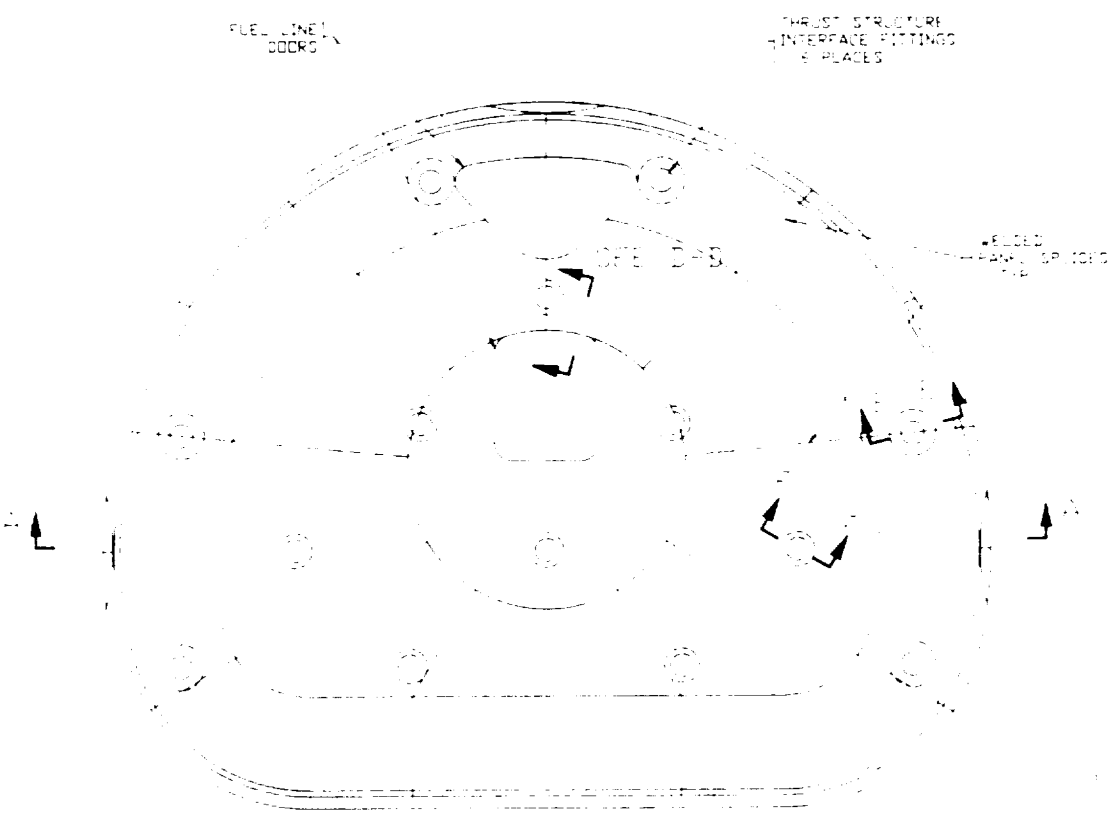

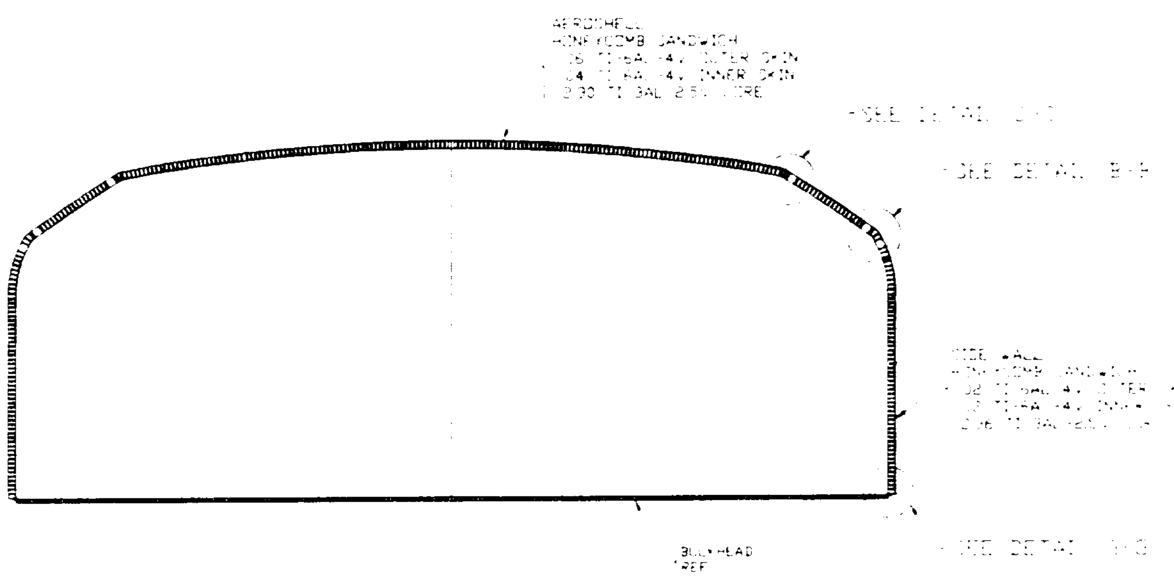

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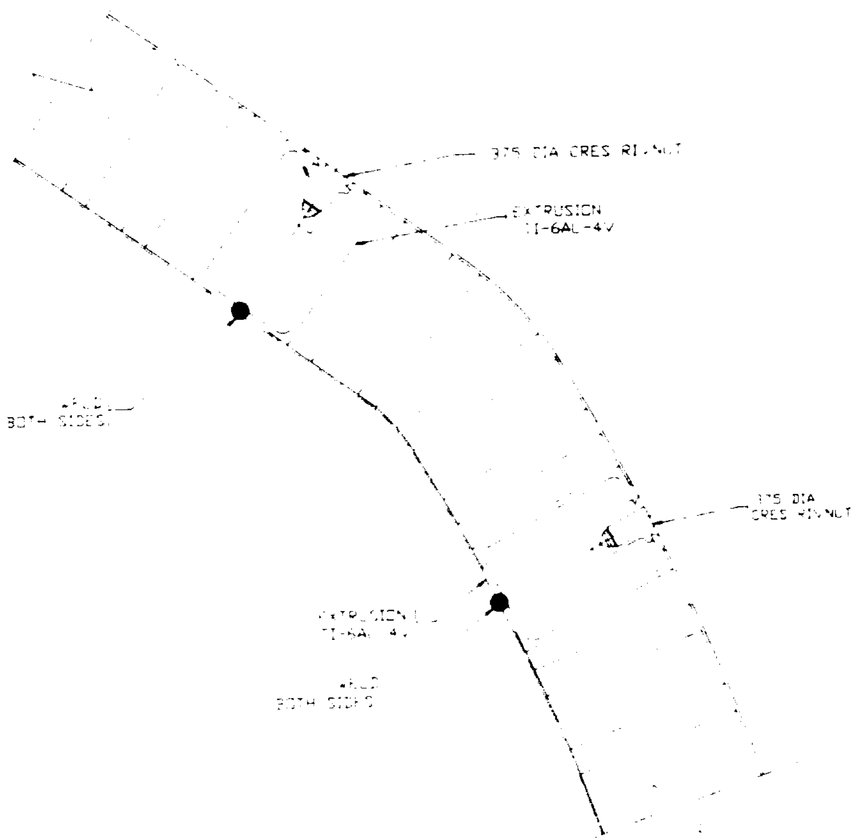

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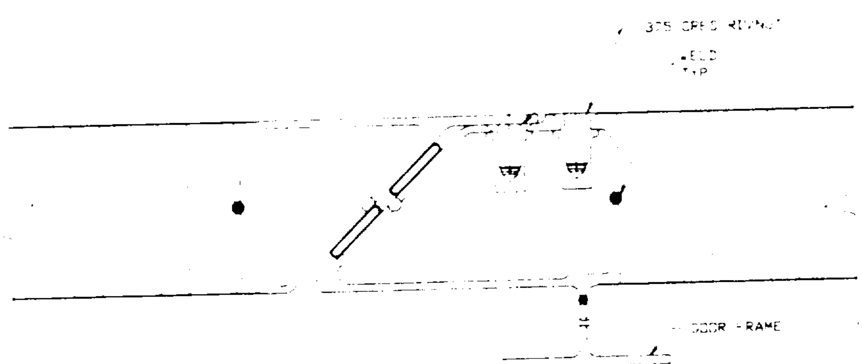

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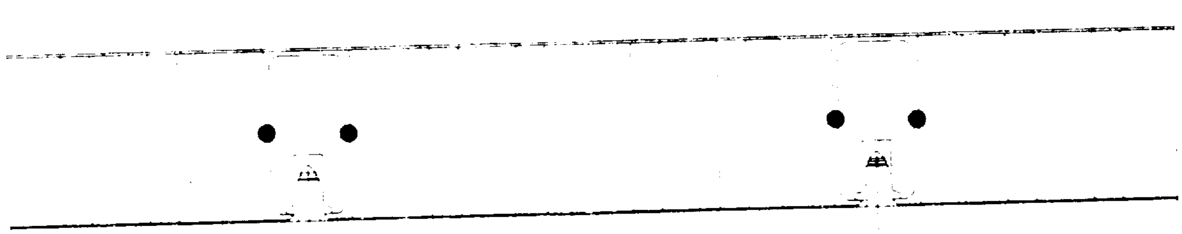

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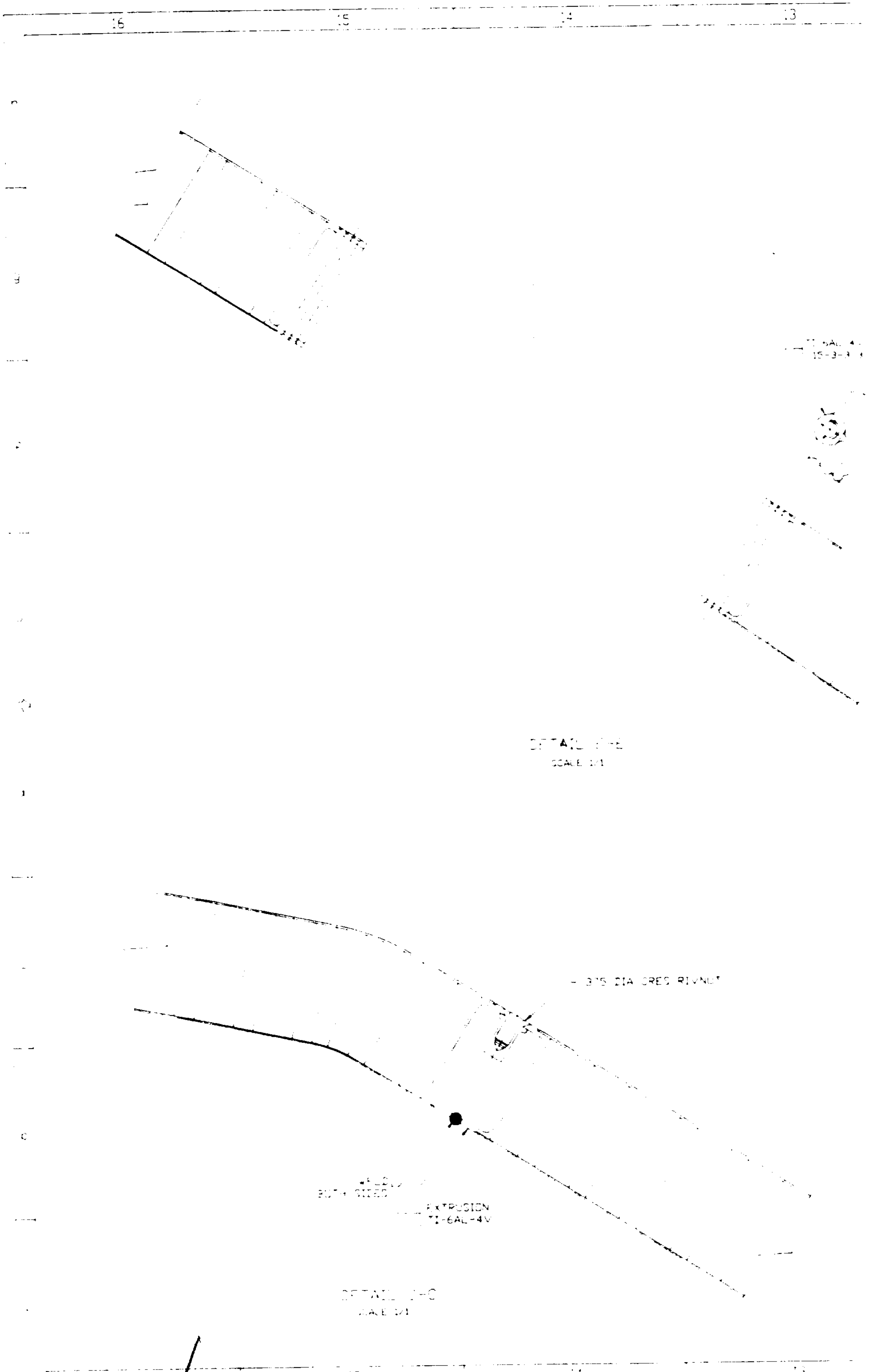

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Two candidate fabrication approaches were defined, as outlined in figure 4.2-13, based on discussions with ASTECH Division of Alcoa/TRE (ref. 4), published reports prepared by Rohr Industries, Inc.(refs. 5, 6) and Boeing in-house capability. In approach A, the sandwich panels are built up in the required shapes with brazing or liquid interface diffusion (LID) bonding. Potential fabricators include Rohr and Aeronca. In approach B, flat panels are fabricated by resistance welding, then diffusion bonding (DB) the core to the face sheets. A potential fabricator is Astech. In both approaches, contoured subpanels are welded together into the final aeroshell configuration. Candidate materials are listed in figure 4.2-14.

Concept A
1. Cut and hot form skin segments to required contours. 2. Extrude/machine panel edge members and fittings. 3. Prepare skin surfaces and core for LID bonding or brazing - clean - plate with braze alloy. 4. Assemble segments in steel tooling. 5. LID bond or braze contoured panel segments. 6. Drill and weld-in inserts for attachments. 7. Weld panel segments into complete aeroshell structure. 8. Inspect welds. 9. Join aeroshell to thrust structure.
Concept B
1. Fabricate preform panels - resistance weld skins to core - diffusion bond at resistance welds in vacuum furnace. 2. Extrude/machine door and frame fittings. 3. Creep form panels to required contours. 4. Trim preform panels to shape. 5. Drill and weld-in inserts for attachments. 6. Weld panel segments into complete aeroshell structure. 7. Inspect welds. 8. Join aeroshell to thrust structure.

Figure 4.2-13. Fabrication Scenerios For Titanium Honeycomb Sandwich P/A Module Aeroshell Structure.

Structure	Material	Fabrication Process
Dome face sheets	Ti-6Al-4V	1) Hot form (concept A) 2) Creep form (concept B)
Side wall face sheets	Ti-6Al-4V	1) Hot form (concept A) 2) Creep form (concept B)
Dome honeycomb core	Ti-3Al-2.5V 4-8 lb/ft^3	1) Braze to face sheets 2) Diffusion bond to face sheets
Sidewall honeycomb core	Ti-3Al-2.5V 4 lb/ft^3	1) Braze to face sheets 2) Diffusion bond to face sheets

Figure 4.2-14. Candidate Materials For Titanium Aeroshell

High Temperature Aluminum Aeroshell. After completing preliminary designs and cost analyses of the Gr/PI and Ti aeroshell concepts, additional benefits of employing HTA alloys became apparent. The defined concept, illustrated in figure 4.2-15, combines the most attractive attributes of the Gr/PI and Ti aeroshells. Specific materials incorporated are listed in figure 4.2-16. FVS 1212 alloy has superior properties also, but is harder to work than 8009 alloy (FVS 0812). FVS 1212 is specified for the dome cap because it appears to be spin formable in the required size. The more severe compound contours at the shoulder require the more workable 8009 which can be stretch formed cold. Stretch forming cold is expected to incur no spring-back, which simplifies tool design and fabrication.

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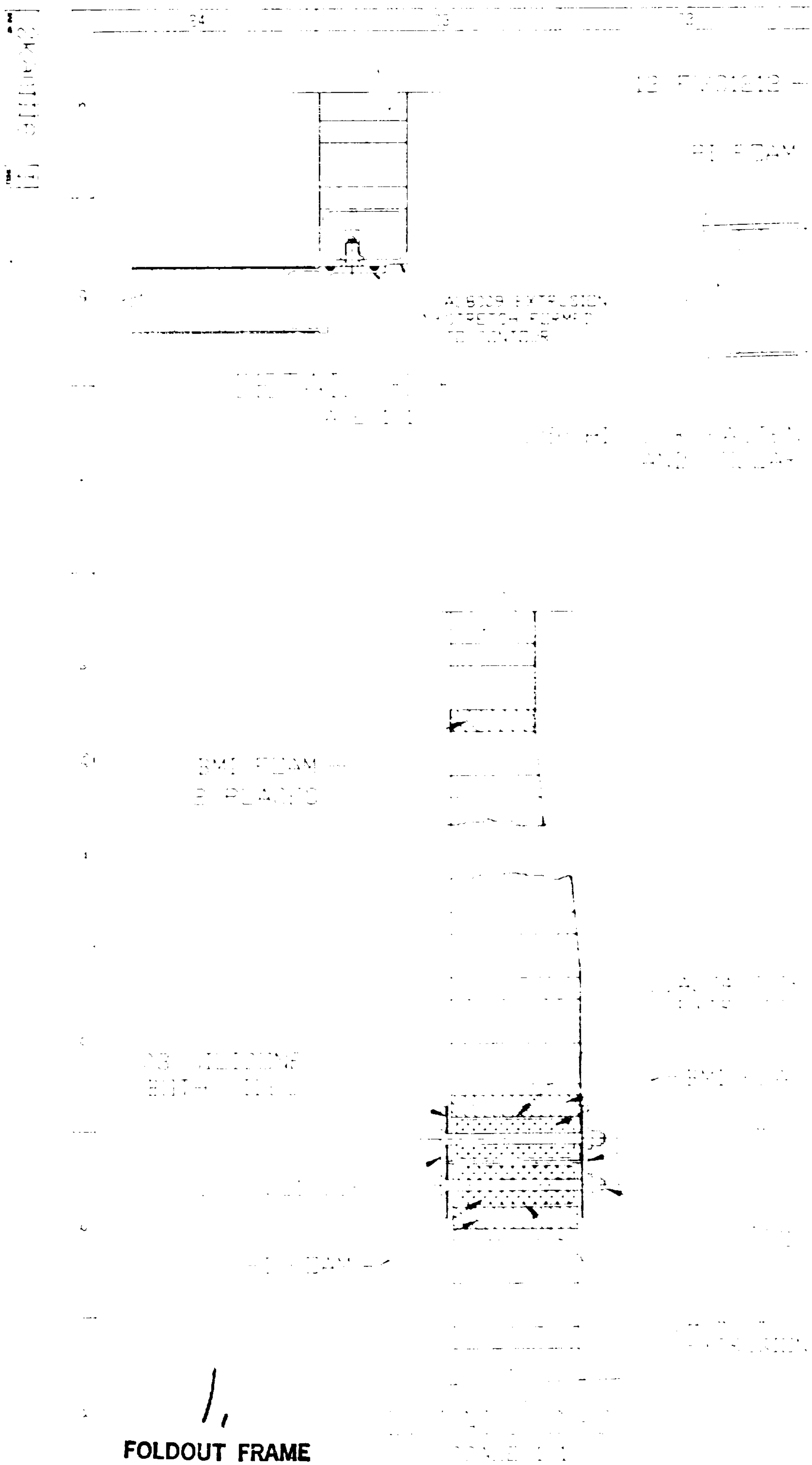

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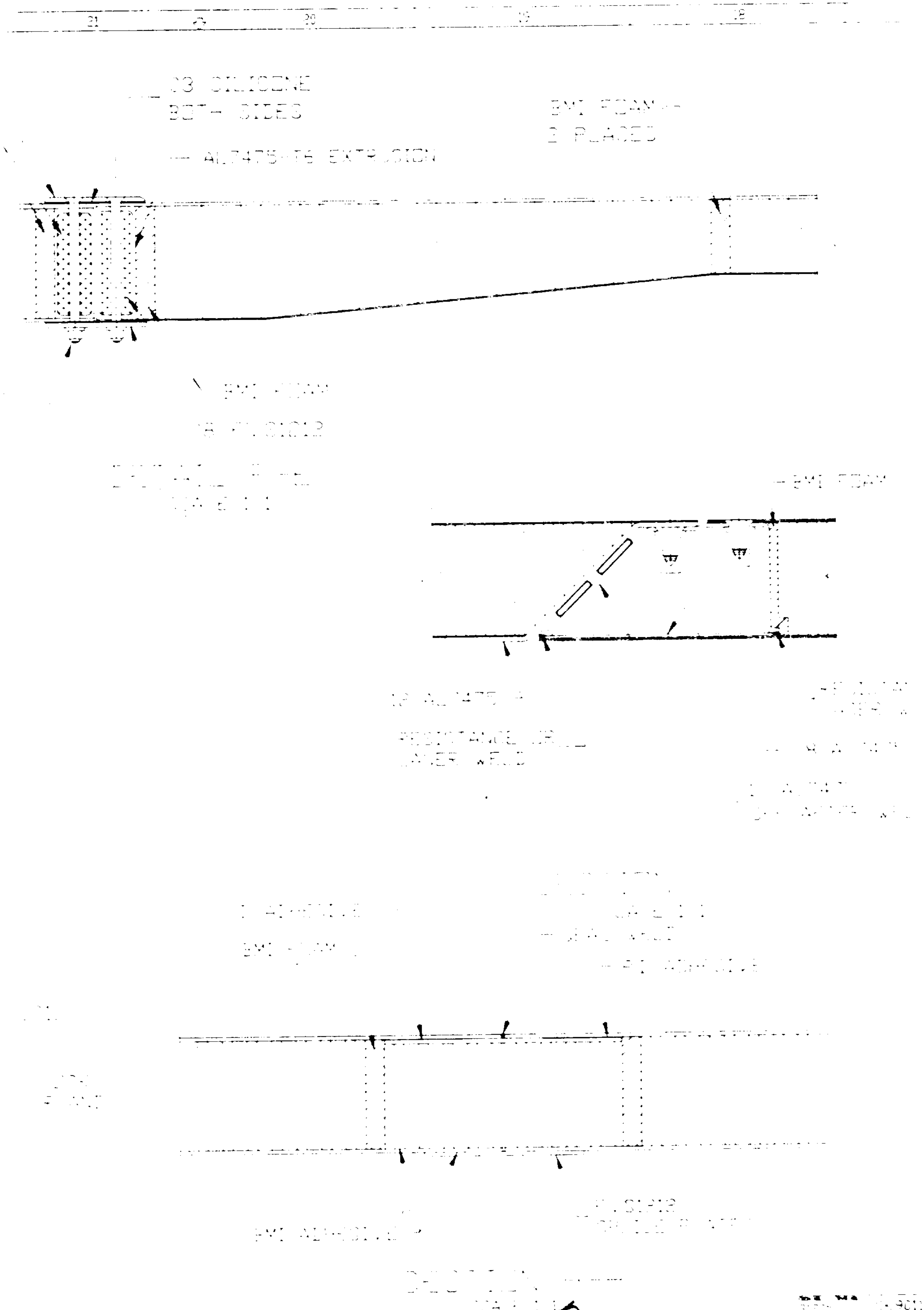

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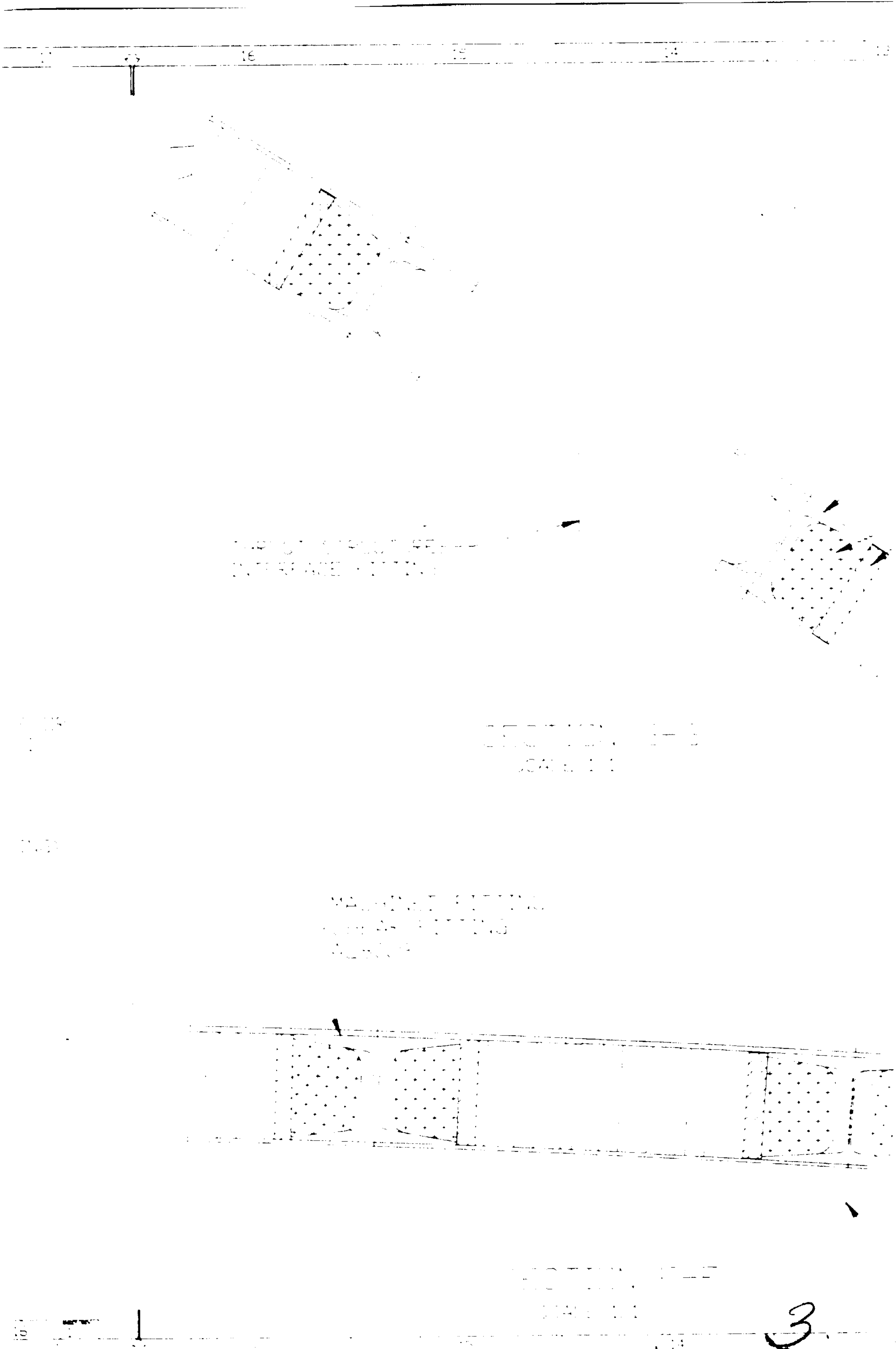

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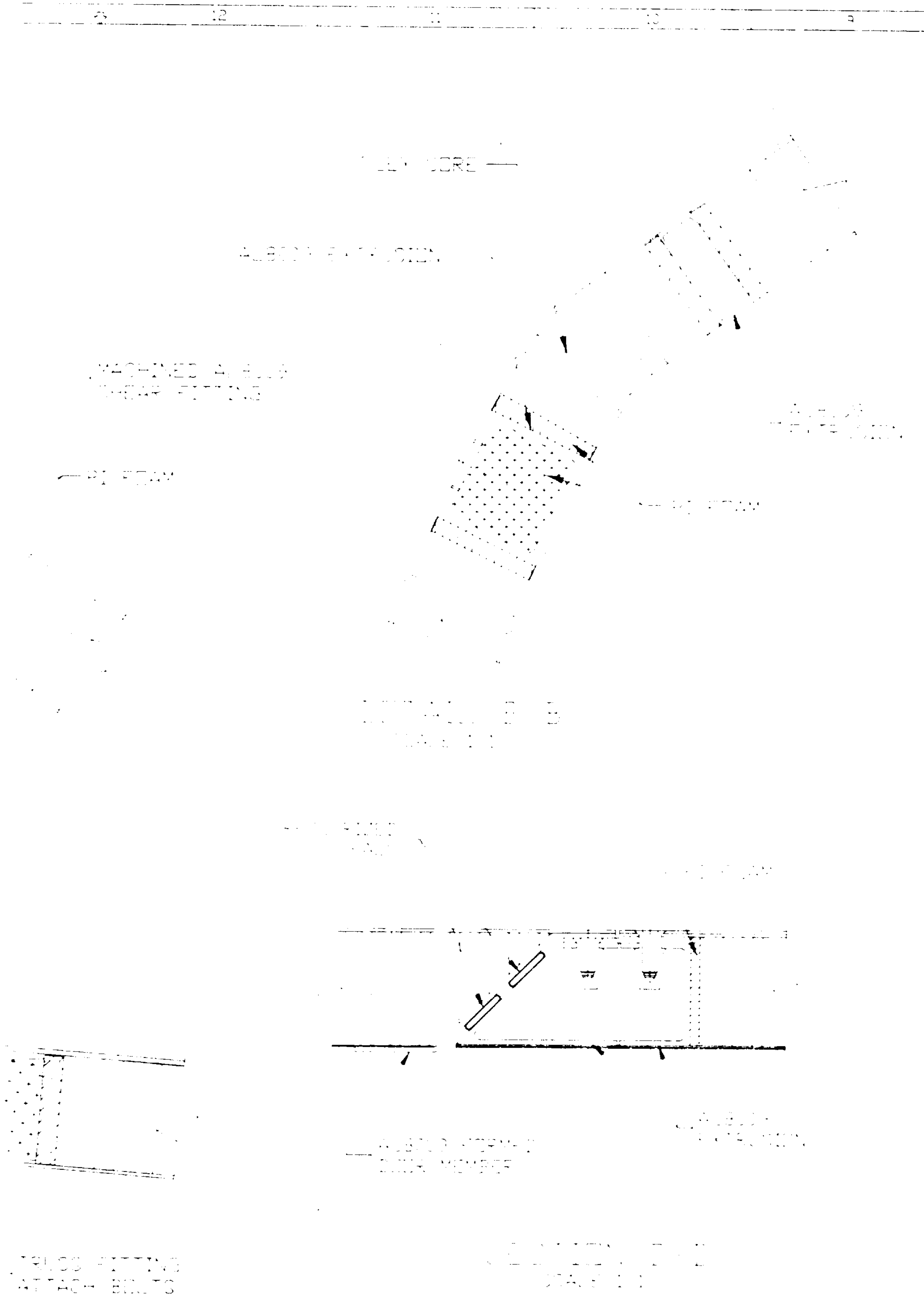

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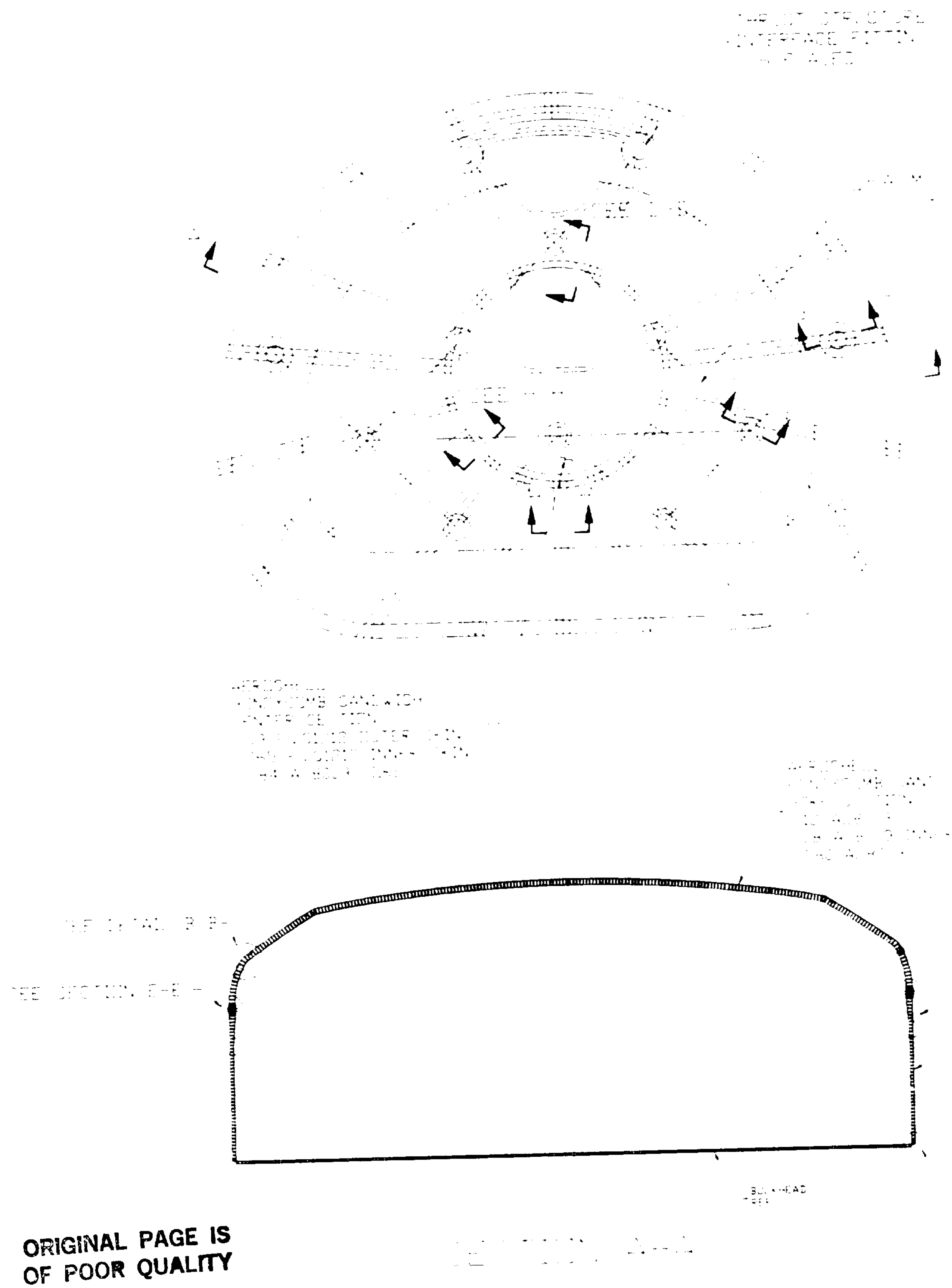

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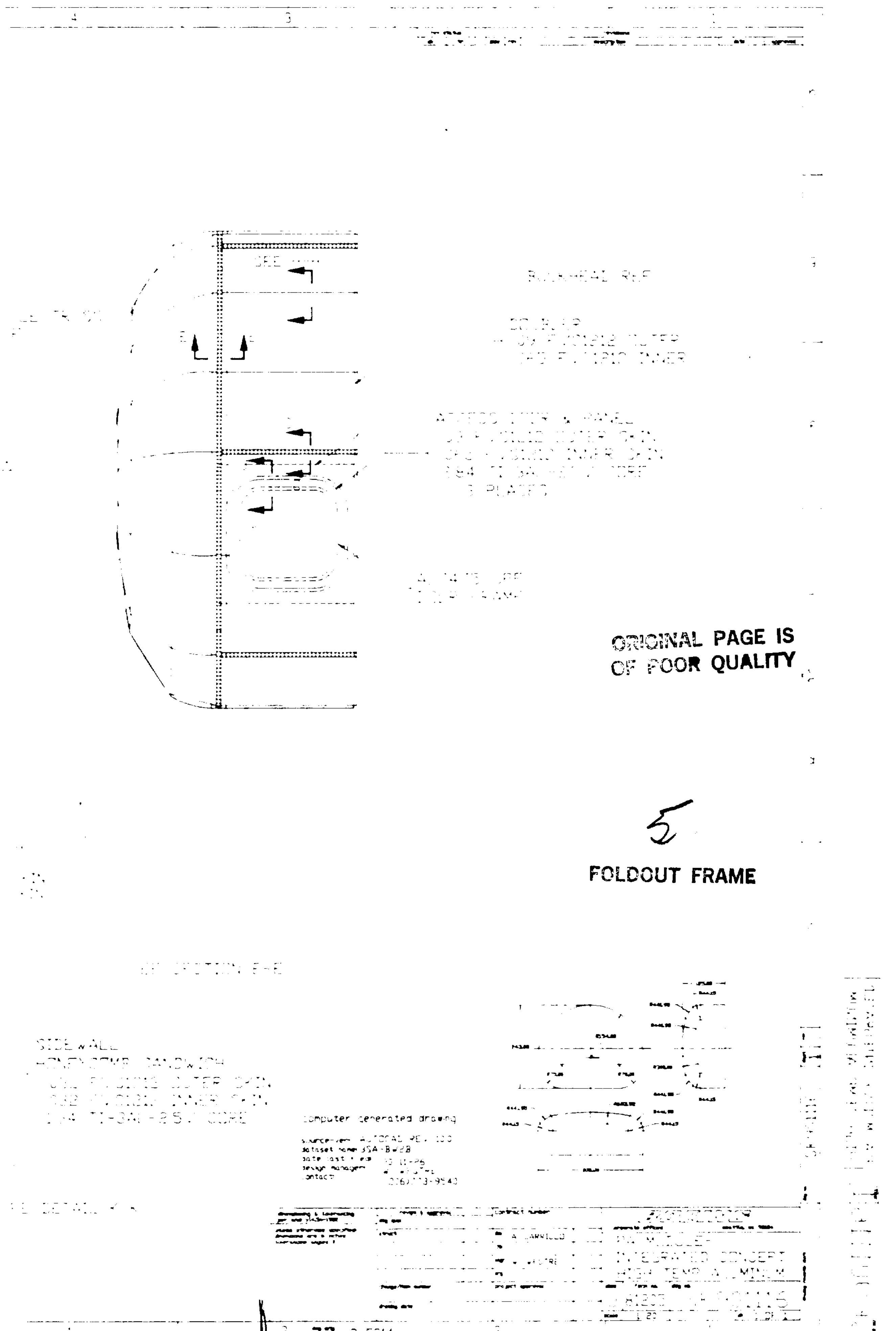


Figure 4.2-15. High-Temperature Aluminum Aeroshell

Structure	Material	Supplier	Fabrication Process
Dome cap face sheets	1) FVS 1212	Allied Signal	Spin form
Dome and shoulder face sheets	1) 8009 Al	Allied Signal	Stretch form cold
Side wall face sheets	1) FVS 1212	Allied Signal	Bonded in place to required contour
High-temperature adhesive	1) FM35 2) PT resin 3) FM 680	American Cyanamide Allied Signal/YLA,Inc. American Cyanamide	Cure at 600°F Cure at 300°F Cure at 600°F
Honeycomb core	1) 5000 Al resistance welded 2) 8009 Al resistance welded 0.002 foil, 0.1875 cell 3) Ti-3-2-2.5 0.002 foil, 0.1875 cell	Allied Signal/TI/Rohr	Bond at 300°F Bond at 600°F

Figure 4.2-16. Candidate Materials for High-Temperature Aluminum Aeroshell

The side walls, although cooler than the dome, are cylindrical shaped and can therefore employ the higher strength of the FVS 1212 material. The honeycomb sandwich is structurally bonded because fusion welding and brazing techniques do not yet look promising for these alloys. Bonding also allows fabricating large sandwich panels in a single autoclave run, thereby reducing joining requirements. A detail of the splice joint between face sheet panels is shown in figure 4.2-17. Splice plates provide load continuity, but are bonded about 1 in from the butted face sheet edges so the nonstructural seal weld does not degrade the bond. A thermal analysis indicates the temperatures listed in the figure. The welds are used only to maintain a water tight seal in the outer face sheet. Shear stress due to weld shrinkage is expected to be insignificant.

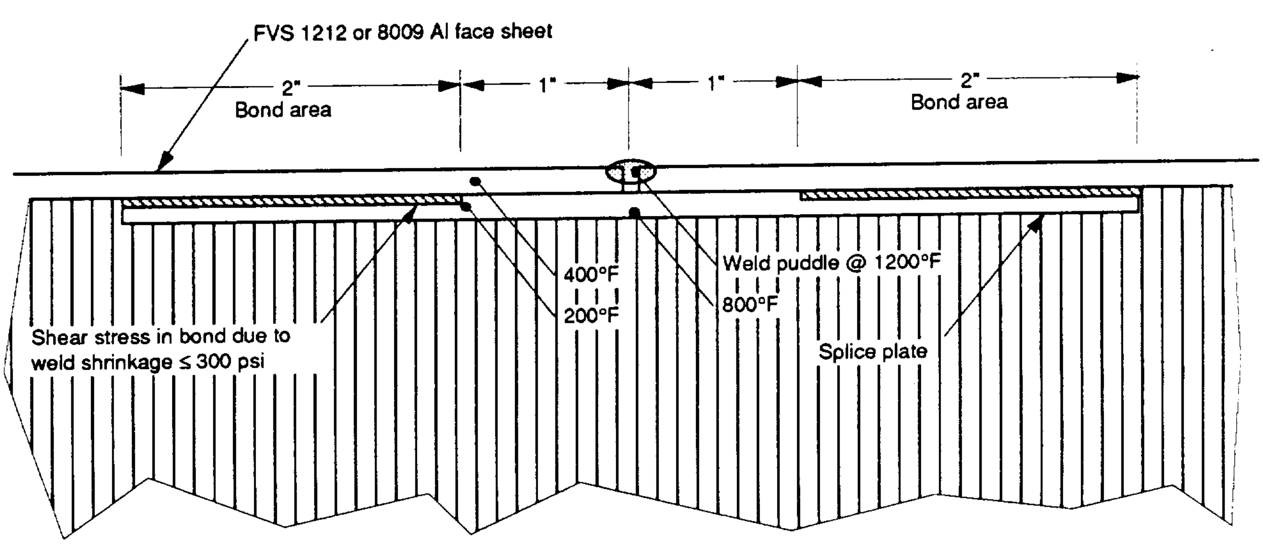


Figure 4.2-17. High Temperature Aluminum Face Sheet Splice Concept Thermal and Stress Analysis Results

A HTA alloy is desired for the honeycomb core because a conventional aluminum core would be annealed to low strength during the time at bonding temperatures. The higher thermal conductivity of aluminum makes it a better core material than titanium for this concept because it conducts heat away from the external face sheet better, keeping the external temperature within material limits. HTA honeycomb core is under development. We understand Allied-Signal is supplying Texas Instruments with material for rolling into foil down to 2 mils thick, which is then formed and resistance welded into core at Rohr Industries.

Propellant line door frames in the dome will be 8009 Al for its thermal capability and so it can be bonded with high-temperature adhesives. Door frames in the sidewalls, which are cooler, will be 7475 Al which can be superplastic formable from sheet for reduced cost and bonded in place with bismaleimide (BMI) adhesive at a lower cure temperature for further cost reduction.

Several candidate bonding adhesives are listed in figure 4.2-16. The PT resin has the benefit of curing at a lower temperature than the others but achieves similar glass transition temperature (Tg) values. This resin is in development, but research quantities are expected to be available. FM 680 is a well established polyimide adhesive.

The fabrication approach is listed in figure 4.2-18.

Dome

1. Spin form center section skins.
2. Stretch-form gore skins.
3. Stretch-form splice plates and attachment members.
4. Machine interface fittings.
5. Prefit external skin details in Bonding Assembly Jig (BAJ).
6. Trim core (use flex or pro-clastic cell design).
7. Clean, phosphoric acid anodize, and prime details with BR680 and bake at 400°F.
8. Install bleeder system and bag.
9. Bond using FM680-1 adhesive and FM30 foam at full vacuum, 100 psi, ramping temperature to 600°F.
10. Remove bugging and prefit inner skin details.
11. Clean, prime with BMI primer and bake details.
12. Assemble inner skin details and bag.
13. Bond using BMI adhesive at full vacuum.
14. Remove bagging and release from BAJ.
15. Inspect bonded structure with TTU and selected areas with other NDE methods.
16. Scrape skin-splice gaps and seal-weld.
17. Penetrant inspect welds.

Sidewall Door Panels

1. Weld door frames and superplastic form.
2. Prefit details (Note: Skins drape-form) and trim core.
3. Clean, phosphoric anodize, prime with BMI primer and bake.
4. Fill edge members with P.I. foam and cure.
5. Assemble all details, bond with BMI adhesive (single stage).
6. NDE with TTU.

Side Panels W/O Doors

1. Stretch edge members.
2. Prefit details and trim core.
3. Clean, anodize, prime and bake (BMI).
4. Assemble, bond (BMI) (single stage).
5. NDE with TTU.

Mechanical Assembly

1. Position aeroshell dome (dome up) in fixture.
2. Raise door panels into position, drill and bolt splice plates using drill jig.
3. Install inter-panels similarly.
4. Proceed with P.A. module assembly from same orientation.

Figure 4.2-18. High Temperature Aluminum Fabrication Scenario.

<u>Aeroshell Stress Analysis.</u> An FEM was composed in ANSYS for the aeroshell, which was then integrated with the thrust structure and bulkhead FEMs to obtain a complex three-dimensional representation of the P/A module structure having 11,064 degrees of freedom and 2122 elements. Masses representing subsystems, such as the main engines, were added to this integrated model enabling complete definition of stresses in the aeroshell.

Because the critical loading on the aeroshell structure occurs during splashdown, we concentrated our analysis efforts there. Water impact presents a nonlinear, dynamic condition, which we addressed using steady-state, static analysis techniques. This is considered conservative, but should be reevaluated as ALS program P/A module water drop tests proceed. Figure 4.2-19 depicts the load application for the FEM. The ANSYS FEM code does not have free-body modeling capabilities, therefore masses and accelerations were included in the model to reduce the reaction forces at the constraint points. This enabled the simulation of an instantaneous free-body impact.

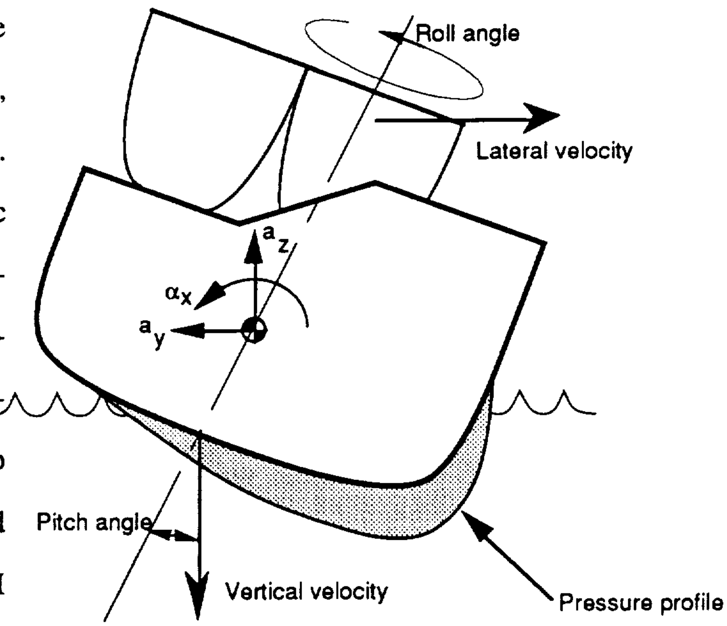


Figure 4.2-19. Aeroshell FEM Loads Application

The FEM representation is shown in figure 4.2-20 along with locations of maximum deflection, strain, and stress for the two primary load conditions. Splashdown loads require adequate support of the aeroshell by the thrust structure, but does result in deflections (exaggerated in the figure) that can be confined to a local area at the center of the pressure distribution. Detailed FEM stress analysis results are summarized in figure 4.2-21. Should the impact point, (i.e., the center of pressure location) change within several degrees of impact angle, similar stresses, strains, and deflections are expected.

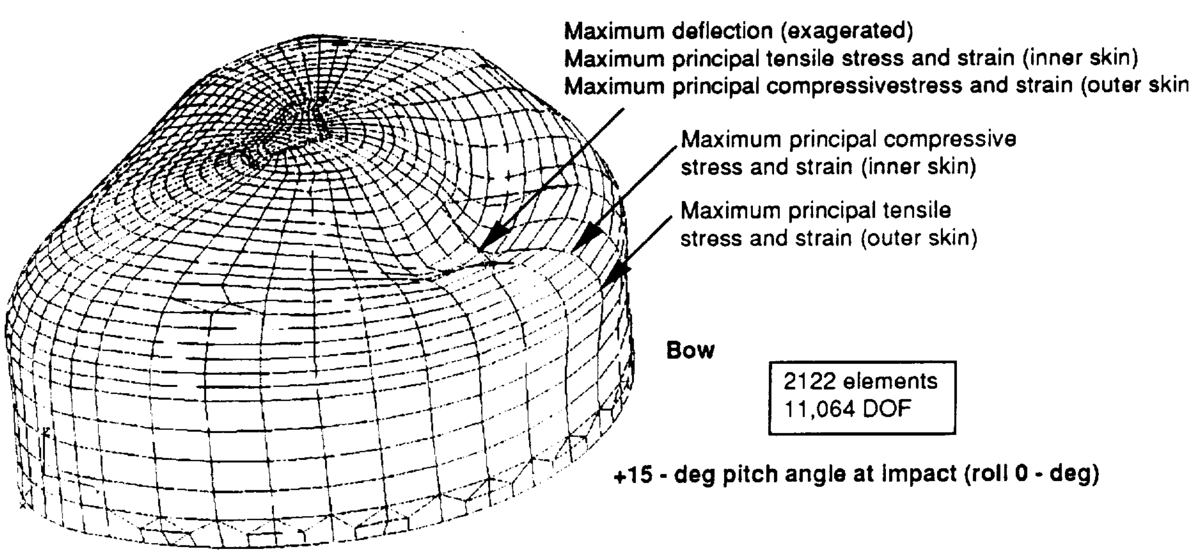


Figure 4.2-20. Aeroshell Locations of Maximum Stress, Strain, and Deflection

Results From or Scaled From Finite Element Model

Aeroshell dome concept	Maximum Tension, ksi	Maximum Compression, ksi
Gr/PI sandwich, 0.10 in. face sheets	19.4 [2942 με] (inner) 18.3 [2346 με] (outer)	29.1 [4162 με] (inner) 51.4 [5650 με] (outer)
Ti sandwich, 0.05 in. face sheets	38.8 (inner) 36.6 (outer)	58.2 (inner) 102.8 (outer)
Hi-temp Al sandwich, 0.13 in. face sheets	14.9 (inner) 14.1 (outer)	22.4 (inner) 39.5 (outer)

Final Aeroshell Face Sheet Thicknesses

Figure 4.2-21. Aeroshell FEM Analysis Results and Face Sheet Sizing Summary.

Aeroshell dome face sheet thicknesses are sized for the water impact loads, while those for the sidewall are close to minimum gage. In general, H/C sandwich thickness (approximately 3-in) is sized by deflection limitations to preclude aeroshell buckling and to protect internal equipment. Additional sandwich face sheet thickness in the areas of high stress or strain are required, which affects relative weights of all concepts approximately equally. However, locally increasing outer face sheet thicknesses may not be cost effective; therefore, we recommend other design solutions be pursued such as providing additional thrust structure support points for the aeroshell.

Thermal Analysis. Thermal analyses were conducted with the Boeing-developed Convection Heating and Ablation Program (CHAP). It is a one-dimensional thermal analyzer which automatically accounts for aerodynamic heating using a given flight profile. Thermal analysis accounts for ablation, structural gaps, energy absorption, radiation, and convection. The boundary layer analysis is coupled with the thermal response analysis to account for wall temperature influence on heat transfer coefficients. Analysis results, such as erosion rates and structural temperatures at surfaces and interfaces, were used to aid aeroshell TPS and structure sizing.

Diagrams of the thermal models are shown in figure 4.2-22. The Ti sandwich was analyzed with both single and multi node 1-D CHAP models to determine if Ti thermal conductivity affected inner and outer face sheet temperatures. Results showed no significant differences. Since Al has a higher thermal conductivity than Ti, the single node approach was also used for analyzing HTA concepts also. The multi node Gr/PI model did identify a lower temperature on the inside of the outer face sheet. A 2-D model of the 44-in radius area of the Ti aeroshell dome, the area experiencing stagnated flow, was used to identify possible effects of inplane conduction away from the stagnation zone. Results also showed no significant differences between the 1-D and 2-D models throughout the 330 second trajectory.

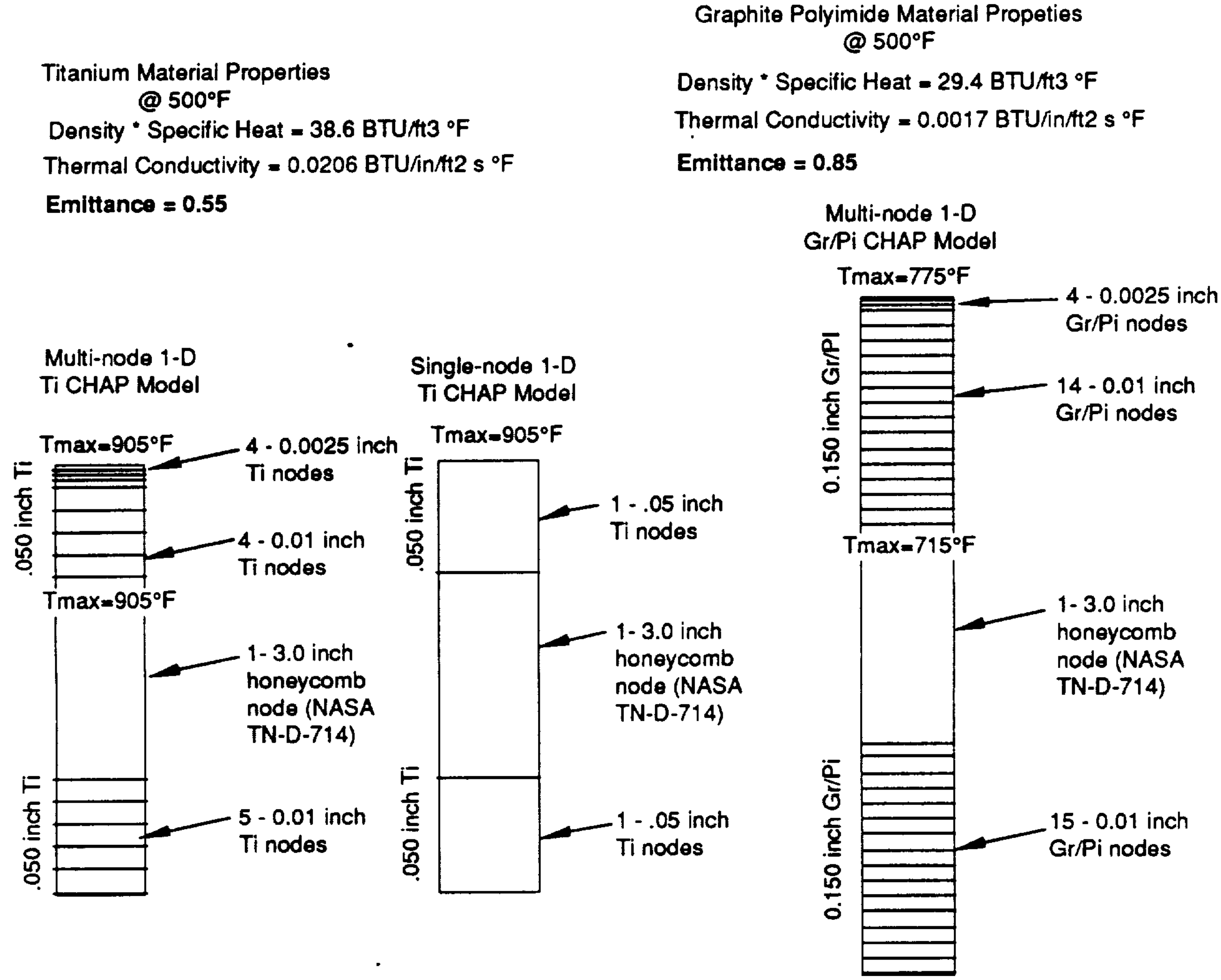


Figure 4.2-22. Thermal Analysis Model For ALS P/A Module Aeroshell at Stagnation Point (see figure 4.1-8)

Temperature plots for the booster P/A module titanium, Gr/PI, and HTA aeroshell sandwich structure concepts are shown in figure 4.2-23. Outer face sheet temperatures peak near 900°F for Ti and 750°F, for Gr/PI, but remain above 600°F for less than 1.5 min per flight for these concepts. Outer surface temperatures (at point A) are sensitive to face sheet thicknesses; thicker sandwich face sheets result in lower temperatures. Although Ti and Gr/PI sandwich face sheet thicknesses are primarily driven by the splashdown loads, increasing the face sheet thickness in the areas of highest temperature can reduce temperatures there. Figure 4.2-24 provides an indication of the areas experiencing the peak temperatures (the stagnation point) for one aeroshell dome configuration. Just slightly off the stagnation point the temperature falls by 60°F, and at the base of the flat sidewall falls by over 370°F to 480°F. For the Ti sandwich aeroshell the maximum structural temperature could be reduced by increasing the outer face sheet thickness in a limited area, thereby avoiding a significant weight penalty. (Note that these temperatures may vary slightly from other temperatures reported for the Ti aeroshell due to adjustments made in the trajectory. These adjustments do not significantly change conclusions.)

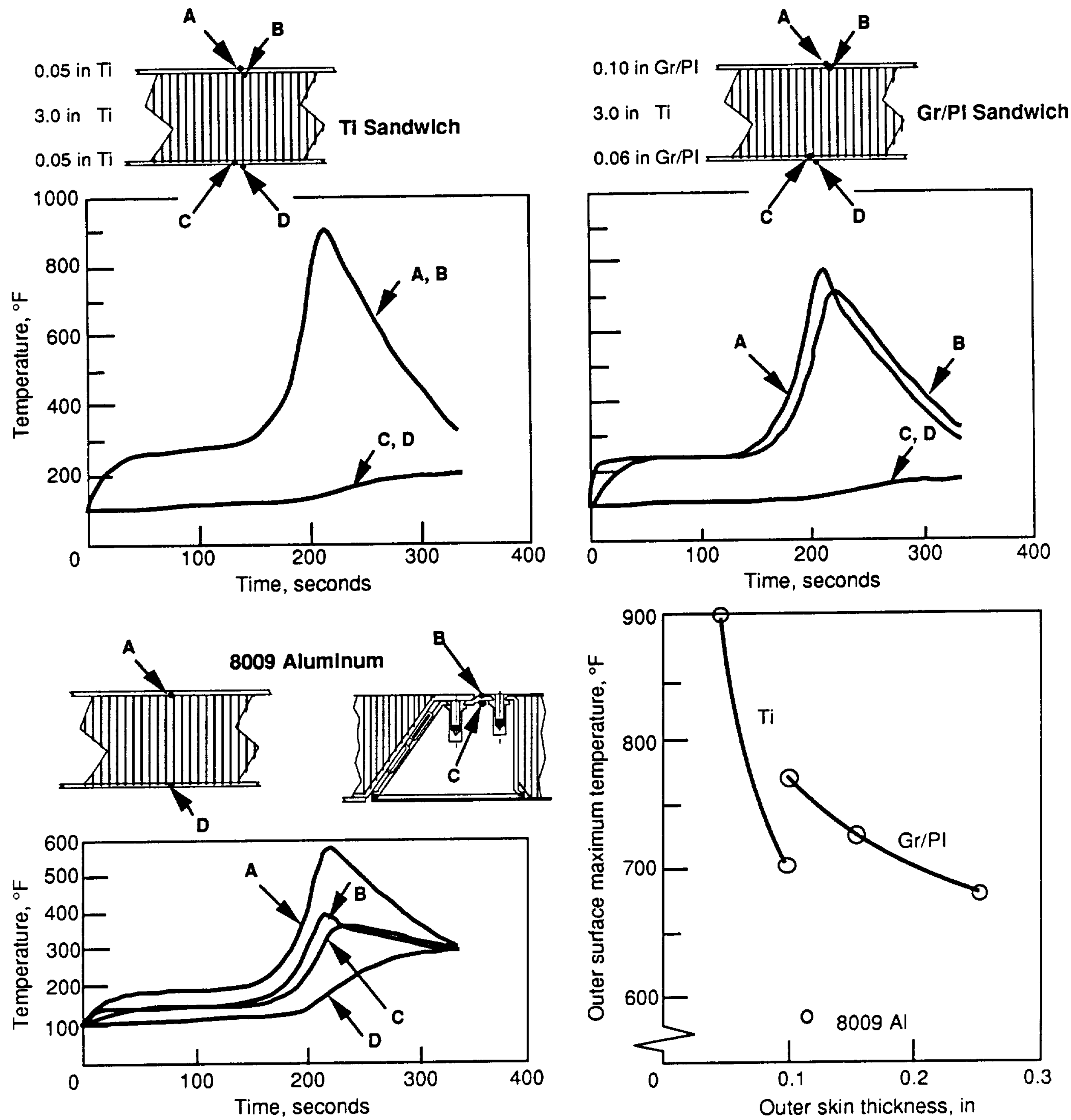


Figure 4.2-23. Booster Aeroshell Sandwich Temperatures From 1 -Dimensional Thermal Analysis

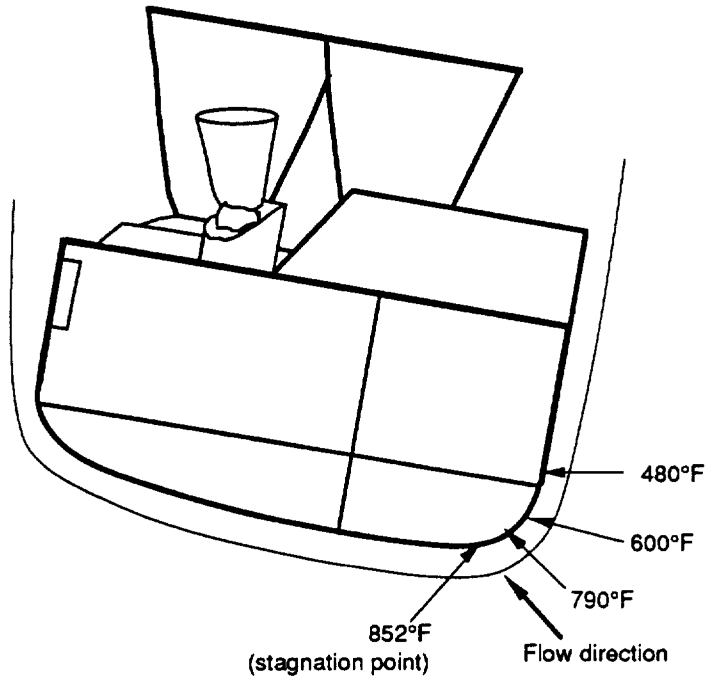


Figure 4.2-24. Maximum Titanium Surface Temperatures During Booster P/A Module Reentry at 10-deg Angle of Attack.

The HTA concept (8009 Al) depends on the outer face sheet thickness and conduction of the honeycomb core to maintain temperatures below 600°F, near the upper limit of a short-term service temperature. The dome door frames, locations B and C in the 8009 Al diagram, are at lower temperatures due to their thermal mass.

Aeroshell Thermal Protection System. For the core P/A module, an attachment clamp secures the replaceable TPS ablator shell onto the dome. For the booster, the TPS is not required; instead, a fairing maintains an aerodynamic surface at the joint. The TPS is designed for simple replacement on the core vehicle. TPS on the dome is in a single piece consisting of cork/phenolic ablative material bonded to a composite substrate. The substrate is stretched over the dome and fastened to an annular ring on the structure with a marmon clamp. This clamp is ejected after reentry allowing the TPS to separate. Five pieces of sidewall TPS are held similarly by clamps and are stretched around the cylindrical surface. These clamps are released during maintenance operations when new interchangeable TPS panels are installed. A concept for securing the TPS at the sidewall access doors is shown in figure 4.2-25. Access for the door closure fasteners are through the ablator; the holes are filled with a trowelable ablator after securing the door.

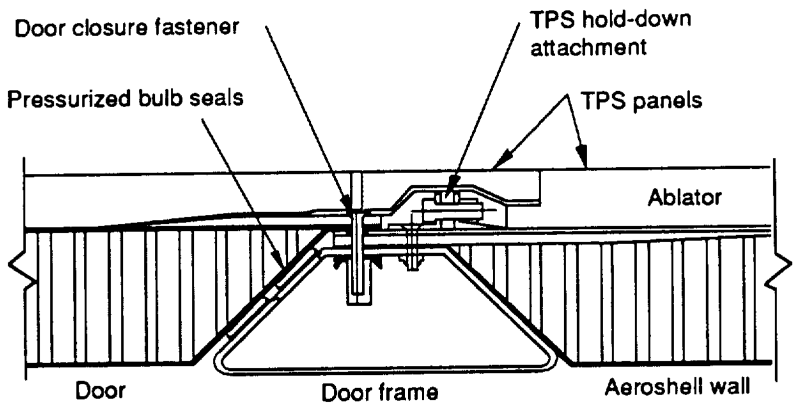


Figure 4.2-25. Aeroshell Door Seal Concept Showing TPS Attachment.

Figure 4.2-26 contains rationale for TPS material selection. Due to the severe reentry environment experienced by the core P/A module, cork/phenolic may be the best choice for the core TPS; although it is not optimum from a manufacturing cost perspective. The other TPS candidates are applicable to the booster aeroshell should it require protection as would the Gr/Ep concept. A test program is required to determine if low density Silastic-E is usable on the core vehicle.

Description	Benefit/Rationale	Application
Cork Phenolic (bonded on substrate in layers)	• High shear resistance at temperature • Known performance • Best combination of insulation and ablative properties at high temperature • Durable	Core
Filled Silicone - MA25S (sprayable) MA25T (trowelable)	• Low shear resistance (maybe to low for core) • Development required forcore application • Fabrication advantage (sprayable) • Shear erosion not known • Sole source: expensive	Booster
Filled Epoxy - MSA-2 (sprayable)	• Development required for this application • Fabrication advantage • Test data available: relatively inexpensive to model	Booster
Low-Density Silastic-E (microballoon filled)	• Development required for this application • Fabrication advantage • Some test data available: relatively inexpensive to model • Test program required	Core/Booster

Figure 4.2-26. Aeroshell TPS Materials

<u>Aeroshell Weights</u>. Detailed weight estimates were made keyed to the indentured parts lists developed for the concept manufacturing plans (discussed in sec. 4.2.4.2). These weight statements are included in Appendix C, and the results are used in the life cycle costing analysis.

4.2.3 Aft Bulkhead Design Concepts

System definition studies (ref. 1) have called for a flat bulkhead which supports subsystems, parachutes, OMS engines, main engine gimbal boots, and contains cutouts for main engines as illustrated in figure 4.2-27. Primary structural attachments include the joint to the aeroshell and crossing beams. Nine structural concepts were defined and preliminarily sized (as shown in Appendix B) for loads due to differential pressure of 1 psi, OMS engines thrust against the support beams, and parachute deployment. Four structural concepts were studied in additional detail: (1) formed corrugated aluminum, (2) bonded aluminum H/C sandwich, (3) superplasticity formed and laser-welded aluminum-lithium (Al-Li) truss-core sandwich, and (4) bonded Gr/Ep H/C sandwich. Potential TPS/insulation concepts required due to plume heating are shown in figure 4.2-28. The Fiberfrax HSA alumina-silica fiber insulation system from Standard Oil Engineered Materials was selected for the thermal analysis to ensure an insulation was available that could protect the bulkhead from the main engine plume heating. This is verified in the Thermal Analysis section that follows.

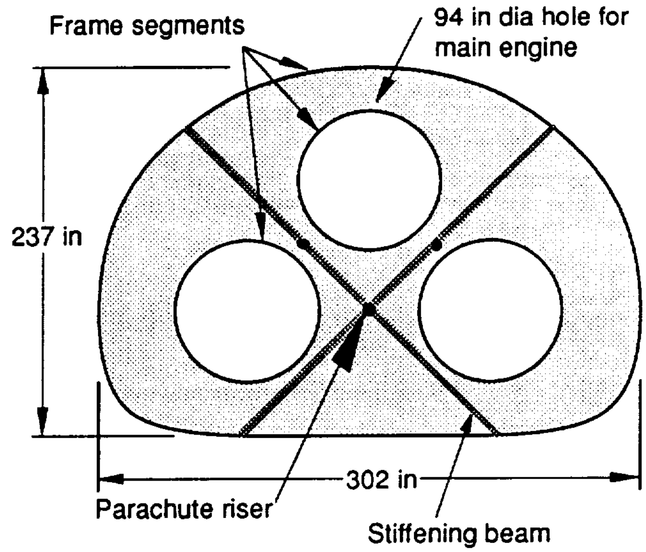


Figure 4.2-27. Bulkhead Geometry and Features

TPS/Insulation Description	Density, pcf	Conductivity at 1000°F, BTU in/hr ft^2 °F	Selection Criteria
Protecal (Bronzavia Aeronautique) Quartz wool between metal sheets (stainless or Ti)	3.6	0.56	Durable due to metallic face sheets
Q-Fiber Felt (Manville) Silica fiber (SiO2); continuous temperatures to 1800° F	6	0.60	Unaffected by moisture
Fiberfrax HSA Paper (Standard Oil) continuous temperatures to 2300° F	8	0.50	Good vibration resistance
Fiberform/Microform (Boeing); continuous temperatures to 2000° F	10-24	XX	Potential for low cost

Figure 4.2-28. Bulkhead TPS and Insulation Alternatives

__Stress Analysis.__ A two-dimensional representation was used for the bulkhead FEM. Both differential pressure and parachute deployment loads, shown in figure 4.1-5, were evaluated. Out-of-plane deflections due to differential pressure were restricted to 1 in, and disctated the required bulkhead stiffness.

__Thermal Analysis.__ A one-dimensional thermal analysis, illustrated in figure 4.2-29, showed that 0.50 in of HSA paper insulation maintains a Gr/Ep bulkhead below 200°F during main engine thrust. This is sufficient to maintain all the materials under consideration below their maximum operating temperature. Approximately 330 ft^2 is required to cover the bulkhead, representing approximately 110 lb of HSA paper (0.33 lb/ft^2), not counting mounting hardware. Two of the other insulations listed in figure 4.2-29 could total less weight if used.

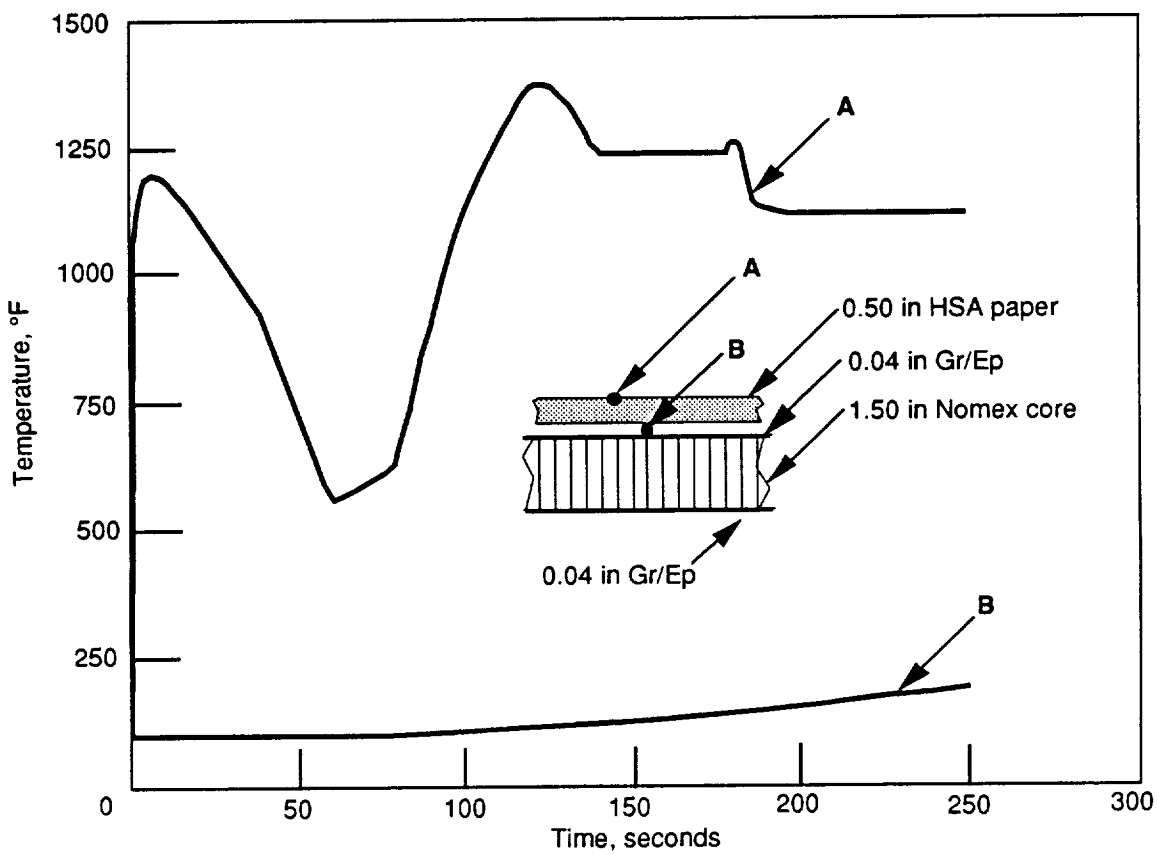


Figure 4.2-29. Temperature Profiles of Aft Bulkhead Structure Protected With HCA Paper TPS

The above design concepts for P/A module structure conform to the preliminary requirements, and provide a basis for further analysis, design definition, and development.

4.2.4 Cost Analysis

A flow chart for the cost analysis approach is shown in figure 4.2-30. This procedure proceeds from the structural concept definition, through a manufacturing cost assessment using historic cost data when relevant and available, and finally into a defined LCC model incorporating factors of learning curve, time value of money, and cost/weight trade-off. The explicit cost estimates are combined with weight factors to define a figure of merit, the LCC. The LCC can be used to compare concepts, but should not be used to estimate a development program or ultimate hardware costs.

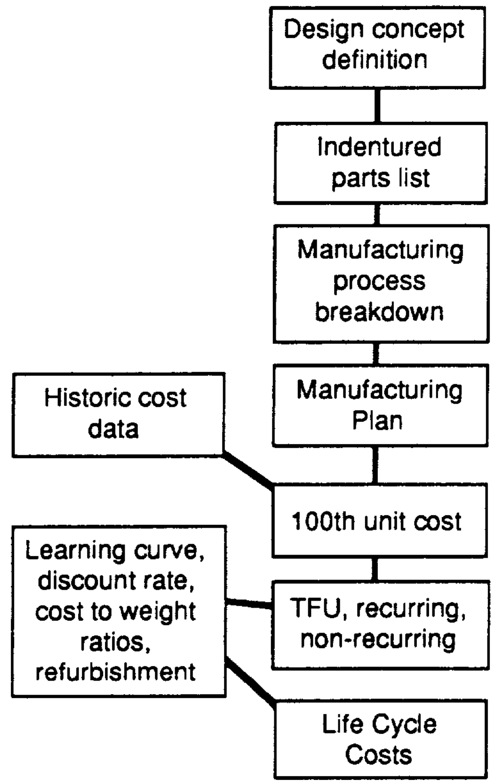


Figure 4.2-30. Manufacturing and Cost Analysis Procedure

__Manufacturing Costs and Quality Assurance__. Detailed manufacturing costs were estimated using a bottoms-up cost procedure which proceeds from the individual structural elements and fabrication steps, and builds up to the complete structure as follows. Each structural concept was broken down into components with an indentured parts list. This served as a framework for a detailed manufacturing process breakdown which accounted for: materials, tooling, numerically controlled (NC) machine programming, and labor.

Using process standards and judgement (standards are often lacking for innovative concepts) costs (recurring and non-recurring) were developed for the 100th unit representing a fairly mature operation. The 30th unit and theoretical first unit (TFU) costs were calculated by applying an inverse learning curve (fig. 4.2-31) to the 100th unit cost. Figure 4.2-32 shows a relative cost breakdown for 30 thrust structure ship sets.

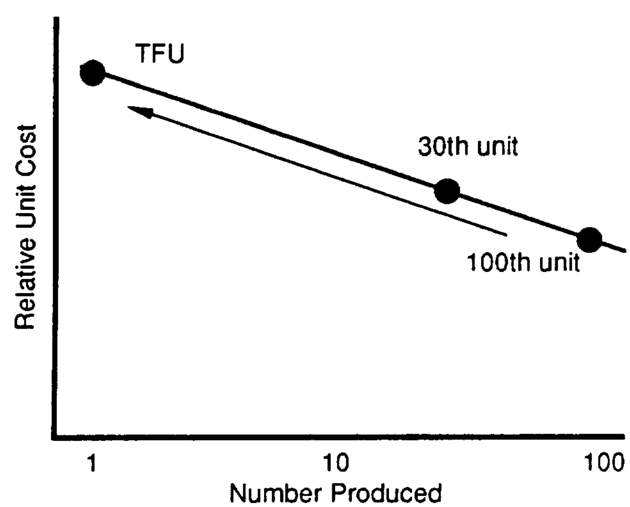
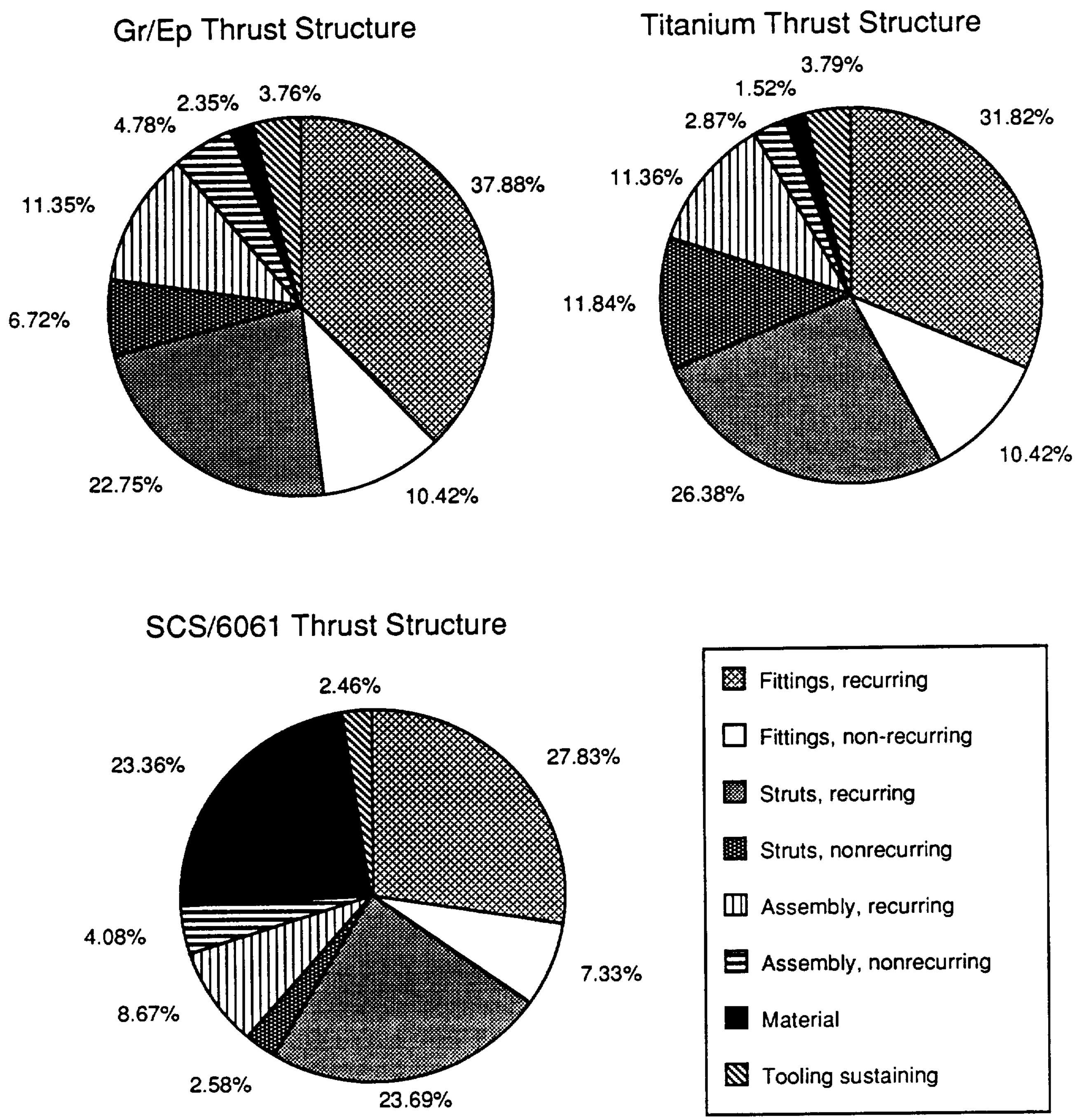


Figure 4.2-31. Cost Estimating Learning Curve



30 ship sets; 85 percent learning curve applies only to recurring and sustaining costs.

Figure 4.2-32. Relative Cost Breakdown for Thrust Structure

Strut end fittings are a substantial portion of the total cost for each concept. The expected high cost of SCS/Al tubes results in high material costs for that concept. This analysis indicates thrust structure cost will benefit most from developing better designs and fabrication techniques for the titanium fittings. Revising the designs to incorporate shear web thrust wings (fig. 4.2-5) could be a strategy for reducing the fitting cost. Time limitations prevented study of this approach.

Due to the large size and complexity of the aeroshell, cost estimates were obtained from Rohr Industries, Inc., ASTECH Division of ALCOA/TRE, Aeronca, Inc., and BP Chemicals (HITCO Inc.) for the Ti and Gr/PI honeycomb sandwich concepts. Each company worked from the design drawings revised to accommodate their favored fabrication approach. These custom revisions were not significant to the stress or thermal analysis, and for all operational purposes can be considered equivalent.

Quality assurance (QA) provisions were addressed during manufacturing concept and plan development to ensure that concepts were easy to inspect to reduce impact on schedule and costs. Specifically, QA concerns for concept critical details were developed, along with methods to minimize or eliminate the concern, as shown in figure 4.2-33 for the thrust structure concepts. Provisions for standard QA are included in the recurring costs.

Concept	Critical Detail	Concern	QA Method	Advanced Method
Gr/Ep tube Ti fittings	Tubes	Tube wall consolidation, integrity, and nonvisible impact damage	Automated pulse-echo ultrasonics on completed tube	Monitor AE during tube cure and cool down
	Tube/fitting bond	Bond line integrity	Pulse-echo ultrasonics on completed bond	1) Monitor AE during bond cure and cool down 2) Monitor AE during proof loading
All Titanium	Fitting casting	Cracking	1) X-ray radiography. 2) Dye penetrant	———
	Joint integrity	Welds	1) Eddy current 2) Ultrasonics	1) Monitor AE during welding . 2) Monitor AE during proof loading
SCS/6061 w/ Ti fittings	Tubes	Fiber-matrix bonding; dimensions	1) X-ray radiography 2) Ultrasonics	Monitor AE during proof loading
	Bolted fitting attachment	Fastener alignment	X-ray radiography	———
All 7075 aluminum	Tube/fitting bond	Bond line integrity	Pulse-echo ultrasonics on completed bond	1) Monitor AE during bond cure and cool down. 2) Monitor AE during proof loading
All dSiC/6061	Tubes	Quality of extruded tube material	Automated pulse-echo ultrasonics on completed tube	———
	Tube/fitting bond	Tube to fitting attachment	Pulse-echo ultrasonics on completed bond	

Acoustic Emission (AE) will not detect lack of adhesion, improper wetting, or lack of epoxy
All bond joints prefered over bolted and bonded joints when employing AE
Flat tube sides prefered for ultrasonic inspection

Figure 4.2-33. Thrust Structure Quality Assurance Summary

Life-Cycle Cost Analysis. LCC analyses were conducted to assess the system effects of cost and performance variations in the design concepts. The structural concept options were evaluated based on their benefit to launch system LCC. Because a full launch-system cost analysis is not only very costly, but not necessary for this study, our analysis is incremental. System LCC sensitivities (cost model factors) were calculated from the system LCC model. Weight enters as a debit to the cost estimates (i.e., structural weight higher than the reference configuration incurs an increased cost; structural weight lower than the reference configuration incurs a reduced cost). The cost and weight (mass) estimates for the structural concepts result in LCC differentials from the reference configuration (i.e., a delta LCC). For comparison purposes, the delta LCCs (differences between the concept LCC and the reference configuration) are the significant result, not the absolute LCC values derived.

The process for calculating LCC, outlined in figure 4.2-34, can be performed on a desktop computer spreadsheet. Elements in shaded boxes represent data calculated or estimated during structural concept definition. Elements in rounded boxes are model factors, and represent assumptions based on launch-system economics. Therefore, LCC results depend on cost and weight estimates for each structural concept compared, and on the LCC model factors assumed. These factors are:

Recurring cost:weight ratio: break-even between cost of hardware and resulting mass saved; numerically determined partial derivative calculated from the mission model for the entire launch system.

Design, development, test, and evaluation (DDT&E) cost:weight ratio: breakeven between cost of development and resulting mass saved; numerically determined partial derivative calculated from the mission model for the entire launch system.

Reusable hardware (H/W) ratio: number of times hardware is reused.

Units/flight adjustment: number of common structures on the launch vehicle determined from the ALS mission model (2 or more P/A modules fly on each launch).

Flight rate adjustment: number of flights in the mission model.

Discount factors: the time value of money; near term costs (non-recurring) are weighted higher than far term costs (recurring).

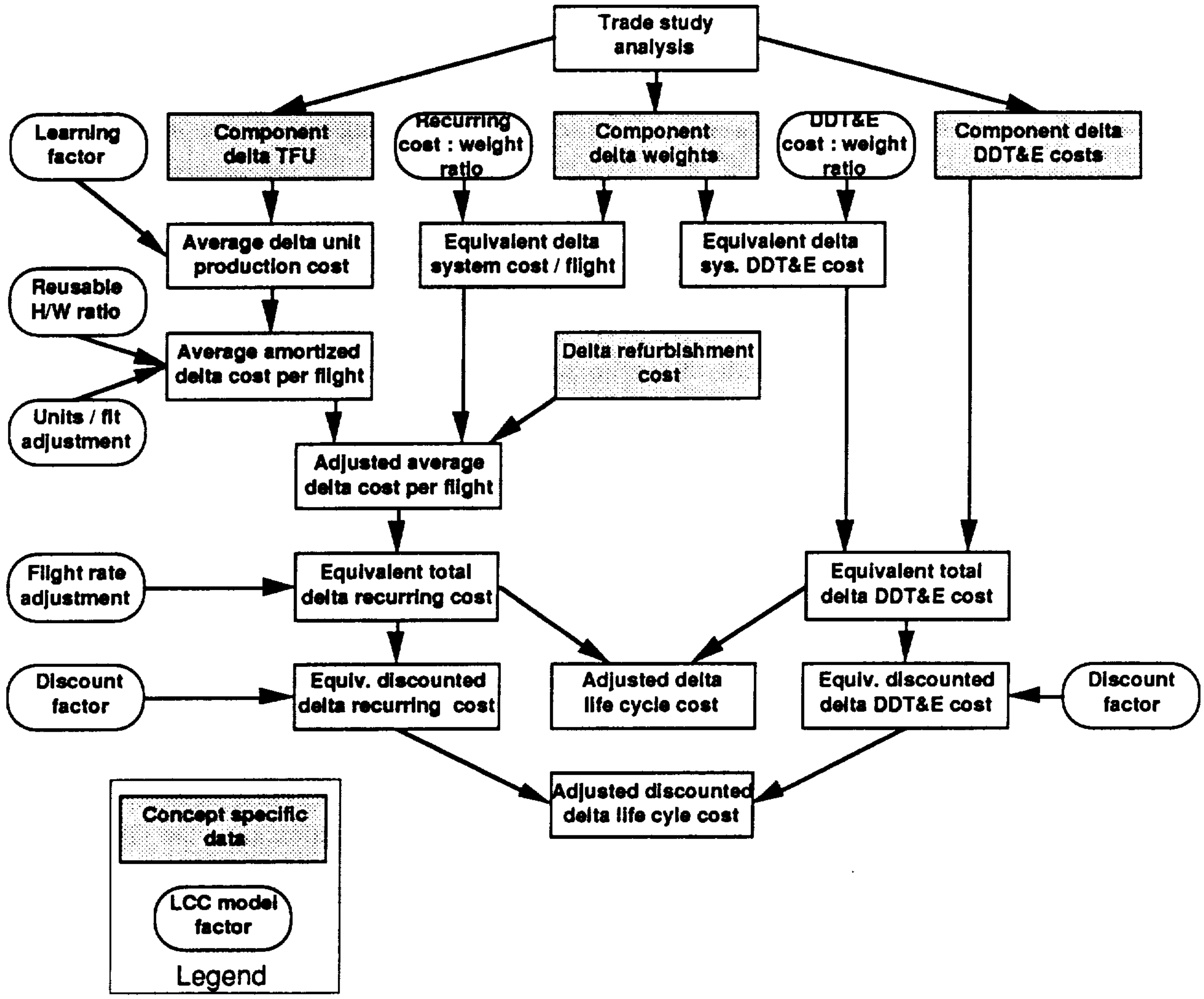


Figure 4.2-34. Procedure for Calculating Delta LCC.

Material, fabrication, and tooling costs are taken from the bottoms-up cost analyses. To determine values for DDT&E and maintenance costs, reference values are taken from ALS parametric cost models and subjectively adjusted for the attributes of the structural concepts. Reference DDT&E costs are based on such inputs as expected weight, complexity, and technical maturity. Then deltas are subjectively estimated from the reference values. For instance, due to their complexity, composite material concepts are typically allocated greater DDT&E and maintenance costs than monolithic materials. Since estimating DDT&E costs is typically more difficult than estimating fabrication costs, using parametric values is most efficient and appropriate approach for this study.

In general, the results of LCC analysis are relatively insensitive to the model factors such as learning curve and discount factors (e.g., the relative rankings of the concepts by LCC does not change). Notable exceptions are the cost:weight ratios, because the greater the premium on reducing mass, the more one is willing to pay in development and fabrication costs. Nevertheless, cost-to-weight ratios within ±50% of their baseline values produce similar concept rankings. For example, the thrust structure LCC (and discounted LCC) is sensitive to reusability involving fewer than 10 reuse cycles (flights), as shown in figure 4.2-35. Fewer reuse cycles implies more modules produced. Above 10 reuse cycles the LCC benefits of reusability flattens as the fixed costs dominate the total costs.

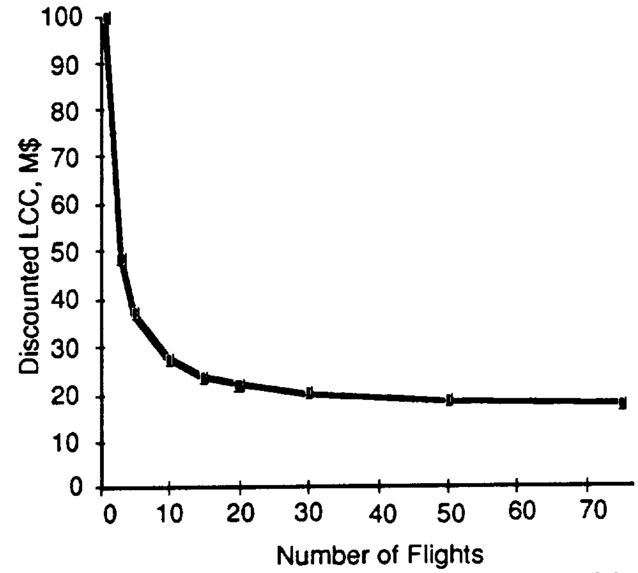


Figure 4.2-35. Reuse Sensitivity of Discounted LCC for Welded Titanium Truss Thrust Structure

<u>Life Cycle Cost Results</u>. Trade study summaries based on LCC for the thrust structure, aeroshell, and bulkhead are shown in figures 4.2-36 through -38 respectively. The cost model factors listed above the tabulations on the figures are consistent across all concepts. The cost analysis tabulations show the theoretical first unit (TFU) cost components, DDT&E and maintenance allocations, and recurring and non-recurring cost summaries. The LCC and discounted LCC results are listed below the tabulated cost elements along with the LCC deltas from the reference concept. Below the matrix, a bar chart is included for visualizing the cost tabulation breakdown.

The dominant cost component for the thrust structure (fig. 4.2-36) is DDT&E which reflects the expected configuration and component complexity assumed in the ALS parametric cost model. Fabrication cost drivers include the high part count (tubes, fittings, and joints); joint complexity; use of multiple/dissimilar materials in the composite concepts; and welding restraint tooling required in the Ti concept. Nevertheless, the LCC and discounted LCC are virtually indistinguishable among these concepts. The additional SCS/Al tube cost, over the Ti and Gr/Ep concepts, is offset by the reduced weight.

Number produced	32
Number of flights	25
Maint learning curve	85%
Discount rate	10%
$ per refurb hour	100

Cost Model Factors (from mission model)	
Recurring cost : weight	150
Fixed cost : weight	14000
Reusable hardware ratio	0.04
Units / flight adjustment	2.5065
Flight rate adjustment	310
Recurring discount factor	0.2424
Nonrecurring discount factor	0.535

Cost Analysis Matrix for Thrust Structure ($M)

	Ref Welded Ti	Concept SCS/Al	Concept Gr/Ep
Learning curve	85%	85%	85%
Weight (lb)	1351	1176	1246
Delta weight	0	-175	-105
DDT&E	18.0	27.0	23.0
Tooling	4.9	3.2	4.3
Debit for weight	0.0	-2.5	-1.5
Total non-recurring cost	**22.9**	**27.8**	**25.8**
TFU - material	0.01	0.18	0.02
TFU - fabrication	1.0	0.9	1.0
TFU - maint per flight (hr)	25.0	100.0	100.0
Material	0.3	5.7	0.5
Fabrication	18.5	16.7	18.6
Maintenance	0.5	2.1	2.1
Debit for weight	0.0	-8.1	-4.9
Total recurring cost	**19.3**	**16.5**	**16.3**
LCC ($M)	**42.2**	**44.2**	**42.1**
Discounted LCC ($M)	**16.9**	**18.8**	**17.8**
Delta LCC ($M)	**0.0**	**2.0**	**-0.1**
Delta Disc. LCC ($M)	**0.0**	**1.9**	**0.8**

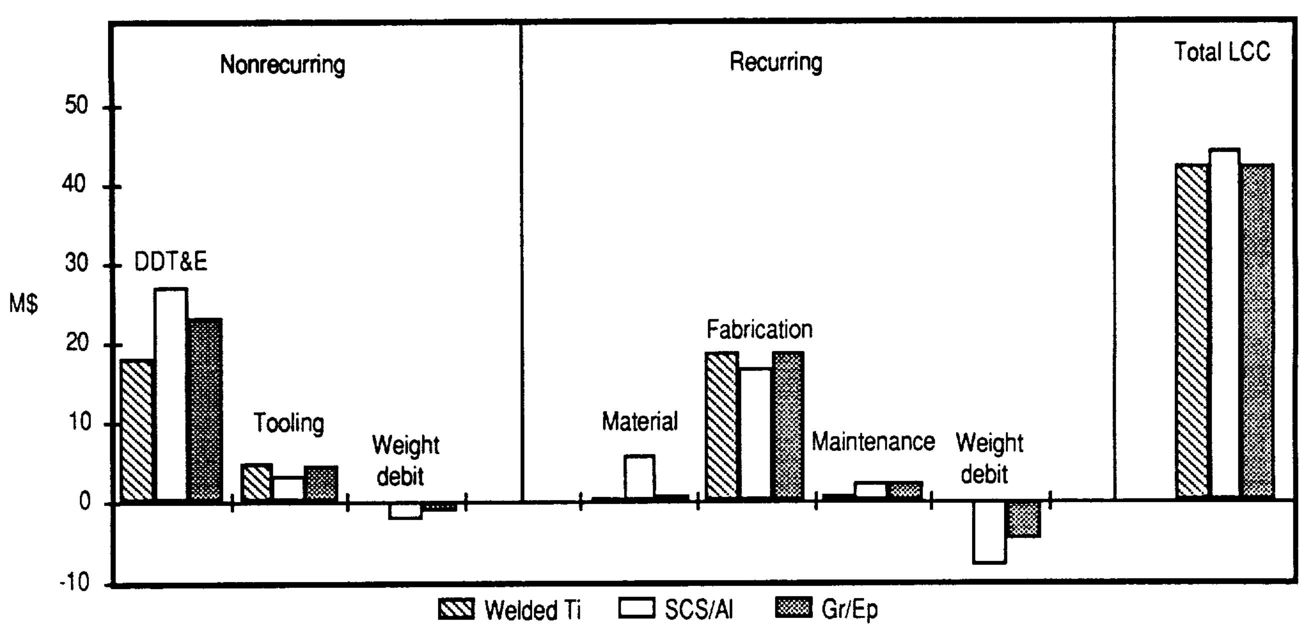


Figure 4.2-36. Thrust Structure Cost Breakdown and LCC Analysis

The LCC summary for the aeroshell concepts is shown in figure 4.2-37. A total of eight cost estimates are included. Four are Boeing estimates developed by the above described procedure, including the Ref Welded Ti concept in the left hand column. The Boeing Gr/PI summary includes the cost of fabricating individual dome and three sidewall panels, then joining them mechanically. In addition, the material and fabrication TFU values have been increased 25% over manufacturing estimated values to reflect a potential scrap rate. For the vendor estimates, no additional factors were applied. Fabrication is the dominant cost component for the aeroshell due to its large size and complex contours. The aeroshell cost bar chart shows averaged values for the Ti and Gr/PI concepts.

The dominant cost component for the bulkhead (fig. 4.2-38) results from the potential for large weight savings and associated LCC savings. Tooling and DDT&E costs are relatively low for the bulkhead because it is a relatively simple component being flat and having few difficult joints.

4.2.5 Concept Scoring and Ranking

Concepts developed for each of the major structural components were cost estimated and weighed, and their relative impact on LCC was determined. Concept scoring and ranking is based on LCC relative impact, as this takes into account concept mass, DDT&E costs, fabrication costs, and maintenance costs. Concept attributes for the thrust structure, aeroshell, and bulkhead are summarized in figures 4.2-39, -40, and -41, respectively. Included are advantages and disadvantages, and technology validation requirements identified for each.

The discounted LCCs for the thrust structure concepts (fig. 4.2-39) are very close. An all-Ti thrust structure was originally conceived as a low-cost, robust approach due to expected lower development costs, and most joints could be welded. Our manufacturing analysis showed that the size of this structure creates difficulties during stress relief of large subassemblies. Since it is not yet clear that the high durability of the welded Ti joints is significant, bonded joints could reduce LCC and still exploit the low cost and low risk features of Ti. The composite tube concepts have a higher expected DDT&E cost due to unknowns in such details as developing effective joints. Nevertheless, the expected weight benefit of high performance composite materials overshadows potential high material costs. Most of the thrust structure cost is in the joints.

TRADE STUDY COST EVALUATOR — Common P/A Module

Number produced	32
Number of flights	25
Refurb learning curve	85%
Discount rate	10%
$ per refurb hour	100

Exchange ratio matrix (from mission model)	
Recurring cost : weight	150
Fixed cost : weight	14000
Reusable hardware ratio	0.04
Units / flight adjustment	2.5065
Flight rate adjustment	310
Recurring discount factor	0.2424
Nonrecurring discount factor	0.535

Cost Analysis Matrix for Aeroshell ($M)

	Ref Welded Ti	Boeing Gr/PI	ASTECH Ti	HITCO Gr/PI	ROHR Gr/PI	Aeronca Ti Low	Boeing Gr/Ep	Boeing Hi-Temp Al
Learning curve	85%	85%	85%	85%	85%	85%	85%	85%
Weight (lb)	3950	3820	4940	3820	3820	5038	5820	4634
Delta weight	0	-130	990	-130	-130	1088	1870	684
DDT&E	12.0	14.0	12.0	14.0	14.0	12.0	12.0	13.0
Tooling	6.2	2.1	4.0	3.2	3.7	7.5	1.4	1.4
Debit for weight	0.0	-1.8	13.9	-1.8	-1.8	15.2	26.2	9.6
Total non-recurring cost	**18.2**	**14.3**	**29.9**	**15.4**	**15.9**	**34.7**	**39.6**	**24.0**
TFU - material	2.38	0.22	1.60	0.20	0.20	0.35	0.14	0.35
TFU - fabrication	1.01	2.04	1.80	1.10	2.00	4.65	1.20	1.20
TFU - refurb per flight (hr)	120.0	150.0	120.0	150.0	150.0	120.0	250.0	130.0
Material	76.2	6.9	51.2	6.4	6.4	11.2	4.5	11.2
Fabrication	18.1	36.7	32.4	19.8	36.0	83.7	21.6	21.6
Refurbishment	2.6	3.2	2.6	3.2	3.2	2.6	5.3	2.8
Debit for weight	0.0	-6.0	46.0	-6.0	-6.0	50.6	87.0	31.8
Total recurring cost	**96.9**	**40.7**	**132.2**	**23.3**	**39.5**	**148.0**	**118.3**	**67.4**
LCC ($M)	**115.1**	**55.0**	**162.0**	**38.7**	**55.4**	**182.8**	**157.9**	**91.3**
Discounted LCC ($M)	**33.2**	**17.5**	**48.0**	**13.9**	**18.1**	**54.5**	**49.9**	**29.2**
Delta LCC ($M)	**0.0**	**-60.1**	**47.0**	**-76.3**	**-59.6**	**67.7**	**42.9**	**-23.7**
Delta Disc. LCC ($M)	**0.0**	**-15.7**	**14.8**	**-19.3**	**-15.1**	**21.3**	**16.7**	**-4.1**

Figure 4.2-37. Aeroshell Cost Breakdown and LCC Analysis (sheet 1 of 2)

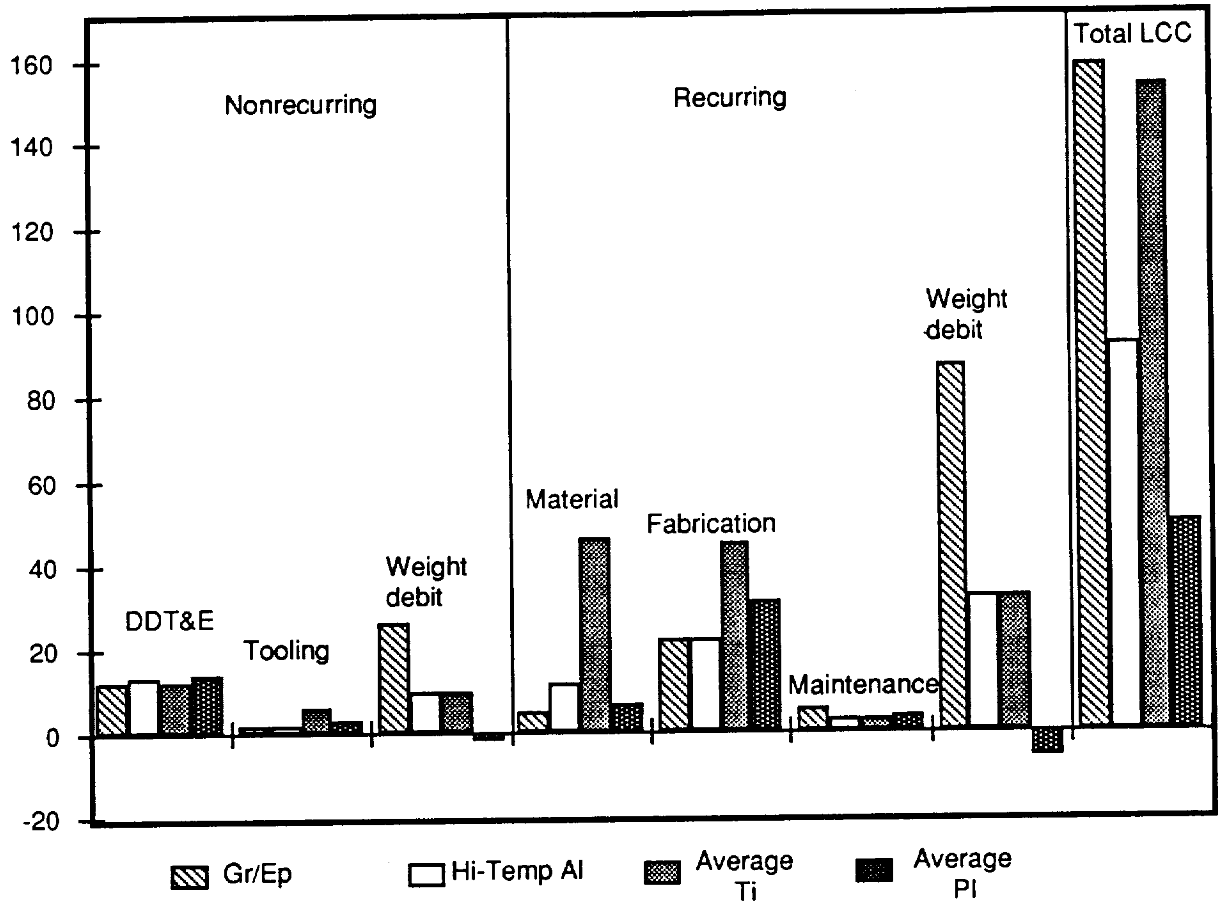


Figure 4.2-37. Aeroshell Cost Breakdown and LCC Analysis (sheet 2 of 2)

Number produced	32
Number of flights	25
Maint learning curve	85%
Discount rate	10%
$ per refurb hour	100

Cost Model Factors (from mission model)	
Recurring cost : weight	150
Fixed cost : weight	14000
Reusable hardware ratio	0.04
Units / flight adjustment	2.5065
Flight rate adjustment	310
Recurring discount factor	0.2424
Nonrecurring discount factor	0.535

Cost Analysis Matrix for Bulkhead ($M)

	Ref Gr/Ep	Aluminum Corrugation	Aluminum Sandwich
Learning curve	85%	85%	85%
Weight (lb)	565	859	899
Delta weight	0	294	334
DDT&E	9.4	4.0	5.0
Tooling	2.0	1.7	1.8
Debit for weight	0.0	4.1	4.7
Total nonrecurring cost	11.4	9.8	11.5
TFU - material	0.04	0.02	0.02
TFU - fabrication	0.6	0.5	0.6
TFU - maint per flight (hr)	20.0	4.0	4.0
Material	1.4	0.6	0.5
Fabrication	10.8	8.4	11.3
Maintenance	0.4	0.1	0.1
Debit for weight	0.0	13.7	15.5
Total recurring cost	12.7	22.8	27.4
LCC ($M)	**24.1**	**32.6**	**38.8**
Discounted LCC ($M)	**9.2**	**10.8**	**12.8**
Delta LCC ($M)	**0.0**	**8.5**	**14.7**
Delta Disc. LCC ($M)	**0.0**	**1.6**	**3.6**

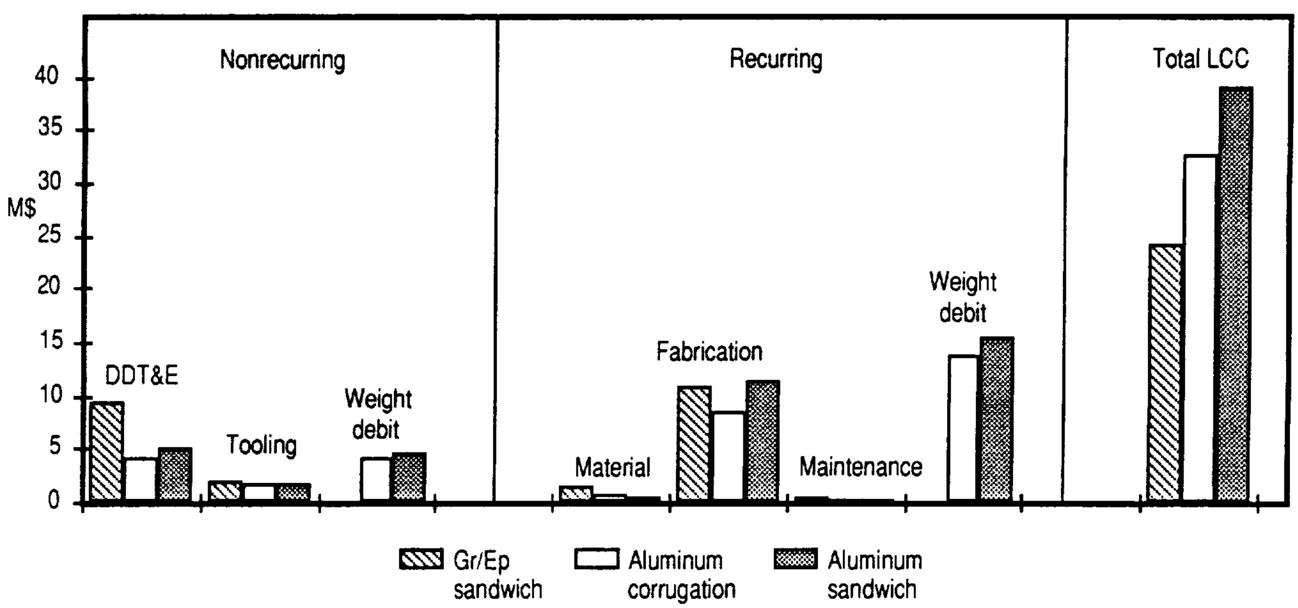


Figure 4.2-38. Bulkhead Cost Breakdown and LCC Analysis

Concept	Advantages	Disadvantages	Technology Validation Requirements	Disc LCC
All Titanium All welded subassemblies (thrust wings and inter truss) bolted together in final assembly.	1. Corrosion-resistant. 2. Maintains high welded strength.	1. Weight penalty. 2. Must prevent distortion during welding.	1. Validate acceptance parameters for automated Class B or C welds.	16.9
Gr/Ep tubes; Ti joints Filament wound strut tubes; Ti end fittings integrally wound; bolted final assembly.	1. Corrosion resistant materials. 2. Hi-temp metals are alternatives. 3. Low risk fabrication approach.	1. Fitting attachment development required. 2. Damage tolerance concerns.	1. Validate low-cost integrally wound end joint concept. 2. Develop investment cast fittings fabricated from dSiC/Al. 3. Validate damage tolerance.	18.8
SCS/Al tubes; Ti joints Pultruded strut tubes bonded and bolted to Ti end fittings; bolted final assembly.	1. Low weight tubes.	1. Availability of tube material. 2. Tube fabrication scale up. 3. Tube to joint attachment development required.	1. Validate end fitting concept to transfer high tube stresses into strut end fittings. 2. Develop investment cast fittings fabricated from dSiC/Al.	17.8
Shear Web; Ti & Al,Bonded honey-comb sandwich shear panels; Ti thrust wings, Al inter panels; bonded and/or bolted assembly.	1. Low weight. 2. Low cost potential.	1. Access to subsystems hindered. 2. Many cutouts in shear webs may be required.	1. Validate damage tolerance and joining techniques of thinner and higher performance dSiC/Al face sheets.	

Figure 4.2-39. Thrust Structure Trade Analysis Summary

Concept	Advantages	Disadvantages	Technology Validation Requirements	Disc LCC
Gr/Ep Honeycomb Sandwich Co-cured assembly .	1. Complete aeroshell cured in one piece. 2. Few joints required. 3. Corrosion resistant. 4. Low mass structure. 5. Layup conforms to complex contour.	1. Large autoclave required (25' dia). 2. Extensive QA required. 3. TPS required on both core and booster vehicles.		49.9
Gr/PI Honeycomb Sandwich Co-cured assembly .	1. Low mass concept. 2. Few joints required. 3. Corrosion resistant. 4. Layup conforms to complex contour.	1. Large autoclave required. (25' dia). 2. Extensive QA may be reqd. 3. Toxic compounds in prepreg. 4. Impact damage sensitive.	1. Panel joint strength under repeated heat and stress cycles. 2. Joint seal under repeated heat and stress cycles.	16.5 (avg)
Titanium sandwich Honey comb panels creep formed and welded, or stretch formed skins, braze to honeycomb core, and weld.	1. Damage tolerant compared to other concepts. 2. Corrosion resistant. 3. Material cost lower than other concepts.	1. Costly tooling. 2. Extensive QA required. 3. Complex welding procedures. 4. Fabricate in relatively small panels.	1. Acceptance parameters for class B or C welds.	45.2 (avg)
High Temperature Aluminum Sandwich Stretch formed skins bonded with high temp. adhesives.	1. Large panel bonding performed in autoclave reducing cost.. 2. Thermal conductivity of aluminum reduces surface temperatures 3. More durable than composites.	1. Cost of alloys currently high. 2. Unknown performance of alloy in honeycomb core and bonded construction.	1. Strength of high temp. Al alloy bonded joint. 2. Strength of bonded high temp. Al honeycomb core. 3. Integrity of bonded joint concept.	29.2

Figure 4.2-40. Aeroshell Concepts Trade Study Analysis Summary.

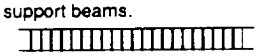
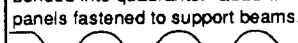
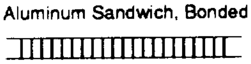
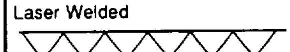
Concept	Advantages	Disadvantages	Technology Validation Requirements	Disc LCC
Gr/Ep Honeycomb Sandwich Co-cured assembly with integral support beams. 	1. Complete bulkhead cured in one piece. 2. Stiffening beams are integral. 3. Fair acoustic attenuation capability. 4. Low corrosion susceptibility.	1. Large autoclave required (>26 ft dia). 2. Extensive QA required. 3. Fasteners required at aeroshell attachment.	1. Validate integration of stiffening beams with panels. 2. Validate acoustic response and capability.	9.2
Aluminum Corrugated Hydroformed subassemblies bonded into quadrants. Quadrant panels fastened to support beams. 	1. Low risk materials can be used . 2. Hi-temp metals are alternatives. 3. Low-risk fabrication approach.	1. Insulation required on exterior surface. 2. Corrugations interrupted for panel splices and cutouts. 3. Poor acoustic attenuation.	1. Validate structural capability of bonded joints and cutout doublers. 2. Validate acoustic response and capability.	10.8
Aluminum Sandwich, Bonded 	1. Established (low risk) fabrication procedures. 2. Resistant to sonic fatigue. 3. Non precision fabrication is feasible. 4. Low cost-risk.	1. Fabricating a one piece bulkhead difficult . 2. Fab. may be labor intensive. 3. Must protect against corrosion at faying surfaces.	1. Validate structural capability of bonded joints and splices. 2. Validate edge-of-panel seals and corrosion resistance.	12.8
Truss core, Al-Li Laser Welded 	1. Low production cost potential. 2. Panel geometry optimization is simplified.	1. Material strength loss at welds. 2. Must protect against corrosion at faying surfaces.	1. Validate structural capability of welded joints and splices. 2. Validate treatment at faying surfaces for corrosion resistance.	

Figure 4.2-41. Bulkhead Concepts Trade Study Analysis Summary.

The cost differences between the aeroshell concepts are more significant as shown in figure 4.2-40. The Ti sandwich concept primary cost driver is fabricating the panel subassemblies. The Ti sandwich face sheets must be hot formed, and this drives up the cost of both tooling and processing. Vacuum furnaces for diffusion bonding or brazing core to face sheets limits panel size. In the large aeroshell, many panels are required in a variety of contours. Maintaining fit-up tolerance for welding so many panels is also costly. The Gr/PI sandwich concept has the lowest discounted LCC, however the costing procedures used cannot fully account for the high risks associated with fabricating this type of material, and with impact damage durability during operation.

A potentially low-risk option is to fabricate a one piece Gr/Ep sandwich aeroshell and use a TPS to protect the booster as well as the core. However, the increased weight and per flight maintenance of the TPS required for booster module trajectory reentry increases the LCC over the Gr/PI concepts.

The bonded HTA aeroshell concept combines the positive features of both the metallic and composite concepts. Large panel segments, including the dome, can be co-bonded in existing autoclaves reducing the amount of joining required. The metal face sheets, although bonded, should diminish the damage tolerance concerns of the composite concepts. Given an appreciation for the uncertainties in cost estimating, the HTA aeroshell may provide a low cost alternative to the Ti concepts, and a more robust alternative to the Gr/Ep and Gr/PI concepts. The uncertainties in applying HTAs to integrated, large structure requires that the HTA concept be validated in continuing research and development. In particular the performance of HTA face sheets bonded to honeycomb core requires investigating. Joints are also critical on the aeroshell from cost and performance perspectives.

Weight differences are most significant for the bulkhead concepts as shown in figure 4.2-41. The corrugated aluminum concept was proposed as potentially the low-cost option, but is penalized by high weight. The bonded aluminum sandwich concept was unexpectedly heavy due to minimum gage limitations. Upon reflection, we feel a Gr/Ep truss core bulkhead is potentially a structurally efficient concept for the bulkhead, and should be considered in future trade studies.

In summary, the aeroshell exceeds both the thrust structure and aft bulkhead in overall LCC impact. This is due to its large weight, cost of tooling, and complex fabrication involving such details as access doors and compound contours. Additional development effort would find the largest payoff if concentrated on the aeroshell structure.

4.3 TASK 3: TECHNOLOGY DEVELOPMENT PLAN

The aeroshell structural concept selected for further development employs HTA alloys and composites. Honeycomb panel construction provides stiffness against water impact (splash-down). For cost effectiveness the honeycomb structure will be bonded. Four candidate adherend alloys for the face sheets are included below.

Candidate Alloy	Advantage	Supplier
8009	High-temperature Al alloy	Allied-Signal
Weldalite	Al-Li alloy with high-temperature capability	Reynolds
SiCp/8009	Reinforcement increases strength and stiffness and may increase temperature capability	Allied-Signal
SiCp/8090	Reinforcement increases strength and stiffness and may increase temperature capability	DWA

Candidate adhesives have been selected to correspond with the temperature capability of the face sheet materials. EA 9674, supplied by Hysol, is a modified bismaleimide film adhesive with structural capability up to 550°F. FM 680 is a well established polyimide adhesive. The PT Resin is an adhesive under development at Allied-Signal. It is a modified phenolic system developed for use in high temperature and high performance applications. Curing is through a total addition reaction, eliminating the generation of volatiles. AF-191 cures at 350°F and is supplied by 3M. It is included for use with the materials that would anneal at the high bonding temperatures required by the other adhesives.

4.3.1 Phase II: Technology Validation

This phase develops the technologies required for successful reusable structures demonstration. A down selection of materials and structural concepts shall be made so that a specific reusable concept can be demonstrated in Phase III.

Task 1: Lap Shear Testing. The first portion of the Phase II test program is to screen candidate adhesives. Lap shear testing will verify the preparation and bonding processes using these advanced adherends and adhesives. Figure 4.3-1 shows the test matrix. Testing will be performed over the temperature range consistent with the material capabilities. The three high temperature adhesives will be fully assessed with 8009 alloy adherends across the representative temperature range. Verification of adhesive capability will be made with the SiCp/8009 material in the high temperature regime.

Adherends	Test Temp, °F	Adhesives EA 9674 (BMI)	FM 680 (PI)	PT Resin	AF191 Epoxy
1 - 8009 Al sheet	-67	5	5	5	—
	72	5	5	5	—
	250	5	5	5	—
	300	5	5	5	—
2 - Weldalite sheet -T8	-67	—	—	—	5
	72	—	—	—	5
	200	—	—	—	5
	250	—	—	—	5
3 - SiCp/8009	-67	—	—	—	—
	72	—	—	—	—
	250	5	5	5	—
	300	5	5	5	—
4 - SiCp/8090	-67	—	—	—	5
	72	—	—	—	5
	200	—	—	—	5
	250	—	—	—	5
			Total lap shear specimens = 130		

Surface treat adherends per BAC 5555 (Phosphoric acid anodizing of aluminum for structural bonding)
Test Specifications - ASTM D1002 & D2295

Figure 4.3-1. Phase II Lap Shear Test Matrix.

Task 2: Sandwich Sub-Element Testing. Subelement testing (matrix shown in fig. 4.3-2) will evaluate the aluminum alloy and adhesive combination in configurations more structurally representative than lap shear specimens, and include flatwise tension and edgewise compression. The best adhesive as indicated from lap shear testing will be chosen for each adherend material. Sandwich element configurations are shown in figure 4.3-3. Selected specimens will be thermal cycled and damaged to assess long-term performance in the structural configuration. Testing will be performed between R.T. and 250° or 300°F.

	Face sheet materials	Adhesive materials	Thermal cycling Yes	No	Test Temperature 72°F	250°F	300°F	Total
Flatwise tension	1	best	√	√	3		3	12
	2	4	√	√	3	3		12
	3	best	√	√	3		3	12
	4	4	√	√	3	3		12
Edgewise compression	1	best	√	√	3		3	12
	2	4	√	√	3	3		12
	3	best	√	√	3		3	12
	4	4	√	√	3	3		12
Edgewise compression Damaged	1	best		√			3	3
	2	4		√		3		3
	3	best		√			3	3
	4	4		√		3		3
Joint element (welded)	1	best	√	√	3		3	12
(unwelded)	1	best	√	√			3	6
					Total sandwich specimens = 126			

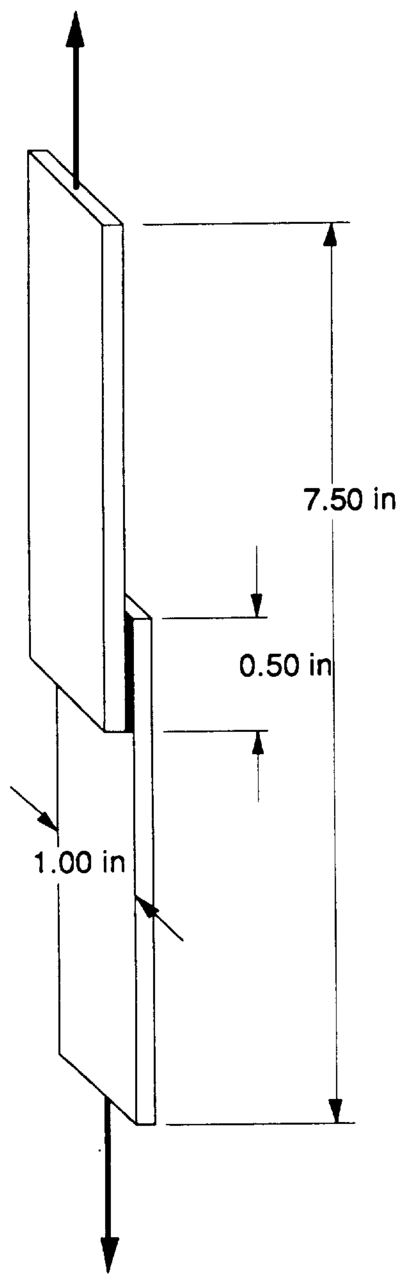
Face sheet materials
1 - 8009 Al sheet
2 - Weldalite sheet -T8
3 - SiCp/8009
4 - SiCp/8090

Adhesives
1 - EA 9674 (BMI)
2 - FM 680 (PI) [Alternative - LARC TPI]
3 - PT Resin
4 - AF 191 Epoxy

Thermal Cycle
50 cycles -67° to 250 or 300°F

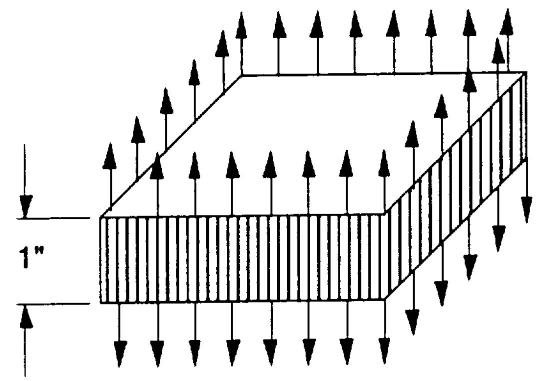
Honeycomb core — Ti 3-2.5 perforated, 1" thick, 6.5 lb/cu ft

Figure 4.3-2. Phase II Sandwich Specimen Test Matrix.



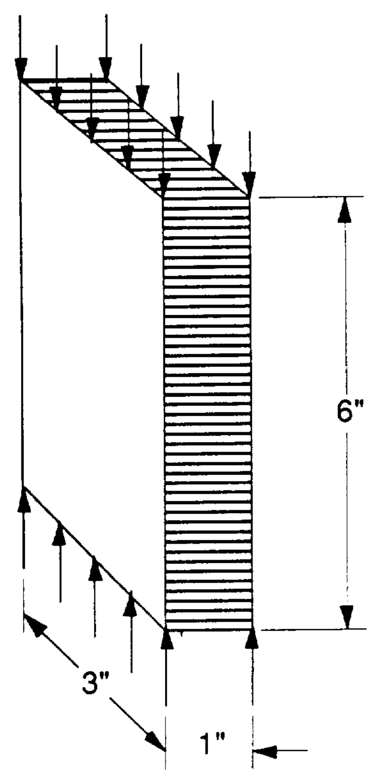
Lap Shear Test
(ASTM D1002 & D2295)

Objective: Validate adhesive strength and surface treatment of high temp Al adherends.



Flatwise Tension Test
(ASTM C 297) (2"X2")

Objective: Validate capability of high-temp adhesives and aluminums in sandwich structure.



Edgewise Compression Test
(ASTM C 364)

Objective: Validate capability of high-temp adhesives and aluminums in sandwich structure.

Figure 4.3-3 High-Temperature Aluminum Materials and Processes Evaluation Specimens.

Task 3: Joint Element Testing. Joints are a critical detail in applying and using the proposed advanced materials. The joint element sandwich specimen represents an innovative joint concept in the high-temperature aluminum aeroshell design developed in Phase 1. A joint element, as shown in figure 4.3-4, will be configured, fabricated, and tested. Selected specimens will be thermally cycled to assess long-term performance, and testing will be performed at R.T. and 300°F as shown in figure 4.3-2.

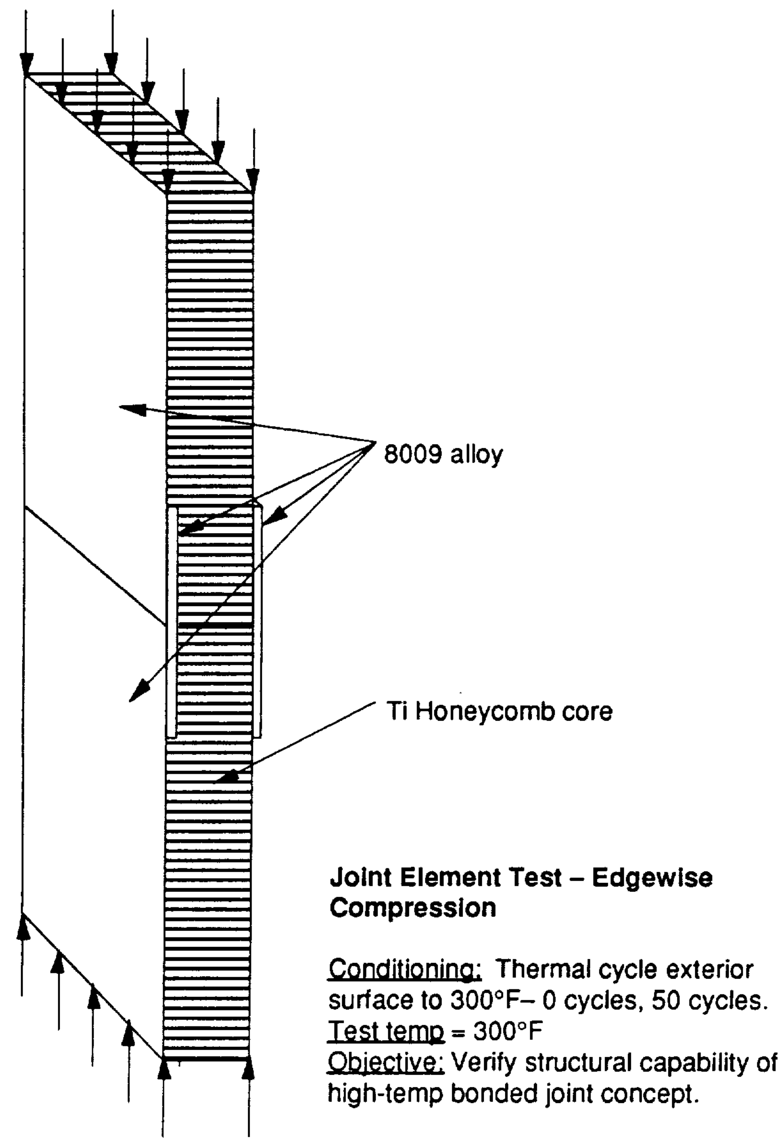


Figure 4.3-4. High-Temperature Bonded Joint Concept Validation Test.

4.3.2 Phase III: Hardware Demonstration

During this phase, a hardware demonstration shall be conducted of a reusable structural concept employing the materials validated in Phase II. This shall entail design, fabrication, test, and evaluation of a panel representative of a significant structural component.

Task 1: Design. The selected demonstration hardware component shall be a panel, such as depicted in figure 4.3-5. This test panel would demonstrate the capability of an access door frame in carrying representative structural loads. A test plan will be prepared for NASA LaRC approval that will include as a minimum panel attached to a boiler plate substructure, attachments for test load introduction, instrumentation, and data collection systems.

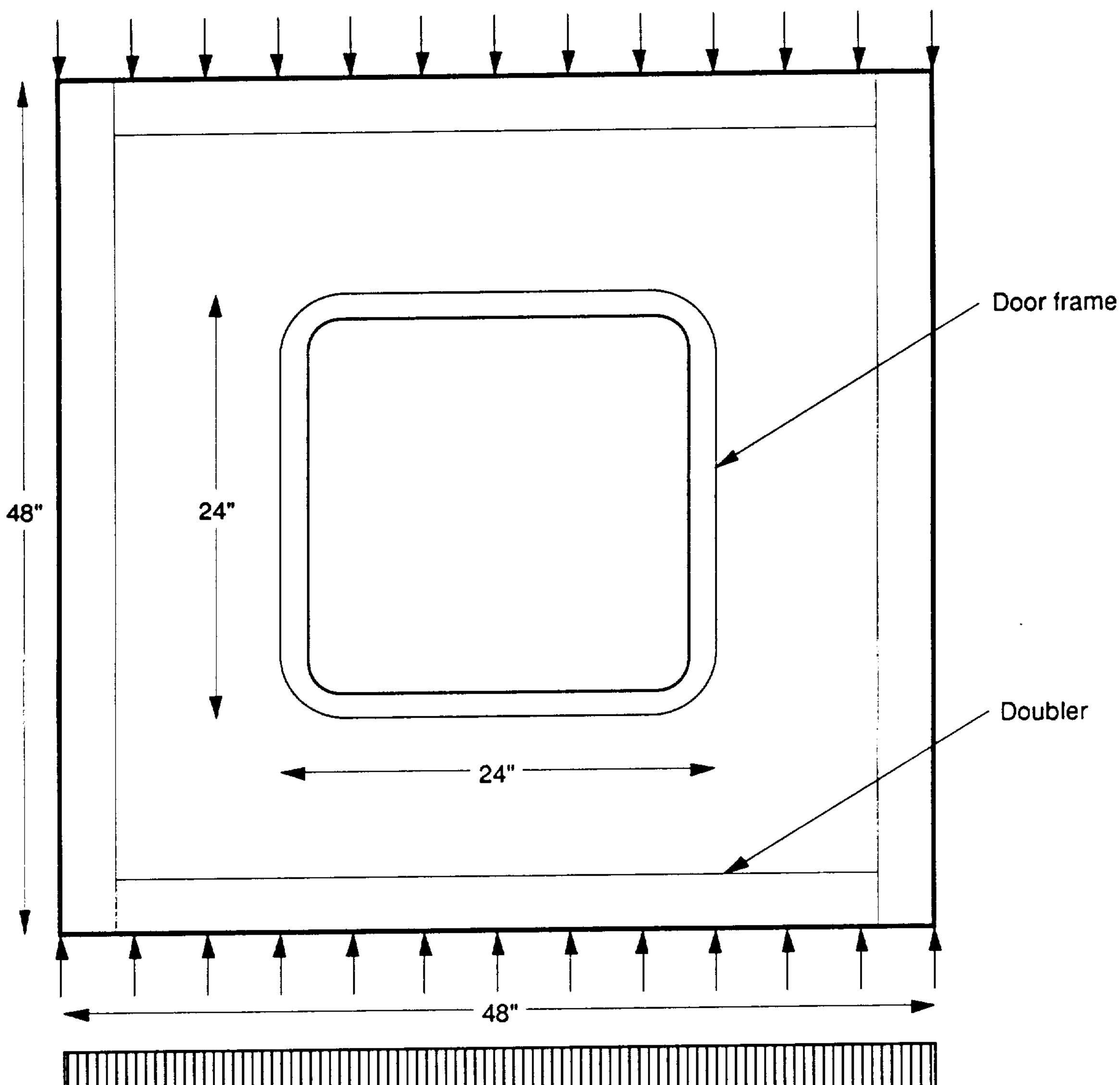


Figure 4.3-5. Phase III Hardware Demonstration P/A Module Aeroshell Door Test.

Task 2 - Fabrication. A fabrication plan will be prepared for NASA LaRC approval that shall include as a minimum detail drawings, material requirements, tool designs, assembly techniques, and quality assurance provisions. Upon approval from NASA LaRC, demonstration panel detail parts will be fabricated and assembled.

Task 3 - Testing and Evaluation. The approved NASA LaRC plan will be executed for testing the demonstration panel. Data will be obtained to validate and possibly refine earlier structural models and analyses. The test data will be evaluated to assess the applicability of the advanced technologies studied here to future reusable structures. Following test and evaluation, the tested panel will be delivered to NASA LaRC.

Schedule:

The schedule for Phase II is shown in figure 4.3-6. Phase II is expected to require approximately 10 months to complete.

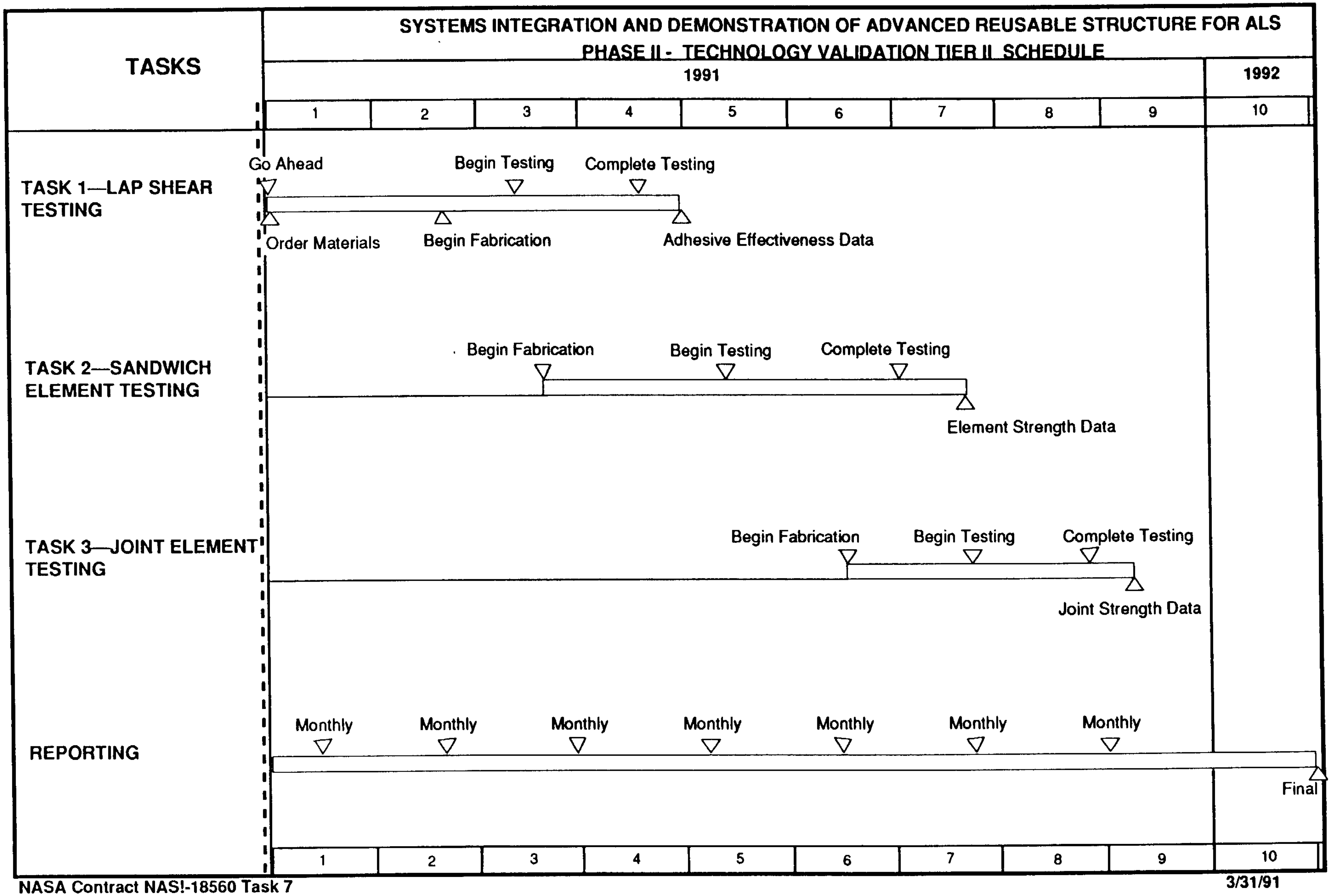


Figure 4.3-6. Phase II Technology Validation Tier II Schedule

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5.0 CONCLUSIONS

Preliminary requirements, loads, and environments are defined for reusable structure on the ALS P/A module.

Design concepts and candidate materials are defined for P/A module structure (thrust structure, aft bulkhead, and aeroshell) that conforms to the preliminary requirements, and these concepts are available for further specification and development. Stress analysis indicates that all structural concepts analyzed can perform to the identified loading conditions.

The baseline thrust structure truss configuration using Gr/Ep, Ti, or SCS/Al tube members is feasible. LCCs are virtually indistinguishable among these concepts. Time limitations prevented full consideration of shear web thrust structure, which may have cost benefits in the highly loaded areas.

Several bulkhead concepts and material applications are available for further development. Cost analysis indicates that lower structural weight provides the Gr/Ep sandwich concept a lower LCC than the Al corrugation or the Al sandwich concepts.

Thermal analysis indicates that mature aeroshell structural materials must be protected (with a TPS) from the temperatures experienced by the core P/A module when reentering the atmosphere upon return from orbit.

The aeroshell has the highest LCC impact of the three structural elements studied, and is dominated by fabrication cost. Therefore, further efforts should concentrate on developing the aeroshell structural elements to offset high-cost features.

The Ti aeroshell LCC is driven by the requirement to hot form or creep form the compound curvatures, and to braze many sandwich structural panels of limited size.

The HTA aeroshell combines the durability of metallic structure with bonded construction permitting large panel fabrication in existing autoclaves. HTA alloys and fabrication methods are less mature than those for Ti and Gr/PI, therefore Phase II of this contract should concentrate on developing HTA technology.

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APPENDIX A - DESIGN DATABASE

These charts list the properties for the structural materials we used in performing our trade studies, design concept preparation, and analyses. A-basis allowables were used when possible. Reduced vendor or typical properties were used otherwise.

These charts show our survey of feasible TPS materials for application to the aeroshell ablator. We feel that reliable data for key ablative properties such as maximum heat flux capability are currently unavailable, and testing is required for further TPS concept definition, performance analysis, and concept optimization.

MATERIAL	Temp (F)	Exposure (hr)	Ftu (ksi)	Fty (ksi)	Fcy (ksi)	Et (msi)	Ec (msi)	CTE µ in/in/°F	e (%)	K1c (ksi-sqrt(in))	density (lb/in3)	Source & Notes
Aluminum												
2024-T81	RT		67	59	57	10.5	10.7		5(Lt)		0.1	BDM (plate) A basis
	350	10	51.6	46	43.9	9.3	9.5					
	400	10	44	41	40	8.9	9.1					
2219-T81	RT		62	47	48	10.5	10.8				0.102	BDM (sheet & plate, 0.02" - 0.249") A basis
	350	10	44.6	36	37	9.5	9.7					
	400	10	38.4	30	30.7	9	9.3					
2519	RT		56.7	54	51.3							
6061	RT		42	36	35	9.9	10.1		8(LT)			BDM (sheet) A basis
	300		33.8	30	29.3	9.5	9.6	15.1				
	400		26.9	25	24	8.9	9.1	15.1				
	600		8.82	7	6.3	6.9	7.1	15.1				
7075-T6	RT		78	70	69	10.3	10.5		8		0.101	BDM (plate) A basis 0.04-.125"
	300	10	54.6	52	52.4	9.2	9.3	14.9				
	350	10	37.4	40	41.4	8.8	8.9	14.9				
	400	10	25.4	23	22.8	8.2	8.4	14.9				
Aluminum-Lithium												
2090-T83	RT		65.5	60	57	11.5	11.8		3		0.093	AMS draft D88AC spec sheet (85% 0f S basis)
	300	0.5	59.5	54					14			
	400	0.5	40	37					18			
	500	0.5	23.8	22					21			
2090-T8E41	RT		67.2	64	na	na			6.5		0.093	Alcoa 17th SAMPE, 85% of typicals
8090-T8	RT		62	54					5		0.092	ALCAN "LITAL" (85% of reported typicals)
	300											
8090-T6	RT		58	46					5.7			ALCAN "LITAL" Sept 1988 (85% 0f typ)
Weldalite-049	RT		81.9	79					5.2		0.099	16hr age at 160C, 0.2" sheet (85% of typ) M.M. 1988
	300			72								
	600			19								
High Temp Al												
Al-Fe-V-S 0812	RT		53.9	48	62.5	10.9	10.9	12.2	10	23.8	0.105	Allied Signal, extrusions & sheet (85% of reported)
	300	0.5	45.8	42	55.3	10.2	10.2		7			
	400	0.5	42	38	52.7				8			
	600	0.5	32.1	30		9	9		9			

MATERIAL	Temp (F)	Exposure (hr)	Ftu (ksi)	Fty (ksi)	Fcy (ksi)	Et (msi)	Ec (msi)	CTE µ in/in/°F	e (%)	K1c (ksi-sqrt(in))	density (lb/in3)	Source & Notes
Al-Fe-V-S 1212	RT		78.4	75	78.2	11.9	11.9	12			0.109	Allied Signal, extrusions & sheet (85% of reported)
	300	0.5	62.2	60	68	10.6	10.6					
	450	0.5	53.8	53	48.5	10.2	10.2					
	650	0.5	35.3	41		9.4	9.4					
Al-Fe-Ce CU78	RT		60.8	57					9.2			Alcoa gas atomized PM
	600		22.4	17					5.5			
Al-Fe-Ce CZ42	RT		56.9	54					11			Lockheed LR31456 (0.045" sheet, from PM)
	450		32.7	30					8.5			
	600		17.5	14					6.3			
Titanium												
Ti-6-4	RT		134	126	132	16	16.4				0.16	BDM A basis, anealed plate <=.1875"
	300	0.5	111.2	97	103	14.72	15.09					
	400	0.5	104.5	89	93.7	14.24	14.6					
	600	0.5	95.14	78	83.2	13.12	13.45					
	800	0.5	87.1	73	77.9	11.84	12.14					
	1000	0.5	68.34	54	59.4	8.32	8.528					
Ti-15-3-3-3	RT		120	116	118	15.2	15.3				0.172	BDM sheet & strip (85% of S basis)
	200	0.5	114	109	111							
	400	0.5	107	97	98.5							
Ti-6-2-4-2	RT		135	125	132	16.5	18				0.164	BDM sheet & strip 0.047"-.093"
	300	0.5	119	104	106	15.3	16.7					
	400	0.5	112	95	96	15	16.4					
	600	0.5	103	81	88	14.3	15.7					
	800	0.5	97	75	82	13.4	14.6					
	1000	0.5	89	70	70	12	13.1					
Ti-6-6-2	RT		155	145	n/a	16	16.4				0.164	BDM A basis annealed sheet <=0.1875"
	300	0.5	135	120		14.9	15.3					
	400	0.5	127	112		14.4	14.8					
	600	0.5	118	99		13.4	13.8					
	800	0.5	110	94		12.5	12.8					
Ti-1100	RT		125	112				14.8	10.3	61		Timet Corp. 6-87 heat V6563:
	400		101	86					11			200F forged + 1100F/8hr
	600		96	79					11			
	900		88	75								
	1200		77	64								

MATERIAL	Temp (F)	Exposure (hr)	Ftu (ksi)	Fty (ksi)	Fcy (ksi)	Et (msi)	Ec (msi)	CTE µ in/in/°F	e (%)	K1c (ksi-sqrt(in))	density (lb/in3)		Source & Notes
Inconel 718	RT		180	147	147	29.4	29.4				0.297		BDM A basis, treated & aged per BAC-5616
	300	0.5	173	141	141	28.5	28.5						sheet 0.01"-0.187"
	400	0.5	169	138	138	28.1	28.1						
	600	0.5	166	135	135	27.2	27.2						
	1000	0.5	160	131	131	25.3	25.3						
	1400	0.5	90	79	79.4	22.3	22.3						
Inconel 625	RT		120	56	52	29.8	29.8				0.305		BDM A-basis annealed 0.06"-0.1" sheet
	300	0.5	113	47	47	26.8	26.8						
	400	0.5	110	44	45	26.2	26.2						
	600	0.5	107	41	43	25.3	25.3						
	900	0.5	102	38	41	24.7	24.7						
	1200	0.5	94.8	38	40	24.1	24.1						
	1500	0.5	46.8	29	30	18.8	18.8						
Rene' 41	RT		170	123	131	31.6	31.6				0.298		BDM A basis, .002"-.187" sheet treated & aged
	300	0.5	162	122	130	30.7							
	400	0.5	160	121	128	30							
	600	0.5	156	119	127	29.7							
	900	0.5	153	118	124	27.8							
	1200	0.5	145	114	117	26.2							
	1500	0.5	81.6	76	82.5	22.1							
	1800	0.5	11.9	9	19.7	13.3							
Incoloy MA 956	RT		79.5	68.2		39.0		6.3	10		0.26		IncoMAP data sheet. Strength values 85% of typicals.
	750		67.0	52.1		35.5		6.8	11				
	1110		33.9	24.8		33.1		7.2	21				
	1470		17.2	15.0		30.2		7.7	12				
	1650		14.2	13.3		29.1		8.0	8				
	1800		12.3	12.0		28.0		8.3	4.5				
	2000		11.2	10.5				8.6	3.5				
	2200		9.8	9.4					2				
Composites													
SCS-6/Ti-15-3-3-3	RT			212	354	24.2	2408	3			0.137		ACMDG unidirectional prop. (1-dir)
	750			184	265	24.1	24.5						(35% fiber vol)
	1200			136	336	21.3	20.9	4.7					85% of typ
SCS-2/Al 6061-F	RT			183	445	20.7	23.2	3.2			0.106		ACMDG unidirectional prop. (1-dir)
	400			100	345	.26	21.4						(50% fiber vol)
	700			83		23.1							85% of typ

MATERIAL	Temp (F)	Exposure (hr)	Ftu (ksi)	Fty (ksi)	Fcy (ksi)	Et (msi)	Ec (msi)	CTE µ in/in/°F	e (%)	K1c (ksi-sqrt(in))	density (lb/in3)	Source & Notes
FVS0812/SiCp	RT		74	69		12.4						Allied-Signal, report by Zedalis, et al
(10% vol SiCp)	300		53	60		11.1						values are 85% of reported
	450		49.3	48		10.5						
	600		35.7	34		9.7						
FVS0812/SiCp	RT		74.8	67		13.3		9.5			0.106	Allied-Signal, report by Zedalis, et al
(15% vol SiCp)	300		59.5	61		12.2						values are 85% of reported
	450		50.2	49		11.5						
	600		36.6	35		10.4						
dSiC/Al 6060-T6	RT			68	63.8	14	12.8	7.5			0.103	ACMDG, 85% of typicals, 20% fiber vol
dSiC/Al 2124	RT			84	65.4	13.3	14.1				0.103	ACMDG, 85% of typicals, 15% fiber vol
	300			72	65.4	11.2	14.1					
dSiC/Al 7090-T6	RT			94	111	13.3	14.2				0.103	ACMDG, 85% of typicals, 20% fiber vol
	600			9	18.7	5.18	10.3					
dSiC/8090-T6	RT		66.81	56		15			3.5		0.96098	BP data sheet, 85% of typicals, 17% fiber vol
Celion 6000/PMR-15	RT			186	125	16.5	15.7	-0.4			0.058	ACMDG, 85% of typicals, 63% fiber vol
	600			197	69.4	17.2	18	0.14				unidirectional lamina properties
P75S/93 Gr/Ep	RT		86.7			35.8						ACMDG, 85% of test, 56% fiber vol, unidirectional
P100/Al 6061	RT			83	45.8	36.8	32.3	0.7			0.086	ACMDG, 85% of typ, 45% fiber vol, unidirectional
Celion 6000/PMR-15	RT		64.69		67.2	7					0.06	85% of typ. test data; 65.3% fiber vol, [0/+45/90/-45]2s
	600		63.58		46.8	6.7					0.06	

NOTES:

ACMDG = Advanced Composite Material Design Guide, typicals

BDM = Boeing Design Manual

Candidate P/A Module TPS Materials

Material	Density (lb/ft3)	Max. Heat Flux Capability (BTU/ft2-sec)	Fabrication Approach	Maintenance Procedures	Attachment Methods
Boeing Fibrous Ceramic (MEFC) - microballon and whisker enhanced fibrous ceramic - All fiber			Water slurry, vacuum felting of shapes or boards, binder infiltration, cure (repeat to required density), final heat treatment to use temperature.	Depending on attachment method: 1. Replace or patch* tile. 2. Cut and replace section of honeycomb or patch* damage. 3. Replace module or patch* *Patch procedure - fabric reinforced thick paste, heat gun cure.	1. Direct bond to Gr/Ep structure with RTV. 2. Imbedded honeycomb - solid metal (Ti, stainless steel or super alloy) - metal mesh. 3. Ceramic matrix composites. 4. Bonding to metallic structures may require a strain isolation pad because of CTE mismatch.
AETB alumina enhanced thermal barrier	12	33	Water slurry with alumina, silica, alumino borosilicate fibers→V blender→ press out water→ dry 180°F overnight → fire 2400°F→ machine→ topcoat by spraying with toughened unipiece fibrous insulation (TUFI)→ dry→ sinter→ finished tile.	1. Replace tile. 2. Repair small chip/minor surface damage with alumina cement.	1. Direct bond to structure with RTV (if structure is Gr/Ep). 2. Topcoat with TUFI. 3. Bonding to metallic structures may require a strain isolation pad because of CTE mismatch.
Phenolic/Cork	30	TBD	1. Premolded sheets, machined shapes. 2. Spray protective seal coating.	1. Removed damaged material with conventional hand, machine tools. 2. Bond patch with RT cure adhesive 3. Repair small areas with trowelable silicone or rubber.	1. Bond premolded sheets and machined shapes to structure or to mechanically attached support substrate.
Phenolic/Carbon	90*	>300	1. Tape-wind or hand lay-up to near net shape. Autoclave cure. Machine mating surfaces.	1. Machine matching surfaces of undamaged material and patch. Bond patch with min. exposed bond line.	1. Bond to structure. 2. Mechanical attachments, using molded-in fittings or internal machined threads.
Phenolic/Silica	109*	TBD	1. Tape-wind, hand lay-up of cloth, or mold with chopped fibers or chopped fabric, to near net shape. Machine mating surfaces.	1. Same as for Phenolic/Carbon.	1. & 2. Same as for Phenolic/Carbon.

*Fillers may be added for lower density, lower conductivity, but also lower ablative shear resistance.

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Candidate P/A Module TPS Materials

Material	Advantages	Drawbacks	Vendor	Cost: Material	Cost: Manuf.	Cost: Maint.
Boeing Fibrous Ceramic (MEFC) - microballon and whisker enhanced fibrous ceramic - All fiber	MEFC - low density • more isotropic* • Higher compression strength* • formable in large shapes • lower processing costs* • good thermal properties • reusable *As compared to shuttle tiles	Shuttle tile qualification testing needed for material and attachment concepts.	• Boeing • Boeing licensed choice of: • Hexcel • Babcock & Wilcox • Carborundum	Lowest- $25/ft^3$ Highest $200/ft^3$ Most likely - $75/ft^3$		
AETB alumina enhanced thermal barrier	1. Light weight. 2. Reusable. 3. Greatly improved impact resistance with TUFI topcoat system.	1. Labor intensive. 2. Not a production process. 3. TUFI may exhibit bubbling at temperatures in excess of 1400°C. 4. One manufacture.	Material - NASA Ames Research Center Tiles - Lockheed Missile Systems			
Phenolic/Cork	1. Good thermal properties. 2. Extensive experience. 3. Easily bonded. 4. Easily repaired. 5. Conforms to complex shapes by moderate bending of sheets, or easy machining. 6. Low cost.	1. Damage susceptible. 2. Moisture protection required. 3. Poor aero. shear resistance.				
Phenolic/Carbon	1. Best ablator in extreme environments (high heat, high shear). 2. Tough, damage and weather resistant. 3. Well characterized properties.	1. Rigid-requires machining of bond surface. 2. Limited Boeing experience 3. Poorer insulator than lower density ablators. 4. Heavy.				
Phenolic/Silica	1. Heat flux and shear capability nearly as good as Phenolic/Carbon. 2. Better insulator than Phenolic/Carbon. 3. Tough, damage and weather resistant. 4. Well characterized properties. 5. Extensive experience (BMS Spec.)	1. Rigid-requires machining of bond surface. 2. Difficult to machine. 3. Poorer insulator than lower density ablators. 4. Heavy.				

Candidate P/A Module TPS Materials

Material	Density (lb/ft3)	Max. Heat Flux Capability (BTU/ft2-sec)	Fabrication Approach	Maintenance Procedures	Attachment Methods
SLA 561 Highly filled silicone elastomer	17	60*	1. Premolded sheets. 2. Spray apply, then cure. 3. Mold in place on structure, by vacuum bagging. 4. Hand compact on structure without vacuum bagging. Machine (all structure must be primed).	1. Bond plug of cured material. 2. Using trowelable material, fill or cover damaged area. Sand smooth.	1. Bond premolded sheets to structure. 2. Apply uncured over adhesive by spray application, molding or hand compacting. 3. Can be applied to metallic or composite skin and mechanically fastened to structure.
MA25S filled silicone (MA25T-trowelable)	27	75*	1. Fabricate in accordance with BAC 5892. a. Spray application. b. Trowel or brush application. c. Premolded sheets.	1. Bond plug of cured material topcoat. 2. Mechanically remove coating down to good coating surface, prime, spray MA25S, sand smooth and topcoat. 3. Slight abrasion/minor damage - use trowelable material or topcoat material. 4. Damage exposing base structure - remove damaged coating, prepare surface per original process, fill void with trowelable material or topcoat. Sand smooth.	1. Bond premolded sheets to structure. 2. Spray on structure (primed), no adhesive required. 3. Bond premolded sheets or spray. Apply on composite skin and mechanically fasten to structure. Can also be brushed or troweled.
MI-15 filled silicone	15		Same as MA 25S	Same as MA 25S	Same as MA 25S
Silicone with microballoons - low density syntactic foam	28	TBD	1. Spray application 2. Premolded sheets 3. Trowel or brush application Bonding surfaces must be primed.	1. Bond plug of cured material. 2. Remove damaged coating; apply uncured rubber to good cured rubber surface; cure. 3. For damage exposing base structure fill void with uncured rubber; cure.	1. Bond premolded sheets to structure. 2. Bond premolded sheets or spray. Apply on composite/metal skin and mechanically fasten to structure. (Brush and trowel application also possible). 3. Spray, brush or trowel directly to primed structure.
NCFI 22-65 isocyanurate foam	2.5	TBD	Spray directly onto structure. Structure must be 120°F or more for good adhesion. Process should be automated with structure on turntable for even material thickness.	1. Mechanically remove foam from damaged area, sand blast surface. Reapply a trowelable foam. NCFI 22-65 is not trowelable. 2. Mechanically abrade foam to good material, prime, and reapply NCFI foam. Note: Best way to repair damaged NCFI is to completely remove it and fill with different trowelable foam.)	Spray onto warmed structure. May not lend itself to prefabrication on composite or metal skins to be attached to structure at some later time. This option may require some further investigation.

*Max heating rate tested - capability may be higher.

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Candidate P/A Module TPS Materials

Material	Advantages	Drawbacks	Vendor	Cost		
				Material	Manuf.	Maint.
SLA 561 Highly filled silicone elastomer	Can be prefabricated. Low density. Good thermal properties. More durable than MA-25S or MI-15. Does not require topcoat.	Material costs are high. Brittle. For moisture resistance and improved weatherability topcoat is required.	Martin Marietta			
MA25S filled silicone (MA25T-trowelable)	1. Self adhering, no adhesive required. 2. All processing and rework procedures detailed in BAC 5892. 3. Highest heat of ablation of MI 15, SLA 561 or NCFI 22-65.	1. Porous material, requires topcoat. 2. Topcoat may require reinforcement with Kevlar fabric to improve impact resistance - labor intensive topcoat system.	Martin Marientta			
MI-15 filled silicone	1. Lower thermal conductivity than MA 25S. 2. Toughened topcoat system does not require addition of fiber reinforcement. 3. Can withstand higher temps than SLA 561 & MA 25S. 4. Lower material and manufacturing costs than MA 25S.	1. Not as good an ablator as MA 25S. 2. Brittle, requires topcoat for durability.	Martin Marietta			
Silicone with microballoons - low density syntactic foam	1. Self adhering, no adhesive required. 2. Can be prefabricated. 3. Good thermal properties.	Topcoat (reinforced) may be required to improve erosion resistance.	Dow Corning			
NCFI 22-65 isocyanurate foam	1. Self adhering. 2. Saves weight, topcoat not required. 3. Tack free in less than 10 sec. subsequent layers can be processed immediately. 4. Most heat resistant foam for this application. 5. Porosity negligible. 92% minimum closed cells.	1. Requires application to warm structure (>120°F). 2. Warm air temperature and foam also required for successful application. 3. May be too light for this application.	North Carolina Foam Industries, Inc.	$2.40/lb.		

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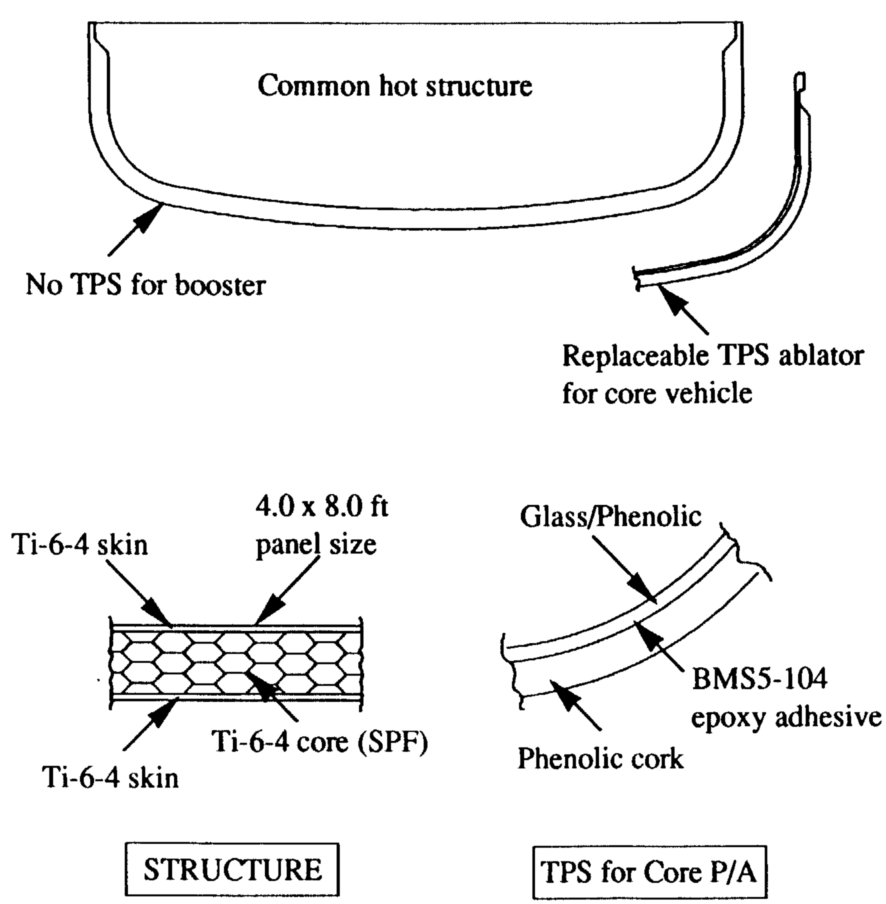
APPENDIX B - STRUCTURAL DESIGN CONCEPTS

The following charts summarize the initial structural concept definitions for the truss, aeroshell, and bulkhead. Summaries include: a) technical details - geometries and materials, that serve as a starting place for concept comparison and development; b) advantages and drawbacks - preliminarily identified issues in fabrication and performance; c) materials options - the various materials applicable to the concept; d) fabrication approach - briefly described process for manufacturing the concept; and e) design features - the features that set the concept apart.

Aeroshell Concept - 1

Superplastic formed Titanium multiwall warm structure



Advantages

- Very durable metal structure
- Simple reinspection-visual
- Only two designs-1 structure and 1 TPS
- Good corrosion properties

Drawbacks

- Multiple panels required
- Intermediate beams required
- Fastening or welding required
- More thermal stress and deformation than composite
- Compression joints in primary load path
- Process developmentd and scale-up required
- Inspection technology development required

Material Options

Structure

- Other titanium alloy combinations
- SiC/Ti doublers

TPS

Glass/BMI
Phenolic/Silica

Fabrication Approach

Structure

- Laser weld SPF packs
- SPF panels
- Fabricate splice beam members
- Assemble dome with bolts

TPS

- Layup glass/phenolic on male tool
- Bond phenolic cork

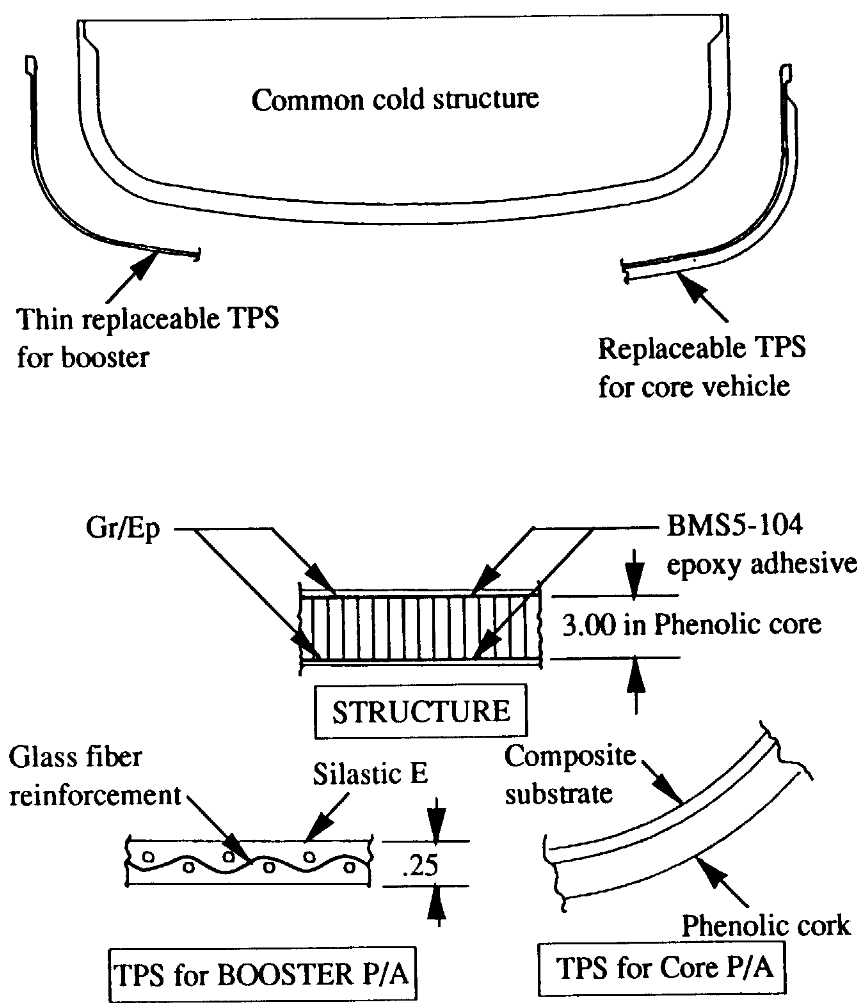
Design Features

- TPS clamps to structure
- SPF sandwich simultaneously expanded and turned to contour

ST/kwo/ww/12/89-1

Aeroshell Concept - 2

Gr/Ep sandwich with TPS



Advantages

- Lower cost composite than Gr/PI
- TPS interchangeable between uses
- Sandwich structure reduces complexity
- Structure helps insulate
- Low thermal stress or distortion
- No joining required, 1 piece cure

Drawbacks

- Less durable than metal
- Requires 3 designs (1 aeroshell, 2 thermal production systems)
- Additonal inspection required
- Process scale-up required

Material Options

<u>Structure</u>

Tape
Stitched preforms } Forms
Filament wound
Many Fiber/resin options

<u>TPS</u>

Glass/Ep substrate
Glass/phenolic substrate
Phenolic/Silica ablator

Fabrication Approach

<u>Structure</u>

- Laminate outer skin in female bond tool and cure
- Bond in core
- Laminate outer skin

<u>TPS</u>

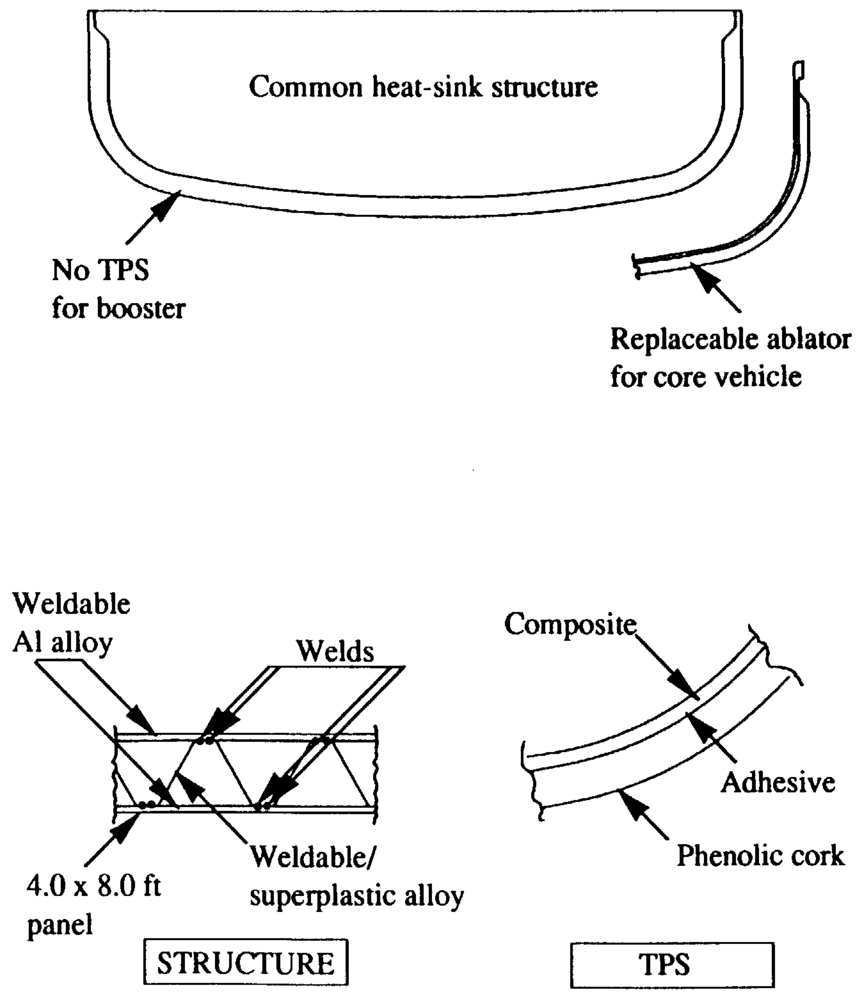
- Layup substrate on male tool
- Bond phenolic cork
- Spray silicone over glass cloth on male tool for Booster TPS

Design Features

- Uses separate TPS designs for core and booster
- TPS has substrate which clamps to structure
- Structure is a single piece

Aeroshell Concept - 3

Superplastic formed aluminum truss core warm structure



Advantages

- Only two designs-1 structure and 1 TPS (reduced DDT&E)
- Durable metal structure
- Lower temperature than composite

Drawbacks

- Multiple panels required
- Intermediate beams required
- More thermal deformation than composite
- Fastening or welding required for assembly
- High-temperature alloys are not superplastic
- 3 sheet SPF panels subject to skin dimpling problems
- Some process development required

Material Options

Structure

Al-Li, Al-Fe-V-S, or other high-temp alum.

Supral

TPS

Glass/Phenolic substrate

Glass/BMI substrate

Phenolic/Silica ablator

Fabrication Approach

Structure

- Weld core pattern in SPF packs
- Roll form 44.00in rad.
- SPF panels
- Machine splice beam members
- Assemble dome with bolts or rivets

TPS

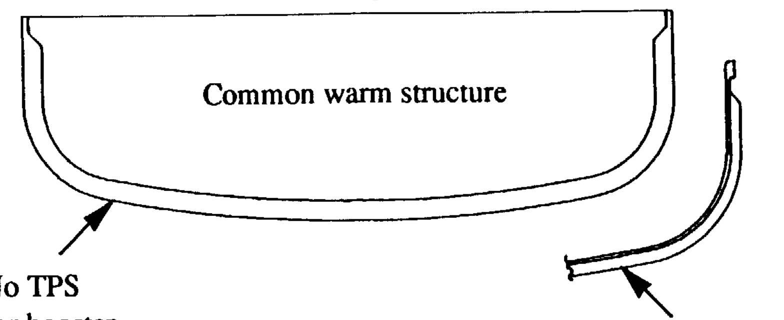
- Layup substrate
- Bond phenolic cork

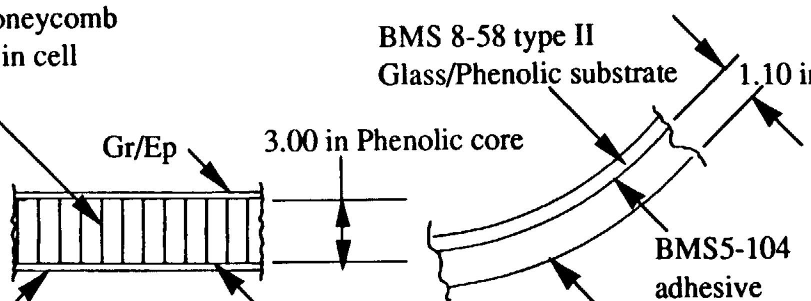
Design Features

- SPF sandwich simultaneously expanded and formed to contour
- TPS clamps to structure
- No TPS required for booster

Aeroshell Concept - 4

Gr/PI - Gr/Ep sandwich





Advantages

- Only two designs-1 structure and 1 TPS (reduced DDT&E)
- Sandwich structure reduces complexity
- Single-piece structure- -no joining required
- Easier to manufacture than all polyimide
- Potential lowest life cycle cost
- Structure helps insulate

Drawbacks

- Multiple stage layup and bond process
- High-temperature BAJ or separate post-cure tool required
- More difficult to manufacture than all Gr/Ep
- Probably requires Q. I. layups (potential weight penalty)
- Additonal inspection required
- Process scale-up required
- Repair technique development required

Material Options

Structure
- BMI skin
- Polyimide core
- Titanium core

TPS
- Glass/BMI
- Phenolic/Silica

Fabrication Approach

Structure
- Laminate Gr/PI in full-size female tool
- Bond in core-flexcore in radiused areas
- Post-cure
- Layup Gr/Ep inner skin over core and cure

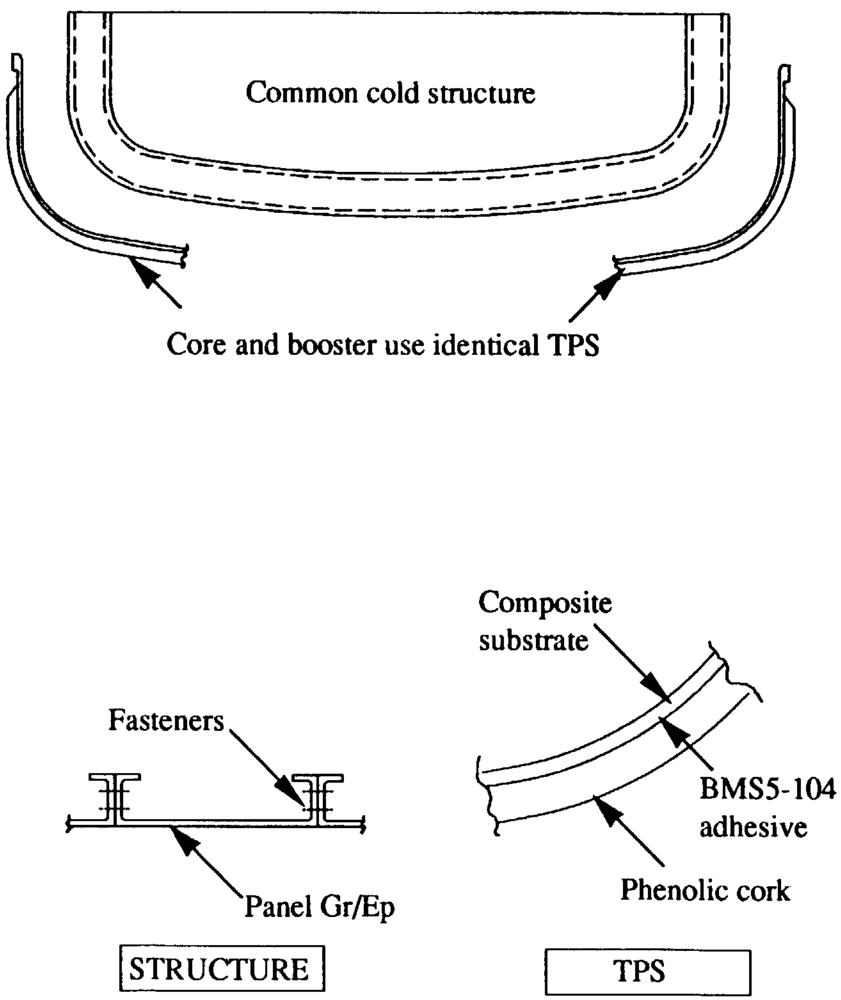
TPS
- Layup Glass/Phenolic on male tool
- Bond Phenolic cork

Design Features

- Low thermal stress with low CTE structure
- TPS clamps to structure
- No TPS required for booster

Aeroshell Concept - 5

Integrally stiffened Gr/Ep skin with TPS



Advantages

- Allows off site fabrication of structure
- Simplifies mounting to truss
- Identical TPS for core and booster
- More durable composite design
- Less tooling cost - identical panels

Material Options

Structure

Q. I. layup with uni-directional stiffened caps

TPS

Glass/Ep or
Glass/BMI substrate
Phenolic/Silica ablator

Fabrication Approach

Structure

- Laminate panel in female tool
- Ship to site
- Assemble in fixture

TPS

- Layup substrate on male tool
- Bond ablator

Drawbacks

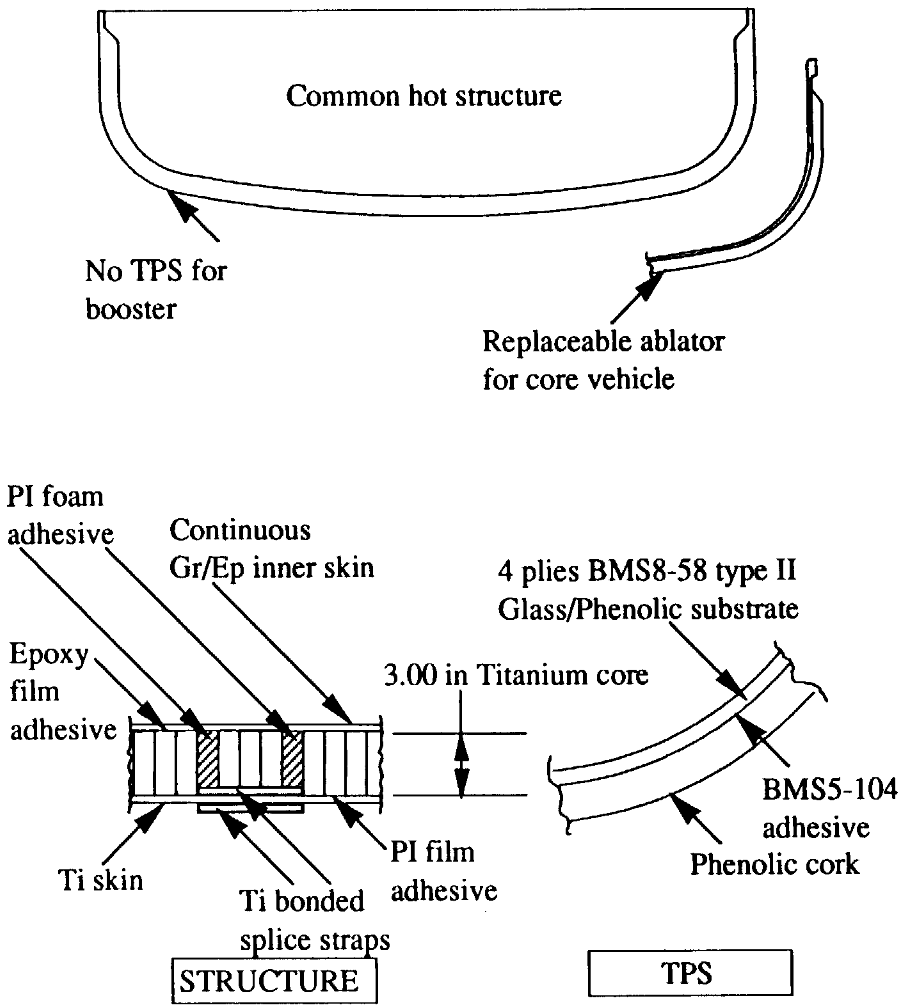
- Weight penalty for booster TPS
- Weight penalty for panel construction
- More assembly time due to fasteners
- Joints in the primary load path
- Biaxial stiffening required for splashdown pressures
- Additional inspection required
- Design specification process development required

Design Features

- Fabricate in panels-ship to site and assemble
- Uses booster TPS (identical to core TPS) for multiple launches

Aeroshell Concept - 6

Ti - Gr/Ep hybrid sandwich warm structure



Advantages

- Durable metallic exterior
- Joining simpler than Ti SPF panel

Drawbacks

- Requires 1 high-temperature and 1 low-temperature cure
- Higher thermal stress than all composite
- Joints in the primary load paths
- Poor aerodynamic smoothness
- Inspection technique development required
- Process development required

Material Options

Structure

- Ti-6Al-4V, Ti-15-3-3-3 } Outer skin
- Ti-3-2.5, Polyimide } Core

TPS

Phenolic silica ablator

Fabrication Approach

Structure

- Form Ti outer sins
  - SPF
  - Cold form
- Join outer skins and bond core with polyimide adhesive
- Layup inner skin and core

TPS

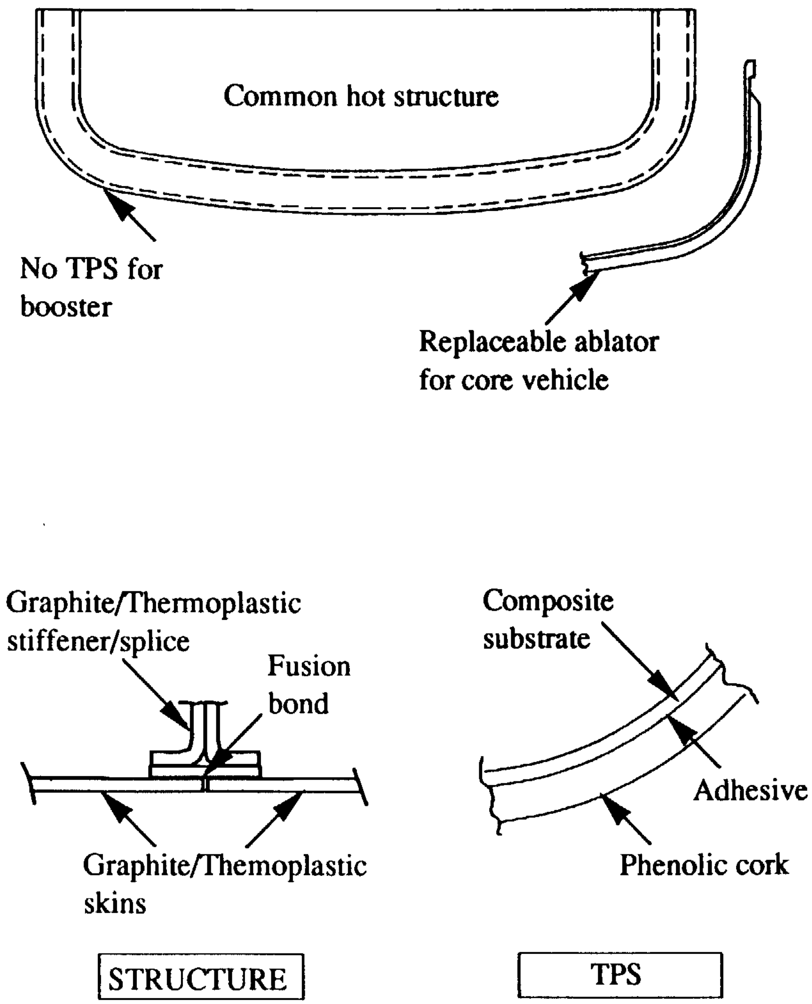
- Layup Glass/phenolic substrate
- Bond phenolic cork

Design Features

- TPS clamps to structure
- Some skins SPF, some cold formed Ti-15-3-3-3

Aeroshell Concept - 7

Stiffened skin Gr/thermoplastic warm structure



Advantages

- Tough resin system
- Low thermal stress and mismatch
- Simpler joining than titanium concepts

Drawbacks

- Temperature critical joints
- High cost tooling for small production run
- Skins probably sized by maximum temperature
- High-cost material and processing
- Biaxial stiffening required for splashdown load
- Additional inspection required
- Process development required

Material Options

Structure

Gr/KIII
Gr/PPS
Torlon

TPS

Phenolic silica ablator

Fabrication Approach

Structure

- Form skins
- Form and fusion bond stiffeners
- Fusion bond assembly in female tool

TPS

- Layup substrate on male tool
- Bond ablator

Design Features

- Radial stiffener pattern
- Fusion bond joints

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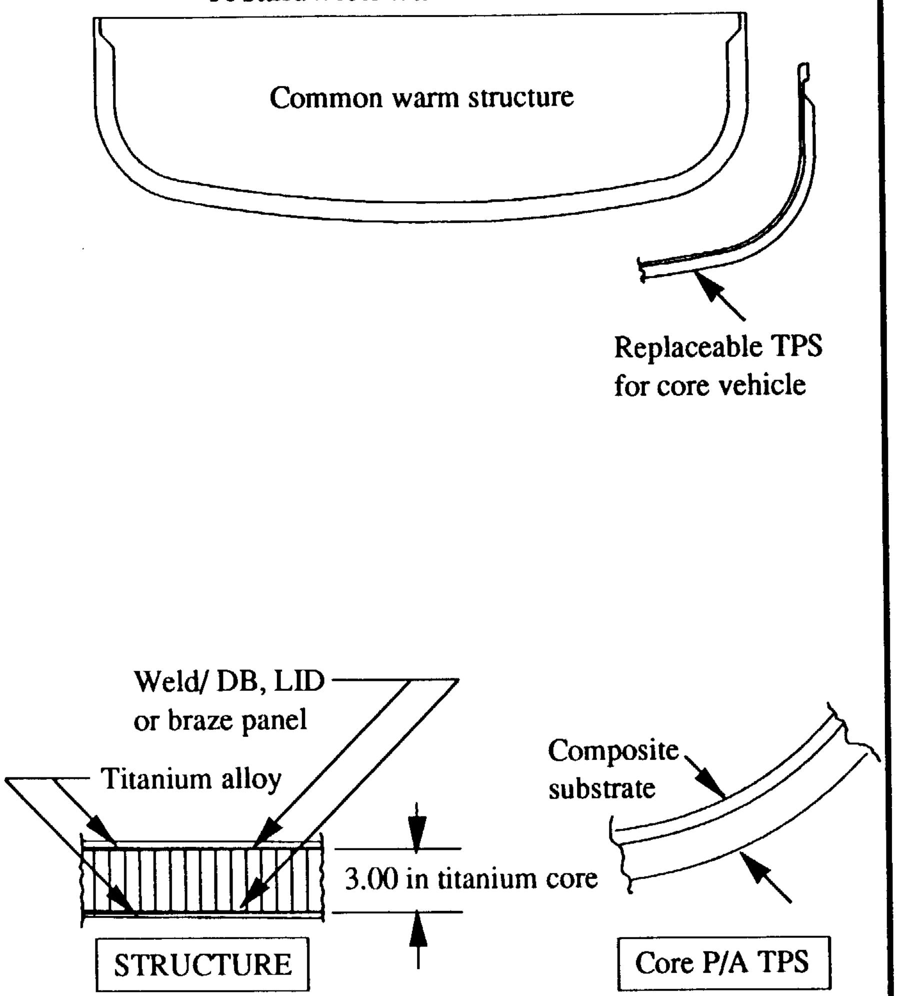
Aeroshell Concept - 8

Ti sandwich warm structure



Advantages

- Very durable metal structure
- Simple reinspection-visual
- Only two designs-1 structure and 1 TPS
- Good corrosion properties
- Fully developed panel technology

Drawbacks

- More thermal stress and deformation during hot flight than composite
- Difficult welding panel joints
  - fitup precision required
  - mismatch
  - stress relief

Material Options

Skins
- Ti6-4
- Ti 15-3-3-3

Core
- Ti3-2.5
- New alloy

TPS
Glass/BMI
Phenolic/Silica

Fabrication Approach

Structure (options)
- LID bonding
  - creep form details
  - LID bond panels
  - laser weld assy
- Weld/DB panel
  - weld flat panels
  - creep form contour
  - weld assembly
  - stress relieve

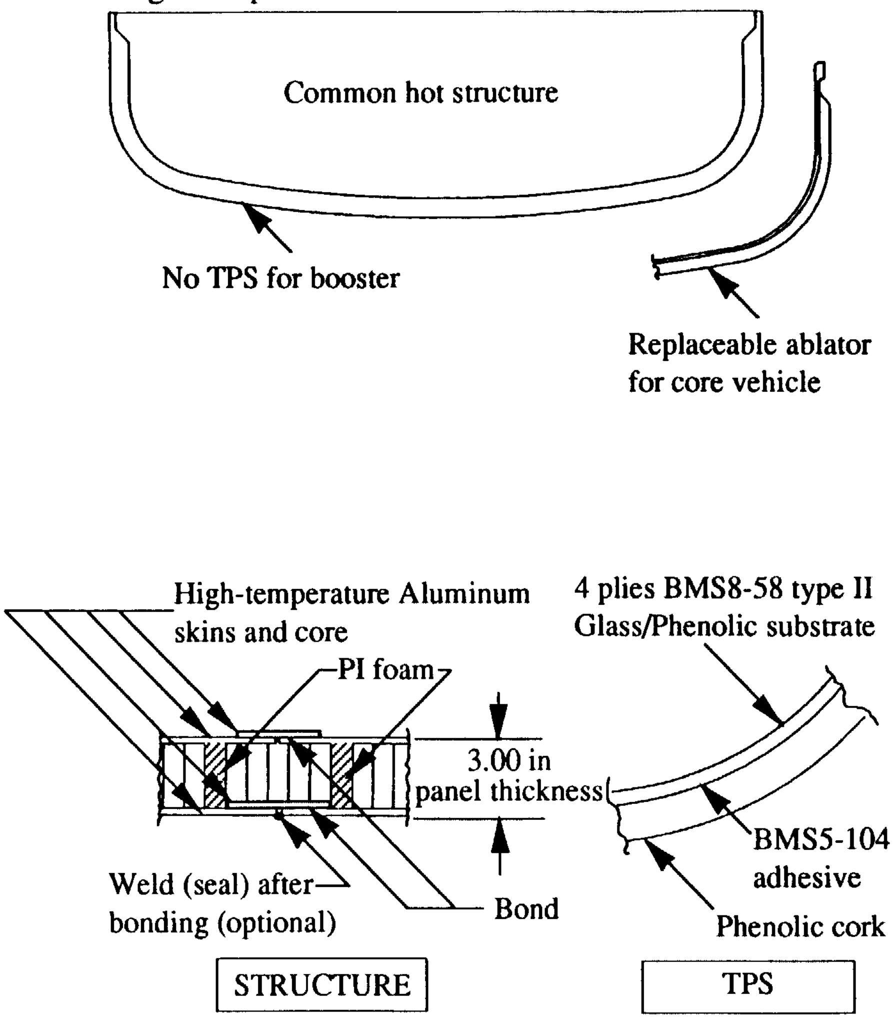
TPS
- Layup glass/phenolic on male tool
- Bond phenolic cork

Design Features

- TPS has substrate which clamps to structure
- Structure is a single piece

Aeroshell Concept - 9

High-temperature aluminum bonded sandwich



Advantages

- Material cost less than composite
- Fabrication cost less than titanium
- Durable metal structure
- Bonding less cost and risk than brazing or welding
- Seal-weld option
- Cold stretch formed skins vs. hot-formed titanium
- Aluminum core lower cost than titanium
- Good corrosion properties
- Repair less complex than composite

Drawbacks

- Thermal distortion mismatch of shell and truss
- Polyimide adhesive required
- Weight penalty over other leading concepts

Material Options

Skins (HTA)
- Al 8009 (FVS 812)
- FVS 1212
- X8019 (CZ42)

Internal Fittings
- HTA Al (aeroshell)
- 7475 Al (sidewall)

Aeroshell Core
- Al 8009 (welded)
- Al coated titanium

Sidewall Core
Titanium

Adhesive
- FM35, FM680, PT

Fabrication Approach

1. Spin form center section skins
2. Stretch form "gore" skins
3. Stretch form internal members
4. Bond outer skins and splice members
5. Bond internal members and core
6. Bond inner skins and splice members
7. Remove from tool and seal (weld) gaps
8. Mechanically assemble

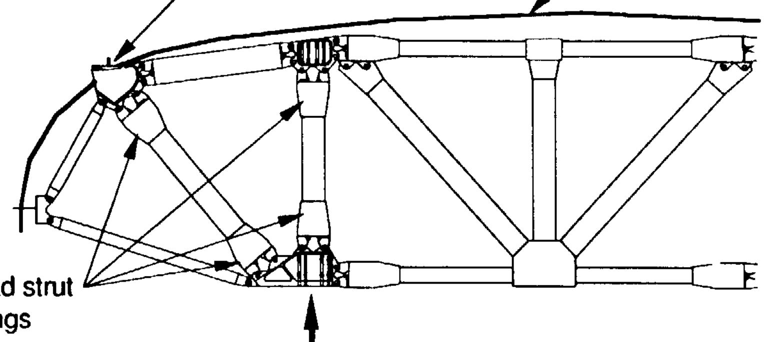
Design Features

- High-temperature aluminum (HTA) skins, core and internal members
- All HTA parts cold formed,sidewall internal members SPF
- Bonded panel fabrication

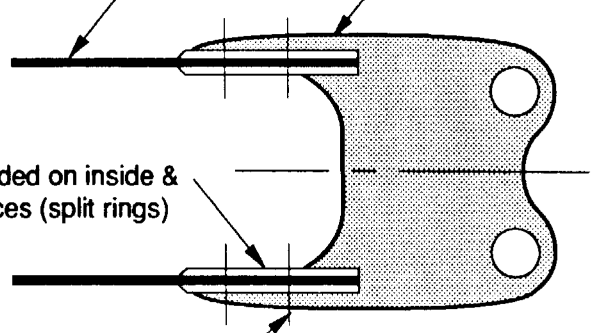
ST/kwo/ww/12/89-9

Thrust Structure Design Concept

All Aluminum (7075) Truss



High-load endfiting detail cross-section



Advantages

- Low cost, well characterized materials and processes.
- Variety of tube sizes available off the shelf.
- Established inspection techniques
- Established repair techniques

Drawbacks

- Expected weight of forgings is relatively high.
- Corrosion suseptability.
- Joining limited to fastening and bonding.

Materials

7075-T6 extrusions and forgings

Options

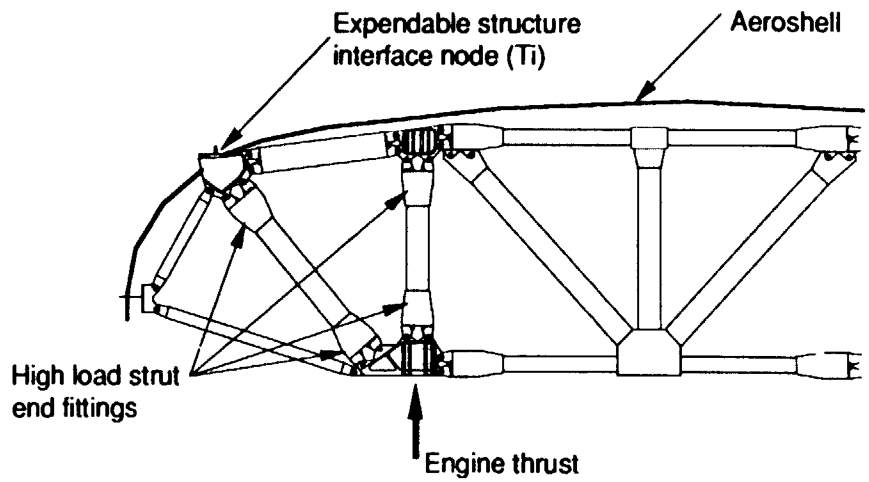
Fabrication Approach

- Attach tubes to tube ends (bond or bolt + bond
- Machine joint interface
- Subassemble main trusses & corners
- Bolt up final assy.

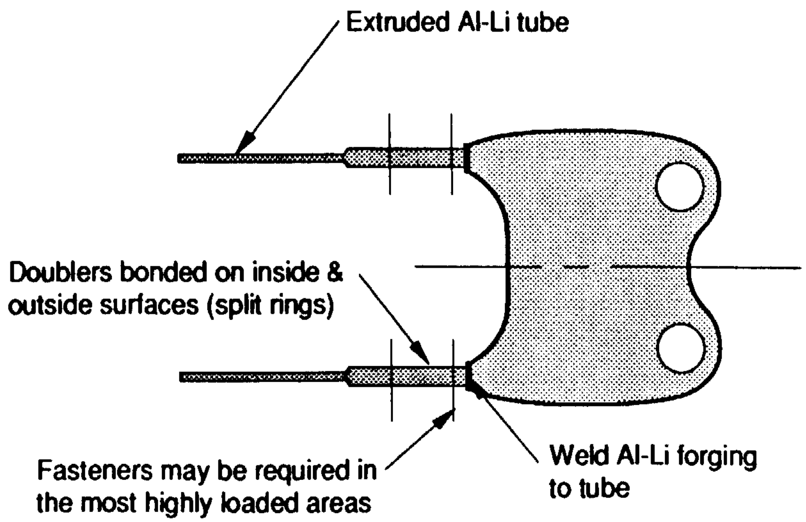
Features

High-strength- aluminum tubes and fittings.

Thrust Structure Design Concept
Aluminum-Litnium Truss



High-load endfiting detail cross-section



Advantages
- Lighter structure than AL-7075-T6
- Materials & process development proceeding rapidly
- Moderate cost
- Good machinability
- Near-term inspection capability expected

Drawbacks
- Current availability of extrusions is poor, should improve though
- Corrosion of Al-Li
- Toughness or Al-Li an issue

Materials
- Al-li 2090 extruded tubes
- Al-Li 2090 forged corner joints

Coated steel fasteners at bolted joints

Fabrication Approach
- Attach tubes to tube ends (bond or bolt + bond
- Machine joint interface
- Subassemble main trusses & corners
- Bolt up final assy.
- Surface requires corrosion protection coating.

Features
High specific stiffness tube material.

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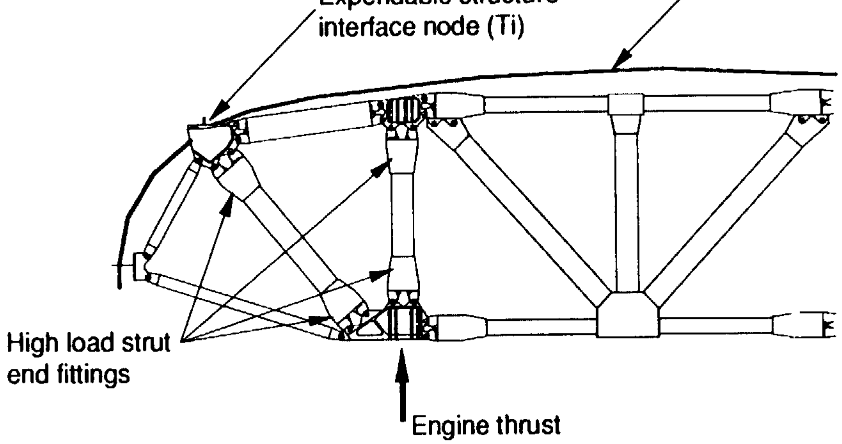
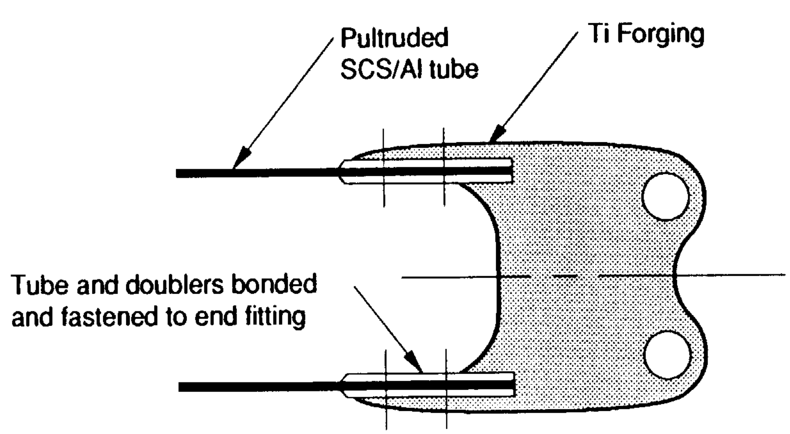
Thrust Structure Design Concept

SCS/6061 Aluminum Truss

(Continous siliconcarbide fiber reinforced aluminum)





Advantages

- Lightweight (probably the lightest of all options)

Drawbacks

- Tube material cost is high
- No standard sizes available.
- Inspection of SCS/Al requires development

Materials

- SCS/6061 pultruded tubes
- Ti fittings & joints

Options

- dSiC/6061 forged joints + tube ends

Fabrication Approach

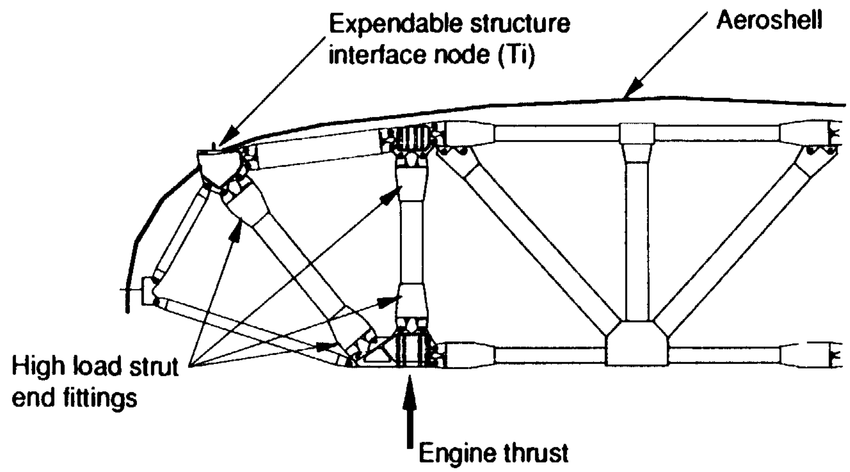
- Pultrude tube members.
- Cast & machine joints and fittings.
- High load members - bolt & bond tubes to fittings; low load members - bond.
- Drill bolt holes in member ends.
- Machine joint castings.
- Bolt together subassembly.
- Bolt together final assembly.

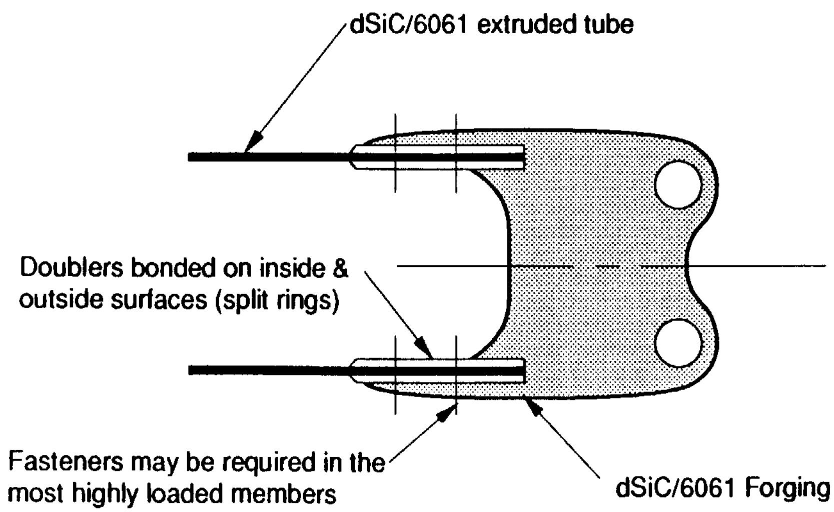
Features

Very high specific stiffness tube material.

Thrust Structure Design Concept

dSiC/6061 Aluminum Truss





Advantages

- Better specific compression modulus than aluminum
- Aluminum bonding processes well developed
- Moderate cost compared to other composites
- Near-term inspection expected

Drawbacks

- More difficult to machine than regular aluminum
- Limited selection of sizes & thicknesses currently available

Materials

- dSiC/6061 exturded tube members
- dSiC/6061 forgings (tube ends + joints)
- Coated steel fasteners at bolted joints

Fabrication Approach

- Extrude tube shapes
- Machine joints and fittings from forgings
- Attach tube ends
- Bolt up subassemblies, main trusses & corners
- Bolt up final assembly

Features

High specific stiffness tube material.

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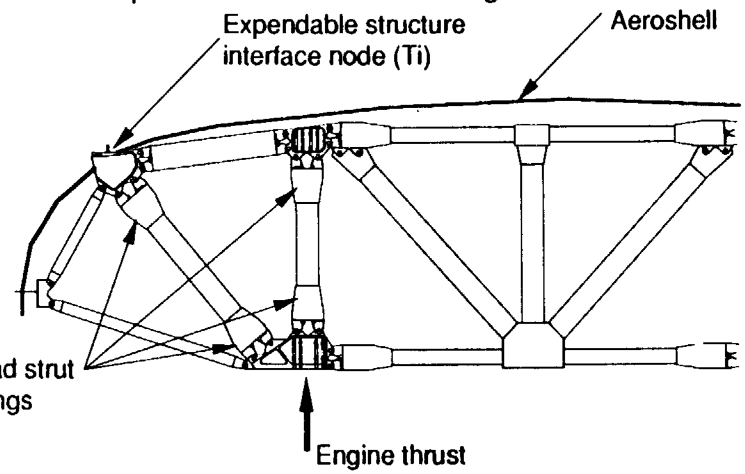
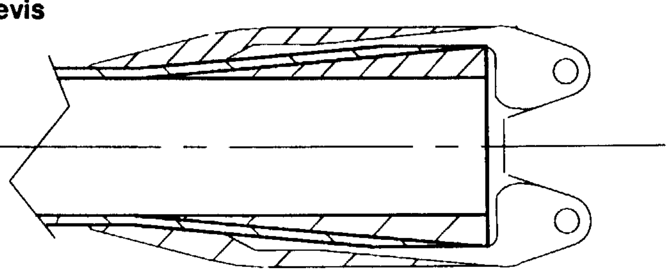
3/25/91

Thrust Structure Design Concept

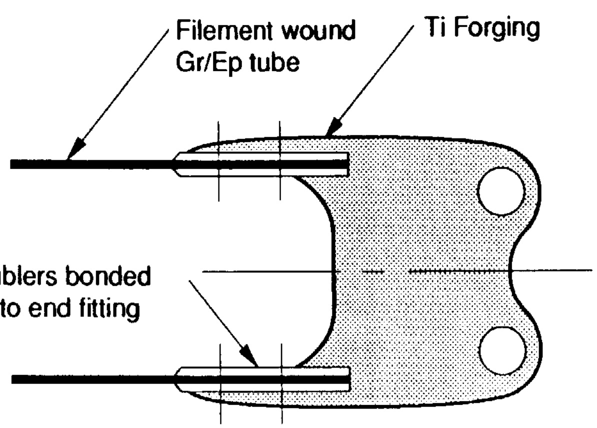
Gr/Ep Tube Truss with Ti Fittings



Integrally wound clevis joint attachment.



Highly loaded joints bolted and bonded.



Advantages

- Structure is light overall
- Strong joints & member ends

Drawbacks

- Potential difficulty achieving precision joint attachments
- Inspection requires development

Materials

- IM6/Ep round tubes
- Ti 6-4 joints (machined interfaces)

Options

- Other high strength graphite RMC

Fabrication Approach

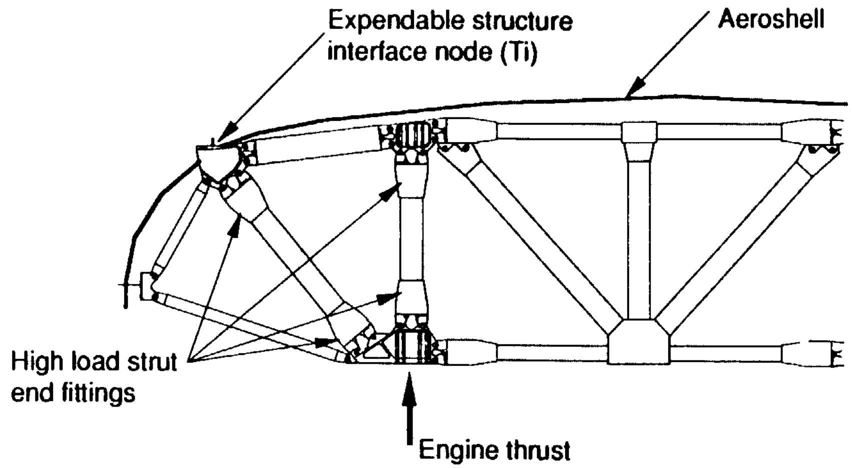
- Filament wind tube members
- Cast & machine joints and fittings
- Integrally wind tube ends (ti) (bolt & bond for high load members)
- Drill bolt holes in member ends
- Machine joint castings
- Bolt together subassembly
- Bolt together final assembly

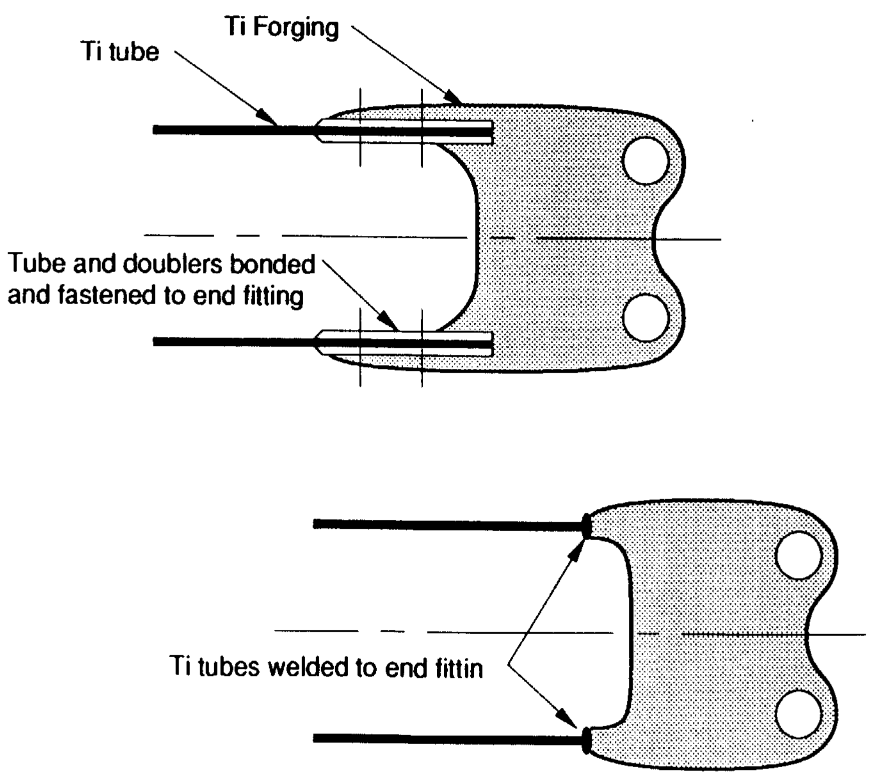
Features

- Low corrosion risk
- Fittings integrally attached to tubes

Thrust Structure Design Concept

Welded Titanium Tube Truss





Advantages

- Ti provides excellent as-welded properties
- Corrosion resistant
- Low risk fabrication
- Established inspection techniques
- Established repair techniques

Materials

- Ti 6-4 extruded tubes
- Ti 6-4 investment casting or forings (bolted joint version)

Drawbacks

- Welding restraint tools costly
- Stress relief of welds costly
- Material cost
- Strategic material

Fabrication Approach

- Extrud tube members
- Cast or forge member fittings and joints
- All welded approach
  - Weld up subassys
  - Stress relief
  - Weld up final assy
  - Stress relief
- Welded + bolted - welded tube ends - bolted final assy.

Features

- Monolithic material, well characterized
- Low corrosion

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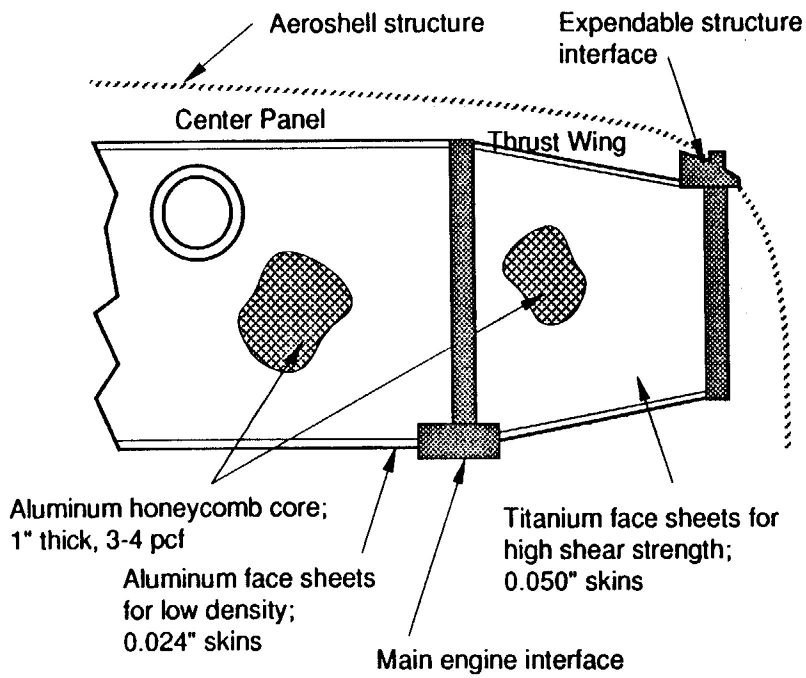
3/25/91

Thrust Structure Design Concept

Metallic Sandwich Shear Web



Advantages

- Many heavy fittings eliminated
- Low risk fabrication approach
- Established inspection techniques

Materials

- Ti 6-4 face sheets
- Aluminum honeycomb core

Options

dSiC/Al or Al-Li face sheets

Drawbacks

- Cut-outs required to accomodate subsystems

Fabrication Approach

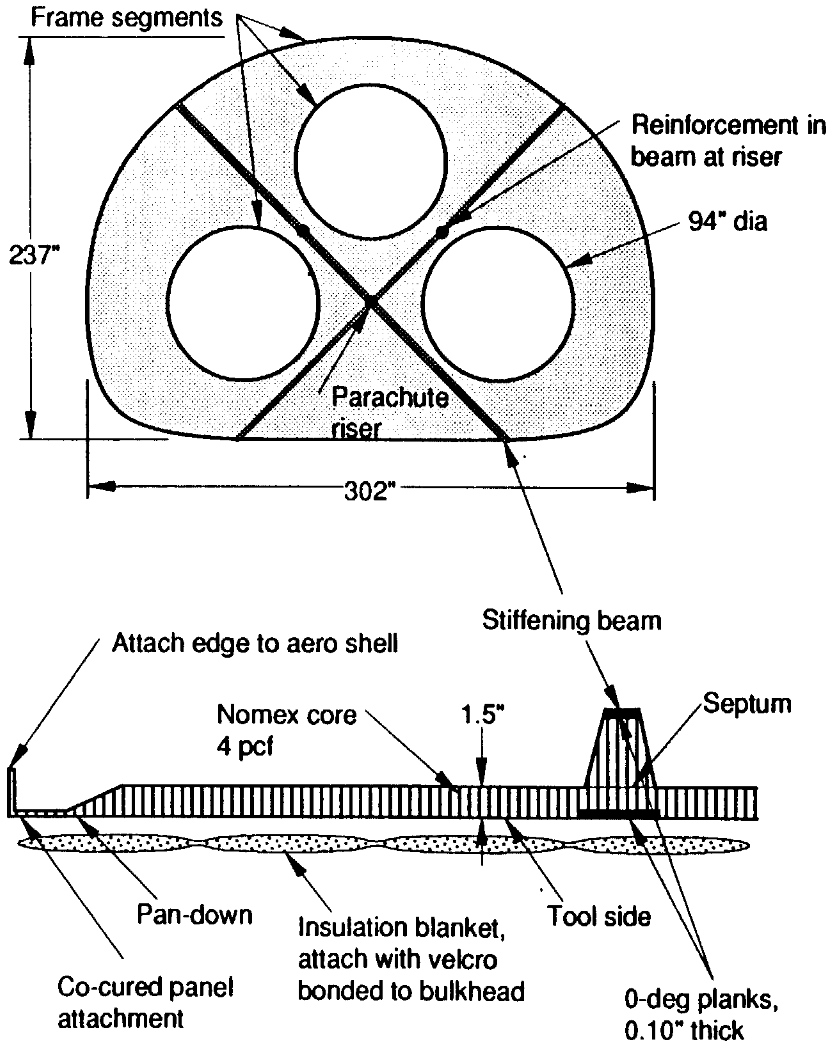
- Adhesively bond sandwich members
- Bond and bolt members for final assembly

Features

- Shear web load transfer from engines to expendable structure.
- All metallic with bonded & bolted joints.

Bulkhead Design Concept-1

Gr/Ep Honeycomb Sandwich, Co-cured



Advantages

1. Complete bulkhead cured in one piece.
2. Stiffening beams are integral.
3. Fair acoustic attenuation capability.
4. Low corrosion susceptibility.

Drawbacks

1. Fabricating a one piece bulkhead (if desired) dependent on facility size (autoclave dia. >26 ft).
2. Insulation required on exterior surface.
3. Attachment to aeroshell is critical design detail.
4. Transportation.
5. Extensive QA increases cost.

Materials

Gr/Ep

Options

Gr/Polyimide
Gr/thermoplastic

Fabrication Approach

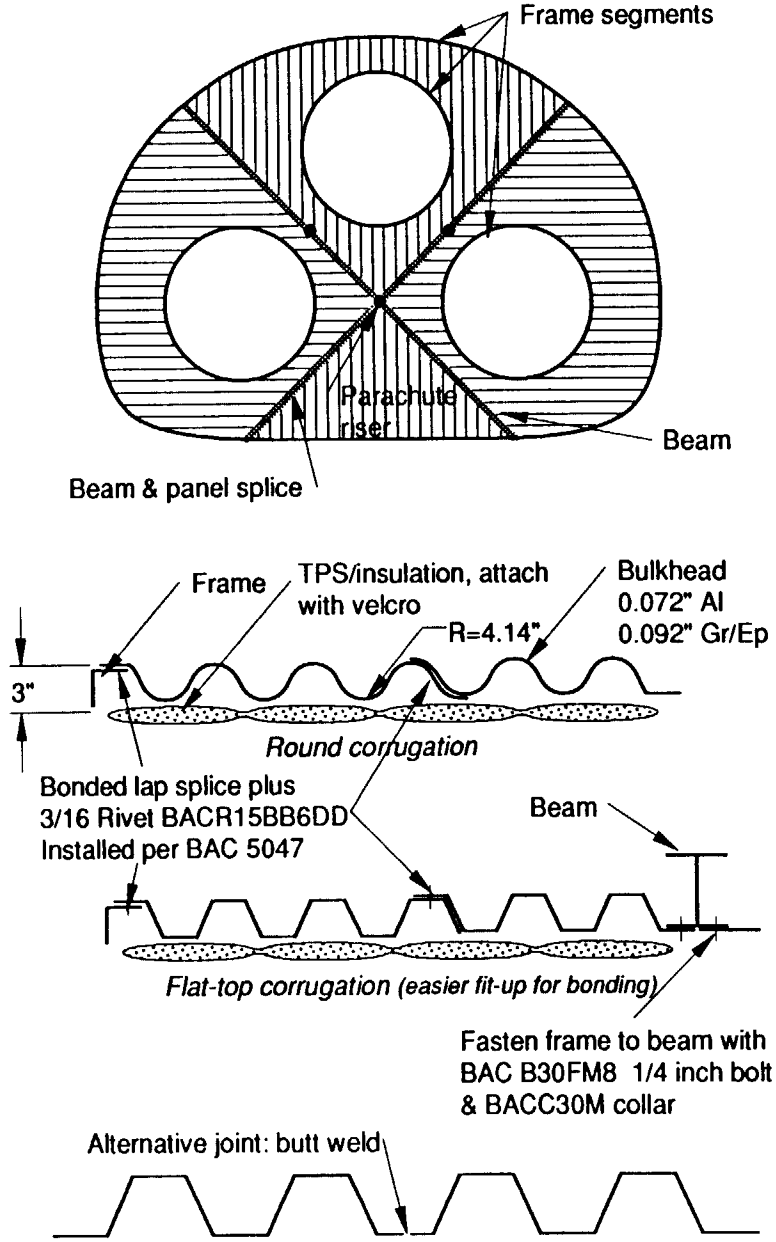
1. Place tool side skin and pad-up strips with ALTM.
2. Machine tapers in core material.
3. Place and splice core segments.
4. Place bag side skin and pad-up strips with ALTM.
5. Place beam core and doublers.
6. Bag and cure in autoclave.
7. Trim edges.

Features

- Light-weight
- Integral stiffening beams
- Co-cured or bonded details

Bulkhead Design Concept-2

Corrugated Aluminum



Advantages

1. Low risk materials can be used when they are thermally insulated.
2. Low risk fabrication approach (schedule and economic).
3. Thermal expansion capability in one direction.
4. Forgiving processing.

Materials

Aluminum (2024, 7075 bondable; 2219, 6061 are weldable)

Options

Hi-temp aluminum
Al-Li (weld)
Gr/Ep
Ti (superplastic form)

Fabrication Approach

1. Hydroform corrugations and edge pan-downs.
2. Trim to shape.
3. Bond corrugated segments into full panels.
4. Bond frame segments around edges.
5. Paint/coat.
6. Extrude beam shapes and trim to length.
7. Fasten panels to beams.
8. Attach TPS/insulation.

Drawbacks

1. Insulation required on exterior surface.
2. Corrugations interrupted for panel splices and cutouts.
3. Poor acoustic attenuation.
4. High tooling cost.
5. Must protect against corrosion at faying surfaces.

Features

- Two corrugation geometries possible
- 4 panels make up the complete bulkhead
- Multiple fabrication approaches

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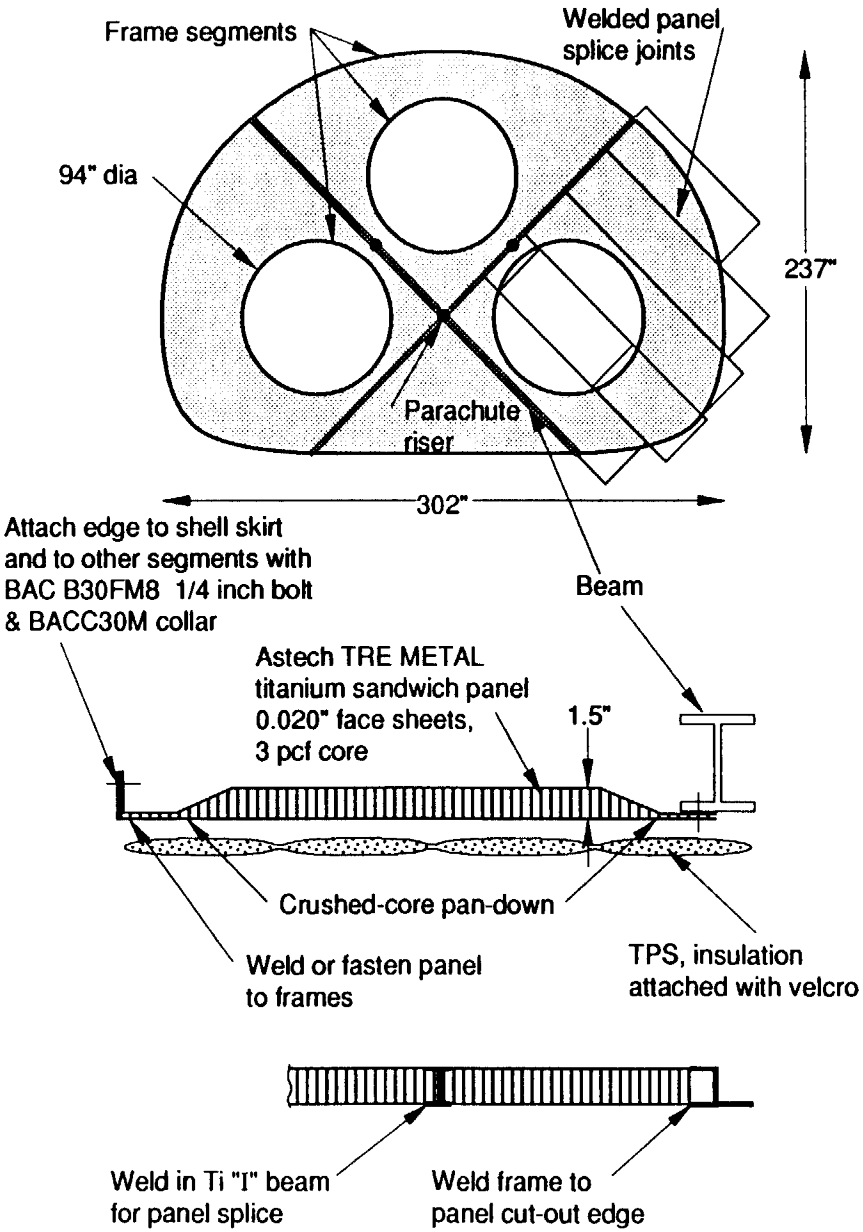
4/19/91

Bulkhead Design Concept-3

Titanium Honeycomb Sandwich



Advantages

1. TRE METAL panels available prefabricated (44" X 120")
2. Welded design concepts are established.
3. High temperature metals can be incorporated.
4. Inspection techniques established.

Drawbacks

1. Panel cut-outs reduce cost payoff.
2. Panels will expand during plume heating if uninsulated.
3. High QA costs.
4. Expensive welding details.

Materials

Titanium

Options

Superalloys
Hi-temp aluminum
(weld development required)

Fabrication Approach

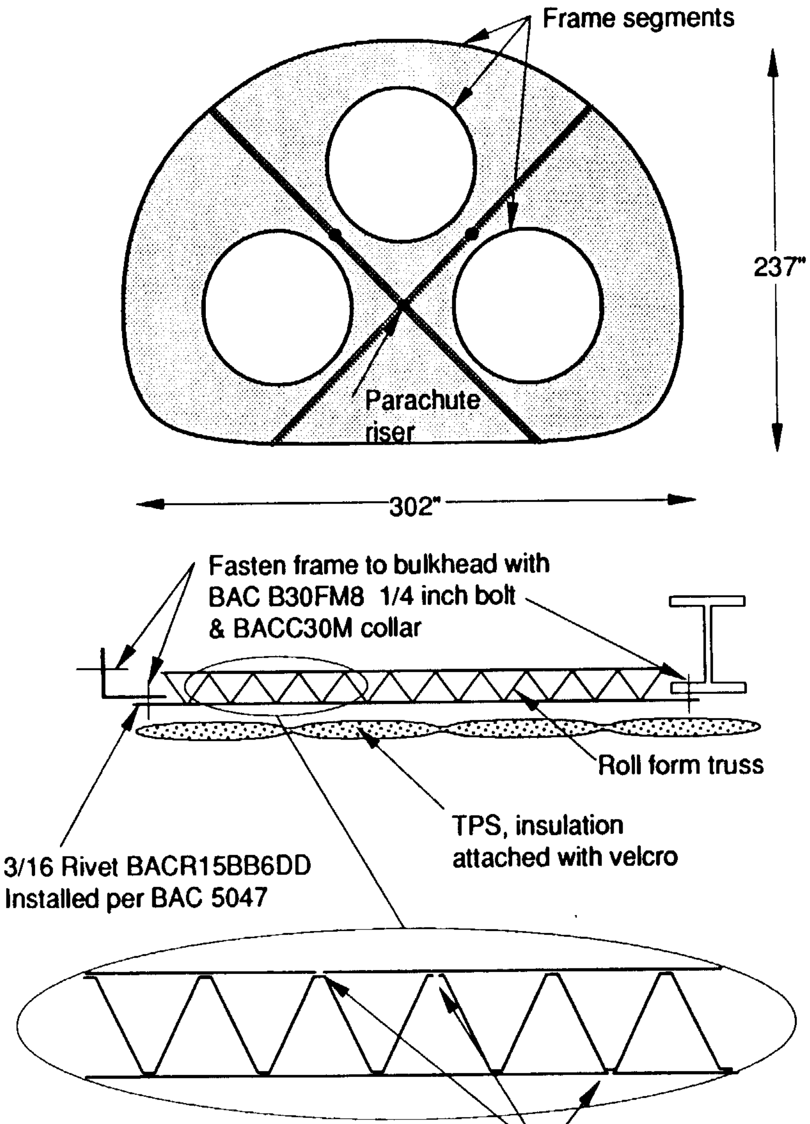
1. Purchase Astech TRE METAL resistance welded sandwich panels.
2. Trim to length and splice (weld).
3. Crush TRE METAL at beam and perimeter edges, and drill for attachment; *OR* Form frame segments and weld to bulkhead edges.
4. Beam section is extruded.
5. Make attachments with standard fasteners.

Features

- Construction similar to aeroshell
- High temperature capability

Bulkhead Design Concept-4

Truss Core (double-faced)



Advantages

1. Low production cost potential.
2. Large panels feasible.

Drawbacks

1. Attaching curved frame introduces complexity.
2. Material strength loss at welds.
3. Must protect against corrosion at faying surfaces.
4. Insulation required externally or internally.

Materials

Aluminum-Lithium

Options

Superalloys
Titanium, Aluminum
Hi-temp aluminum
(weld development required)

Fabrication Approach

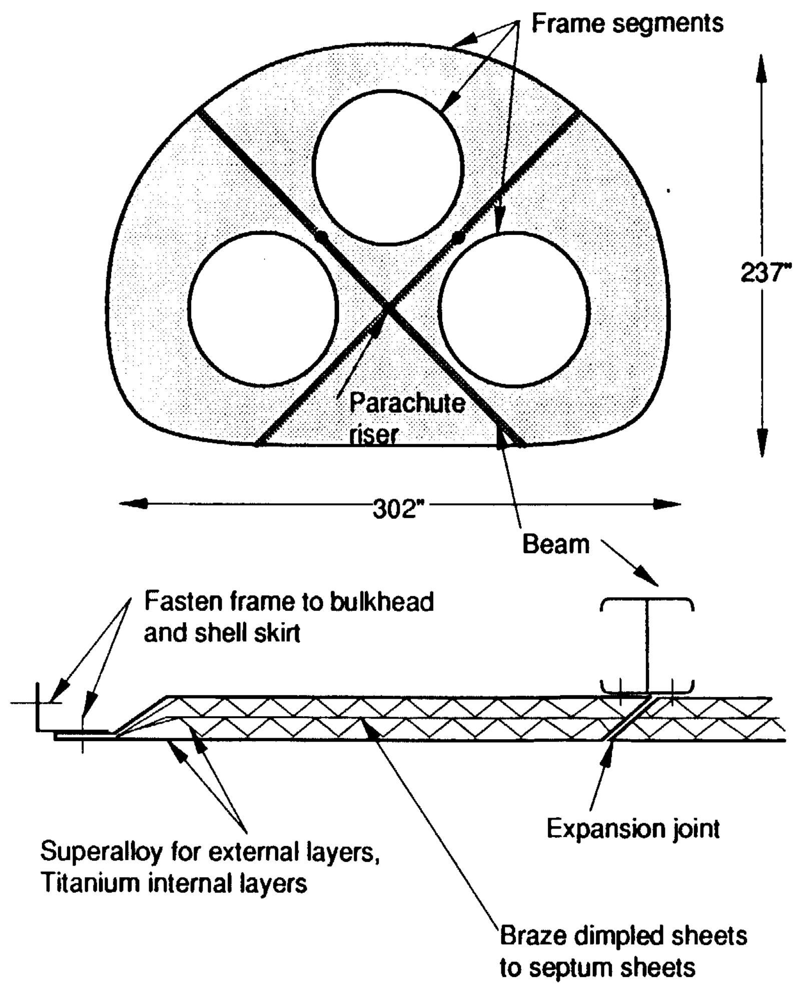
1. Roll form center truss.
2. Laser (or resistance) weld face sheets.
3. Trim finished panel to desired curvature.
4. Attach frames.
5. Prepare edges for attachment to beams and sidewall.

Features

- Laser welded construction
- High temperature capability with proper material selection

Bulkhead Design Concept-5

Metallic Multi-wall



Advantages

1. Structure acts as TPS (no extra weight or complexity).
2. Durable insulation (low refurb costs.)

Drawbacks

1. High tooling/capital cost.
2. Complex, precise, and labor intensive fabrication techniques.
3. Fabrication approach limits panel size. (braze furnace 10' dia max)
4. Beams required at each panel joint.
5. External/internal surface thermal expansion mismatch.
6. Design & process development required.

Materials

Inconel

Options

Titanium
Hi-temp aluminum
Superalloys

Fabrication Approach

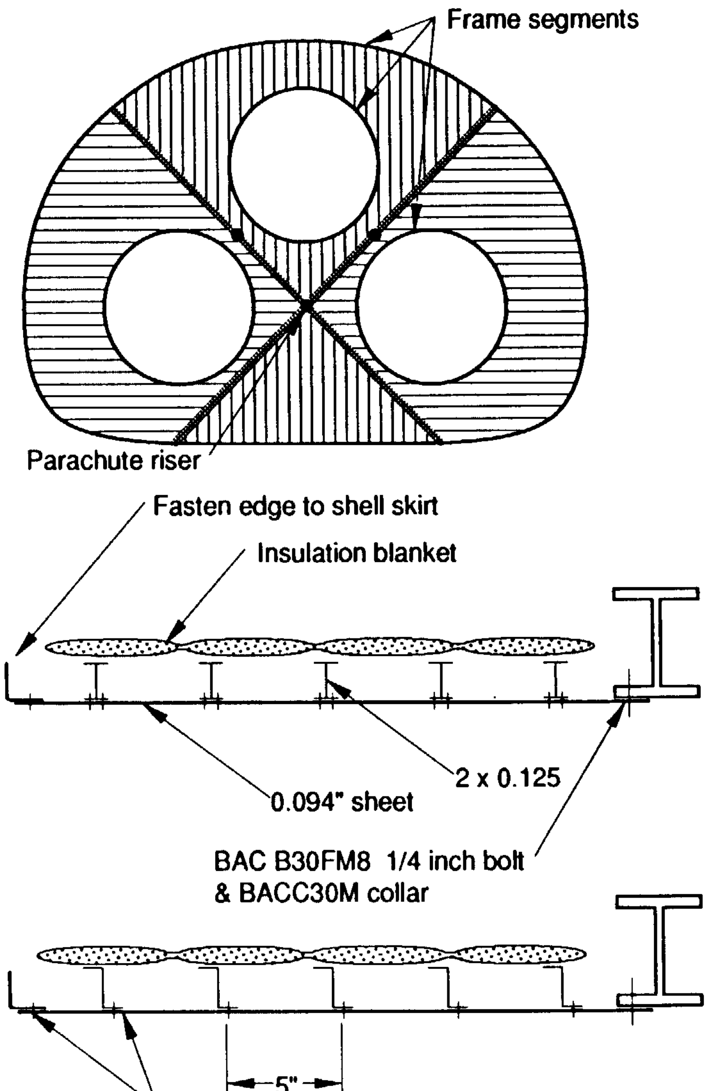
1. Hot form dimpled sheets.
2. Trim dimpled sheets and septum sheets to required shape.
3. Prepare sheets for brazing.
4. Braze sheets into multiwall sandwich.
5. Attach frames.

Features

- TPS/Insulation for plume heating may not be required

Bulkhead Design Concept-6

Stiffened Skin



Advantages

1. Low-cost tooling
2. Low risk approach (like commercial airplane structure)
3. Established inspection and repair techniques.

Drawbacks

1. Some insulation required externally or internally.
2. Many fasteners required.
3. Poor acoustic attenuation.

Materials

Aluminum

Options

Hi-temp aluminum
Superalloys (weld)
Titanium (welding feasible)
Al-Li

Fabrication Approach

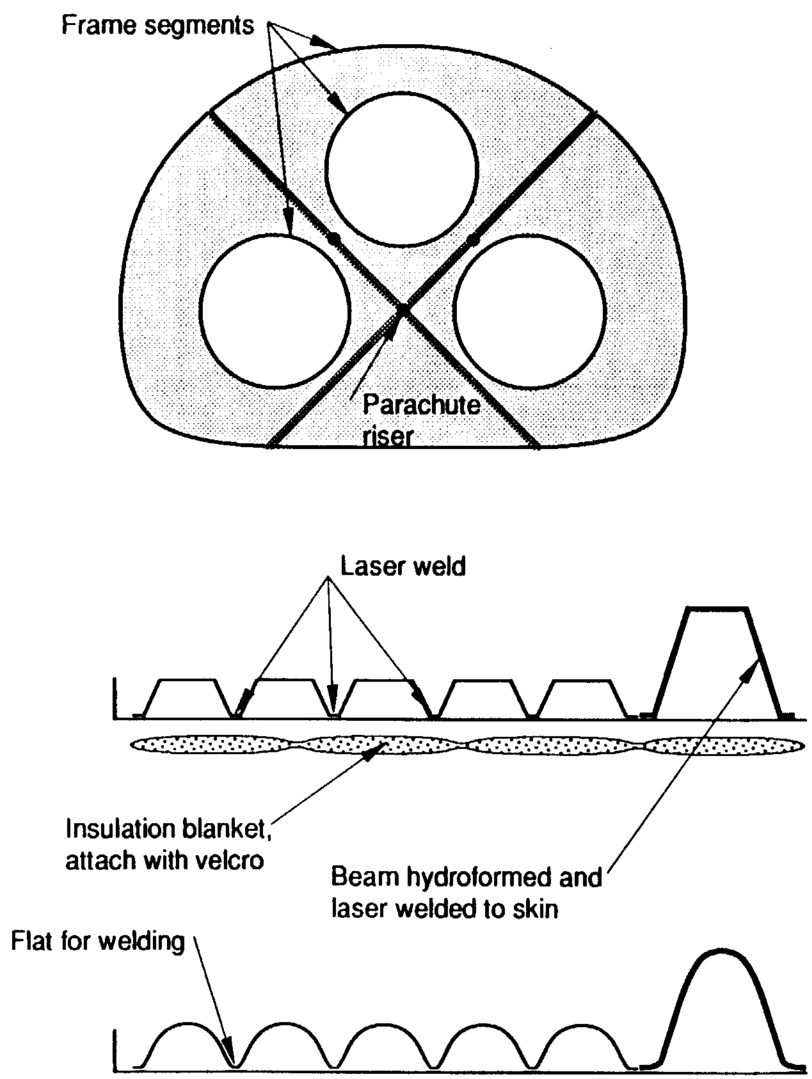
1. Extrude stiffener & edge shapes
2. Form edge shapes to required curvature
3. Cut skin sheet to size
4A. Rivet/fasten stiffeners to skin
4B. Alternative–Bond stiffeners to skin.
4C. Bond and fasten.

Features

- Airplane structure approach

Bulkhead Design Concept-7

Truss Panel (single faced)



Alternative Configuration

Advantages

1. Low-cost tooling
2. Automation potential

Drawbacks

1. Insulation required externally or internally.
2. Attaching curved frames may add complexity.
3. Must protect against corrosion at faying surfaces.
4. Material strength loss at welds.

Materials

Al-Li

Options

Hi-temp aluminum (welding techniques must be developed)

Al; Ti (corrosion resistant)

Fabrication Approach

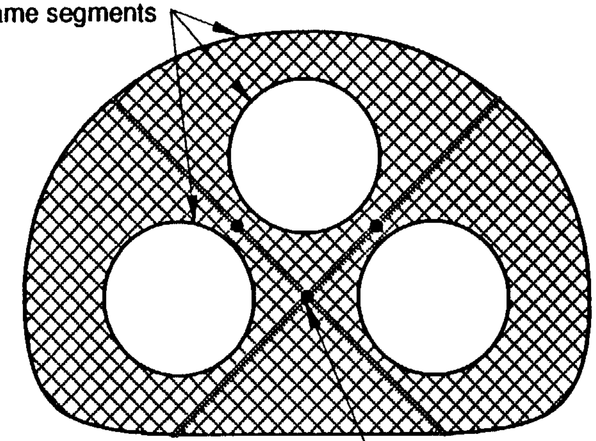
1. Break/roll form corrugations.
2. Hydroform beams.
3. Laser-weld corrugated panels and beams to flat panel.
4. Trim panels to shape Attach frames with fasteners or welds.

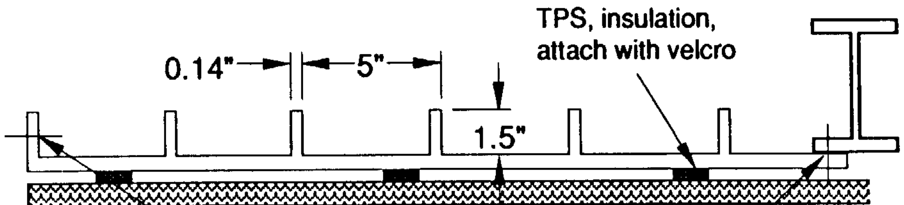
Features

- Laser welded construction
- Several stiffening geometries feasible
- Integral stiffening beam

Bulkhead Design Concept-8

Orthogrid Stiffened





Advantages

1. Automated fabrication feasible.
2. Support and attachment details easily incorporated.
3. Existing fabrication approach applicable (low risk).
4. Shear stiffness superior to stringer stiffened.
5. Established inspection techniques.
6. Stiffener geometry is tailorable to requirements.
7. Cost risk is low.

Drawbacks

1. Extensive machining required may penalize some materials.
2. Poor acoustic attenuation.

Materials

Aluminum

Options

Hi-temp aluminum (material in required thickness not currently available)

Al-Li (can't recycle chips)

Fabrication Approach

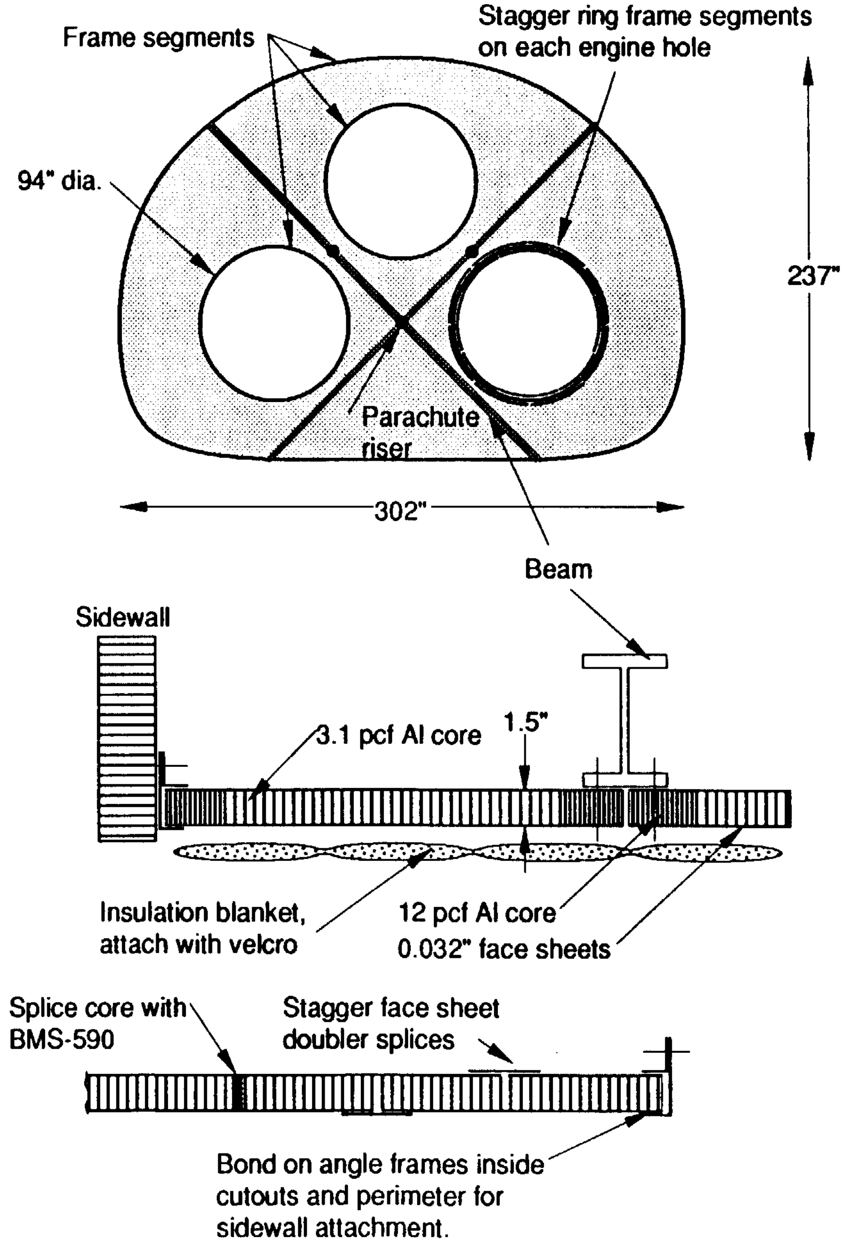
1. Machine from plate orthogrid pockets, frames, and attachments in panels.
2. Attach insulation.

Features

- Robust structure
- Integrally machined stiffening

Bulkhead Design Concept-9

Bonded Aluminum Sandwich



Advantages

1. Established (low risk) fabrication procedures.
2. Resistant to sonic fatigue.
3. Non precision fabrication is feasible.
4. Low cost-risk.

Drawbacks

1. Requires TPS or insulation for plume heating environment.
2. Bonding a one piece bulkhead (if desired) dependent on facility size (autoclave dia. >26 ft).
3. Must protect against corrosion at faying surfaces.

Materials

Aluminum

Options

2024
7075

Fabrication Approach

1. Vacuum bag or autoclave bond face sheets and doublers to core.
2. Stretch form angle frame segments; bond to segments to panels staggering the gaps.
3. Fasten to beams through high density core.
4. Fasten to sidewall with barrel nut or at frame flange.

Features

- High performance / low risk
- Mostly bonded construction feasible

APPENDIX C - WEIGHTS ANALYSIS

The following weights statements of selected structural concepts were prepared by the Boeing ALS Project weights staff. These analyses serve as a check on the weights estimates used during concept definition and comparison during preliminary trade studies.

AEROSHELL WEIGHT SUMMARY
POLYIMIDE HONEYCOMB SANDWICH CONCEPT
DRAWING NO. SK891230

ITEM	AREA (IN2)	AREA (FT2)	THICKNESS (IN)	XAREA (IN2)	LENGTH (IN)	DENSITY (LB/IN3)	DENSITY (LB/FT3)	WEIGHT (LB)			UNIT WEIGHT (LB/FT2)		
SANDWICH PANELS (EXCL CUTOUTS, DOUBLERS, INSERTS)	155680	1081								2683			2.48
DOME PANELS, INCLUDING CAP	36704	255							758			2.98	
OUTER SKIN (GR / POLYIMIDE)			0.100			0.060		220					
INNER SKIN (GR / EPOXY)			0.100			0.060		220					
CORE (TITANIUM)			2.750				4.70	275					
ADHESIVE (FM-35 FOR OUTER SKIN, BMS 5-80 FOR INNER SKIN)			0.030			0.039	68.00	43			0.17		
DOME SHOULDER PANELS	30116	209							622			2.98	
OUTER SKIN (GR / POLYIMIDE)			0.100			0.060		181					
INNER SKIN (GR / EPOXY)			0.100			0.060		181					
CORE (TITANIUM)			2.750				4.70	225					
ADHESIVE (FM-35 FOR OUTER SKIN, BMS 5-80 FOR INNER SKIN)			0.030			0.039	68.00	36			0.17		
SIDE WALL PANELS (INCL AFT EXTENSIONS)	88860	617							1303			2.11	
OUTER SKIN (GR / POLYIMIDE)			0.060			0.060		320					
INNER SKIN (GR / EPOXY)			0.040			0.060		213					
CORE (TITANIUM)			2.750				4.70	665					
ADHESIVE (FM-35 FOR OUTER SKIN, BMS 5-80 FOR INNER SKIN)			0.030			0.039	68.00	105			0.17		
CUTOUTS	-18050	-125								-284			-2.26
LO2 LINE DOOR CUTOUT	-1730	-12							-36			-2.98	
LH2 LINE DOOR CUTOUT	-1470	-10							-30			-2.98	
THRUST STRUCTURE INTERFACE CUTOUTS (6)	-300	-2.1							-4			-2.11	
ACCESS DOOR CUTOUTS (3)	-14550	-101							-213			-2.11	
STIFFENERS, CLOSEOUTS, AND FASTENER INSERTS										461			
STIFFENER TUBE - SHOULDER TO SIDE WALL JUNCTION									141				
CORE REMOVAL				-11.00	878	0.003	4.70	-26					
TUBE INSTALLATION				11.00	878	0.017	30.00	168					
CLOSEOUTS - THRUST STRUCTURE INTERFACE CUTOUTS (6)									60				
FASTENER INSERT TUBES - AIR BAG ATTACH (2)									160				
CORE REMOVAL				-6.60	1659	0.003	4.70	-30					
TUBE INSTALLATION				6.60	1659	0.017	30.00	190					
FASTENER INSERT TUBES- DOME SUPPORT (8)									24				
CORE REMOVAL				-6.60	251	0.003	4.70	-5					
TUBE INSTALLATION				6.60	251	0.017	30.00	29					
FASTENER INSERT TUBES - THRUST STRUCUTRE INTERFACES (6)									29				
CORE REMOVAL				-6.60	302	0.003	4.70	-5					
TUBE INSTALLATION				6.60	302	0.017	30.00	35					
FASTENER INSERT TUBES- HEAT SHIELD ATTACH - LONGITUDINAL (2)									17				
CORE REMOVAL				-6.60	180	0.003	4.70	-3					
TUBE INSTALLATION				6.60	180	0.017	30.00	21					
FASTENER INSERT TUBES- AFT BULKHEAD ATTACH - AFT / CIRCUM (3)									28				
CORE REMOVAL				-6.60	291	0.003	4.70	-5					
TUBE INSTALLATION				6.60	291	0.017	30.00	33					
ACCESS DOOR INSTALLATIONS (3)	14550	101								512			5.06
SANDWICH PANEL DOUBLERS - BODY SIDE (6)	10020	70							60				
OUTER SKIN DOUBLERS (3)			0.040			0.060		24					
INNER SKIN DOUBLERS (3)			0.060			0.060		36					
DOOR FRAMES - BODY SIDE (3)									199				
CORE REMOVAL				-10.00	747	0.003	4.70	-20					
TUBE INSTALLATION				10.00	747	0.017	30.00	130					
STIFFENER FRAME				2.00	747	0.060		90					
DOOR FRAMES - DOOR SIDE (3)				0.50	730	0.060			22				
DOOR SANDWICH PANELS (3)	9420	65							195			2.98	
DOOR FASTENERS (TBD)									24				
DOOR SEALS (3)									12				
PROPELLANT LINE DOOR INSTALLATIONS (2)	3200	22								444			20.00
AEROSHELL WEIGHT		1081								3816			3.53

NOTE: DOOR INSTALLATION AREA AND UNIT WEIGHT ARE REFERENCED TO THE EQUIVALENT DOOR CUTOUT AREA PRIOR TO FRAMING.

AEROSHELL WEIGHT SUMMARY
POLYIMIDE HONEYCOMB SANDWICH CONCEPT OUTER SKIN = 0.20" THICK
DRAWING NO. SK891230

ITEM	AREA (IN2)	AREA (FT2)	THICKNESS (IN)	XAREA (IN2)	LENGTH (IN)	DENSITY (LB/IN3)	DENSITY (LB/FT3)	WEIGHT (LB)			UNIT WEIGHT (LB/FT2)		
SANDWICH PANELS (EXCL CUTOUTS, DOUBLERS, INSERTS)	**155680**	**1081**								**3084**			**2.85**
DOME PANELS, INCLUDING CAP	36704	255							979			3.84	
OUTER SKIN (GR / POLYIMIDE)			0.200			0.060		440					
INNER SKIN (GR / EPOXY)			0.100			0.060		220					
CORE (TITANIUM)			2.750				4.70	275					
ADHESIVE (FM-35 FOR OUTER SKIN, BMS 5-80 FOR INNER SKIN)			0.030			0.039	68.00	43			0.17		
DOME SHOULDER PANELS	30116	209							803			3.84	
OUTER SKIN (GR / POLYIMIDE)			0.200			0.060		361					
INNER SKIN (GR / EPOXY)			0.100			0.060		181					
CORE (TITANIUM)			2.750				4.70	225					
ADHESIVE (FM-35 FOR OUTER SKIN, BMS 5-80 FOR INNER SKIN)			0.030			0.039	68.00	36			0.17		
SIDE WALL PANELS (INCL AFT EXTENSIONS)	88860	617							1303			2.11	
OUTER SKIN (GR / POLYIMIDE)			0.060			0.060		320					
INNER SKIN (GR / EPOXY)			0.040			0.060		213					
CORE (TITANIUM)			2.750				4.70	665					
ADHESIVE (FM-35 FOR OUTER SKIN, BMS 5-80 FOR INNER SKIN)			0.030			0.039	68.00	105			0.17		
CUTOUTS	**-18050**	**-125**								**-303**			**-2.42**
LO2 LINE DOOR CUTOUT	-1730	-12							-46			-3.84	
LH2 LINE DOOR CUTOUT	-1470	-10							-39			-3.84	
THRUST STRUCTURE INTERFACE CUTOUTS (6)	-300	-2.1							-4			-2.11	
ACCESS DOOR CUTOUTS (3)	-14550	-101							-213			-2.11	
STIFFENERS, CLOSEOUTS, AND FASTENER INSERTS										**461**			
STIFFENER TUBE - SHOULDER TO SIDE WALL JUNCTION									141				
CORE REMOVAL				-11.00	878	0.003	4.70	-26					
TUBE INSTALLATION				11.00	878	0.017	30.00	168					
CLOSEOUTS - THRUST STRUCTURE INTERFACE CUTOUTS (6)									60				
FASTENER INSERT TUBES - AIR BAG ATTACH (2)									160				
CORE REMOVAL				-6.60	1659	0.003	4.70	-30					
TUBE INSTALLATION				6.60	1659	0.017	30.00	190					
FASTENER INSERT TUBES- DOME SUPPORT (8)									24				
CORE REMOVAL				-6.60	251	0.003	4.70	-5					
TUBE INSTALLATION				6.60	251	0.017	30.00	29					
FASTENER INSERT TUBES - THRUST STRUCTURE INTERFACES (6)									29				
CORE REMOVAL				-6.60	302	0.003	4.70	-5					
TUBE INSTALLATION				6.60	302	0.017	30.00	35					
FASTENER INSERT TUBES- HEAT SHIELD ATTACH - LONGITUDINAL (2)									17				
CORE REMOVAL				-6.60	180	0.003	4.70	-3					
TUBE INSTALLATION				6.60	180	0.017	30.00	21					
FASTENER INSERT TUBES- AFT BULKHEAD ATTACH - AFT / CIRCUM (3)									28				
CORE REMOVAL				-6.60	291	0.003	4.70	-5					
TUBE INSTALLATION				6.60	291	0.017	30.00	33					
ACCESS DOOR INSTALLATIONS (3)	**14550**	**101**								**568**			**5.62**
SANDWICH PANEL DOUBLERS - BODY SIDE (6)	10020	70							60				
OUTER SKIN DOUBLERS (3)			0.040			0.060		24					
INNER SKIN DOUBLERS (3)			0.060			0.060		36					
DOOR FRAMES - BODY SIDE (3)									199				
CORE REMOVAL				-10.00	747	0.003	4.70	-20					
TUBE INSTALLATION				10.00	747	0.017	30.00	130					
STIFFENER FRAME				2.00	747	0.060		90					
DOOR FRAMES - DOOR SIDE (3)				0.50	730	0.060			22				
DOOR SANDWICH PANELS (3)	9420	65							251			3.84	
DOOR FASTENERS (TBD)									24				
DOOR SEALS (3)									12				
PROPELLANT LINE DOOR INSTALLATIONS (2)	**3200**	**22**								**444**			**20.00**
AEROSHELL WEIGHT		**1081**								**4254**			**3.94**

NOTE: DOOR INSTALLATION AREA AND UNIT WEIGHT ARE REFERENCED TO THE EQUIVALENT DOOR CUTOUT AREA PRIOR TO FRAMING.

BASELINE: SANDWICH TOTAL THICKNESS = 3.0 INCHES
DOME OUTER SKIN THICKNESS = 0.100 INCHES
DOME AND SIDEWALL CORE DENSITY = 4.0 PCF

AEROSHELL WEIGHT SUMMARY
TANIUM HONEYCOMB SANDWICH CONCEPT (ASTECH)
DRAWING NO. SK891226

ITEM	AREA (IN2)	AREA (FT2)	THICKNESS (IN)	XAREA (IN2)	LENGTH (IN)	DENSITY (LB/IN3)	DENSITY (LB/FT3)	WEIGHT (LB)			UNIT WEIGHT (LB/FT2)	
SANDWICH PANELS (EXCL CUTOUTS, DOUBLERS, INSERTS)	**155680**	**1081**								**3120**		**2.89**
DOME PANELS, INCLUDING CAP	36704	255							1067		4.19	
OUTER SKIN			0.100			0.160		587				
INNER SKIN			0.040			0.160		235				
CORE			2.880				4.00	245				
DOME SHOULDER PANELS	30116	209							875		4.19	
OUTER SKIN			0.100			0.160		482				
INNER SKIN			0.040			0.160		193				
CORE			2.880				4.00	201				
SIDE WALL PANELS (INCL AFT EXTENSIONS)	88860	617							1178		1.91	
OUTER SKIN			0.020			0.160		284				
INNER SKIN			0.020			0.160		284				
CORE			2.960				4.00	609				
CUTOUTS	**-19019**	**-132**								**-316**		**-2.40**
LO2 LINE DOOR CUTOUT	-1730	-12							-50		-4.19	
LH2 LINE DOOR CUTOUT	-1470	-10							-43		-4.19	
THRUST STRUCTURE INTERFACE CUTOUTS (6)	-300	-2.1							-9		-4.19	
ACCESS DOOR CUTOUTS (3)	-14550	-101							-193		-1.91	
FASTENER INSERT CUTOUTS - DOME (462)	-567	-3.9							-16		-4.19	
FASTENER INSERT CUTOUTS - SIDE WALL (328)	-402	-2.8							-5		-1.91	
STIFFENERS, CLOSEOUTS, AND FASTENER INSERTS										**520**		
STIFFENER FRAME - FORWARD FACE TO SHOULDER				1.10	660	0.160			116			
STIFFENER FRAME - SHOULDER TO SIDE WALL				1.10	846	0.160			149			
STIFFENER / CLOSEOUT FRAME - BULKHEAD ATTACH									123			
AFT EDGE EXCLUDING AFT EXTENSION REGIONS				0.70	616	0.160		69				
AFT EXTENSION REGIONS (3)				1.15	291	0.160		54				
CLOSEOUTS - THRUST STRUCTURE INTERFACE CUTOUTS (6)	432	3.0	0.080			0.160			6			
FASTENER INSERTS - AIR BAG ATTACH (280)									45			
FASTENER INSERTS - DOME SUPPORT (80)									13			
FASTENER INSERTS - THRUST STRUCTURE INTERFACES (102)									16			
FASTENER INSERTS - HEAT SHIELD ATTACH (328)									52			
ACCESS DOOR INSTALLATIONS (3)	**14550**	**101**								**678**		**6.71**
SANDWICH PANEL DOUBLERS - BODY SIDE (6)	10020	70	0.060			0.160			96			
DOOR FRAMES - BODY SIDE (3)				2.44	747	0.160			292			
DOOR FRAMES - DOOR SIDE (3)				1.19	681	0.160			130			
DOOR SANDWICH PANELS (3)	9420	65				0.160			125		1.91	
DOOR FASTENERS (TBD)									24			
DOOR SEALS (3)									12			
PROPELLANT LINE DOOR INSTALLATIONS (2)	**3200**	**22**								**444**		**20.00**
AEROSHELL WEIGHT		**1081**								**4446**		**4.11**

NOTE: DOOR INSTALLATION AREA AND UNIT WEIGHT ARE
REFERENCED TO THE DOOR CUTOUT AREA PRIOR TO FRAMING.

file: B. Ti Sand Wt Sum Alt 4 4/5/90

BASELINE: SANDWICH TOTAL THICKNESS = 3.0 INCHES
DOME OUTER SKIN THICKNESS = 0.100 INCHES
DOME AND SIDEWALL CORE DENSITY = 8.0 PCF

AEROSHELL WEIGHT SUMMARY
TANIUM HONEYCOMB SANDWICH CONCEPT (ASTECH)
DRAWING NO. SK891226

ITEM	AREA (IN2)	AREA (FT2)	THICKNESS (IN)	XAREA (IN2)	LENGTH (IN)	DENSITY (LB/IN3)	DENSITY (LB/FT3)	WEIGHT (LB)			UNIT WEIGHT (LB/FT2)	
SANDWICH PANELS (EXCL CUTOUTS, DOUBLERS, INSERTS)	**155680**	**1081**								**4174**		**3.86**
DOME PANELS, INCLUDING CAP	36704	255							1312		5.15	
OUTER SKIN			0.100			0.160		587				
INNER SKIN			0.040			0.160		235				
CORE			2.880				8.00	489				
DOME SHOULDER PANELS	30116	209							1076		5.15	
OUTER SKIN			0.100			0.160		482				
INNER SKIN			0.040			0.160		193				
CORE			2.880				8.00	402				
SIDE WALL PANELS (INCL AFT EXTENSIONS)	88860	617							1786		2.89	
OUTER SKIN			0.020			0.160		284				
INNER SKIN			0.020			0.160		284				
CORE			2.960				8.00	1218				
CUTOUTS	**-19019**	**-132**								**-446**		**-3.38**
LO2 LINE DOOR CUTOUT	-1730	-12							-62		-5.15	
LH2 LINE DOOR CUTOUT	-1470	-10							-53		-5.15	
THRUST STRUCTURE INTERFACE CUTOUTS (6)	-300	-2.1							-11		-5.15	
ACCESS DOOR CUTOUTS (3)	-14550	-101							-293		-2.89	
FASTENER INSERT CUTOUTS - DOME (462)	-567	-3.9							-20		-5.15	
FASTENER INSERT CUTOUTS - SIDE WALL (328)	-402	-2.8							-8		-2.89	
STIFFENERS, CLOSEOUTS, AND FASTENER INSERTS										**520**		
STIFFENER FRAME - FORWARD FACE TO SHOULDER				1.10	660	0.160			116			
STIFFENER FRAME - SHOULDER TO SIDE WALL				1.10	846	0.160			149			
STIFFENER / CLOSEOUT FRAME - BULKHEAD ATTACH									123			
AFT EDGE EXCLUDING AFT EXTENSION REGIONS				0.70	616	0.160		69				
AFT EXTENSION REGIONS (3)				1.15	291	0.160		54				
CLOSEOUTS - THRUST STRUCTURE INTERFACE CUTOUTS (6)	432	3.0	0.080			0.160			6			
FASTENER INSERTS - AIR BAG ATTACH (280)									45			
FASTENER INSERTS - DOME SUPPORT (80)									13			
FASTENER INSERTS - THRUST STRUCTURE INTERFACES (102)									16			
FASTENER INSERTS - HEAT SHIELD ATTACH (328)									52			
ACCESS DOOR INSTALLATIONS (3)	**14550**	**101**								**743**		**7.35**
SANDWICH PANEL DOUBLERS - BODY SIDE (6)	10020	70	0.060			0.160			96			
DOOR FRAMES - BODY SIDE (3)				2.44	747	0.160			292			
DOOR FRAMES - DOOR SIDE (3)				1.19	681	0.160			130			
DOOR SANDWICH PANELS (3)	9420	65				0.160			189		2.89	
DOOR FASTENERS (TBD)									24			
DOOR SEALS (3)									12			
PROPELLANT LINE DOOR INSTALLATIONS (2)	**3200**	**22**								**444**		**20.00**
AEROSHELL WEIGHT		**1081**								**5435**		**5.03**

NOTE: DOOR INSTALLATION AREA AND UNIT WEIGHT ARE
REFERENCED TO THE DOOR CUTOUT AREA PRIOR TO FRAMING.

BASELINE: SANDWICH TOTAL THICKNESS = 3.0 INCHES
DOME OUTER SKIN THICKNESS = 0.080-IN
DOME AND SIDEWALL CORE DENSITY = 8.0 PCF

AEROSHELL WEIGHT SUMMARY
TITANIUM HONEYCOMB SANDWICH CONCEPT (ASTECH)
DRAWING NO. SK891226

ITEM	AREA (IN2)	AREA (FT2)	THICKNESS (IN)	XAREA (IN2)	LENGTH (IN)	DENSITY (LB/IN3)	DENSITY (LB/FT3)	WEIGHT (LB)			UNIT WEIGHT (LB/FT2)	
SANDWICH PANELS (EXCL CUTOUTS, DOUBLERS, INSERTS)	**155680**	**1081**								**3960**		**3.66**
DOME PANELS, INCLUDING CAP	36704	255							1194		4.68	
OUTER SKIN			0.080			0.160		470				
INNER SKIN			0.040			0.160		235				
CORE			2.880				8.00	489				
DOME SHOULDER PANELS	30116	209							980		4.68	
OUTER SKIN			0.080			0.160		385				
INNER SKIN			0.040			0.160		193				
CORE			2.880				8.00	402				
SIDE WALL PANELS (INCL AFT EXTENSIONS)	88860	617							1786		2.89	
OUTER SKIN			0.020			0.160		284				
INNER SKIN			0.020			0.160		284				
CORE			2.960				8.00	1218				
CUTOUTS	**-19019**	**-132**								**-433**		**-3.28**
LO2 LINE DOOR CUTOUT	-1730	-12							-56		-4.68	
LH2 LINE DOOR CUTOUT	-1470	-10							-48		-4.68	
THRUST STRUCTURE INTERFACE CUTOUTS (6)	-300	-2.1							-10		-4.68	
ACCESS DOOR CUTOUTS (3)	-14550	-101							-293		-2.89	
FASTENER INSERT CUTOUTS - DOME (462)	-567	-3.9							-18		-4.68	
FASTENER INSERT CUTOUTS - SIDE WALL (328)	-402	-2.8							-8		-2.89	
STIFFENERS, CLOSEOUTS, AND FASTENER INSERTS										**520**		
STIFFENER FRAME - FORWARD FACE TO SHOULDER				1.10	660	0.160			116			
STIFFENER FRAME - SHOULDER TO SIDE WALL				1.10	846	0.160			149			
STIFFENER / CLOSEOUT FRAME - BULKHEAD ATTACH									123			
AFT EDGE EXCLUDING AFT EXTENSION REGIONS				0.70	616	0.160		69				
AFT EXTENSION REGIONS (3)				1.15	291	0.160		54				
CLOSEOUTS - THRUST STRUCTURE INTERFACE CUTOUTS (6)	432	3.0	0.080			0.160			6			
FASTENER INSERTS - AIR BAG ATTACH (280)									45			
FASTENER INSERTS - DOME SUPPORT (80)									13			
FASTENER INSERTS - THRUST STRUCTURE INTERFACES (102)									16			
FASTENER INSERTS - HEAT SHIELD ATTACH (328)									52			
ACCESS DOOR INSTALLATIONS (3)	**14550**	**101**								**743**		**7.35**
SANDWICH PANEL DOUBLERS - BODY SIDE (6)	10020	70	0.060			0.160			96			
DOOR FRAMES - BODY SIDE (3)				2.44	747	0.160			292			
DOOR FRAMES - DOOR SIDE (3)				1.19	681	0.160			130			
DOOR SANDWICH PANELS (3)	9420	65				0.160			189		2.89	
DOOR FASTENERS (TBD)									24			
DOOR SEALS (3)									12			
PROPELLANT LINE DOOR INSTALLATIONS (2)	**3200**	**22**								**444**		**20.00**
AEROSHELL WEIGHT		**1081**								**5234**		**4.84**

NOTE: DOOR INSTALLATION AREA AND UNIT WEIGHT ARE REFERENCED TO THE DOOR CUTOUT AREA PRIOR TO FRAMING.

ALTERNATE 1: SANDWICH TOTAL THICKNESS = 3.0 INCHES
DOME OUTER SKIN THICKNESS = 0.050-IN
DOME AND SIDEWALL CORE DENSITY = 8.0 PCF

AEROSHELL WEIGHT SUMMARY
TITANIUM HONEYCOMB SANDWICH CONCEPT (ASTECH)
DRAWING NO. SK891226

ITEM	AREA (IN2)	AREA (FT2)	THICKNESS (IN)	XAREA (IN2)	LENGTH (IN)	DENSITY (LB/IN3)	DENSITY (LB/FT3)	WEIGHT (LB)	UNIT WEIGHT (LB/FT2)
SANDWICH PANELS (EXCL CUTOUTS, DOUBLERS, INSERTS)	**155680**	**1081**						**3649**	**3.38**
DOME PANELS, INCLUDING CAP	36704	255						1023	4.01
OUTER SKIN			0.050			0.160		294	
INNER SKIN			0.040			0.160		235	
CORE			2.910				8.00	494	
DOME SHOULDER PANELS	30116	209						839	4.01
OUTER SKIN			0.050			0.160		241	
INNER SKIN			0.040			0.160		193	
CORE			2.910				8.00	406	
SIDE WALL PANELS (INCL AFT EXTENSIONS)	88860	617						1786	2.89
OUTER SKIN			0.020			0.160		284	
INNER SKIN			0.020			0.160		284	
CORE			2.960				8.00	1218	
CUTOUTS	**-19019**	**-132**						**-414**	**-3.13**
LO2 LINE DOOR CUTOUT	-1730	-12						-48	-4.01
LH2 LINE DOOR CUTOUT	-1470	-10						-41	-4.01
THRUST STRUCTURE INTERFACE CUTOUTS (6)	-300	-2.1						-8	-4.01
ACCESS DOOR CUTOUTS (3)	-14550	-101						-293	-2.89
FASTENER INSERT CUTOUTS - DOME (462)	-567	-3.9						-16	-4.01
FASTENER INSERT CUTOUTS - SIDE WALL (328)	-402	-2.8						-8	-2.89
STIFFENERS, CLOSEOUTS, AND FASTENER INSERTS								**520**	
STIFFENER FRAME - FORWARD FACE TO SHOULDER				1.10	660	0.160		116	
STIFFENER FRAME - SHOULDER TO SIDE WALL				1.10	846	0.160		149	
STIFFENER / CLOSEOUT FRAME - BULKHEAD ATTACH								123	
AFT EDGE EXCLUDING AFT EXTENSION REGIONS				0.70	616	0.160		69	
AFT EXTENSION REGIONS (3)				1.15	291	0.160		54	
CLOSEOUTS - THRUST STRUCTURE INTERFACE CUTOUTS (6)	432	3.0	0.080			0.160		6	
FASTENER INSERTS - AIR BAG ATTACH (280)								45	
FASTENER INSERTS - DOME SUPPORT (80)								13	
FASTENER INSERTS - THRUST STRUCTURE INTERFACES (102)								16	
FASTENER INSERTS - HEAT SHIELD ATTACH (328)								52	
ACCESS DOOR INSTALLATIONS (3)	**14550**	**101**						**743**	**7.35**
SANDWICH PANEL DOUBLERS - BODY SIDE (6)	10020	70	0.060			0.160		96	
DOOR FRAMES - BODY SIDE (3)				2.44	747	0.160		292	
DOOR FRAMES - DOOR SIDE (3)				1.19	681	0.160		130	
DOOR SANDWICH PANELS (3)	9420	65				0.160		189	2.89
DOOR FASTENERS (TBD)								24	
DOOR SEALS (3)								12	
PROPELLANT LINE DOOR INSTALLATIONS (2)	**3200**	**22**						**444**	**20.00**
AEROSHELL WEIGHT		**1081**						**4942**	**4.57**

NOTE: DOOR INSTALLATION AREA AND UNIT WEIGHT ARE
REFERENCED TO THE DOOR CUTOUT AREA PRIOR TO FRAMING.

ALTERNATE 2: SANDWICH TOTAL THICKNESS = 3.0 INCHES
DOME OUTER SKIN THICKNESS = 0.050-IN
DOME AND SIDEWALL CORE DENSITY = 4.0 PCF

AEROSHELL WEIGHT SUMMARY
TITANIUM HONEYCOMB SANDWICH CONCEPT (ASTECH)
DRAWING NO. SK891226

ITEM	AREA (IN2)	AREA (FT2)	THICKNESS (IN)	XAREA (IN2)	LENGTH (IN)	DENSITY (LB/IN3)	DENSITY (LB/FT3)	WEIGHT (LB)			UNIT WEIGHT (LB/FT2)	
SANDWICH PANELS (EXCL CUTOUTS, DOUBLERS, INSERTS)	**155680**	**1081**								**2590**		**2.40**
DOME PANELS, INCLUDING CAP	36704	255							776		3.04	
OUTER SKIN			0.050			0.160		294				
INNER SKIN			0.040			0.160		235				
CORE			2.910				4.00	247				
DOME SHOULDER PANELS	30116	209							637		3.04	
OUTER SKIN			0.050			0.160		241				
INNER SKIN			0.040			0.160		193				
CORE			2.910				4.00	203				
SIDE WALL PANELS (INCL AFT EXTENSIONS)	88860	617							1178		1.91	
OUTER SKIN			0.020			0.160		284				
INNER SKIN			0.020			0.160		284				
CORE			2.960				4.00	609				
CUTOUTS	**-19019**	**-132**								**-284**		**-2.15**
LO2 LINE DOOR CUTOUT	-1730	-12							-37		-3.04	
LH2 LINE DOOR CUTOUT	-1470	-10							-31		-3.04	
THRUST STRUCTURE INTERFACE CUTOUTS (6)	-300	-2.1							-6		-3.04	
ACCESS DOOR CUTOUTS (3)	-14550	-101							-193		-1.91	
FASTENER INSERT CUTOUTS - DOME (462)	-567	-3.9							-12		-3.04	
FASTENER INSERT CUTOUTS - SIDE WALL (328)	-402	-2.8							-5		-1.91	
STIFFENERS, CLOSEOUTS, AND FASTENER INSERTS										**520**		
STIFFENER FRAME - FORWARD FACE TO SHOULDER				1.10	660	0.160			116			
STIFFENER FRAME - SHOULDER TO SIDE WALL				1.10	846	0.160			149			
STIFFENER / CLOSEOUT FRAME - BULKHEAD ATTACH									123			
AFT EDGE EXCLUDING AFT EXTENSION REGIONS				0.70	616	0.160		69				
AFT EXTENSION REGIONS (3)				1.15	291	0.160		54				
CLOSEOUTS - THRUST STRUCTURE INTERFACE CUTOUTS (6)	432	3.0	0.080			0.160			6			
FASTENER INSERTS - AIR BAG ATTACH (280)									45			
FASTENER INSERTS - DOME SUPPORT (80)									13			
FASTENER INSERTS - THRUST STRUCTURE INTERFACES (102)									16			
FASTENER INSERTS - HEAT SHIELD ATTACH (328)									52			
ACCESS DOOR INSTALLATIONS (3)	**14550**	**101**								**678**		**6.71**
SANDWICH PANEL DOUBLERS - BODY SIDE (6)	10020	70	0.060			0.160			96			
DOOR FRAMES - BODY SIDE (3)				2.44	747	0.160			292			
DOOR FRAMES - DOOR SIDE (3)				1.19	681	0.160			130			
DOOR SANDWICH PANELS (3)	9420	65				0.160			125		1.91	
DOOR FASTENERS (TBD)									24			
DOOR SEALS (3)									12			
PROPELLANT LINE DOOR INSTALLATIONS (2)	**3200**	**22**								**444**		**20.00**
AEROSHELL WEIGHT		**1081**								**3948**		**3.65**

NOTE: DOOR INSTALLATION AREA AND UNIT WEIGHT ARE
REFERENCED TO THE DOOR CUTOUT AREA PRIOR TO FRAMING.

TPS WEIGHT SUMMARY
PHEONLIC / CORK ABLATOR OVER PHEONLIC / GLASS SUBSTRATE
DRAWING NO. SK891240

ITEM	AREA (IN2)	AREA (FT2)	THICKNESS (IN)	XAREA (IN2)	LENGTH (IN)	DENSITY (LB/IN3)	DENSITY (LB/FT3)	WEIGHT (LB)			UNIT WEIGHT (LB/FT2)
DOME TPS - INFLIGHT JETTISONABLE	68114	473								1425	3.01
ABLATOR (PHEONLIC / CORK)									973		
OVER DOME FORWARD FACE, EXCLUSIVE OF DOORS	34802	242	0.750			0.018	30.50	461			
OVER DOME SHOULDER, EXCLUSIVE OF DOORS	26224	182	1.000			0.018	30.50	463			
OVER MARMON CLAMP	3091	21	0.900			0.018	30.50	49			
ABLATOR (PHEONLIC / SILICA)									31		
ALONG EDGE OF THRUST STRUCTURE INTERFACE DOOR CUTOUT (6)	498	3	1.000			0.063	109.00	31			
SUBSTRATE (PHENOLIC / GLASS)									200		
BASIC SHEET	64614	449	0.040			0.070	121.00	181			
EDGE BUILDUP AT MARMON CLAMP				0.30	883	0.070	121.00	19			
ADHESIVE									13		
ABLATOR TO SUBSTRATE	61523	427	0.005			0.039	68.00	12			0.0283
ABLATOR TO MARMON CLAMP	3091	21	0.005			0.039	68.00	1			0.0283
SHOULDER CONTOUR STRUCTURE									149		
CORE (ALUMINUM)	26741	186	0.500				8.00	62			
INNER SKIN (PHEONLIC / GLASS)	26741	186	0.040			0.052	90.00	56			
ADHESIVE (CORE TO SUBSTRATE + CORE TO INNER SKIN)	26741	186	0.030			0.039	68.00	32			0.1700
MARMON CLAMP - FWD / CIRCUMFERENTIAL									60		
STRAP SEGMENTS(5), WITH END FITTINGS (10)			0.050	0.20	883	0.283		55			
INTERCONNECTING BOLTS, EXPLOSIVE TYPE (5)								5			
DOME TPS - FIXED TO AEROSHELL										247	
ABLATOR (PHEONLIC / CORK)									35		
OVER LO2 LINE DOOR, EXCLUSIVE OF EDGE	1220	8	1.000			0.018	30.50	22			
OVER LH2 LINE DOOR, EXCLUSIVE OF EDGE	1050	7	0.750			0.018	30.50	14			
ABLATOR (PHEONLIC / SILICA)									71		
ALONG LO2 LINE DOOR EDGE	510	4	1.000			0.063	109.00	32			
ALONG LH2 LINE DOOR EDGE	420	3	0.750			0.063	109.00	20			
OVER THRUST STRUCTURE INTERFACES DOORS (6)	300	2	1.000			0.063	109.00	19			
DOOR THERMAL SEALS (SILICON)									10		
LO2 LINE DOOR				0.50	170	0.052	90.00	4			
LH2 LINE DOOR				0.50	140	0.052	90.00	4			
THRUST STRUCTURE INTERFACE DOORS (6)				0.25	150	0.052	90.00	2			
ADHESIVE									1		
ABLATOR TO DOORS	3500	24	0.005			0.039	68.00	1			0.0283
MARMON CLAMP EJECTOR SPRING INSTALLATIONS (20)									10		
THRUST STRUCTURE INTERFACE DOOR INSTALLATIONS (6)									120		
SIDEWALL TPS - GROUND REMOVEABLE	88860	617								1012	1.64
ABLATOR (PHEONLIC / CORK)									647		
OVER SUBSTRATE	70263	488	0.500			0.018	30.50	620			
OVER MARMON CLAMP	2949	20	0.400			0.018	30.50	21			
OVER RETENTION CLAMPS	1098	8	0.300			0.018	30.50	6			
SUBSTRATE (PHEONLIC / GLASS)									269		
BASIC SHEET	74310	516	0.040			0.070	121.00	208			
EDGE BUILDUP AT CLAMPS / AT ACCESS DOORS				0.30	2897	0.070	121.00	61			
ADHESIVE									15		
ABLATOR TO SUBSTRATE	70263	488	0.005			0.039	68.00	14			0.0283
ABLATOR TO MARMON CLAMP	2949	20	0.005			0.039	68.00	1			0.0283
ABLATOR TO RETENTION STRAPS	1098	8	0.005			0.039	68.00	0			0.0283
MARMON CLAMP - AFT / CIRCUMFERENTIAL									59		
STRAP SEGMENTS (5), WITH END FITTINGS (10)			0.050	0.20	907	0.283		56			
INTERCONNECTING BOLTS (5)								3			
RETENTION CLAMPS - LONGITUDINAL (2)									23		
STRAP SEGMENTS (2)			0.200	1.20	180	0.100		22			
FASTENERS (30)								1			
SIDEWALL TPS - ATTACHED TO AEROSHELL										234	
ABLATOR (PHENOLIC / CORK)									128		
OVER ACCESS DOORS (3)	14550	101	0.500			0.018	30.50	128			
MARMON CLAMP PROVISIONS - AFT / CIRCUMFERENTIAL									63		
CLAMP POSITIONING RING (ALUMINUM)				0.65	907	0.100		59			
FASTENERS - RING ATTACHMENT (150)								5			
RETENTION CLAMP PROVISIONS - LONGITUDINAL (2)									12		
CLAMP POSITIONING PLATE EXCLUDING FASTENER INSERTS (ALUM)				0.50	180	0.100		9			
RETENTION STRAP FASTENER INSERTS (75)								1			
FASTENERS - PLATE ATTACHMENT (150)								2			
SUBSTRATE TENSIONING PROVISIONS AT ACCESS DOORS									30		
TPS WEIGHT		1090								2918	2.68

NOTE: DOOR AREA IS DOOR CUTOUT AREA PRIOR TO FRAMING

AFT BULKHEAD WEIGHT SUMMARY
GRAPHITE/EPOXY SANDWICH CONCEPT

ITEM	AREA (IN2)	AREA (FT2)	THICKNESS (IN)	XAREA (IN2)	LENGTH (IN)	DENSITY (LB/IN3)	DENSITY (LB/FT3)	WEIGHT (LB)	UNIT WEIGHT (LB/FT2)
SANDWICH PANEL (EXCLUDING CUTOUTS, EDGE FRAMING, INSERTS)	**59728**	**415**						**554**	**1.33**
INNER SKIN (GR / EPOXY)			0.040			0.060		143	
OUTER SKIN (GR / EPOXY)			0.040			0.060		143	
CORE (NOMEX)			1.420				4.00	196	
ADHESIVE			0.030			0.039	68.00	71	0.170
MAIN ENGINE CUTOUTS - 94.0 IN DIA (3)	**-20820**	**-145**						**-192**	**-1.33**
MAIN ENGINE CUTOUT EDGE FRAMING INCREMENT (3)								**25**	
SANDWICH PANEL CORE TRIM ALONG CUTOUT EDGE				1.42	895		4.00	-3	
FRAMES				0.50	895	0.060		27	
ADHESIVE INCREMENT - FRAMES TO CORE	1285	9	0.015			0.039	68.00	1	0.085
PERIMETER EDGE FRAMING INCREMENT								**15**	
SANDWICH PANEL CORE TRIM ALONG PERIMETER EDGE				5.80	883		4.00	-12	
FRAME				0.60	888	0.060		27	
PARACHUTE RISER INSERTS (3)								**15**	
STIFFENING BEAMS INCREMENT (2)								**132**	
SANDWICH PANEL INNER SKIN REDUCTION (0.040-IN TO 0.010-IN)	6095		-0.030			0.060		-11	
SANDWICH PANEL CORE TRIM ALONG OUTER SKIN				-1.15	530		4.00	-1	
BEAM COVER SKIN	10600		0.040			0.060		25	
BEAM PLANK- INNER	2120		0.100	0.40	530	0.060		13	
BEAM PLANK- OUTER	6095		0.100	1.15	530	0.060		37	
BEAM CORE INCREMENT				50.38	530		4.00	62	
BEAM ADHESIVE INCREMENT - 5 MIL	8745	61	0.005			0.039	68.00	2	0.028
BEAM ADHESIVE INCREMENT -15 MIL	10070	70	0.015			0.039	68.00	6	0.085
FASTENERS - BULKHEAD TO AEROSHELL								**18**	
AFT BULKHEAD WEIGHT		**415**						**565**	**1.36**

AFT BULKHEAD WEIGHT SUMMARY
BONDED ALUMINUM SANDWICH CONCEPT

ITEM	AREA (IN2)	AREA (FT2)	THICKNESS (IN)	XAREA (IN2)	LENGTH (IN)	DENSITY (LB/IN3)	DENSITY (LB/FT3)	WEIGHT (LB)	UNIT WEIGHT (LB/FT2)
SANDWICH PANELS (EXCLUDING CUTOUTS, EDGE FRAMING, INSERTS) (4)	**59728**	**415**						**612**	**1.47**
INNER SKIN			0.032			0.100		191	
OUTER SKIN			0.032			0.100		191	
CORE (ALUMINUM)			1.436				3.10	154	
ADHESIVE - SKINS TO CORE			0.030			0.039	68.00	71	0.170
ADHESIVE - CORE TO CORE SPLICES	345	2	0.100			0.039	68.00	1	0.567
SPLICE STRAPS	720	5	0.050	0.15	240	0.100		4	
ADHESIVE - SPLICE STRAPS TO SKINS	720	5	0.005			0.039	68.00	0	0.028
MAIN ENGINE CUTOUTS - 94.0 IN DIA (3)	**-20820**	**-145**						**-213**	**-1.47**
MAIN ENGINE CUTOUT EDGE FRAMING (3)								**46**	
FRAMES				0.50	895	0.100		45	
ADHESIVE - FRAMES TO SANDWICH PANEL CORE	1285	9	0.015			0.039	68.00	1	0.085
ADHESIVE - FRAMES TO SANDWICH PANEL SKINS	2685	19	0.005			0.039	68.00	1	0.028
PERIMETER EDGE FRAMING INCREMENT								**74**	
SANDWICH PANEL CORE CHANGE ALONG PERIMETER (DELETE 3.1 PCF CORE)				-4.31	883		3.10	-7	
SANDWICH PANEL CORE CHANGE ALONG PERIMETER (ADD 12.0 PCF CORE)				+4.31	883		12.00	26	
FRAME				0.60	888	0.100		53	
ADHESIVE - FRAME TO SANDWICH PANEL CORE	1275	9	0.015			0.039	68.00	1	0.085
ADHESIVE - FRAME TO SANDWICH PANEL SKINS	2664	19	0.005			0.039	68.00	1	0.028
PARACHUTE RISER INSERTS (3)								**15**	
STIFFENING BEAMS INCREMENT (INCL PANEL TO PANEL SPLICES) (2)								**347**	
SANDWICH PANEL CORE CHANGE ALONG BEAMS (DELETE 3.1 PCF CORE)				-8.62	530		3.10	-8	
SANDWICH PANEL CORE CHANGE ALONG BEAMS (ADD 12.0 PCF CORE)				+8.62	530		12.00	32	
I-BEAMS				5.20	530	0.100		276	
SPLICE STRAPS - PANEL TO PANEL (OUTER SURFACE ONLY)	2650	18	0.100	0.50	530	0.100		27	
FASTENERS - BEAMS TO SANDWICH PANEL								21	
FASTENERS - BULKHEAD TO AEROSHELL								**18**	
AFT BULKHEAD WEIGHT		**415**						**899**	**2.17**

THRUST STRUCTURE WEIGHT SUMMARY
COMBINED TITANIUM SANDWICH / ALUMINUM SANDWICH CONCEPT

ITEM	AREA (IN2)	AREA (FT2)	THICKNESS (IN)	XAREA (IN2)	LENGTH (IN)	DENSITY (LB/IN3)	DENSITY (LB/FT3)	WEIGHT (LB)			UNIT WEIGHT (LB/FT2)		
MID CENTER PANEL (174.0-IN X 63.7-IN, 2219 ALUMINUM)	**11084**	**77**								**201**			**2.62**
SANDWICH WEB (174.0-IN X 62.9-IN)	10945	76							84			1.099	
FACE SKINS	21890	152	0.024			0.102		54					
CORE(174.0-IN X 57.9-IN X 1.0-IN, 5052 ALUM)	10075	70	1.000				3.10	18					
ADHESIVE - SKINS TO CORE	20150	140	0.015			0.039	68.00	12			0.085		
CHORDS (2)				2.70	348	0.102			96				
POTTING BOND - CHORDS TO SANDWICH				1.60	348	0.039	68.00		22				
MID SIDE PANEL NO.1 (123.0-IN X 63.7-IN, 2219 ALUMINUM)	**7835**	**54**								**142**			**2.62**
SANDWICH WEB (123.0-IN X 62.9-IN)	7737	54							59			1.099	
FACE SKINS	15474	107	0.024			0.102		38					
CORE(123.0-IN X 57.9-IN X 1.0-IN, 5052 ALUM)	7122	49	1.000				3.10	13					
ADHESIVE - SKINS TO CORE	14244	99	0.015			0.039	68.00	8			0.085		
CHORDS (2)				2.70	246	0.102			68				
POTTING BOND - CHORDS TO SANDWICH				1.60	246	0.039	68.00		15				
MID SIDE PANEL NO.2										**142**			**2.62**
WING PANEL NO.1 (57.6-IN X 63.7-IN, 6AL-4V TITANIUM)	**3669**	**25**								**172**			**6.75**
SANDWICH WEB (57.2-IN X 62.9-IN)	3598	25							71			2.835	
FACE SKINS	7196	50	0.050			0.160		58					
CORE(54.7-IN X 57.9-IN X 1.00-IN, 5052 AL)	3167	22	1.000				5.20	10					
ADHESIVE - SKINS TO CORE	6334	44	0.015			0.039	68.00	4			0.085		
CHORDS (2)				2.70	115	0.160			50				
EDGE MEMBER				4.00	63	0.160			40				
POTTING BOND - CHORDS TO SANDWICH				1.60	115	0.039	68.00		7				
POTTING BOND - EDGE MEMBER TO SANDWICH				1.60	63	0.039	68.00		4				
WING PANELS NO.2 THRU NO.6	**18345**	**127**								**860**			**6.75**
PANEL TO PANEL SPLICES / THRUST POSTS (6AL-4V TITANIUM) (3)										**258**			
WEB TO WEB SPLICE ANGLES (12) (4 PER THRUST POST)	3822	27	0.200	12.00	64	0.160			122				
CHORD TO CHORD SPLICE PLATES (6)	1500	10	0.400			0.160			96				
CHORD TO CHORD SPLICE FITTINGS (24)	600	4	0.400			0.160			38				
BOND - SPLICE ANGLES TO SANDWICH WEBS	3822	27	0.010			0.039	68.00		2				
TANK MODULE INTERFACE FITTINGS (TITANIUM) (6)										**180**			
MAIN ENGINE INTERFACE FITTINGS (TITANIUM) (3)										**450**			
MAIN ENGINE ACTUATOR SUPPORTS (TITANIUM) (6)										**360**			
AEROSHELL SUPPORT TRUSSES (TITANIUM) (2)										**150**			
AEROSHELL LOCAL INTERFACE STRUCTURES (TITANIUM) (8)										**120**			
SECONDARY STRUCTURES, FASTENERS, ETC										**200**			
THRUST STRUCTURE WEIGHT										**3237**			

ALTERNATE 2: SANDWICH TOTAL THICKNESS = 3.0 INCHES
DOME OUTER SKIN THICKNESS = 0.125-IN

AEROSHELL WEIGHT SUMMARY
HIGH TEMPERATURE ALUMINUM CONCEPT
DRAWING NO. SK 901116

ITEM	AREA (IN2)	AREA (FT2)	THICKNESS (IN)	XAREA (IN2)	LENGTH (IN)	DENSITY (LB/IN3)	DENSITY (LB/FT3)	WEIGHT (LB)			UNIT WEIGHT (LB/FT2)	
SANDWICH PANELS (EXCL CUTOUTS, DOUBLERS, INSERTS)	**155680**	**1081**								**3582**		**3.31**
DOME PANELS, INCLUDING CAP	36704	255							1139		4.47	
OUTER SKIN - FVS 1212			0.120			0.109		480				
INNER SKIN			0.080			0.109		320				
CORE – 0.002" foil, 3/16" cell			2.800				5.70	339				
DOME SHOULDER PANELS	30116	209							911		4.35	
OUTER SKIN - 8009 AL			0.120			0.105		379				
INNER SKIN			0.080			0.105		253				
CORE – 0.002" foil, 3/16" cell			2.800				5.70	278				
SIDE WALL PANELS (INCL AFT EXTENSIONS)	88860	617							1533		2.48	
OUTER SKIN			0.080			0.109		775				
INNER SKIN			0.040			0.109		387				
CORE – Ti, 4 PCF			1.800				4.00	370				
CUTOUTS	**-19019**	**-132**								**-382**		**-2.89**
LO2 LINE DOOR CUTOUT	-1730	-12							-54		-4.47	
LH2 LINE DOOR CUTOUT	-1470	-10							-44		-4.35	
THRUST STRUCTURE INTERFACE CUTOUTS (6)	-300	-2.1							-9		-4.35	
ACCESS DOOR CUTOUTS (3)	-14550	-101							-251		-2.48	
FASTENER INSERT CUTOUTS - DOME (462)	-567	-3.9							-17		-4.35	
FASTENER INSERT CUTOUTS - SIDE WALL (328)	-402	-2.8							-7		-2.48	
STIFFENERS, CLOSEOUTS, AND FASTENER INSERTS										**422**		
STIFFENER FRAME - FORWARD FACE TO SHOULDER				1.25	660	0.105			87			
STIFFENER FRAME - SHOULDER TO SIDE WALL				1.25	846	0.105			111			
STIFFENER / CLOSEOUT FRAME - BULKHEAD ATTACH									95			
AFT EDGE EXCLUDING AFT EXTENSION REGIONS				0.85	616	0.105		55				
AFT EXTENSION REGIONS (3)				1.30	291	0.105		40				
CLOSEOUTS - THRUST STRUCTURE INTERFACE CUTOUTS (6)	432	3.0	0.080			0.105			4			
FASTENER INSERTS - AIR BAG ATTACH (280)									45			
FASTENER INSERTS - DOME SUPPORT (80)									13			
FASTENER INSERTS - THRUST STRUCTURE INTERFACES (102)									16			
FASTENER INSERTS - HEAT SHIELD ATTACH (328)									52			
ACCESS DOOR INSTALLATIONS (3)	**14550**	**101**								**567**		**5.61**
SANDWICH PANEL DOUBLERS - BODY SIDE (6)	10020	70	0.060			0.105			63			
DOOR FRAMES - BODY SIDE (3)				2.75	747	0.105			216			
DOOR FRAMES - DOOR SIDE (3)				1.25	681	0.105			89			
DOOR SANDWICH PANELS (3)	9420	65				0.105			162		2.48	
DOOR FASTENERS (TBD)									24			
DOOR SEALS (3)									12			
PROPELLANT LINE DOOR INSTALLATIONS (2)	**3200**	**22**								**444**		**20.00**
AEROSHELL WEIGHT		**1081**								**4634**		**4.29**

NOTE: DOOR INSTALLATION AREA AND UNIT WEIGHT ARE
REFERENCED TO THE DOOR CUTOUT AREA PRIOR TO FRAMING.

File: High temp aluminum wt.

11/21/90

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Task Manager: Allan Taylor
Langley Technical Monitor: Dick M. Royster

16. Abstract
The objective of this program was to investigate the potential of advanced materials to achieve life cycle cost (LCC) benefits for reusable structure on the advanced launch system. Three structural elements were investigated - all components of an Advanced Launch System reusable propulsion/avionics module. Leading aeroshell configurations included sandwich structure using titanium, graphite/polyimide (Gr/PI), or high-temperature aluminum (HTA) face sheets. Thrust structure truss concepts used titanium, graphite/epoxy, or silicon carbide/aluminum struts. Leading aft bulkhead concepts employed graphite epoxy and aluminum.

The technical effort focused on the aeroshell because the greatest benefits were expected there. Thermal analyses show the structural temperature profiles during operation. Finite element analyses show stresses during splash-down. Weight statements and manufacturing cost estimates were prepared for calculation of LCC for each design. The Gr/PI aeroshell showed the lowest potential LCC, but the HTA aeroshell was judged to be lower risk. A technology development plan was prepared to validate the applicable structural technology.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
High Temperature Aluminum, Life Cycle Cost Thermal Protection System, Graphite Polyimide, Honeycomb sandwich	Unclassified - Unlimited subject category 15

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