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Low Cost Large Core Vehicle Structures Assessment

Final Report

for the period
November 1997 to March 1998

Contract H-28971D

Submitted to

NASA Marshall Spaceflight Center

March 13, 1998

Executive Summary

Boeing Information, Space, and Defense Systems executed a Low Cost Large Core Vehicle Structures Assessment (LCLCVSA) under contract to NASA Marshall Space Flight Center (MSFC) between November 1997 and March 1998. NASA is interested in a low-cost launch vehicle, code named Magnum, to place heavy payloads into low earth orbit for missions such as a manned mission to Mars, a Next Generation Space Telescope, a lunar-based telescope, the Air Force's proposed space based laser, and large commercial satellites. In this study, structural concepts with the potential to reduce fabrication costs were evaluated in application to the Magnum Launch Vehicle (MLV) and the Liquid Fly Back Booster (LFBB) shuttle upgrade program.

Seventeen concepts were qualitatively evaluated to select four concepts for more in-depth study. The four structural concepts selected were: an aluminum-lithium monocoque structure, an aluminum-lithium machined isogrid structure, a unitized composite sandwich structure, and a unitized composite grid structure. These were compared against a baseline concept based on the Space Shuttle External Tank (ET) construction. It was found that unitized composite structures offer significant cost and weight benefits to MLV structures. The limited study of application to LFBB structures indicated lower, but still significant benefits.

Technology and facilities development roadmaps to prepare the approaches studied for application to MLV and LFBB were constructed. It was found that the cost and schedule to develop these approaches were in line with both MLV and LFBB development schedules. Current Government and Boeing programs which address elements of the development of the technologies identified are underway. It is recommended that NASA devote resources in a timely fashion to address the specific elements related to MLV and LFBB structures.

Magnum Launch Vehicle Program

LCLCVSA Program

- ❑ Objective: Deliver large payloads to LEO using large core Magnum Launch Vehicle (MLV)
- ❑ MLV supports missions such as:
  - Manned mission to Mars
    - Place Mars mission hardware (8.4 m diameter x 30 m long) weighing 80 metric tons into Earth orbit
    - Approximately 6 MLV payload deliveries required to support 1 Mars mission
  - Next Generation Space Telescope
  - Proposed lunar-based telescope
  - Air Force Space Based Laser
  - Large commercial satellites

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NASA is currently developing preliminary plans for an expendable launch vehicle which can support future NASA and Air Force missions. The program is named the Magnum Launch Vehicle or MLV, and would be primarily focused on a manned Mars exploration and development mission, but would be able to support additional missions including the Next Generation Space Telescope, the Lunar Telescope, the Air Force Space Based Laser, and large commercial satellites.

Heavy Lift Launch Vehicle Technology

LCLCVSA Program

❑ **Titan 4 is largest ELV in current US inventory**

- **16.7 ft. diameter x 86 ft. max length payload fairing**
- **Delivers about 22,000 kg to Low Earth Orbit (LEO)**
- **\$250M-\$450M per launch (\$5000~\$9000/lb)**

❑ **MLV Goals**

- **27.5 ft. diameter x 128 ft. max length payload fairing**
- **Deliver 80,000 kg to LEO**
- **Approximately \$175M per launch (<\$1000/lb)**

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The impetus for MLV development is driven by the lack of extreme heavy lift capability in the current US (and world) inventory. MLV has further goals of significantly reduced cost while delivering a larger payload to orbit.

MLV Operations Approach Minimizes Cost through Use of Existing Facilities

LCLCVSA Program

- ❑ **Final assembly at KSC in existing Vehicle Assembly Building (VAB)**
  - Structures fabricated at convenient facilities
  - Barge transport to KSC
- ❑ **Maintain Shuttle SRB configuration**
  - Identical attachment and tie down arrangement
  - Use existing mobile launch platforms
  - Use existing crawler-transporter
  - Use modified pads 39A and 39B (new towers required)
  - Optionally use Liquid Fly-Back Boosters (LFBB) instead of SRB's

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The NASA concept for achieving MLV goals is to minimize operations costs by utilizing existing infrastructure. This drives much of the vehicle configuration to match the current Shuttle layout, although planned upgrades to the Shuttle (such as Liquid Fly-Back Boosters (LFBB) in place of the Solid Rocket Boosters) are under consideration as well.

Preliminary MLV Family Comparison

LCLCVSA Program

	MLV - SDV-1a	MLV - SDV-1b	MLV - SDV-2	MLV - SDV-3	MLV - SDV-4	MLV w/ LFBB	Program Metric
Concept Description	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
Preliminary Performance [illegible]	120 K	207 K	176 K	201 K	141 K	205 K	175 K
DDT&E Cost [illegible]							$1.9B
TFU							N/A
Average Unit Cost (over 25 flights)							$995 / lb LEO [illegible]
GLOW	4.62 Mlb	7.34 Mlb	4.70 Mlb	5.22 Mlb	7.11 Mlb	5.72 Mlb	N/A

MLV-SDV-2 configuration used for this study

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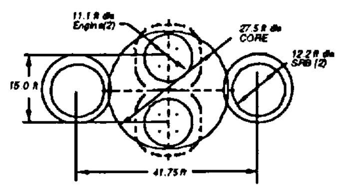
MSFC has developed a family of configurations of varying performance and baseline cost. Of these, the MLV-SDV-2 configuration most closely matched the stated performance goals, and was selected for evaluation in this study.

Core Vehicle Elements Similar Across MLV Configurations

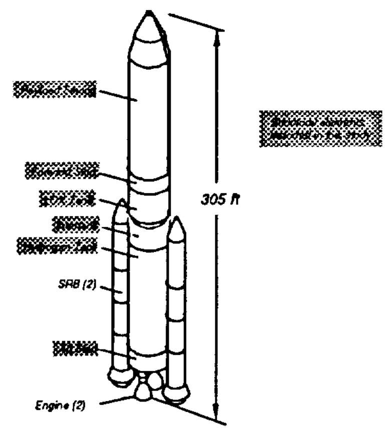
LCLCVSA Program

MLV SDV - 1a

Component	Prop Load (lbs)	Outside Dia (ft)	Length (ft)
Payload Fairing		27.5	128.00
Payload		25.0 cyl	92.00
Fwd Skirt		27.5	11.75
LOX Tank (29 psig)	1447895	27.5	41.70
Intertank		27.5	22.53
LH2 Tank (34 psig)	241316	27.5	101.70
Aft Skirt		27.5	13.75
Engine (2)		11.1 exit	23.95



Aft End View



Core based on ET tooling
Core engine arrangement dependent on engine envelope and gimbal requirements
6 degree square pattern core gimbal assumed
Aft skirt may require engine fairings
SRB / Core maintain NSTS attach points
Nozzle exits in different planes
Kick stage integrated into payload volume

Mark Gerry / PO23
4/4/97

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The core elements do not change significantly between the MLV configurations. Dimensions available for the MLV-SDV-1a configuration were thus selected for definition of the core elements in this study.

Low Cost Large Core Vehicle Structures Assessment Program Plan

LCLCVSA Program

- **Objective**
  - Assess low cost composite and metal approaches for MLV core and LFBB structures
- **Approach**
  - Task 1 - Concept Selection
    - Select two metallic and two composite concepts based on potential to reduce cost
  - Task 2 - Trade Study
    - Evaluate cost and weight impact of the selected concepts on MLV core structures
  - Task 3 - Development Roadmap
    - Identify technology and facilities advances needed to enable low cost MLV structures

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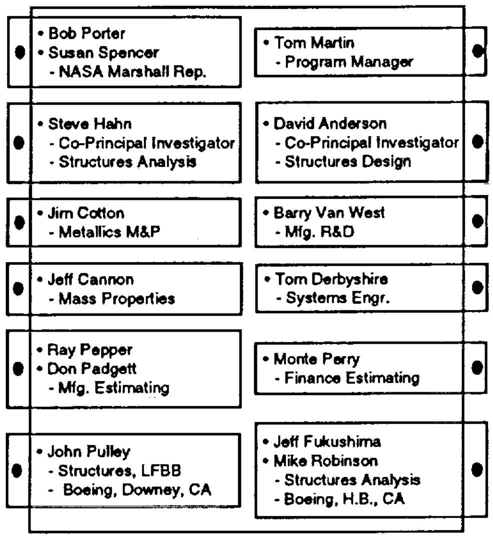
The objective of the Low Cost Large Core Vehicle Structures Assessment study was to evaluate low cost manufacturing approaches, in both metals and composites, for the production of MLV core structures. The key feature of the study was focus on low cost, rather than performance. The study comprised three technical tasks plus a final report (this document). Task 1 was completed on Boeing IRAD funding, while Tasks 2 and 3 were performed with NASA funds. This report follows the program organization, with a section devoted to each task.

LCLCVSA Team

LCLCVSA Program



- ❑ Integrated Product Team organization
- ❑ Participation from across the new Boeing
  - Broad experience in launch vehicles, advanced technology
- ❑ Direct Customer participation
  - Ensure utility of results

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The study was performed by a cross-functional team bringing together all the experience of the new Boeing, and including NASA representation. Organization into an integrated product team enabled quick response and team-wide buy-in to results.

Executive Summary of Results

LCLCVSA Program

- Composite structure concepts which utilize large, unitized construction were found to reduce both cost and weight
- Primary cost drivers were identified for each concept which could be reduced through technology and facilities advancements
- Investment roadmaps for technology and facilities improvements were developed
- Reduction of structures costs was found to be an important step towards achieving NASA goals for MLV cost performance

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It was discovered that large, unitized composite structures reduced both the weight and cost of MLV core structures. Specific cost drivers for each concept studied were identified which had further cost reduction potential through the application of advanced technologies. Roadmaps for development of these technologies and the facilities to implement them on an MLV scale were produced.

Overall, it was found that significant reductions in structural fabrication cost could be achieved, and that these cost savings would translate into significant savings at the vehicle level. However, these structural cost savings alone were insufficient to achieve the stated NASA goals for MLV.

Task 1 - Concept Selection

LCLCVSA Program

Section Topics:

- ❑ Attributes of low cost structure
- ❑ Material, manufacturing, and structural configuration options
- ❑ Potentially high payoff concepts
- ❑ Rating process
- ❑ Selection results

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Potential Payoff Cost Attributes

LCLCVSA Program

- ❑ **Minimize Part Count**
  - Standardize, Reuse of Components
  - Low part count designs
- ❑ **Minimize Manufacturing Flow**
  - Standardize and Optimize Processes
  - Automate Processes
- ❑ **Eliminate or Simplify Tooling**
  - Standardize or Reuse of Tooling
  - Soft Tooling, Built in Tooling, etc.
- ❑ **Reduce Inspection with Reliable Processes**
- ❑ **Minimize New Capital Equipment**

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The initial task was to identify those attributes of a manufacturing approach which would tend to reduce cost. Primary among these was the reduction of the number of parts in a design. This reduces direct touch labor in part fabrication and assembly, and also reduces design and development costs. Additional considerations were reduction of processing steps, tooling simplification, inspection reduction, and minimization of capital equipment requirements.

Material, Manufacturing, and Structural Configuration Options

LCLCVSA Program

Composite Specific Options

Fibers
- Low modulus
- Intermediate modulus
- Glass
- Kevlar

Fiber Orientation/ Stitching
- Fabric weave
- Tape
- Tow
- Long discontinuous
- Stitched preform
- 3-D weave
- P4A

Lay-up Process
- Hand lay-up
- Contour tape lay-up machine (CTLM)
- Drape forming
- Filament winding
- Fiber placement
- Resin Infusion
  - SCRIMP
  - Resin transfer molding (RTM)
  - Resin film infusion (RFI)
- Pultrusion

Cure Process
- Autoclave cure
- Vacuum bag/oven
- Induction cure
- Low temp. cure
- E-beam cure

Resins
- 250 deg. F.
- 350 deg. F.
- Thermoplastic
- Low temp (w/ free-standing postcure)
- Pultrusion compatible
- E-beam initiated

Tooling Approach
- Invar
- Aluminum
- Graphite epoxy
- Thermally expendable elastomer
- Wood
- Foam
- Ceramic
- Stereo lithography
- Built-in tooling (i.e. fly-away)

Joining Process
- Mechanical fasteners
- Adhesive bonding
- Cocure/cobond
- Dual resin bond
- Induction weld
- Ultrasonic weld
- Unitized structure
- Interlocking

Metal Specific Options

Material
- Al-2XXX
- Al-7XXX
- CRES
- Titanium
- Al-Li

Forming/Machining Process
- Traditional machining
- Chemical milling
- High speed machining
- Roll forming
- Bump/break forming
- Stretch forming
- Spin forming
- Superplastic forming
- Stiffened panel extrusion

Tooling Approach
- Hard tooling
  - Fixed tooling
  - Collapsible tooling
- Soft tooling
- Built-in tooling (i.e. fly-away)

Joining Process
- Mechanical fasteners
- Welding
  - GTAW
  - VPPA welding
  - Laser welding
  - Friction Stir Welding (FSW)
- Adhesive bonding
- Brazing
- Diffusion bonding
- Interlocking

Stiffening Options

- Monocoque
- Skin/Stringer/Frame
- Sandwich Stiffened
  - Foam core
  - Honeycomb core
  - Truss core
- Corrugated Stiffening
- Grid Stiffened
  - Iso-grid
  - Ortho-grid
  - Angled-grid

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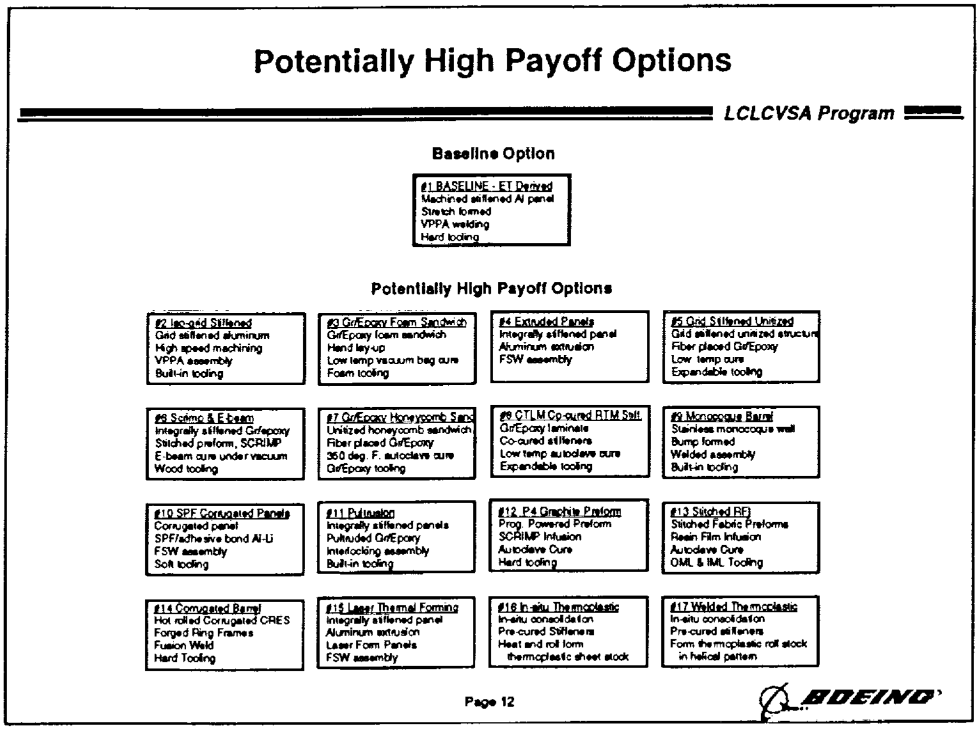
Specific concepts for structural configurations, and metal and composite materials and processes were identified which could potentially reduce MLV fabrication costs.



The concepts identified on the previous chart were combined into end-to-end options. These options were then evaluated in a qualitative rating procedure to select configurations for detailed study in Task 2.

Concept Rating Sheet

LCLCVSA Program

Concept # ______		Ranking (1-4) Tanks	Ranking (1-4) Dry Struct	Comments
Potential Payoff	**Minimized Part Count** Standardize, Reuse of Components Low Part Count			
Potential Payoff	**Minimized Manufacturing Flow** Standardize and Optimize Processes Automate Processes			
Potential Payoff	**Eliminated or Simplify Tooling** Standardize or Reuse of Tooling Soft Tooling, Built-in Tooling, etc.			
Potential Payoff	**Reduced Inspection with Reliable Processes**			
Potential Payoff	**Minimized New Capital Equipment**			
Potential Payoff	**Overall weight Savings**			
Probability of Success Scalability, Process Complexity, R&D Requirements, Test Requirements				
Technology Readiness Level (1-9)				
Total Score				

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Each option was rated using the form shown.

Rating Guidelines

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- Concepts were rated against potential payoff and probability of success attributes from one to four
  - 1 - Lowest rating, do not recommend
  - 2 - Some problems with concept, but it has potential for high payoff if problems can be overcome
    - or - the concept provides small payoff with very few obstacles to overcome
  - 3 - Moderate payoff expected
  - 4 - High pay-off, the concept should be investigated

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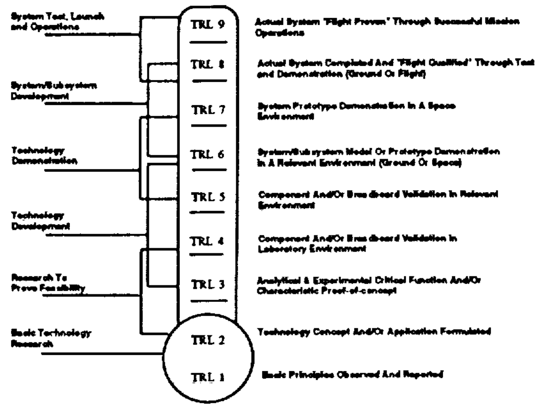
Specific rating guidelines were established to minimize variation between evaluators.

NASA Technology Readiness Level (TRL) Scale

LCLCVSA Program



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The standard NASA Technology Readiness Level Scale was used to rate technical maturity.

Weighting Factors Applied to Ratings

LCLCVSA Program

Three weighting schemes were applied to concept ratings:

Selection Criteria	Criteria Weighting Emphasis		
	W1 Structural Cost	W2 Structural Weight	W3 Uniform
Cost Payoff	50%	35%	34%
Minimize part count	(10%)	(7%)	(7%)
Minimize mfg flow	(8%)	(4%)	(5%)
Reduced tooling	(15%)	(11%)	(10%)
Reduced inspection	(3%)	(2%)	(2%)
Minimize new equipment	(15%)	(11%)	(10%)
Weight Payoff	35%	50%	33%
Probability of Success	15%	15%	33%
TRL	Secondary Selection Criteria		

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The scores for each option were modified by a weighting factor in three different schemes. This was done to evaluate the robustness of the selection process.

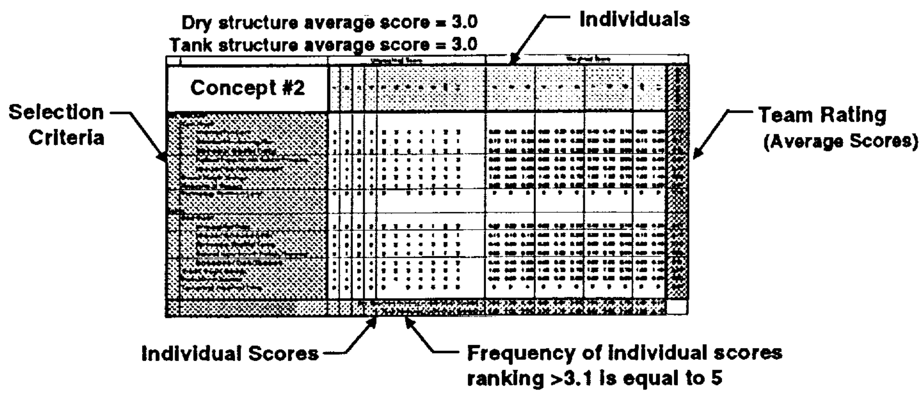
The first scheme mirrored the program emphasis on low cost. The second considered a performance driven cases. The third evaluated a balanced approach. In each case, technical maturity was relegated to a secondary criterion, as the goal of the study was to identify technologies, the development of which, would provide a benefit to MLV.

Compiling Concept Ratings

LCLCVSA Program

Ratings were adjusted with weighting factors, then compiled by:

- **High team average score**
- **High frequency of well rated individual scores**



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The weighted ratings were added to establish a single score for each option. The scores assigned by the various team members were combined in two ways, again to verify a robust selection process.

The first method was to look at the average score for an option across the team. The second was to look at the frequency with which a particular option was rated highly by the various team members.

It was found that the same set of options scored well regardless of weighting scheme or selection method. This is illustrated on the proceeding charts.

Concepts Ranked by Team Average Score

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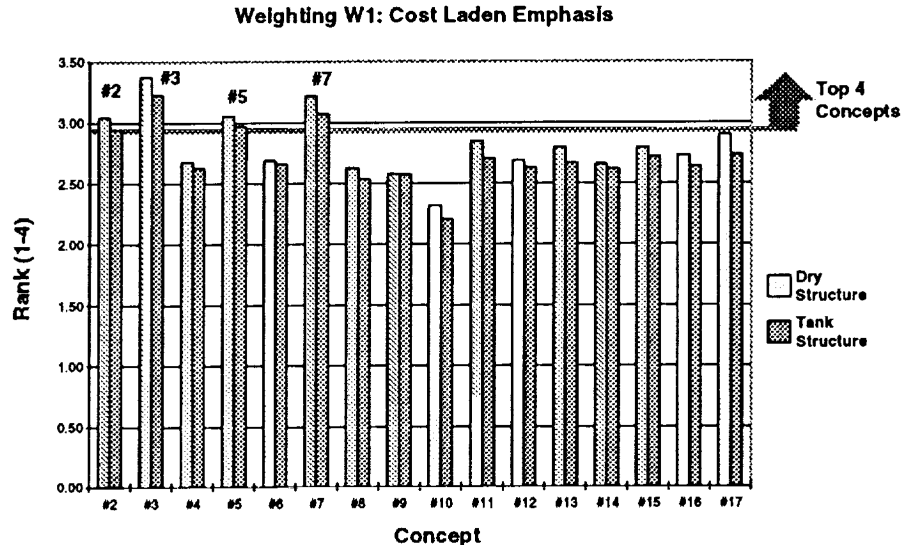

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Concepts Ranked by Frequency of Top Scores

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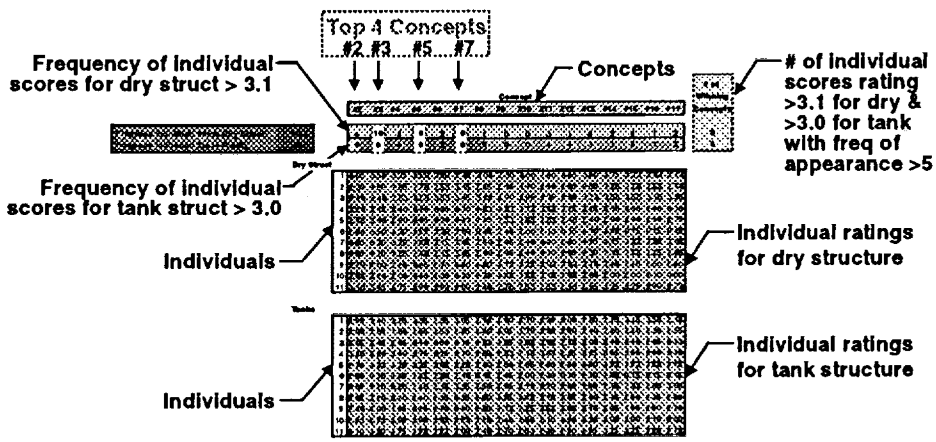
Weighting W1: Cost Laden Emphasis



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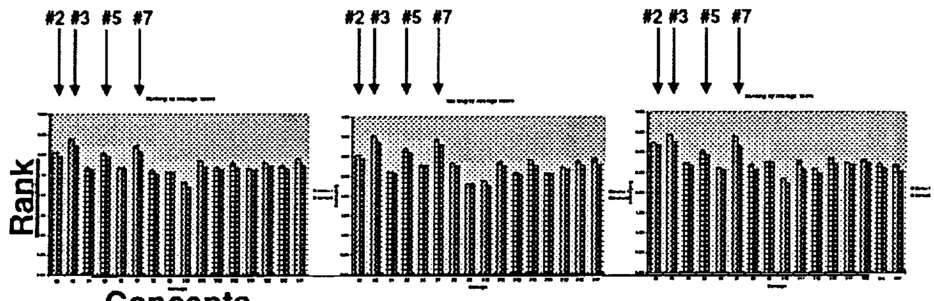
Sensitivity Studies

LCLCVSA Program

Ranking results showed little sensitivity to weighting scheme when determining top concepts by average ratings



Cost Laden (W1)	Weight Laden (W2)	Uniform Laden (W3)

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Sensitivity Studies

LCLCVSA Program

Ranking results showed little sensitivity to weighting scheme when determining top concepts by frequency of occurrence

	Top Concepts	
Weighting Scheme	**Dry Structure**	**Tank Structure**
W1: Cost	#3, #5, #7	#2, #3, #5, #7
W2: Weight	#2, #3, #5, #7	#2, #3, #5, #7
W3: Uniform	#2, #3, #5, #7	#2, #3, #5, #7, #13

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Concepts Selected for Task 2

LCLCVSA Program

Concept #2:	Iso-grid Stiffened Structure	
Concept #3:	Gr/Epoxy Foam Sandwich Structure	Similar concepts combined for Task 2
Concept #7:	Gr/Epoxy Honeycomb Sandwich Structure	
Concept #5:	Grid Stiffened Unitized Structure	
Concept #9:	Monocoque Barrel Structure	Concept added by team consensus

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The four concepts which consistently scored well were selected for further study in Task 2. The two sandwich concepts were considered too similar for meaningful distinction in this study, and were combined. An additional concept, a monocoque section, was added by team acclamation. The following charts give a succinct description of the concepts considered in Task 2.

Monocoque Barrel Structure
Concept Description

LCLCVSA Program

- ❑ 2195 Al-Li alloy (8 panels around circumference)
- ❑ Uniform panel thickness - no machining required
- ❑ Bump form panels to shape
- ❑ Friction stir welded assembly
- ❑ Forged ring frames

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Iso-grid Stiffened Structure
Concept Description

- ❑ 2195 Al-Li alloy (8 plates around circumference)
- ❑ Machine isogrid pattern with advanced machining
- ❑ Bump form panels to shape
- ❑ Friction stir welded assembly
- ❑ Extruded ring frames

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Graphite/Epoxy Sandwich Stiffened Structure
Concept Description

- ❑ Hand lay-up graphite/epoxy skins (IM7 fiber)
- ❑ 60" wide pre-laminated material to minimize layup
- ❑ Rohacell foam core
- ❑ Composite ring frames co-cured
- ❑ Sandwich construction eliminates stiffener fab
- ❑ Unitized structure eliminates assembly operations

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Grid Stiffened Unitized Structure
Concept Description

LCLCVSA Program

- Graphite/epoxy towpreg (IM7 fiber)
- Automated fiber placement layup
- Tooling accommodates grid stiffening pattern
- Composite ring frames fiber placed together with grid pattern
- Unitized structure eliminates assembly operations

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Task 1 Summary

LCLCVSA Program

- ❑ Concept Identification
  - Materials and processes identified
  - Potentially high payoff concepts identified
- ❑ Rating process
  - Low cost approach drives selection
  - Selection criteria based on cost, weight and risk
- ❑ Selection results
  - Selection is based on frequency of occurrence of individual scores and on average team scores
  - Top rated concepts are insensitive to weighting schemes
  - Similar concepts were combined and an additional metallic concept selected

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In Task 1, the attributes which lead to low cost fabrication were successfully identified, along with composite and metal materials and processes which have these attributes. Through a robust selection process, four of the highest payoff concepts were selected for detailed study in Task 2.

Task 2 - Trade Study

LCLCVSA Program

Section Topics:

- ❑ **MLV core trade study**
  - Loads and requirements
    - Typical requirements
    - LCLCVSA subset
    - Thermal, acoustic, and mechanical loads
  - Material properties
  - Structural sizing and design summaries
  - Vehicle resize and weight estimates
  - Cost estimates
- ❑ **Thrust structure assessment**
- ❑ **LFBB assessment**

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Task 2 comprised structural definition and weight and cost estimation activities to support a trade study between the four concepts selected in Task 1.

ALS LH_2 Tank Requirements

LCLCVSA Program

Functional Requirements

Provide Support	Provide Access	Provide Environmental Control	Provide Interfaces	Servicability
• Contain pressurized LH2 • Transfer primary loads • Cable trays and LO2 feedline • Range safety components • Antivortex and slosh baffles, bolt strainer, fluid level sensors • Ground handling	• Tank interior	• Contain LH2 with acceptable boiloff • Maintain cleanliness of LH2	• Cable trays and lines • Range safety systems • Fluid supply, vent and pressurization systems • Ground handling • Intertank and thrust structure	• Low cost repair features • Inspectability

Design Requirements

- Provide strength for primary structural loads
- Provide thermal environment for containment of LH2
  - Forward dome, -205°F
  - Aft dome, -423°F
- Proof test each tank
  - Proof test = 35.5 psig (both)
  - 1.05 min proof factor
  - Hydrostatic, ambient temperature
  - Based on MEOP at T = 125 sec
- Propellant suppression control

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Detailed design of launch vehicle structures involves satisfying numerous requirements. As an example, the requirements for the elements of the ALS mapping to the MLV core are shown on the proceeding charts.

ALS LOX Tank Requirements

LCLCVSA Program

Functional Requirements

Provide Support	Provide Access	Provide Environmental Control	Provide Interfaces	Servicability
• Contain pressurized LOX • Transfer primary loads • Cable trays • Range safety components • Antivortex and slosh baffles, bolt strainer, fluid level sensors • Ground handling	• Tank interior	• Maintain cleanliness of LOX • Provide thermal control	• Cable trays and lines • Range safety systems • Fluid supply, vent and pressurization systems • Ground handling • Intertank and forward structure	• Low cost repair features • Inspectability

Design Requirements

- Provide strength for primary structural loads
- Proof test each tank
  - Proof test = 59.4 psig
  - 1.05 min proof factor
  - Hydrostatic, ambient temperature
  - Based on MEOP at T = 125 sec
- Propellant suppression control

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ALS Payload Module Requirements

LCLCVSA Program

Functional Requirements

Provide Support	Provide Environmental Control	Provide Interfaces	Fairing Separation
• Adapter supports payloads for ground handling and flight • TPS • Ground handling attachments • Instrumentation • Wire harness	• Launch and ground environments imposed on payload per ALS Environments Data book • Regulate vent boost pressure	• Standard mechanical cargo interface allowing for rapid payload replacement • Ground support interface • Payload electromagnetic transmission through shroud • Hazardous gas detection system • Payload cryogenic and hazardous materials per ALS Payload Planning Handbook	• Controlled fairing separation

Design Requirements

- Payload module structure shall carry a payload 80 ft in length by 15 ft in dia., with a clear diameter of 27.5 ft.
- The payload adapter shall be rated for a cargo mass of not less than 100,000 lbs to LEO
- Cargo Interface - provide minimum services as outlined in the ALS payload Planning Handbook (Appendix IV) (TBD)
- Cargo Mechanical Interface
  - Simple mechanical interface
  - No cargo access after integration
  - Cargo separation shall not be at or part of the cargo attachment points
- Minimize ground operations
- Provide repairable structure (at low cost)
- Provide inspectable structure

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ALS Intertank Requirements

LCLCVSA Program

Functional Requirements

Provide Support	Provide Access	Provide Environmental Control	Provide Interfaces	Servicability
• Transfer primary structural loads • Transfer Core/Booster thrust loads • Range safety • Separation system • GSE • Subsystems • Instrumentation	• Internal components • Inspection	• Acceptable environment for internal components • Boost venting • Inert gas environment	• Booster/Core stage attachment hardware separation bolts and hard points • Propellant tanks • Cable trays • Feedlines • Hazardous gas detection system	• Low cost repair features • Inspectability

Design Requirements

- Provide strength for primary structural loads
- Maintain internal ascent pressure lag < 1.0 psig
- Provide access to interior components
- Provide repairable structure (at low cost)
- Provide inspectable structure

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ALS Aft Skirt Requirements

LCLCVSA Program

Functional Requirements

Provide Support	Provide Access	Provide Environmental Control	Provide Interfaces	Servicability
• Transfer P/A module loads to LH2 tank • Transfer launch hold down loads • Booster/Core attachment loads • Feedline and wires • Subsystem components • Separation hardpoints • GSE • Instrumentation	• Propulsion subsystem • Inspection • Separation joint	• Thermal seal to P/A module • Acceptable internal environment • Boost venting • Inert gas environment	• P/A Module separation joint/thermal seal • Booster/Core separation • LH2 tank field joint • Booster/Core attachment hardware • Feedlines/electrical lines • TPS • Boost venting	• Accessability • Low cost repair features • Inspectability

Design Requirements

- Provide strength for primary structural loads
  - Flight thrust loads
  - Booster/Core loads
  - Launch hold down
- Provide proper stiffness to support LH2 tank, P/A module, booster/Core interface, and launch hold down
- Minimize ground operations
- Provide repairable structure (at low cost)
- Provide inspectable structure
- Ascent internal pressure lag < 1.0 psig
- Maintain acceptable skin temperature

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Design Requirements Addressed in LCLCVSA

LCLCVSA Program

- ❑ High level focus precludes attention to full range of design requirements
- ❑ Compressive line loads and tank pressures
  - MSFC provided values supplemented with Boeing generated data
  - Loads combined to minimize pressure relieving effect
- ❑ Factors of safety per NASA-STD-5001
  - Prototype verification approach
  - Include hydrostatic proof test factors
- ❑ Damage tolerance
  - Metal minimum gage 0.020 inch
  - Composite minimum gage 0.030 inch
- ❑ Additional cost and weight impacts (acoustic and thermal insulation, separation system, etc.) will be included by similarity to historical programs

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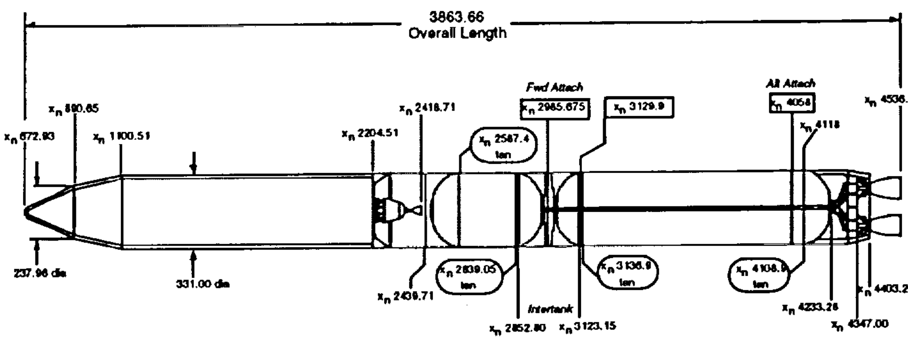
The scope of the LCLCVSA study did not allow consideration of all these requirements. Primary focus was on the mechanical load carrying requirements, with secondary consideration of additional items.

Magnum Launch Vehicle with X-Stations

LCLCVSA Program



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Basic geometric data were provided by MSFC.

Fairing Acoustic Environments

LCLCVSA Program

Vehicle	External Overall Sound Pressure Level at Fairing
Titan IV	152.5 db
Jarvis	152 db
Sea Launch	154 db
ALS	151 db
Shuttle (STS-4)	153 db

Sea Launch acoustic treatment weights representative

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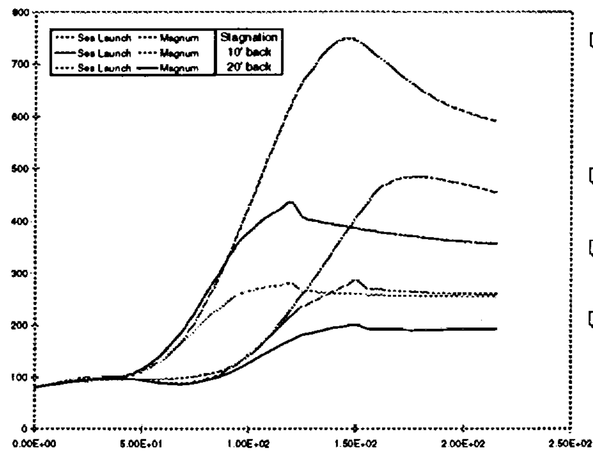
A survey of historical data indicated that acoustic requirements did not vary much from vehicle to vehicle. Sea Launch data were easily accessible, and were used in the MLV trades as representative.

Thermal Environment Comparison

LCLCVSA Program



- Magnum and Sea Launch trajectories applied to Sea Launch geometry
- 12 inch nose radius assumed
- Temperatures for no insulation
- Peak heating rates
  - SL: 7.5
  - MLV: 4.1

Sea Launch TPS weights conservative

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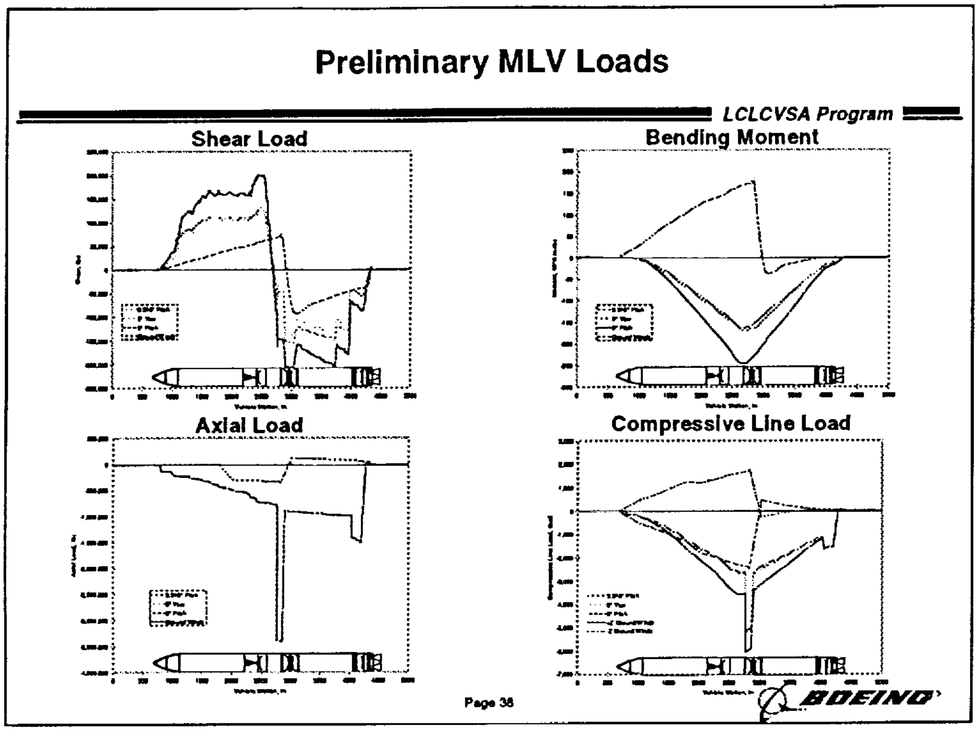
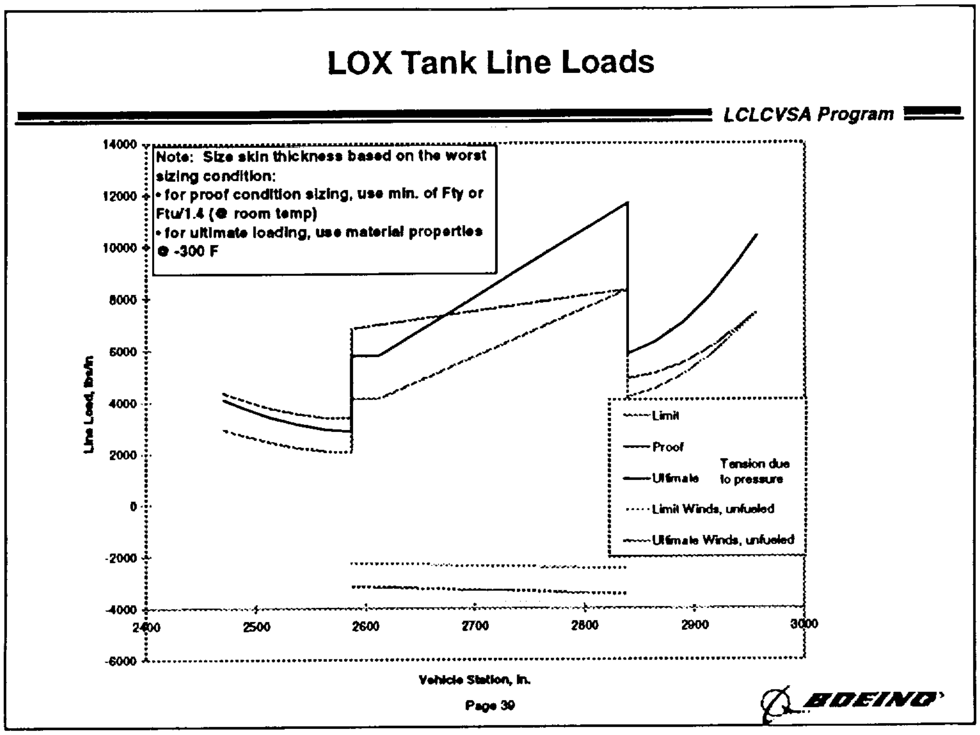
BOEING

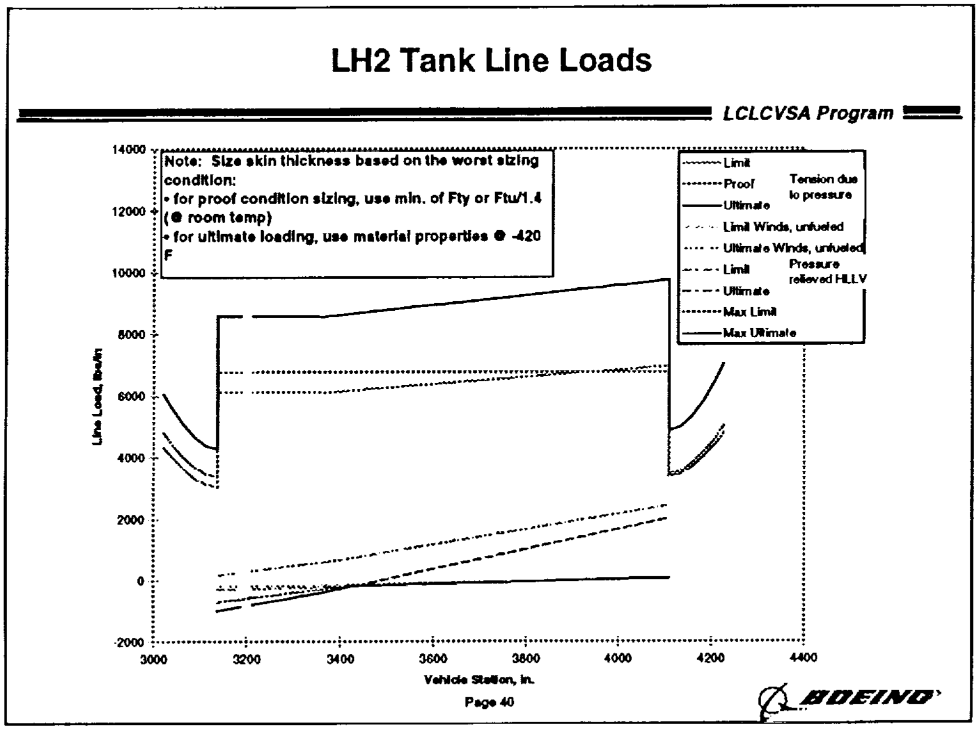
Preliminary calculations of MLV aeroheating environments indicated that they were less stringent than those projected for the Sea Launch program. Again, as the Sea Launch data were easily accessible, they were used in this study.



Preliminary MLV mechanical loads provided by MSFC. These loads were derived from previous vehicle studies. The loads were compared to historical programs, and found to be representative and conservative. A ground winds load case was added to supplement the critical conditions.



Pressurization loads in the tanks were added to the flight and ground load cases.



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Aluminum and Al-Li Properties

LCLCVSA Program

Material	Aluminum 2195		Aluminum 2219	
Form	Sheet & Plate		Sheet & Plate	
Specification	N/A		QQ-A-250/30	
Temper	-T8	-T8	-T87	-T87
Thickness	Up to 0.625	>0.625	0.020-0.249	0.250-2.000
Basis	Preliminary[1]	Preliminary[1]	A[2]	A[2]
Mechanical Properties				
Ftu (ksi)				
L	77	75	63	63
LT	77	75	64	64
45 deg.	68	71	–	–
ST	--	71	–	–
Fty (ksi)				
L	72	70	51	50
LT	72	70	52	51
45 deg.	63	65	–	--
ST	--	65	–	–
Fcy (ksi)				
L	69	–	52	51
LT	74	–	55	52
45 deg.	64	–	–	–
ST	--	–	–	–
Fsu (ksi)	40	40	36	37
Fbru (ksi)				
(e/D =1.5)	103	100	99	99
(e/D =2.0)	133	130	126	126
Fbry (ksi)				
(e/D =1.5)	92	90	83	82
(e/D =2.0)	110	108	96	94
E (msi)	11.0		10.5	
Ec (msi)	11.3		10.8	
G (msi)	4.0		4.0	
μ, Elastic	0.33		0.33	
ρ, (lbs/in^3)	0.098		0.103	
Notes:				
1. Values were obtained from limited test data and should be considered preliminary allowables only.				
2. "A"-basis allowables are per MIL-HDBK-5.				

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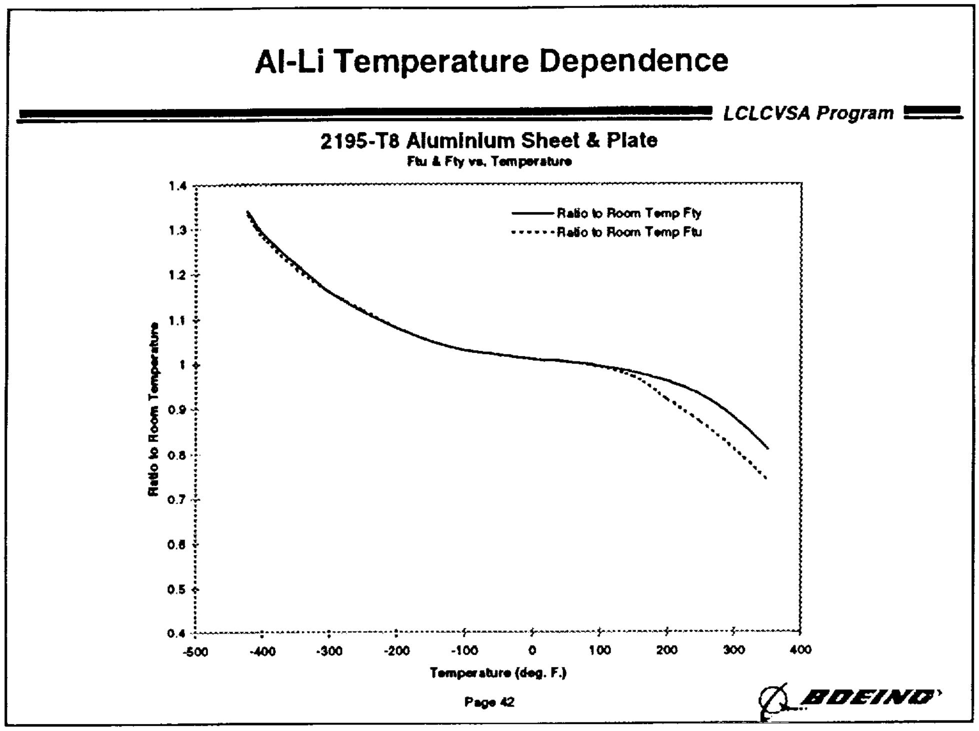
Appropriate material properties were collected from various sources.



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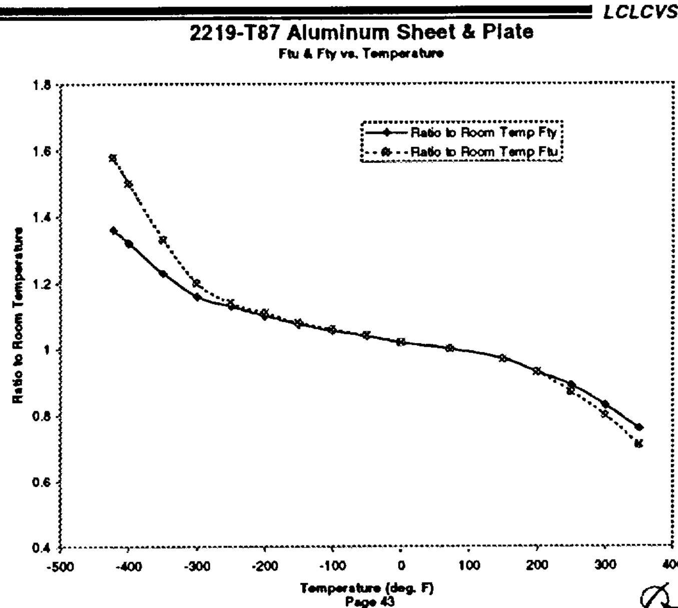
Aluminum Temperature Dependence

LCLCVSA Program



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Graphite/Epoxy Prepreg Properties

LCLCVSA Program

Material			
Form	Fabric Prepreg	Uni-Tape Prepreg (Ref)	Tow Prepreg
Specification			
Temperature (deg F)	RT	RT	RT
Per Ply Thickness	0.015	0.006	0.006
Basis	Preliminary[1]	Preliminary[2]	Preliminary[3]
Mechanical Properties			
Lamina			
E11t (11 or warp) (msi)	--	24.00	20.60
E11c (11 or warp) (msi)	--	21.30	18.28
E22t (22 or fill) (msi)	--	1.67	1.43
E22c (22 or fill) (msi)	--	1.82	1.56
G12 (msi)	--	0.77	0.66
ν12	--	0.31	0.31
Ftu11, 0 deg (ksi)	--	394	338.11
Fcu11, 0 deg, (ksi)	--	262	224.83
Ftu22, 90 deg (ksi)	--	16.1	13.81
Fcu22, 90 deg, (ksi)	--	44	37.76
Fsu12, (ksi)	--	17.7	15.18
Quasi-Isotropic			
Et (msi)	9.00	--	--
Ec (msi)	9.00	--	--
G_{xy} (msi)	1.20	--	--
ν12	0.30	--	--
Ftu (ksi)	88.50	--	--
Fcu (ksi)	80.00	--	--
Fsu (ksi)	--	--	--
ρ, (lbs/in^3)	0.058	0.057	0.057

Notes:

1. Preliminary poperties generated from X-33 test data.
2. Pleliminary properties data obtained from vendor test data.
3. Preliminary tow prepreg properties data calculated as 86% of unidirectional tape prepreg properties.

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Rohacell Foam Core Properties

LCLCVSA Program

Material	Rohacell (Polymethacrylimide) Rigid Foam
Form	110 WF
Specification	Rohacell
Temperature (deg F)	RT
Thickness	N/A
Basis	Preliminary
Mechanical Properties	
Et (ksi)	20
Ec (ksi)	20
G (ksi)	7
ν	0.45
Ftu (ksi)	–
Fcu (psi)	522
ρ, (lbs/in^3)	0.00398

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Shell Sizing Methods

LCLCVSA Program

- Size skins and stiffeners
  - By line load for dry structure
  - By body station for tanks
  - Minimum gage provided cutoff
- Existing analysis techniques used
  - NASA SP-8007 used for all stability calculations
  - Aluminum skin-stringer-frame (baseline)
    - STASS program from NASA-MSFC
    - Boeing-developed optimization code
  - Al-Li monocoque
    - Closed form methods from Boeing Design Manual
    - Required thickness at weld lands used to size panels
  - Al-Li isogrid
    - Boeing-developed code
  - Graphite/epoxy-foam sandwich
    - PANDA2 program
  - Grid stiffened composite
    - GRID program from Stanford University

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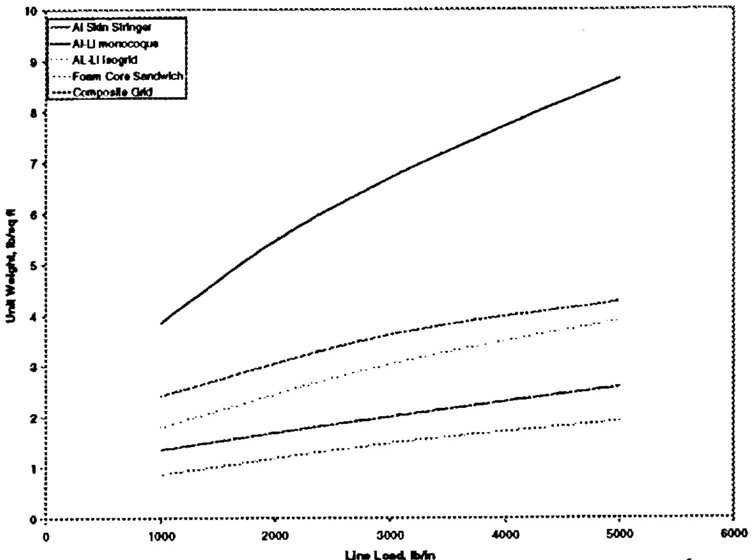
Sizing methods and computer programs consistent with a preliminary design level were used to establish the configuration of MLV shell structures. Trends with line load for dry structure, and with body station for pressurized structure were developed. The results of the shell sizing are summarized on the subsequent charts.

Dry Structure Shell Sizing

LCLCVSA Program



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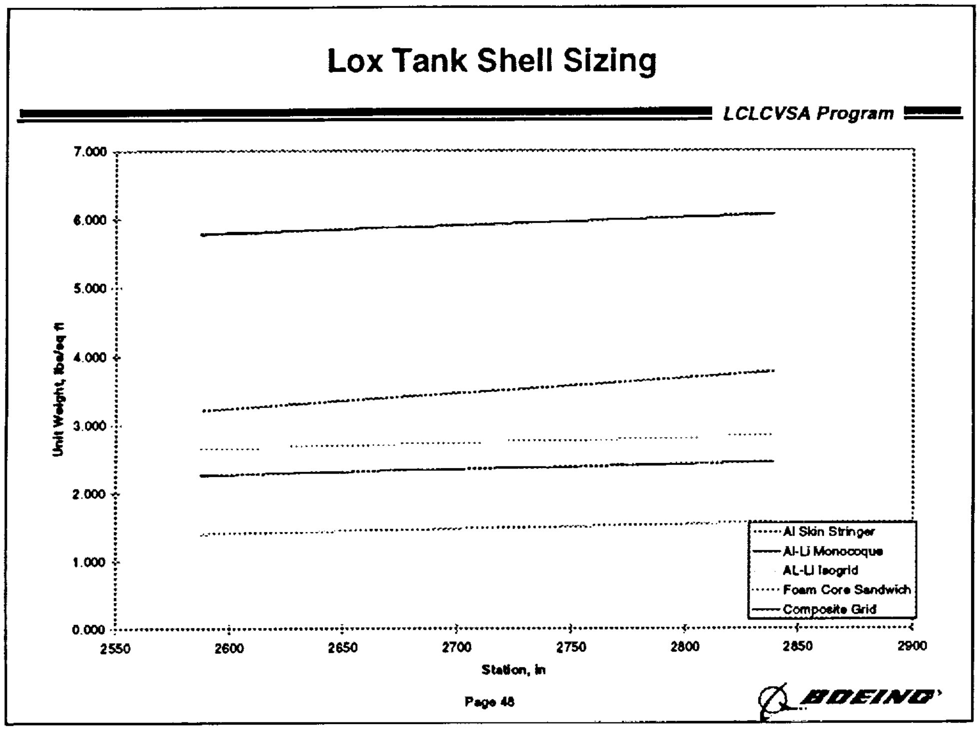

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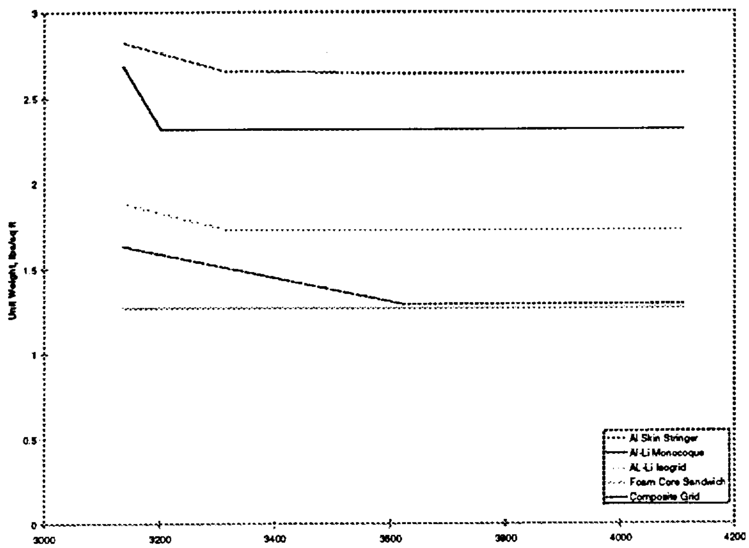
LH2 Tank Shell Sizing

LCLCVSA Program



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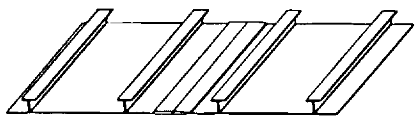
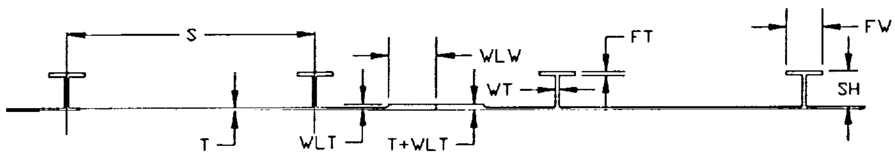
Baseline Concept
Integral Skin Stringer

LCLCVSA Program



Baseline Design Summary - Dry Structure

Line Load (lbs/in)	1000	3000	5000
Skin Thickness (inch) - (T)	0.11	0.16	0.20
— numbers of stringers	100	100	100
— stringer spacing (S)	10.399	10.399	10.399
— stringer height (SH)	1.5	3.0	3.0
— flange width (FW)	1.5	3.0	3.0
— flange thickness (FT)	0.15	0.12	0.12
— web thickness (WT)	0.15	0.12	0.12
— weld land thickness (WLT)	0.02	0.02	0.02
— weld land width (WLW)	2.00	2.00	2.00
— Weight per square foot (lbs)	2.41	3.62	4.27
Major frame spacing	240	240	240
Intermediate frame spacing	48	60	60



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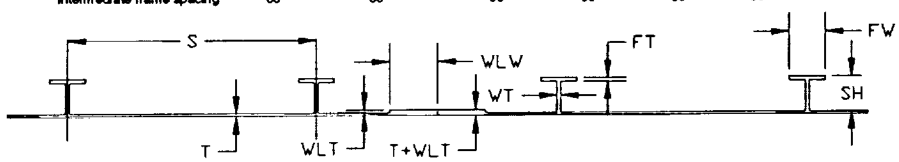
Baseline Concept
Integral Skin Stringer

LCLCVSA Program

Baseline Design Summary - Pressurized Structure

	Lox Tank		Hydrogen Tank			
Location	2587.4	2839.05	3136.9	3311.9	3623.019	4108.9
Line Load, hoop (lbs/in)	6829	8331	6306	6306	6306	6306
Skin Thickness (inch) - (T)	0.152	0.185	0.140	0.140	0.140	0.140
— numbers of stringers	100	100	100	100	100	100
— stringer spacing (S)	10.399	10.399	10.399	10.399	10.399	10.399
— stringer height (SH)	2.25	2.25	2.1	1.65	1.0	1.0
— flange width (FW)	2.0	2.25	1.8	1.25	1.0	1.0
— flange thickness (FT)	0.15	0.15	0.08	0.10	0.08	0.08
— web thickness (WT)	0.11	0.11	0.08	0.10	0.08	0.08
— weld land thickness (WLT)	0.02	0.02	0.02	0.02	0.02	0.02
— weld land width (WLW)	2.00	2.00	2.00	2.00	2.00	2.00
— Weight per square foot (lbs)	3.21	3.77	2.63	2.60	2.37	2.37
Major frame spacing	240	240	240	240	240	240
Intermediate frame spacing	60	60	60	60	60	60



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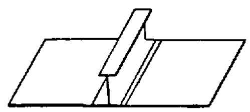
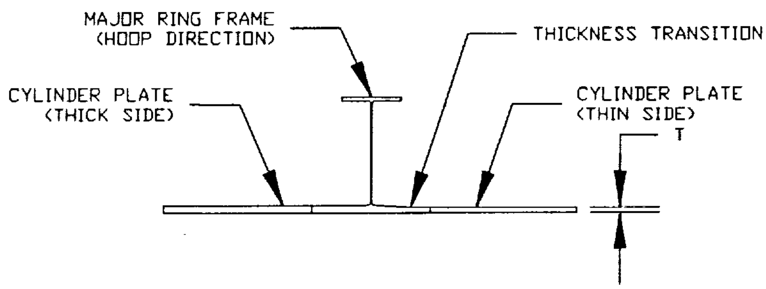
Aluminum Lithium
Monocoque Design Summary

LCLCVSA Program



Baseline Design Summary - Dry Structure

Line Load (lbs/in)	1000	2000	3000	4000	5000
Plate Thickness (inch) - (T)	0.274	0.387	0.474	.547	.612
— Weight per square foot (lbs)	3.87	5.46	6.69	7.72	8.64
Major frame spacing	300	300	300	300	300
Intermediate frame spacing	60	60	60	60	60



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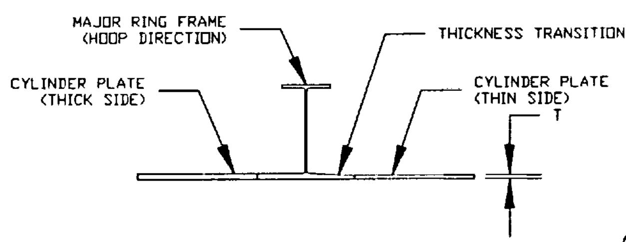
Aluminum Lithium Monocoque Design Summary

LCLCVSA Program

Baseline Design Summary - Pressurized Structure

	Lox Tank		Hydrogen Tank			
Location	2587.4	2839.05	3136.9	3311.9	3623.019	4108.9
Line Load, hoop (lbs/in)	6829	8331	6306	6306	6306	6306
Plate Thickness (inch) - (T)	0.410	0.430	0.190	0.164	0.164	0.164
— Weight per square foot (lbs)	5.79	6.07	2.68	2.31	2.31	2.31
Major frame spacing	300	300	300	300	300	300
Intermediate frame spacing	60	60	60	60	60	60
— weld land thickness (WLT)	0.02	0.02	0.02	0.02	0.02	0.02
— weld land width (WLW)	2.00	2.00	2.00	2.00	2.00	2.00



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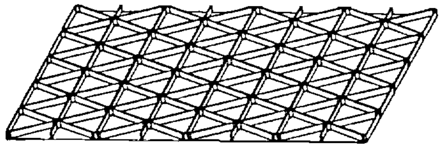
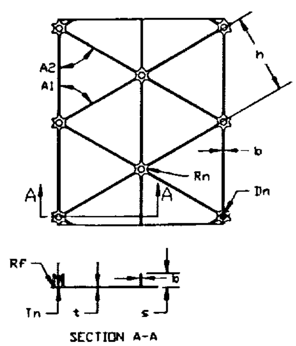
Aluminum Lithium
Isogrid Design Summary

LCLCVSA Program





Al-Li Isogrid Design Summary - Dry Structure

Line Load (lbs/in)	1000	3000	5000
Plate Thickness (inch) - (s)	1.000	1.510	1.839
— isogrid height (h)	5.540	6.904	7.762
— rib thickness (b)	0.112	0.168	0.204
— pocket thickness (t)	0.066	0.110	0.141
— node diameter (Dn)	0.500	0.500	0.500
— pocket radius (Rn)	0.300	0.300	0.300
— fillet radius (Rf)	0.060	0.060	0.060
— weld land thickness (WLT)	0.02	0.02	0.02
— weld land width (WLW)	2.00	2.00	2.00
— Weight per square foot (lbs)	1.80	3.04	3.90
Major frame spacing	300	300	300
Intermediate frame spacing	NA	NA	NA

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BOEING

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Aluminum Lithium
Isogrid Design Summary

LCLCVSA Program

Al-Li Isogrid Design Summary - Dry Structure

	Lox Tank		Hydrogen Tank			
Location	2587.4	2639.05	3136.9	3311.9	3623.019	4108.9
Line Load, hoop (lbs/in)	6829	8331	6306	6306	6306	6306
Plate Thickness (inch) - (s)	1.353	1.474	0.960	0.710	0.710	0.500
— Isogrid height (h)	6.487	0.958	16.998	30.000	30.000	30.000
— rib thickness (b)	0.151	0.162	0.101	0.071	0.071	0.060
— pocket thickness (t)	0.096	0.127	0.118	0.121	0.121	0.12
— node diameter (Dn)	0.500	0.500	0.500	0.500	0.500	0.500
— pocket radius (Rn)	0.300	0.300	0.300	0.300	0.300	0.300
— fillet radius (Rf)	0.060	0.060	0.060	0.060	0.060	0.060
— node thickness (Tn)	0.060	0.060	0.060	0.060	0.060	0.060
— weld land thickness (WLT)	0.02	0.02	0.02	0.02	0.02	0.02
— weld land width (WLW)	2.00	2.00	2.00	2.00	2.00	2.00
— Weight per square foot (lbs)	2.64	2.84	1.88	1.73	1.73	1.73
Major frame spacing	300	300	300	300	300	300
Intermediate frame spacing	NA	NA	NA	NA	NA	NA

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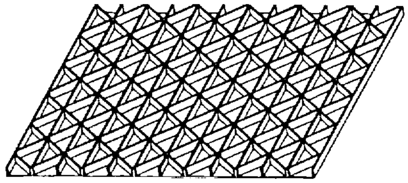
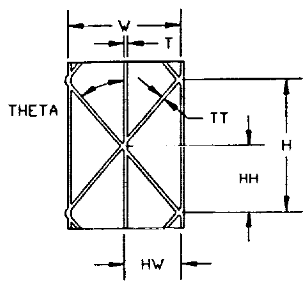
Composite Grid Design Summary

LCLCVSA Program





Composite Grid Design Summary - Dry Structure

Line Load (lbs/in)	1000	3000	5000
Ply Thickness = 0.0114 (inch)			
Skin Thickness (inch)	0.0798	0.0798	0.0912
# 0 deg. plies	0	0	0
# 90 deg. plies	3	3	4
# 20 deg. plies	2	2	2
# -20 deg. plies	2	2	2
— Rib Height	1.25	1.625	1.875
— 0 deg rib thickness (TT)	0.2	0.325	0.377
— +/- 40 deg rib thickness (T)	0.175	0.25	0.30
— Unit cell width (W)	13.866	13.866	13.866
— Unit cell half width (HW)	6.933	6.933	6.933
— Unit cell height (H)	16.526	16.526	16.526
— Unit cell half height (HH)	8.263	8.263	8.263
— Weight per square foot (lbs)	1.35	2.00	2.58
Major frame spacing	NA	NA	NA
Intermediate frame spacing	330	330	330

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Composite Grid Design Summary

LCLCVSA Program

Composite Grid Design Summary - Pressurized Structure

	Lox Tank		Hydrogen Tank			
Location	2587.4	2839.05	3136.9	3311.9	3623.019	4108.9
Line Load, hoop (lbs/in)	6829	8331	6306	6306	6306	6306
Skin Thickness (inch)	0.1482	0.1596	0.140	0.140	0.140	0.140
# 0 deg. plies	6	5	4	4	2	2
# 90 deg. plies	3	3	3	3	2	2
# +70 deg. plies	2	3	2	2	2	2
# -70 deg. plies	2	3	2	2	2	2
Rib Height	1.5	1.5	1.0	1.0	1.0	1.0
— 0 deg rib thickness (TT)	0.325	0.325	0.25	.175	.175	.175
— +/- 40 deg rib thickness (T)	0.265	0.30	0.25	0.25	0.25	0.25
— Unit cell width (W)	25.136	25.136	31.06	31.06	31.06	31.06
— Unit cell half width (HW)	12.568	12.568	15.53	15.53	15.53	15.53
— Unit cell height (H)	11.722	11.722	11.304	11.304	11.304	11.304
— Unit cell half height (HH)	5.861	5.861	5.652	5.652	5.652	5.652
— Weight per square foot (lbs)	2.26	2.45	1.63	1.29	1.29	1.29
Major frame spacing	NA	NA	NA	NA	NA	NA
Intermediate frame spacing	330	330	330	330	330	330

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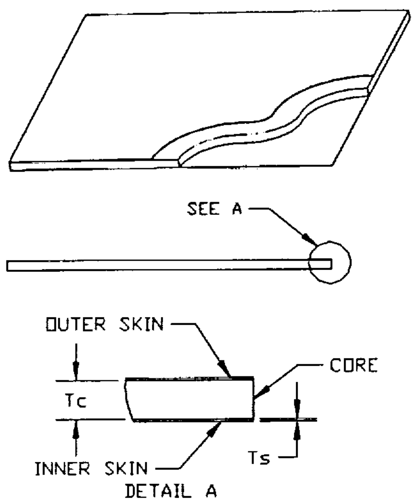
Composite Sandwich Design Summary

LCLCVSA Program



Composite Grid Design Summary - Dry Structure

Line Load (lbs/in)	1000	3000	5000
Skin Thickness (inch) - (Ts)	0.030	0.041	0.062
Ply Thickness (inch)	0.015	0.0103	0.0155
# 0 deg. plies	1	1	1
# 90 deg. plies	0	1	1
# +45 deg. plies	1	1	1
# -45 deg. plies	0	1	1
— Core thickness (Tc)	0.638	1.399	1.552
— Weight per square foot (lbs)	0.87	1.48	1.91
Major frame spacing	NA	NA	NA
Intermediate frame spacing	330	330	330

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Composite Sandwich Design Summary

Composite Grid Design Summary - Pressurized Structure

	Lox Tank		Hydrogen Tank			
Location	2587.4	2839.05	3136.9	3311.9	3623.019	4108.9
Line Load, hoop (lbs/in)	6829	8331	6306	6306	6306	6306
Skin Thickness (inch) - (Ts)	0.060	0.0729	.059	.059	.059	.059
Ply Thickness (inch)	0.030	0.0182	0.0148	0.0148	0.0148	0.0148
# 0 deg. plies	1	1	1	1	1	1
# 90 deg. plies	0	1	1	1	1	1
# +45 deg. plies	1	1	1	1	1	1
# -45 deg. plies	0	1	1	1	1	1
— Core thickness (Tc)	0.7043	0.6161	0.50	0.50	0.50	0.50
— Weight per square foot (lbs)	1.40	1.57	1.17	1.17	1.17	1.17
Major frame spacing	NA	NA	NA	NA	NA	NA
Intermediate frame spacing	330	330	330	330	330	330

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Weight Estimation Method

LCLCVSA Program

- ❑ Vehicle and element weight estimates for baseline design (including subsystems) generated using parametric program calibrated to ET weight
- ❑ Boeing Weight Estimation Tool used to generate vehicle weight estimates from unit weight values for each concept
- ❑ Vehicle inert weight trends for each concept generated to support vehicle resizing

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The shell structure weight trends were rolled up to the total vehicle weight using established preliminary design methods and computer programs.

Vehicle Resize Method

LCLCVSA Program

- ❑ **Performance calculated using SPOT based on inert weight trending from weight estimate**
- ❑ **Vehicle GLOW adjusted to maintain constant performance (payload to LEO)**
  - **27.5 ft diameter maintained (except monocoque)**
  - **Monocoque diameter increased to 31.5 ft to prevent core nozzle exit planes from extending below SRBs**
  - **Impact of shorter tanks (up to 20 ft with composite sandwich) on other concepts not addressed**
    - – **Nozzle exit planes**
    - – **SRB attachment**

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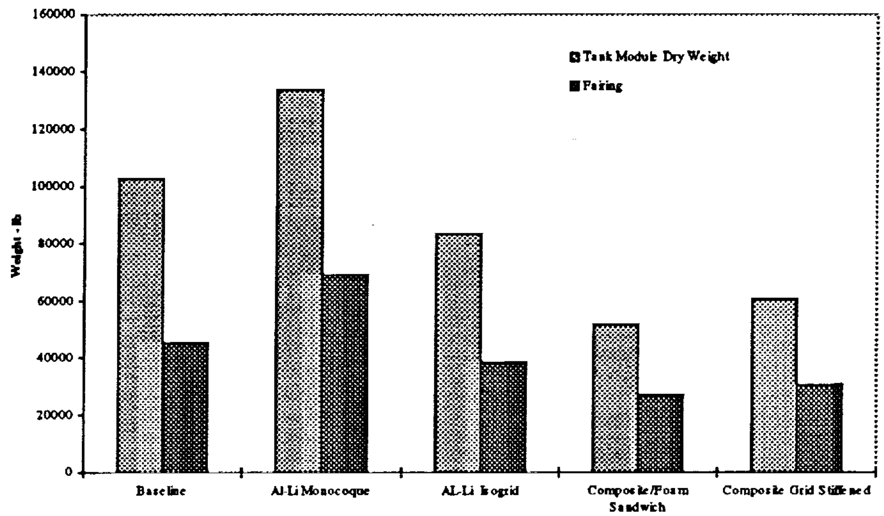
Established preliminary design methods and computer programs were used to assess the feedback of vehicle dry weights changes on propellant requirements, and in turn, vehicle dry weight. In this calculation, vehicle performance and diameter were kept constant, except for the monocoque concept, which could not be closed within the 27.5 foot diameter constraint without extending the core engine nozzles beyond the SRB exit plane. The monocoque core was allowed to grow to 31.5 feet diameter to avoid this situation. Similarly, resizing lighter concepts would result in core engine nozzle exits further above the SRB exit plane than the baseline concept. Shortening of the tank module (up to 20 feet with the composite sandwich concept) could also impact the SRB attachment scheme.

Vehicle Sizing - Dry Weight Comparison

LCLCVSA Program



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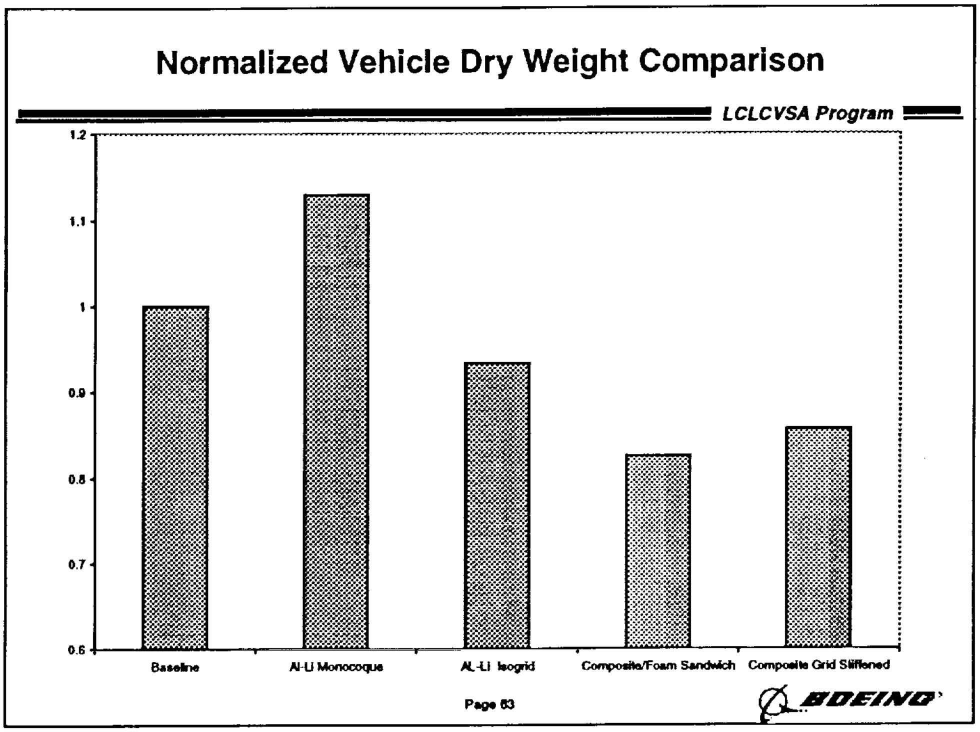
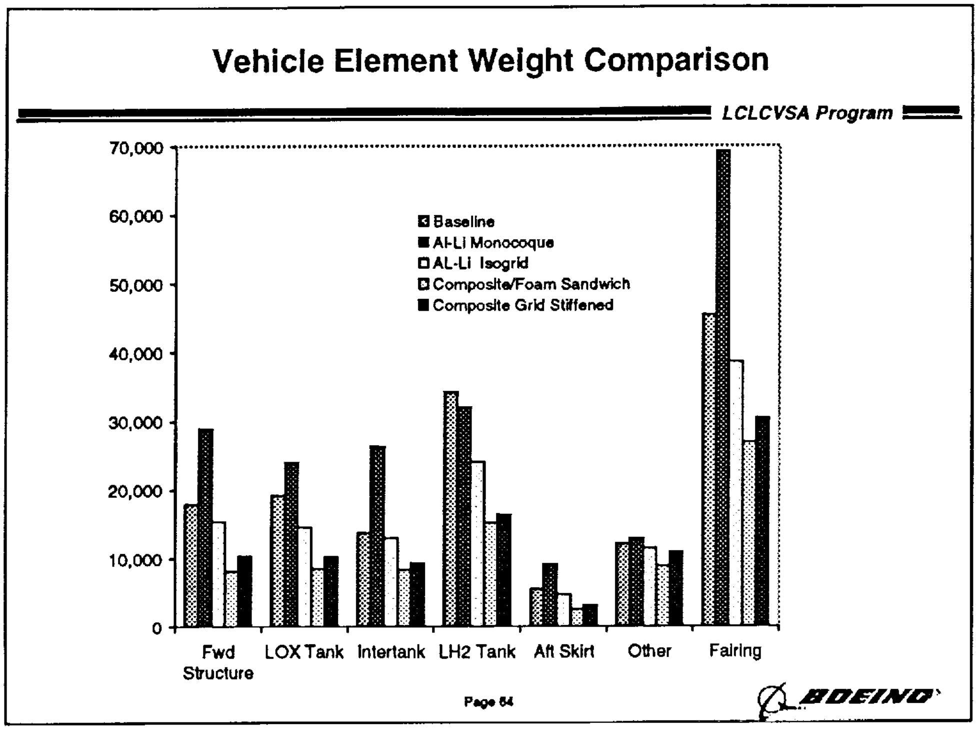
BOEING

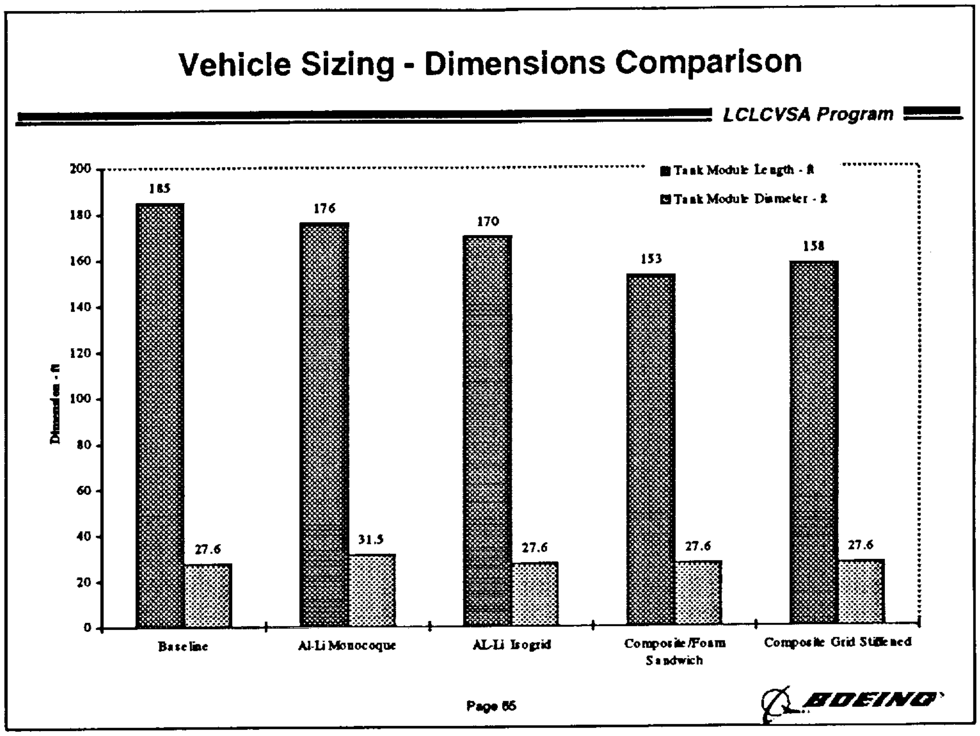
The variation of overall vehicle weight for the concepts was similar to the structural weight variations. Additional details are presented on the subsequent charts.



Composite concepts provided the greatest weight payoff, reducing vehicle dry weight 14 to 18%.



Relative weights were similar between the structural elements studies, with the notable exception of the LH2 tank. This was attributed to the minimal compressive axial loads in the tank, as compared with the pressure loading, and the minimum stiffener requirements imposed on the stiffened shell designs.



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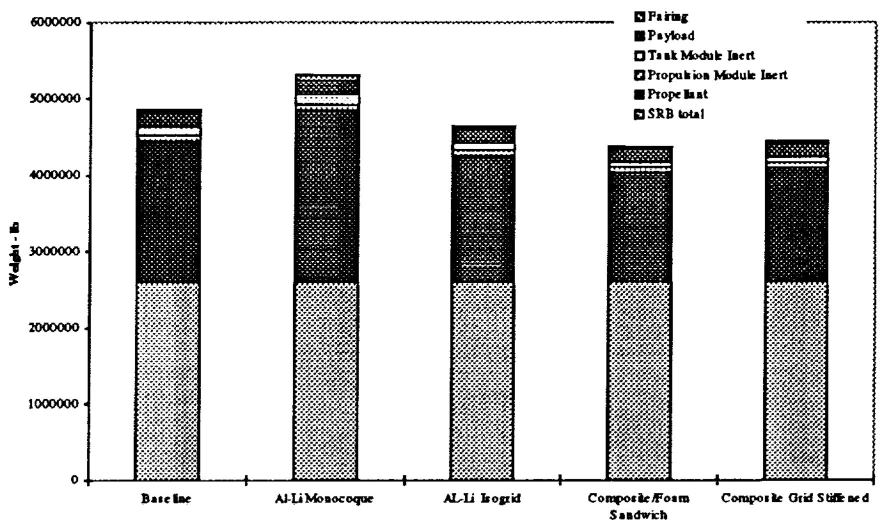
Vehicle Sizing - GLOW Comparison

LCLCVSA Program



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Impact on the vehicle gross lift-off weight was less pronounced; however, the composite configurations were still projected to reduce GLOW but up to 11%.

Cost Estimation Method

LCLCVSA Program

- ❑ Vehicle and element costs estimated for baseline design using a parametric approach (NAFCOM)
- ❑ Core structures for each concept estimated using "bottoms-up" (BCM) approach
- ❑ Factor applied to BCM estimates to reconcile with the parametric estimate
  - Accounts for items not included in BCM estimate
  - Factor adjusted for relative complexity of each concept
- ❑ NAFCOM used to develop full vehicle cost estimate
  - Adjusted BCM estimates fed in as pass-through items
  - Other items adjusted to reflect the change in vehicle size
    - TPS, wiring, propulsion lines, etc.
    - Main engines not changed

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BOEING

Two techniques were employed to estimate the cost of the MLV core. NAFCOM was used to develop parametric vehicle level estimates. Bottoms up estimates for fabrication of structures were prepared for the various concepts using established methods and computer programs. These detailed cost estimates were fed into NAFCOM to produce vehicle level estimates for the various concepts.

Items Not Included in Detailed Cost Estimates

LCLCVSA Program

- ❑ Structural Details
  - Slosh baffles
  - LH2 tank SRB attachment structure
- ❑ Fabrication tooling and ground support equipment
- ❑ Subsystem integration and check-out
- ❑ Program management and other overhead costs

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BOEING

The scope of the study precluded inclusion of all relevant details. These were accounted for by application of an adjustment factor prior to development of the NAFCOM full vehicle estimate.

Cost Estimation Groundrules

LCLCVSA Program

- All costs were estimated in constant 1997 $ using NASA escalation indices. No fee or contingency was included and G&A was assumed to be 10%.
- No operations costs or facilities were included. DDT&E was reduced 32.8% and mfg. T#1 was reduced 25% to account for class I changes that are in the model's data. These reductions were not taken on throughput costs from BCM, off the shelf hardware, or systems costs.
- The APUs, fairing separation and main engines were throughput costs from quotes (APUs) or historical data (separation and SSME).
- A 90% learning curve was assumed for all hardware estimated by NAFCOM or BCM estimates. 95% learning was assumed for off the shelf hardware (APUs, SSMEs, separation). The annual production rate was 6 units, with a total program buy of 60 units.
- Because of the unique nature of the semi-reusable concept under study, it was necessary to make the manufacturing estimate in 2 separate runs. The first had DDT&E, STH (does not fly) and two units of production of all three major elements (propulsion module (p/m), tank, fairing). The second run had 58 units of tanks and fairings starting at unit 3.
- The engines for the test p/m were assumed to be used engines and did not contain the 30% factor added to newly designed hardware for STH. New engines were assumed for the 2 production p/m. No refurbishment cost for the engine between flights was included from the model. No engine design cost was included.

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NAFCOM Cost Estimation Groundrules

LCLCVSA Program

- When running the NAFCOM model with BCM throughputs, this had an impact on systems costs. The estimate was taken outside the model and the systems costs were left as generated from the model using aluminum hardware.
- Subsystems and components other than composite structures were estimated using the weight for that configuration. The design estimate for composite components was estimated with the weight of the baseline aluminum component.
- In a separate run of the model the second p/m per flight set was accounted for by putting through the cost of a second p/m as a separate component. This was necessary since NAFCOM does not allow input of different quantities of hardware and some of the weight (ex. Main Propulsion) was estimated as a subsystem with Main Propulsion in the Tank Module. This allowed us to get the recurring support cost of integrating the second PM to the launch vehicle.
- No complexity judgments were made other than what is implicitly assumed in the choice of data points and adjustment of the BCM estimates.
- Non structure subsystems were estimated as whole subsystems. In order to present the estimate for p/m, tank module, and fairing; the estimates for whole subsystems were distributed by weight outside the model.
- For more information about how the estimate was derived see the attached sheet which shows the platform and data point numbers assumed for each component / subsystem.

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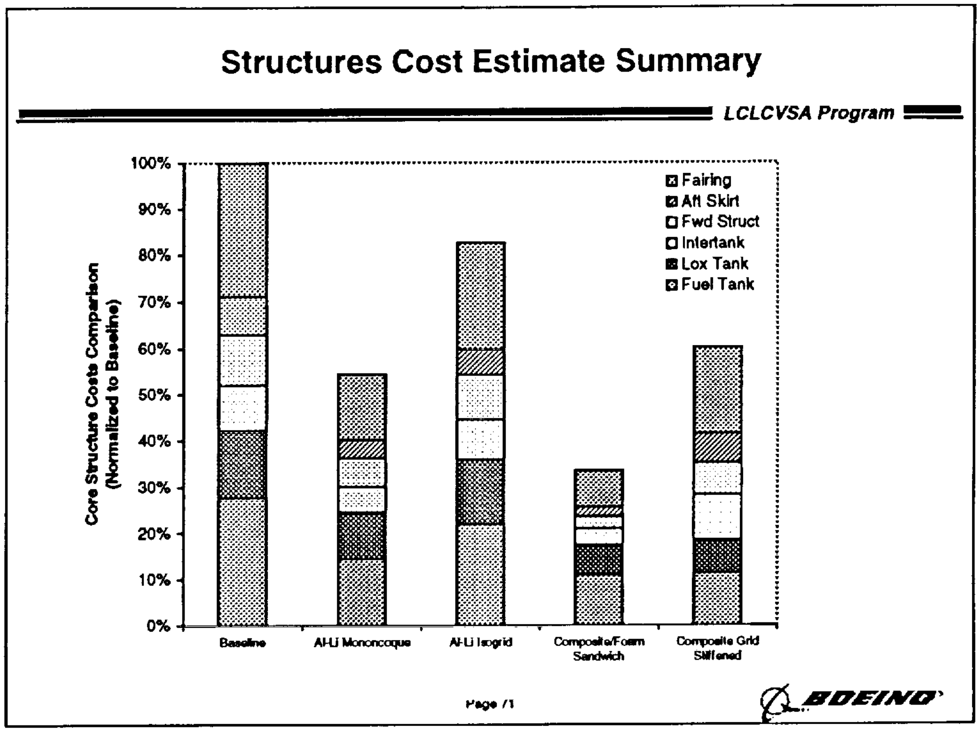
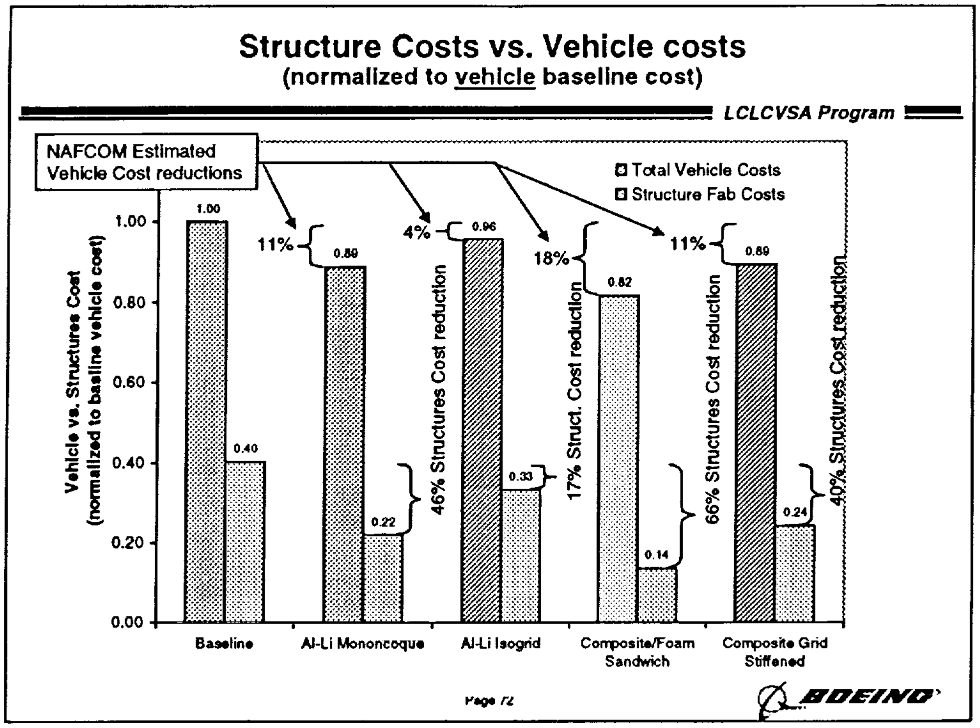
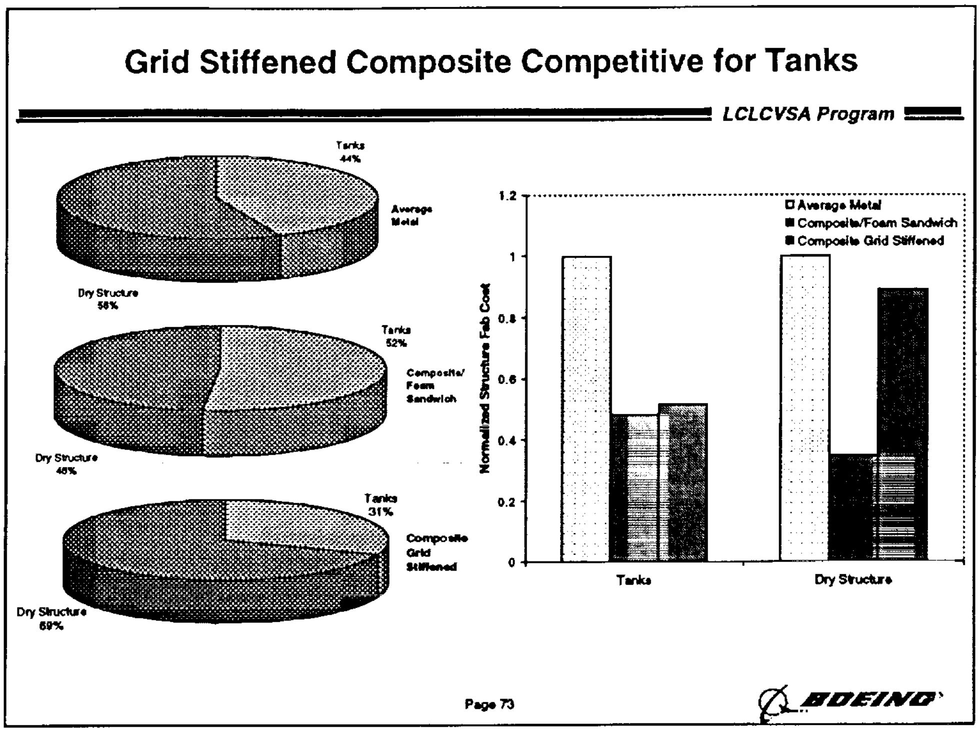


The next few charts present the cost estimation results. The relative cost of the core structures and the breakdown by element is shown above.



Fabrication of large, unitized composite structures was found to eliminate or reduce assembly cost significantly. Elimination of machining in the monocoque concept was also found to reduce cost. At the core vehicle level, less impact was observed; however, cost reductions up to 18% were predicted.



The grid stiffened composite concept did not show as great a cost benefit as the sandwich configuration; however, the result was dependent on the structure in question. The tanks were very close in cost, whereas the dry structure was significantly more expensive. This could be due to a number of factors. The tanks and dry structure have different requirements, and the cost could be a reflection of the applicability of the two concepts for different types of structure. It is also possible that the routine used to define the grid structure closed closer to an optimal manufacturing configuration for the tank structure, and that a design optimization including manufacturing as a constraint would find a lower overall cost for that concept. Development of facilities optimized for grid stiffened structure fabrication could reduce costs as well.

Trade Study Conclusions

LCLCVSA Program

- ❑ Unitized composite structures offer major benefits in both cost and weight
- ❑ Even major reductions in structures costs alone are insufficient to meet NASA goal of $175M/flt
  - Engine, SRB and operations costs must also be reduced
  - LFBB projected to save $500M/yr on orbiter (7 flt/yr)
- ❑ Technology and design improvements would improve the performance of some concepts
  - High speed machining
  - AGS design for producibility
  - Multiple head FP

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It was concluded that advanced technologies offer potentially significant cost and weight benefits to MLV structures; however, these benefits alone will be insufficient to reach the program goals of $1000/lb to LEO. Gains must also be made in other vehicle systems and operations to enable that level of cost reduction. For example, LFBB is projected to save significantly over SRBs applied to the Shuttle.

Technology improvements beyond the level assumed in this study could reduce structural costs even further.

Recommended Future Work

LCLCVSA Program

- ❑ More in-depth study of high-payoff composite concepts
  - Tooling
  - Impact of further technology advances
  - More detailed cost and weight assessment
- ❑ Systems level study to optimize vehicle configuration
- ❑ Operations study to identify potential cost savings

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In addition to the technology and facilities developments laid out in Task 3, we also recommend further study to refine the fidelity of these preliminary estimates, consider vehicle configuration changes, and identify areas for cost savings in operations.

Thrust Structure Assessment

LCLCVSA Program

- State-of-the-art thrust structure designs consist of two distinct elements: (a) Aft Skirt, and (b) Propulsion Element.
- Aft skirt structure is similar in function and form to other dry-structure "barrel" sections.
- The propulsion element of an expendable design consists of the main rocket engines, propulsion-related systems and engine-mount structure, the last being of truss-type construction.
- In a recoverable P/A (Propulsion/Avionics) module, the above systems are accompanied by avionics, electric power and recovery-related systems (aeroshell, TPS, RCS, and parachutes).

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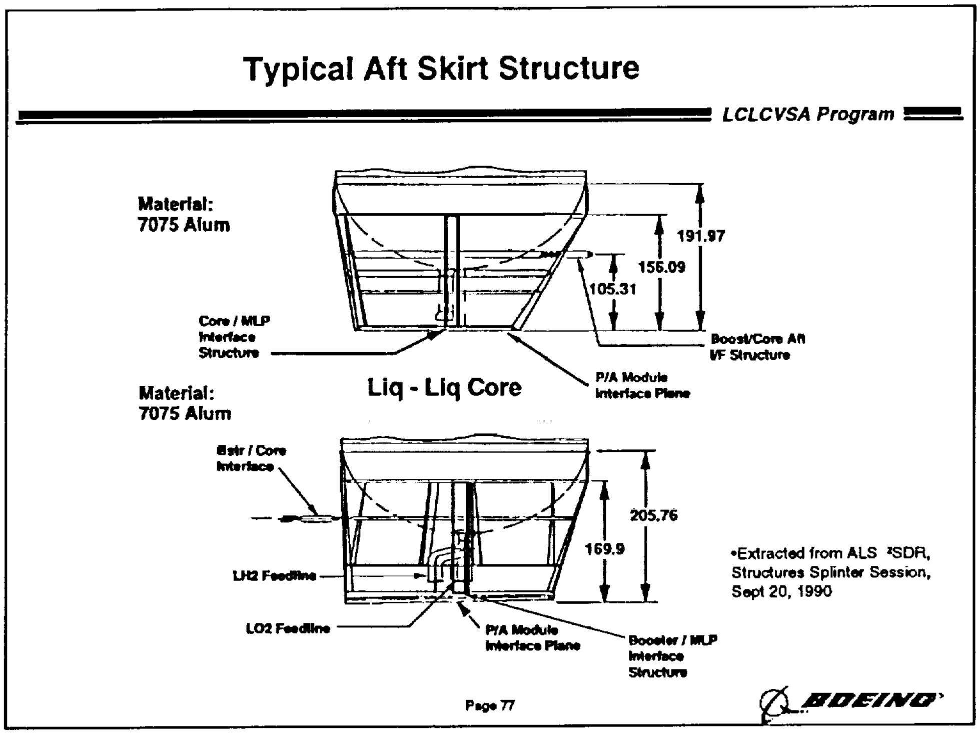
The relative cost of fixed versus reusable thrust structure was also considered in Task 2. Boeing has performed significant design work on reusable propulsion modules dating back to ALS (see subsequent charts).



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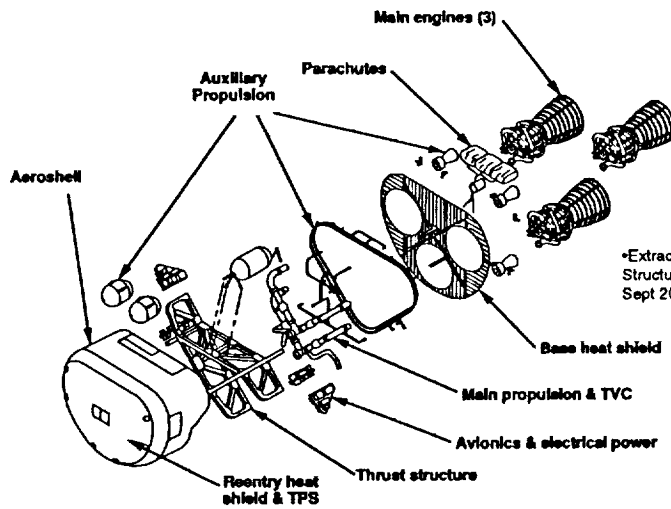
P/A (Propulsion/Avionics) Module

LCLCVSA Program



•Extracted from ALS *SDR, Structures Splinter Session, Sept 20, 1990

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Reusability Trade Results

LCLCVSA Program

- Recently-conducted, internally-consistent studies, (using NAFCOM CERs anchored to ALS study data) are summarized in two accompanying graphical charts and indicate that:
  - The "break-even" point between expendable and partly-recoverable systems lies between 45 and 120 launches (depending on development cost assumptions)
  - In the range of 50 to 60 launches, the difference in total Life Cycle Cost is relatively small (less than 10%)

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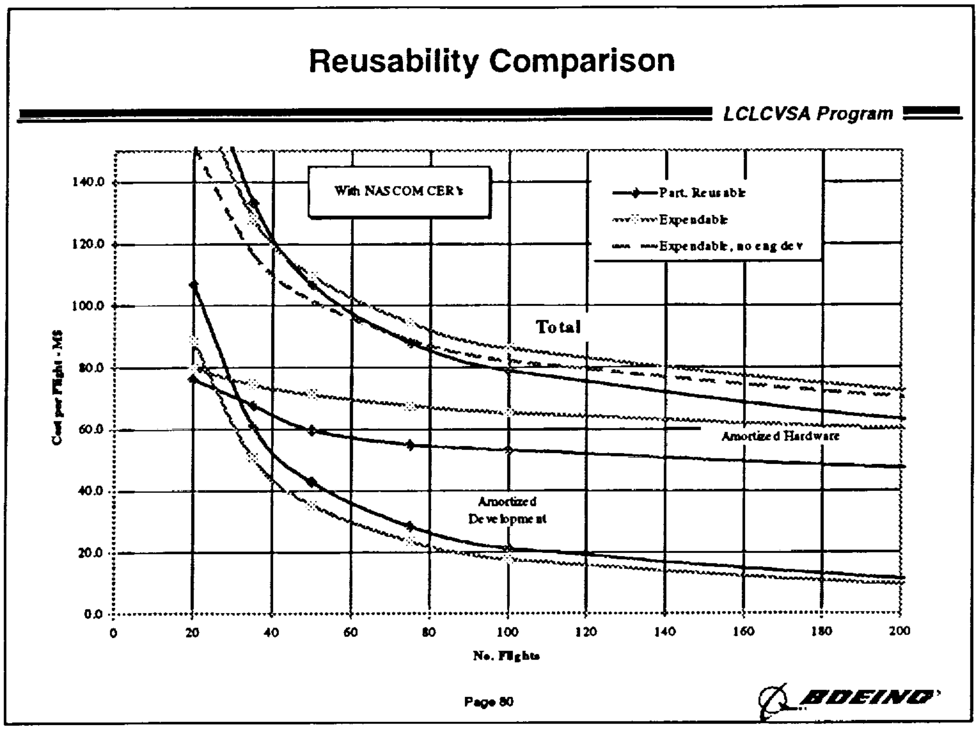
Recent studies indicate that the payoff for partial reusability when the total program is 60 launches would be less than 10%, and could evaporate entirely, depending on development costs.



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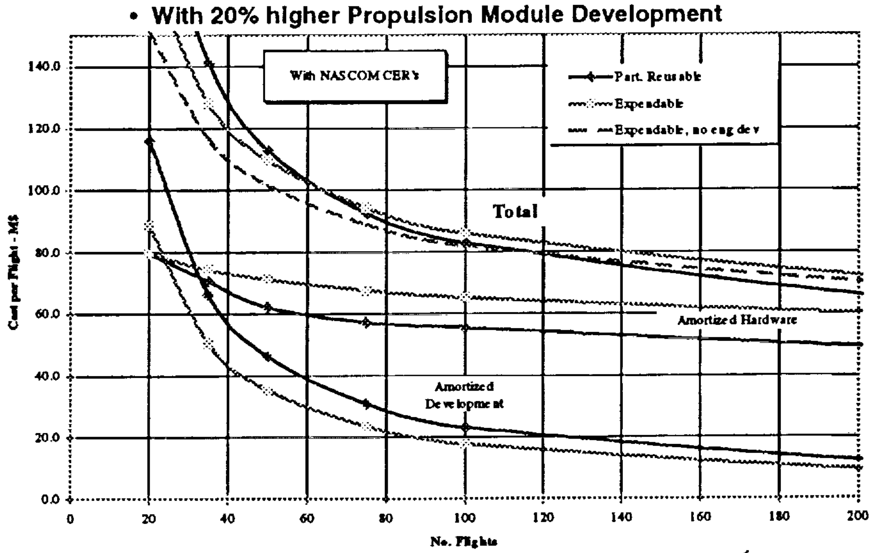
Reusability Comparison

LCLCVSA Program

- **With 20% higher Propulsion Module Development**



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LCLCVSA TECHNOLOGY APPLICATIONS TO LFBB

Members of the Boeing LFBB program in Downey, CA evaluated the MLV trade study concepts for applicability to the LFBB system. This study involved quick estimation of impact on both weight and cost of the advanced technology concepts as compared to the LFBB baseline.

WEIGHT ESTIMATE GROUNDRULES

LFBB

LIQUID FLY BACK BOOSTER

- BASED ON DESIGN DATA PRESENTED AT JANUARY 13, 1998 TELECON
- WEIGHT PER UNIT AREA ESTABLISHED RELATIVE TO AXIAL LOADING LEVELS FOR DRY AREAS AND TANKS
  - 1000 TO 8000 LBS. PER INCH
- UNIT WEIGHTS SCALED TO LFBB AXIAL LOAD LEVELS
  - 7700 TO 12000 LBS. PER INCH
- LFBB VEHICLE STRUCURE AND SUBSYSTEMS RESIZED DUE TO DECREASED/INCREASED BARREL SECTION WEIGHT
  - VEHICLE PHYSICAL SIZE, PLANFORM NOT RESIZED

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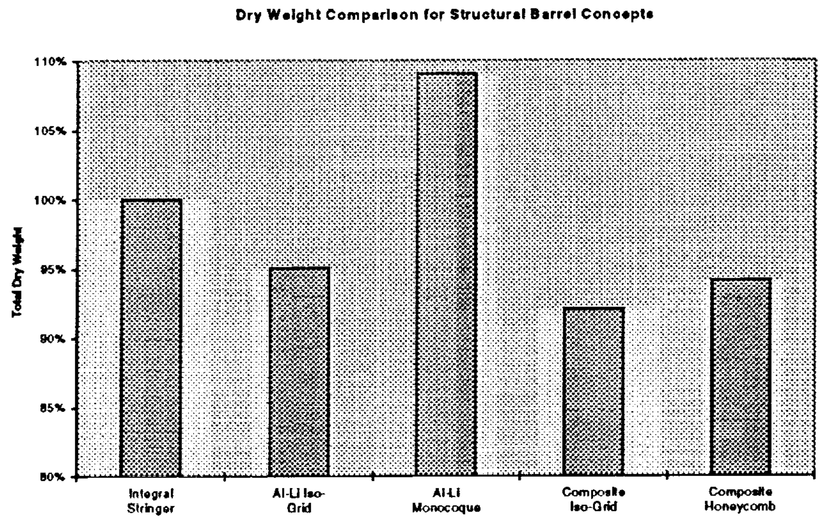
The unit weight trends generated during the MLV trade study were extrapolated to cover the LFBB load range and used to calculate LFBB weight impacts. Vehicle resize was limited to subsystems in this part of the study.

DRY WEIGHT COMPARISON FOR BARREL SECTIONS

LFBB
LIQUID FLY BACK BOOSTER



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The vehicle dry weight comparison parallels that of the MLV trade study, although the differences are less dramatic. The composite concepts provided weight reductions of6 to 8%. The difference is due to several factors, including the difference in load levels, and the lack of a complete vehicle resize.

LFBB COST ESTIMATION GROUNDRULES

LFBB
LIQUID FLY BACK BOOSTER

- The cost will be the sum of Design, Development, Test & evaluation (DDT&E); Production and Operations through FY 2030
- Contract ATP will be October 2000
- Costs will be developed at the lowest level of the WBS
- The cost estimate will be based on the dual configuration using the RS-76 engines
- December baseline configurations to be costed
- Estimates in FY 98 dollars
- Estimates at the cost line, no fee
- Costs will be time phased by GFY for
  - Total LFBB program
  - DDT&E
  - Production
  - Operations

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Cost estimation was performed using LFBB methods, according to a set of groundrules independent from those used in the MLV study.

LFBB COST ESTIMATION GROUNDRULES (cont.)

LFBB
LIQUID FLY BACK BOOSTER

- Life cycle cost data will be developed using Aerostruc+ parametric model
- There will be a total of three flight units
- There will be a two year transition from SRB to LFBB
- The production completion will support the LFBB operational flight schedules
  - Year 1 - 2 flights
  - Year 2 - 6 flights
  - Year 3 - Manifest supported by LFBB
- All GSE be completed by DDT&E (1 set)
- DDT&E and Operations cost will include propellant
- Software will be fully developed and tested in DDT&E and there will be no changes in production
- BME and FBE quotes will be provided by the vendor
- Initial spares for production @ 5% plus overhaul and maintenance

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LFBB COST ESTIMATION GROUNDRULES (cont.)

LFBB
LIQUID FLY BACK BOOSTER

- Estimates supplied by other organizations will be used for
  - WBS 1.1.3.3.2 (Propulsion Sys - Main Engine) Stennis Test Ops Support and Phillips Lab Test Ops Support
  - WBS 1.1.3.3.3 (Propulsion Sys - FEB) LeRC Test Ops Support
  - WBS 1.1.4.1.2~5 (Facilities - KSC, Stennis, LeRC, Philips Lab)
  - WBS 1.1.7 (STS Integration) and WBS 1.3.8 (Operations - Facilities - KSC)
    - NASA Shuttle Integration
    - NASA Program Support
- Final Integration, assembly and checkout of the LFBB vehicle will be done in Palmdale
- All deliverables will be to KSC from Palmdale via the Shuttle 747 (GFP) with 6 stops
- Shuttle upgrades have been implemented and are available for LFBB
  - Avionics, OMS/RCS, APU, EMAs for SSME

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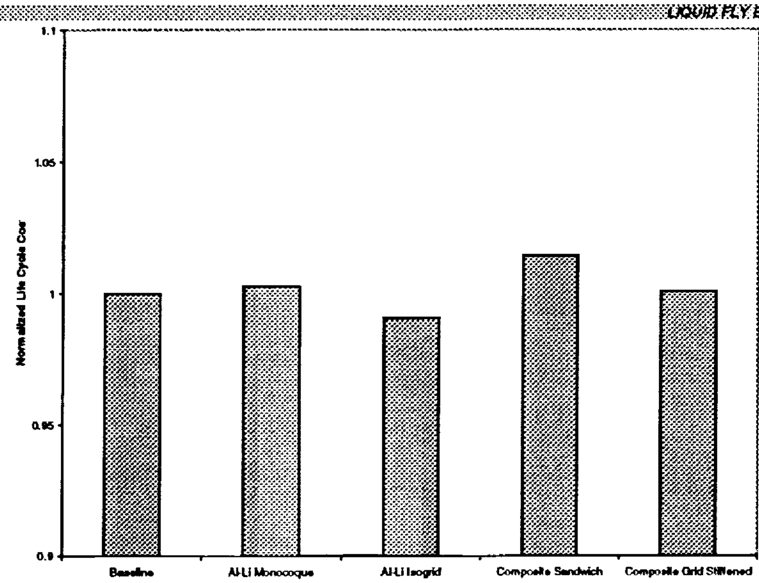
LFBB Cost Trade Using AEROSTRUC+ Model

LFBB
LIQUID FLY BACK BOOSTER



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Overall vehicle costs were found to be relatively insensitive to concept. The small (three vehicle), reusable fleet, and the relative importance of DDT&E costs contributed to this lack of sensitivity. The AEROSTRUC+ cost model used was not set up to capture the advanced manufacturing concepts in the same detail as the more in-depth MLV procedure.

LFBB ASSESSMENT CONCLUSIONS

LFBB

LIQUID FLY BACK BOOSTER

- LFBB results distinct from MLV
  - Different scale
  - Different loads and requirements
  - Reusable system
- Less sensitivity to concept observed in LFBB comparison
  - Performance benefit evident for composite concepts
  - Costs of concepts indistinguishable
  - Vehicle resize not performed
  - Cost estimation technique did not capture advanced manufacturing approaches
- Many technical elements can be ready to support LFBB development and production

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Despite limitations on the scope of the LFBB evaluation, it is apparent that performance benefits would accrue from inclusion of advanced technology concepts. While the cost benefits of these technologies were not conclusive, it would appear that at a minimum, there is no cost penalty. As will be shown in the next section, many of the technology developments necessary to include these concepts in LFBB can be accomplished within the required schedule.

Task 3 - Development Roadmaps

LCLCVSA Program

Section Topics:

- ❑ **Existing capital equipment and facilities**
  - Boeing facilities around the US
  - NASA facilities for ET production
- ❑ **Technology and facility development roadmaps**
  - High payoff technologies evaluated in trade study
  - Enhancing technologies for additional payoff
  - Facility development requirements
- ❑ **Current and planned technology development programs**

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Task 3 focused on identification of existing facilities for MLV core structures production, technology and facilities development requirements to support MLV and LFBB, and programs which support those requirements.

Manufacturing Plan Overview

LCLCVSA Program

- ❑ **Metallic Concepts Manufacturing**
  - Vertical barrel section assembly
  - Horizontal element assembly
  - Barge to major structures to launch site
  - Vertical assembly at launch site (use VAB at KSC)
- ❑ **Composite Concepts Manufacturing**
  - Vertical fabric/tow placement & vacuum bag/cure
    - Reduces tooling stiffness requirements
    - Building height issues
    - Optional horizontal autoclave cure
  - Barge to major elements to launch site
  - Vertical assembly at launch site (use VAB at KSC)

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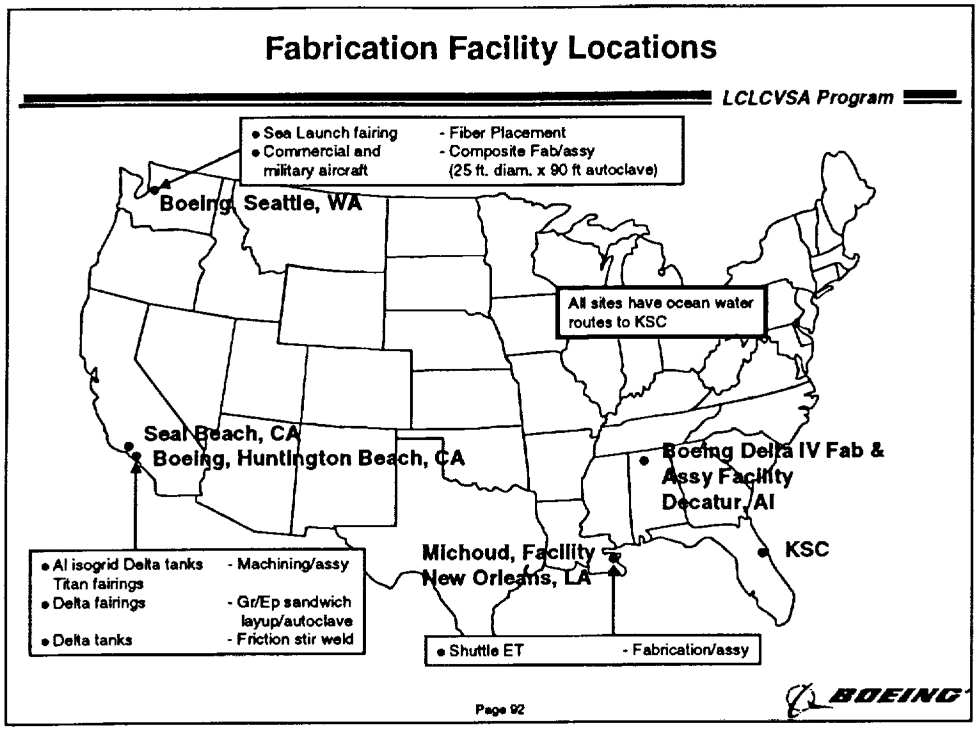
The overall manufacturing flow would be similar for either metallic or composite MLV core structures. The core elements would be fabricated, then shipped to KSC for vehicle assembly. Due to the size of the elements, vertical fabrication minimizes stiffness concerns, but raises issues regarding facilities. A major issue would be the availability of autoclave facilities able to accommodate MLV scale structures. Non-autoclave cure technology is an attractive alternative.



NASA and Boeing have major facilities around the country which are appropriate for MLV fabrication support.

Fabrication Facility Capabilities

LCLCVSA Program

Locations & Products	Facility	Capabilities
Seattle, Washington • Sea Launch fairing • Various military programs	• Fiber Placement Machine	• 20 ft. dia x 70 ft long (qty2)
	• Autoclaves (Extensive composite fabrication)	• 25 ft. dia x 90 ft long (qty 2) 22 ft. dia x 40 ft long (qty 4) 15 ft. dia x 30 ft long (qty 4)
	• Large 5-axis Routers	• 120 ft x 20 ft. table (qty 2)
	• Composite Fabrication Center	• 400,000 sq ft. composite fab center, additional fab areas 45 ft hook height bays 350 ft x 350 ft typical, ultrasonic inspection, waterjet trim, Class 100,000 clean room
Huntington Beach, CA • Delta 2, 3 fab / assy • Titan fairings • Various military programs	• Isogrid Panel Machining	• 12 ft x 48 ft table
	• FSW facility (on-line 9/98)	• 8 ft diam x 50 ft length tank fabrication facility (FSW machine can support 6 ft. dia. to 30+ ft. dia. tank welding)
	• Autoclave for composite sandwich fabrication of Delta fairing	• 15 ft. dia. x 40 ft long • 115 ft hook height high bay

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Composite fabrication facilities in particular are not currently capable of the scale of fabrication needed to support MLV. Since unitized composite fabrication was found to provide significant cost and weight benefits to MLV core structures, this is a serious shortfall.

4

Roadmap Caveats

LCLCVSA Program

- Development efforts phased to enable insertion into LFBB wherever possible
- Where funding constraints do not support development to support LFBB schedule, development efforts can be slid or stretched as appropriate to mesh with MLV schedule
- ROM engineering estimates of funding requirements are provided for planning purposes only and are not to be construed as a firm commitment on the part of The Boeing Company

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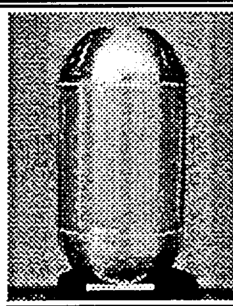
Boeing prepared the technology and facilities development roadmaps to enable technology insertion into the LFBB program wherever possible. Stretching or sliding individual program elements would allow accommodation of funding restrictions. This should not impact the overall investment requirements to a great degree.

Al-Li Monocoque Structure

LCLCVSA Program



Al-Li 2195
3 ft. Diam
Demo Tank

Benefits

- Simple construction eliminates machining costs, reduces tooling requirements
- Friction stir welding (FSW) reduces assembly cost, improves repeatability
- Al-Li provides higher performance, lower density
- Enhancing technology
    - Laser thermoforming

Technology Challenges

- Controlling vehicle weight, size growth
- Handling of unstiffened structures during fabrication
- Optimize FSW process parameters
- Develop FSW repair techniques
- Laser thermoforming process development

Facility Requirements

- Laser thermoforming facility
- FSW facility

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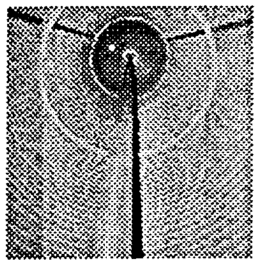
The benefits, technical challenges, and facilities requirements of each of the concepts studied in Task 2 are shown on charts like the one above for Al-Li monocoque structure.

Al-Li Isogrid Stiffened Structure

LCLCVSA Program



Delta Isogrid Tank

Benefits

- Efficient isogrid construction improves structural mass fraction
- Friction stir welding (FSW) reduces assembly cost, improves repeatability
- Al-Li provides higher performance, lower density
- Enhancing technology
    - High speed machining

Technology Challenges

- Optimize FSW process parameters
- Develop FSW repair techniques
- High speed machining process development

Facility Requirements

- High speed machining facility
- FSW facility

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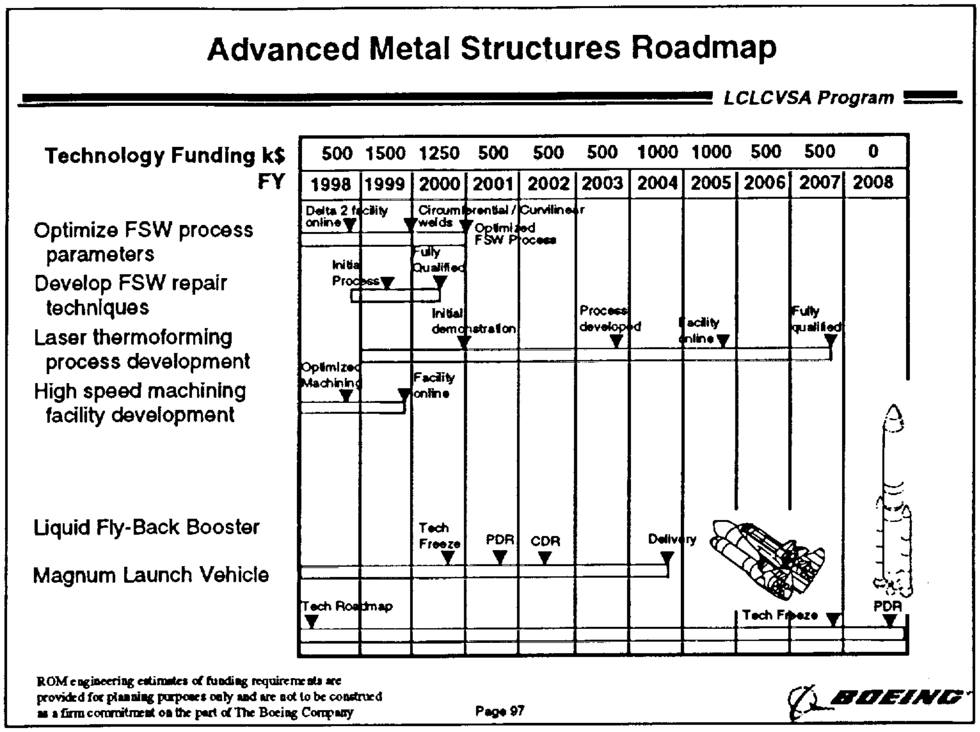
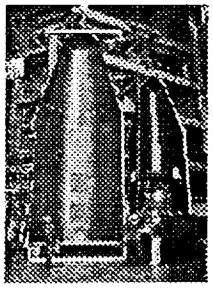


Time phasing and investment requirements for the facility and technology requirements identified are shown on charts like the one above for each of the concepts studied. The schedules for LFBB and MLV development are shown along the bottom.

Composite Sandwich Stiffened Structure

LCLCVSA Program



Delta Composite Sandwich Fairing

Benefits

- Efficient composite sandwich construction improves structural mass fraction
- Sandwich construction eliminates parasitic cryogenic insulation
- Demonstrated low-cost thick ply fabrication technique reduces acquisition cost
- Integrated health monitoring (HM)
- Enhancing technology
  - Low temperature/electron beam curing

Technology Challenges

- Material LOX compatibility, short term permeability
- "Y"-joint configuration
- Ring frame attachment
- Low temperature/e-beam cure
- Low cost, low temperature tooling
- Performance verification

Facility Requirements

- Autoclave, oven, or e-beam facility

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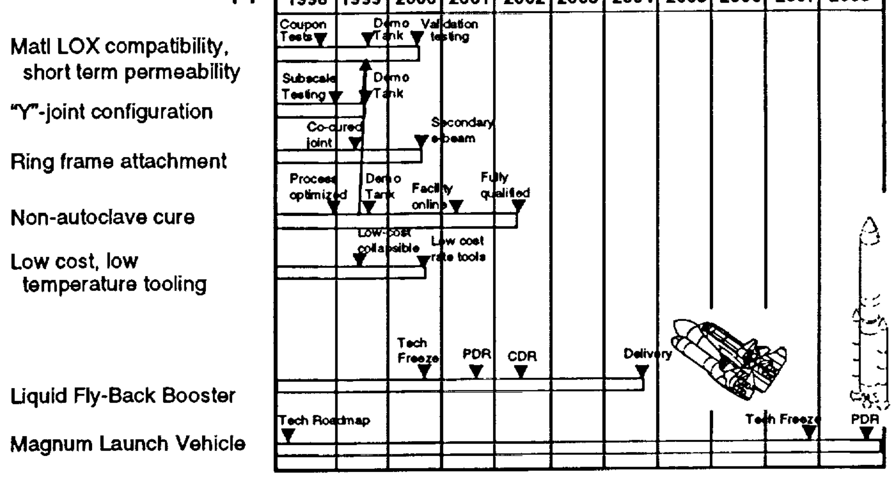
Composite Sandwich Structures Roadmap

LCLCVSA Program

Technology Funding k$	2000	2750	2000	1000	250	0	0	0	0	0	0
FY	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008



ROM engineering estimates of funding requirements are provided for planning purposes only and are not to be construed as a firm commitment on the part of The Boeing Company

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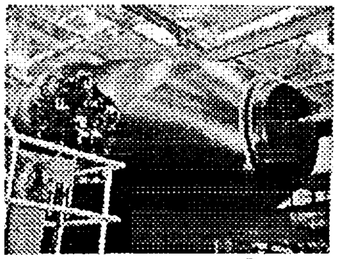
Composite Grid Stiffened Structure

LCLCVSA Program



Seattle Fiber Placement Facility

Benefits

- Efficient composite grid stiffened construction improves structural mass fraction
- Demonstrated low-cost fiber placed (FP) thermoset matl reduces acquisition cost
- Integrated health monitoring (HM)
- Enhancing technology
    - Low temperature/electron beam curing
    - Multiple head fiber placement

Technology Challenges

- Fiber placed grid stiffened composite structures development
- Thick tow prepreg
- Material LOX compatibility, short term permeability
- Performance verification
- Low temperature/e-beam cure
- Low temperature tooling development
- E-beam "cure on the fly"

Facility Requirements

- Fiber placement facility (possibly multiple head)
- Autoclave, oven, or e-beam facility

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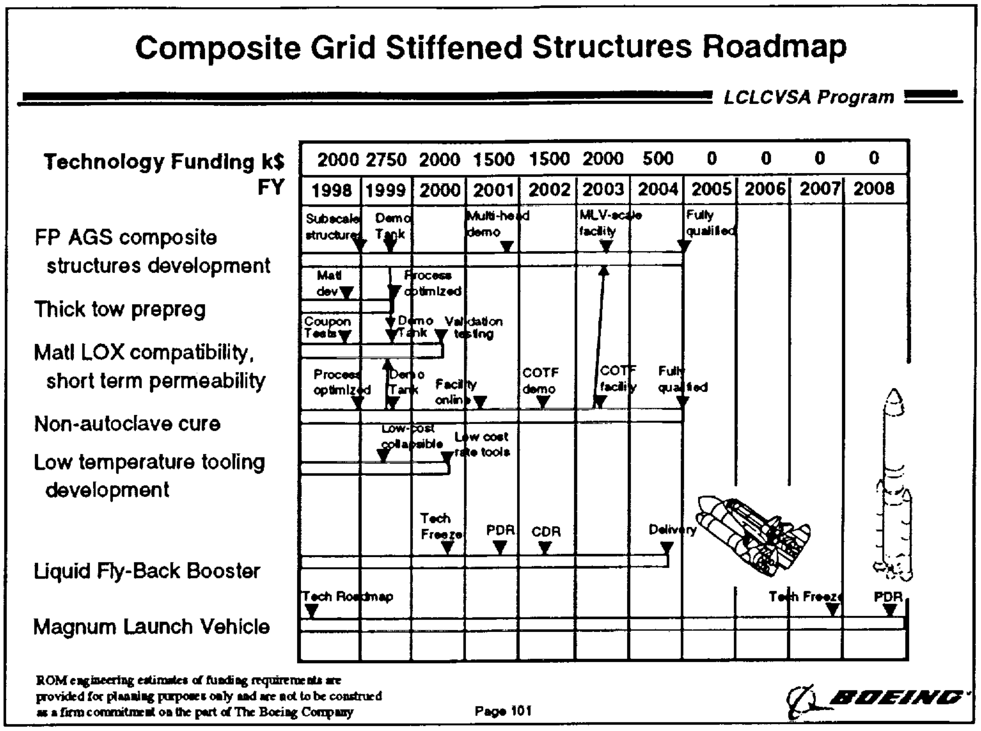

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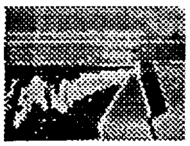
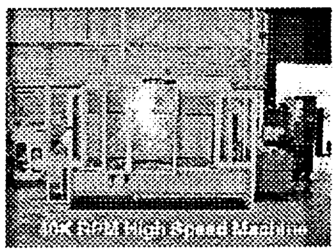
High Speed Machining Facility

LCLCVSA Program



High speed machining (40K+ RPM) offers

- Machining speed increases of up to 16 times
- Machining cost reductions of 3 to 4 times (includes part set-up)
- Thinner gage structure to optimize weight
- No warping or heat damage
- Multiple spindle machining for higher productivity



High Speed Machining Facility
cost estimate: $8 - 11 M

12 ft. x 50 ft. machining table

- ❑ Foundation included in estimate
- ❑ Fabrication of buildings excluded
- ❑ Lead time approximately 24-36 months
- ❑ Amortized cost of $11M machine over 60 vehicles is $183k/vehicle

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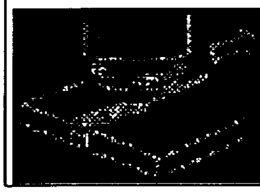
The next few charts list the development requirements for the major facilities identified in this study.

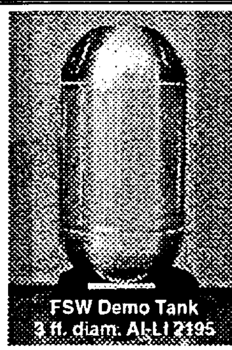
Friction Stir Welding Facility

LCLCVSA Program



Friction Stir Welding provides improved weldability:

- Higher strength welds
- Fewer weld defects and improved grain structure
- Low-heat process minimizes distortion
  - minimizes distortion
  - eliminates cracking
  - eliminates weld metal evaporation & alloy composition changes
- No warping or heat damage



Friction Stir Welding Facilities Estimate

FSW Machine	Cost Estimate
Curvilinear dome gore Welding	$2.0M
Linear barrel welds	$1.6M
Circumferential assembly welds	$2.5M

- ❑ Foundation included in estimate
- ❑ Fabrication of buildings excluded
- ❑ Lead time approximately 24 months
- ❑ Amortized cost of $6M total facility over 60 vehicles is $100k/vehicle

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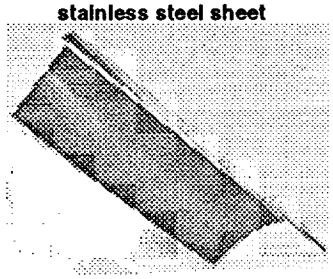
Laser Thermal Forming Facility

LCLCVSA Program

- ❑ Laser thermal forming utilizes a laser to selectively heat sheet or plate stock without melting to induce a controlled residual stress
- ❑ No forming or mold tooling is required
- ❑ Tolerances to 0.0005" have been demonstrated in laboratory studies
- ❑ Large, precision formed structures would reduce assembly costs

Typical laser formed stainless steel sheet



Facility cost estimate: $8 - 12 M
(depending on features)

12 ft. x 50 ft. forming table

- ❑ Laser, machine table, support equipment, control systems and foundation included in estimate
- ❑ Fabrication of buildings excluded
- ❑ Lead time 12 to 18 months
- ❑ Amortized cost of $10M facility over 60 vehicles is $170k/vehicle

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Fiber Placement Facility

LCLCVSA Program

- Automated fiber placement of composite structures can reduce material placement costs
- Multiple placement heads would further reduce lay-up times
- Technique amenable to combination with electron beam curing for cure-on-the-fly system

Facility cost estimate: $15 - 25 M
(depending on features)

Capable of 40 ft. diameter x 120 ft long

- Fiber placement head(s), head/tail stocks, control systems and foundation included in estimate
- Fabrication of buildings excluded
- Lead time approximately 24 months
- Amortized cost of $20M facility over 60 vehicles is $333k/vehicle

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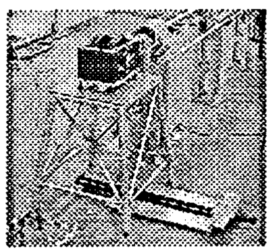
E-beam Cure Facility

LCLCVSA Program

- ❑ Electron-beam curing offers low-cost composite fabrication:
  - Lower direct operating costs
  - Enables low cost, low temperature tooling materials
- ❑ Also reduces internal residual cure stresses
- ❑ Technique amenable to combination with automated fiber placement for cure-on-the-fly system

Boeing Laboratory Facility:



Facility cost estimate: $8 - 10M
(depending on features)

Capable of 40 ft. diameter x 120 ft long

- ❑ Accelerator, support equipment, control systems and radiation hardened building included
- ❑ Lead time 12 to 18 months
- ❑ Amortized cost of $10M facility over 60 vehicles is $170k/vehicle
- ❑ Cure-on-the-fly fiber placement facility estimate $30-35M

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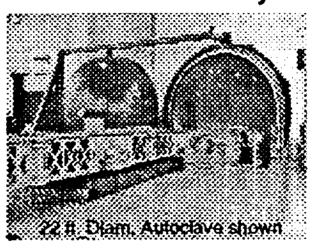
Alternative Autoclave Cure Facility

LCLCVSA Program

- ❑ Non-autoclave processes such as e-beam cure promise lower operating costs, enable low cost, low temperature tooling materials, and reduce internal residual cure stresses
- ❑ Autoclave cure facility is effective back-up technology
  - Ensures good compaction and high fiber volume

Autoclave Facility:



Autoclave cost estimate: $80 - 125 M
(depending on features)

40-45 ft. diameter shell x 120 ft long

- ❑ Autoclave, support equipment, control systems and autoclave foundation included in estimate
- ❑ Fabrication of buildings excluded
- ❑ Lead time 42 to 48 months
- ❑ Amortized cost of $100M autoclave over 60 vehicles is $1.7M/vehicle

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Development of non-autoclave composite cure technology will provide fabrication cost benefits for many large scale aerospace structures programs in the future. If technology development investments are not available, however, large scale autoclave facilities could be constructed, given sufficient lead time.

Technology Development Programs

LCLCVSA Program

- ❑ High speed machining technology is currently used in production environments at Boeing, St. Louis facility - technology can be transferred for MLV Fabrication
- ❑ Advanced Technology Development programs exist at numerous Boeing locations which can be applied to support MLV development

Technology	Development Location
• E-beam composite cure	• Seattle, Huntington Beach
• Low temperature composite cure	• Seattle, Huntington Beach
• Friction Stir Welding	• All Major Boeing Locations

- ❑ Current/planned NASA and AF programs
  - ❑ NASA Reusable Launch Vehicle (RLV) program
  - ❑ NASA Advanced Space Transportation Program (ASTP)
  - ❑ NASA Advanced Reusable Space Transportation Technologies Research NRA
  - ❑ AF Military Spaceplane (MSP) program
  - ❑ AF Grid Stiffened Composite Shroud program

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Government programs administered within NASA and the Air Force are already focused on development of many of the important technologies identified in this study. The objectives and scale of the target vehicles for these program are distinct from MLV requirements, however, and the funding levels of these programs alone will not meet the needs of MLV. Complementary MLV specific programs should be considered to ensure the requisite technologies and facilities are in place when needed.

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Steven E. Hahn, David M. Anderson

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13. ABSTRACT *(Maximum 200 words)*

NASA is interested in a low-cost launch vehicle, code named Magnum, to place heavy payloads into low earth orbit for missions such as a manned mission to Mars and other Government and commercial missions. In this study, structural concepts with the potential to reduce fabrication costs were evaluated in application to the Magnum Launch Vehicle (MLV) and the Liquid Fly Back Booster (LFBB) shuttle upgrade program.

Seventeen concepts were qualitatively evaluated to select four concepts for more in-depth study. It was found that unitized composite structures offer significant cost and weight benefits to MLV structures. The limited study of application to LFBB structures indicated lower, but still significant benefits.

Technology and facilities development roadmaps to prepare the approaches studied for application to MLV and LFBB were constructed. It was found

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Task 3 Conclusions

LCLCVSA Program

- ❑ NASA and Boeing have extensive facilities to support conventional or advanced technology fabrication of MLV structures
- ❑ Advanced technologies studied in Task 2 can be matured to support MLV and LFBB development
  - Cost and schedule within reason
  - Additional technologies would further reduce cost and enhance performance
- ❑ Significant Government and Boeing programs are underway which will provide some of the necessary funding

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Much of the infrastructure to support MLV fabrication and assembly exists today. Composite fabrication facilities, however, are not currently available to support structures of MLV scale. Development of cost and performance enhancing technologies in time to support MLV and LFBB production is achievable. On-going Government and industry programs will provide some of the necessary developments; however, MLV-specific funding is likely to be required.

that the cost and schedule to develop these approaches were in line with both MLV and LFBB development schedules. Current Government and Boeing programs which address elements of the development of the technologies identified are underway. It is recommended that NASA devote resources in a timely fashion to address the specific elements related to MLV and LFBB structures.