NASA/CR-2008-215120

Evaluation of Advanced Composite Structures Technologies for Application to NASA's Vision for Space Exploration

Ross Messinger
The Boeing Company, Phantom Works, Huntington Beach, California

July 2008

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Ross Messinger
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National Aeronautics and
Space Administration

Langley Research Center
Hampton, Virginia 23681-2199

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PREFACE

This final report of task order NNL07AD56T of NASA contract NAS-1-NNL04AA11B, entitled Structures and Materials and Aerodynamic, Aerothermodynamic and Acoustics (SMAAA) Technology for Aerospace Vehicles, satisfies the final report deliverable as defined in Section 4.0 of the statement of work. The report summarizes Boeing contractor products developed during the task order period of performance between July 23, 2007 and February 6, 2008.

ACKNOWLEDGEMENTS

The Boeing Company, its PhantomWorks business unit, and the PhantomWorks Materials and Structures Technology group acknowledges the following personnel for their valuable contribution to this task order. In addition, over 30 Boeing subject matter experts contributed to the assessment of 103 composite structure technologies and 33 Constellation structure applications.

Dan Hansen (Boeing management oversight)

Dawn Jegley (NASA technical monitor)

Ross Messinger (Boeing principal investigator)

George Mills (Boeing data analysis)

ABSTRACT

An assessment was performed to identify the applicability of composite material technologies to major structural elements of the NASA Constellation program. A qualitative technology assessment methodology was developed to document the relative benefit of 24 structural systems with respect to 33 major structural elements of Ares I, Orion, Ares V, and Altair. Technology maturity assessments and development plans were obtained from more than 30 Boeing subject matter experts for more than 100 technologies. These assessment results and technology plans were combined to generate a four-level hierarchy of recommendations. An overarching strategy is suggested, followed by a Constellation-wide development plan, three integrated technology demonstrations, and three focused projects for a task order follow-on.

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1.0 INTRODUCTION

1.1 Objective and Approach

The objective of this task order was to perform a survey and study of composite material technologies and their potential application to NASA's Space Exploration Architecture Elements (Constellation program).

The approach was to develop qualitative technology assessment methodology, obtain technology assessment data from Boeing subject matter experts, assess applicability of composite material technologies to major structural elements of NASA Constellation program, and derive recommendations for potential follow-on activities.

1.2 Ground Rules and Assumptions

Figure 1.2-1 summarizes the ground rules and assumptions. The large scope of the task, involving a broad variety of Constellation elements and an equally broad array of composite structures technologies, necessitated that the assessment be qualitative and relative. The results and recommendations are nevertheless valid, being derived from substantial expert opinion. Also, there is no Boeing proprietary or otherwise restricted information presented or referenced in this report. Finally, several technologies and programmatic factors are not considered in the assessment. For example, the current (early 2008) Ares I upper stage cryotanks are designed with aluminum-lithium. The study includes these cryotanks, thus indicating possible future weight or cost reduction initiatives.

- **Analysis and results are relative and qualitative**
- **Only public domain and no ITAR -restricted literature are used for reference**
- **Not considered**
  - Existing programmatic decisions
    - e.g., Ares I and Orion
  - Pressurized cargo carrier (Orion variant)
  - Main propulsion system components
    - Feedlines , valves, etc.
  - Fabrication locations or logistical constraints
    - Especially large -scale Ares V structures
  - Inflatable structures
  - Nano-composites technologies
  - Surface elements
    - Rovers, cranes, etc.

Figure 1.2-1. Ground Rules and Assumptions

1.3 Study Organization

The study was executed in nine related steps (Figure 1.3-1). The technology assessment characterized 103 individual technologies in terms of TRL, performance and cost benefits, Boeing assessment expertise, and suggested development activities. A structural system assessment rated 24 sets of technologies in terms of four criteria. The requirements criticality of each of the 33 Constellation elements was defined during the Constellation element assessment step. This information became the basis for the calculation of Technical fit, which related the benefit of each structural system to the requirements of each Constellation element. Similarly, Program fit was calculated by determining the relationship between the maturity of each structural system and the time to technology commitment for each Constellation element. Technical-Program fit combined Technical fit and Program fit for each structural system and each Constellation element. The Technical-Program fit metric was used to identify cross-cutting structural systems for further study. Each cross-cutting structural system was detailed with a high-fit intersection description. The final step involved identifying technology recommendations and associated development plans based on the selected cross-cutting structural systems and the technology assessment database.

The methodology uses Excel spreadsheets that can be readily modified and updated with other scoring methods, composite (and metallic) technologies, and Constellation elements.

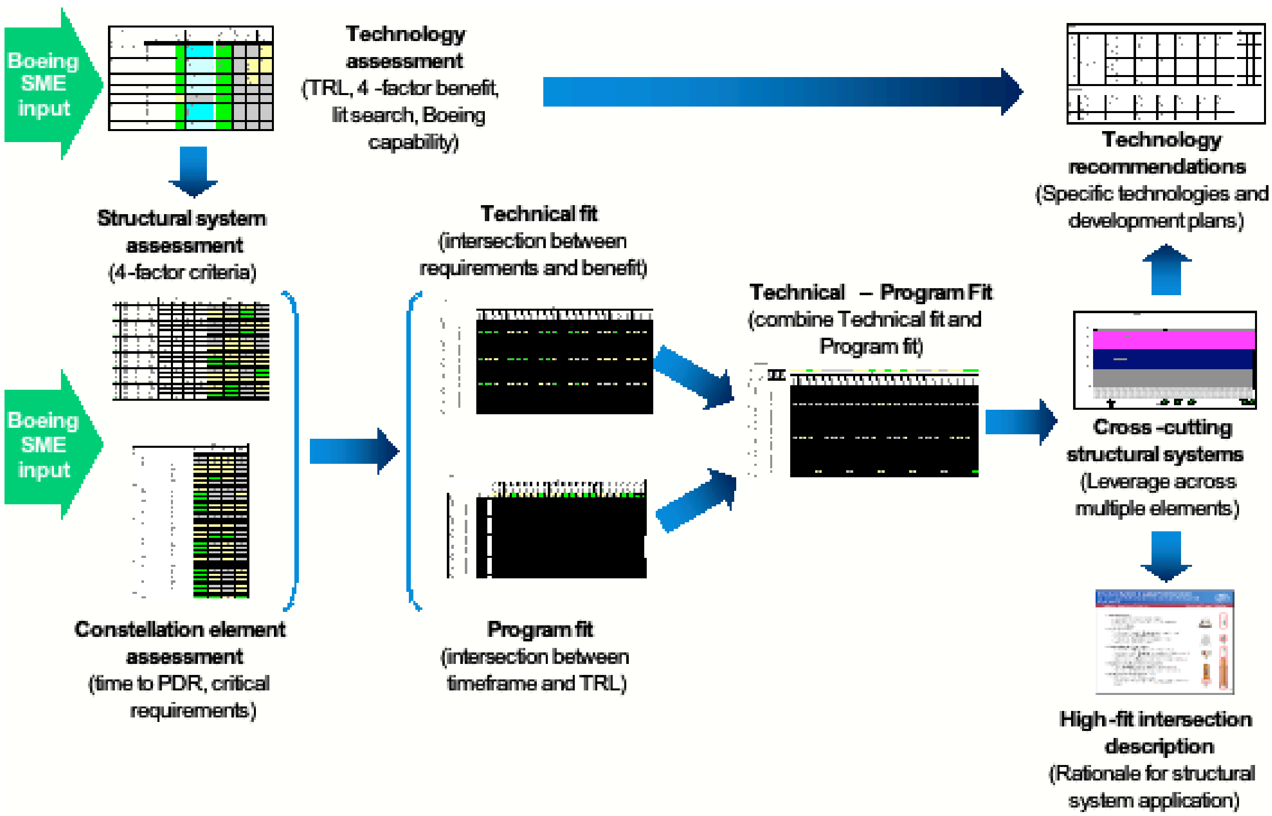
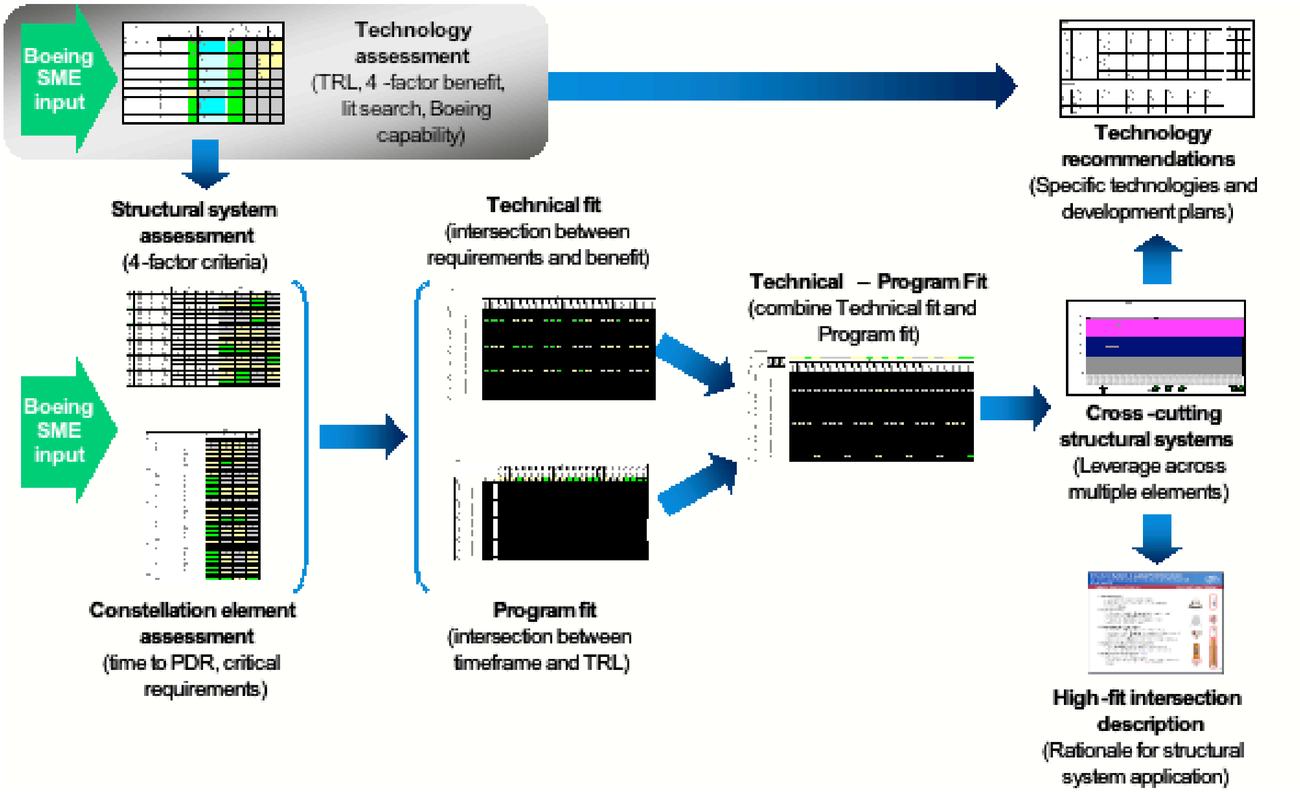


Figure 1.3-1. Study Approach Flowchart

2.0 TECHNOLOGY ASSESSMENT



2.1 Assessment Expertise

Figure 2.1-1 illustrates some related programs, including LDEF, Space Shuttle, X-37, RAH-66, 787, ACT Wing, Delta, ISS, V-22, A-160, HSR, Composite cryotanks, Minotaur, C-17, 702, and F-22. Many of the subject matter experts who provided input to this study have related experience in these (and numerous other) development and production programs.

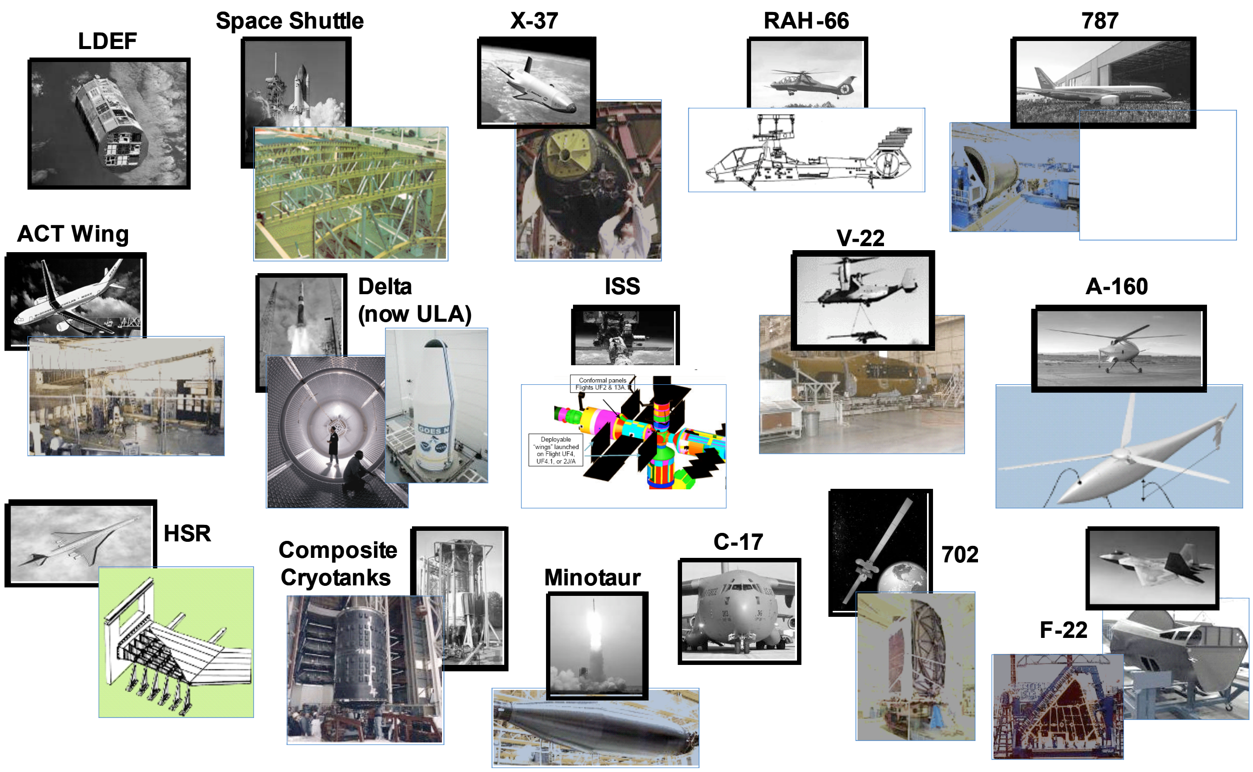


Figure 2.1-1. Related programs reflect substantial Boeing composites assessment expertise.

2.2 TRL, Boeing Expertise, Technology Value to Constellation

A database of individual technologies was developed for this study to provide the foundation for the focused recommendations (Figure 2.2-1). The database is organized by the seven NASA-provided categories. The original "Threat/Environment" category was changed to "Design for Threat/Environment" to highlight the need for special design technologies to mitigate against degradation or failure from various environmental conditions.

Figure 2.2-2 shows the rating scales used in the following technology assessment. TRL has a three-point scale and is color-coded to readily visualize technology maturity. Boeing capability is differentiated as to whether the technology is in production, or is either in development or is provided by a supplier. Technology value/benefit is indicated as being highly beneficial (enabling), moderately beneficial (enhancing), or of little value to the Constellation program. The scoring of the value/benefit was defined to allow no more than one enabling benefit in order to focus on the most important aspect of the technology.

Figures 2.2-3 through 2.2-18 contain the assessment of all 103 technologies considered in this study. The benefit of each technology was considered with respect to performance, development cost, production cost, and operation cost. Materials and Processes technologies provide primarily performance benefits (Figures 2.2-3 and 2.2-4). Manufacturing Methods technologies offer primarily production cost benefit (Figures 2.2-5 through 2.2-7). Innovative Design technologies primarily provide performance (e.g., reduced weight) value (Figures 2.2-8 through 2.2-10). Analysis, Modeling, and Simulation technologies offer performance value, such as safety, weight, and reliability improvements, and to a lesser extent, lower development cost

(Figures 2.2-11 through 2.2-13). Design Criteria and Allowables technologies have primarily performance value, and specifically offer safety, weight, and reliability improvements (Figures 2.2-14 and 2.2-15). Development, QA, and Certification technologies reduce development cost (Figures 2.2-16 and 2.2-17). Design for Threat/Environment technologies have performance and operation cost improvements (Figure 2.2-18).

A mapping between the NASA-provided technologies and the assessed set of technologies is provided in the Appendix B.

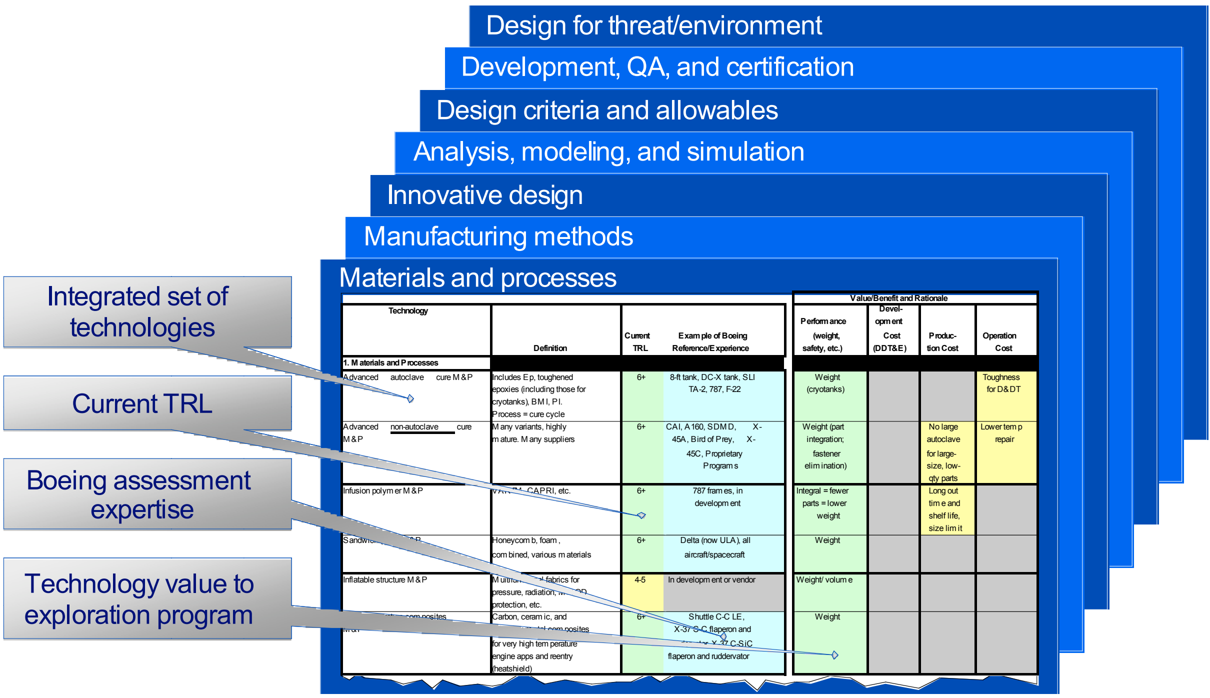


Figure 2.2-1. Overview of Individual Technologies, Boeing Expertise, and Technology Value

TRL
6+
5
4-

Boeing Capability
Production
In development or vendor

Figure 2.2-2. Technology Rating Scales

Technology	Definition	Current TRL	Example of Boeing Reference/Experience	Value/Benefit and Rationale: Perfor-mance (weight, safety, etc.)	Devel-opment Cost (DDT&E)	Produc-tion Cost	Operation Cost
1. Materials and Processes							
Advanced autoclave cure M&P	Includes Ep, toughened epoxies (including those for cryotanks), BMI, PI. Process = cure cycle	6+	8-ft tank, DC-X tank, SLI TA-2, 787, F-22	Weight (cryotanks)			Toughness for D&DT
Advanced non-autoclave cure M&P	Many variants, highly mature. Many suppliers	6+	CAI, A160, SDMD, X-45A, Bird of Prey, X-45C, Proprietary Programs	Weight (part integration; fastener elimination)		No large autoclave for large-size, low-qty parts	Lower temp repair
Infusion polymer M&P	VARTM, CAPRI, etc.	6+	787 frames, in development	Integral = fewer parts = lower weight		Long out time and shelf life, size limit	
Sandwich (core) M&P	Honeycomb, foam, combined, various materials	6+	Delta (now ULA), all aircraft/spacecraft	Weight			
Inflatable structure M&P	Multifunctional fabrics for pressure, radiation, MMOD protection, etc.	4-5	In development or vendor	Weight/ volume			
High-temperature composites M&P	Carbon, ceramic, and refractory metal composites for very high temperature engine apps and reentry (heatshield)	6+	Shuttle C-C LE, X-37 C-C flaperon and ruddervator, X-37 C-SiC flaperon and ruddervator	Weight			
Molding compounds M&P	For fittings, padups, and engine parts (e.g., HexMC)	6+	787 window frames	Weight			

Figure 2.2-3. Technology Assessment (1 of 16)—Materials and Processes

Technology	Definition	Current TRL	Example of Boeing Reference/Experience	Value/Benefit and Rationale: Perfor-mance (weight, safety, etc.)	Devel-opment Cost (DDT&E)	Produc-tion Cost	Operation Cost
1. Materials and Processes							
Bonded joining M&P (adhesives)	Co-cure, cobond, and secondary Many variants, highly mature. Many industries	6+	All platforms, CAI	Weight		Eliminate cost of drilling and inspecting holes, fasteners, rework	
Bolted joining M&P (fasteners)	Permanent and removable types	6+	All platforms, esp. 787 Shuttle, X-37	Weight		Assembly fastener sourcing	Access
Coatings and sealants	For galvanic and other corrosion, propellant leakage, EMI, etc.	6+	All platforms				Operational life (AO, corrosion, etc.)
Nano-composites	Chemical and physical property enhancements	4-ish	In development or vendor	Weight, cost, customer appeal, greater durability of structure	Reduced qual and cert costs since multiple materials replaced by one	Mfg rate Improve-ments through reduced materials usage	Enhanced adhesion = reduced paint problems; acoustic improve-ments in fairings
3-D woven preforms	For Y joints and other 3-dimensional geometry	4	In development or vendor	Weight and reliability			

Figure 2.2-4. Technology Assessment (2 of 16)—Materials and Processes

Technology	Definition	Current TRL	Example of Boeing Reference/Experience	Value/Benefit and Rationale: Performance (weight, safety, etc.)	Development Cost (DDT&E)	Production Cost	Operation Cost
2. Manufacturing Methods							
Non-autoclave manufacturing methods	For carbon/polymers Scale-up of oven-cure process (1.6)	6+	CAI, A160, SDMD, X-45A, Bird of Prey, X-45C, Proprietary Programs	Weight (part integration; fastener elimination)	Shorter time	No large autoclave for large-size, low-qty parts	Repairability
Autoclave manufacturing methods	Large autoclaves to large (33-ft dia) structures	6+	787 fuselage, Delta IV (now ULA) 5-m fairings	Highest properties = low weight			
Fiber placement methods	Tape/tow/broadgoods placement machines for very high fiber laydown rates	6+	787 fuselage, Delta (now ULA) fairings			Laydown time	
Large (reusable) tooling	Monolithic or breakdown Address large moments of inertia, stability, and structural rigidity of rotating tools for large structures	6+	787 fuselage (high qty)	Accuracy and repeatability = higher allowables		Large size, low qty	
Sandwich (core) manufacturing methods	Sandwich core splicing	6+	Delta (now ULA) foam fairings, Shuttle (HC core) PL doors, airplane sec str, A-160	Reliability			
Resin Infusion manufacturing methods	CAPRI, VARTM, etc.	6+	787 fuselage frames, C-17 gear doors, NASA studies			Large, complex shapes	

Figure 2.2-5. Technology Assessment (3 of 16)—Manufacturing Methods

Technology	Definition	Current TRL	Example of Boeing Reference/Experience	Value/Benefit and Rationale: Performance (weight, safety, etc.)	Development Cost (DDT&E)	Production Cost	Operation Cost
2. Manufacturing Methods							
In-process inspection techniques	More important with larger scales Acceptance methodology	6+	All platforms	Quality/reliability (fewer defects)		Less scrap, repair	
Ultrasonic curing manufacturing methods	Also E-beam curing? Requires specialized material?	4-5	In development or vendor			No autoclave $	
Low-cost (expendable) tooling	Foam and/or low-temp cure epoxy fabric composites. Match with non-autoclave manufacturing methods	6+	A160 helicopter		Shorter tooling build time for low-qty, large, complex parts	Low qty	
Improved assembly methods	Such as self-tooling, reducing imperfections, and guaranteeing adequate tolerance	6+	CAI, (F-35 fwd fus) 787 metrology			Fewer tools	
Inflatable shell manufacturing	Packing, deployment	4-ish	In development or vendor	LV fairing packing efficiency			

Figure 2.2-6. Technology Assessment (4 of 16)—Manufacturing Methods

Technology	Definition	Current TRL	Example of Boeing Reference/Experience	Value/Benefit and Rationale: Performance (weight, safety, etc.)	Development Cost (DDT&E)	Production Cost	Operation Cost
2. Manufacturing Methods							
Bonded assembly	Co-cured, cobonded, secondary	6+	787 stringers (co-cured)	Fastener weight		Assy time	
Bolted assembly	Bolts, rivets, mechanical fasteners	6+	787 fuselage/wing assembly			Optimum part size	Repairability
Molding compound	Also 3D woven for lightly loaded fittings and frames	4-5	787 window frames	Weight			
High temp composites manufacturing	CVD, furnaces	6+	In development or vendor	Weight			
3D reinforcement	Stitching, pinning, weaving, etc., Optional part of infusion str sys	6+	C-17 doors				Durability and DT for longer life and less repair
Grid-stiffened structure manufacturing methods	Trapped rubber and fiber placement process	9	Minotaur payload fairings	Tailored to loads = lower weight		Integrated structure = less labor	

Figure 2.2-7. Technology Assessment (5 of 16)—Manufacturing Methods

Technology	Definition	Current TRL	Example of Boeing Reference/Experience	Value/Benefit and Rationale: Performance (weight, safety, etc.)	Development Cost (DDT&E)	Production Cost	Operation Cost
3. Innovative Design							
Efficient bolted joints between large sections	Optimize Mechanical Fastener Use	6+	787 fuselage barrel and frame) attach, Delta (now ULA) LV inter-stage joints	Weight		Determin-istic assy for less tooling	
Multifunctional designs	Actuation, strength, thermal, radiation, acoustic, etc.)	6+	All platforms, especially spacecraft (702)	Weight			
Sandwich designs	Link with multifunctional structures	6+	All platforms	Weight			
Isogrid/orthogrid designs	Integral stiffeners	6+	Delta (isogrid) fairings and tanks, Minotaur payload fairings	Weight			
Hybrid (metal/composite) structures	GLARE, TiGr, other FMLs for lower cost and longer fatigue life	4-5	787 composite/titanium studies; ARALL on C17 cargo door	Weight			Wear reistance, durability, fatigue life, Impact DT

Figure 2.2-8. Technology Assessment (6 of 16)—Innovative Design

Technology	Definition	Current TRL	Example of Boeing Reference/Experience	Value/Benefit and Rationale: Performance (weight, safety, etc.)	Development Cost (DDT&E)	Production Cost	Operation Cost
3. Innovative Design							
Tailored composites	Tow steered, variable stiffness	6+	787 fuselage Boeing JSF inlet duct	Weight		Less waste	
Primarily bonded structures	Co-cured, cobonded, sec bonded. Limited by size, fail safety	5	Co-cured 787 fuselage hats, ATCAS, CAI	Weight			
Stitched designs	Eliminate most fasteners, benign failure mode	6+	C-17 nose and main LG doors	Weight, safety			Durability
Point load introduction	Fittings (metal/composite), 3-D woven or other out-of-plane reinforcement for complex local loading	6+	Rotorcraft, Shuttle PLBD, Delta (now ULA), 787	Weight			
Inflatables (multifunctional shell, hatches)	Bigelow, gossamer experiments	5	CRV landing airbags, ISAT	Weight			
High temperature engine and heatshield design	Ceramic (C/SiC and C-C) and refractory metal composites	6+	X-37, Shuttle	Weight			
Composite pressure vessels (nonintegral)	Deleted "overwrap" (with or without metal or polymer liner) High pressure (3-5000psi)	6+	Delta (now ULA), Shuttle pressurant tanks	Weight			
Crashworthiness incorporated in design	For Orion hard landing?	6+	Manned rotorcraft (Apache), 787	Safety			

Figure 2.2-9. Technology Assessment (7 of 16)—Innovative Design

Technology	Definition	Current TRL	Example of Boeing Reference/Experience	Value/Benefit and Rationale: Performance (weight, safety, etc.)	Development Cost (DDT&E)	Production Cost	Operation Cost
3. Innovative Design							
Interaction between components	Payload fairings/shroud (acoustics, payload…)	6+	Delta (now ULA), Sea Launch	Weight		Assy and integration	
Integrated TPS, radiation protection	Cooptimization (also MMOD, thermal, EMI, etc.)	6+	SLI, 8-ft tank, Shuttle, ISS (MMOD)	Weight			
Lightweight structure for load transfer	High-efficency space frames, trusses, and shear panels	6+	Delta upper stage truss, payload adapter, Space Telescope metering truss	Weight			
Methods of preventing damage growth	Crack stoppers (discrete feature = SSF design), softening strips	6+	ACT wing (stitching). 787	Safety, Reliability			Operational life
MMOD resistant design	Whipple/multilayer shields, component vulnerability	6+	ISS, Shuttle	Weight, Safety			Operate with damage
Skin-stringer-frame design	Combinations of bonded/bolted stringers and frames	6+	787 fuselage and wing cover, 8-ft tank	Weight, safety			

Figure 2.2-10. Technology Assessment (8 of 16)—Innovative Design

Technology	Definition	Current TRL	Example of Boeing Reference/Experience	Value/Benefit and Rationale: Perfor-mance (weight, safety, etc.)	Devel-opment Cost (DDT&E)	Produc-tion Cost	Operation Cost
4. Analysis, Modeling and Simulation							
Sandwich analysis	For primary structure (not control surfaces)	5	primarily for control surfaces	Weight	Less testing		
Isogrid and orthogrid analysis	Composite, tailored integral stiffening, survivability	6+	Used to size Minotaur fairings. Successfully launched.	Weight	Less testing		
SSF analysis	Optimize SSF structures	6+	787	Weight	Less testing		
Analysis of effects of defects	(E.g., missing stitches, local debonds, porosity	6+	787	Weight	Less testing		
Analysis of highly tailored composites	Typically for aerodynamic wings rotors	6+	787 fuselage skin tailoring	Weight	Less testing		
Simulated test and evaluation	"Virtual test"	4	In development or vendor	Weight	Less physical testing		
Thermo-structural analysis	E.g., CMC hot str. to cold str (e.g., thermally compliant joints)	5	NASP, X-37 Messinger patent 6,042,055	Weight	Less testing		
Failure mechanism/prediction	Include progressive failure methods at RT or extreme temperatures	6+	Shuttle LE, 787	Reliability	Less testing		
Optimization methods	Part of multifunctional and multiscale systems (not just structure, not just macro)	6+	787	Weight	Less testing		

Figure 2.2-11. Technology Assessment (9 of 16)—Analysis, Modeling, and Simulation

Technology	Definition	Current TRL	Example of Boeing Reference/Experience	Value/Benefit and Rationale: Perfor-mance (weight, safety, etc.)	Devel-opment Cost (DDT&E)	Produc-tion Cost	Operation Cost
4. Analysis, Modeling and Simulation							
Fatigue/life prediction	Exploration missions are short term, fatigue-wise	6+	787 (about 50,000 hrs)	Weight	Less testing		
Probabilistic risk assessment —NASA technology	Link up with reliabiltiy and maintainability allocation, link up with MMOD risk assessment	6	Shuttle Upgrade, Delta IV Engine, Delta IV EVBS, Orbital Space Plan	Safety, reliability	Less testing		Less main-tenance
Reliability-based or risk-based design and analysis	Link up with safety factors based on aircraft approach, standardized allowable, optimization methods, and knockdown factor analysis	6	SLI, IR&D, EELV	Weight	Less testing		Less main-tenance
Certification to needed risk or reliability —similar to simulated test and evaluation	Link up with accelerated aging and test methods, certification by analysis, certification by simulation, improved test methods, and postdamage detection and prognostics	5	Accelerated Insertion of Composite Material	Safety, reliability	Less testing		
Risk-based or reliability-based maintenance —similar to fatigue/life prediction	Link with NDE standard, in situ damage detection, and prognostics, structural health monitoring, diagnostics, and prognostics, postdamage reliability prediction, damage tolerance DC&A, in-space/ground repair methods	6	B-1 and C17 Aging Aircraft Risk Assessment	Safety, reliability	Less testing		Less main-tenance

Figure 2.2-12. Technology Assessment (10 of 16)—Analysis, Modeling, and Simulation

Technology	Definition	Current TRL	Example of Boeing Reference/Experience	Value/Benefit and Rationale: Performance (weight, safety, etc.)	Development Cost (DDT&E)	Production Cost	Operation Cost
4. Analysis, Modeling and Simulation							
Hierarchical analysis	Substructuring	6+	All platforms	Weight	Less testing		
Internal and residual stress analysis	Typically limited to thick and/or thermal gradients	5	In development or vendor	Reliability	Less testing		
Scaling and validation	Especially large propellant tanks	5	SSTO, 8-ft tank		Smaller scale = less $		
MMOD impact analysis	Spacecraft kinetic threat survivability and vulnerability assessment (like Bumper)	6+	ISS, Shuttle, CEV Ph 1	Weight, safety	Less testing		
Bonded joint analysis	Optimize bonding, adhesion	6+	All platforms	Weight	Less testing		
Bolted joint analysis	Optimize fastener use	6+	All platforms	Weight	Less testing		
Inflatable structure analysis		4-ish	In development or vendor	Reliability	Difficult ground testing		
Cost analysis	P-BEAT, COSTADE,	5	All platforms	Balance cost with other weight safety and reliability criteria	Develop optimum system with cost credibility		

Figure 2.2-13. Technology Assessment (11 of 16)—Analysis, Modeling, and Simulation

Technology	Definition	Current TRL	Example of Boeing Reference/Experience	Value/Benefit and Rationale: Performance (weight, safety, etc.)	Development Cost (DDT&E)	Production Cost	Operation Cost
5. Design Criteria and Allowables							
Damage tolerance DC&A	Not MMOD; bird strike during launch; operational collisions	6+	ACT wing (stitching), 787, Shuttle	Weight, safety			Operate with damage to reduce maintenance
Radiation protection DC&A	Cosmic ray/thermal protection of humans, electronics, and structural integrity	6+	ISS, Shuttle	Safety and reliability			
MMOD resistant DC&A	Damage tolerance	6+	ISS, SLI (LEO), CEV Phase 1	Weight, safety			
Standardized allowables	Such as MIL-HDBK-17 modifications	6+	All platforms	Weight	Less testing		
Environmental durability DC&A	Use DOE to reduce testing; environmental influence on design	6+	ISS	Weight			Longer life lowers maintenance

Figure 2.2-14. Technology Assessment (12 of 16)—Design Criteria and Allowables

Technology	Definition	Current TRL	Example of Boeing Reference/Experience	Value/Benefit and Rationale: Performance (weight, safety, etc.)	Development Cost (DDT&E)	Production Cost	Operation Cost
5. Design Criteria and Allowables							
Knockdown factors	Develop and justify less conservative factors	6+	787	Weight			
Safety factors based on aircraft approach	Develop and justify more reasonable FSs	6+	787/FARs	Safety			
Develop NDE standards	Design common use composites standards	6+	All platforms			Less inventory	Fewer standards required
Minimum gage specifications	Develop composites standards	6+	787, rotorcraft	Weight			
Bonded joint DC&A	Joint width, thickness, flaw size, etc.	6+	787	Weight			
Bolted joint DC&A	FAA	6+	787	Weight			
Inflatable shell DC&A		4-ish	In development or vendor	Reliability, weight			

Figure 2.2-15. Technology Assessment (13 of 16)—Design Criteria and Allowables

Technology	Definition	Current TRL	Example of Boeing Reference/Experience	Value/Benefit and Rationale: Performance (weight, safety, etc.)	Development Cost (DDT&E)	Production Cost	Operation Cost
6. Development, Quality Assurance and Certification							
Nondestructive inspection methods	C-scan, X-ray, thermo, etc.	6+	All platforms	Reliability		Insp time	
QA to structural performance correlation	Effects of defects	4-ish	In development or vendor	Reliability			
Postdamage reliability prediction	Tested predicted level of accepted damage tolerance	4-ish	In development or vendor	Weight			
In situ damage detection and prognostics	In-flight SHM prognostics = TRL 3	5	DC-XA LH2 tank, X-34 wing, AFRL SOV SHM		Less testing	QA	Lower maint and insp
Structural health monitoring, diagnostics, and prognostics	Ground/flight damage detection; prognostics = TRL 3	5	Delta IV structural proof/qualification testing		Less testing	QA	
Hot spot interrogation	Design with integrated SHM; Establish minimum complexity	5	787 composite damage detection		Less testing	QA	Lower maint and insp
Scaling effects	Identify smallest test scale where full environmental (including in-space) simulation is required	6+	Shuttle stack (1/4 scale dynamic), ISS ground test qual		Subscale or substructuring to reduce cost		

Figure 2.2-16. Technology Assessment (14 of 16)—Development, QA, and Certification

Technology	Definition	Current TRL	Example of Boeing Reference/Experience	Value/Benefit and Rationale: Performance (weight, safety, etc.)	Development Cost (DDT&E)	Production Cost	Operation Cost
6. Development, Quality Assurance and Certification							
Certification by analysis	Also termed qualification by analysis	6+	All platforms	Weight	Less testing		
Certification by simulation	System-level only	4-ish	In development or vendor	Weight	Less testing		
Improved test methods	Bonded, bolted, shell, etc.	6+	787 fuselage panels	Weight	Less testing		
Database development	Multiscale	4-ish	HSR, CAI		Less testing		
Accelerated aging and test methods	LDEF, simulation	4-ish	HSR		Shorter test time		
In-space/ground repair methods	QA function, applies to sandwich, grid, and SSF design concepts	6+	Shuttle LE, 787	Safety		Reduce spares	Operational life
Improved leak detection	O2 and H2 detection ground, ascent, and in space	5	Shuttle aft fuselage	Safety			Reliability

Figure 2.2-17. Technology Assessment (15 of 16)—Development, QA, and Certification

Technology	Definition	Current TRL	Example of Boeing Reference/Experience	Value/Benefit and Rationale: Performance (weight, safety, etc.)	Value/Benefit and Rationale: Development Cost (DDT&E)	Value/Benefit and Rationale: Production Cost	Value/Benefit and Rationale: Operation Cost
7. Design for Threat/Environment							
MMOD (lunar/LEO)	Impact survivability	6+	ISS, SLI (LEO)	Weight, safety			
Lunar dust	Contamination, also coatings	3-ish	In development or vendor				Reliability
Aging in lunar and space environment	Also in deep space environment	4-ish	Satellites (702, etc.) bus and solar arrays, ISS, MISSE	Reliability			Operational life
Static charge	(On Earth or Moon)	6+	Satellites (702, etc.)	Reliability			Operational life
Thermal cycling	Lunar polar extreme	6+	HSR, Satellites, 8-ft tank	Reliability			Operational life
Radiation	Cosmic, solar, etc.	6+	ISS, Satellites (702, etc.)	EMI/EMC, safety			Operational life
Noise	Cryofoam, MLI, acoustic blankets (shrouds)	6+	All platforms	Cryo, high temp, LEO			
Toxicity and outgassing	VOCs	6+	Satellites (702, etc.)	Contamination			

Figure 2.2-18. Technology Assessment (16 of 16)—Design for Threat/Environment

2.3 Individual Technology Development Plan

The third part of the technology assessment comprises the individual suggested development plans of all assessed technologies (Figure 2.3-1 through 2.3-15). At least 30 Boeing subject matter experts were solicited to obtain a few important development activities. Some development plans were augmented, substantiated, or obtained from the public domain literature, which is referenced in Appendix A.

Technology	Definition	Development Plan Options
1. Materials and Processes		
Advanced autoclave cure M&P	Includes Ep, toughened epoxies (including those for cryo tanks), BMI, PI. Process = cure cycle	1. Use higher operating temperature toughened Ep and BMI with lower cure temp and pressure 2. Use higher operating temp thermoplastics with lower consolidation temp and pressure 3. Improve hydrogen impermeability for cryotanks 4. Employ thin-ply laminates (ref. Tsai)
Advanced non-autoclave cure M&P	Primarily Epoxy (including those for cryo tanks)	1. Develop material and process with across-the-board autoclave-like properties 2. Acquire epoxies with a lower cure temp and a higher working temp
Infusion polymer M&P	VARTM, CAPRI, etc.	1. Acquire higher temperature resins 2. Develop higher modulus fiber reinforcement 3. Improve rapid preforming
Sandwich (core) M&P	Honeycomb, foam, combined, various materials	1. Design a multifunctional, multicomponent core with strength, thermal, radiation, self-repair, etc., properties 2. Incorporate sandwich panel purge/vent system integration 3. Use low permeability co-cured sandwich facesheets
Inflatable structure M&P	Multifunctional fabrics for pressure, radiation, MMOD protection, etc.	1. Evaluate a TransHab-type MMOD protection concept with potential Constellation options; impact data is available
High-temperature composites M&P	Carbon, ceramic, and refractory metal composites for very high temperature engine apps and reentry (heatshield)	1. Develop/characterize one C-C system with balanced processibility, operating temperature, properties, integration, operability, and cross-cutting applicability (including other non-Exploration NASA missions) 2. Develop one well-characterized C-SiC system

Figure 2.3-1. Technology Development Plan (1 of 15)—Materials and Processes

Technology	Definition	Development Plan Options
1. Materials and Processes		
Molding compounds M&P	For fittings, padups, and engine parts (e.g., HexMC)	1. Adapt BCA MCs for space apps
Bonded joining M&P (adhesives)	Co-cure, co-bond, and secondary Many variants, highly mature. Many industries	1. Develop open air plasma treatment for lower cost and cycle time for cobond/secondary bond applications 2. Develop inspection process for surface preparation prior to secondary bonding 3. Scale-up and validate surface energy-based methods developed in CAI program 4. Improve joint design/durability/damage tolerance for cryotanks 5. Develop bonded joint NDE methods (correlate to strength)
Bolted joining M&P (fasteners)	Permanent and removable types	1. Implement low-cost fasteners for composites
Coatings and sealants	For galvanic and other corrosion, propellant leakage, EMI, etc.	1. Develop multifunctional, multicomponent coatings (including nano) with thermal, radiation, repair, etc., properties 2. Implement more durable conductive thermal control coatings 3. Use a chrome-free cryogenic primer for LO2/LH2 cryotanks 4. Develop low-cost conductive thermal control coatings (silicone resin/zinc oxide) for space applications
Nano-composites	Chemical and physical enhancements	1. Multifunctional, multicomponent coatings with (electical, thermal, radiation, repair, acoustic,mechanical, etc., properties (ref. Rice University/NASA URETI project)
3-D woven preforms	For Y joints and other 3-dimensional geometry	1. Use 3-D woven ring frames 2. Integrate woven preforms with resin infusion M&P

Figure 2.3-2. Technology Development Plan (2 of 15)—Materials and Processes

Technology	Definition	Development Plan Options
2. Manufacturing Methods		
Non-autoclave manufacturing methods	For Gr/Ep Scale-up of oven-cure process	1. Develop material and process with across-the-board autoclave-like properties
Autoclave manufacturing methods	For structures as large as 33-ft dia	1. Define large-scale autoclave (10 m) design, fabrication, operation, and cost
Fiber placement methods	Tape/tow/broadgoods placement machines for very high fiber laydown rates	1. Increase material laydown rates with multiple head processes for larger scale parts 2. Trade hybrid processes that mix 3 in to 12 in tape with 1/8 to 1/2 in tow for optimal rates 3. Optimize machine configuration for 5 m parts and for 10 m parts (Ares V) 4. Design low-cost, right-sized fiber placement process
Large (reusable) tooling	Monolithic or breakdown. Address large moments of inertia, stability and structural rigidity of rotating tools for large structures	1. Develop tooling materials and fabrication for large-scale (10 m) cryotanks (optimum number of parts and joints) 2. Identify interaction of mass, inertia, and deflection for large scale part on production equipment and autoclave processes
Sandwich (core) manufacturing methods	Sandwich core machining, handling, cleaning, splicing, etc.	1. Implement single-cure for facesheets and core (of various types) 2. Consider all edge details and inserts
Resin Infusion	CAPRI, VARTM, etc	1. Scale-up for integrally reinforced and complex-geometry parts 2. Validate cost/weight savings versus other approaches
In-process inspection techniques	more important with larger scales acceptance methodology	1. Promote in-process inspection —link up with nondestructive inspection methods and QA to structural performance methods
Ultrasonic curing M&P	also E-beam curing? Requires specialized material?	No recommendation

Figure 2.3-3. Technology Development Plan (3 of 15)—Manufacturing Methods

Technology	Definition	Development Plan Options
2. Manufacturing Methods		
Low-cost (expendable) tooling	Foam and/or low-temp cure epoxy fabric composites	1. Develop the capability of tooling epoxies with a low cure temperature and a high working temperature.
Improved assembly methods	such as self-tooling, reducing imperfections and guaranteeing adequate tolerance	1. Promote determinant assembly (ref. Factory of the Future) 2. Use laser metrology (ref. Cramer)
Inflatable shell manufacturing	Packing, deployment,	No recommendation
Bonded assembly	co-cured, co-bonded, secondary	1. Promote a balanced use of bonding and bolting methods
Bolted assembly	bolts, rivets, mechanical fasteners	1. Adapt 787 technology for low production quantity (less automated)
Molding compound	For lightly loaded fittings and frames	1. Develop composite molding for highly loaded fittings and frames
High temp composites manufacturing	CVD, furnaces	No recommendation
3D reinforcement	Uses stitching, pinning, weaving, etc. Optional part of infusion str sys	1. Specify 3D woven fabrics for high-load fittings 2. Implement stitching for high-damage prone applications
Grid-stiffened structure manufacturing methods	Trapped rubber and fiber placement process	1. Scale-up to moderate-scale applications 2. Develop flyaway (foam) tooling 3. Demo subsystem integration (attachment) 4. Develop low-cost, reusable compaction tooling 5. Develop high-rate grid fabrication processes

Figure 2.3-4. Technology Development Plan (4 of 15)—Manufacturing Methods

Technology	Definition	Development Plan Options
3. Innovative Design		
Efficient bolted joints between large sections	Optimize mechanical fastener use	1. Develop an all-composite bolted joint (replace Al or Ti fitting or ring frame)
Multifunctional designs	Actuation (SMAs) (strength, thermal, radiation, acoustic, etc.)	1. Incorporate MMOD-radiation-acoustic protection in structure for long-duration space applications (ref. ISS) 2. Implement active vibration control for LV payloads
Sandwich designs	Multifunctional structures, incorporate shielding, TPS in laminate	1. Minimize weight penalty of openings and joints combine core 2. Develop sandwich for failure-redundant propellant tank with multifunctional core thermal, MMOD, acoustic
Isogrid/orthogrid	Composite	1. Increase the strength of blade-to-skin attachment
Hybrid (metal/composite)	GLARE, TiGr, other FMLs for lower cost and longer fatigue	1. Develop hybrids for higher-efficiency bolted joints (ref. Fink)
Tailored composites	Tow steered, variable stiffness	1. Apply fiber steering to large structures 2. Identify methods of controlling and analyzing steering 3. Perform mechanical testing to validate modeling results 4. Determine weight savings for various structure types
Primarily bonded structures	Co-cured, cobonded, sec bonded. Limited by size, fail safety	1. Develop/validate Z-reinforced cobonded/cocured joints for fail safety (composite-composite and metal-composite joints) 2. Balance bolted and bonded approaches
Stitched designs	Eliminate most fasteners, benign failure mode	1. Evaluate stitched designs under MMOD impact
Point load introduction	Fittings (metal/composite), 3-D woven or other out-of-plane reinforcement for complex local loading	1. Use composite fittings with molding compounds or resin infusion

Figure 2.3-5. Technology Development Plan (5 of 15)—Innovative Design

Technology	Definition	Development Plan Options
3. Innovative Design		
Inflatables (multi-functional shell, hatches)	Bigelow, gossamer experiments	No recommendation
High temperature engine and heatshield design	Ceramic (C/SiC and C-C) and refractory metal composites	1. Evaluate X-37 C-SiC development for Orion heatshield
Composite pressure vessels (nonintegral)	Deleted "overwrap" (with or without metal or polymer liner) high pressure (3-5000psi)	1. Develop tanks with and without polypropylene liner for (1) short-term, then (2) long-term, storage of cryogenic fluids or gaseous He
Crashworthiness incorporated in design	For Orion hard landing?	No recommendation
Interaction between components	Payload fairings/shroud (acoustics issues, payload, etc.)	No recommendation
Integrated TPS, radiation protection	Co-optimization (also MMOD, thermal, EMI, etc.)	1. Implement sandwich (with septum) designs that enable multi-layer MMOD protection and leak redudancy 2. Promote the dentification and prioritization of material performance for MMOD and radiation protection emphasizing materials that provide best for both—particularly in fiber or resin selection for composites; establish a standard or materials requirement template for Constellation use

Figure 2.3-6. Technology Development Plan (6 of 15)—Innovative Design

Technology	Definition	Development Plan Options
3. Innovative Design		
Lightweight structure for load transfer	High-efficency space frames, trusses, and shear panels	1. Develop truss structure with integral and/or composite end fittings
Methods of preventing damage growth	Crack stoppers (discrete feature = SSF design), softening strips	1. Apply stitching to local damage-prone areas only
MMOD resistant design	Whipple/multilayer shields, component vulnerability	1. Investigate further development of the Apollo hypervelocity impact database on honeycomb cell sizing to minimize channeling effects of honeycomb core; would apply to composite or metallic honeycomb. (required for honeycomb sandwich use) 2. Work to mitigate the tendency of composites to delaminate and debond upon hypervelocity impact. (required for composite use) 3. Determine the maximum / optimum height for honeycomb sandwiches; for MMOD, more space is better (sandwich improvement, i.e., lower priority than 1 and 2)
Skin-stringer-frame design	Combinations of bonded/bolted stringers and frames	1. Minimize fastened parts for minimum weight 2. Design for secondary bonding (with minimum fasteners) of frame caps or other buildup

Figure 2.3-7. Technology Development Plan (7 of 15)—Innovative Design

Technology	Definition	Development Plan Options
4. Analysis, Modeling, and Simulation		
Sandwich analysis	For primary structure (not control surfaces)	1. Improve analytical techniques for predicting disbond and crack arrestment in sandwich structures
Isogrid/orthogrid analysis	Composite, tailored integral stiffening, survivability	1. Automate analysis procedure
Skin-stringer-frame analysis	Optimize SSF structures	1. Analyze stiffener terminations and discontinuities
Analysis of effects of defects	Such as missing stitches, local debonds, porosity	1. Adapt commercial aircraft defect analysis BOK
Analysis of highly tailored composites	Typically for aerodynamic wings rotors	1. Study the cost and benefit of highly-tailored composite structures
Simulated test and evaluation	"Virtual test"	1. Develop simulations to complement test and evaluation efforts and to lessen the need for repetitive testing
Thermo-structural analysis	Hot (CMC)-to-cold str (e.g., thermally compliant joints)	1. Adapt X-37 lessons learned to Orion (and other) heatshield
Failure mechanism/prediction	Include progressive failure methods at RT or extreme temperatures	1. Analyze failure modes 2. Develop a database
Optimization methods	Part of multifunctional and multiscale systems (not just structure or macro)	1. Develop multifactor (performance and cost) and multifunctional (structure, radiation, MMOD, etc.) optiimization techniques
Fatigue/life prediction	Exploration missions are short term, fatigue-wise	1. Characterize environmental (e.g., thermal cycling) degradation

Figure 2.3-8. Technology Development Plan (8 of 15)—Analysis, Modeling, and Simulation

Technology	Definition	Development Plan Options
4. Analysis, Modeling, and Simulation		
Probabilistic risk assessment	Link up with reliabiltiy and maintainability allocation; link up with MMOD risk assessment	1. Evaluate, balance level of engineering data available to support PRAs: MMOD is usually fairly detailed since design is statistically driven; others often are less probabilistic in nature 2. Develop common data requirements for Constellation program to use in data set acquisition and development 3. Document data confidence levels
Reliability-based or risk-based analysis	Link up with safety factors based on aircraft approach, standardized allowable, optimization methods, and knockdown factor analysis	1. Develop a database to support reliability-based design and analysis 2. Link up with factors of safety based on an aircraft approach 3. Develop standardized allowables, optimization methods, and knockdown factor analysis
Certification to needed risk or reliability - similar to Simulated test and evaluation	Link up with accelerated aging and test methods, certification by analysis, certification by simulation,	1. Develop database to support probabilistic certification 2. Link up with Accelerated aging and test methods, certification by analysis, certification by simulation, improved test methods, and postdamage detection and prognostics.
Risk-based or reliability-based maintenance —similar to fatigue/life prediction	Link up with NDE standard, in situ damage detection and prognostics, structural health monitoring, diagnostics, and prognostics, postdamage reliability prediction, damage tolerance DC&A, in-space/ground repair methods	1. Develop a database to support reliability-based maintenance program 2. Link up with NDE standard, in situ damage detection and prognostics, structural health monitoring, diagnostics, and prognostics, postdamage reliability prediction, damage tolerance DC&A, in-space/ground repair methods
Hierarchical analysis	Substructuring	1. Develop the hierarchical analysis of structural systems 2. Link up with nanotech efforts

Figure 2.3-9. Technology Development Plan (9 of 15)—Analysis, Modeling, and Simulation

Technology	Definition	Development Plan Options
4. Analysis, Modeling, and Simulation		
Internal and residual stress analysis	Typically limited to thick and/or thermal gradients	1. Minimize residual stresses through cure cycle optimization
Scaling and validation	Especially large propellant tanks	1. Implement scaling and validation of scaled composites (ref. esp. Johnson, Morton, Kellas, and Jackson)
MMOD impact analysis	Spacecraft kinetic threat survivability and vulnerability asessment (like Bumper)	1. Automate the transfer of CAD models into Bumper-compatible formats 2. Continue algorithm development —the shadowing algorithm in Bumper has restrictions on relative size of elements; work has been done on ISS to develop new algorithm to remove this restriction (models from #1 tend to have significant variation in element sizing) 3. Improve body of knowledge on failure criteria as it is a significant source of impact analysis error. Need to plan for agency/industry wide development of common database; on ISS we're trying to obtain residual asset hardware for impact testing with some success; this approach needs to be expanded
Bonded joint analysis	Optimize bonding, adhesion	1. Apply new 3D parametric FEM tools to bonded joints 2. Enable inclusion of nonlinear behavior and both peel and shear stress in bondline, and be able to predict both cohesive failures in adhesive as well as failures in composite adherends in one integrated anlysis model 3. Use Strain Invariant Failure Theory for damage initiation and growth prediction in both adhesive layer and surrounding composite plies 4. Use new fracture interface element methods for damage growth predictions. Analytical tools exist, but need to measure appropriate materials properties and validate across a range of joint designs and environments
Bolted joint analysis	Optimize fastener use	1. Incorporate thermal effects, seals and leakage
Inflatable structure analysis		No recommendation
Cost analysis	P-BEAT, COSTADE	1. Validate tools with hardware design, build, and test

Figure 2.3-10. Technology Development Plan (10 of 15)—Analysis, Modeling, and Simulation

Technology	Definition	Development Plan Options
5. Design Criteria and Allowables		
Damage tolerance DC&A	Not MMOD; bird strike during launch; operational collisions	1. Characterize acceptable and reasonable levels and likelihood of damage for complete life cycle (with and without on-board SHM)
Radiation protection DC&A	Cosmic ray/thermal protection of humans, electronics, and structural integrity	1. Characterize materials evaluation/assessment; particle transport and dose attenuation in lunar environment
MMOD resistant DC&A	Damage tolerance	1. Develop improved failure critera, mainly through impact testing; including database of all performed nonproprietary impact tests and developed equations (ref. JSC good database) 2. Document confidence levels in the data
Standardized allowables	Such as MIL-HDBK-17 modifications	1. Develop and standardize body of knowledge on allowables
Environmental durability DC&A	Such as DOE to reduce testing. Influence of environment on design	1. Empirically establish environmental effects on most likely (cross-cutting) structural systems

Figure 2.3-11. Technology Development Plan (11 of 15)—Design Criteria and Allowables

Technology	Definition	Development Plan Options
5. Design Criteria and Allowables		
Knockdown factors	Develop and justify less conservative factors	1. Validate knockdown factors with probabilistic analysis
Safety factors based on aircraft approach	Develop and justify more reasonable FSs	1. Trade the levels of test, analysis, and allowable safety factors (commercial and military AC can amortize extensive testing and analysis) 2. Evaluate the use of qualified commercial or military aircraft systems with FAA-approved factors of safety
Develop NDE standards	Design common use composites standards	1. Develop standards for NDE during product development
Minimum gage specifications	Develop composites standards	1. Evaluate extra-thin prepreg tape while considering all other criteria
Bonded joint DC&A	Joint width, thickness, flaw size, etc.	1. Adapt FAA criteria for space applications
Bolted joint DC&A	FAA	1. Adapt FAA criteria for space applications
Inflatable shell DC&A		No recommendation

Figure 2.3-12. Technology Development Plan (12 of 15)—Design Criteria and Allowables

Technology	Definition	Development Plan Options
6. Development, Quality Assurance, and Certification		
Nondestructive inspection methods	C-scan, X-ray, thermo, etc.	1. Scale-up and validate the laser-based inspection device (LBID) for interrogating the strength of bonded joints 2. Develop ultrasonic phased-array technology
QA to structural performance correlation	Effects of defects	1. Scale-up and validate LBID for interrogating the strength of bonded joints
Postdamage reliability prediction	Tested predicted level of accepted damage tolerance	1. Develop postdamage reliability prediction methods to determine availability versus given flight risks 2. Link-up with damage tolerance design criteria and allowables
In situ damage detection and prognostics	In-flight SHM prognostics = TRL 3	1. SHM reasoner —develop an integrated SHM reasoner that will integrate multisensor systems to detect, diagnose, and report structural health information for supporting mission planning and maintenance actions 2. Adapt flight system testing and qualification to in situ methods
Structural health monitoring, diagnostics, and prognostics	Ground damage detection prognostics = TRL 3	1. Develop diagnostic criteria for various damage/failure modes that are of concern to structural test and production 2. Develop tools and processes for structural health monitoring, diagnostics, and prognostics
Hot spot interrogation	Design with integrated SHM and minimum overall complexity	1. Develop enhanced diagnostic capability with a minimum complexity added to the structures
Scaling effects	Identify smallest test scale where full environmental (including in-space) simulation is required	1. Analytically model and experimentally verify the scaling of large cryotank structures

Figure 2.3-13. Technology Development Plan (13 of 15)—Development, QA, and Certification

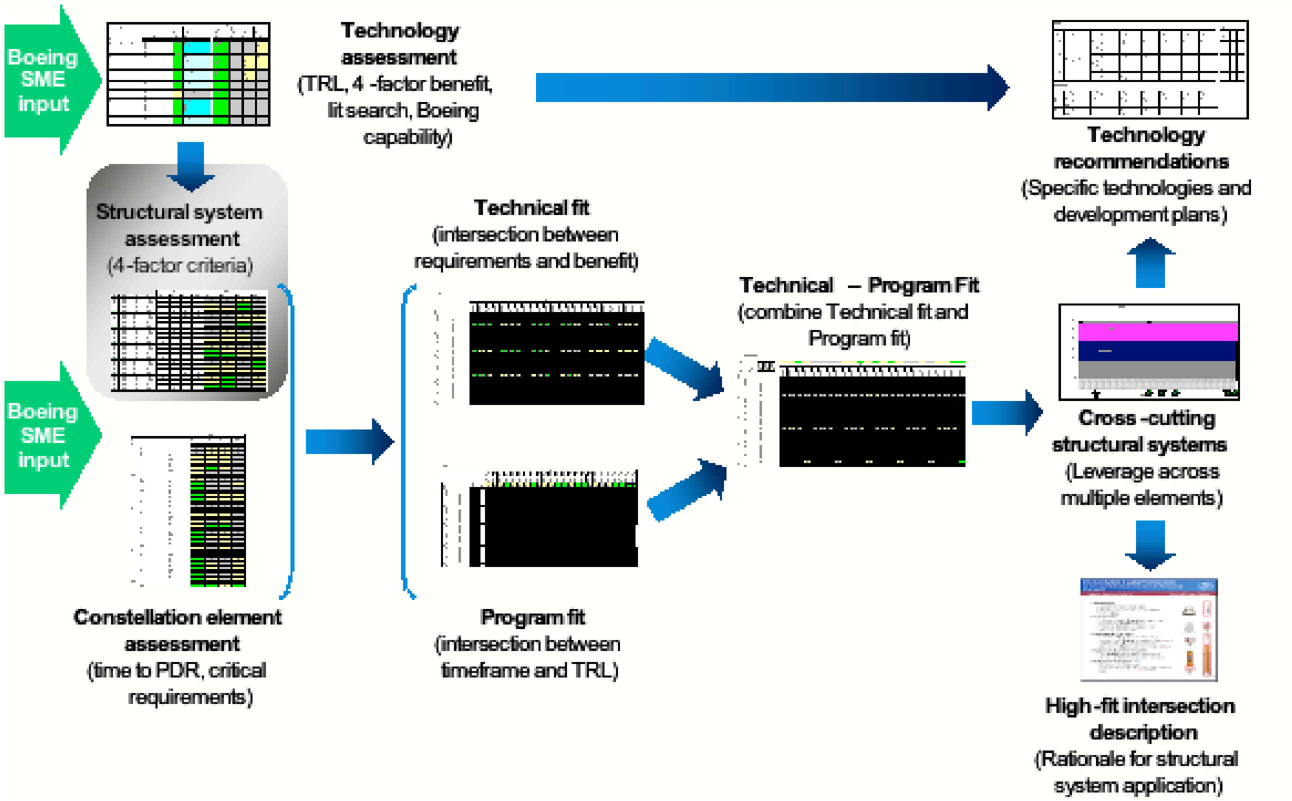
Technology	Definition	Development Plan Options
6. Development, Quality Assurance, and Certification		
Certification by analysis	Also termed qualification by analysis	1. Assess probabilistic certification methodology (ref. Han-Pin Kan)
Certification by simulation	System-level only	1. Develop simulation methods for certification of flight structures esp. for uninhabited vehicles
Improved test methods	Bonded, bolted, shell, etc.	1. Standardize MMOD certification; currently variations exist between programs that produce nontrivial cost and weight impacts on certification
Database development	Multiscale	1. Promote the development of a certification body of knowledge (BOK) and database 2. Link up with the adaptation of commercial aircraft BOK for the certification of composite airstructures
Accelerated aging and test methods	LDEF, simulation	1. Assess probabilistic aging method (ref. Torng) 2. Review HSR methods
In-space/ground repair methods	QA function; applies to sandwich, grid, and SSF design concepts	1. Investigate self-healing methods
Improved leak detection	O2 and H2 detection ground, ascent, and in space	1. Develop fiber-optic sensors for lightweight and higher reliability 2. Develop noncontact leak detectors

Figure 2.3-14. Technology Development Plan (14 of 15)—Development, QA, and Certification

Technology	Definition	Development Plan Options
7. Design for Threat/Environment		
MMOD (lunar/LEO)	Impact survivability	1. Develop ultra-high-speed (15 - 20 km/sec) launch capability to characterize meteor impact effects; three-stage light gas guns are under development, but not "production"; integrate Navy's development work with rail guns for weaponry and general increases in materials technology (ability to withstand high rail contact pressures during launch at higher velocities) may have enabled technology
Lunar dust	Contamination, also coatings	1. Incorporate NASA Glenn antidust coatings for lunar and Mars dust —a coating of Americium-241 paint to neutralize the electrostatic charge on the dust particles 2. Repeat LDEF on lunar surface or at LLO
Aging in lunar and space environment	Also in deep space environment	1. Repeat LDEF on lunar surface or at LLO
Static charge	(On Earth or Moon)	1. Study static charge mitigation in structures for both dust repulsion and the management of ESD risks to life and electronics
Thermal cycling	Lunar polar extreme	1. Repeat LDEF on lunar surface or at LLO
Radiation	Cosmic, solar, etc.	1. Radiation effects on electronics parts using lunar LDEF
Noise	Cryofoam, MLI, acoustic blankets (shrouds)	1. Use multifunctional sandwich structures
Toxicity and outgassing	VOCs	1. Repeat LDEF on lunar surface or at LLO

Figure 2.3-15. Technology Development Plan (15 of 15)—Design for Threat/Environment

3.0 STRUCTURAL SYSTEM ASSESSMENT



3.1 Definition of Structural Systems

The first part of this section is a definition of a structural system, a fundamental concept used in this study. The technologies evaluated in this study are organized into sets termed structural systems. A structural system consists of a number of unique technologies and selected common technologies (Figure 3.1-1). The study assessment evaluates 24 rigid shell structural systems with respect to the Constellation elements. In addition, two joint structural systems are defined and become an integral part of the technology recommendations. There are also a set of common technologies that apply equally to all rigid shell and joint structural systems.

A typical composite structural system consists of three constituent types—material, design concept, and manufacturing method (Figure 3.1-2). A few major options for each constituent type were selected in this assessment. Material options include lower performance and cost Gr/Ep, and higher performance and cost Gr/Ep Fabrication methods include fiber placement (includes filament winding), Resin infusion, and hand layup. Design concepts include skin-stringer-frame, iso/orthogrid, sandwich, and monocoque. Given these nine constituents, there are 24 possible structural systems.

Figures 3.1-3 through 3.1-8 describe the unique technologies associated with each of the 24 rigid shell structural systems. Each structural system has a three-component abbreviation as defined on the right side of the figures. For example, structural system 1 comprises a relatively lower performance and cost composite material, fiber placement and non-autoclave curing manufacturing, and skin-stringer-frame design and analysis. This structural system, like all of the other systems, also requires many of the Common technologies listed previously that are associated with the categories of Design Criteria and Allowables; Development, QA, and Certification; and Design for Threat/environment. Structural system 1 is abbreviated LoMat-Fiber-SSF.

Joint structural systems consist of a set of technologies with the same seven categories as for the rigid shell structural systems (Figure 3.1-9). The bonded joint structural system consists of adhesives M&P, bonded assembly manufacturing, primarily bonded structures design, and bonded joint analysis technology. The Design Criteria, Development, and Threat categories include a number of common technologies, the specific technologies depending on the particular Constellation application. A similar definition applies to the bolted joint structural system.

NASA provided a list of technologies early in the study period. Many of those technologies are necessary for any rigid shell or joint structural system. As such, these common technologies are aggregated in Figure 3.1-10 and are an essential part of any future development program, regardless of which unique shell or joint structural system is selected.

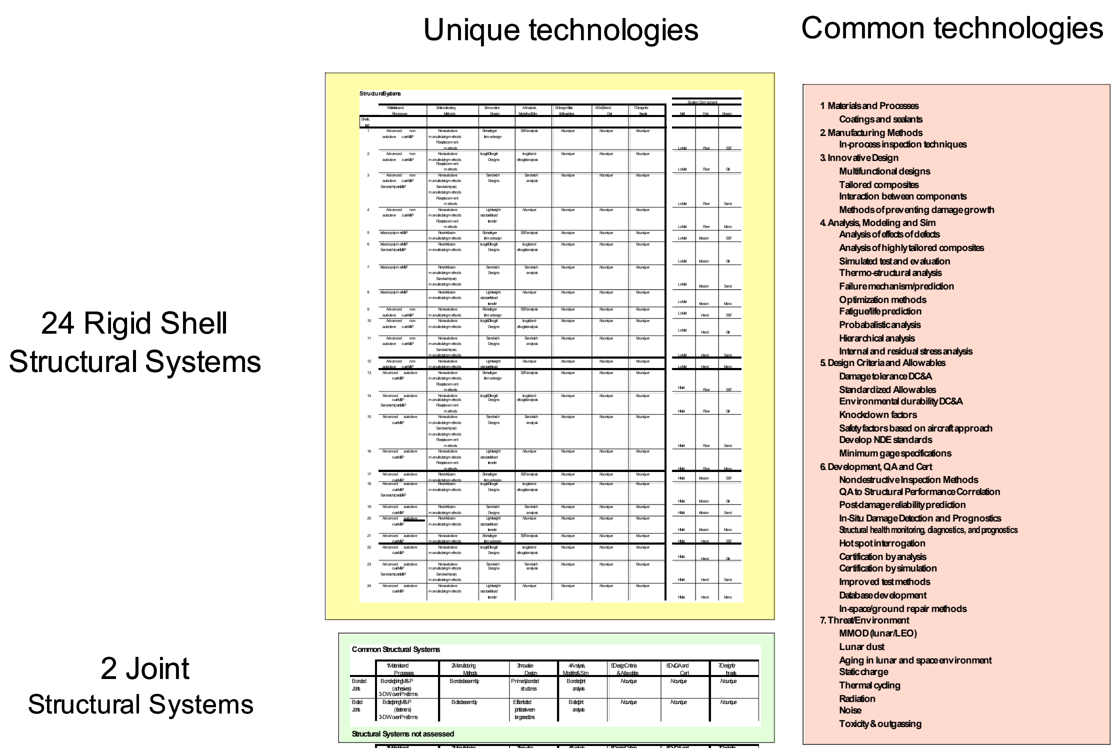


Figure 3.1-1. Structural Systems—Overview

	Constituent Type								
	1. Materials and Processes		2. Manufacturing Methods			3. Innovative Design			
	Material System		Fabrication			Design			
Structural System	Low Perf and Cost	High Perf and Cost	Fiber Placement	Resin Infusion	Hand Layup	SSF	Iso/ Orthogrid	Sandwich	Monocoque
1	■		■			■			
2	■		■				■		
3	■		■					■	
4	■		■						■
5	■			■		■			
6	■			■			■		
7	■			■				■	
8	■			■					■
9	■				■	■			
10	■				■		■		
11	■				■			■	
12	■				■				■
13		■	■			■			
14		■	■				■		
15		■	■					■	
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17		■		■		■			
18		■		■			■		
19		■		■				■	
20		■		■					■
21		■			■	■			
22		■			■		■		
23		■			■			■	
24		■			■				■

Figure 3.1-2. 24 Structural systems organize a wide range of related structures technologies.

Shells, Rigid	1. Materials and Processes	2. Manufacturing Methods	3. Innovative Design	4. Analysis, Modeling, and Simulation	5. Design Criteria and Allowables	6. Develop-ment, QA, and Certification	7. Design for Threats	System Component: Material	Fab	Design
1	Advanced non-autoclave cure M&P	Non-autoclave manufacturing methods Fiber placement methods	Skin-stringer-frame design	SSF analysis	*No unique (Common)*	*No unique (Common)*	*No unique (Common)*	LoMat	Fiber	SSF
2	Advanced non-autoclave cure M&P	Non-autoclave manufacturing methods Fiber placement methods	Isogrid/ orthogrid designs	Isogrid and orthogrid analysis	*No unique (Common)*	*No unique (Common)*	*No unique (Common)*	LoMat	Fiber	Grid
3	Advanced non-autoclave cure M&P Sandwich (core) M&P	Non-autoclave manufacturing methods Sandwich (core) manufacturing methods Fiber placement methods	Sandwich designs	Sandwich analysis	*No unique (Common)*	*No unique (Common)*	*No unique (Common)*	LoMat	Fiber	Sand
4	Advanced non-autoclave cure M&P	Non-autoclave manufacturing methods Fiber placement methods	Lightweight structure for load transfer	*No unique (Common)*	*No unique (Common)*	*No unique (Common)*	*No unique (Common)*	LoMat	Fiber	Mono

Figure 3.1-3. Rigid Shell Structural Systems (1 of 6)

Shells, Rigid	1. Materials and Processes	2. Manufacturing Methods	3. Innovative Design	4. Analysis, Modeling, and Simulation	5. Design Criteria and Allowables	6. Develop-ment, QA, and Certification	7. Design for Threats	System Component: Material	System Component: Fab	System Component: Design
5	Infusion polymer M&P	Resin Infusion manufacturing methods	Skin-stringer-frame design	SSF analysis	*No unique (Common)*	*No unique (Common)*	*No unique (Common)*	LoMat	Infusion	SSF
6	Infusion polymer M&P Sandwich (core) M&P	Resin Infusion manufacturing methods	Isogrid/ orthogrid designs	Isogrid and orthogrid analysis	*No unique (Common)*	*No unique (Common)*	*No unique (Common)*	LoMat	Infusion	Grid
7	Infusion polymer M&P	Resin Infusion manufacturing methods Sandwich (core)	Sandwich designs	Sandwich analysis	*No unique (Common)*	*No unique (Common)*	*No unique (Common)*	LoMat	Infusion	Sand
8	Infusion polymer M&P	Resin Infusion manufacturing methods	Lightweight structure for load transfer	*No unique (Common)*	*No unique (Common)*	*No unique (Common)*	*No unique (Common)*	LoMat	Infusion	Mono

Figure 3.1-4. Rigid Shell Structural Systems (2 of 6)

Shells, Rigid	1. Materials and Processes	2. Manufacturing Methods	3. Innovative Design	4. Analysis, Modeling, and Simulation	5. Design Criteria and Allowables	6. Develop-ment, QA, and Certification	7. Design for Threats	System Component: Material	System Component: Fab	System Component: Design
9	Advanced non-autoclave cure M&P	Non-autoclave manufacturing methods	Skin-stringer-frame design	SSF analysis	*No unique (Common)*	*No unique (Common)*	*No unique (Common)*	LoMat	Hand	SSF
10	Advanced non-autoclave cure M&P	Non-autoclave manufacturing methods	Isogrid/ orthogrid designs	Isogrid and orthogrid analysis	*No unique (Common)*	*No unique (Common)*	*No unique (Common)*	LoMat	Hand	Grid
11	Advanced non-autoclave cure M&P	Non-autoclave manufacturing methods Sandwich (core) manufacturing methods	Sandwich designs	Sandwich analysis	*No unique (Common)*	*No unique (Common)*	*No unique (Common)*	LoMat	Hand	Sand
12	Advanced non-autoclave cure M&P	Non-autoclave manufacturing methods	Lightweight structure for load transfer	*No unique (Common)*	*No unique (Common)*	*No unique (Common)*	*No unique (Common)*	LoMat	Hand	Mono

Figure 3.1-5. Rigid Shell Structural Systems (3 of 6)

Shells, Rigid	1. Materials and Processes	2. Manufacturing Methods	3. Innovative Design	4. Analysis, Modeling, and Simulation	5. Design Criteria and Allowables	6. Develop-ment, QA, and Certification	7. Design for Threats	System Component: Material	System Component: Fab	System Component: Design
13	Advanced autoclave cure M&P	Autoclave manufacturing methods, Fiber placement methods	Skin-stringer-frame design	SSF analysis	*No unique (Common)*	*No unique (Common)*	*No unique (Common)*	HiMat	Fiber	SSF
14	Advanced autoclave cure M&P Sandwich (core) M&P	Autoclave manufacturing methods Fiber placement methods	Isogrid/ orthogrid designs	Isogrid and orthogrid analysis	*No unique (Common)*	*No unique (Common)*	*No unique (Common)*	HiMat	Fiber	Grid
15	Advanced autoclave cure M&P	Autoclave manufacturing methods Sandwich (core) manufacturing methods Fiber placement methods	Sandwich designs	Sandwich analysis	*No unique (Common)*	*No unique (Common)*	*No unique (Common)*	HiMat	Fiber	Sand
16	Advanced autoclave cure M&P	Autoclave manufacturing methods Fiber placement methods	Lightweight structure for load transfer	*No unique (Common)*	*No unique (Common)*	*No unique (Common)*	*No unique (Common)*	HiMat	Fiber	Mono

Figure 3.1-6. Rigid Shell Structural Systems (4 of 6)

Shells, Rigid	1. Materials and Processes	2. Manufacturing Methods	3. Innovative Design	4. Analysis, Modeling, and Simulation	5. Design Criteria and Allowables	6. Develop-ment, QA, and Certification	7. Design for Threats	System Component: Material	Fab	Design
17	Advanced autoclave cure M&P	Resin Infusion manufacturing methods	Skin-stringer-frame design	SSF analysis	*No unique (Common)*	*No unique (Common)*	*No unique (Common)*	HiMat	Infusion	SSF
18	Advanced autoclave cure M&P Sandwich (core) M&P	Resin Infusion manufacturing methods	Isogrid/ orthogrid designs	Isogrid and orthogrid analysis	*No unique (Common)*	*No unique (Common)*	*No unique (Common)*	HiMat	Infusion	Grid
19	Advanced autoclave cure M&P	Resin Infusion manufacturing methods	Sandwich designs	Sandwich analysis	*No unique (Common)*	*No unique (Common)*	*No unique (Common)*	HiMat	Infusion	Sand
20	Advanced autoclave cure M&P	Resin Infusion manufacturing methods	Lightweight structure for load transfer	*No unique (Common)*	*No unique (Common)*	*No unique (Common)*	*No unique (Common)*	HiMat	Infusion	Mono

Figure 3.1-7. Rigid Shell Structural Systems (5 of 6)

Shells, Rigid	1. Materials and Processes	2. Manufacturing Methods	3. Innovative Design	4. Analysis, Modeling, and Simulation	5. Design Criteria and Allowables	6. Develop-ment, QA, and Certification	7. Design for Threats	System Component: Material	Fab	Design
21	Advanced autoclave cure M&P	Autoclave manufacturing methods	Skin-stringer-frame design	SSF analysis	*No unique (Common)*	*No unique (Common)*	*No unique (Common)*	HiMat	Hand	SSF
22	Advanced autoclave cure M&P	Autoclave manufacturing methods	Isogrid/ orthogrid designs	Isogrid and orthogrid analysis	*No unique (Common)*	*No unique (Common)*	*No unique (Common)*	HiMat	Hand	Grid
23	Advanced autoclave cure M&P Sandwich (core) M&P	Autoclave manufacturing methods Sandwich (core) manufacturing methods	Sandwich designs	Sandwich analysis	*No unique (Common)*	*No unique (Common)*	*No unique (Common)*	HiMat	Hand	Sand
24	Advanced autoclave cure M&P	Autoclave manufacturing methods	Lightweight structure for load transfer	*No unique (Common)*	*No unique (Common)*	*No unique (Common)*	*No unique (Common)*	HiMat	Hand	Mono

Figure 3.1-8. Rigid Shell Structural Systems (6 of 6)

	1. Materials and Processes	2. Manufacturing Methods	3. Innovative Design	4. Analysis, Modeling, and Simulation	5. Design Criteria and Allowables	6. Develop-ment, QA, and Certification	7. Design for Threats
Bonded Joints	Bonded joining M&P (adhesives) 3-D woven preforms	Bonded assembly	Primarily bonded structures	Bonded joint analysis	*No unique (Common)*	*No unique (Common)*	*No unique (Common)*
Bolted Joints	Bolted joining M&P (fasteners) 3-D woven preforms	Bolted assembly	Efficient bolted joints between large sections	Bolted joint analysis	*No unique (Common)*	*No unique (Common)*	*No unique (Common)*

Figure 3.1-9. Joint Structural Systems

1. Materials and Processes
   - Coatings and sealants
2. Manufacturing Methods
   - In-process inspection techniques
3. Innovative Design
   - Multifunctional designs
   - Tailored composites
   - Interaction between components
   - Methods of preventing damage growth
4. Analysis , Modeling, and Simulation
   - Analysis of effects of defects
   - Analysis of highly tailored composites
   - Simulated test and evaluation
   - Thermo -structural analysis
   - Failure mechanism/prediction
   - Optimization methods
   - Fatigue/life prediction
   - Probabilistic analys is
   - Hierarchical analysis
   - Internal and residual stress analysis
5. Design Criteria and Allowables
   - Damage tolerance DC&A
   - Standardized Allowables
   - Environmental durability DC&A
   - Knockdown factors
   - Safety factors based on aircraft approach
   - Develop NDE sta ndards
   - Minimum gage specifications
6. Development, QA, and Certification
   - Nondestructive inspection methods
   - QA to structural performance correlation
   - Postdamage reliability prediction
   - In situ damage detection and prognostics
   - Structural health monitorin g, diagnostics, and prognostics
   - Hot spot interrogation
   - Certification by analysis
   - Certification by simulation
   - Improved test methods
   - Database development
   - In-space/ground repair methods
7. Threat/Environment
   - MMOD (lunar/LEO)
   - Lunar dust
   - Thermal cyclin g
   - Aging in lunar and space environment
   - Static charge
   - Radiation
   - Noise
   - Toxicity and outgassing

Figure 3.1-10. Common Technologies

3.2 Four-Factor Rating of Structural System

The second part of the structural system assessment is a four-factor rating of each structural system. This rating will be used in subsequent Technical fit and Program Fit analyses.

A simplified rating scale allows for the relative and subjective comparison of the structural system constituents with respect to performance, development cost, production cost, and operations cost criteria. A brief rationale is provided. In general, the cost factors are defined in terms of cost reduction (or avoidance) potential. This definition allows the scoring to indicate that a higher score is better, such that more cost reduction is potentially available from a particular constituent. Also, monocoque design is a separate type of structure which cannot be directly compared with the other design concepts. As indicated in the Technical, Program fit, and Technical-Program fit spreadsheets, monocoque is applicable to certain structural elements. For example. monocoque performance is exceptionally high for pressure vessels. Since monocoque is only applied to such pressure-only applications, then its rating is given a 3 (high).

A simple 3-point rating scale allows for the relative and subjective comparison of the structural system constituents with respect to performance and development cost avoidance criteria (Figure 3.2-1). Higher performance is associated with autoclave curing materials, fiber placement manufacturing, and sandwich (or monocoque) design. Higher development cost avoidance is associated with well-established autoclave-cured epoxy composites, non-automated hand layup fabrication, and lower-part-count sandwich (or monocoque) design.

The relative and subjective comparison of the structural system constituents with respect to production cost avoidance and operations cost avoidance criteria is provided in Figure 3.2-2.

Higher production cost avoidance is associated with non-autoclave curing materials, hand layup manufacturing, and sandwich (or monocoque) design. Higher operations cost avoidance is associated with toughened epoxy composites, infusion manufacturing (with stitching for durability), and grid or stiffened designs for easier inspection.

The performance rating of each structural system is based on the performance of the constituent material, fabrication method, and design concept (Figure 3.2-3). The constituent ratings are applied to each structural system. The rating of each structural system is the addition of the ratings of the three constituents. The ratings are then converted to a three-point (1-3) score that will be used in the intersection analysis. Structural system 15 (toughened Gr/Ep, tape placement manufacturing, and sandwich design) has the highest non-monocoque performance. Structural system 16, the highest-performance monocoque system, consists of toughened Gr/Ep, tape placement manufacturing, and monocoque design.

The development cost avoidance of each structural system is based on the development cost avoidance of the constituent material, fabrication method, and design concept (Figure 3.2-4). Structural system 23 (toughened Gr/Ep, hand layup, sandwich) has the highest development cost avoidance (or lowest development cost). Structural system 24 (toughened Gr/Ep, hand layup, monocoque) has the highest development cost avoidance for a monocoque system.

The production cost avoidance of each structural system is based on the production cost avoidance of the constituent material, fabrication method, and design concept (Figure 3.2-5). Structural system 3 (non-autoclave Gr/Ep, fiber placement, sandwich) and Structural system 4 (non-autoclave Gr/Ep, fiber placement, monocoque) have the highest production cost avoidance.

The operation cost avoidance of each structural system is based on the operation cost avoidance of the constituent material, fabrication method, and design concept (Figure 3.2-6). Of the monocoque systems, Structural system 20 (toughened Gr/Ep, infusion, monocoque) has the highest operation cost avoidance. Other than non-monocoque systems, Structural systems 17 (toughened Gr/Ep, infusion, SSF) and 18 (toughened Gr/Ep, infusion, grid) have the highest operation cost avoidance.

The normalized scores are summarized to indicate the highest value structural systems in terms of performance, development cost avoidance, production cost, and operations cost avoidance (Figure 3.2-7). This result is purely generic and does not consider Constellation requirements. The requirements criticality of the Constellation elements will significantly affect the applicability ("value added") of a particular structural system. These normalized scores will be used in the intersection analysis. In general, sandwich-based structural systems tend to have the highest performance. Hand-layup structural systems tend to have the highest development cost avoidance (lowest development cost). Non-autoclave-cure structural systems have the highest production cost avoidance (lowest production cost). Resin infusion-based structural systems have the highest operation cost avoidance (lowest operation cost).

Performance (Weight)

		Relative Value	Rationale
Material	LoMat	1	Lower allowables at temp
	HiMat	3	Higher allowables at temp
Fabrication	Infusion	1	Fabric preforms
	Hand	2	Prepreg limited placement
	Fiber	3	Optimum fiber volume, placement
Design	SSF	1	More holes, knockdowns
	Grid	2	Integral, fewer joints
	Sand	3	High buckling allowable, large acreage
	Mono	3	Efficient for pressure and tubes only

Development Cost Avoidance

		Relative Value	Rationale
Material	LoMat	1	Few flying spacecraft parts
	HiMat	3	More flying spacecraft parts
Fabrication	Infusion	1	Limited aerospace experience
	Fiber	2	Many wound parts; machine development required
	Hand	3	More aerospace applications
Design	Grid	2	Fewer parts, lower aerospace experience
	SSF	2	Higher parts, higher primary structure experience
	Sand	3	Fewer parts, higher primary structure experience
	Mono	3	Fewest parts, higher aerospace experience

Figure 3.2-1. Structural System Constituent Rating Scales (1 of 2)

Production Cost Avoidance

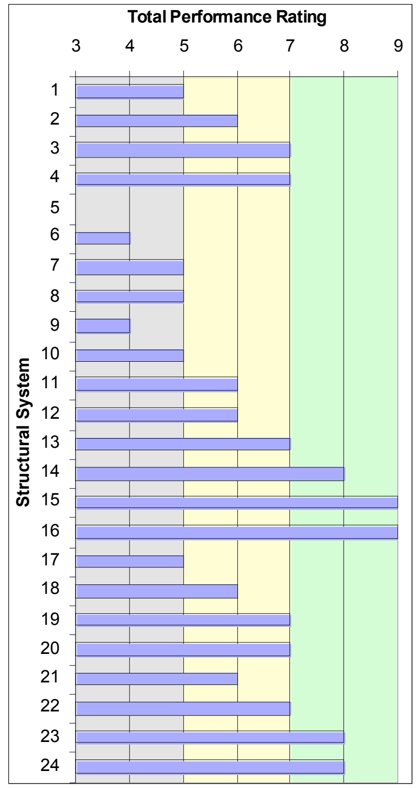
		Relative Value	Rationale
Material	HiMat	1	Autoclave, hard tooling
	LoMat	3	Non-autoclave, soft tooling
Fabrication	Hand	1	Less setup, not as scalable
	Infusion	2	More setup, scalable (boats)
	Fiber	3	Less setup, scalable
Design	SSF	1	More parts, more complex tooling
	Grid	2	Fewer parts, more complex tooling
	Sand	3	Fewer parts, less complex tooling
	Mono	3	Fewer parts, less complex tooling

Operations Cost Avoidance

		Relative Value	Rationale
Material	LoMat	1	Untoughened —more repair
	HiMat	3	Toughened —less repair
Fabrication	Hand	1	More tailored
	Fiber	2	Less tailored
	Infusion	3	Assume stitched
Design	Sand	1	Difficult inspection, difficult repair
	SSF	2	Easier inspection, harder repair
	Grid	2	Easier inspection, harder repair
	Mono	3	Easiest inspection and repair

Figure 3.2-2. Structural System Constituent Rating Scales (2 of 2)

	System Component			Constituent Score			Total
Sys	Matl	Fab	Design	Matl	Fab	Design	Score
1	LoMat	Fiber	SSF	1	3	1	5
2	LoMat	Fiber	Grid	1	3	2	6
3	LoMat	Fiber	Sand	1	3	3	7
4	LoMat	Fiber	Mono	1	3	3	7
5	LoMat	Infusion	SSF	1	1	1	3
6	LoMat	Infusion	Grid	1	1	2	4
7	LoMat	Infusion	Sand	1	1	3	5
8	LoMat	Infusion	Mono	1	1	3	5
9	LoMat	Hand	SSF	1	2	1	4
10	LoMat	Hand	Grid	1	2	2	5
11	LoMat	Hand	Sand	1	2	3	6
12	LoMat	Hand	Mono	1	2	3	6
13	HiMat	Fiber	SSF	3	3	1	7
14	HiMat	Fiber	Grid	3	3	2	8
15	HiMat	Fiber	Sand	3	3	3	9
16	HiMat	Fiber	Mono	3	3	3	9
17	HiMat	Infusion	SSF	3	1	1	5
18	HiMat	Infusion	Grid	3	1	2	6
19	HiMat	Infusion	Sand	3	1	3	7
20	HiMat	Infusion	Mono	3	1	3	7
21	HiMat	Hand	SSF	3	2	1	6
22	HiMat	Hand	Grid	3	2	2	7
23	HiMat	Hand	Sand	3	2	3	8
24	HiMat	Hand	Mono	3	2	3	8



Rating	Score	Description
3-5	1	Lower weight savings
6-7	2	Medium weight savings
8-9	3	Higher weight savings

Figure 3.2-3. Structural System Performance Rating

	System Component			Constituent Score			Total
Sys	Matl	Fab	Design	Matl	Fab	Design	Score
1	LoMat	Fiber	SSF	1	2	2	5
2	LoMat	Fiber	Grid	1	2	2	5
3	LoMat	Fiber	Sand	1	2	3	6
4	LoMat	Fiber	Mono	1	2	3	6
5	LoMat	Infusion	SSF	1	1	2	4
6	LoMat	Infusion	Grid	1	1	2	4
7	LoMat	Infusion	Sand	1	1	3	5
8	LoMat	Infusion	Mono	1	1	3	5
9	LoMat	Hand	SSF	1	3	2	6
10	LoMat	Hand	Grid	1	3	2	6
11	LoMat	Hand	Sand	1	3	3	7
12	LoMat	Hand	Mono	1	3	3	7
13	HiMat	Fiber	SSF	3	2	2	7
14	HiMat	Fiber	Grid	3	2	2	7
15	HiMat	Fiber	Sand	3	2	3	8
16	HiMat	Fiber	Mono	3	2	3	8
17	HiMat	Infusion	SSF	3	1	2	6
18	HiMat	Infusion	Grid	3	1	2	6
19	HiMat	Infusion	Sand	3	1	3	7
20	HiMat	Infusion	Mono	3	1	3	7
21	HiMat	Hand	SSF	3	3	2	8
22	HiMat	Hand	Grid	3	3	2	8
23	HiMat	Hand	Sand	3	3	3	9
24	HiMat	Hand	Mono	3	3	3	9

Rating	Score	Description
3-5	1	Lower weight savings
6-7	2	Medium weight savings
8-9	3	Higher weight savings

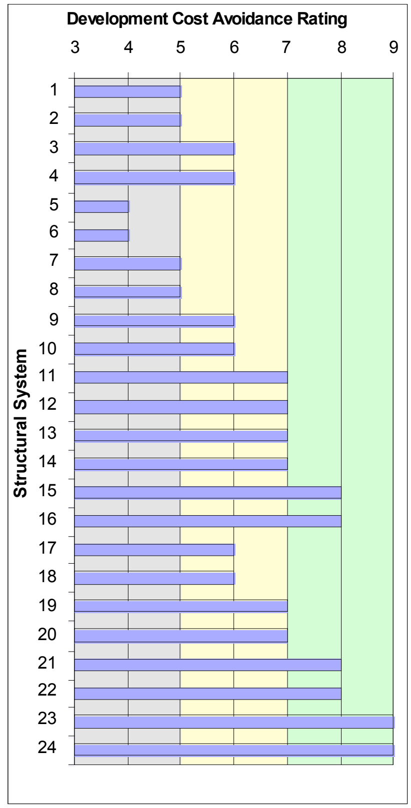


Figure 3.2-4. Structural System Development Cost Avoidance Rating

	System Component			Constituent Score			Total
Sys	Matl	Fab	Design	Matl	Fab	Design	Score
1	LoMat	Fiber	SSF	3	3	1	7
2	LoMat	Fiber	Grid	3	3	2	8
3	LoMat	Fiber	Sand	3	3	3	9
4	LoMat	Fiber	Mono	3	3	3	9
5	LoMat	Infusion	SSF	3	2	1	6
6	LoMat	Infusion	Grid	3	2	2	7
7	LoMat	Infusion	Sand	3	2	3	8
8	LoMat	Infusion	Mono	3	2	3	8
9	LoMat	Hand	SSF	3	1	1	5
10	LoMat	Hand	Grid	3	1	2	6
11	LoMat	Hand	Sand	3	1	3	7
12	LoMat	Hand	Mono	3	1	3	7
13	HiMat	Fiber	SSF	1	3	1	5
14	HiMat	Fiber	Grid	1	3	2	6
15	HiMat	Fiber	Sand	1	3	3	7
16	HiMat	Fiber	Mono	1	3	3	7
17	HiMat	Infusion	SSF	1	2	1	4
18	HiMat	Infusion	Grid	1	2	2	5
19	HiMat	Infusion	Sand	1	2	3	6
20	HiMat	Infusion	Mono	1	2	3	6
21	HiMat	Hand	SSF	1	1	1	3
22	HiMat	Hand	Grid	1	1	2	4
23	HiMat	Hand	Sand	1	1	3	5
24	HiMat	Hand	Mono	1	1	3	5

Rating	Score	Description
3-5	1	Lower weight savings
6-7	2	Medium weight savings
8-9	3	Higher weight savings

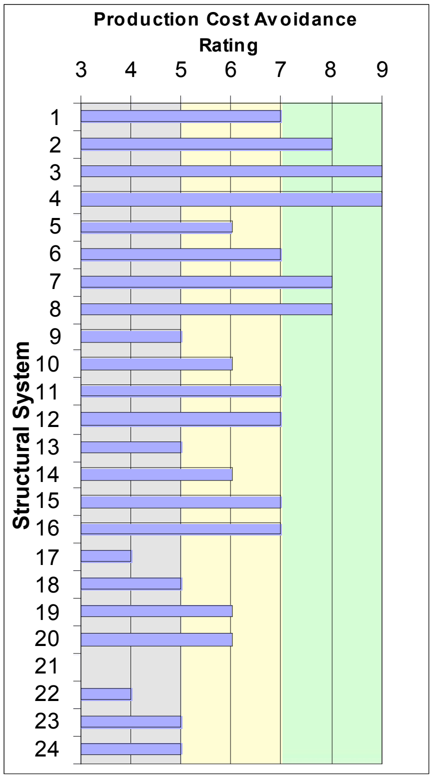


Figure 3.2-5. Structural System Production Cost Avoidance Rating

	System Component			Constituent Score			Total
Sys	Matl	Fab	Design	Matl	Fab	Design	Score
1	LoMat	Fiber	SSF	1	2	2	5
2	LoMat	Fiber	Grid	1	2	2	5
3	LoMat	Fiber	Sand	1	2	1	4
4	LoMat	Fiber	Mono	1	2	3	6
5	LoMat	Infusion	SSF	1	3	2	6
6	LoMat	Infusion	Grid	1	3	2	6
7	LoMat	Infusion	Sand	1	3	1	5
8	LoMat	Infusion	Mono	1	3	3	7
9	LoMat	Hand	SSF	1	1	2	4
10	LoMat	Hand	Grid	1	1	2	4
11	LoMat	Hand	Sand	1	1	1	3
12	LoMat	Hand	Mono	1	1	3	5
13	HiMat	Fiber	SSF	3	2	2	7
14	HiMat	Fiber	Grid	3	2	2	7
15	HiMat	Fiber	Sand	3	2	1	6
16	HiMat	Fiber	Mono	3	2	3	8
17	HiMat	Infusion	SSF	3	3	2	8
18	HiMat	Infusion	Grid	3	3	2	8
19	HiMat	Infusion	Sand	3	3	1	7
20	HiMat	Infusion	Mono	3	3	3	9
21	HiMat	Hand	SSF	3	1	2	6
22	HiMat	Hand	Grid	3	1	2	6
23	HiMat	Hand	Sand	3	1	1	5
24	HiMat	Hand	Mono	3	1	3	7

Rating	Score	Description
3-5	1	Lower weight savings
6-7	2	Medium weight savings
8-9	3	Higher weight savings

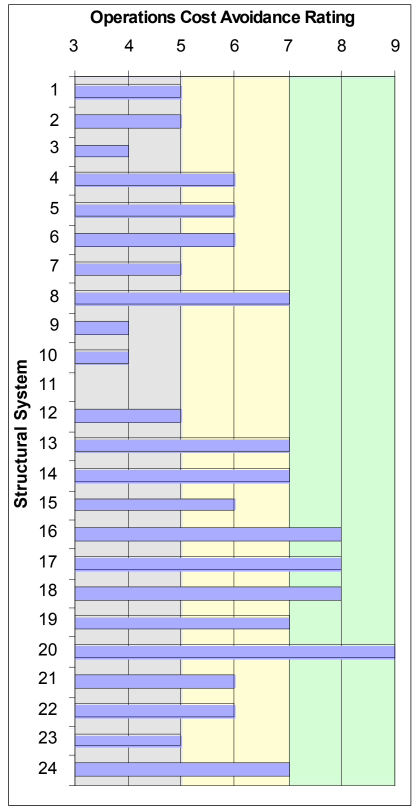
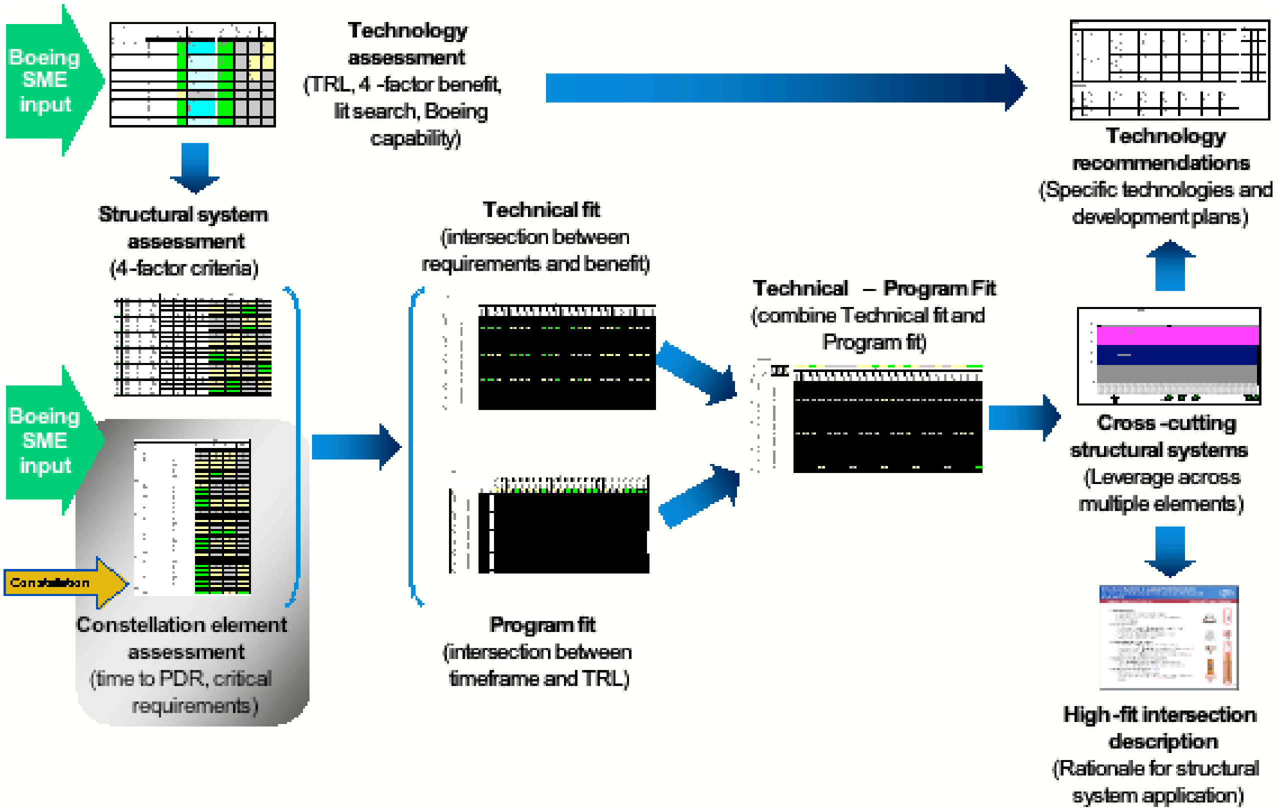


Figure 3.2-6. Structural System Operation Cost Avoidance Rating

				Total Score				Normalized Score			
Sys	Matl	Fab	Design	Perf	Dvt	Prod	Ops	Performance	Dvt Cost	Prod Cost	Ops cost
1	LoMat	Fiber	SSF	5	5	7	5	1	1	2	1
2	LoMat	Fiber	Grid	6	5	8	5	2	1	3	1
3	LoMat	Fiber	Sand	7	6	9	4	2	2	3	1
4	LoMat	Fiber	Mono	7	6	9	6	2	2	3	2
5	LoMat	Infusion	SSF	3	4	6	6	1	1	2	2
6	LoMat	Infusion	Grid	4	4	7	6	1	1	2	2
7	LoMat	Infusion	Sand	5	5	8	5	1	1	3	1
8	LoMat	Infusion	Mono	5	5	8	7	1	1	3	2
9	LoMat	Hand	SSF	4	6	5	4	1	2	1	1
10	LoMat	Hand	Grid	5	6	6	4	1	2	2	1
11	LoMat	Hand	Sand	6	7	7	3	2	2	2	1
12	LoMat	Hand	Mono	6	7	7	5	2	2	2	1
13	HiMat	Fiber	SSF	7	7	5	7	2	2	1	2
14	HiMat	Fiber	Grid	8	7	6	7	3	2	2	2
15	HiMat	Fiber	Sand	9	8	7	6	3	3	2	2
16	HiMat	Fiber	Mono	9	8	7	8	3	3	2	3
17	HiMat	Infusion	SSF	5	6	4	8	1	2	1	3
18	HiMat	Infusion	Grid	6	6	5	8	2	2	1	3
19	HiMat	Infusion	Sand	7	7	6	7	2	2	2	2
20	HiMat	Infusion	Mono	7	7	6	9	2	2	2	3
21	HiMat	Hand	SSF	6	8	3	6	2	3	1	2
22	HiMat	Hand	Grid	7	8	4	6	2	3	1	2
23	HiMat	Hand	Sand	8	9	5	5	3	3	1	1
24	HiMat	Hand	Mono	8	9	5	7	3	3	1	2

Figure 3.2-7. Summary of Structural System Normalized Scores

4.0 CONSTELLATION ELEMENT ASSESSMENT



4.1 Constellation Element Description

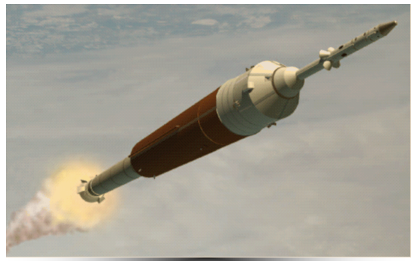
The NASA Constellation program consists of several major transportation and lunar surface elements. Each major element in turn consists of structural elements that were evaluated in this study (Figure 4.1-1). Not included in this study are surface elements such as habitats and rovers. Nevertheless, the results for may be expected to be similar to those generated for Altair and, in particular, the Altair crew cabin.

The Ares I program has baselined the conceptual structural design of the first stage, interstage, upper stage, and instrument unit (Figure 4.1-2). For example, the intertank is baselined as a common bulkhead. Also, the five-segment solid rocket motor first stage is included in this assessment, despite the fact that the baseline uses the existing metal case design. These results may be useful when considering weight reduction initiatives.

Orion is also in advanced development, but its major structures are included in this assessment (Figure 4.1-3).

The major elements of Ares V and Altair are in concept design and have the opportunity to be designed with composites technologies (Figures 4.1-4 and 4.1-5, respectively).

Constellation Element		
Ares 1		
	First stage	
	Interstage	
	Upper stage	Aft Section
		LO2 tank
		Intertank (CB)
		LH2 tank
		Instrument Unit
Orion		
	Spacecraft adapter	
	Service module	Tanks
		Shell
	Crew module	Crew cabin
		Aeroshell , fwd
		Aeroshell , aft
	LAS	Shroud
		Tower
Ares V		
	First stage	Aft section
		LO2 tank
		Intertank
		LH2 tank
	Interstage	
	EDS	Aft section
		LO2 tank
		Intertank
		LH2 tank
	LSAM Shroud	
Altair		
	Descent stage	LO2 tank(s)
		Support Str
		LH2 tank(s)
		Legs
	Ascent stage	LO2 tank(s)
		Support str
		LCH4 tank(s)
		Crew cabin



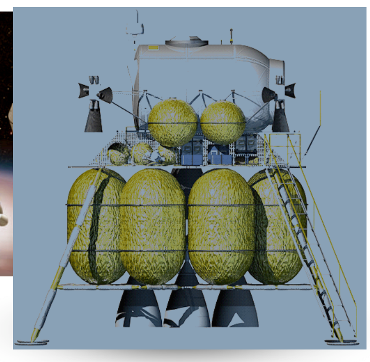


Figure 4.1-1. Constellation Elements and Associated Primary Structures

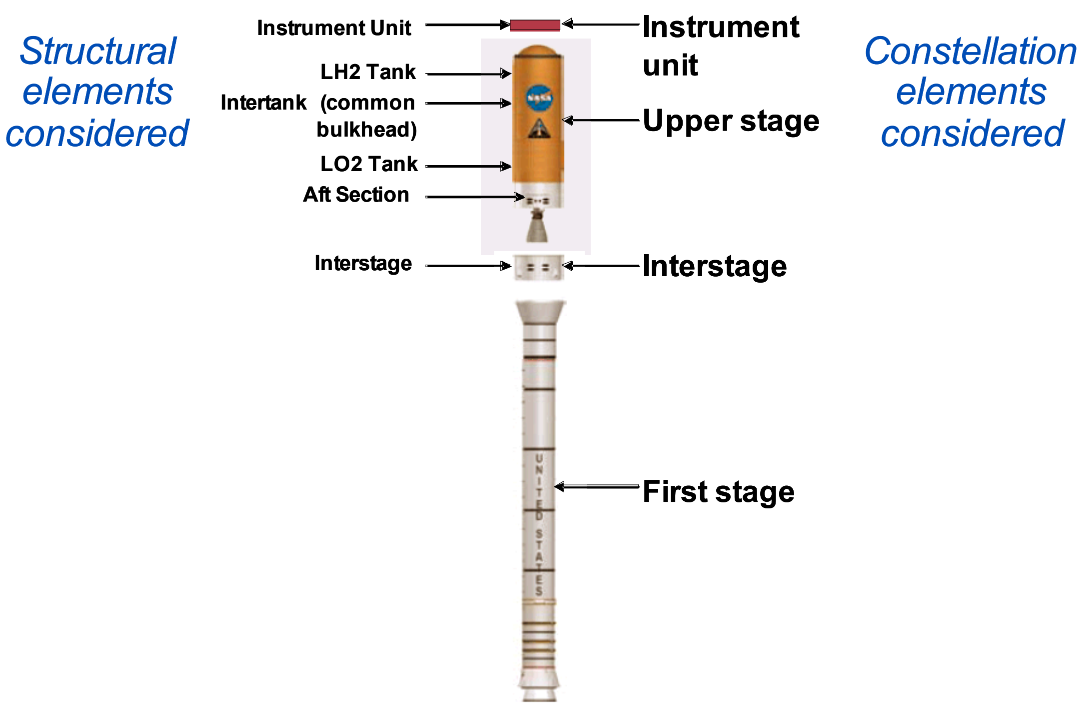


Figure 4.1-2. Constellation Elements: Ares I

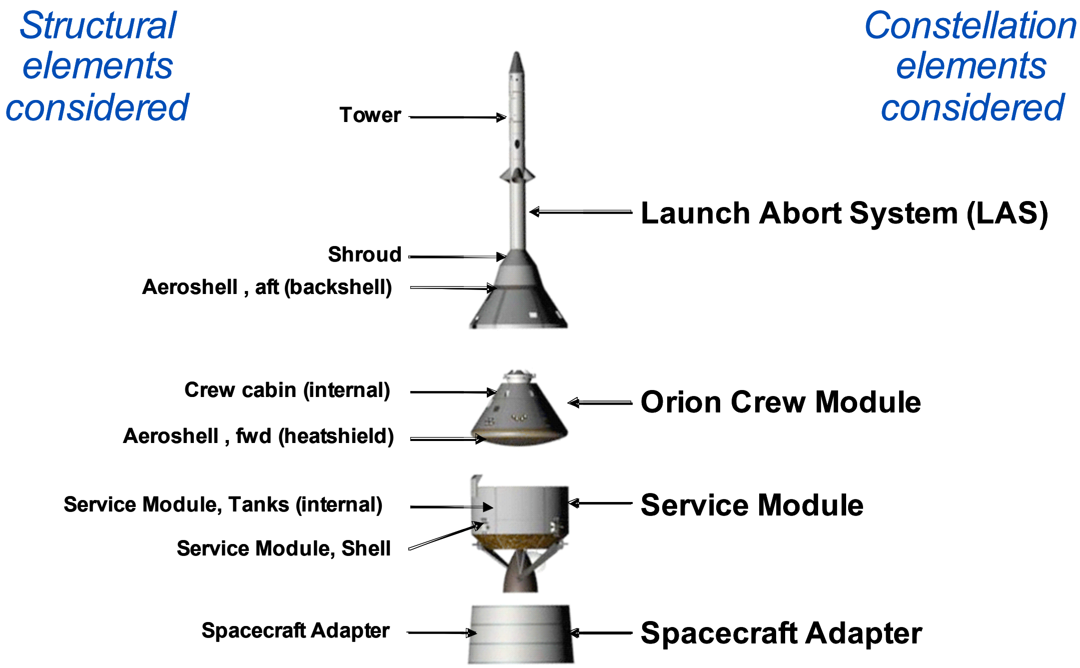


Figure 4.1-3. Constellation Elements: Orion

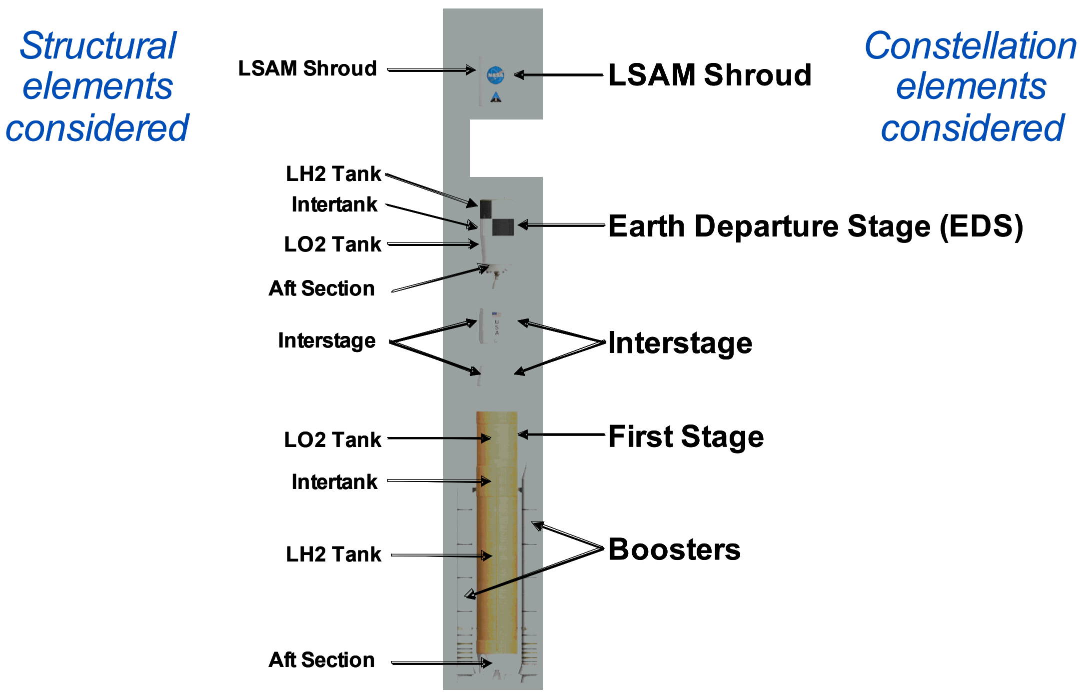


Figure 4.1-4. Constellation Elements: Ares V

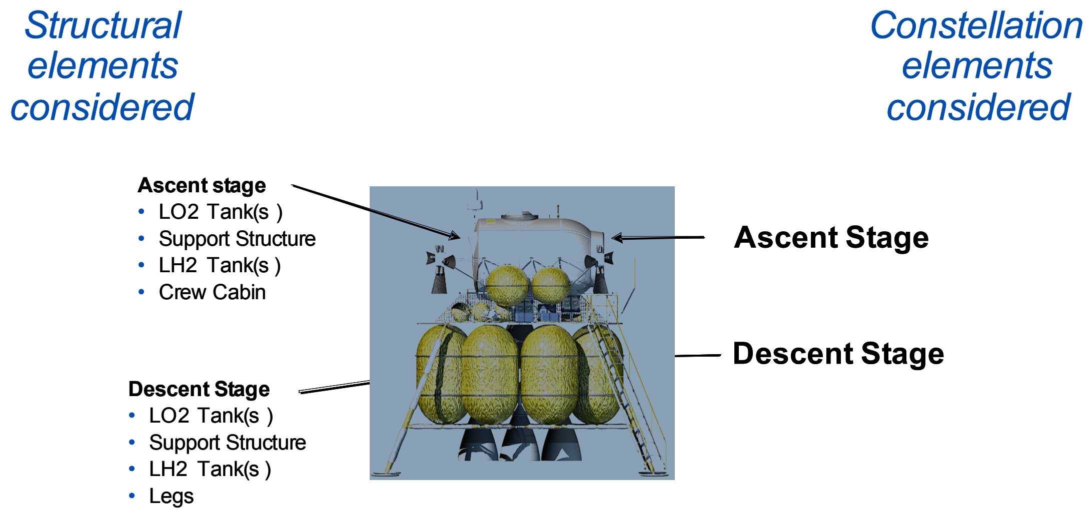


Figure 4.1-5. Constellation Elements: Altair

4.2 Constellation Element Requirements

Constellation requirements are categorized by performance, development cost, production cost, and operations cost. As shown in Figure 4.2-1, each category has a three-level criticality scale (low, medium, and high). Performance criticality depends primarily on the weight sensitivity of the Constellation element in the launch stack and the total impact (size) on system-level performance. Development cost criticality depends on the size of the Constellation element. Production cost criticality depends on the complexity of the Constellation element. Operation cost criticality depends on operational life time and whether the element is reusable or expendable.

In Figure 4.1-2, the Constellation elements are scored with the 3-point relative scale in terms of performance, development cost, production cost, and operation cost. For example, performance-critical elements are those that travel to (and/or from) the lunar surface. High development cost and high production cost elements include large cryogenic hydrogen tanks. Relatively low criticality elements include dry structure such as intertanks and shrouds.

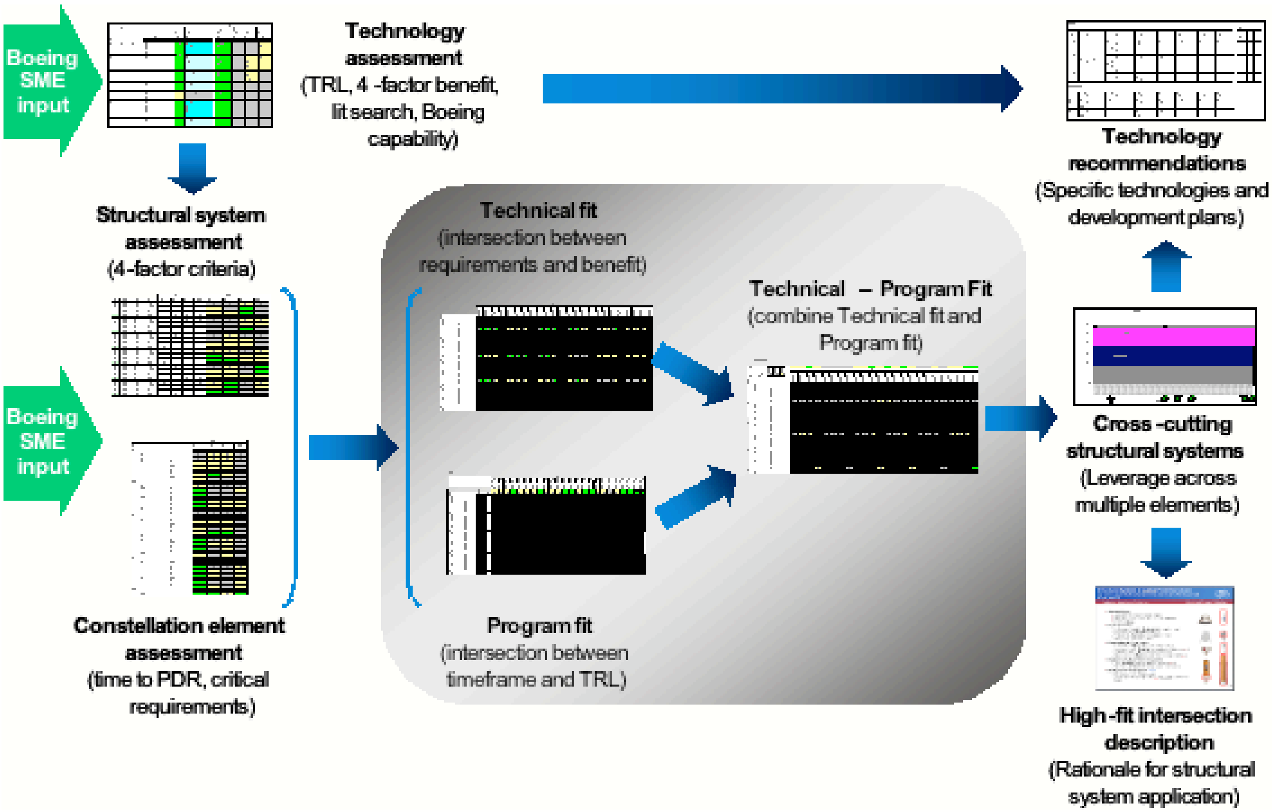
Category Criticality	Value	Approximate Description	Rationale
Performance			
Low	1	First stage; smaller	Low system weight impact
Medium	2	Second stage	Moderate system weight impact
High	3	Lunar stage; larger	High system weight impact
Development cost			
Low	1	Low complexity	
Medium	2	Moderate Complexity	Number of parts, temps, life cycles
High	3	High complexity	
Production cost			
Low	1	<10-ft diameter	
Medium	2	10 to 20-ft diameter	All elements of low quantity and rate
High	3	>20-ft diameter	
Operations cost			
Low	1	Short life, expendable	e.g., ELV
Medium	2	Long life, expendable	e.g., LSAM
High	3	Reusable	e.g., crew cabin, hab module

Figure 4.2-1. Constellation Requirement Factors and Scales

Constellation Element			Requirements			
			Perf (wt)	Dvt $	Prod $	Ops $
Ares 1						
	First stage		1	2	2	1
	Interstage		1	2	2	1
	Upper stage	Aft Section	2	2	2	1
		LO2 tank	2	2	2	1
		Intertank (CB)	2	1	1	1
		LH2 tank	2	3	2	1
		Instrument Unit	2	1	1	1
Orion						
	Spacecraft adapter		2	1	1	1
	Service module	Tanks	3	1	1	2
		Shell	3	1	1	1
	Crew module	Crew cabin	3	3	2	3
		Aeroshell, fwd	3	2	2	2
		Aeroshell, aft	3	2	2	2
	LAS	Shroud	1	1	1	1
		Tower	1	1	1	1
Ares V						
	First stage	Aft section	2	2	2	1
		LO2 tank	2	2	3	1
		Intertank	2	1	2	1
		LH2 tank	2	3	3	1
	Interstage		2	1	2	1
	EDS	Aft section	3	1	2	1
		LO2 tank	3	2	2	1
		Intertank	3	1	2	1
		LH2 tank	3	3	3	1
	LSAM Shroud		2	1	2	1
Altair						
	Descent stage	LO2 tank(s)	3	2	1	2
		Support str	3	1	1	2
		LH2 tank(s)	3	2	1	2
		Legs	3	2	1	2
	Ascent stage	LO2 tank(s)	3	2	1	2
		Support str	3	1	1	2
		LCH4 tank(s)	3	2	1	2
		Crew cabin	3	3	2	3

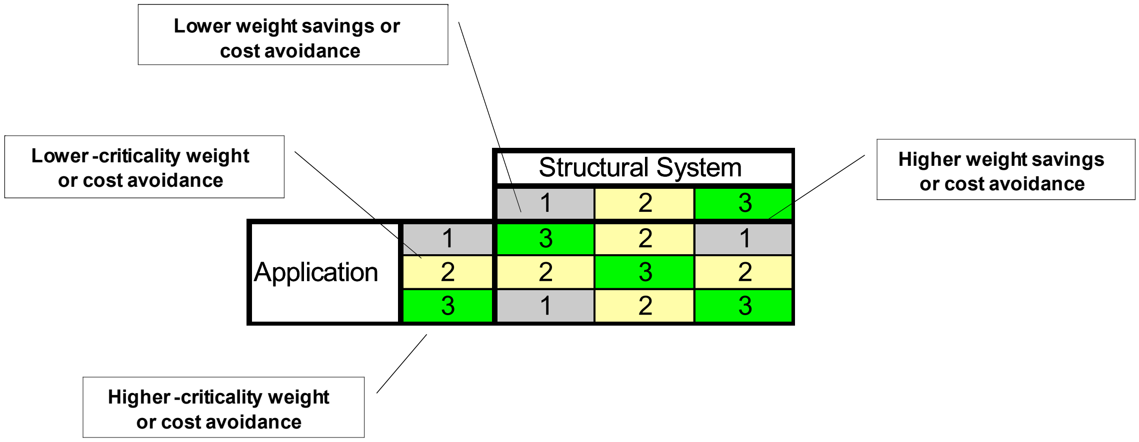
Figure 4.2-2. Constellation Element Requirement Scoring

5.0 TECHNICAL FIT, PROGRAM FIT, AND TECHNICAL-PROGRAM FIT



5.1 Intersections

The intersection score is a relative, three-level indication of the ability of a structural system to satisfy the requirements of a Constellation element. Each intersection between a structural system and a Constellation element consists of four criteria - performance, development cost, production cost, and operations cost. The intersections are determined by comparing the requirement criticality with the structural system benefit. As shown in Figure 5.1-1, a good match between requirement and benefit yields a high-scoring intersection. Conversely, a low (or high) criticality requirement is poorly matched with a high (or low) benefit. The intersection scores, provided in Figures 5.1-2 through 5.1-7, are used to calculate Technical fit in the subsequent section.



Score	Match	Description
1	Poor	Structural system over-capable of satisfying application requirement
2	Partial	
3	Perfect	Structural system perfectly satisfies application requirement
2	Partial	
1	Poor	Structural system under-capable of satisfying application requirement

Figure 5.1-1. Intersection Scoring Method

			Requirements				Structural Systems: 1 (LoMat Fiber SSF)				2 (LoMat Fiber Grid)				3 (LoMat Fiber Sand.)				4 (LoMat Fiber Mono)			
Exploration Application			Perf	Dvt $	Prod $	Ops $	Perf	Dvt $	Prod $	Ops $	Perf	Dvt $	Prod $	Ops $	Perf	Dvt $	Prod $	Ops $	Perf	Dvt $	Prod $	Ops $
							1	1	2	1	2	1	3	1	2	2	3	1	2	2	3	2
Ares 1																						
	First stage		1	2	2	1													2	3	2	2
	Interstage		1	2	2	1	3	2	3	3	2	2	2	3	2	3	2	3				
	Upper stage	Aft Section	2	2	2	1	2	2	3	3	3	2	2	3	3	3	2	3				
		LO2 tank	2	2	2	1	2	2	3	3	3	2	2	3	3	3	2	3				
		Intertank (CB)	2	2	1	1	2	2	2	3	3	2	1	3	3	3	1	3				
		LH2 tank	2	3	2	1	2	1	3	3	3	1	2	3	3	2	2	3				
		Instrument Unit	2	1	1	1	2	3	2	3	3	3	1	3	3	2	1	3	3	2	1	2
Orion																						
	Spacecraft adapter		2	1	1	1	2	3	2	3	3	3	1	3	3	2	1	3				
	Service module	Tanks	3	1	1	2	1	3	2	2	2	3	1	2	2	2	1	2	2	2	1	3
		Shell	3	1	1	1	1	3	2	3	2	3	1	3	2	2	1	3				
	Crew module	Crew cabin	3	3	2	3	1	1	3	1	2	1	2	1	2	2	2	1				
		Aeroshell, fwd	3	2	2	2	1	2	3	2	2	2	2	2	2	3	2	2				
		Aeroshell, aft	3	2	2	2	1	2	3	2	2	2	2	2	2	3	2	2				
	LAS	Shroud	1	1	1	1	3	3	2	3	2	3	1	3	2	2	1	3				
		Tower	1	1	1	1	3	3	2	3	2	3	1	3	2	2	1	3	2	2	1	2
Ares V																						
	First stage	Aft section	2	2	2	1	2	2	3	3	3	2	2	3	3	3	2	3				
		LO2 tank	2	2	3	1	2	2	2	3	3	2	3	3	3	3	3	3				
		Intertank	2	1	2	1	2	3	3	3	3	3	2	3	3	2	2	3				
		LH2 tank	2	3	3	1	2	1	2	3	3	1	3	3	3	2	3	3				
	Interstage		2	1	2	1	2	3	3	3	3	3	2	3	3	2	2	3				
	EDS	Aft section	3	1	2	1	1	3	3	3	2	3	2	3	2	2	2	3				
		LO2 tank	3	2	2	1	1	2	3	3	2	2	2	3	2	3	2	3				
		Intertank	3	1	2	1	1	3	3	3	2	3	2	3	2	2	2	3				
		LH2 tank	3	3	3	1	1	1	2	3	2	1	3	3	2	2	3	3				
	LSAM Shroud		2	1	2	1	2	3	3	3	3	3	2	3	3	2	2	3				
Altair																						
	Descent stage	LO2 tank(s)	3	2	1	2													2	3	1	3
		Support str	3	1	1	2													2	2	1	3
		LH2 tank(s)	3	2	1	2													2	3	1	3
		Legs	3	2	1	2													2	3	1	3
	Ascent stage	LO2 tank(s)	3	2	1	2													2	3	1	3
		Support str	3	1	1	2													2	2	1	3
		LCH4 tank(s)	3	2	1	2													2	3	1	3
		Crew cabin	3	3	2	3	1	1	3	1	2	1	2	1	2	2	2	1	2	2	2	2

Figure 5.1-2. Intersections (1 of 6)—Systems 1-4

Exploration Application			Requirements				Structural Systems 5 (LoMat Infus. SSF)				6 (LoMat Infus. Grid)				7 (LoMat Infus. Sand.)				8 (LoMat Infus. Mono)			
			Perf	Dvt$	Prod $	Ops $	Perf	Dvt$	Prod $	Ops $	Perf	Dvt$	Prod $	Ops $	Perf	Dvt$	Prod $	Ops $	Perf	Dvt$	Prod $	Ops $
							1	1	2	2	1	1	2	2	1	1	3	1	1	1	3	2
Ares 1																						
	First stage		1	2	2	1													3	2	2	2
	Interstage		1	2	2	1	3	2	3	2	3	2	3	2	3	2	2	3				
	Upper stage	Aft Section	2	2	2	1	2	2	3	2	2	2	3	2	2	2	2	3				
		LO2 tank	2	2	2	1	2	2	3	2	2	2	3	2	2	2	2	3				
		Intertank (CB)	2	2	1	1	2	2	2	2	2	2	2	2	2	2	1	3				
		LH2 tank	2	3	2	1	2	1	3	2	2	1	3	2	2	1	2	3				
		Instrument Unit	2	1	1	1	2	3	2	2	2	3	2	2	2	3	1	3	2	3	1	2
Orion																						
	Spacecraft adapter		2	1	1	1	2	3	2	2	2	3	2	2	2	3	1	3				
	Service module	Tanks	3	1	1	2	1	3	2	3	1	3	2	3	1	3	1	2	1	3	1	3
		Shell	3	1	1	1	1	3	2	2	1	3	2	2	1	3	1	3				
	Crew module	Crew cabin	3	3	2	3	1	1	3	2	1	1	3	2	1	1	2	1				
		Aeroshell, fwd	3	2	2	2	1	2	3	3	1	2	3	3	1	2	2	2				
		Aeroshell, aft	3	2	2	2	1	2	3	3	1	2	3	3	1	2	2	2				
	LAS	Shroud	1	1	1	1	3	3	2	2	3	3	2	2	3	3	1	3				
		Tower	1	1	1	1	3	3	2	2	3	3	2	2	3	3	1	3	3	3	1	2
Ares V																						
	First stage	Aft section	2	2	2	1	2	2	3	2	2	2	3	2	2	2	2	3				
		LO2 tank	2	2	3	1	2	2	2	2	2	2	2	2	2	2	3	3				
		Intertank	2	1	2	1	2	3	3	2	2	3	3	2	2	3	2	3				
		LH2 tank	2	3	3	1	2	1	2	2	2	1	2	2	2	1	3	3				
	Interstage		2	1	2	1	2	3	3	2	2	3	3	2	2	3	2	3				
	EDS	Aft section	3	1	2	1	1	3	3	2	1	3	3	2	1	3	2	3				
		LO2 tank	3	2	2	1	1	2	3	2	1	2	3	2	1	2	2	3				
		Intertank	3	1	2	1	1	3	3	2	1	3	3	2	1	3	2	3				
		LH2 tank	3	3	3	1	1	1	2	2	1	1	2	2	1	1	3	3				
	LSAM Shroud		2	1	2	1	2	3	3	2	2	3	3	2	2	3	2	3				
Altair																						
	Descent stage	LO2 tank(s)	3	2	1	2													1	2	1	3
		Support str	3	1	1	2													1	3	1	3
		LH2 tank(s)	3	2	1	2													1	2	1	3
		Legs	3	2	1	2													1	2	1	3
	Ascent stage	LO2 tank(s)	3	2	1	2													1	2	1	3
		Support str	3	1	1	2													1	3	1	3
		LCH4 tank(s)	3	2	1	2													1	2	1	3
		Crew cabin	3	3	2	3	1	1	3	2	1	1	3	2	1	1	2	1	1	1	2	2

Figure 5.1-3. Intersections (2 of 6)—Systems 5-8

Exploration Application			Requirements				Structural Systems 9 (LoMat Hand SSF)				10 (LoMat Hand Grid)				11 (LoMat Hand Sand.)				12 (LoMat Hand Mono)			
			Perf	Dvt$	Prod $	Ops $	Perf	Dvt$	Prod $	Ops $	Perf	Dvt$	Prod $	Ops $	Perf	Dvt$	Prod $	Ops $	Perf	Dvt$	Prod $	Ops $
							1	2	1	1	1	2	2	1	2	2	2	1	2	2	2	1
Ares 1																						
	First stage		1	2	2	1													2	3	3	3
	Interstage		1	2	2	1	3	3	2	3	3	3	3	3	2	3	3	3				
	Upper stage	Aft Section	2	2	2	1	2	3	2	3	2	3	3	3	3	3	3	3				
		LO2 tank	2	2	2	1	2	3	2	3	2	3	3	3	3	3	3	3				
		Intertank (CB)	2	2	1	1	2	3	3	3	2	3	2	3	3	3	2	3				
		LH2 tank	2	3	2	1	2	2	2	3	2	2	3	3	3	2	3	3				
		Instrument Unit	2	1	1	1	2	2	3	3	2	2	2	3	3	2	2	3	3	2	2	3
Orion																						
	Spacecraft adapter		2	1	1	1	2	2	3	3	2	2	2	3	3	2	2	3				
	Service module	Tanks	3	1	1	2	1	2	3	2	1	2	2	2	2	2	2	2	2	2	2	2
		Shell	3	1	1	1	1	2	3	3	1	2	2	3	2	2	2	3				
	Crew module	Crew cabin	3	3	2	3	1	2	2	1	1	2	3	1	2	2	3	1				
		Aeroshell, fwd	3	2	2	2	1	3	2	2	1	3	3	2	2	3	3	2				
		Aeroshell, aft	3	2	2	2	1	3	2	2	1	3	3	2	2	3	3	2				
	LAS	Shroud	1	1	1	1	3	2	3	3	3	2	2	3	2	2	2	3				
		Tower	1	1	1	1	3	2	3	3	3	2	2	3	2	2	2	3	2	2	2	3
Ares V																						
	First stage	Aft section	2	2	2	1	2	3	2	3	2	3	3	3	3	3	3	3				
		LO2 tank	2	2	3	1	2	3	1	3	2	3	2	3	3	3	2	3				
		Intertank	2	1	2	1	2	2	2	3	2	2	3	3	3	2	3	3				
		LH2 tank	2	3	3	1	2	2	1	3	2	2	2	3	3	2	2	3				
	Interstage		2	1	2	1	2	2	2	3	2	2	3	3	3	2	3	3				
	EDS	Aft section	3	1	2	1	1	2	2	3	1	2	3	3	2	2	3	3				
		LO2 tank	3	2	2	1	1	3	2	3	1	3	3	3	2	3	3	3				
		Intertank	3	1	2	1	1	2	2	3	1	2	3	3	2	2	3	3				
		LH2 tank	3	3	3	1	1	2	1	3	1	2	2	3	2	2	2	3				
	LSAM Shroud		2	1	2	1	2	2	2	3	2	2	3	3	3	2	3	3				
Altair																						
	Descent stage	LO2 tank(s)	3	2	1	2													2	3	2	2
		Support str	3	1	1	2													2	2	2	2
		LH2 tank(s)	3	2	1	2													2	3	2	2
		Legs	3	2	1	2													2	3	2	2
	Ascent stage	LO2 tank(s)	3	2	1	2													2	3	2	2
		Support str	3	1	1	2													2	2	2	2
		LCH4 tank(s)	3	2	1	2													2	3	2	2
		Crew cabin	3	3	2	3	1	2	2	1	1	2	3	1	2	2	3	1	2	2	3	1

Figure 5.1-4. Intersections (3 of 6)—Systems 9-12

			Requirements				Structural Systems: HiMat Fiber SSF 13				HiMat Fiber Grid 14				HiMat Fiber Sand. 15				HiMat Fiber Mono 16			
							Perf	Dvt$	Prod $	Ops $	Perf	Dvt$	Prod $	Ops $	Perf	Dvt$	Prod $	Ops $	Perf	Dvt$	Prod $	Ops $
Exploration Application			Perf	Dvt$	Prod $	Ops $	2	2	1	2	3	2	2	2	3	3	2	2	3	3	2	3
Ares 1																						
	First stage		1	2	2	1													1	2	3	1
	Interstage		1	2	2	1	2	3	2	2	1	3	3	2	1	2	3	2				
	Upper stage	Aft Section	2	2	2	1	3	3	2	2	2	3	3	2	2	2	3	2				
		LO2 tank	2	2	2	1	3	3	2	2	2	3	3	2	2	2	3	2				
		Intertank (CB)	2	2	1	1	3	3	3	2	2	3	2	2	2	2	2	2				
		LH2 tank	2	3	2	1	3	2	2	2	2	2	3	2	2	3	3	2				
		Instrument Unit	2	1	1	1	3	2	3	2	2	2	2	2	2	1	2	2	2	1	2	1
Orion																						
	Spacecraft adapter		2	1	1	1	3	2	3	2	2	2	2	2	2	1	2	2				
	Service module	Tanks	3	1	1	2	2	2	3	3	3	2	2	3	3	1	2	3	3	1	2	2
		Shell	3	1	1	1	2	2	3	2	3	2	2	2	3	1	2	2				
	Crew module	Crew cabin	3	3	2	3	2	2	2	2	3	2	3	2	3	3	3	2				
		Aeroshell, fwd	3	2	2	2	2	3	2	3	3	3	3	3	3	2	3	3				
		Aeroshell, aft	3	2	2	2	2	3	2	3	3	3	3	3	3	2	3	3				
	LAS	Shroud	1	1	1	1	2	2	3	2	1	2	2	2	1	1	2	2				
		Tower	1	1	1	1	2	2	3	2	1	2	2	2	1	1	2	2	1	1	2	1
Ares V																						
	First stage	Aft section	2	2	2	1	3	3	2	2	2	3	3	2	2	2	3	2				
		LO2 tank	2	2	3	1	3	3	1	2	2	3	2	2	2	2	2	2				
		Intertank	2	1	2	1	3	2	2	2	2	2	3	2	2	1	3	2				
		LH2 tank	2	3	3	1	3	2	1	2	2	2	2	2	2	3	2	2				
	Interstage		2	1	2	1	3	2	2	2	2	2	3	2	2	1	3	2				
	EDS	Aft section	3	1	2	1	2	2	2	2	3	2	3	2	3	1	3	2				
		LO2 tank	3	2	2	1	2	3	2	2	3	3	3	2	3	2	3	2				
		Intertank	3	1	2	1	2	2	2	2	3	2	3	2	3	1	3	2				
		LH2 tank	3	3	3	1	2	2	1	2	3	2	2	2	3	3	2	2				
	LSAM Shroud		2	1	2	1	3	2	2	2	2	2	3	2	2	1	3	2				
Altair																						
	Descent stage	LO2 tank(s)	3	2	1	2													3	2	2	2
		Support str	3	1	1	2													3	1	2	2
		LH2 tank(s)	3	2	1	2													3	2	2	2
		Legs	3	2	1	2													3	2	2	2
	Ascent stage	LO2 tank(s)	3	2	1	2													3	2	2	2
		Support str	3	1	1	2													3	1	2	2
		LCH4 tank(s)	3	2	1	2													3	2	2	2
		Crew cabin	3	3	2	3	2	2	2	2	3	2	3	2	3	3	3	2	3	3	3	3

Figure 5.1-5. Intersections (4 of 6)—Systems 13-16

			Requirements				Structural Systems: HiMat Infus. SSF 17				HiMat Infus. Grid 18				HiMat Infus. Sand. 19				HiMat Infus. Mono 20			
							Perf	Dvt$	Prod $	Ops $	Perf	Dvt$	Prod $	Ops $	Perf	Dvt$	Prod $	Ops $	Perf	Dvt$	Prod $	Ops $
Exploration Application			Perf	Dvt$	Prod $	Ops $	1	2	1	3	2	2	1	3	2	2	2	2	2	2	2	3
Ares 1																						
	First stage		1	2	2	1													2	3	3	1
	Interstage		1	2	2	1	3	3	2	1	2	3	2	1	2	3	3	2				
	Upper stage	Aft Section	2	2	2	1	2	3	2	1	3	3	2	1	3	3	3	2				
		LO2 tank	2	2	2	1	2	3	2	1	3	3	2	1	3	3	3	2				
		Intertank (CB)	2	2	1	1	2	3	3	1	3	3	3	1	3	3	2	2				
		LH2 tank	2	3	2	1	2	2	2	1	3	2	2	1	3	2	3	2				
		Instrument Unit	2	1	1	1	2	2	3	1	3	2	3	1	3	2	2	2	3	2	2	1
Orion																						
	Spacecraft adapter		2	1	1	1	2	2	3	1	3	2	3	1	3	2	2	2				
	Service module	Tanks	3	1	1	2	1	2	3	2	2	2	3	2	2	2	2	3	2	2	2	2
		Shell	3	1	1	1	1	2	3	1	2	2	3	1	2	2	2	2				
	Crew module	Crew cabin	3	3	2	3	1	2	2	3	2	2	2	3	2	2	3	2				
		Aeroshell, fwd	3	2	2	2	1	3	2	2	2	3	2	2	2	3	3	3				
		Aeroshell, aft	3	2	2	2	1	3	2	2	2	3	2	2	2	3	3	3				
	LAS	Shroud	1	1	1	1	3	2	3	1	2	2	3	1	2	2	2	2				
		Tower	1	1	1	1	3	2	3	1	2	2	3	1	2	2	2	2	2	2	2	1
Ares V																						
	First stage	Aft section	2	2	2	1	2	3	2	1	3	3	2	1	3	3	3	2				
		LO2 tank	2	2	3	1	2	3	1	1	3	3	1	1	3	3	2	2				
		Intertank	2	1	2	1	2	2	2	1	3	2	2	1	3	2	3	2				
		LH2 tank	2	3	3	1	2	2	1	1	3	2	1	1	3	2	2	2				
	Interstage		2	1	2	1	2	2	2	1	3	2	2	1	3	2	3	2				
	EDS	Aft section	3	1	2	1	1	2	2	1	2	2	2	1	2	2	3	2				
		LO2 tank	3	2	2	1	1	3	2	1	2	3	2	1	2	3	3	2				
		Intertank	3	1	2	1	1	2	2	1	2	2	2	1	2	2	3	2				
		LH2 tank	3	3	3	1	1	2	1	1	2	2	1	1	2	2	2	2				
	LSAM Shroud		2	1	2	1	2	2	2	1	3	2	2	1	3	2	3	2				
Altair																						
	Descent stage	LO2 tank(s)	3	2	1	2													2	3	2	2
		Support str	3	1	1	2													2	2	2	2
		LH2 tank(s)	3	2	1	2													2	3	2	2
		Legs	3	2	1	2													2	3	2	2
	Ascent stage	LO2 tank(s)	3	2	1	2													2	3	2	2
		Support str	3	1	1	2													2	2	2	2
		LCH4 tank(s)	3	2	1	2													2	3	2	2
		Crew cabin	3	3	2	3	1	2	2	3	2	2	2	3	2	2	3	2	2	2	3	3

Figure 5.1-6. Intersections (5 of 6)—Systems 17-20

							Structural Systems															
							HiMat Hand SSF				HiMat Hand Grid				HiMat Hand Sand.				HiMat Hand Mono			
							21				22				23				24			
			Requirements				Perf	Dvt $	Prod $	Ops $	Perf	Dvt $	Prod $	Ops $	Perf	Dvt $	Prod $	Ops $	Perf	Dvt $	Prod $	Ops $
Exploration Application			Perf	Dvt $	Prod $	Ops $	2	3	1	2	2	3	1	2	3	3	1	1	3	3	1	2
Ares 1																						
	First stage		1	2	2	1													1	2	2	2
	Interstage		1	2	2	1	2	2	2	2	2	2	2	2	1	2	2	3				
	Upper stage	Aft Section	2	2	2	1	3	2	2	2	3	2	2	2	2	2	2	3				
		LO2 tank	2	2	2	1	3	2	2	2	3	2	2	2	2	2	2	3				
		Intertank (CB)	2	2	1	1	3	2	3	2	3	2	3	2	2	2	3	3				
		LH2 tank	2	3	2	1	3	3	2	2	3	3	2	2	2	3	2	3				
		Instrument Unit	2	1	1	1	3	1	3	2	3	1	3	2	2	1	3	3	2	1	3	2
Orion																						
	Spacecraft adapter		2	1	1	1	3	1	3	2	3	1	3	2	2	1	3	3				
	Service module	Tanks	3	1	1	2	2	1	3	3	2	1	3	3	3	1	3	2	3	1	3	3
		Shell	3	1	1	1	2	1	3	2	2	1	3	2	3	1	3	3				
	Crew module	Crew cabin	3	3	2	3	2	3	2	2	2	3	2	2	3	3	2	1				
		Aeroshell, fwd	3	2	2	2	2	2	2	3	2	2	2	3	3	2	2	2				
		Aeroshell, aft	3	2	2	2	2	2	2	3	2	2	2	3	3	2	2	2				
	LAS	Shroud	1	1	1	1	2	1	3	2	2	1	3	2	1	1	3	3				
		Tower	1	1	1	1	2	1	3	2	2	1	3	2	1	1	3	3	1	1	3	2
Ares V																						
	First stage	Aft section	2	2	2	1	3	2	2	2	3	2	2	2	2	2	2	3				
		LO2 tank	2	2	3	1	3	2	1	2	3	2	1	2	2	2	1	3				
		Intertank	2	1	2	1	3	1	2	2	3	1	2	2	2	1	2	3				
		LH2 tank	2	3	3	1	3	3	1	2	3	3	1	2	2	3	1	3				
	Interstage		2	1	2	1	3	1	2	2	3	1	2	2	2	1	2	3				
	EDS	Aft section	3	1	2	1	2	1	2	2	2	1	2	2	3	1	2	3				
		LO2 tank	3	2	2	1	2	2	2	2	2	2	2	2	3	2	2	3				
		Intertank	3	1	2	1	2	1	2	2	2	1	2	2	3	1	2	3				
		LH2 tank	3	3	3	1	2	3	1	2	2	3	1	2	3	3	1	3				
	LSAM Shroud		2	1	2	1	3	1	2	2	3	1	2	2	2	1	2	3				
Altair																						
	Descent stage	LO2 tank(s)	3	2	1	2													3	2	3	3
		Support str	3	1	1	2													3	1	3	3
		LH2 tank(s)	3	2	1	2													3	2	3	3
		Legs	3	2	1	2													3	2	3	3
	Ascent stage	LO2 tank(s)	3	2	1	2													3	2	3	3
		Support str	3	1	1	2													3	1	3	3
		LCH4 tank(s)	3	2	1	2													3	2	3	3
		Crew cabin	3	3	2	3	2	3	2	2	2	3	2	2	3	3	2	1	3	3	2	2

Figure 5.1-7. Intersections (6 of 6)—Systems 21-24

5.2 Technical Fit, Program Fit, and Technical-Program Fit

Scoring scales were chosen to be analytically simple and visually apparent for this qualitative study (Figure 5.2-1). Each structural system is subjectively evaluated with respect to each Constellation element using these scales. Scoring scales are defined to determine relative Technical fit, Program fit, and Technical-Program fit.

For Technical fit, each structural system is subjectively evaluated in terms of its ability to satisfy the requirements of each Constellation element (Figure 5.2-2). Program fit depends on the structural system initial TRL and development time period of the Constellation element (Figure 5.2-3). Thus, Program fit is the risk and investment required to achieve TRL 6 within a given time period. Technical-Program fit for each Constellation element and each structural system is a combination of Technical fit and Program fit (Figure 5.2-4).

Technical Fit

		Technology Score		
		1	2	3
Application Score	1	1	1	1
	2	1	2	2
	3	1	2	3

Program Fit

		TRL		
		2-3 (1)	4-5 (2)	6+ (3)
Application time to tech commitment	<5 yr (1)	1	1	2
	5-10 yr (2)	1	2	3
	>10 yr (3)	2	3	3

Program-Technical Fit

		Technical Fit		
		Low (4,5,6)	Med (7,8,9)	High (10,11,12)
Program Fit	Low (1)	1	1	2
	Medium (2)	1	2	3
	High (3)	2	3	3

Figure 5.2-1. Scoring Scales for Technical Fit, Program Fit, and Technical-Program Fit

Technical Fit

		Technology Score		
		1	2	3
Application Score	1	1	1	1
	2	1	2	2
	3	1	2	3

Constellation Element		Structural System																							
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
		LoMat Fiber SSF	LoMat Fiber Grid	LoMat Fiber Sand	LoMat Fiber Mono	LoMat Infus SSF	LoMat Infus Grid	LoMat Infus Sand	LoMat Infus Mono	LoMat Hand SSF	LoMat Hand Grid	LoMat Hand Sand	LoMat Hand Mono	HiMat Fiber SSF	HiMat Fiber Grid	HiMat Fiber Sand	HiMat Fiber Mono	HiMat Infus SSF	HiMat Infus Grid	HiMat Infus Sand	HiMat Infus Mono	HiMat Hand SSF	HiMat Hand Grid	HiMat Hand Sand	HiMat Hand Mono
Ares 1																									
First stage					9				9				11				7				9				7
Interstage		11	9	10		10	10	10		11	12	11		9	9	8		8	8	10		8	8	8	
Upper stage	Aft Section	10	10	11		9	9	9		10	11	12		10	10	9		7	9	11		9	9	9	
	LO2 tank	10	10	11		9	9	9		10	11	12		10	10	9		7	9	11		9	9	9	
	Intertank (CB)	9	9	10		8	8	8		11	10	11		11	9	8		8	10	10		10	10	10	
	LH2 tank	9	9	10		8	8	8		9	10	11		9	9	10		6	8	10		10	10	10	
	Instrument Unit	10	10	9	8	9	9	9	8	10	9	10	10	10	8	7	6	7	9	9	8	9	9	9	8
Orion																									
Spacecraft adapter		10	10	9		9	9	9		10	9	10		10	8	7		7	9	9		9	9	9	
Service module	Tanks	8	8	7	8	9	9	7	9	8	7	8	9	10	10	9	7	6	9	9	8	9	9	9	8
	Shell	9	9	8		8	8	8		9	8	9		9	9	8		6	8	8		8	8	10	
Crew module	Crew cabin	6	6	7		7	7	5		6	7	8		8	10	11		5	9	9		9	9	9	
	Aeroshell, fwd	8	8	9		9	9	7		8	9	10		10	12	11		6	9	11		9	9	9	
	Aeroshell, aft	8	8	9		9	9	7		8	9	10		10	12	11		6	9	11		9	9	9	
LAS	Shroud	11	9	8		10	10	10		11	10	9		9	7	6		8	8	8		8	8	8	
	Tower	11	9	8	7	10	10	10	9	11	10	9	9	9	7	6	5	8	8	8	7	8	8	8	7
Ares V																									
First stage	Aft section	10	10	11		9	9	9		10	11	12		10	10	9		7	9	11		9	9	9	
	LO2 tank	9	11	12		8	8	10		9	10	11		9	9	8		6	8	10		8	8	8	
	Intertank	11	11	10		10	10	10		9	10	11		9	9	8		6	8	10		8	8	8	
	LH2 tank	8	10	11		7	7	9		8	9	10		8	8	9		5	7	9		9	9	9	
Interstage		11	11	10		10	10	10		9	10	11		9	9	8		6	8	10		8	8	8	
EDS	Aft section	10	10	9		9	9	9		8	9	10		8	10	9		5	7	9		7	7	9	
	LO2 tank	9	9	10		8	8	8		9	10	11		9	11	10		6	8	10		8	8	10	
	Intertank	10	10	9		9	9	9		8	9	10		8	10	9		5	7	9		7	7	9	
	LH2 tank	7	9	10		6	6	8		7	8	9		7	9	10		4	6	8		8	8	10	
LSAM Shroud		11	11	10		10	10	10		9	10	11		9	9	8		6	8	10		8	8	8	
Altair																									
Descent stage	LO2 tank(s)				9				7				9				9				9				11
	Support str				8				8				8				8				8				10
	LH2 tank(s)				9				7				9				9				9				11
	Legs				9				7				9				9				9				11
Ascent stage	LO2 tank(s)				9				7				9				9				9				11
	Support str				8				8				8				8				8				10
	LCH4 tank(s)				9				7				9				9				9				11
	Crew cabin	6	6	7	8	7	7	5	6	6	7	8	8	8	10	11	12	5	9	9	10	9	9	9	10

Figure 5.2-2. Technical Fit

Program Fit

Application time to tech commitment	TRL 2-3 (1)	TRL 4-5 (2)	TRL 6+ (3)
<5 yr (1)	1	1	2
5-10 yr (2)	1	2	3
>10 yr (3)	2	3	3

Structural Systems

Constellation Element		Time frame	TRL	1 LoMat Fiber SSF	2 LoMat Fiber Grid	3 LoMat Fiber Sand	4 LoMat Fiber Mono	5 LoMat Infus SSF	6 LoMat Infus Grid	7 LoMat Infus Sand	8 LoMat Infus Mono	9 LoMat Hand SSF	10 LoMat Hand Grid	11 LoMat Hand Sand	12 LoMat Hand Mono	13 HiMat Fiber SSF	14 HiMat Fiber Grid	15 HiMat Fiber Sand	16 HiMat Fiber Mono	17 HiMat Infus SSF	18 HiMat Infus Grid	19 HiMat Infus Sand	20 HiMat Infus Mono	21 HiMat Hand SSF	22 HiMat Hand Grid	23 HiMat Hand Sand	24 HiMat Hand Mono
				2	2	2	3	2	2	2	3	2	2	2	3	3	2	3	3	2	2	1	2	3	3	3	3
Ares 1																											
First stage		1					2				2				2				2				1				2
Interstage		1		1	1	1		1	1	1		1	1	1		2	1	2		1	1	1		2	2	2	
Upper stage	Aft section	1		1	1	1		1	1	1		1	1	1		2	1	2		1	1	1		2	2	2	
	LO2 tank	1		1	1	1		1	1	1		1	1	1		2	1	2		1	1	1		2	2	2	
	Intertank (CB)	1		1	1	1		1	1	1		1	1	1		2	1	2		1	1	1		2	2	2	
	LH2 tank	1		1	1	1		1	1	1		1	1	1		2	1	2		1	1	1		2	2	2	
	Instrument Unit	1		1	1	1	2	1	1	1	2	1	1	1	2	2	1	2	2	1	1	1	1	2	2	2	2
Orion																											
Spacecraft adapter		1		1	1	1		1	1	1		1	1	1		2	1	2		1	1	1		2	2	2	
Service module	Tanks	1		1	1	1	2	1	1	1	2	1	1	1	2	2	1	2	2	1	1	1	1	2	2	2	2
	Shell	1		1	1	1		1	1	1		1	1	1		2	1	2		1	1	1		2	2	2	
Crew module	Crew cabin	1		1	1	1		1	1	1		1	1	1		2	1	2		1	1	1		2	2	2	
	Aeroshell, fwd	1		1	1	1		1	1	1		1	1	1		2	1	2		1	1	1		2	2	2	
	Aeroshell, aft	1		1	1	1		1	1	1		1	1	1		2	1	2		1	1	1		2	2	2	
LAS	Shroud	1		1	1	1		1	1	1		1	1	1		2	1	2		1	1	1		2	2	2	
	Tower	1		1	1	1	2	1	1	1	2	1	1	1	2	2	1	2	2	1	1	1	1	2	2	2	2
Ares V																											
First stage	Aft section	2		2	2	2		2	2	2		2	2	2		3	2	3		2	2	1		3	3	3	
	LO2 tank	2		2	2	2		2	2	2		2	2	2		3	2	3		2	2	1		3	3	3	
	Intertank	2		2	2	2		2	2	2		2	2	2		3	2	3		2	2	1		3	3	3	
	LH2 tank	2		2	2	2		2	2	2		2	2	2		3	2	3		2	2	1		3	3	3	
Interstage		2		2	2	2		2	2	2		2	2	2		3	2	3		2	2	1		3	3	3	
EDS	Aft section	2		2	2	2		2	2	2		2	2	2		3	2	3		2	2	1		3	3	3	
	LO2 tank	2		2	2	2		2	2	2		2	2	2		3	2	3		2	2	1		3	3	3	
	Intertank	2		2	2	2		2	2	2		2	2	2		3	2	3		2	2	1		3	3	3	
	LH2 tank	2		2	2	2		2	2	2		2	2	2		3	2	3		2	2	1		3	3	3	
LSAM Shroud		2		2	2	2		2	2	2		2	2	2		3	2	3		2	2	1		3	3	3	
Altair																											
Descent stage	LO2 tank(s)	2					3				3				3				3				2				3
	Support str	2					3				3				3				3				2				3
	LH2 tank(s)	2					3				3				3				3				2				3
	Legs	2					3				3				3				3				2				3
Ascent stage	LO2 tank(s)	2					3				3				3				3				2				3
	Support str	2					3				3				3				3				2				3
	LCH4 tank(s)	2					3				3				3				3				2				3
	Crew cabin	3		3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	2	3	3	3	3	3

Figure 5.2-3. Program Fit

Program-Technical Fit

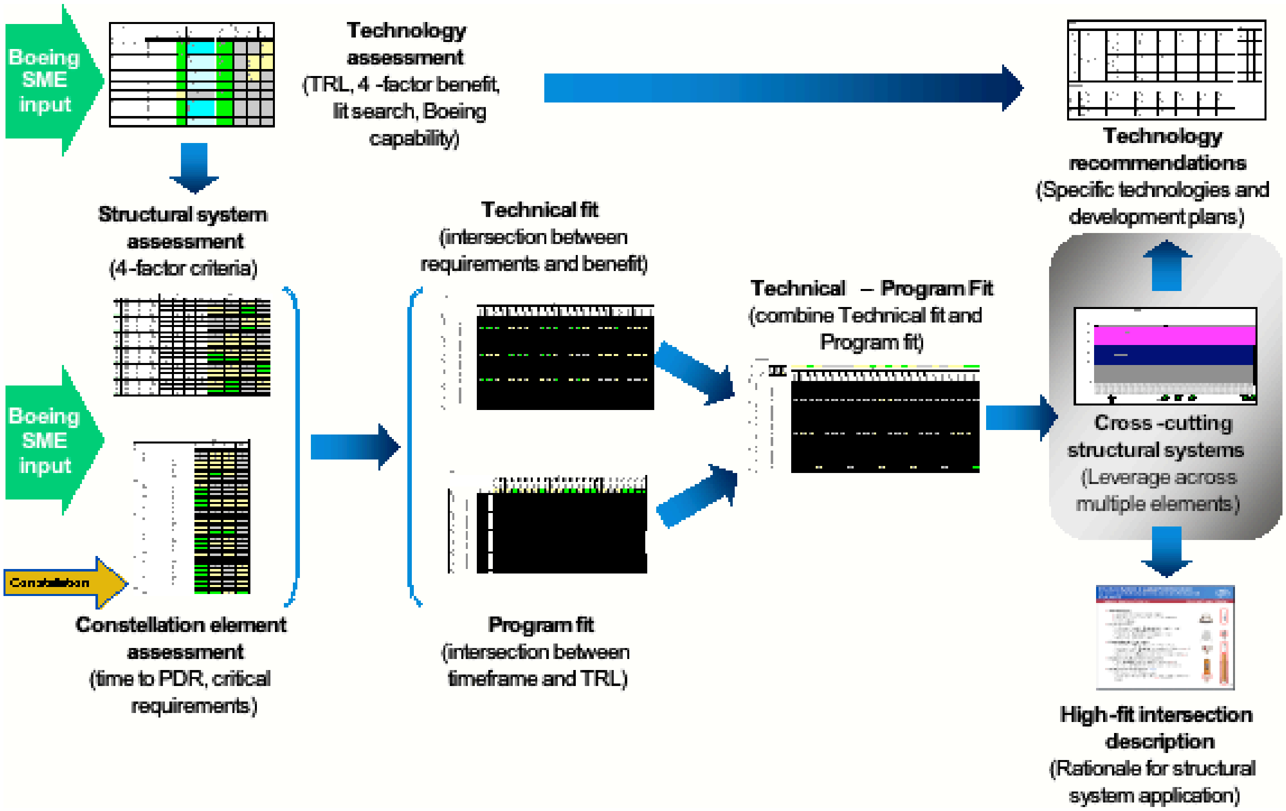
Program Fit	Technical Fit Low (4,5,6)	Technical Fit Med (7,8,9)	Technical Fit High (10,11,12)
Low(1)	1	1	2
Medium (2)	1	2	3
High (3)	2	3	3

Structural Systems

Constellation Element		1 LoMat Fiber SSF	2 LoMat Fiber Grid	3 LoMat Fiber Sand	4 LoMat Fiber Mono	5 LoMat Infus SSF	6 LoMat Infus Grid	7 LoMat Infus Sand	8 LoMat Infus Mono	9 LoMat Hand SSF	10 LoMat Hand Grid	11 LoMat Hand Sand	12 LoMat Hand Mono	13 HiMat Fiber SSF	14 HiMat Fiber Grid	15 HiMat Fiber Sand	16 HiMat Fiber Mono	17 HiMat Infus SSF	18 HiMat Infus Grid	19 HiMat Infus Sand	20 HiMat Infus Mono	21 HiMat Hand SSF	22 HiMat Hand Grid	23 HiMat Hand Sand	24 HiMat Hand Mono
Ares 1																									
First stage					1				1				2				1				1				1
Interstage		2	1	1		1	1	1		2	2	2		1	1	1		1	1	1		1	1	1	
Upper stage	Aft Section	1	1	2		1	1	1		1	2	2		2	1	1		1	1	2		1	1	1	
	LO2 tank	1	1	2		1	1	1		1	2	2		2	1	1		1	1	2		1	1	1	
	Intertank (CB)	1	1	1		1	1	1		2	1	2		2	1	1		1	1	1		2	2	2	
	LH2 tank	1	1	1		1	1	1		1	1	2		1	1	2		1	1	1		2	2	2	
	Instrument Unit	1	1	1	1	1	1	1	1	1	1	1	2	2	1	1	1	1	1	1	1	1	1	1	1
Orion																									
Spacecraft adapter		1	1	1		1	1	1		1	1	1		2	1	1		1	1	1		1	1	1	
Service module	Tanks	1	1	1	1	1	1	1	1	1	1	1	1	2	1	1	1	1	1	1	1	1	1	1	1
	Shell	1	1	1		1	1	1		1	1	1		1	1	1		1	1	1		1	1	2	
Crew module	Crew cabin	1	1	1		1	1	1		1	1	1		1	1	2		1	1	1		1	1	1	
	Aeroshell, fwd	1	1	1		1	1	1		1	1	1		2	2	2		1	1	2		1	1	1	
	Aeroshell, aft	1	1	1		1	1	1		1	1	1		2	2	2		1	1	2		1	1	1	
LAS	Shroud	2	1	1		1	1	1		2	1	1		1	1	1		1	1	1		1	1	1	
	Tower	2	1	1	1	1	1	1	1	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Ares V																									
First stage	Aft section	2	2	2		1	1	1		2	2	3		2	2	2		1	1	2		2	2	2	
	LO2 tank	1	2	3		1	1	2		1	2	2		2	1	1		1	1	1		1	1	1	
	Intertank	2	2	2		2	2	2		1	2	2		2	1	1		1	1	1		1	1	1	
	LH2 tank	1	2	2		1	1	1		1	1	2		1	1	2		1	1	1		2	2	2	
Interstage		2	2	2		2	2	2		1	2	2		2	1	1		1	1	1		1	1	1	
EDS	Aft section	2	2	1		1	1	1		1	1	2		1	2	2		1	1	1		1	1	2	
	LO2 tank	1	1	2		1	1	1		1	2	2		2	2	2		1	1	1		1	1	2	
	Intertank	2	2	1		1	1	1		1	1	2		1	2	2		1	1	1		1	1	2	
	LH2 tank	1	1	2		1	1	1		1	1	1		1	1	2		1	1	1		1	1	2	
LSAM Shroud		2	2	2		2	2	2		1	2	2		2	1	1		1	1	1		1	1	1	
Altair																									
Descent stage	LO2 tank(s)				2				1				2				2				1				3
	Support Str				1				1				1				1				1				2
	LH2 tank(s)				2				1				2				2				1				3
	Legs				2				1				2				2				1				3
Ascent stage	LO2 tank(s)				2				1				2				2				1				3
	Support str				1				1				1				1				1				2
	LH2 tank(s)				2				1				2				2				1				3
	Crew cabin	1	1	1	1	1	1	1	1	1	1	1	1	1	2	3	3	1	2	1	2	2	2	2	2

Figure 5.2-4. Technical – Program Fit

6.0 ANALYSIS OF ASSESSMENT RESULTS



6.1 Analysis by Structural System

Analysis of the assessment results is provided in this section. Figure 6.1-1 plots the total (2 and 3) Technical-Program fit scores of the 24 structural systems. Higher scores indicate higher degree of applicability of a structural system to various Constellation elements. A three-tier (top, middle, and bottom) classification is used to arbitrarily differentiate between the highest and lowest cross-cutting systems Structural systems in the top tier are strong candidates for further development. Structural systems in the middle tier are candidates for limited development. Structural systems in the bottom tier would not be candidates for further development.

A narrative description of each structural system is provided in Figures 6.1-2 through 6.1-5. Figure 6.1-5 summarizes the results of the assessment analysis. In particular, six high cross-cutting structural systems are the basis for subsequent analysis and recommendations.

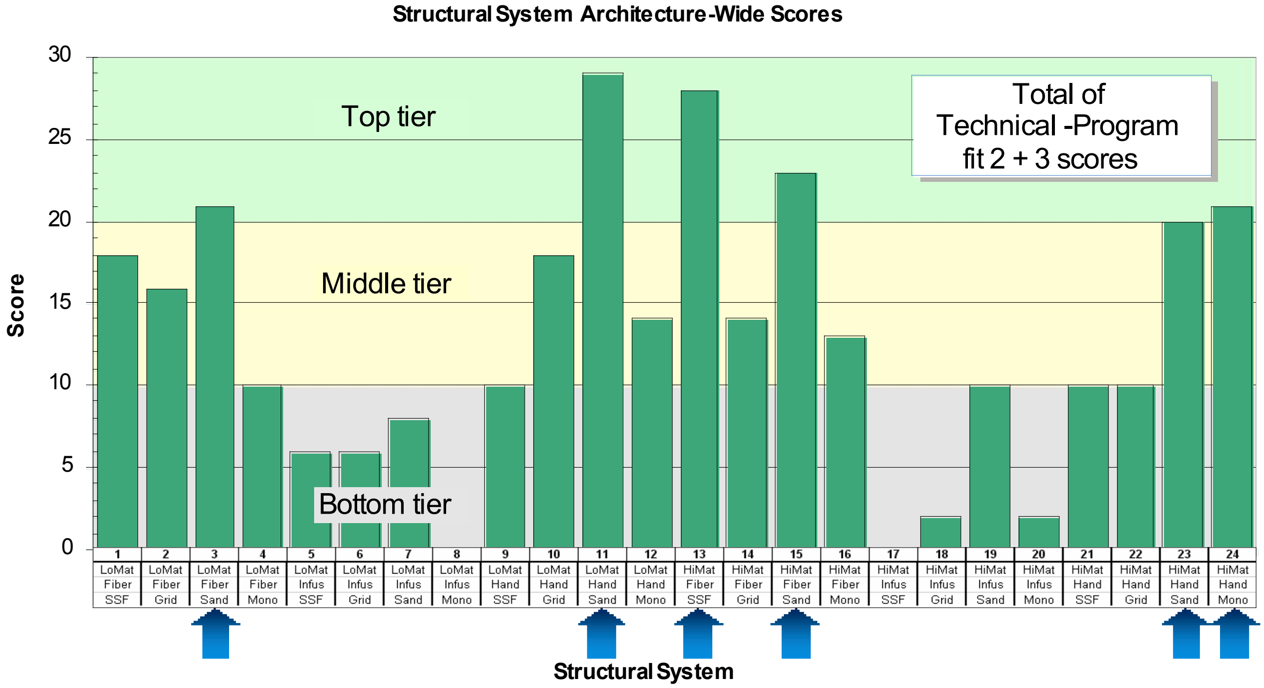


Figure 6.1-1. Six structural systems have the greatest cross-cutting applicability.

SS	Matl	Fab	Design	Narrative Analysis
1	LoMat	Fiber	SSF	Moderate fit for Ares V dry structure
2	LoMat	Fiber	Grid	Moderate fit for Ares V dry structure and cryotanks
3	LoMat	Fiber	Sand	Moderate fit for Ares V intertank and EDS High fit for Ares V first-stage LO2 tank
4	LoMat	Fiber	Mono	Moderate fit for several Altair elements
5	LoMat	Infusion	SSF	Low fit due to lower M&P maturity
6	LoMat	Infusion	Grid	Low fit due to lower M&P and design maturity
7	LoMat	Infusion	Sand	Low fit overall due to lower M&P maturity
8	LoMat	Infusion	Mono	Low fit overall due to lower M&P maturity, even for monocoque applications

Top Tier	
Middle Tier	
Bottom Tier	

Figure 6.1-2. Narrative Analysis (1 of 3)—Structural Systems 1-8

SS	Matl	Fab	Design	Narrative Analysis
9	LoMat	Hand	SSF	Low-moderate fit for near-term and mid-term, moderate size, dry structure
10	LoMat	Hand	Grid	Moderate fit for Ares I interstage and Ares V first-stage aft section
11	LoMat	Hand	Sand	Moderate fit for Ares I upper stage High fit for Ares V first-stage aft section
12	LoMat	Hand	Mono	Moderate fit for Altair
13	HiMat	Fiber	SSF	Moderate fit for most dry structure and LO2 tanks
14	HiMat	Fiber	Grid	Moderate fit for EDS and crew module aeroshell
15	HiMat	Fiber	Sand	Moderate fit for entire EDS crew module aeroshell, and LH2 tanks High fit for hab module
16	HiMat	Fiber	Mono	Moderate for for Altair High fit for crew cabin

Top Tier	
Middle Tier	
Bottom Tier	

Figure 6.1-3. Narrative Analysis (2 of 3)—Structural Systems 9-12

SS	Matl	Fab	Design	Narrative Analysis
17	HiMat	Infusion	SSF	Low fit overall
18	HiMat	Infusion	Grid	Low fit overall
19	HiMat	Infusion	Sand	Moderate fit for Ares I aft section, crew module aeroshell, and Ares V first-stage aft section
20	HiMat	Infusion	Mono	Moderate fit for crew cabin only
21	HiMat	Hand	SSF	Moderate fit for Ares I upper stage intertank and LH2 tank, Ares V first-stage aft section, and crew cabin
22	HiMat	Hand	Grid	Moderate fit for Ares I upper stage intertank and LH2 tank, Ares V first-stage aft section, and crew cabin
23	HiMat	Hand	Sand	Moderate fit for Ares I upper stage intertank and LH2 tank, Orion SM shell, and entire EDS stage
24	HiMat	Hand	Mono	Moderate-high fit for entire Altair Moderate fit for crew cabin

Top Tier	
Middle Tier	
Bottom Tier	

Figure 6.1-4. Narrative Analysis (3 of 3)—Structural Systems 17-24

- **6 top-tier structural systems provide highest technical-program fit across the Constellation program**
  - May be candidates for follow-on quantitative trade studies
  - Associated technologies are candidates for high-priority development funding
  - PowerPoint descriptions are provided for these structural systems
- **11 middle-tier structural systems provide moderate technical-program fit across the Constellation program**
  - May be candidates for follow-on qualitative trade studies
  - Associated technologies are candidates for lower-priority development funding
- **7 bottom-tier structural systems and associated technologies are likely not candidates for further evaluation or development**

Figure 6.1-5. Intersection Evaluation Summary

6.2 Analysis by Constellation Element

Analysis of the assessment results by Constellation element is provided in this section. Figure 6.2-1 plots the average (2 and 3) Technical-Program fit scores of the Constellation elements. Higher scores indicate a higher number of applicable (high-fit) structural systems. A three-tier (top, middle, and bottom) classification is used to arbitrarily differentiate between Constellation elements. Constellation elements in the top tier may benefit from a wide variety of structural systems. Constellation elements in the middle tier may benefit from a moderate number of structural systems. Constellation elements in the may benefit from only a few structural systems. For example, Ares I has higher Technical fit and lower Program fit. Consequently, the Technical-Program fit is low-moderate. Conversely, Altair has moderate Technical fit and high Program fit. The resulting Technical-Program fit is high.

A narrative description of each Constellation element in terms of Technical, Program, and Technical-Program fit is provided in Figures 6.2-2 through 6.2-4. Figure 6.2-5 summarizes the results of the assessment analysis.

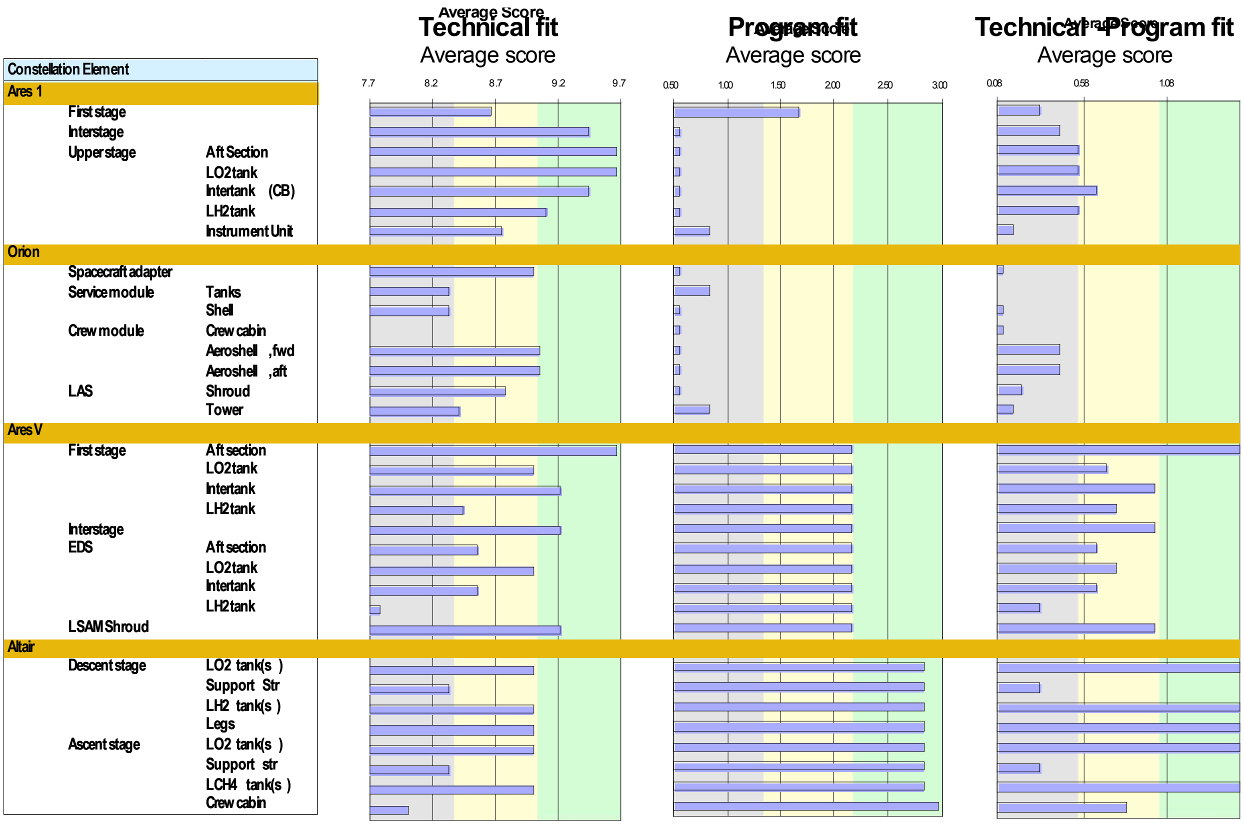


Figure 6.2-1. Technical and Program fit by Constellation element reflects number of applicable structural systems.

Constellation Element			Narrative Analysis
Ares 1			
	First stage		Near-term technical maturity yields lower program fit Lower requirements (first-stage expendable) yields low technical fit
	Interstage		
	Upper stage	Aft section	Near-term technical maturity yields lower program fit. Nevertheless, relatively smaller size allows some higher-maturity structural systems to be considered
		LO2 tank	
		Intertank (CB)	
		LH2 tank	
		Instrument unit	Lower 4-factor requirements does not need composites benefits
Orion			
	Spacecraft adapter		Near-term technical maturity yields lower program fit Complex (multiple, high 4-factor) requirements yields moderate technical fit
	Service module	Tanks	
		Shell	
	Crew module	Crew cabin	
		Aeroshell, fwd	
		Aeroshell, aft	
	LAS	Shroud	
		Tower	

Figure 6.2-2. Narrative Analysis by Constellation Element (1 of 3)—Ares I and Orion

Constellation Element			Narrative Analysis
Ares V			
	First stage	Aft section	Mid-term technical maturity allows consideration of many structural systems for moderate/high program fit Moderate-criticality 4-factor requirements yields moderate/high technical fit with many structural systems
		LO2 tank Intertank LH2 tank	Mid-term technical maturity allows consideration of many structural systems for moderate/high program fit Moderate-criticality 4-factor requirements yields moderate/high technical fit with many structural systems (LoMat systems higher scoring than HiMat)
	Interstage		
	EDS	Aft section LO2 tank Intertank	Mid-term technical maturity allows consideration of many structural systems for moderate/high program fit High-criticality performance requirement yields moderate/high technical fit with many structural systems
		LH2 tank	Mid-term technical maturity allows consideration of many structural systems for moderate/high program fit High-criticality performance and development cost requirements yields lower technical fit with many structural systems
	LSAM Shroud		Mid-term technical maturity allows consideration of many structural systems for moderate/high program fit Moderate-criticality 4-factor requirements yields moderate/high technical fit with many structural systems (LoMat systems higher scoring/fit than HiMat)

Figure 6.2-3. Narrative Analysis by Constellation Element (2 of 3)—Ares V

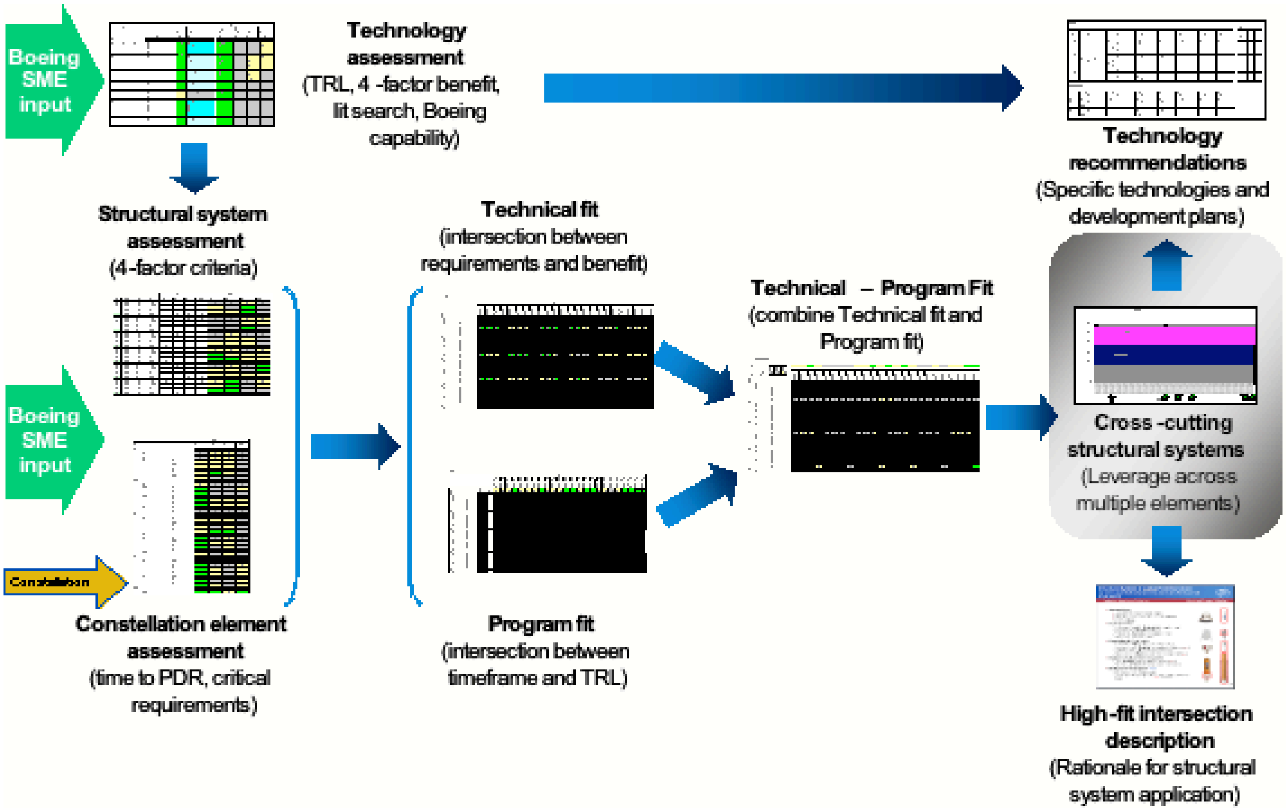
Constellation Element			Narrative Analysis
Altair			
	Descent stage	LO2 tank(s)	Mid-term technical maturity allows consideration of many monocoque structural systems for high program fit High-criticality performance requirement yields moderate technical fit with many monocoque structural systems
		Support str	Mid-term technical maturity allows consideration of many monocoque structural systems for high program fit Lower-criticality cost avoidance requirement yields lower technical fit with many monocoque structural systems
		LH2 tank(s) Legs	Mid-term technical maturity allows consideration of many monocoque structural systems for high program fit Lower-criticality cost avoidance requirement yields lower technical fit with many monocoque structural systems
	Ascent stage	LO2 tank(s)	Mid-term technical maturity allows consideration of many monocoque structural systems for high program fit Lower-criticality cost avoidance requirement yields lower technical fit with many monocoque structural systems
		Support str	Mid-term technical maturity allows consideration of many monocoque structural systems for high program fit Lower-criticality production cost avoidance requirement yields lower technical fit with many monocoque structural systems
		LCH4 tank(s)	Mid-term technical maturity allows consideration of many monocoque structural systems for high program fit High-criticality performance requirement yields moderate technical fit with many monocoque structural systems
		Crew cabin	Long-term technical maturity allows consideration of all structural systems for high program fit High-criticality 4-factor requirements yields higher technical fit with many HiMat structural systems

Figure 6.2-4. Narrative Analysis by Constellation Element (3 of 3) Altair Descent and Ascent Stage

- **6 top-tier Constellation Elements benefit from many, diverse structural systems**
  - May be candidates for follow-on quantitative trade studies
  - Associated technologies are candidates for high-priority development funding (e.g., design criteria, environmental degradation)
- **13 middle-tier Constellation Elements benefit from selected structural systems**
  - May be candidates for follow-on qualitative trade studies
  - Associated technologies are candidates for development funding if selected as part of cross-cutting system of structural systems
- **14 bottom-tier Constellation Elements may not significantly benefit from composite structures**
  - Near-term need date *and* lower technical payoff discourage further study

Figure 6.2-5. Intersection Evaluation Summary—by Constellation Element

7.0 Highly Cross-Cutting Structural Systems



This section contains a summary of each of the six highly cross-cutting structural systems (Figures 7-1 through 7-6). The technical fit, program fit, and technical-program fit data for each structural system is extracted from the overall respective spreadsheets to summarize and explain the results.

- **Structural System definition**
  - Lower-performance/cost (Gr/Ep) prepreg material
  - Fiber placement, non-autoclave cure fabrication
  - Sandwich design
- **Technical fit**
  - Moderate performance – mod. perf matches mod req.
  - Moderate development cost for material/design database
  - Lower production cost for large-scale apps
  - Lower operations cost avoidance matches expendable app's
- **Program fit**
  - **Moderate** TRL constrains near-term apps
- **Technical-Program fit**
  - **Moderate** T-P fit primarily for Ares V
  - **High** T-P fit for Ares V first stage LO2 tank

			Structural System 3		
			Technical Fit	Program Fit	Technical-Program Fit
Constellation Element				2	
Ares 1					
	First stage				
	Interstage		10	1	1
	Upper stage	Aft section	11	1	2
		LO2 tank	11	1	2
		Intertank (CB)	10	1	1
		LH2 tank	10	1	1
		Instrument unit	9	1	1
Orion					
	Spacecraft adapter		9	1	1
	Service module	Tanks	7	1	1
		Shell	8	1	1
	Crew module	Crew cabin	7	1	1
		Aeroshell, fwd	9	1	1
		Aeroshell, aft	9	1	1
	LAS	Shroud	8	1	1
		Tower	8	1	1
Ares V					
	First stage	Aft section	11	2	2
		LO2 tank	12	2	3
		Intertank	10	2	2
		LH2 tank	11	2	2
	Interstage		10	2	2
	EDS	Aft section	9	2	1
		LO2 tank	10	2	2
		Intertank	9	2	1
		LH2 tank	10	2	2
	LSAM shroud		10	2	2
Altair					
	Descent stage	LO2 tank(s)			
		Support str			
		LH2 tank(s)			
		Legs			
	Ascent stage	LO2 tank(s)			
		Support str			
		LCH4 tank(s)			
		Crew cabin	7	3	1

Figure 7-1. Structural System 3: LoMat/Fiber/Sandwich

- **Structural System definition**
  - Lower-performance/cost (Gr/Ep) prepreg material
  - Hand-layup, non-autoclave cure fabrication
  - Sandwich design
- **Technical fit**
  - Moderate Performance matches low req
  - Moderate Development cost from database development
  - Moderate Production cost for scale-up
  - Higher Operations cost matches expendable apps
- **Program fit**
  - **Moderate** (about 5) TRL delays applicability until Mid-/Far-term
- **Technical-Program fit**
  - **Moderate** fit for Ares I
  - **Moderate** fit for Ares V
  - **High** fit for Ares V First Stage Aft Section

			Structural System 11		
			Technical Fit	Program Fit	Technical-Program Fit
Constellation Element				2	
Ares 1					
	First stage				
	Interstage		11	1	2
	Upper stage	Aft Section	12	1	2
		LO2 tank	12	1	2
		Intertank (CB)	11	1	2
		LH2 tank	11	1	2
		Instrument Unit	10	1	1
Orion					
	Spacecraft adapter		10	1	1
	Service module	Tanks	8	1	1
		Shell	9	1	1
	Crew module	Crew cabin	8	1	1
		Aeroshell, fwd	10	1	1
		Aeroshell, aft	10	1	1
	LAS	Shroud	9	1	1
		Tower	9	1	1
Ares V					
	First stage	Aft section	12	2	3
		LO2 tank	11	2	2
		Intertank	11	2	2
		LH2 tank	10	2	2
	Interstage		11	2	2
	EDS	Aft section	10	2	2
		LO2 tank	11	2	2
		Intertank	10	2	2
		LH2 tank	9	2	1
	LSAM Shroud		11	2	2
Altair					
	Descent stage	LO2 tank(s)			
		Support str			
		LH2 tank(s)			
		Legs			
	Ascent stage	LO2 tank(s)			
		Support str			
		LCH4 tank(s)			
		Crew cabin	8	3	1

Figure 7-2. Structural System 11: LoMat/Hand/Sandwich

- **Structural system definition**
  - Higher -performance/cost (Gr/Ep) prepreg material
  - Fiber/tape placement, autoclave cure fabrication
  - Skin-stringer-frame design
- **Technical fit**
  - Moderate performance matches lower stage requirements
  - Moderate development cost for scale-up
  - Moderate production cost for large scale
  - Moderate operations cost matches expendable elements
- **Program fit**
  - **High** TRL (ref. 787 production) allows **near-term** adaptation to space
- **Technical-Program fit**
  - **Moderate** fit primarily for wide range of dry structure and LO2 tanks

Constellation Element			Structural System 13: Technical Fit	Structural System 13: Program Fit	Structural System 13: Technical-Program Fit
Constellation Element				3	
Ares 1					
	First stage				
	Interstage		9	2	1
	Upper stage	Aft section	10	2	2
		LO2 tank	10	2	2
		Intertank (CB)	11	2	2
		LH2 tank	9	2	1
		Instrument unit	10	2	2
Orion					
	Spacecraft adapter		10	2	2
	Service module	Tanks	10	2	2
		Shell	9	2	1
	Crew module	Crew cabin	8	2	1
		Aeroshell, fwd	10	2	2
		Aeroshell, aft	10	2	2
	LAS	Shroud	9	2	1
		Tower	9	2	1
Ares V					
	First stage	Aft section	10	3	2
		LO2 tank	9	3	2
		Intertank	9	3	2
		LH2 tank	8	3	1
	Interstage		9	3	2
	EDS	Aft section	8	3	1
		LO2 tank	9	3	2
		Intertank	8	3	1
		LH2 tank	7	3	1
	LSAM shroud		9	3	2
Altair					
	Descent stage	LO2 tank(s)			
		Support str			
		LH2 tank(s)			
		Legs			
	Ascent stage	LO2 tank(s)			
		Support str			
		LCH4 tank(s)			
		Crew cabin	8	3	1

Figure 7-3. Structural System 13: HiMat/Fiber/SSF

- **Structural System Definition**
  - Higher-performance/cost (Gr/Ep) prepreg material
  - Tape placement, autoclave cure fabrication,
  - Sandwich design
- **Technical fit**
  - Higher Performance matches weight critical apps
  - Lower Development cost – (adapt existing material/fab/design)
  - Moderate Production cost – (moderate scale)
  - Lower Operations cost matches long-term app's
- **Program fit**
  - **High** TRL allows near-term adaptation
- **Technical-Program fit**
  - **Moderate** fit primarily for Orion and EDS

Constellation Element			Structural System 15: Technical Fit	Structural System 15: Program Fit	Structural System 15: Technical-Program Fit
Constellation Element				3	
Ares 1					
	First stage				
	Interstage		8	2	1
	Upper stage	Aft section	9	2	1
		LO2 tank	9	2	1
		Intertank (CB)	8	2	1
		LH2 tank	10	2	2
		Instrument unit	7	2	1
Orion					
	Spacecraft adapter		7	2	1
	Service module	Tanks	9	2	1
		Shell	8	2	1
	Crew module	Crew cabin	11	2	2
		Aeroshell, fwd	11	2	2
		Aeroshell, aft	11	2	2
	LAS	Shroud	6	2	1
		Tower	6	2	1
Ares V					
	First stage	Aft section	9	3	2
		LO2 tank	8	3	1
		Intertank	8	3	1
		LH2 tank	9	3	2
	Interstage		8	3	1
	EDS	Aft section	9	3	2
		LO2 tank	10	3	2
		Intertank	9	3	2
		LH2 tank	10	3	2
	LSAM shroud		8	3	1
Altair					
	Descent stage	LO2 tank(s)			
		Support str			
		LH2 tank(s)			
		Legs			
	Ascent stage	LO2 tank(s)			
		Support str			
		LCH4 tank(s)			
		Crew cabin	11	3	3

Figure 7-4. Structural System 15: HiMat/Fiber/Sandwich

- **Structural System Definition**
  - High-performance/cost (toughened Gr/Ep) material
  - Hand lay-up, autoclave-cure fabrication
  - Sandwich design
- **Technical fit**
  - Higher Performance matches weight-critical apps
  - Lower Development cost for near-term apps
  - Higher Production cost – (fab. matches moderate scale)
  - Higher Operations cost matches expendable apps
- **Program fit**
  - **High** TRL allows near-term adaptation
- **Technical-Program fit**
  - **Moderate** fit primarily for EDS and Ares I US and weight-critical Altair crew cabin

			Structural system 23		
			Technical Fit	Program Fit	Technical-Program Fit
Constellation Element				3	
Ares 1					
	First stage				
	Interstage		8	2	1
	Upper stage	Aft Section	9	2	1
		LO2 tank	9	2	1
		Intertank (CB)	10	2	2
		LH2 tank	10	2	2
		Instrument Unit	9	2	1
Orion					
	Spacecraft adapter		9	2	1
	Service module	Tanks	9	2	1
		Shell	10	2	2
	Crew module	Crew cabin	9	2	1
		Aeroshell, fwd	9	2	1
		Aeroshell, aft	9	2	1
	LAS	Shroud	8	2	1
		Tower	8	2	1
Ares V					
	First stage	Aft section	9	3	2
		LO2 tank	8	3	1
		Intertank	8	3	1
		LH2 tank	9	3	2
	Interstage		8	3	1
	EDS	Aft section	9	3	2
		LO2 tank	10	3	2
		Intertank	9	3	2
		LH2 tank	10	3	2
	LSAM Shroud		8	3	1
Altair					
	Descent stage	LO2 tank(s)			
		Support str			
		LH2 tank(s)			
		Legs			
	Ascent stage	LO2 tank(s)			
		Support str			
		LCH4 tank(s)			
		Crew cabin	9	3	2

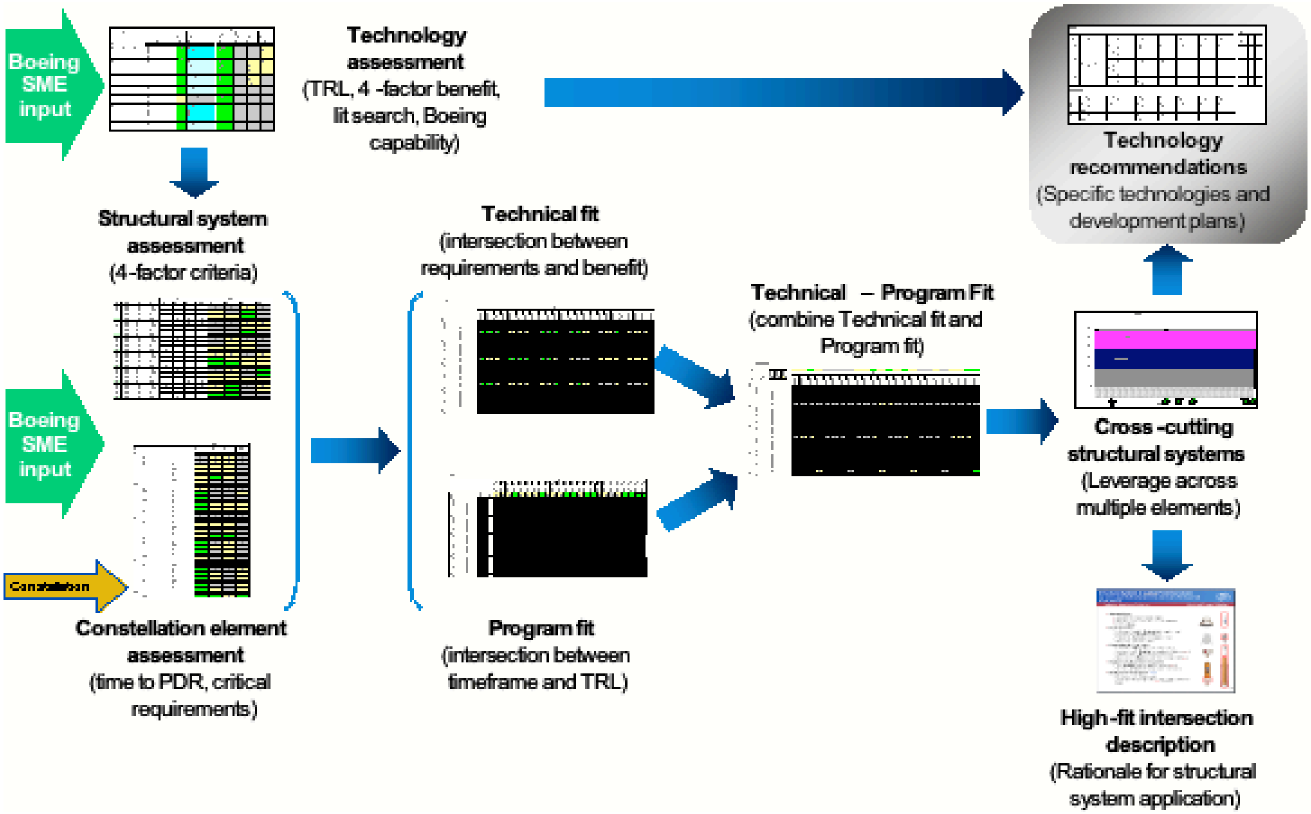
Figure 7-5. Structural System 23: HiMat/Hand/Sand

- **Structural System Definition**
  - Higher-performance/cost (Gr/Ep) prepreg material
  - Hand-layup, autoclave cure fabrication
  - Monocoque design
- **Technical fit**
  - Higher Performance – (high perf. system matches high req.)
  - Lower Development cost - environmental effects database required
  - Higher Production cost matches low qty, smaller sizes
  - Moderate Operations cost matches long duration apps
- **Program fit**
  - **High** TRL enables near-term opportunities
- **Technical-Program fit**
  - **Moderate/High** fit for all Altair elements

			Structural System 24		
			Technical Fit	Program Fit	Technical-Program Fit
Constellation Element				3	
Ares 1					
	First stage		7	2	1
	Interstage				
	Upper stage	Aft section			
		LO2 tank			
		Intertank (CB)			
		LH2 tank			
		Instrument unit	8	2	1
Orion					
	Spacecraft adapter				
	Service module	Tanks	8	2	1
		Shell			
	Crew module	Crew cabin			
		Aeroshell, fwd			
		Aeroshell, aft			
	LAS	Shroud			
		Tower	7	2	1
Ares V					
	First stage	Aft section			
		LO2 tank			
		Intertank			
		LH2 tank			
	Interstage				
	EDS	Aft section			
		LO2 tank			
		Intertank			
		LH2 tank			
	LSAM shroud				
Altair					
	Descent stage	LO2 tank(s)	11	3	3
		Support str	10	3	2
		LH2 tank(s)	11	3	3
		Legs	11	3	3
	Ascent stage	LO2 tank(s)	11	3	3
		Support str	10	3	2
		LCH4 tank(s)	11	3	3
		Crew cabin	10	3	2

Figure 7-6. Structural System 24: HiMat/Hand/Mono

8.0 TECHNOLOGY RECOMMENDATIONS



Three of the six cross-cutting structural systems were found to minimize the number of materials and processes, fabrication methods, and design concepts that needed to be characterized, thus minimizing Constellation-wide complexity, risk, and cost (Figure 8-1). Structural systems 13, 15, and 24 are highly complementary, with structural system 13 most beneficial for Ares I, Orion, and lower-stage parts of Ares V. Structural system 15 applies to the entire Orion crew module and entire EDS. Structural system 24 has highly applicable to Altair. In contrast, structural systems 3, 11, and 12—all LoMat—were not as comprehensive as the HiMat-based system of structural systems. Thus, the set of three structural systems is defined in this study as a system of structural systems.

This section consists of a hierarchical set of technology recommendations, organized into a general strategy, a Constellation-wide program, integrated technology demonstrations, and task order follow-on projects (Figure 8-2). These recommendations are based on the set of three structural systems defined above.

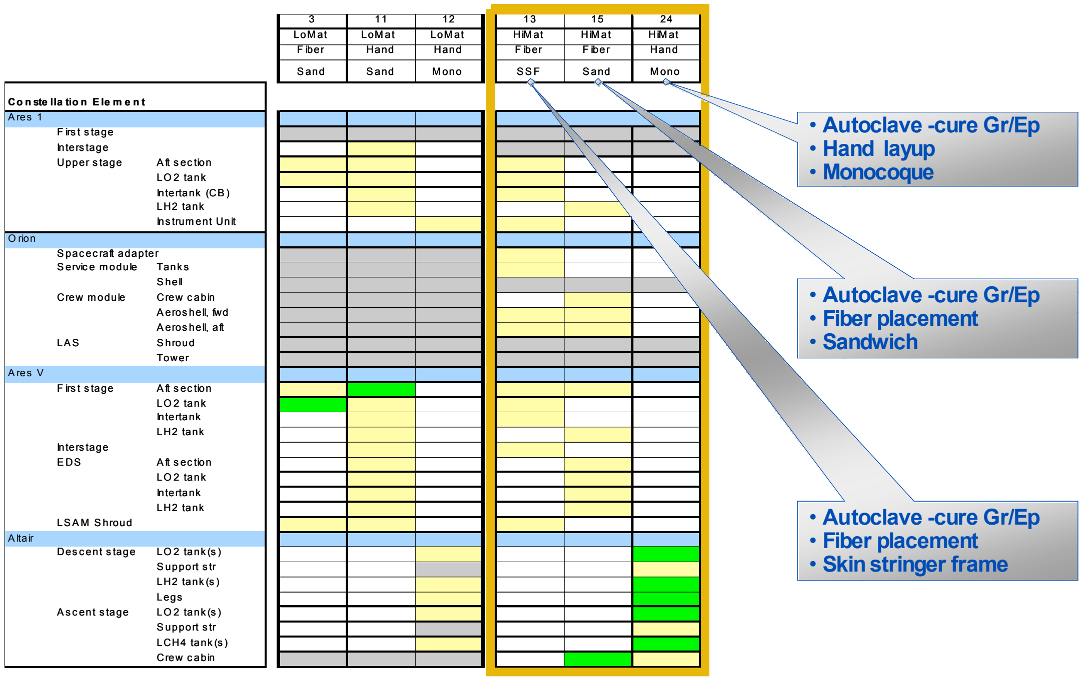


Figure 8-1. Three related, single-material structural systems satisfy majority of Constellation program.

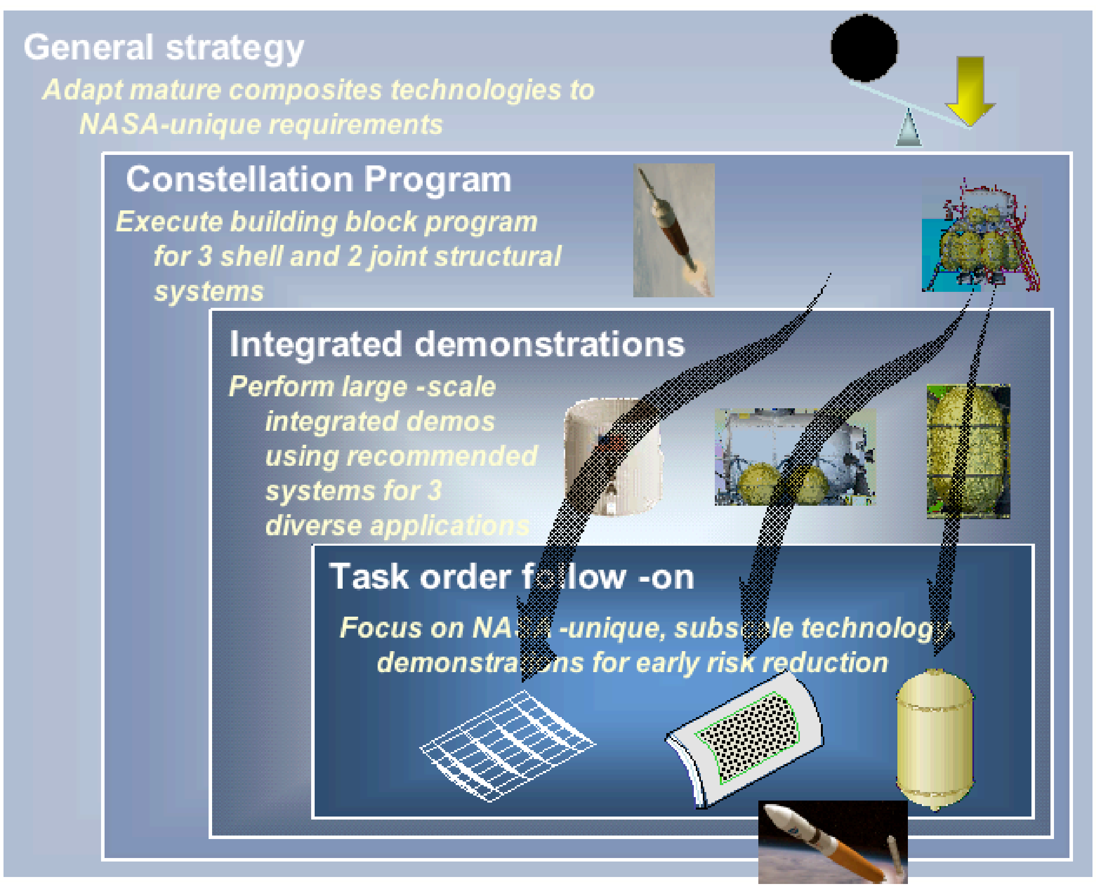


Figure 8-2. Hierarchical Set of Recommendations

8.1 General Strategy

Figure 8.1-1 summarizes the recommended general strategy. This strategy is based on the observation that most of the applicable technologies have been developed to at least TRL 6 in other aerospace programs.

- ***Adapt* commercially available and/or nonunique technologies for Constellation applications**
  - Most individual technologies have been developed for aerospace to TRL 6+
  - Minimize development cost/risk with little performance penalty
  - e.g., extend existing autoclave -cure M&P to space environment
- **Develop *unique* technologies for Constellation applications**
  - Multifunctional designs (Innovative Design category)
    - For extremely weight -critical applications (e.g., Altair)
  - All aspects of Design for Threat/environment category
    - MMOD, lunar dust, aging, static charge, thermal cycling, radiation, noise, and toxicity and outgassing
  - Large-scale, expendable, and low -quantity structures
  - Cryotanks

Figure 8.1-1. Recommended General Strategy

8.2 Constellation-wide Technology Development Plan

The second level of the hierarchy of technology recommendations involves the building-block development of the integrated set of technologies associated with the three Rigid Shell Structural Systems, the two joint structural systems, and the applicable common technologies (Figure 8.2-1). A recommended Constellation-wide technology development plan is a classic building block approach that focuses on the selected system of structural systems. Quantitative trade studies are required to finalize the selected systems and to benchmark performance and cost attributes. These trade studies are used to identify and select specific structural system constituents and associated technologies. For example, IM7/977-2, a toughened Gr/Ep prepreg, is a likely candidate for all three structural systems. A detailed development plan defines the building block program. The building block development program would proceed using the selected constituents.

The system of structural systems consists of three rigid shell structural systems, two joint structural systems, and applicable common technologies (Figure 8.2-2). These parts provide the framework for the entire technology portfolio. Three rigid shell structural systems consist of unique technologies related to the material, design, and manufacturing method. Common technologies are associated with the analysis, design criteria, certification, and environmental technology categories. Two (bolted and bonded) joint structural systems also are characterized by unique material, design, and manufacturing method technologies.

Common technologies are those which may apply to all 24 rigid shell structural systems and two joint structural systems (Figure 8.2-3), depending on the Constellation element application. For example, Coatings and Sealants technology is required for all structural systems and all

Constellation elements and thus needs to matured to the same level as all other constituents of a selected structural system before the structural system is committed to production. A different type of common technology is exemplified by the Internal and Residual Stress Analysis technology, which is common to the extent that a Constellation element requires thick laminates or complex geometries.

Figures 8.2-4 through 8.2-18 are a compilation of all technologies associated with the three rigid shell structural systems and the two joint structural systems. The development plan is extracted from the comprehensive technology plan described earlier. The third column identifies the structural system to which the technology refers. The fourth column indicates the top-level strategy to either adapt an existing capability or to uniquely develop the technology for NASA's Constellation program.

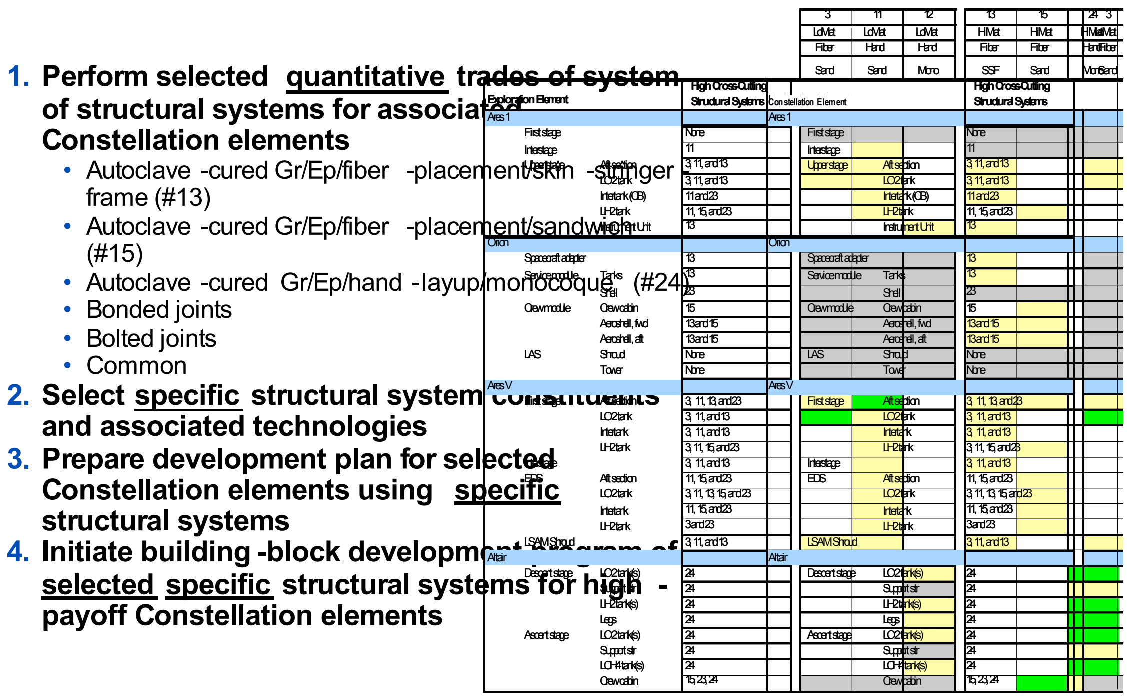


Figure 8.2-1. Recommended Constellation-wide Technology Development Program

Rigid shell structural systems

Shells, Rigid	1. Materials and Processes	2. Manufacturing Methods	3. Innovative Design	4. Analysis, Modeling, and Simulation	5. Design Criteria and Allowables	6. Dvt, QA, and Cert	7. Design for Threats
13	Advanced autoclave cure M&P	Autoclave manufacturing methods Fiber placement methods	Skin-stringer-frame design	SSF analysis	*No unique (Common)*	*No unique (Common)*	*No unique (Common)*
15		Autoclave manufacturing methods Sandwich (core) manufacturing methods Fiber placement methods	Sandwich designs	Sandwich analysis	*No unique (Common)*	*No unique (Common)*	*No unique (Common)*
24		Autoclave manufacturing methods	Lightweight structure for load transfer	*No unique*	*No unique (Common)*	*No unique (Common)*	*No unique (Common)*

- Autoclave -cure Gr/Ep
- Fiber placement
- Skin stringer frame

- Autoclave -cure Gr/Ep
- Fiber placement
- Sandwich

- Autoclave -cure Gr/Ep
- Hand layup
- Monocoque

Joint structural systems

	1. Materials and Processes	2. Manufacturing Methods	3. Innovative Design	4. Analysis, Modeling, and Simulation	5. Design Criteria and Allowables	6. Dvt, QA, and Cert	7. Design for Threats
Bonded Joints	Bonded joining M&P (adhesives) 3-D woven preforms	Bonded assembly	Primarily bonded structures	Bonded joint analysis	*No unique (Common)*	*No unique (Common)*	*No unique (Common)*
Bolted Joints	Bolted joining M&P (fasteners) 3-D woven preforms	Bolted assembly	Efficient bolted joints between large sections	Bolted joint analysis	*No unique (Common)*	*No unique (Common)*	*No unique (Common)*

Figure 8.2-2. System of structural systems includes all technology categories and two joint systems.

1 Materials and Processes
- Coatings and sealants

2. Manufacturing Methods
- In-process inspection techniques

3. Innovative Design
- Multifunctional designs
- Tailored composites
- Interaction between components
- Methods of preventing damage growth

4. Analysis, Modeling and Sim
- Analysis of effects of defects
- Analysis of highly tailored composites
- Simulated test and evaluation
- Thermo-structural analysis
- Failure mechanism/prediction
- Optimization methods
- Fatigue/life prediction
- Probabalistic analysis
- Hierarchical analysis
- Internal and residual stress analysis

5. Design Criteria and Allowables
- Damage tolerance DC&A
- Standardized Allowables
- Environmental durability DC&A
- Knockdown factors
- Safety factors based on aircraft approach
- Develop NDE standards
- Minimum gage specifications

6. Development, QA and Cert
- Nondestructive Inspection Methods
- QA to Structural Performance Correlation
- Post-damage reliability prediction
- In-Situ Damage Detection and Prognostics
- Structural health monitoring, diagnostics, and prognostics
- Hot spot interrogation
- Certification by analysis
- Certification by simulation
- Improved test methods
- Database development
- In-space/ground repair methods

7. Threat/Environment
- MMOD (lunar/LEO)
- Lunar dust
- Aging in lunar and space environment
- Static charge
- Thermal cycling
- Radiation
- Noise
- Toxicity & outgassing

Figure 8.2-3. Recommended Constellation-wide Technology Portfolio (Common)

Technology	Development Plan	Structural System	Strategy
1. Materials and Processes			
Advanced autoclave cure M&P	1. Utilize higher operating temperature toughened Ep and BMI with lower cure temp and pressure 2. Utilize higher operating temp thermoplastics with lower consolidation temp and pressure 3. Improve hydrogen impermeability for cryotanks 4. Employ thin-ply laminates to minimize microcracking in cryotanks (ref. Tsai)	13,15,24	Adapt
Sandwich (core) M&P	1. Design a multifunctional, multicomponent core with strength, thermal, radiation, self-repair, etc., properties 2. Incorporate sandwich panel purge/vent system integration 3. Utilize low permeability co-cured sandwich facesheets	15	Adapt
Molding compounds M&P	1. Adapt BCA MCs for space applications	Bolted	Adapt
Bonded joining M&P (adhesives)	1. Develop open-air plasma treatment for lower cost and cycle time for cobond/secondary bond applications 2. Develop inspection process for surface preparation prior to secondary bonding 3. Scale up and validate surface energy-based methods developed in CAI program 4. Improve joint design/durability/damage tolerance for cryotanks 5. Develop bonded joint NDE methods (correlate to strength)	Bonded	Adapt

Figure 8.2-4. Constellation-wide Technology Development Plan (1 of 15)—M&P

Technology	Development Plan	Structural System	Strategy
1. Materials and Processes			
Bolted joining M&P (fasteners)	1. Implement low-cost fasteners for composites	Bolted	Adapt
Coatings and sealants	1. Develop multifunctional, multicomponent coatings (including nano) with thermal, radiation, repair, etc., properties 2. Implement more durable conductive thermal control coatings 3. Utilize a chrome-free cryogenic primer for LO2/LH2 cryotanks 4. Develop low-cost conductive thermal control coatings (silicone resin/zinc oxide) for space applications	Common	Adapt
Nano-composites	1. Develop multifunctional, multicomponent coatings with (electrical, thermal, radiation, repair, acoustic, mechanical, etc., properties (ref. Rice University/NASA URETI project)	Common	NASA-unique
3-D woven preforms	1. Utilize 3-D woven ring frames 2. Integrate woven preforms with resin infusion M&P	Common	Adapt

Figure 8.2-5. Constellation-wide Technology Development Plan (2 of 15)—M&P

Technology	Development Plan	Structural System	Strategy
2. Manufacturing Methods			
Autoclave manufacturing methods	1. Define large-scale autoclave (10 m) design, fabrication, operation, and cost	13,15,24	Adapt
Fiber placement methods	1. Increase material laydown rates with multiple head processes for larger scale parts 2. Trade hybrid processes that mix 3 in to 12 in tape with 1/8 to 1/2 in tow for optimal rates 3. Optimize machine configuration for 5 m parts and for 10 m parts (Ares V) 4. Design low-cost, right-sized fiber placement process	13,15,24	Adapt
Large (reusable) tooling	1. Develop tooling materials and fabrication for large-scale (10 m) cryotanks (optimum number of parts and joints) 2. Identify interaction of mass, inertia, and deflection for large-scale part on production equipment and autoclave processes	13,15,24	Adapt
Sandwich (core) manufacturing methods	1. Implement single-cure for facesheets and core (and all edge details and inserts)	15	Adapt

Figure 8.2-6. Constellation-wide Technology Development Plan (3 of 15)—Manufacturing Methods

Technology	Development Plan	Structural System	Strategy
2. Manufacturing Methods			
In-process inspection techniques	1. Promote in-process inspection —link up with nondestructive inspection methods and QA to structural performance methods	Common	Adapt
Improved assembly methods	1. Promote determinant assembly (ref. Factory of the Future) 2. Utilize laser metrology (ref. Cramer)	Common	Adapt
Bonded assembly	1. Promote a balanced use of bonding and bolting methods	Bonded	Adapt
Bolted assembly	1. Adapt 787 technology for low production quantity (less automated)	Bolted	Adapt
Molding compound	1. Develop composite molding for highly loaded fittings and frames	Bolted	Adapt
3D reinforcement	1. Specify 3D woven fabrics for high-load fittings 2. Implement stitching for high-damage prone applications	Bolted	Adapt

Figure 8.2-7. Constellation-wide Technology Development Plan (4 of 15)—Manufacturing Methods

Technology	Development Plan		
3. Innovative Design		**Structural System**	**Strategy**
Efficient bolted joints between large sections	1. Develop an all-composite bolted joint (replace Al or Ti fitting or ring frame)	Bolted	Adapt
Multifunctional designs	1. Incorporate MMOD-radiation-acoustic protection in structure for long-duration space applications (ref ISS) 2. Implement active vibration control for LV payloads	Common	NASA
Sandwich designs	1. Minimize weight penalty of openings and joints combine core 2. Develop sandwich for failure-redundant propellant tank with multifunctional core thermal, MMOD, acoustic)	15	Adapt
Hybrid (metal/ composite) structures	1. Develop hybrids for higher-efficiency bolted joints (ref Fink)	Bolted	Adapt
Tailored composites	1. Apply fiber steering to large structures 2. Identify methods of controlling and analyzing steering 3. Perform mechanical testing to validate modeling results 4. Determine weight savings for various structure types	Common	Adapt
Primarily bonded structures	1. Develop/validate Z-reinforced cobonded/co-cured joints for fail safety (composite-composite and metal-composite joints) 2. Balance bolted and bonded approaches	Bonded	Adapt
Point load introduction	1. Utilize composite fittings with molding compounds or resin infusion	Bolted	Adapt

Figure 8.2-8. Constellation-wide Technology Development Plan (5 of 15)—Innovative Design

Technology	Development Plan		
3. Innovative Design		**Structural System**	**Strategy**
Composite pressure vessels (nonintegral)	1. Develop tanks with and without polypropylene liner for (1) short-term, then (2) long-term, storage of cryogenic fluids or gaseous He	24	Adapt
Lightweight structure for load transfer	1. Develop truss structure with integral and/or composite end fittings	24	Adapt
Methods of preventing damage growth	1. Apply stitching to local damage-prone areas only	Common	Adapt
MMOD resistant design	1. Investigate further development of the Apollo hypervelocity impact database on honeycomb cell sizing to minimize channeling effects of honeycomb core; would apply to composite or metallic honeycomb (required for honeycomb sandwich use) 2. Work to mitigate the tendency of composites to delaminate and debond upon hypervelocity impact (required for composite use) 3. Determine the maximum/optimum height for honeycomb sandwiches; for MMOD, more space is better (sandwich improvement, i.e., lower priority than 1 and 2)	Common	NASA
Skin-stringer-frame design	1. Minimize fastened parts for minimum weight 2. Design for secondary bonding (with minimum fasteners) of frame caps or other buildup	13	Adapt

Figure 8.2-9. Constellation-wide Technology Development Plan (6 of 15)—Innovative Design

Technology	Development Plan	Structural System	Strategy
4. Analysis, Modeling and Simulation			
Sandwich analysis	1. Improve analytical techniques for predicting disbond and crack arrestment in sandwich structures	15	Adapt
Skin-stringer-frame analysis	1. Analyze stiffener terminations and discontinuities	13	Adapt
Analysis of effects of defects	1. Adapt commercial aircraft defect analysis BOK	Common	Adapt
Analysis of highly-tailored composites	1. Study the cost and benefit of highly tailored composite structures	Common	Adapt
Simulated test and evaluation	1. Develop simulations to complement test and evaluation efforts and to lessen the need for repetitive testing	Common	Adapt
Thermo-structural analysis	1. Adapt X-37 lessons learned to Orion (and other) heatshield	Common	Adapt
Failure mechanism/ prediction	1. Analyze failure modes 2. Develop a database	Common	Adapt

Figure 8.2-10. Constellation-wide Technology Development Plan (7 of 15)—Analysis, Modeling, and Simulation

Technology	Development Plan	Structural System	Strategy
4. Analysis, Modeling and Simulation			
Optimization methods	1. Develop multifactor (performance and cost) and multifunctional (structure, radiation, MMOD, etc.) optimization techniques	Common	Adapt
Fatigue/life prediction	1. Characterize environmental (e.g., thermal cycling) degradation	Common	Adapt
Probabilistic risk assessment	1. Evaluate, balance level of engineering data available to support PRAs: MMOD is usually fairly detailed since design is statistically driven; others often are less probabilistic in nature 2. Develop common data requirements for Constellation programs to use in data set acquisition and development 3. Document data confidence levels	Common	Adapt
Reliability-based or risk-based analysis	1. Develop a database to support reliability-based design and analysis 2. Link up with factors of safety based on an aircraft approach 3. Develop standardized allowables, optimization methods, and knockdown factor analysis	Common	Adapt
Certification to needed risk or reliability — similar to simulated test and evaluation	1. Develop a database to support probabilistic certification 2. Link up with accelerated aging and test methods, certification by analysis, certification by simulation, improved test methods, and postdamage detection and prognostics.	Common	Adapt

Figure 8.2-11. Constellation-wide Technology Development Plan (8 of 15)—Analysis, Modeling, and Simulation

Technology	Development Plan	Structural System	Strategy
4. Analysis, Modeling and Simulation			
Risk-based or reliability-based maintenance — similar to fatigue/life prediction	1. Develop a database to support reliability-based maintenance program 2. Link up with NDE standard, in situ damage detection and prognostics, structural health monitoring, diagnostics, and prognostics, postdamage reliability prediction, damage tolerance DC&A, in-space/ground repair methods	Common	Adapt
Hierarchical analysis	1. Develop the hierarchical analysis of structural systems 2. Link up with nanotech efforts	Common	Adapt
Internal and residual stress analysis	1. Minimize residual stresses through cure cycle optimization	Common	Adapt
Scaling and validation	1. Implement scaling and validation of scaled composites (ref. esp. Johnson, Morton, Kellas, and Jackson)	Common	Adapt
MMOD impact analysis	1. Automate the transfer of CAD models into Bumper-compatible formats 2. Continue algorithm development–the shadowing algorithm in Bumper has restrictions on relative size of elements; work has been done on ISS to develop new algorithm to remove this restriction (models from #1 tend to have significant variation in element sizing 3. Improve body of knowledge on failure criteria as it is a significant source of impact analysis error. Need to plan for agency/industry wide development of common database; on ISS we're trying to obtain residual asset hardware for impact testing with some success; this approach needs to be expanded	Common	NASA

Figure 8.2-12. Constellation-wide Technology Development Plan (9 of 15)—Analysis, Modeling, and Simulation

Technology	Development Plan	Structural System	Strategy
4. Analysis, Modeling and Simulation			
Bonded joint analysis	1. Apply new 3D parametric FEM tools to bonded joints 2. Enable inclusion of nonlinear behavior and both peel and shear stress in bondline, and be able to predict both cohesive failures in adhesive as well as failures in composite adherends in one integrated analysis model 3. Use Strain Invariant Failure Theory for damage initiation and growth prediction in both adhesive layer and surrounding composite plies 4. Use new fracture interface element methods for damage growth predictions. Analytical tools exist, but need to measure appropriate materials properties and validate across a range of joint designs and environments	Bonded	Adapt
Bolted joint analysis	1. Incorporate thermal effects, seals and leakage	Bolted	Adapt
Cost analysis	1. Validate tools with hardware design, build, and test	Common	Adapt

Figure 8.2-13. Constellation-wide Technology Development Plan (10 of 15)—Analysis, Modeling, and Simulation

Technology	Development Plan		
5. Design Criteria and Allowables		**Structural System**	**Strategy**
Damage tolerance DC&A	1. Characterize acceptable and reasonable levels and likelihood of damage for complete life cycle (with and without on-board SHM)	Common	Adapt
Radiation protection DC&A	1. Characterize materials evaluation/assessment; particle transport & dose attenuation in lunar environment	Common	Adapt
MMOD resistant DC&A	1. Develop improved failure criteria, mainly through impact testing; including database of all performed non-proprietary impact tests and developed equations (ref JSC good database) 2. Document confidence levels in the data	Common	NASA
Standardized allowables	1. Develop and standardize body of knowledge on allowables	Common	Adapt
Environmental durability DC&A	1. Empirically establish environmental effects on most likely (cross-cutting) structural systems	Common	Adapt
Knockdown factors	1. Validate knockdown factors with probabilistic analysis	Common	Adapt

Figure 8.2-14. Constellation-wide Technology Development Plan (11 of 15)—Design Criteria and Allowables

Technology	Development Plan		
5. Design Criteria and Allowables		**Structural System**	**Strategy**
Safety factors based on aircraft approach	1. Trade the levels of test, analysis, and allowable safety factors (commercial and military AC can amortize extensive testing and analysis) 2. Evaluate the use of qualified commercial or military aircraft systems with FAA-approved factors of safety	Common	Adapt
Develop NDE standards	1. Develop standards for NDE during product development	Common	Adapt
Minimum gage specifications	1. Evaluate extra-thin prepreg tape while considering all other criteria	Common	Adapt
Bonded joint DC&A	1. Adapt FAA criteria for space applications	Bonded	Adapt
Bolted joint DC&A	1. Adapt FAA criteria for space applications	Bolted	Adapt

Figure 8.2-15. Constellation-wide Technology Development Plan (12 of 15)—Design Criteria and Allowables

Technology	Development Plan		
6. Development, Quality Assurance, and Certification		**Structural System**	**Strategy**
Nondestructive inspection methods	1. Scale up and validate the laser-based inspection device (LBID) for interrogating the strength of bonded joints 2. Develop ultrasonic phased-array technology	Common	Adapt
QA to structural performance correlation	1. Scale up and validate the LBID for interrogating the strength of bonded joints	Common	Adapt
Postdamage reliability prediction	1. Develop postdamage reliability prediction methods to determine availability versus given flight risks 2. Link up with damage tolerance design criteria and allowables	Common	Adapt
In situ damage detection and prognostics	1. SHM Reasoner: Develop an integrated SHM reasoner that will integrate multisensor systems to detect, diagnose, and report structural health information for supporting mission planning and maintenance actions 2. Adapt flight system testing and qualification to in situ methods	Common	Adapt
Structural health monitoring, diagnostics, and prognostics	1. Develop diagnostic criteria for various damage/failure modes that are of concern to structural test and production 2. Develop tools and processes for structural health monitoring, diagnostics, and prognostics	Common	Adapt

Figure 8.2-16. Constellation-wide Technology Development Plan (13 of 15)—Development, QA, and Certification

Technology	Development Plan		
6. Development, Quality Assurance, and Certification		**Structural System**	**Strategy**
Hot spot interrogation	1. Develop enhanced diagnostic capability with a minimum complexity added to the structures	Common	Adapt
Scaling effects	1. Analytically model and experimentally verify the scaling of large cryotank structures	Common	Adapt
Certification by analysis	1. Assess probabilistic certification methodology (ref. Han-Pin Kan)	Common	Adapt
Certification by simulation	1. Develop simulation methods for certification of flight structures especially for uninhabited vehicles	Common	Adapt
Improved test methods	1. Standardize MMOD certification; currently variations exist between programs that produce nontrivial cost and weight impacts on certification	Common	Adapt
Database development	1. Promote the development of a certification body of knowledge (BOK) and database 2. Link up with the adaptation of commercial aircraft BOK for the certification of composite air structures	Common	Adapt
Accelerated aging and test methods	1. Assess probabilistic aging method (ref Tomg) 2. Review HSR methods	Common	Adapt
In space/ground repair methods	1. Investigate self-healing methods	Common	Adapt
Improved leak detection	1. Develop fiber optic sensors for lighter weight and higher reliability 2. Develop noncontact leak detectors	Common	NASA

Figure 8.2-17. Constellation-wide Technology Development Plan (14 of 15)—Development, QA, and Certification

Technology	Development Plan	Structural System	Strategy
7. Design for Threat/Environment			
MMOD (lunar/LEO)	1. Develop ultrahigh-speed (15 to 20 km/sec) launch capability to characterize meteor impact effects; three-stage light gas guns are under development, but not "production"; integrate Navy's development work with rail guns for weaponry and general increases in materials technology (ability to withstand high-rail contact pressures during launch at higher velocities) may have enabled technology	Common	NASA
Lunar dust	1. Incorporate NASA Glenn antidust coatings for Lunar and Mars dust—a coating of Americium-241 paint to neutralize the electrostatic charge on the dust particles 2. Repeat LDEF on lunar surface or at LLO	Common	NASA
Aging in lunar and space environment	1. Repeat LDEF on lunar surface or at LLO	Common	NASA
Static charge	1. Study static charge mitigation in structures for both dust repulsion and the management of ESD risks to life and electronics	Common	NASA
Thermal cycling	1. Repeat LDEF on lunar surface or at LLO	Common	NASA
Radiation	1. Radiation effects on electronics parts using lunar LDEF	Common	NASA
Noise	1. Utilize multifunctional sandwich structures	Common	NASA
Toxicity and outgassing	1. Repeat LDEF on lunar surface or at LLO	Common	NASA

Figure 8.2-18. Constellation-wide Technology Development Plan (15 of 15)—Design for Threat/ Environment

8.3 Integrated Technology Demonstrations

The third level of the hierarchy of recommendations consists of three Integrated Technology Demonstrations (ITDs). These ITDs are based on the Constellation-wide technology development plan, and were selected to represent a broad array of NASA-unique technologies. Each ITD represents one of the three cross-cutting structural systems and a major Constellation element (Figure 8.3-1). ITD 1 represents structural system 13 as applied to the Ares V Interstage. This ITD demonstrates large-scale producibility and weight-critical structure (Figures 8.3-2 through 8.3-5). ITD 2 develops structural system 15 specifically for the Altair Crew Cabin. Unique features include multi-functional and weight-critical sandwich structure (Figures 8.3-6 through 8.3-15). ITD 3 uses structural system 24 to demonstrate long-term durability of LO_2 tanks (Figure 8.3-16 through 8.3-22).

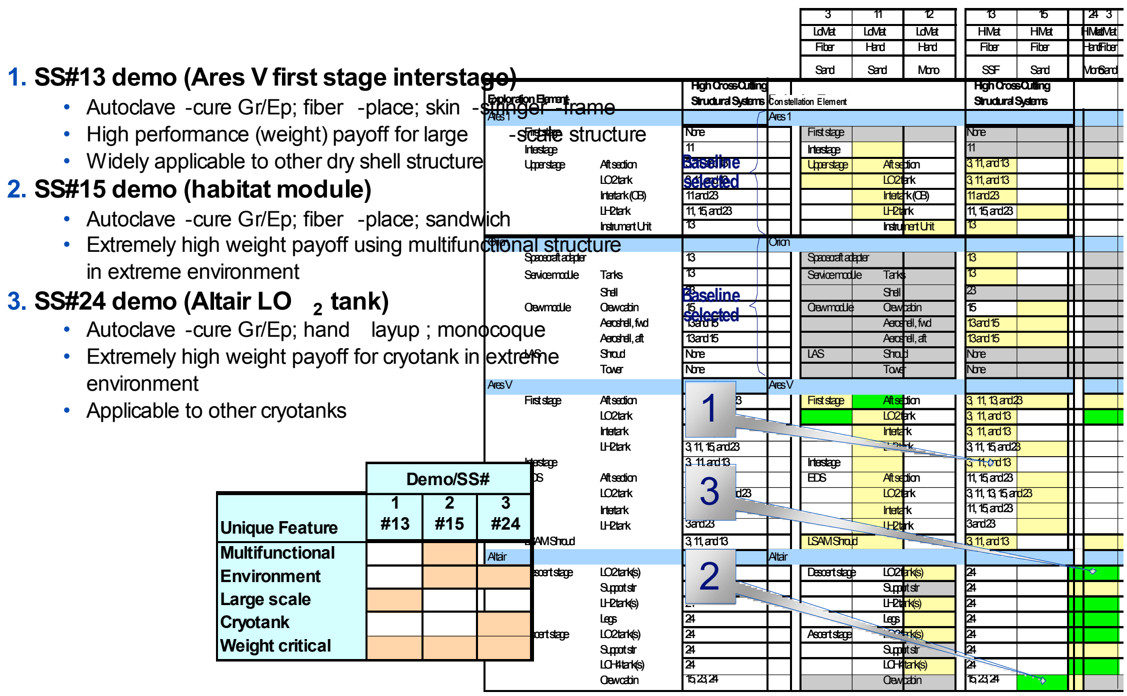


Figure 8.3-1. Recommended Integrated Technology Demonstrations

Technology	Development Plan		
1. Materials and Processes		**Structural System**	**Strategy**
Advanced autoclave cure M&P	1. Utilize higher operating temperature toughened Ep and BMI with lower cure temp and pressure	13	Adapt
Bolted joining M&P (fasteners)	1. Implement low-cost fasteners for composites	Bolted	Adapt
3D woven preforms	1. Utilize 3-D woven ring frames 2. Integrate woven preforms with resin infusion M&P	Common	Adapt

Figure 8.3-2. Recommended Technologies for ITD 1 (1 of 4)

Technology	Development Plan	Structural System	Strategy
2. Manufacturing Methods			
Autoclave manufacturing methods	1. Define large-scale autoclave (10 m) design, fabrication, operation, and cost	13	Adapt
Fiber placement methods	1. Increase material laydown rates with multiple head processes for larger scale parts 2. Trade hybrid processes that mix 3-in to 12-in tape with 1/8 to 1/2 in tow for optimal rates 3. Optimize machine configuration for 5m parts and for 10-m parts (Ares V) 4. Design low-cost, right-sized fiber placement process	13	Adapt
Large (reusable) tooling	1. Develop tooling materials and fabrication for large-scale (10-m) cryotanks (optimum number of parts and joints) 2. Identify interaction of mass, inertia, and deflection for large-scale part on production equipment and autoclave processes	13	Adapt
Improved assembly	1. Utilize determinant assembly (ref. Factory of the Future) 2. Utilize laser metrology (ref. Cramer)	Common	Adapt
Bolted assembly	1. Adapt 787 technology for low production quantity (less automated)	Bolted	Adapt
3D reinforcement	1. Specify 3D woven fabrics for high-load fittings 2. Implement stitching for high-damage prone applications	Bolted	Adapt

Figure 8.3-3. Recommended Technologies for ITD 1 (2 of 4)

Technology	Development Plan	Structural System	Strategy
3. Innovative Design			
Efficient bolted joints between large sections	1. Develop an all-composite bolted joint (replace Al or Ti fitting or ring frame)	Bolted	Adapt
Point load introduction	1. Utilize composite fittings with molding compounds or resin infusion	Bolted	Adapt
Skin-stringer-frame design	1. Minimize fastened parts for minimum weight. 2. Design for secondary bonding (with minimum fasteners) of frame caps or other buildup	13	Adapt

Technology	Development Plan	Structural System	Strategy
4. Analysis, Modeling, and Simulation			
Skin-stringer-frame analysis	1. Analyze stiffener terminations and discontinuities	13	Adapt
Simulated test and evaluation	1. Develop simulations to complement test and evaluation efforts and to lessen the need for repetitive testing	Common	Adapt
Hierarchical analysis	1. Develop the hierarchical analysis of structural systems	Common	Adapt
Scaling and validation	1. Implement scaling and validation of scaled composites (ref. esp. Johnson, Morton, Kellas, and Jackson)	Common	Adapt
Bolted joint analysis	1. Incorporate thermal effects, seals and leakage	Bolted	Adapt
Cost analysis	1. Validate tools with hardware design, build, and test	Common	Adapt

Figure 8.3-4. Recommended Technologies for ITD 1 (3 of 4)

Technology	Development Plan	Structural System	Strategy
5. Design Criteria and Allowables			
Safety factors based on aircraft approach	1. Trade the levels of test, analysis, and allowable safety factors (commercial and military AC can amortize extensive testing and analysis) 2. Evaluate the use of qualified commercial or military aircraft systems with FAA-approved factors of safety	Common	Adapt
Bolted joint DC&A	1. Adapt FAA criteria for space applications	Bolted	Adapt

Technology	Development Plan	Structural System	Strategy
6. Development, Quality Assurance, and Certification			
Nondestructive Inspection Methods	1. Scale-up and validate the laser-based inspection device (LBID) for interrogating the strength of bonded joints 2. Develop ultrasonic phased-array technology	Common	Adapt
Scaling effects	1. Analytically model and experimentally verify the scaling of large cryotank structures	Common	Adapt

Technology	Development Plan	Structural System	Strategy
7. Design for Threat/Environment			

Figure 8.3-5. Recommended Technologies for ITD 1 (4 of 4)

Technology	Development Plan	Structural System	Strategy
1. Materials and Processes			
Advanced autoclave cure M&P	1. Utilize higher operating temperature toughened Ep and BMI with lower cure temp and pressure 4. Employ thin-ply laminates to minimize microcracking	15	Adapt
Sandwich (core) M&P	1. Design a multifunctional, multicomponent core with strength, thermal, radiation, self-repair, etc., properties 2. Incorporate sandwich panel purge/vent system integration 3. Utilize low permeability co-cured sandwich facesheets	15	Adapt
Molding compounds M&P	1. Adapt BCA MCs for space applications	Bolted	Adapt
Bonded joining M&P (adhesives)	1. Develop open air plasma treatment for lower cost and cycle time for cobond/secondary bond applications. 2. Develop inspection process for surface preparation prior to secondary bonding. 3. Scale-up and validate surface energy-based methods developed in CAI program. 4. Improve joint design/durability/damage tolerance 5. Develop bonded joint NDE methods (correlate to	Bonded	Adapt
Coatings and sealants	1. Develop multifunctional, multicomponent coatings (including nano) with thermal, radiation, repair, etc., properties 2. Implement more durable conductive thermal control coatings 3. Utilize a chrome-free cryogenic primer for LO2/LH2 cryotanks 4. Develop low-cost conductive thermal control coatings (silicone resin/zinc oxide) for space applications	Common	Adapt

Figure 8.3-6. Recommended Technologies for ITD 2 (1 of 10)

Technology	Development Plan	Structural System	Strategy
2. Manufacturing Methods			
Autoclave manufacturing methods	1. Define large-scale autoclave (10m) design, fabrication, operation, and cost	15	Adapt
Fiber placement methods	4. Design low-cost, right-sized fiber placement process	15	Adapt
Sandwich (core) manufacturing methods	1. Implement single-cure for facesheets and core (and all edge details and inserts)	15	Adapt
In-process inspection techniques	1. Promote in-process inspection--link up with Nondestructive Inspection Methods and QA to structural performance methods	Common	Adapt
Bonded assembly	1. Promote a balanced use of bonding and bolting methods	Bonded	Adapt
Molding compound	1. Develop composite molding for highly loaded fittings and frames	Bolted	Adapt

Figure 8.3-7. Recommended Technologies for ITD 2 (2 of 10)

Technology	Development Plan	Structural System	Strategy
3. Innovative Design			
Multifunctional designs	1. Incorporate MMOD-radiation-acoustic protection in structure for long-duration space apps (ref ISS) 2. Implement active vibration control for LV payloads	Common	Adapt
Sandwich Designs	1. Minimize weight penalty of openings and joints combine core 2. Develop sandwich for failure-redundant propellant tank with multifunctional core thermal, MMOD, acoustic)	15	Adapt
Primarily bonded structures	1. Develop/validate Z-reinforced cobonded/cocured joints for fail safety (Composite-composite and metal-composite joints) 2. Balance bolted and bonded approaches	Bonded	Adapt
Point load introduction	1. Utilize composite fittings with molding compounds or resin infusion	Bolted	Adapt
Methods of preventing damage growth	1. Apply stitching to local damage-prone areas only	Common	Adapt
MMOD Resistant Design	1. Investigate further development of the Apollo hypervelocity impact database on honeycomb cell sizing to minimize channeling effects of honeycomb core; would apply to composite or metallic honeycomb. (required for honeycomb sandwich use) 2. Mitigate tendency of composites to delaminate and debond upon hypervelocity impact. (required for composite use)	Common	NASA

Figure 8.3-8. Recommended Technologies for ITD 2 (3 of 10)

Technology	Development Plan	Structural System	Strategy
4. Analysis, Modeling, and Simulation			
Sandwich analysis	1. Improve analytical techniques for predicting disbond and crack arrestment in sandwich structures	15	Adapt
Analysis of effects of defects	1. Adapt commercial aircraft defect analysis BOK	Common	Adapt
Simulated test and evaluation	1. Develop simulations to complement test and evaluation efforts and to lessen the need for repetitive testing	Common	Adapt
Thermo-structural analysis	1. Adapt X-37 lessons learned to Orion (and other) heatshield	Common	Adapt
Failure mechanism/ prediction	1. Analyze failure modes 2. Develop a database	Common	Adapt
Optimization methods	1. Develop multifactor (performance and cost) and multifunctional (structure, radiation, MMOD, etc.) optiimization techniques	Common	Adapt
Fatigue/life prediction	1. Characterize environmental (e.g., thermal cycling) degradation	Common	Adapt

Figure 8.3-9. Recommended Technologies for ITD 2 (4 of 10)

Technology	Development Plan	Structural System	Strategy
4. Analysis, Modeling, and Simulation			
Probabilistic risk assessment	1. Evaluate, balance level of engineering data available to support PRAs: MMOD is usually fairly detailed since design is statistically driven; others often are less probabilistic in nature 2. Develop common data requirements for Constellation programs to use in data set acquisition and development 3. Document data confidence levels	Common	Adapt
Reliability-based or risk-based analysis	1. Develop a database to support reliability-based design and analysis 2. Link up with factors of safety based on an aircraft approach 3. Develop standardized allowables, optimization methods, and knockdown factor analysis	Common	Adapt
Certification to needed risk or reliability —similar to simulated test and evaluation	1. Develop a database to support probabilistic certification 2. Link up with accelerated aging and test methods, certification by analysis, certification by simulation, improved test methods, and postdamage detection and prognostics	Common	Adapt

Figure 8.3-10.. Recommended Technologies for ITD 2 (5 of 10)

Technology	Development Plan	Structural System	Strategy
4. Analysis, Modeling, and Simulation			
Risk-based or reliability-based maintenance — similar to fatigue/life prediction	1. Develop a database to support reliability-based maintenance program 2. Link up with NDE standard, in situ damage detection and prognostics, structural health monitoring, diagnostics, and prognostics, postdamage reliability prediction, damage tolerance DC&A, in-space/ground repair methods	Common	Adapt
MMOD impact analysis	1. Automate the transfer of CAD models into Bumper compatible formats 2. Continue algorithm development —the shadowing algorithm in Bumper has restricitons on relative size of element 3. Improve body of knowledge on failure criteria as it is a significant source of impact analysis error. Need to plan for agency/industry wide development of common database	Common	NASA
Bonded joint analysis	1. Apply new 3D parametric FEM tools to bonded joints 2. Enable inclusion of nonlinear behavior and both peel and shear stress in bondline, and be able to predict both cohesive failures in adhesive as well as failures in composite adherends in one integrated anlysis model 3. Use Strain Invariant Failure Theory for damage initiation and growth prediction in both adhesive layer and surrounding composite plies 4. Use new fracture interface element methods for damage growth predictions	Bonded	Adapt

Figure 8.3-11. Recommended Technologies for ITD 2 (6 of 10)

Technology	Development Plan	Structural System	Strategy
5. Design Criteria and Allowables		**Structural System**	**Strategy**
Damage tolerance DC&A	1. Characterize acceptable and reasonable levels and likelihood of damage for complete life cycle (with and without onboard SHM)	Common	Adapt
Radiation protection DC&A	1. Characterize materials evaluation/assessment; particle transport and dose attenuation in lunar environment	Common	Adapt
MMOD resistant DC&A	1. Develop improved failure critera, mainly through impact testing; including database of all performed nonproprietary impact tests and developed equations (ref. JSC good database)	Common	NASA
Environmental durability DC&A	1. Empirically establish environmental effects on most likely (cross-cutting) structural systems	Common	Adapt
Knockdown factors	1. Validate knockdown factors with probabilistic analysis	Common	Adapt
Safety factors based on aircraft approach	1. Trade the levels of test, analysis, and allowable safety factors (commercial and military AC can amortize extensive testing and analysis) 2. Evaluate the use of qualified commercial or military aircraft systems with FAA-approved factors of safety	Common	Adapt
Develop NDE standards	1. Develop standards for NDE during product development	Common	Adapt
Minimum gage specifications	1. Evaluate extra-thin prepreg tape while considering all other criteria	Common	Adapt
Bonded joint DC&A	1. Adapt FAA criteria for space applications	Bonded	Adapt

Figure 8.3-12. Recommended Technologies for ITD 2 (7 of 10)

Technology	Development Plan	Structural System	Strategy
6. Development, Quality Assurance, and Certification		**Structural System**	**Strategy**
Nondestructive Inspection Methods	1. Scale-up and validate the laser-based inspection device (LBID) for interrogating the strength of bonded joints 2. Develop ultrasonic phased-array technology	Common	Adapt
QA to structural performance correlation	1. Scale-up and validate the LBID for interrogating the strength of bonded joints	Common	Adapt
Postdamage reliability prediction	1. Develop postdamage reliability prediction methods to determine availability versus given flight risks 2. Link-up with damage tolerance design criteria and allowables	Common	Adapt
In situ damage detection and prognostics	1. SHM Reasoner —Develop an integrated SHM reasoner that will integrate multisensor systems to detect, diagnose, and report structural health information for supporting mission planning and maintenance actions 2. Adapt flight system testing and qualification to in situ methods	Common	Adapt

Figure 8.3-13. Recommended Technologies for ITD 2 (8 of 10)

Technology	Development Plan	Structural System	Strategy
6. Development, Quality Assurance, and Certification			
Structural health monitoring, diagnostics, and prognostics	1. Develop diagnostic criteria for various damage/failure modes that are of concern to structural test and production 2. Develop tools and processes for structural health monitoring, diagnostics, and prognostics	Common	Adapt
Certification by analysis	1. Assess probabilistic certification methodology (ref. Han-Pin Kan)	Common	Adapt
Improved test methods	1. Standardize MMOD certification; currently variations exist between programs that produce nontrivial cost and weight impacts on certification	Common	Adapt
Accelerated aging and test methods	1. Assess probabilistic aging method (ref. Torng) 2. Review HSR methods	Common	Adapt
In-space/ground repair methods	1. Investigate self-healing methods	Common	Adapt
Improved leak detection	1. Develop fiberoptic sensors for lightweight and higher reliability	Common	NASA

Figure 8.3-14. Recommended Technologies for ITD 2 (9 of 10)

Technology	Development Plan	Structural System	Strategy
7. Design for Threat/Environment			
MMOD (lunar/LEO)	1. Develop ultra-high-speed (15 to 20 km/sec) launch capability to characterize meteor impact effects	Common	NASA
Lunar dust	1. Incorporate NASA Glenn anti-dust coatings for Lunar and Mars dust —a coating of Americium-241 paint to neutralize the electrostatic charge on the dust particles 2. Repeat LDEF on lunar surface or at LLO	Common	NASA
Aging in lunar and space environment	1. Repeat LDEF on lunar surface or at LLO	Common	NASA
Static charge	1. Study static charge mitigation in structures for both dust repulsion and the management of ESD risks to life and electronics	Common	NASA
Thermal cycling	1. Repeat LDEF on lunar surface or at LLO	Common	NASA
Radiation	1. Radiation effects on electronics parts using lunar LDEF	Common	NASA
Noise	1. Utilize multifunctional sandwich structures	Common	NASA
Toxicity and outgassing	1. Repeat LDEF on lunar surface or at LLO	Common	NASA

Figure 8.3-15. Recommended Technologies for ITD 2 (10 of 10)

Technology	Development Plan	Structural System	Strategy
1. Materials and Processes			
Advanced autoclave cure M&P	1. Improve hydrogen impermeability for cryotanks 2. Employ thin-ply laminates to minimize microcracking in cryotanks (ref. Tsai)	24	Adapt
Coatings and sealants	1. Develop multifunctional, multicomponent coatings (including nano) with thermal, radiation, repair, etc., properties 2. Implement more durable conductive thermal control coatings 3. Utilize a chrome-free cryogenic primer for LO2/LH2 cryotanks 4. Develop low-cost conductive thermal control coatings (silicone resin/zinc oxide) for space applications	Common	Adapt

Technology	Development Plan	Structural System	Strategy
2. Manufacturing Methods			

Figure 8.3-16. Recommended Technologies for ITD 3 (1 of 6)

Technology	Development Plan	Structural System	Strategy
3. Innovative Design			
Multifunctional designs	1. Incorporate MMOD-radiation-acoustic protection in structure for long-duration space applcations (ref. ISS) 2. Implement active vibration control for LV payloads	Common	Adapt
Composite pressure vessels (non-integral)	1. Develop tanks with and without polypropylene liner for (1) short-term, then (2) long-term, storage of cryogenic fluids or gaseous He	24	Adapt
Lightweight structure for load transfer	1. Develop truss structure with integral and/or composite end fittings	24	Adapt
MMOD Resistant Design	2. Mitigate the tendency of composites to delaminate and debond upon hypervelocity impact 3. Determine the maximum/optimum height for honeycomb sandwiches; for MMOD, more space is better (sandwich improvement, i.e., lower priority than 1 and 2)	Common	NASA

Figure 8.3-17. Recommended Technologies for ITD 3 (2 of 6)

Technology	Development Plan	Structural System	Strategy
4. Analysis, Modeling, and Simulation			
Simulated test and evaluation	1. Develop simulations to complement test and evaluation efforts and to lessen the need for repetitive testing	Common	Adapt
Optimization methods	1. Develop multifactor (performance and cost) and multifunctional (structure, radiation, MMOD, etc.) optimization techniques	Common	Adapt
Probabilistic risk assessment	1. Evaluate, balance level of engineering data available to support PRAs: MMOD is usually fairly detailed since design is statistically driven; others often are less probabilistic in nature 2. Develop common data requirements for Constellation programs to use in data set acquisition and development 3. Document data confidence levels	Common	Adapt
MMOD impact analysis	1. Automate the transfer of CAD models into Bumper compatible formats 2. Continue algorithm development —the shadowing algorithm in Bumper has restricitons on relative size of elements 3. Improve body of knowledge on failure criteria as it is a significant source of impact analysis error	Common	NASA

Figure 8.3-18. Recommended Technologies for ITD 3 (3 of 6)

Technology	Development Plan	Structural System	Strategy
5. Design Criteria and Allowables			
Radiation protection DC&A	1. Characterize materials evaluation/assessment; particle transport and dose attenuation in lunar environment	Common	Adapt
MMOD resistant DC&A	1. Develop improved failure critera, mainly through impact testing; including database of all performed nonproprietary impact tests and developed equations (ref. JSC good database) 2. Document confidence levels in the data	Common	NASA
Environmental durability DC&A	1. Empirically establish environmental effects on most likely (cross-cutting) structural systems	Common	Adapt
Safety factors based on aircraft approach	1. Trade the levels of test, analysis, and allowable safety factors (commercial and military AC can amortize extensive testing and analysis) 2. Evaluate the use of qualified commercial or military aircraft systems with FAA-approved factors of safety	Common	Adapt
Develop NDE standards	1. Develop standards for NDE during product development	Common	Adapt
Minimum gage specifications	1. Evaluate extra-thin prepreg tape while considering all other criteria	Common	Adapt

Figure 8.3-19. Recommended Technologies for ITD 3 (4 of 6)

Technology	Development Plan		
6. Development, Quality Assurance, and Certification		**Structural System**	**Strategy**
Structural health monitoring, diagnostics, and prognostics	1. Develop diagnostic criteria for various damage/failure modes that are of concern to structural test and production 2. Develop tools and processes for structural health monitoring, diagnostics, and prognostics	Common	Adapt
Certification by analysis	1. Assess probabilistic certification methodology (ref. Kan)	Common	Adapt
Improved test methods	1. Standardize MMOD certification; currently variations exist between programs that produce nontrivial cost and weight impacts on certification	Common	Adapt
Accelerated aging and test methods	1. Assess probabilistic aging method (ref. Torng) 2. Review HSR methods	Common	Adapt
Improved leak detection	1. Develop fiberoptic sensors for lightweight and higher reliability 2. Develop noncontact leak detectors	Common	NASA

Figure 8.3-21. Recommended Technologies for ITD 3 (5 of 6)

Technology	Development Plan		
7. Design for Threat/Environment		**Structural System**	**Strategy**
MMOD (lunar/LEO)	1. Develop ultra-high-speed (15 to 20 km/sec) launch capability to characterize meteor impact effects; three-stage light gas guns are under development, but not "production"; integrate the Navy's development work with rail guns for weaponry and general increases in materials technology (ability to withstand high rail contact pressures during launch at higher velocities) may have enabled	Common	NASA
Aging in lunar and space environment	1. Repeat LDEF on lunar surface or at LLO	Common	NASA
Static charge	1. Study static charge mitigation in structures for both dust repulsion and the management of ESD risks to life and electronics	Common	NASA
Thermal cycling	1. Repeat LDEF on lunar surface or at LLO	Common	NASA
Radiation	1. Radiation effects on electronics parts using lunar LDEF	Common	NASA
Toxicity and outgassing	1. Repeat LDEF on lunar surface or at LLO	Common	NASA

Figure 8.3-22. Recommended Technologies for ITD 3 (6 of 6)

8.4 Recommended Technologies for Task Order Follow-on

At the lowest (and most specific) level of the hierarchy of recommendations, three projects are recommended that may be executed as an immediate follow-on to the current Task Order.

Task order Project 1 is derived from Integrated Technology Demonstration 1 (Figure 8.4-1). This project represents a section of the Ares V Interstage. Four subtasks are proposed, each of which is described by a development plan taken from the comprehensive technology database.

The second proposed Task Order project provides initial data for the design of a multi-functional shell for a Ascent Stage Crew Cabin (Figure 8.4-2). Eight subtasks are proposed to demonstrate multi-functional and weight-critical sandwich structure.

The third Task Order project would provide initial data for the design of an Altair LO_2 tank (Figure 8.4-3). This project, and its parent ITD 3, uses structural system 24 to demonstrate long-term durability of LO_2 tanks. Four subtasks are proposed.

Subtask	Technology	Development Plan	Structural System	Strategy
	2. Manufacturing Methods			
1a	Fiber placement methods	1. Increase material laydown rates with multiple head processes for larger-scale parts 2. Trade hybrid processes that mix 3 inch to 12 inch tape with 1/8 to 1/2 in tow for optimal rates 3. Optimize machine configuration for 5 m parts and for 10 m parts	13	Adapt
1b	Large (reusable) tooling	1. Develop tooling materials and fabrication for large-scale (10 m) cryotanks and dry structure (optimum no. of parts and joints) 2. Identify interaction of mass, inertia, and deflection for large scale part on production equipment and autoclave processes	13	Adapt
	4. Analysis, Modeling, and Simulation			
1c	Cost analysis	1. Validate tools with hardware design, build, and test	Common	Adapt
	5. Design Criteria Allowables			
1d	Knockdown factor	1. Validate knockdown factors with test and statistical analysis	Common	Adapt

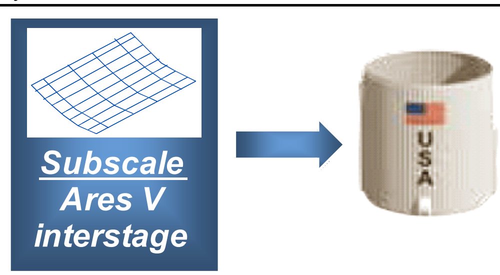


Figure 8.4-1. Recommended Task Order Project 1

	Technology	Development Plan		
Subtask	**1. Materials and Processes**		**Structural System**	**Strategy**
2a	Sandwich (core) M&P	1. Design a multifunctional, multicomponent core and facesheets with strength, thermal, radiation, self-repair, etc., properties 2. Incorporate sandwich panel purge/vent system integration 3. Utilize low-permeability co-cured sandwich facesheets	15	Adapt
	3. Innovative Design			
2b	Multifunctional designs	1. Incorporate MMOD-radiation-acoustic protection in structure for long-duration space apps (ref ISS)	Common	Adapt
2c	Sandwich Designs	1. Minimize weight penalty of openings and joints 2. Develop sandwich for failure-redundant propellant tank and dry structure with multifunctional properties	15	Adapt
	4. Analysis, Modeling, and Simulation			
2d	Optimization methods	1. Develop multifactor (performance and cost) and multifunctional (structure, radiation, MMOD, etc.) optiimization techniques	Common	Adapt
	5. Criteria and Allowables			
2e	Safety factors based on aircraft approach	1. Trade levels of test, analysis, and safety factors 2. Evaluate use of FAA-approved commercial or military aircraft factors of safety	Common	Adapt
	6. Development, QA and Cert			
2f	Accelerated aging and test methods	1. Assess probabilistic aging method (ref Torng) 2. Review HSR methods	Common	Adapt
	7. Design for Threat/Environment			
2g	MMOD (lunar/LEO)	1. Develop ultra high-speed (15 - 20 km/sec) launch capability to characterize meteor impact effects	Common	NASA
2h	Radiation	1. Evaluate radiation effects on electronics parts and crew	Common	NASA

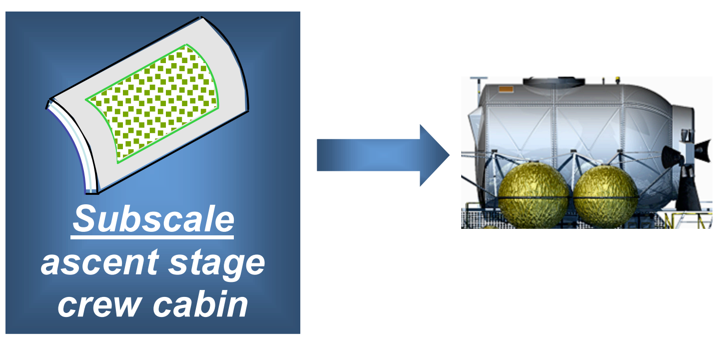


Figure 8.4-2. Recommended Task Order Project 2

	Technology	Development Plan		
Subtask	1. Materials and Processes		Structural System	Strategy
3a	Advanced autoclave cure M&P	3. Improve hydrogen impermeability and LO_2 compatibiity for cryotanks 4. Employ thin-ply laminates to minimize microcracking in cryotanks (ref. Tsai)	24	Adapt
	3. Innovative Design			
3b	Composite pressure vessels (non-integral)	1. Develop tanks with and without liner for (1) short-term, then (2) long-term, storage of cryogenic fluids or gases	24	Adapt
	6. Development, QA, and Certification			
3c	Accelerated aging and test methods	1. Assess probabilistic aging method (ref Tomg) 2. Review HSR methods	Common	Adapt
3d	Improved leak detection	1. Develop fiber-optic sensors for low weight and high reliability	Common	NASA

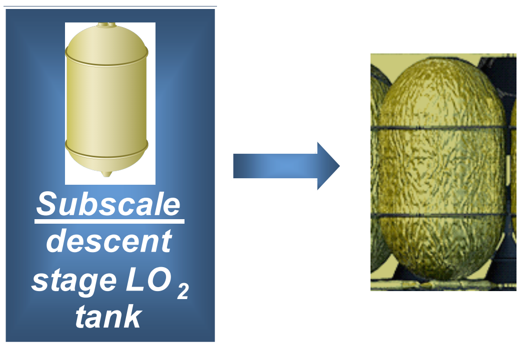


Figure 8.4-3. Recommended Task Order Project 3

9.0 SUMMARY

Figure 9-1 summarizes the major accomplishments of the task order. This task order generated a well-grounded and highly-integrated set of recommendations. The recommendations are based on the inputs of over 30 subject matter experts and set of public-domain references. A QFD-like methodology was created specifically to address the wide scope of over 100 composite structures technologies and 33 Constellation structural elements. The methodology identified the Constellation elements most likely to benefit from the application of composite structures technologies. At a higher level, all structures development needs to be coordinated as a system of structural systems. The ultimate benefit of this approach is to minimize development cost, reduce technical and program risks, and increase the acceptance of advanced composite structures in NASA Exploration missions.

- **Developed comprehensive qualitative (QFD-like) assessment methodology and composite structure technology database from public-domain literature and Boeing expertise on related programs**
- **Recommended one system of structural systems that provides integrated solution for Constellation-wide structure requirements**
- **Defined a comprehensive technology development plan based on recommended system of structural systems**
- **Identified three integrated demonstrations that support the comprehensive technology development plan**
- **Derived focused technology development plans for a Task Order follow-on**

Figure 9-1. Summary

APPENDIX A BIBLIOGRAPHY

General

Composites World staff, "Boeing 787 Update," Composites World, May 2007. http://www.compositesworld.com/hpc/issues/2007/May/111535/3

Roger Renstrom, "Boeing's big gamble: half-plastic Dreamliner," PlasticsNews.com, July 2, 2007. http://www.plasticsnews.com/subscriber/printer.html?id=07070200402

Reinforced Plastics News staff, "Boeing opts for composites for 7E7," Reinforced Plastics, Volume 47, Issue 7, July 2003, p. 10

Jay Spenser, "Technology pollination: Boeing technologies developed for commercial jetliners are now being integrated into some military products," Boeing Frontiers Online, The Boeing Company, January 2006.
http://www.boeing.com/news/frontiers/archive/2005/december/ts_sf10.html

Russell, John, "Market Trends: The Composites Affordability Initiative, Part 1," High Performance Composites, March 2007.

Composite Materials

Bednarcyk, et al. "Preliminary Structural Sizing and Alternative Material Trade Study of CEV Crew Module," NASA/TM—2007-214947, AIAA–2007–2175, National Aeronautics and Space Administration, August 2007.
http://gltrs.grc.nasa.gov/reports/2007/TM-2007-214947.pdf

Committee on New Materials for Advanced Civil Aircraft, "New Materials for Next-Generation Commercial Transports," National Materials Advisory Board (NMAB), National Research Council, NATIONAL ACADEMY PRESS, Washington, D.C. 1996.

M. Kawai and A Hachinohe, "Two-stress level fatigue of unidirectional fiber-metal hybrid composite: GLARE 2," Institute of Engineering Mechanics and Systems, University of Tsukuba, Japan**,** International Journal of Fatigue Volume 24, Issue 5, May 2002, Pages 567-580.

C.T. Sun, *Proceedings of the American Society for Composites, Seventeenth Technical Conference.* CRC Press, 2002.

Exploration Elements

K. Chauncey Wu, Jeffrey Antol, Judith J. Watson, Rudolph J. Saucillo, David D. North and Daniel D. Mazanek, "Lunar Lander Structural Design Studies at NASA Langley," AIAA SPACE 2007 Conference & Exposition, 18 - 20 September 2007, Long Beach, California.

1. Materials and Processes

Materials for cryo applications for fuel containment (e.g., microcracking, permeability, durability and insulation)

XCOR press release and article, "XCOR Aerospace Develops New Composite Material," HobbySpace News, April 2006.
http://www.hobbyspace.com/nucleus/index.php?itemid=1347

Autoclave materials

S. Tsai, Stanford University, Stanford, CA; S. Sihn and R. Kim, University of Dayton Research Institute, Dayton, OH, "Thin Ply Composites," AIAA-2005-2005. 46th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference, Austin, Texas, Apr. 18-21, 2005.

Surface preparation and bonding processes for improved adhesive joints

Jason Bardis and Keith Kedward, "Effects of Surface Preparation on Long-Term Durability of Composite Adhesive Bonds," U.S. Department of Transportation,
Federal Aviation Administration, DOT/FAA/AR-01/8, April 2001.

Bonded joining materials (adhesives)

LJ Hart-Smith, "Adhesive Bonding of Composite Structures-Progress Date and Some Remaining Challenges," Journal of Composites Technology and Research, ASTM International, 2002.
http://journalsip.astm.org/JOURNALS/COMPTECH/PAGES/235.htm

Co-cure, co-bond, and secondary bond process characterization for repeatable production of bonded structures

Jennifer Koury, "Composites Affordability Initiative," as presented at the Science and Technology Affordability Conference, October 1998. www.ncat.com/cai.pdf

Advanced non-autoclave cure materials

Tooru, et al. "Development of Composite Structure of HOPE-X," Proceedings of the JSASS/JSME Structures Conference, VOL.43rd; NO.;PAGE.29-32(2001).

Toshiyuki Shimokawa, Yoshiaki Kakuta, Daisuke Saeki, and Yoshiyasu Kogo, "Carbon Plain-Weave Fabric Low-Temperature Vacuum Cure Epoxy Composite: Static and Fatigue Strength at Room and High Temperatures and Practicality Evaluation," Journal of Composite Materials, Vol. 41, No. 18, 2245-2265 (2007).

L.W. Davies, R.J. Day, D. Bond, A. Nesbitt, J. Ellis, and E. Gardon, "Effect of cure cycle heat transfer rates on the physical and mechanical properties of an epoxy matrix composite," Composites Science and Technology Volume 67, Issue 9, July 2007, Pages 1892-1899.

Adhesives

Sang-Guk Kang, Myung-Gon Kim, and Chun-Gon Kim, "Evaluation of cryogenic performance of adhesives using composite–aluminum double-lap joints," Korea Advanced Institute of Science and Technology, South Korea. Composite Structures, Volume 78, Issue 3, May 2007, Pages 440-446.

Hybrids

E.C. Botelho, R.S. Almeida, L.C. Pardini, and M.C. Rezende, "Elastic properties of hygrothermally conditioned glare laminate," International Journal of Engineering Science Volume 45, Issue 1, January 2007, Pages 163-172.

Dennis A Burianek, Dong-Jin Shim and S. Mark Spearing, "Durability of Hybrid Fiber Metal Composite Laminates," Department of Aeronautics and Astronautics, Massachusetts of Institute of Technology, Proceedings of the 11th International Conference on Fracture, March 2005.

R. Alderliesten and R. Benedictus, Delft University of Technology, Delft, The Netherlands, "Fiber/Metal composite technology for future primary aircraft structures," AIAA-2007-2404. 48th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, Honolulu, Hawaii, Apr. 23-26, 2007.

Polymethylacrylimide (PMI) foam—ROHACELL trade name

http://www.rohacell.com/en/performanceplastics8344.html

Carbon foam

Sangwook Sihn and Brian P. Rice, "Sandwich Construction with Carbon Foam Core Materials," Journal of Composite Materials, Vol. 37, No. 15, 1319-1336 (2003).

Honeycomb

S. Elam, M. Effinger, R. Holmes, J. Lee (NASA, Marshall Space Flight Center, Huntsville, AL), and M. Jaskowiak (NASA, Glenn Research Center, Cleveland, OH), "Lightweight chambers for thrust cell applications," AIAA-2000-3131, AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, 36th, Huntsville, AL, July 16-19, 2000.

Nanocomposites

Michael Berger for Nanowerk Spotlight, "Nanostructure will become design variable for materials engineers," Nanowerk, June 26, 2007. http://www.nanowerk.com/spotlight/spotid=2131.php

K. Colavito, B. Kilic, E. Celik, and E. Madenci, The University of Arizona, Tucson, AZ; E. Askari, The Boeing Company, Seattle, WA; and S. Silling, Sandia National Laboratories, Albuquerque, NM, "Effect of Nanoparticles on Stiffness and Impact Strength of Composites," AIAA-2007-2021. 48th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, Honolulu, Hawaii, Apr. 23-26, 2007.

3D Reinforced composites

L. Tong, A.P. Mouritz, and M. Bannister, *3D FIBRE REINFORCED POLYMER COMPOSITES,* Elsevier Science, 2002.

Coatings and Sealants

K. Aflatooni, Aerojet, Sacramento, CA, “LPC Lined Epoxy Composite Ducts and Lines for Cryogenic Engine Application,” AIAA-2006-4711. 42nd AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, Sacramento, California, July 9-12, 2006.

Composites World News Staff, “Emerging material for space applications,” Composites World.com, May 2007. http://www.compositesworld.com/news/cwweekly/2007/May/cw111588

2. Manufacturing Methods

General

J. Jones and L. Hazlehurst, The Boeing Company, Seattle, WA, “Factory of the Future,” AIAA-2003-2545. AIAA International Air and Space Symposium and Exposition: The Next 100 Years, Dayton, Ohio, July 14-17, 2003.

Develop improved non-autoclave processes for traditional carbon/resin systems

Ridgard, Chris, “US Air Force Contract: Low Temperature Composite Processing,” Review of Program Status, September 2003, Advanced Composites Group, Inc. Presented at SAMPE Technical Conference, Dayton, Ohio.

Ridgard, Chris, “Low Temperature Composite Processing Program Review,” Advanced Composites Group, Inc., SAMPE, November 2005.

Scale-up of autoclave curing manufacturing methods to large (33-ft dia) structures

Composites World News Staff, “Thermal Equipment Corp. to build Boeing autoclave for 7E7,” Composites World.com, July 2004.
http://www.compositesworld.com/hpc/issues/2004/July/497

Barry Berenberg, “Improving Autoclave Performance,” Composites World.com, March 2003.
http://www.compositesworld.com/hpc/issues/2003/March/30

Vought Aircraft Industries press release, October 2007.
http://www.voughtaircraft.com/newsFactGallery/factsheets/programs/787.htm

Manufacturing technologies for large scale structures, e.g., tape/tow/broadgoods placement machines for very high laydown rates

Spacemart, “New Approaches For Producing Large Composite Structures,” Spacemart.com, January 2007.
http://www.spacemart.com/reports/New_Approaches_For_Producing_Large_Composite_Structures_999.html

Jim Lorincz, “Composites Fly Lighter, Stronger,” Manufacturing Engineering, March 2006.

Develop methodology to address large moments of inertia, stability and structural rigidity of rotating tools for large structures

Lori Gunter, “International Industrialization,” Boeing Frontiers Online, The Boeing Company, July 2006.
http://www.boeing.com/news/frontiers/archive/2006/july/cover.pdf

Cramer, Craig, “Dimensional Management of Composite Tooling for the World’s Largest One Piece, All Composite Aircraft Fuselage,” The Boeing Company, Seattle, WA, CMSC 2005.

Vented core and core splicing—Sandwich

GKN Aerospace, “Experience in Manufacturing Nomex Composites Sandwich Structures,” FAA Workshop on Adhesive Bonded Structures, 26th, 27th October 2004, UK Civil Aviation Authority, Aviation House, Gatwick Airport.
https://www.niar.wichita.edu/NIARWorkshops/LinkClick.aspx?fileticket=%2FIvOF5Oiwkc%3D&tabid=104&mid=568.

Non-traditional cure methods such as ultrasonics

Player, et al. “UTL Consolidation and Out-of-Autoclave Curing of Thick Composite Structures,” Department of Materials Science and Engineering, MIT,
Cambridge, MA.
http://web.mit.edu/roylance/www/sampe00.pdf

Low-cost tooling

Sandia National Laboratory press release.
http://www.sandia.gov/mst/technologies/composites.html

Resin Infusion (CAPRI, etc.)

National Institute for Aviation Research at Wichita State University, “VARTM, variability and substantiation,” Wichita State University, November 2005.
http://www.niar.wichita.edu/media/pdf/nationalpublication/Nov_23_05.pdf

E-beam curing

Oak Ridge National Laboratory, “Electron Beam Curing of Composites -
Space Age Technology for the 21st Century.”

http://www.ms.ornl.gov/researchgroups/composites/new%20orccmt%20pages/pages/ebwhat.html

Catherine A. Byrne, "Non-Autoclave Materials for Large Composite Structures," Science Research Lab Inc., Somerville, MA, November 2000.
http://www.stormingmedia.us/89/8974/A897483.html

Scott A. Kowalchuk, "Electron Beam Curing of Composite Structures for Space Applications," University of Kansas Space Engineering.
http://www.engr.ku.edu/~rhale/ae510/websites/kowalchuk.ppt

Bonded assembly

Composites World News, "New concept for out-of-autoclave cure of bonded structures," Composites World.com, May 2005.
http://www.compositesworld.com/hpc/issues/2005/May/846

Deobald, L.R., Grose, D., Mabson, G.E., and Dopker, B., "Optimal Bonded Joint Design for UCAV-Based Structure", SAMPE 2002.

Engelstad, S.P. , Berry, O.T. , Renieri, G.D., Deobald, L.R., Mabson, G.E., Dopker, B., Nottorf, E.W., and Clay, S.B., "A High Fidelity Composite Bonded Joint Analysis Validation Study – Part I: Analysis" (AIAA Paper No. 2005-2166) presented at the 46th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference, April 18-21, 2005

Bolted assembly

James Wallace's Seattle Post-Intelligencer Aerospace Blog:
http://blog.seattlepi.nwsource.com/aerospace/archives/116545.asp

Piping (feedlines)

Thomas K. DeLay, "Composite-material pipes for corrosive and cryogenic liquids," NASA Tech Briefs, October 2000.

3. Innovative Design

Efficient bolted (or bonded) joints between large sections

Hiratsuka, et al. "One Piece Barrel Fastening," SAE International, 2007.

Multifunctional designs (strength, thermal, radiation, acoustic, …)

Miller, et al. "Multifunctional composite structures for space applications," SPIE, June 2000.

Sandwich Designs

Jandro L. Abot, "Hybrid Nano/Micro Composite Sandwich Structures: Mechanical, Impact and Thermal Behavior," The University of Cincinnati Aerospace Engineering & Engineering Mechanics Graduate Seminar, February 2003. http://www.ase.uc.edu/graduate/seminar/Abotseminar.pdf

M. V. Hosur, M. Abdullah and S. Jeelani, "Manufacturing and low-velocity impact characterization of hollow integrated core sandwich composites with hybrid face sheets," Composite Structures Volume 65, Issue 1, July 2004, Pages 103-115.

Airbus

Thomsen, O.T., E. Bozhevolnaya and A. Lyckegaard, Sandwich Structures 7: Advancing with Sandwich Structures and Materials. Proceedings of the 7th International Conference on Sandwich Structures, Aalborg University, Aalborg, Denmark, 29–31 August 2005. Springer Netherlands. 2006.

J. Fogarty, "A Fastener-Free Primary Structural Joint Between Sandwich Panels," *40th Internation SAMPE Technical Conference,* Memphis, TN, October 2008.

Patrick Sheahen, Larry Bersuch (Lockheed Martin Tactical Aircraft Systems, Fort Worth, TX), Tom Holcombe, and Bill Baron (USAF, Wright Lab., Wright-Patterson AFB, OH), "Robust composite sandwich structures," AIAA-1998-1873. AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference and Exhibit, 39th, and AIAA/ASME/AHS Adaptive Structures Forum, Long Beach, CA, Apr. 20-23, 1998, Collection of Technical Papers. Pt. 3 (A98-25178 06-39).

Iso-, Ortho-Grid Stiffened Designs, selective reinforcement

About.com, "Advanced Grid Stiffened Composite Structures," About.com: Composites/Plastics, May 1998. http://composite.about.com/library/weekly/aa980525.htm

Collier, Craig, Yarrington, Phil, and Van West, Barry, "Composite, Grid-Stiffened Panel Design for Post Buckling Using Hypersizer," Collier Research Corporation, 2001.

Higgins, John E., Wegner, Peter M., Van West, Barry, and Viisoreanu, Adrian, "Design and testing of the Minotaur advanced grid-stiffened fairing," *Composite Structures*, 2004. pp. 339-349.

Higgins, John E., Wegner, Peter M., Van West, Barry, and Viisoreanu, Adrian, "Failure Criteria for Composite Isogrid Structures," Air Force Research Laboratory (AFRL)/The Boeing Company, Phantom Works, 2003.

Hassan Mahfuz, Derrick Dean, Shaik Jeelani, Mohammed Baseer, and Gamaleldin Mohamed, "Innovative Manufacturing and Structural Analysis of Composite Isogrid Structures for Space Applications," Tuskegee University, AL, December, 2003. http://www.stormingmedia.us/86/8689/A868914.html

Thomas D. Kim, "Fabrication and testing of thin composite isogrid stiffened panel," Composite Structures Volume 49, Issue 1, May 2000, Pages 21-25.

Van West, Barry P., and Wegner, Peter, "Fiber-Placed Composite Grid-Stiffened Structures," 33rd SAMPE Intl Technical Conference, November 2001, Seattle.

P. Wegner and J. Higgins, Air Force Research Laboratory, Kirtland AFB, NM; B. VanWest, Boeing Phantom Works, Seattle, WA, "Application of Advanced Grid-Stiffened Structures Technology to the Minotaur Payload Fairing," AIAA-2002-1336. 43rd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, Denver, Colorado, Apr. 22-25, 2002.

R. Wippich-Dienhart, M. Bitzes and T. Tyahla, The Boeing Company, St. Louis, MO; F. Abrahms and R. Holzwarth, Air Force Research Laboratory, Wright-Patterson AFB, OH, "Design and Test of Full-Scale VARTM Integrally Stiffened CAI Cockpit Tub," AIAA-2004-1625. 45th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference, Palm Springs, California, Apr. 19-22, 2004.

Hybrid (metal/composite) stiffened structures

Axel Fink and Dr. Boris Kolesnikov, "HYBRID TITANIUM COMPOSITE MATERIAL IMPROVING COMPOSITE STRUCTURE COUPLING," German Aerospace Center, Institute of Composite Structures and Adaptive Systems, 38104 Braunschweig, Germany.

Webb telescope

Polis, et al. "Cryogenic Durability of a Carbon Fiber Reinforced Cyanate Ester Composite: Degree-of-Cure Effect," National Aeronautics and Space Administration. http://code541.gsfc.nasa.gov/Recent_Publications/05-12_Polis.pdf

Minimum gage

Minguet, Pierre J. (Boeing Co., Helicopters Div., Philadelphia, PA), "A model for predicting the behavior of impact-damaged minimum gage sandwich panels under compression," AIAA-1991-1075. AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, 32nd, Baltimore, MD, Apr 8-10, 1991, Technical Papers. Pt. 2 (A91-31826 12-39). Washington, DC, American Institute of Aeronautics and Astronautics, 1991, p. 1112-1122.

Tailored (tow steered, variable stiffness) composites

"Fiber placement and fiber steering systems and corresponding software for composite structures," US Patent Issued on September 28, 2004. http://www.patentstorm.us/patents/6799081-description.html

D. Baker, NASA Langley Research Center, Hampton, VA, "Analysis and Test of Tailored Extension-Shear-Coupled Composite Panels,"AIAA-2003-1461. 44th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, Norfolk, Virginia, Apr. 7-10, 2003.

D. Buchanan, R. Alexander, and J. Thomas, “Structural Design of Fiber Placed Inlet Duct.” American Institute of Aeronautics and Astronautics, April 1999

Primarily bonded structures

Science and Technology Office of Transition. CAI III IBSV - Aircraft Primary Structure Adhesive Bonding Development
http://www.onr.navy.mil/sci_tech/3t/mantech/search.asp?Action=GetProject&IdPBText=600&menu=Project&submenu=completed&SearchCurrent=false

Deobald, L.R., Grose, D., Mabson, G.E., and Dopker, B., “Design of Robust Bonded Composite Joints Using CAI Pervasive Developed Analysis Tools”, Defence Manufacturers Conference, Composites Processing and Fabrication, November 2001.

Stitched Designs

Dawn C. Jegley, “Improving strength of postbuckled panels through stitching,” Composite Structures Volume 80, Issue 2, September 2007, Pages 298-306.

Point load introduction

Boeing news release, “Boeing 787 Dreamliner Demonstration Wing Box Complete; Testing Set to Begin,” The Boeing Company, July 2006.
http://www.boeing.com/news/releases/2006/q3/060717a_nr.html

Inflatables (multifunctional shell, hatches)

ILC Dover corporate website, “Space Inflatables.”
http://www.ilcdover.com/products/aerospace_defense/spaceinflatables.htm

Mark S. Grahne and David P. Cadogan, “Inflatable Solar Arrays: Revolutionary Technology?” SAE 1998.
http://www.ilcdover.com/products/aerospace_defense/supportfiles/solar.pdf

In-space/ground repair methods

Julie Bassler and Richard Grugel, “In Situ Fabrication and Repair,” National Aeronautics and Space Administration. http://isfr.nasa.gov/textversion.html

Nanocomposites

The Universities of Texas at Austin and A&M at College Station, “Cyanate Ester-Buckytubes Nanocomposites Processing and Characterization,” Society for Advancement of Material and Process Engineering, 2007. http://www.sampe.org/store/paper.aspx?pid=4482

Composite pressure vessels (non-integral)

EDO Corporation, “Composites: Tanks & Vessels ”
http://www.edocorp.com/CompositesTanksVessels.htm

Steven M. Arnold, Brett A. Bednarcyk, Craig S. Collier and Phillip W. Yarrington, “Spherical Cryogenic Hydrogen Tank Preliminary Design Trade Studies,” Prepared for the 48th Structures, Structural Dynamics, and Materials Conference cosponsored by the AIAA, ASME, ASCE, AHS, and ASC, National Aeronautics and Space Administration, April 2007.

Crashworthiness incorporated in design

Sean Snyder, “Announcement of Boeing Fuselage Crash Test Results,” Design News, September 2007. http://www.designnews.com/article/CA6476379.html

Integrated TPS, radiation protection

Andrews S. Keys, “Aerocapture Technologies,” Earth Science Technology Conference 2006, National Aeronautics and Space Administration, June 2006. http://www.esto.nasa.gov/conferences/estc2006/presentations/C9P1.pdf

National Security Space Road Map (NSSRM), “Structural Systems,” NSSA, July 1997. http://www.fas.org/spp/military/program/nssrm/initiatives/strucsys.htm

Lightweight mechanisms for load transfer

Supernova Acceleration Probe (SNAP). http://snap.lbl.gov/pubdocs/mk3_slides.pdf

Eric Ponslet, Franz Biehl, Roger Smith, “Conceptual Design Notes for Primary Metering Structures for the SNAP Telescope,” Hytec Inc., April 2000. http://snap.lbl.gov/pubdocs/HTN-113901-0001.pdf

Methods of preventing damage growth

M. V. Hosur, U. K. Vaidya, C. Ulven, and S. Jeelani, “Performance of stitched/unstitched woven carbon/epoxy composites under high velocity impact loading,” Composite Structures Volume 64, Issues 3-4, June 2004, Pages 455-466.

MMOD Resistant Design

Wanthal, S., Wippich-Dienhard, R., Cenedella, A., Mabson, G., Deobald, L., Owens, S., Li, V., and Kane, D. "Interlaminar Reinforced Composites Development for Improved Damage Tolerance", accepted for publication, SAMPE 2000.

Inflatable (habitats)

I. Kondyurina, A. Kondyurin, B. Lauke, Ł. Figiel, R. Vogel, and U. Reuter, “Polymerisation of composite materials in space environment for development of a Moon base,” Advances in Space Research Volume 37, Issue 1, 2006, Pages 109-115.

Air Force Research Laboratory (AFRL) Fact Sheet, “Innovative Space-based radar Antenna Technology (ISAT) Flight Demonstrator,” AFRL, March 2006. http://www.kirtland.af.mil/shared/media/document/AFD-070404-098.pdf

Damage tolerance

L. Chen, R. Ballarini, H. Kahn, A.H. Heuer, "Bioinspired micro-composite structure," Materials Research Society, January 2007. http://www.mrs.org/s_mrs/sec_subscribe.asp?CID=7279&DID=183511&action=detail

Self healing

R S Trask, I P Bond, and C O A Semprimoschnig, "Self-Healing of Composite Structures in a Space Environment," Department of Aerospace Engineering, University of Bristol, Bristol, UK. http://www.aer.bris.ac.uk/research/fibres/sr_pics/10thISMSE.pdf

4. Advanced Analysis, Modeling and Simulation

Peter W.R. Beaumont, "Pushing the performance limit of composite structures Part 1: Modelling," Cambridge University Engineering Department, Cambridge, UK, Reinforced Plastics Volume 50, Issue 8, September 2006, Pages 58-63.

Joseph F. Rakow and Alfred M. Pettinger , "Failure Analysis of Composite Structures in Aircraft Accidents," Exponent Failure Analysis Associates, presented at the ISASI Annual Air Safety Seminar, September 2006. See esp. Figure 2, "The growing use of composites." http://www.exponent.com/about/docs/ISASI2006_paper.pdf

Bolted joint analysis

Sawicki, A. J. (Boeing Defense and Space Group, Philadelphia, PA) Grant, P. (Boeing Defense and Space Group, Philadelphia, PA) Mabson, G. E. (Boeing Commercial Airplane Group, Seattle, WA), "Mechanical assembly of commercial transport fuselage utilizing tow-placed and textile composites," AIAA-1994-1429. AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, 35th, Hilton Head, SC, Apr 18-20, 1994, Technical Papers. Pt. 2 (A94-23876 06-39), Washington, DC, American Institute of Aeronautics and Astronautics, 1994, p. 993-1007.

Bonded Joint Analysis

Bartoszyk, A., "Current Progress on the Design and Analysis of the JWST ISIM Bonded Joints for Survivability at Cryogenic Temperatures," FEMCI workshop, May 5, 2005.

Effects of defects in novel design concepts, e.g., missing stitches, local debonds, porosity

Mabson, G.E., Deobald, L.R., Dopker, B., "Fracture Interface Elements for the Implementation of the Virtual Crack Closure Technique", (AIAA-2007-2376) presented at the 48th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference, April 23-26, 2007.

Deobald, L.R., Mabson, G.E., Dopker, B., Hoyt, D.M., Baylor, J.S., and Graesser, D.L., "Interlaminar Fatigue Elements for Crack Initiation Onset and Growth Based on Virtual Crack

Closure Technique", presented at the 48th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference, April 23-26, 2007

John Russell, "Market Trends: Composites Affordability Initiative, Part II," CompositesWorld.com, May 2007.
http://www.compositesworld.com/hpc/issues/2007/May/111540

J. Fogarty, "Steam Pressure Induced Delamination Of Honeycomb Core Sandwich Panels," *37th Internation SAMPE Technical Conference,* Seattle,WA, November 2005.

Ragnar Larsson, "A discontinuous shell-interface element for delamination analysis of laminated composite structures," Computer Methods in Applied Mechanics and Engineering Volume 193, Issues 30-32, 30 July 2004, Pages 3173-3194.

Mabson, G.E. and Graesser, D.L., "Predicting Stringer Delamination Loads in a Pressurized Composite Fuselage", Poster for 2nd Northwest Mechanical & Structural Engineering Technical Excellence Summit, Boeing Oct 2007.

Mabson, G.E., and Deobald, L.R., "Design Curves for Sizing Unreinforced, Z-pinned and Stitched Composite Structures that Fail by Composite Delamination", Second Boeing Technical Excellence Conference, Seattle, WA, February 2002.

Mabson, G.E., Dopker, B., and Deobald, L.R., "Interface Finite Element for the Analysis of Composite Delamination", Second Boeing Technical Excellence Conference, Seattle, WA, February 2002.

Dopker, B., Mabson, G., Deobald, L., Grose, D., and Lee, A., "Newly Developed Fracture Mechanics Interface Elements for Practical Composite Delamination Analysis" Boeing Composites Technical Exchange 2002, St. Louis, October 29, 2002.

Skin-stringer analysis

Martinovic, Zoran N., "Structural Design and Analysis of Un-pressurized Cargo Delivery Vehicle," NASA Langley Research Center, Hampton, Virginia, 23681-2199.

Improved methods of analyzing highly tailored composites

Naba corporate website. http://naba-tcs.com/nabaSite.swf

Virtual testing

The University of South Carolina's Virtual test bed.
http://vtb.engr.sc.edu/

Thermo-structural design, e.g., thermally compliant joints

DiChiara, Robert, and Chen, Victor, "X-37 Hot Structure Control Surface Qualification Program Overview," 30th Annual Conference on Composites, Materials, and Structures, Cocoa Beach, FL, January, 2006.

DiChiara, Robert, Frankel, Craig, and Keidel, John, "X-37 Hot Structures Control Surface Development Lessons Learned," 30th Annual Conference on Composites, Materials, and Structures, Cocoa Beach, FL, January, 2005.

R. Ramesh Kumar, G. Vinod, S. Renjith, G. Rajeev, M.K. Jana, and R. Harikrishna, "Thermo-structural analysis of composite structures," Materials Science and Engineering: A Volume 412, Issues 1-2, 5 December 2005, Pages 66-70.

Failure mechanism/prediction at RT (or extreme temperatures)

Higgins, John E., Wegner, Peter M., Van West, Barry, and Viisoreanu, Adrian, "Post-Buckling Test Response and Analysis of Fiber Composite Grid-Stiffened Structures," American Institute of Aeronautics and Astronautics (AIAA), 2002.

Hoyt, D.M., Mabson, G.E., Deobald, L.R., Dopker, B., Graesser, D.L, Walker, T.H. "Applying and Validating Fracture Methods to Structural Analysis of Aircraft Components – Practical Issues and Challenges", invited presentation to ASTM Workshop on Computational Fracture Mechanics for Composites, Salt Lake City, UT, March 2004.

Mabson, Gerald E., Enjuto, Patrick W., Lee, Hangki, Smith, Gregory J., "An Enhanced Analysis Methodology for Laminated Composite Local Buckling, Effective Width, Element Crippling, Section Crippling and Column Buckling", presented at the Boeing Northwest Structural Mechanical Systems Technical Excellence Summit, June 14, 2006, Seattle, WA

Mabson, G.E., Deobald, L.R., and Dopker, B., "Fracture Interface Elements", Invited seminar to Aeronautics and Astronautics Department, University of Washington, Seattle, WA, April 2006.

Optimization methods

M. A. Droegkamp, K. S. Dry, D. A. Koshiba, S. P. Renze, and A. M. Wilson (Boeing Co., Seattle, WA), "Designing affordable lightweight airframes using structural optimization techniques," AIAA-1998-1817. AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference and Exhibit, 39th, and AIAA/ASME/AHS Adaptive Structures Forum, Long Beach, CA, Apr. 20-23, 1998, Collection of Technical Papers. Pt. 2 (A98-25092 06-39).

Ilcewicz, L.B., Smith, P.J., Hanson, C.T., Walker, T.H., Metschan, S.L., Mabson, G.E., Willden, K.S., Flynn, B.W., Scholz, D.B., Polland, D.R., Fredrikson, H.G., Olson, J.T. and Backman, B.F., "Advanced Technology Composite Fuselage - Program Overview", *NASA CR-4734*, 1996.

Ilcewicz, L.B., Mabson, G.E., Metschan, S.L., Swanson, G.D., Proctor, M.R., Tervo, D.K., Fredrikson, H.G., Gutowski, T.G., Neoh, E.T., and Polgar, K.C., "Cost Optimization Software for Transport Aircraft Design Evaluation (COSTADE)- Design Cost Methods", *NASA CR-4737*.

Mabson, G.E., Metschan, S.L. and Proctor, M.R. "Cost Optimization Software for Transport Aircraft Design Evaluation - Tutorial", Jan 1997, NASA Langley.

Mabson, G.E. and Graesser, D.L., "Cost Optimization Software for Transport Aircraft Design Evaluation (COSTADE) - User's Manual 3.13", 1997.

Mabson, G.E., Ilcewicz, L.B., Graesser, D.L., Metschan, S.L., Proctor, M.R., Tervo, D.K., Tuttle, M.E. and Zabinsky, Z.B., "Cost Optimization Software for Transport Aircraft Design Evaluation (COSTADE) - Overview", *NASA CR-4736*.

Mabson, G.E., Fredrikson, H.G., Graesser, D.L., Metschan, S.L, Proctor, M.R., Stogin, D.C., Tervo, D.K., Tuttle, M.E., Zabinsky, Z.B. and Gutowski, T.G., "Cost Optimization Software for Transport Aircraft Design Evaluation", Society of Manufacturing Engineers, Composites '96 Manufacturing and Tooling Conference, January 22-24, 1996, Anaheim, CA. (Invited Presentation)

Mabson, G.E., Fredrikson, H.G., Graesser, D.L., Metschan, S.L, Proctor, M.R., Stogin, D.C., Tervo, D.K., Tuttle, M.E., Zabinsky, Z.B. and Gutowski, T.G., "Cost Optimization Software for Transport Aircraft Design Evaluation", *Sixth NASA/DOD/ARPA Advanced Composite Technology Conference*, Vol I, NASA CP-3326, 1996.

Mabson, G.E., Carbery, D.J., Graesser, D.L., Griess, K.H. and Metschan, S.L., "Interaction of COSTADE with Internal Loads Models for Advanced Composite Fuselage Structural Development", 11th DOD/NASA/FAA Conference on Fibrous Composites in Structural Design, August 26-29, 1996, Fort Worth Texas.

Ryosuke Matsuzaki and Akira Todoroki, “Stacking-sequence optimization using fractal branch-and-bound method for unsymmetrical laminates,” Composite Structures**,** Volume 78, Issue 4, June 2007, Pages 537-550.

V. V. Khil’chevskii, V. H. Dubenets, and E. V. Savchenko, “Optimization of passively damped composite structures,” Strength of Materials, Springer New York, November 2006.

Fatigue/life prediction

Mabson, G.E., Deobald, L.R., Dopker, B., Hoyt, D.M., Baylor, J.S., Graesser, D.L., “Fracture Interface Elements for Static and Fatigue Analysis”, 2nd Northwest Mechanical & Structural Engineering Technical Excellence Summit, Boeing Oct 2007.

Mabson, G.E., Deobald, L.R., Dopker, B., Hoyt, D.M., Baylor, J.S., Graesser, D.L., “Fracture Interface Elements for Static and Fatigue Analysis”, Session Keynote presentation and paper, ICCM-16, July 2007, Kyoto, Japan.

Probabilistic analysis

Levon Minnetyan, Frank Abdi, and Christos C. Chamis, “Probabilistic Assessment of Fracture in Stitched and Unstitched Composite Laminates,” American Institute of Aeronautics and Astronautics, Inc., 1998.

Yongming Liu and Sankaran Mahadevan, "Corrigendum to "Probabilistic fatigue life prediction of multidirectional composite laminates" [Composite Structures 69 (2005) 11–19]," Composite Structures Volume 77, Issue 1, January 2007, Page 125.

Han-Pin Kan, "Assessment of Probabilistic Certification Methodology for Composite Structures," U.S. Department of Transportation: Federal Aviation Administration, January 2001. http://www.tc.faa.gov/its/worldpac/techrpt/ar00-74.pdf

Antonio Miravete, "Composites Properties and Applications," Woodhead, 1993.

Frank Abdi and Cody Godines, "Probabilistic Impact Analysis and Risk Assessment Supporting Shuttle Return-to-Flight Procedures," Alpha STAR Corporation, Long Beach, California**,** 2004. http://www.alphastarcorp-genoa.com/Publications/SAMPE2004/ReturnToFlight/FINAL_SAMPE_2004_Impact_NormalizeValues.pdf

Torng, T. Y., Xiao, Q., Zillmer, S., and Rogers, G., "Practical Reliability-based Design Optimization Strategy," presented and published in the Proceedings of the 42nd AIAA Structures, Structural Dynamics and Material Conference, Seattle, WA, April 16-19, 2001. Chaired one session.

Xiao, Q., Torng, T. Y., Zillmer, S., and Rogers, G., "Practical Reliability-based Design Optimization Application," presented and published in the Proceedings of the 42nd AIAA Structures, Structural Dynamics and Material Conference, Seattle, WA, April 16-19, 2001

Torng, T. Y., "An Advanced Aging Aircraft Risk Assessment Method", presented and published in the Proceedings of the 9th International Conference on Structural Safety and Reliability (ICOSSAR), Rome, Italy, June 19-23, 2005

Torng, T. Y., "Probabilistic Analysis and Design System (PADS)", The Boeing Company, 2005.

Torng, T. Y., Lin, H.Z., Khalessi, M.R., and Chandler, Frank O., "Probabilistic Thin Shell Structural Design," Reusable Space Systems, Boeing North American, Inc.39th AIAA/ASME/ASCE/AHS/ASC SDM Conference, April 20-23, 1998, Long Beach, California.

Progressive failure methods

Mabson, G.E., Karayev, K., Finn, S., Aksel, G., Jiang, X., Shim, D.J., Hoyt, D.M., Walker, T., "GE/Boeing Initiative for Composite Progressive Failure Predictions", 2nd Northwest Mechanical & Structural Engineering Technical Excellence Summit, Boeing, Oct. 2007.

PROGRESSIVE FAILURE ANALYSIS OF THIN WALLED COMPOSITE TUBES UNDER LOW ENERGY IMPACT, Chian-Fong Yen, Thomas Cassin,
Joel Patterson, and Matt Triplett
http://www.materials-sciences.com/papers/impact.pdf

Alpha STAR Corporate website.
http://www.alphastarcorp.com/Overview_of_the_Genoa_Analysis%20Process.pdf

Hierarchical analysis

Peter J. Nicklin, Graham H. Powell, and Jeffery P. Hollings, "Hierarchical data management for structural analysis," Springer London, February 2005.

A. Alzina, E. Toussaint, A. Béakou, and B. Skoczen, "Multiscale modelling of thermal conductivity in composite materials for cryogenic structures," Composite Structures, Volume 74, Issue 2, July 2006, Pages 175-185.

P. S. Theocaris and G. E. Stavroulakis, "Multilevel optimal design of composite structures including materials with negative Poisson's ratio," Springer Berlin/Heidelberg, February 2005.

C. Soutis and P.W.R. Beaumont, "Multi-scale Modelling of Composite Material Systems: The Art of Predictive Damage Modelling," CRC Press, 2005.

D.G. Liaw, M.C. Shiao, S.N. Singhal, and Christos C. Chamis, "Probabilistic Simulation of Multi-Scale Composite Behavior," prepared for the Sixth Japan-United States Conference on Composite Materials, National Aeronautics and Space Administration, June 1992.
http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19930019444_1993019444.pdf

Prediction of internal and residual stresses and design to minimize or take advantage of such stresses

M.A. Seif, U.A. Khashaba, and R. Rojas-oviedo, "Residual stress measurements in CFRE and GFRE composite missile shells," Composite Structures, Volume 79, Issue 2, July 2007, Pages 261-269.

Jong Woon Kim, Ji Hyung Lee, Hyoung Geun Kim, Hak Sung Kim, and Dai Gil Lee, "Reduction of residual stresses in thick-walled composite cylinders by smart cure cycle with cooling and reheating," **Composite Structures** Volume 75, Issues 1-4, September 2006, Pages 261-266.

Scaling and validation

Roger Crane, "Overview of Composites Structures R&D at Carderock Division," Brief to JTEG Meeting on "Composite Manufacturing and Repair" 4-6 Nov 2003.
http://www.jdmag.wpafb.af.mil/s%20overview%20of%20composites%20structures%20r&d%20at%20carderock.pdf

R. Clifton Moody, James S. Harris, and Anthony J. Vizzini, "Scaling and Curvature Effects on the Damage Tolerance of Impacted Composite Sandwich Panels," Journal of Sandwich Structures and Materials, Vol. 4, No. 1, 71-82 (2002).

Coupled Loads analysis

J.M. Dickens, M.J. Wittbrodt, M.M. Gate, L.H. Li, and A. Stroeve, "Coupled Loads Analysis Accuracy from the Space Vehicle Perspective," Acta Astronautica, Volume 48, Number 1, January 2001 , pp. 21-28(8).

Hermann Fischer AOES, ESA/ESTEC Structures Section, "Ariane 5 Coupled Loads Analysis," ESTEC, October 2003. http://www.fenet.org/downloads/FENet_Meetings/Noordwijk_Netherlands_Oct_2003/FENET_Noordwijk_Oct2003_MPA_Fischer.pdf

Grid Analysis

C. Collier and P. Yarrington, Collier Research Corporation, Hampton, VA; B. Van West, The Boeing Company, Seattle, WA, "Composite, Grid-Stiffened Panel Design for Post Buckling Using HyperSizer," AIAA-2002-1222. 43rd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, Denver, Colorado, Apr. 22-25, 2002.

Scaling

Johnson, David P., John Morton, Sotiris Kellas, and Karen Jackson, "Scaling Effects in Sublaminate-Level Scaled Composite Laminates," AIAA Journal 1998. 0001-1452 vol.36 no.3 (441-447).

Norton, J., "Scaling of Impact-Loaded Carbon-Fiber Composites," AIAA Journal, Vol. 26, No. 8, 1988, pp. 989-994.

Kellas, S., and Morton, J., "Strength Scaling in Fiber Composites," AIAA Journal, Vol. 30, No. 4, 1992, pp. 1074-1080.

Kellas, S., and Morton, J., "Damage and Failure Mechanisms in Scaled Angled-Ply Laminates," Fourth Composites Symposium on Fatigue and Fracture, edited by W. Stinchcomb, ASTM STP 1156, American Society for Testing and Materials, New York, 1993, pp. 257-280.

Jackson, K. E., "Scaling Effects in the Static and Dynamic Response of Graphite-Epoxy Beam-Columns," NASA TM 102697, July 1990.

5. Design Criteria and Allowables

Define damage tolerance requirements

T.H. Walker, P.J. Minguet, B.W. Flynn, D.J. Carbery, G.D. Swanson, and L.B. Ilcewicz, "Advanced Technology Composite Fuselage - Structural Performance," NSE Composites. http://www.nsecomposites.com/Abstracts/Tom/StrPerf_abstr.htm

Allen J. Fawcett and Gary D. Oakes, "Boeing Composite Airframe Damage Tolerance and Service Experience," The Boeing Company.

https://www.niar.wichita.edu/NIARWorkshops/LinkClick.aspx?fileticket=I3VvzKxCXpo%3D&tabid=99&mid=537

Caiazzo, A., Orlet, M., McShane, H.,Strait, L., And Rachau, C., "The Effects of Marcel Defects on Composite Structural Properties," *Composite Structures: Theory and Practice, ASTM STP 1383.* P. Grant and C.Q. Rousseau, Eds., American Society for Testing and Materials, West Conshohocken, PA, 2000, pp. 158-187.

E. Askari and J. Xu, The Boeing Company, Bellevue, WA; S. Silling, Sandia National Laboratories, Albuquerque, NM, "Peridynamic Analysis of Damage and Failure in Composites," AIAA-2006-88. 44th AIAA Aerospace Sciences Meeting and Exhibit, Reno, Nevada, Jan. 9-12, 2006.

Radiation Protection

Tariq Malik, "Shields Up! New Radiation Protection for Spacecraft and Astronauts," Space.com, May 2004.
http://www.space.com/businesstechnology/technology/rad_shield_040527.html

Space environmental effects

I. Kondyurina, A. Kondyurin, B. Lauke, Ł. Figiel, R. Vogel, and U. Reuter, "Polymerisation of composite materials in space environment for development of a Moon base," Advances in Space Research Volume 37, Issue 1, 2006, Pages 109-115.

Develop and justify less conservative knockdown factors

Federal Aviation Administration, "Temperature differential between Wet Glass Transition," Policy # PS-ACE100-2-18-1999.
http://rgl.faa.gov/Regulatory_and_Guidance_Library/rgPolicy.nsf/0/8d097971d03c830186256fb200727b4b!OpenDocument

R.A. Shenoi, Stuart S.J. Moy, and Leonard Hollaway, *Advanced Polymer Composites for Structural Applications in Construction,* Thomas Telford, 2002.

John W. Bristow and P.E. Irving, "Safety factors in civil aircraft design requirements**,"** Engineering Failure Analysis Volume 14, Issue 3, April 2007, Pages 459-470.

Develop NDE standards

Federal Aviation Administration, "Joint Advanced Materials and Structures (JAMS) Center of Excellence," Airport and Aircraft Safety R&D Division.
http://www.coe.faa.gov/4thMeeting/CDavies.pdf

Develop database for better understanding of damage

J. Tomblin, T. Lacy, B. Smith, S. Hooper, A. Vizzini, and S. Lee, "Review of Damage Tolerance for Composite Sandwich Airframe Structures," Federal Aviation Administration, August 1999.
http://www.tc.faa.gov/its/worldpac/techrpt/ar99-49.pdf

6. Development, Quality Assurance and Certification

M. Mohaghegh, The Boeing Company, Seattle, WA, "Validation and Certification of Aircraft Structures," AIAA-2005-2162. 46th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference , Austin, Texas, Apr. 18-21, 2005.

Marshall Rouse, Damodar R. Ambur (NASA, Langley Research Center, Hampton, VA), Bernard Dopker (Boeing Commercial Airplane Group, Seattle, WA), and Bharat Shah (Lockheed Martin Aeronautical Systems, Marietta, GA), "Response of composite fuselage sandwich side panels subjected to internal pressure and axial tension," AIAA-1998-1708. AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference and Exhibit, 39th, and AIAA/ASME/AHS Adaptive Structures Forum, Long Beach, CA, Apr. 20-23, 1998, Collection of Technical Papers. Pt. 1 (A98-25001 06-39).

Alan Dobyns, Bruce Barr, and John Adelmann, "RAH-66 Comanche Building Block Structural Qualification Program," Composite Structures: Theory and Practice, ASTM, 2000.

Fu-Kuo Chang, "Structural Health Monitoring 2007: *Quantification, Validation, and Implementation,*" Proceedings of the Sixth International Workshop on Structural Health Monitoring, September 11–13, 2007.
http://www.destechpub.com/pageview.asp?pageid=32903

R. Messinger and J. Pulley, The Boeing Company, Huntington Beach, CA, "Thermal-Mechanical Cyclic Test of a Composite Cryogenic Tank for Reusable Launch Vehicles," AIAA-2003-1766. 44th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, Norfolk, Virginia, Apr. 7-10, 2003.

G. Sanford, V. Stavast, and A. Biskner, CSA Engineering, Inc., Albuquerque, NM; and J. Higgins, Air Force Research Laboratory, Kirtland AFB, NM, "Test Design and Static Testing of the Atlas V CCB Conical InterStage Adapter," AIAA-2007-2254. 48th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, Honolulu, Hawaii, Apr. 23-26, 2007.

Inspection Methods

Mark R. Leifeste, "Interrelationship of Nondestructive Evaluation Methodologies Applied to Testing of Composite Overwrapped Pressure Vessels," as presented at the Second IAASS Conference - Space Safety in a Global World; National Aeronautics and Space Administration, May 2007.
http://ntrs.nasa.gov/search.jsp?R=580455&id=6&qs=Ne%3D35%26Ns%3DPublicationYear%257C1%26N%3D4294964632%2B4294888757

Lamarre, Andre, "Portable array multi-techniques instrument for aircraft maintenance and manufacturing," Olympus NDT, presented at the Aerospace Testing Conference, Long Beach, CA November 2005.

Cost analysis

Composites Affordability Initiative (CAI) Cost Analysis Tool (CAICAT):
https://www.dodmantech.com/successes/AirForce/03-07/CAICAT.pdf

Choi, Jin-Woo, Kelly, Donald, Raju, John, and Reidsema, Carl, "Knowledge Based Engineering System to Estimate Manufacturing Cost for Composite Structures,"
Journal of Aircraft, 2005. 0021-8669 vol.42 no.6 (1396-1386).

Structural health monitoring, diagnostics, and prognostics

Xinlin P. Qing, Shawn Beard, Amrita Kumar, Teng K. Ooi, Fu-Kuo Chang, "Built-in Sensor Network for Structural Health Monitoring of Composite Structure," Journal of Intelligent Material Systems and Structures 2007;18:39.

Establish minimum complexity for design hot spot interrogation

Simone Mancini, Giorgio Tumino, and Paolo Gaudenzi, "Structural Health Monitoring for Future Space Vehicles," Journal of Intelligent Material Systems and Structures, Vol. 17, No. 7, 577-585 (2006).

Dennis Roach, "Smart' Aircraft Structures: a Future Necessity," CompositesWorld.com, January 2007.
http://www.compositesworld.com/hpc/issues/2007/January/1573

Certification by analysis

Christopher L. Clay, "Certification by Analysis," Air Force Research Laboratory, August 2001.
http://csm.ncsa.uiuc.edu/tmp/aiaa/lean_certification/Docs/2002.09.Clay.pdf

Reducing development cost

Grant, Peter and Carl Q. Rousseau, *Composite Structures: Theory and Practice.* ASTM International. 2001.

Improved test methods

J.Y. Cognard, P. Davies, B. Gineste, and L. Sohier, "Development of an improved adhesive test method for composite assembly design," Composites Science and Technology, March 2005; 65(3-4): 359-368.
http://www.ifremer.fr/docelec/doc/2005/publication-765.pdf

Accelerated aging and accelerated test methods

The Committee on High Speed Research, "U.S. Supersonic Commercial Aircraft: Assessing Nasa's High Speed Research Program," National Research Council (U. S.), National Academies Press, 1997.

7. Threat/Environment

General

Michel Parcelier and Jean Pierre Assié, "Effect of Space Environment on Composite Materials and Thermal Coatings," LDEF, 69 months in space : first post-retrieval symposium. Edited by Arlene S. Levine. Washington, D.C.: National Aeronautics and Space Administration, 1991, Office of Management, Scientific and Technical Information Program., p.1163. http://adsabs.harvard.edu/abs/1991NASCP3134.1163P

C. A. Smith, M. M. Hasegawa, and C. A. Jones: Space Station WP-2 Application of LDEF MLI Results. Presented at the LDEF Materials Results for Spacecraft Conference, Huntsville, Alabama, 27-28 October 1992.

C. A. Smith: The Long Duration Exposure Facility Satellite. Presented to the Society for Applied Spectroscopy, Southern California Section, September 19, 1990.

eoPOrtal.org, "LDEF (Long Duration Exposure Facility."
http://directory.eoportal.org/pres_LDEFLongDurationExposureFacility.html

European Space Agency, "The 10th International Symposium on Materials in a Space Environment & The 8th International Conference on Protection of Materials and Structures in a Space Environment," June 2006.
http://www.esa.int/esapub/conference/toc/tocSP616.pdf

Aging

Edwards, David and Kleiman, Jacob, "Introduction: Space Environmental Effects on Materials," Journal of Spacecraft and Rockets, 2005, 2006. 0022-4650 vol.41 no.3 (321-321), 0022-4650 vol.43 no.3 (481-481), 0022-4650 vol.43 no.2 (385-385).

X. Jiang; M. Soltani; E. Haddad; R. Kruzelecky; D. Nikanpour; M. Chaker, "Effects of Atomic Oxygen on the Thermochromic Characteristics of VO2 Coating," Journal of Spacecraft and Rockets, 2006. 0022-4650 vol.43 no.3 (497-500).

Chen, Philip T., (NASA, Goddard Space Flight Center, Greenbelt, MD), "Contamination effects due to space environmental interactions," AIAA-2001-95. Aerospace Sciences Meeting and Exhibit, 39th, Reno, NV, Jan. 8-11, 2001.

D. Crider, J. Prebola and D. Crews, Aerospace Testing Alliance, Arnold AFB, TN, "Space Environment Simulation Capabilities and Developments at AEDC," AIAA-2005-7635. 2005 U.S. Air Force TandE Days, Nashville, Tennessee, Dec. 6-8, 2005.

A. Adler, J. Guarnieri, G. Spanjers, J. Winter, and M. Tolliver, U.S. Air Force Research Laboratory, Kirtland AFB, NM; G. Ginet and B. Dichter, U.S. Air Force Research Laboratory, Hanscom AFB, MA; and D. Cohen, U.S. Air Force Research Laboratory, Kirtland AFB, NM, "Overview of the AFRL's Demonstration and Science Experiments (DSX) Program," AIAA-2006-7509. Space 2006, San Jose, California, Sep. 19-21, 2006.

D. Cohen, Sequoia Technologies Inc., Albuquerque, NM; G. Spanjers, J. Winter, G. Ginet, B. Dichter and M. Tolliver, U.S. Air Force Research Laboratory, Kirtland AFB, NM, "MEO Wave-Particle Interaction, Space Weather, and Environmental Effects Payloads on AFRL's Demonstration and Science Experiments (DSX)," AIAA-2006-475.
44th AIAA Aerospace Sciences Meeting and Exhibit, Reno, Nevada, Jan. 9-12, 2006

Rao, Niranjan S., and Wallace, Brian E., (The Boeing Company, Huntsville, AL), "Considerations for the design of lunar rover structures and mechanisms for prolonged operation in the lunar environment," AIAA-1993-993. Aerospace Design Conference, Irvine, CA, Feb 3-6, 1992.

MMOD impact (lunar/LEO)

SLI report (JSC)

Shuttle MMOD Risk Assessments (Tech folder)

Lunar dust (contamination) wear

http://www.moondaily.com/reports/Dust_Busting_Lunar_Style_999.html

E. Nader Khalili, "Lunar Structures Generated and Shielded with On-site Materials," American Society of Civil Engineers Journal of Aerospace Engineering Vol. 2 No. 3 Jul. 1989.
http://www.calearth.org/lunar.htm

Improved leak detection

NASA 1996 SBIR Phase I, "Autonomous Hydrogen Leak Detection and Control System," National Aeronautics and Space Administration, 1996.
http://sbir.nasa.gov/SBIR/abstracts/96/sbir/phase1/SBIR-96-1-14.07-2018.html

Ambient aging

CompositesWorld.com staff news writers, "FAA's CECAM begins Aging of Composite Structures study," CompositesWorld.com, 2007.
http://www.compositesworld.com/news/cwweekly/2006/June/cw110531

Space aging

Long Duration Exposure Facility, Laminate Materials list, National Aeronautics and Space Administration, Langley.
http://setas-www.larc.nasa.gov/PrISMtoHTML/data/Materials/Laminate.html

Moon

Govert Schilling, "Static Electricity Could Short-Circuit Moon Missions," *Science*NOW Daily News, 18 April 2007.
http://sciencenow.sciencemag.org/cgi/content/full/2007/418/3

Lunar polar extreme temperature fluctuations

Space station Thermal cycling

MISSE

William H. Kinard, “Materials International Space Station Experiment - 6A and 6B (MISSE-6A and 6B),” National Aeronautics and Space Administration, November 2007.
http://www.nasa.gov/mission_pages/station/science/experiments/MISSE-6A-and-6B.html

James C. Seferis, “Cryogenic Cycling Behavior of Polymeric Composite Materials,” University of Washington, December 2002.
http://www.stormingmedia.us/23/2318/A231814.html

Radiation hardened structures

B.D. Spieth, K.S. Qassim, R.N. Pittman, and D.A. Russell, “Shielding Electronics Behind Composite Structures,” IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 45, NO. 6, DECEMBER 1998.

Noise, insulation

H. Osman, The Boeing Company, Huntington Beach, CA; N. Atalla and S. Ghinet, Université de Sherbrooke, Sherbrooke, Quebec, Canada, “Transmission Loss Testing and Analysis of a Curved Sandwich Composite Panel,” AIAA-2004-2821. 10th AIAA/CEAS Aeroacoustics Conference , Manchester, GREAT BRITAIN, May 10-12, 2004.

Integrated elastomer layer

L.A. Krakers, “The accoustical and structural efficiency of a composite fuselage with an integrated elastomer layer in the context of the cost reduction concept,” Delft University of Technology, 1999.
http://www.tudelft.nl/live/pagina.jsp?id=690e20c0-3032-4e40-aa1c-1b35beb24618&lang=en

Atomic oxygen

Kleiman, Jacob I. and Zelina Iskanderova, Protection of Materials and Structures from Space Environment. Springer Netherlands, April 2006.

Permeability

Composite Technology Development, Inc., “An Overview of Kiboko composite pressure vessels and cryotanks,” CTD materials press release.

USDOT, “APPENDIX A: BASIC REQUIREMENTS FOR FULLY WRAPPED CARBON-FIBER REINFORCED ALUMINUM LINED CYLINDERS,” (DOT-CFFC)DATE: NOVEMBER 2000 (FOURTH REVISION)

Paul A. Lessing, “Low Permeation Liner for Hydrogen Gas Storage Tanks,” US Department of Energy, 2003.
http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/iiia5_lessing.pdf

Mallick, et al., “Ultralight Linerless Composite Tanks for In-Space Applications,” AIAA, 2004.

Mallick, et al., “An Integrated Systematic Approach to Linerless Composite Tank Development,” AIAA, 2005.

Y. Yamada-Takamura, F. Koch, H. Maier, and H. Bolt, “Hydrogen permeation barrier performance characterization of vapor deposited amorphous aluminum oxide films using coloration of tungsten oxide,” Surface and Coatings Technology Volume 153, Issues 2-3, 15 April 2002, Pages 114-118.

EMI

James R. Gaier, “Radiation Protection of New Lightweight Electromagnetic Interference Shielding Materials Determined,” National Aeronautics and Space Administration, April 1996.
http://www.grc.nasa.gov/WWW/RT1995/5000/5480g.htm

NASA SBIR, “Composite Materials for Lightweight EMI Shielding,” National Aeronautics and Space Administration, Glenn Research Center 1996 Phase II.
http://sbir.gsfc.nasa.gov/SBIR/successes/ss/3-096text.html

Toxicity including outgassing

Birmingham and McLaren Composites, “Instrumentation: Solar-B: EIS Composite Structure,” University of Birmingham Astrophysics and Space Research Group, Birmingham, UK, 2007.
http://www.sr.bham.ac.uk/instrument/solarb_comp.html

R. H. Kassanchine ; A. V. Grigorevskiy; A. N. Galygin, “Simulation of Outgassing Processes in Spacecraft Coatings Induced by Thermal Vacuum Influence,” Journal of Spacecraft and Rockets, 2005. 0022-4650 vol.41 no.3 (384-388).

Charles L. Hakes (Lockheed Martin Engineering and Sciences, Houston, TX), Jeffrey W. Garrett (Lockheed Martin Missiles and Space, Sunnyvale, CA), Horst K. F. Ehlers, and Keith Albyn (NASA, Johnson Space Center, Houston, TX), “Measurements of condensable outgassing rates of external materials on the International Space Station,” AIAA-1996-628. Aerospace Sciences Meeting and Exhibit, 34th, Reno, NV, Jan. 15-18, 1996.

APPENDIX B MAPPING NASA-PROVIDED TECHNOLOGIES TO ASSESSED SET OF TECHNOLOGIES

NASA 1. Materials and Processes	Boeing 1. Materials and Processes
1.1. Materials for cryo applications for fuel containment (e.g., microcracking, permeability, durability and insulation)	Advanced autoclave cure M&P
1.2. Surface preparation and bonding processes for improved adhesive joints	
1.3. Bonded joining concepts, e.g., pi-joints	
1.4. Co-cure, co-bond, and secondary bond process characterization for repeatable production of bonded structures	Bonded joining M&P (adhesives)
1.5. Establish equivalence of out-of-autoclave cure processes by detailed screening, and characterization	
1.6. Advanced non-autoclave cure methods (materials)	Advanced non-autoclave cure M&P
1.7. Long out-time/Long shelf-life materials	
1.8. Nanocomposite development	Infusion polymer M&P
	Sandwich (core) M&P
	Inflatable structure M&P
	High-temperature composites M&P
	Molding compounds M&P
	Bolted joining M&P (fasteners)
	Coatings and sealants
	3-D Woven Preforms

Technology Mapping (1 of 8)—Materials and Processes

NASA	Boeing
2. Manufacturing Methods	**2. Manufacturing Methods**
2.1. Develop improved non-autoclave processes for traditional carbon/resin systems	Non-autoclave manufacturing methods
2.2. Scale up of manufacturing methods to large (33-ft dia) structures	Autoclave manufacturing methods
2.3. Manufacturing technologies for large scale structures, e.g., tape/tow/broadgoods placement machines for very high laydown rates	
2.4. Develop methodology to address large moments of inertia, stability and structural rigidity of rotating tools for large structures	Large (reusable) tooling
2.5. Vented core and core splicing technology (fabrication) development	Sandwich (core) manufacturing methods
2.6. In-process inspection techniques and acceptance methodology	In-process inspection techniques
2.7. Nontraditional cure methods such as ultrasonics	Ultrasonic curing manufacturing methods
2.8. Low-cost tooling	Low-cost (expendable) tooling
2.9. Improved assembly process such as self-tooling, reducing imperfections and guaranteeing adequate tolerance	Improved assembly methods
	Fiber placement methods
	Resin Infusion manufacturing methods
	Inflatable shell manufacturing
	Bonded assembly
	Bolted assembly
	Molding compound
	High temp composites manufacturing
	3D reinforcement
	Grid-stiffened structure manufacturing methods

Technology Mapping (2 of 8)—Materials and Processes

NASA	Boeing
3. Innovative Design	**3. Innovative Design**
3.1. Efficient bolted or bonded joints between large sections	Efficient bolted joints between large sections
3.2. Multifunctional designs (strength, thermal, radiation, acoustic, …)	Multifunctional designs
3.3. Sandwich designs	Sandwich designs
3.4. Iso-, Orthogrid stiffened designs, selective reinforcement	Isogrid/orthogrid designs
3.5. Hybrid (metal/composite) stiffened structures	Hybrid (metal/composite) structures
3.6. Tailored (tow steered, variable stiffness) composites	Tailored composites
3.7. Primarily bonded structures	Primarily bonded structures
3.8. Stitched designs	Stitched designs
3.9. Point load introduction	Point load introduction
3.10. Inflatables	Inflatables (multifunctional shell, hatches)
3.11. In-space/ground repair methods	
3.12. Nanocomposites for load bearing applications and reduce damage growth	
3.13. Nanocomposites for nonload bearing applications such as electrical, IVHM, thermal	
3.14. Very high temperature capability as needed for engines and on reentry	High temperature engine and heatshield design
3.15. Composite overwrap pressure vessels	Composite pressure vessels (non-integral)
3.16. Crashworthiness incorporated in design	Crashworthiness incorporated in design
3.17. Interaction between components (acoustics issues, payload…)	Interaction between components
3.18. Integrated TPS, radiation protection	Integrated TPS, radiation protection
3.19. Lightweight mechanisms for load transfer	
3.20. Methods of preventing damage growth	Methods of preventing damage growth
	Lightweight structure for load transfer
	MMOD Resistant Design
	Skin-stringer-frame design

Technology Mapping (3 of 8)—Materials and Processes

NASA	Boeing
4. Advanced Analysis, Modeling, and Simulation	**4. Analysis, Modeling, and Simulation**
4.1. Advanced analysis for composite shell structures considering imperfections, failure mechanisms	
4.2. Design methodology for stiffener terminations and other discontinuities	
4.3. Effects of defects in novel design concepts, e.g., missing stitches, local debonds, porosity	Analysis of effects of defects
4.4. Improved methods of analyzing highly tailored composites	Analysis of highly tailored composites
4.5. Simulated test and evaluation of structural designs	Simulated test and evaluation
4.6. Thermo-structural design, e.g., thermally compliant joints	Thermo-structural analysis
4.7. Failure mechanism/prediction at RT or extreme temperatures	Failure mechanism/prediction
4.8. Optimization methods	Optimization methods
4.9. Failure mechanism/prediction at extreme temperature	
4.10. Fatigue/life prediction	Fatigue/life prediction
4.11. Probabalistic design	
4.12. Progressive failure methods	
4.13. Hierarchical analysis	Hierarchical analysis
4.14. Prediction of internal and residual stresses and design to minimize or take advantage of such stresses	

Technology Mapping (4 of 8)—Materials and Processes

NASA	Boeing
4. Advanced Analysis, Modeling, and Simulation	**4. Analysis, Modeling, and Simulation**
4.15. Scaling and validation	Scaling and validation
4.16. Coupled Loads analysis	
	Sandwich analysis
	Isogrid and orthogrid analysis
	SSF analysis
	Probabilistic risk assessment —NASA technology
	Reliability-based or risk-based design and analysis
	Certification to needed risk or reliability —similar to simulated test and
	Risk-based or reliability-based maintenance —similar to fatigue/life prediction
	Internal and residual stress analysis
	MMOD impact analysis
	Bonded joint analysis
	Bolted joint analysis
	Inflatable structure analysis
	Cost analysis

Technology Mapping (5 of 8)—Materials and Processes

NASA	Boeing
5. Design Criteria and Allowables	**5. Design Criteria and Allowables**
5.1. Define damage tolerance requirements	Damage tolerance DC&A
5.2. Radiation protection	Radiation protection DC&A
5.3. MMOD resistant design	MMOD resistant DC&A
5.4. Standardized allowables such as MIL-HDBK-17 modifications	Standardized allowables
5.5. In-space durability and environmental influence on design	Environmental durability DC&A
5.6. Develop and justify less conservative knockdown factors	Knockdown factors
5.7. Develop and justify more reasonable safety factors based on aircraft approach	Safety factors based on aircraft approach
5.8. Develop NDE standards	Develop NDE standards
5.9. Better understand and refine minimum gage specifications	Minimum gage specifications
5.10. Develop database for better understanding of damage	
	Bonded joint DC&A
	Bolted joint DC&A
	Inflatable shell DC&A

Technology Mapping (6 of 8)—Materials and Processes

NASA	Boeing
6. Development, Quality Assurance, and Certification	**6. Development, Quality Assurance, and Certification**
6.1. Inspection methods	Nondestructive inspection methods
6.2. QA to structural performance correlation	QA-to-structural performance correlation
6.3. Postdamage reliability prediction	Postdamage reliability prediction
6.4. In situ damage detection and prognostics	In situ damage detection and prognostics
6.5. Structural health monitoring, diagnostics, and prognostics	Structural health monitoring, diagnostics, and prognostics
6.6. Establish minimum complexity for design hot spot interrogation	Hot spot interrogation
6.7. Identify smallest test scale where full environmental (including in-space) simulation is required	Scaling effects
6.8. Establish level of certification that can be accomplished by analysis	Certification by analysis
6.9. Increased reliance on simulation rather than testing for certification	Certification by simulation
6.10. Reducing development cost	
6.11. Improved test methods	Improved test methods
6.12. Database development	Database development
6.13. Accelerated aging and accelerated test methods	Accelerated aging and test methods
	In-space/ground repair methods
	Improved leak detection

Technology Mapping (7 of 8)—Materials and Processes

NASA	Boeing
7. Threat and Environment	**7. Design for Threat/Environment**
7.1. MMOD protection (lunar/lEO)	MMOD (lunar/LEO)
7.2. Lunar dust impacts	Lunar dust
7.3. Improved leak detection (H2, O2, air)	
7.4. Aging in lunar environment	Aging in lunar and space environment
7.5. Static charge issues (on Earth or Moon)	Static charge
7.6. Lunar polar extreme temperature fluctuations	Thermal cycling
7.7. Radiation hardened structures	Radiation
7.8. Noise, insulation	Noise
7.9. Coatings and sealants	
7.10. Toxicity including outgassing	Toxicity and outgassing

Technology Mapping (8 of 8)—Materials and Processes

APPENDIX C BLOCK 2 SCENARIO

Objective

- Determine technology applicability to block upgrade to entire Constellation program
- Identify technology advancements (and in turn performance enhancements) available to each Element

Approach

- Increase Constellation element timeframe rating by 1.
- Compare Block 1 and Block 2 results

		Technology TRL		
		2-3 (1)	4-5 (2)	6+ (3)
Application time to tech commitment	<5 yrs (1)	1	1	2
	5-10 yrs (2)	1	2	
	>10 yrs (3)	2	3	

Block 1 Timeframe

Constellation Element			Time frame
Ares 1			
	First stage		1
	Interstage		1
	Upper stage	Aft section	1
		LO2 tank	1
		Intertank (CB)	1
		LH2 tank	1
		Instrument Unit	1
Orion			
	Spacecraft adapter		1
	Service module	Tanks	1
		Shell	1
	Crew module	Crew cabin	1
		Aeroshell, fwd	1
		Aeroshell, aft	1
	LAS	Shroud	1
		Tower	1
Ares V			
	First stage	Aft section	2
		LO2 tank	2
		Intertank	2
		LH2 tank	2
	Interstage		2
	EDS	Aft section	2
		LO2 tank	2
		Intertank	2
		LH2 tank	2
	LSAM Shroud		2
Altair			
	Descent stage	LO2 tank(s)	2
		Support str	2
		LH2 tank(s)	2
		Legs	2
	Ascent stage	LO2 tank(s)	2
		Support str	2
		LCH4 tank(s)	2
		Crew cabin	3

Block 2 Timeframe

Constellation Element			Time frame
Ares 1			
	First stage		2
	Interstage		2
	Upper stage	Aft section	2
		LO2 tank	2
		Intertank (CB)	2
		LH2 tank	2
		Instrument Unit	2
Orion			
	Spacecraft adapter		2
	Service module	Tanks	2
		Shell	2
	Crew module	Crew cabin	2
		Aeroshell, fwd	2
		Aeroshell, aft	2
	LAS	Shroud	2
		Tower	2
Ares V			
	First stage	Aft section	3
		LO2 tank	3
		Intertank	3
		LH2 tank	3
	Interstage		3
	EDS	Aft section	3
		LO2 tank	3
		Intertank	3
		LH2 tank	3
	LSAM Shroud		3
LSAM			
	Descent stage	LO2 tank	3
		Support str	3
		LH2 tank	3
		Legs	3
	Ascent stage	LO2 tank	3
		Support str	3
		LCH4 tank	3
		Crew Cabin	3

Comparison Between Block 1 and Block 2 Constellation Element Timeframes

Exploration Element			Structural System 1 LoMat Fiber SSF	2 LoMat Fiber Grid	3 LoMat Fiber Sand	4 LoMat Fiber Mono	5 LoMat Infus SSF	6 LoMat Infus Grid	7 LoMat Infus Sand	8 LoMat Infus Mono	9 LoMat Hand SSF	10 LoMat Hand Grid	11 LoMat Hand Sand	12 LoMat Hand Mono	13 HiMat Fiber SSF	14 HiMat Fiber Grid	15 HiMat Fiber Sand	16 HiMat Fiber Mono	17 HiMat Infus SSF	18 HiMat Infus Grid	19 HiMat Infus Sand	20 HiMat Infus Mono	21 HiMat Hand SSF	22 HiMat Hand Grid	23 HiMat Hand Sand	24 HiMat Hand Mono
Ares 1																										
	First stage					9				9				11				7				9				7
	Interstage		11	9	10		10	10	10		11	12	11		9	9	8		8	8	10		8	8	8	
	Upperstage	Aft Section	10	10	11		9	9	9		10	11	12		10	10	9		7	9	11		9	9	9	
		LO2 tank	10	10	11		9	9	9		10	11	12		10	10	9		7	9	11		9	9	9	
		Intertank (CB)	9	9	10		8	8	8		11	10	11		11	9	8		8	10	10		10	10	10	
		LH2 tank	9	9	10		8	8	8		9	10	11		9	9	10		6	8	10		10	10	10	
		Instrument Unit	10	10	9	8	9	9	9	8	10	9	10	10	10	8	7	6	7	9	9	8	9	9	9	8
Orion																										
	Spacecraft adapter		10	10	9		9	9	9		10	9	10		10	8	7		7	9	9		9	9	9	
	Service module	Tanks	8	8	7	8	9	9	7	9	8	7	8	9	10	10	9	7	6	9	9	8	9	9	9	8
		Shell	9	9	8		8	8	8		9	8	9		9	9	8		6	8	8		8	8	10	
	Crew module	Crew cabin	6	6	7		7	7	5		6	7	8		8	10	11		5	9	9		9	9	9	
		Aeroshell, fwd	8	8	9		9	9	7		8	9	10		10	12	11		6	9	11		9	9	9	
		Aeroshell, aft	8	8	9		9	9	7		8	9	10		10	12	11		6	9	11		9	9	9	
	LAS	Shroud	11	9	8		10	10	10		11	10	9		9	7	6		8	8	8		8	8	8	
		Tower	11	9	8	7	10	10	10	9	11	10	9	9	9	7	6	5	8	8	8	7	8	8	8	7
Ares V																										
	First stage	Aft section	10	10	11		9	9	9		10	11	12		10	10	9		7	9	11		9	9	9	
		LO2 tank	9	11	12		8	8	10		9	10	11		9	9	8		6	8	10		8	8	8	
		Intertank	11	11	10		10	10	10		9	10	11		9	9	8		6	8	10		8	8	8	
		LH2 tank	8	10	11		7	7	9		8	9	10		8	8	9		5	7	9		9	9	9	
	Interstage		11	11	10		10	10	10		9	10	11		9	9	8		6	8	10		8	8	8	
	EDS	Aft section	10	10	9		9	9	9		8	9	10		8	10	9		5	7	9		7	7	9	
		LO2 tank	9	9	10		8	8	8		9	10	11		9	11	10		6	8	10		8	8	10	
		Intertank	10	10	9		9	9	9		8	9	10		8	10	9		5	7	9		7	7	9	
		LH2 tank	7	9	10		6	6	8		7	8	9		7	9	10		4	6	8		8	8	10	
	LSAM Shroud		11	11	10		10	10	10		9	10	11		9	9	8		6	8	10		8	8	8	
LSAM																										
	Descent stage	LO2 tank(s)				9				7				9				9				9				11
		Support str				8				8				8				8				8				10
		LH2 tank(s)				9				7				9				9				9				11
		Legs				9				7				9				9				9				11
	Ascent stage	LO2 tank(s)				9				7				9				9				9				11
		Support str				8				8				8				8				8				10
		LH2 tank(s)				9				7				9				9				9				11
Surface elements																										
	Habitat module		6	6	7	8	7	7	5	6	6	7	8	8	8	10	11	12	5	9	9	10	9	9	9	10

Block 2 Technical Fit remains the same as that for Block 1.

Exploration Application			Time frame	TRL	Structural Systems 1 LoMat Fiber SSF	2 LoMat Fiber Grid	3 LoMat Fiber Sand	4 LoMat Fiber Mono	5 LoMat Infus SSF	6 LoMat Infus Grid	7 LoMat Infus Sand	8 LoMat Infus Mono	9 LoMat Hand SSF	10 LoMat Hand Grid	11 LoMat Hand Sand	12 LoMat Hand Mono	13 HiMat Fiber SSF	14 HiMat Fiber Grid	15 HiMat Fiber Sand	16 HiMat Fiber Mono	17 HiMat Infus SSF	18 HiMat Infus Grid	19 HiMat Infus Sand	20 HiMat Infus Mono	21 HiMat Hand SSF	22 HiMat Hand Grid	23 HiMat Hand Sand	24 HiMat Hand Mono
					2	2	2	3	2	2	2	3	2	2	2	3	3	2	3	3	2	2	1	2	3	3	3	3
Ares 1																												
	First stage		2					3				3				3				3				2				3
	Interstage		2		2	2	2		2	2	2		2	2	2		3	2	3		2	2	1		3	3	3	
	Upperstage	Aft section	2		2	2	2		2	2	2		2	2	2		3	2	3		2	2	1		3	3	3	
		LO2 tank	2		2	2	2		2	2	2		2	2	2		3	2	3		2	2	1		3	3	3	
		Intertank (CB)	2		2	2	2		2	2	2		2	2	2		3	2	3		2	2	1		3	3	3	
		LH2 tank	2		2	2	2		2	2	2		2	2	2		3	2	3		2	2	1		3	3	3	
		Instrument Unit	2		2	2	2	3	2	2	2	3	2	2	2	3	3	2	3	3	2	2	1	2	3	3	3	3
Orion																												
	Spacecraft adapter		2		2	2	2		2	2	2		2	2	2		3	2	3		2	2	1		3	3	3	
	Service module	Tanks	2		2	2	2	3	2	2	2	3	2	2	2	3	3	2	3	3	2	2	1	2	3	3	3	3
		Shell	2		2	2	2		2	2	2		2	2	2		3	2	3		2	2	1		3	3	3	
	Crew module	Crew cabin	2		2	2	2		2	2	2		2	2	2		3	2	3		2	2	1		3	3	3	
		Aeroshell, fwd	2		2	2	2		2	2	2		2	2	2		3	2	3		2	2	1		3	3	3	
		Aeroshell, aft	2		2	2	2		2	2	2		2	2	2		3	2	3		2	2	1		3	3	3	
	LAS	Shroud	2		2	2	2		2	2	2		2	2	2		3	2	3		2	2	1		3	3	3	
		Tower	2		2	2	2	3	2	2	2	3	2	2	2	3	3	2	3	3	2	2	1	2	3	3	3	3
Ares V																												
	First stage	Aft section	3		3	3	3		3	3	3		3	3	3		3	3	3		3	3	2		3	3	3	
		LO2 tank	3		3	3	3		3	3	3		3	3	3		3	3	3		3	3	2		3	3	3	
		Intertank	3		3	3	3		3	3	3		3	3	3		3	3	3		3	3	2		3	3	3	
		LH2 tank	3		3	3	3		3	3	3		3	3	3		3	3	3		3	3	2		3	3	3	
	Interstage		3		3	3	3		3	3	3		3	3	3		3	3	3		3	3	2		3	3	3	
	EDS	Aft section	3		3	3	3		3	3	3		3	3	3		3	3	3		3	3	2		3	3	3	
		LO2 tank	3		3	3	3		3	3	3		3	3	3		3	3	3		3	3	2		3	3	3	
		Intertank	3		3	3	3		3	3	3		3	3	3		3	3	3		3	3	2		3	3	3	
		LH2 tank	3		3	3	3		3	3	3		3	3	3		3	3	3		3	3	2		3	3	3	
	LSAM Shroud		3		3	3	3		3	3	3		3	3	3		3	3	3		3	3	2		3	3	3	
LSAM																												
	Descent stage	LO2 tank	3					3				3				3				3				3				3
		Support str	3					3				3				3				3				3				3
		LH2 tank	3					3				3				3				3				3				3
		Legs	3					3				3				3				3				3				3
	Ascent stage	LO2 tank	3					3				3				3				3				3				3
		Support str	3					3				3				3				3				3				3
		LCH4 tank	3					3				3				3				3				3				3
		Crew Cabin	3		3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	2	3	3	3	3	3

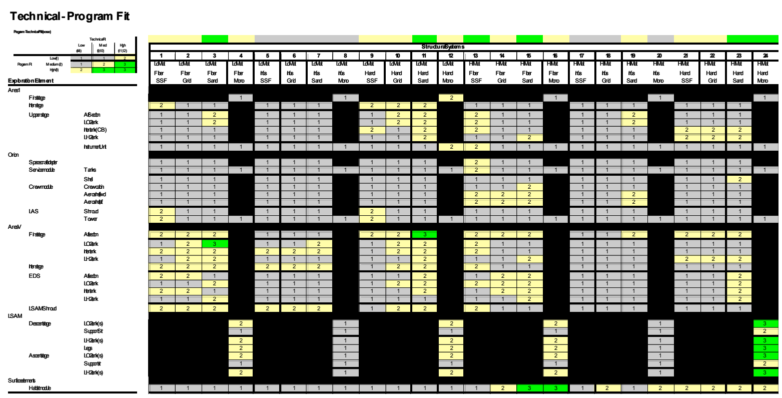
Block 2 Program Fit

Exploration Element			Structural Systems 1 LoM at Fiber SSF	2 LoM at Fiber Grid	3 LoM at Fiber Sand	4 LoM at Fiber Mono	5 LoM at Infus SSF	6 LoM at Infus Grid	7 LoM at Infus Sand	8 LoM at Infus Mono	9 LoM at Hand SSF	10 LoM at Hand Grid	11 LoM at Hand Sand	12 LoM at Hand Mono	13 HiM at Fiber SSF	14 HiM at Fiber Grid	15 HiM at Fiber Sand	16 HiM at Fiber Mono	17 HiM at Infus SSF	18 HiM at Infus Grid	19 HiM at Infus Sand	20 HiM at Infus Mono	21 HiM at Hand SSF	22 HiM at Hand Grid	23 HiM at Hand Sand	24 HiM at Hand Mono
Ares 1																										
	First stage					2				2				3				1				1				1
	Interstage		2	1	2		2	2	2		2	3	2		2	1	1		1	1	1		1	1	1	
	Upper stage	Aft Section	2	2	2		1	1	1		2	2	3		2	2	2		1	1	2		2	2	2	
		LO2 tank	2	2	2		1	1	1		2	2	3		2	2	2		1	1	2		2	2	2	
		Intertank (CB)	1	1	2		1	1	1		2	2	2		3	1	1		1	2	1		2	2	2	
		LH2 tank	1	1	2		1	1	1		1	2	2		2	1	2		1	1	1		2	2	2	
		Instrument Unit	2	2	1	1	1	1	1	1	2	1	2	3	2	1	1	1	1	1	1	1	2	2	2	1
Orion																										
	Spacecraft adapter		2	2	1		1	1	1		2	1	2		2	1	1		1	1	1		2	2	2	
	Service module	Tanks	1	1	1	1	1	1	1	2	1	1	1	2	2	2	2	1	1	1	1	1	2	2	2	1
		Shell	1	1	1		1	1	1		1	1	1		2	1	1		1	1	1		1	1	2	
	Crew module	Crew cabin	1	1	1		1	1	1		1	1	1		1	2	3		1	1	1		2	2	2	
		Aeroshell, fwd	1	1	1		1	1	1		1	1	2		2	3	3		1	1	2		2	2	2	
		Aeroshell, aft	1	1	1		1	1	1		1	1	2		2	3	3		1	1	2		2	2	2	
	LAS	Shroud	2	1	1		2	2	2		2	2	1		2	1	1		1	1	1		1	1	1	
		Tower	2	1	1	1	2	2	2	2	2	2	1	2	2	1	1	1	1	1	1	1	1	1	1	1
Ares V																										
	First stage	Aft section	2	2	3		2	2	2		2	3	3		2	2	2		1	2	2		2	2	2	
		LO2 tank	2	3	3		1	1	2		2	2	3		2	2	1		1	1	2		1	1	1	
		Intertank	3	3	2		2	2	2		2	2	3		2	2	1		1	1	2		1	1	1	
		LH2 tank	1	2	3		1	1	2		1	2	2		1	1	2		1	1	1		2	2	2	
	Interstage		3	3	2		2	2	2		2	2	3		2	2	1		1	1	2		1	1	1	
	EDS	Aft section	2	2	2		2	2	2		1	2	2		1	2	2		1	1	1		1	1	2	
		LO2 tank	2	2	2		1	1	1		2	2	3		2	3	2		1	1	2		1	1	2	
		Intertank	2	2	2		2	2	2		1	2	2		1	2	2		1	1	1		1	1	2	
		LH2 tank	1	2	2		1	1	1		1	1	2		1	2	2		1	1	1		1	1	2	
	LSAM Shroud		3	3	2		2	2	2		2	2	3		2	2	1		1	1	2		1	1	1	
LSAM																										
	Descent stage	LO2 tank(s)				2				1				2				2				2				3
		Support Str				1				1				1				1				1				2
		LH2 tank(s)				2				1				2				2				2				3
		Legs				2				1				2				2				2				3
	Ascent stage	LO2 tank(s)				2				1				2				2				2				3
		Support str				1				1				1				1				1				2
		LH2 tank(s)				2				1				2				2				2				3
		Crew Cabin	1	1	1	1	1	1	1	1	1	1	1	1	1	2	3	3	1	2	1	2	2	2	2	2

Block 2 Technical – Program Fit

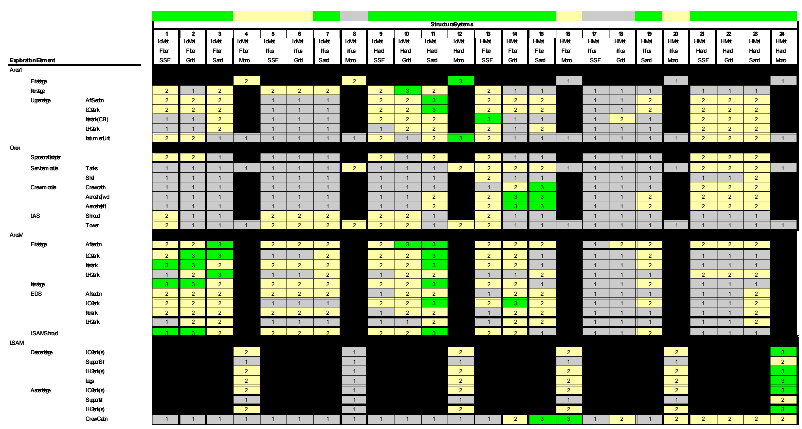
Block 1

Technical -Program Fit

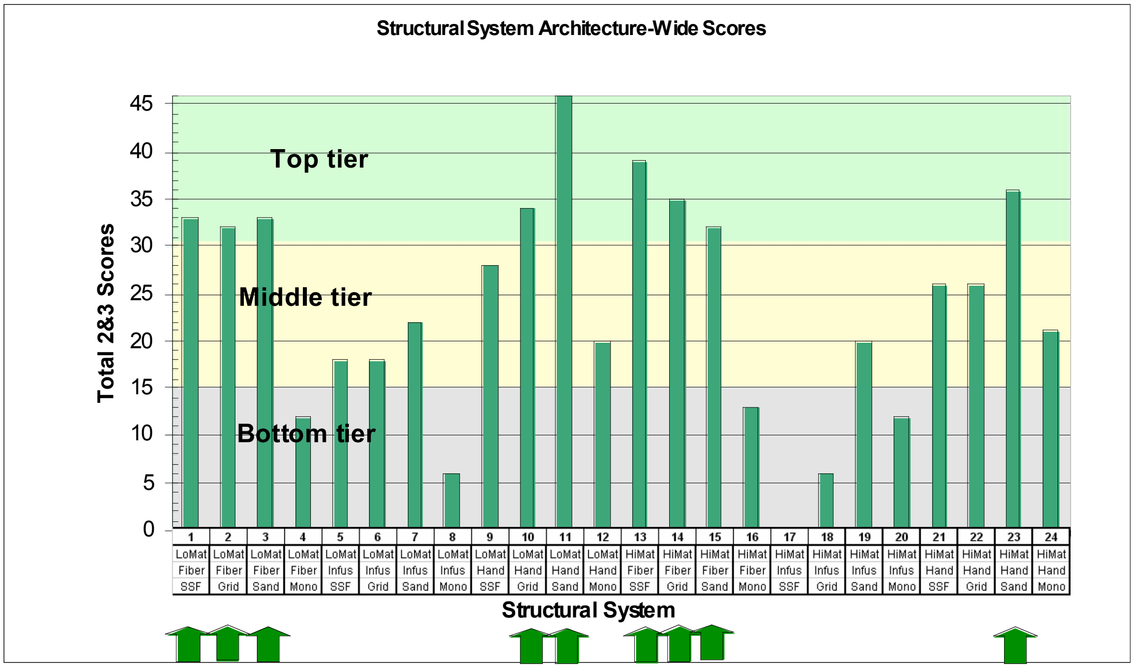


Block 2

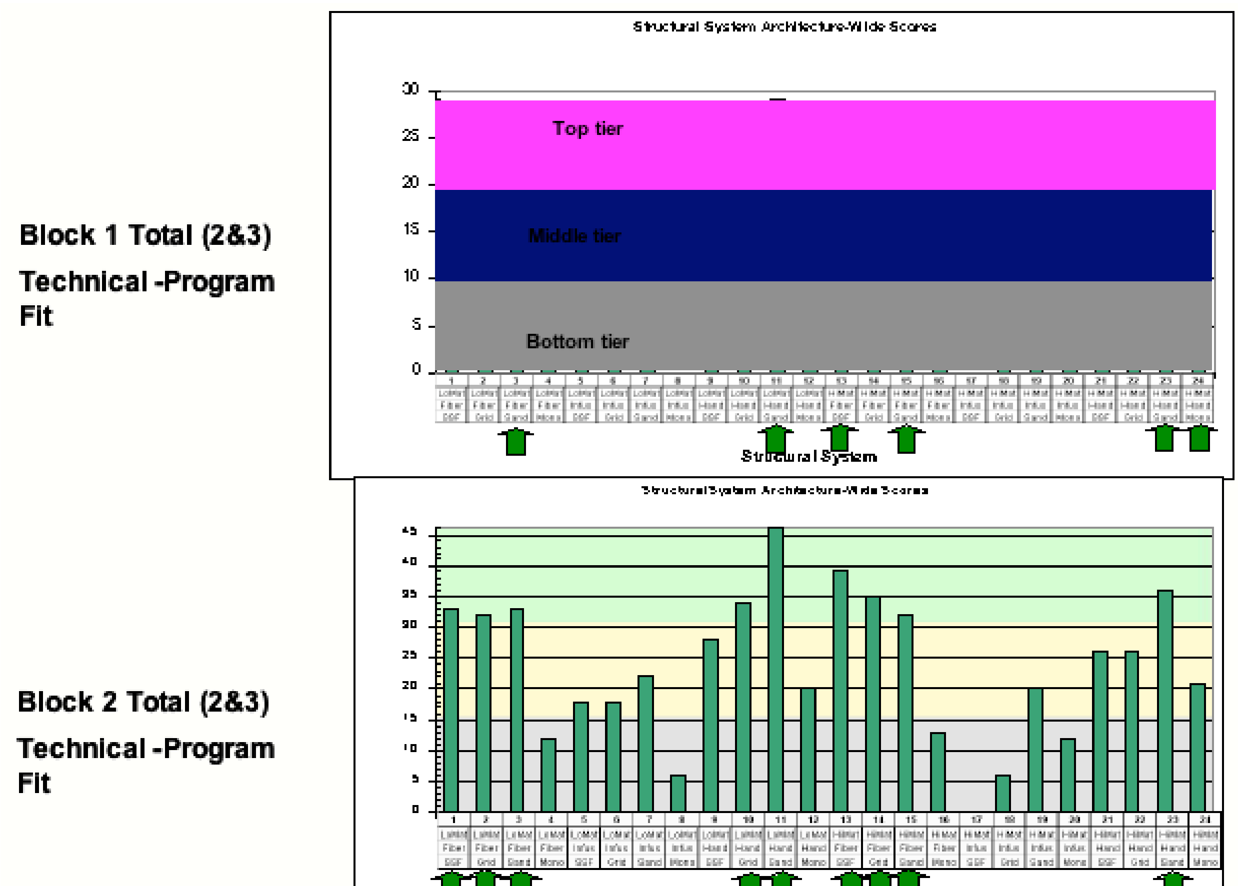
Technical -Program Fit



Comparison Between Block 1 and Block 2 Technical-Program Fit

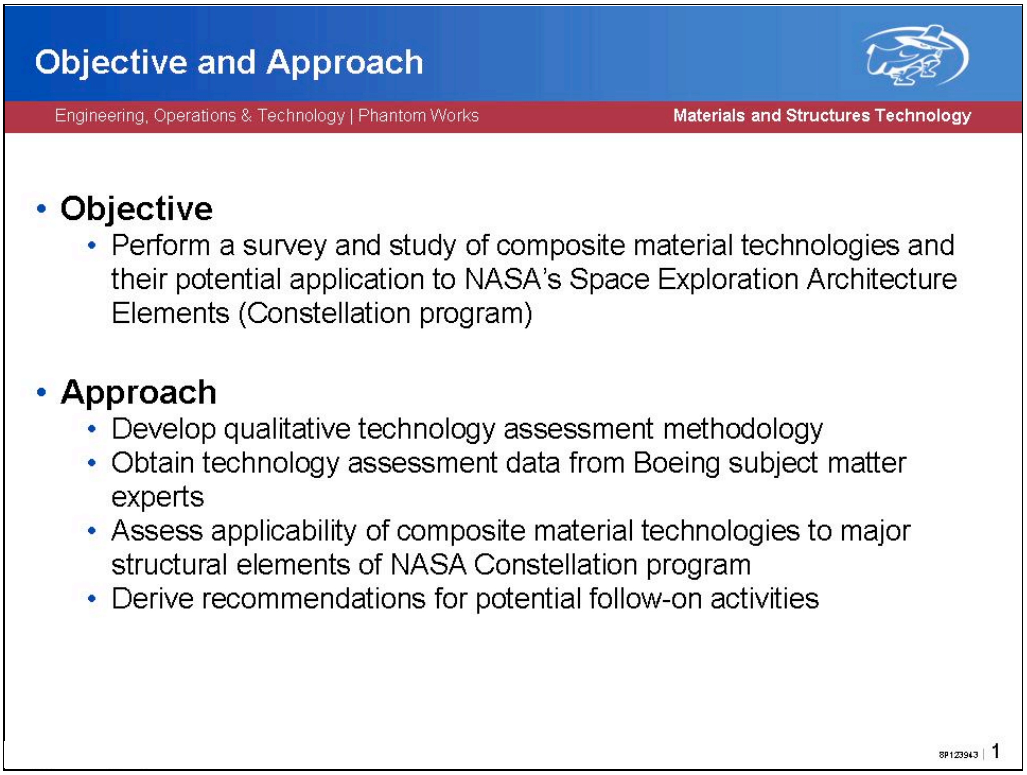


Block 2 Structural System Total (2 and 3) Technical-Program Fit Scores



Comparison Between Block 1 and Block 2 Technical-Program Fit

APPENDIX D JANUARY 23, 2008, FINAL BRIEFING



Constellation Elements

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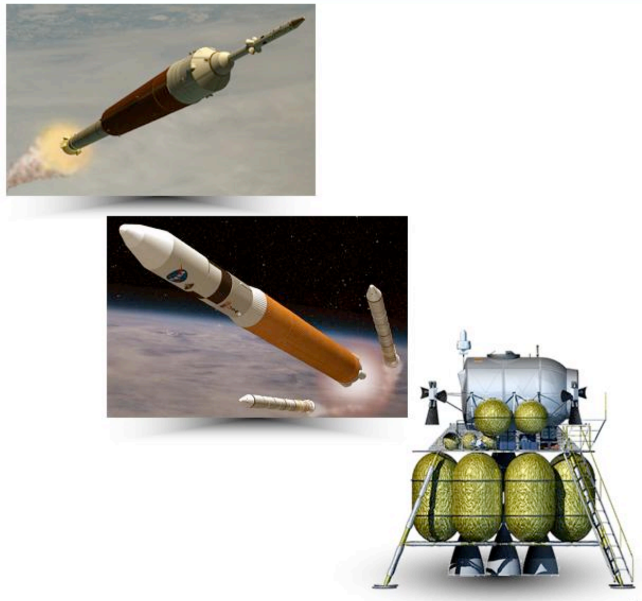
Constellation Element		
Ares 1		
	First stage	
	Interstage	
	Upper stage	Aft Section
		LO2 tank
		Intertank (CB)
		LH2 tank
		Instrument Unit
Orion		
	Spacecraft adapter	
	Service module	Tanks
		Shell
	Crew module	Crew cabin
		Aeroshell, fwd
		Aeroshell, aft
	LAS	Shroud
		Tower
Ares V		
	First stage	Aft section
		LO2 tank
		Intertank
		LH2 tank
	Interstage	
	EDS	Aft section
		LO2 tank
		Intertank
		LH2 tank
	LSAM Shroud	
Altair		
	Descent stage	LO2 tank(s)
		Support Str
		LH2 tank(s)
		Legs
	Ascent stage	LO2 tank(s)
		Support str
		LCH4 tank(s)
		Crew cabin



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Study Approach Flowchart

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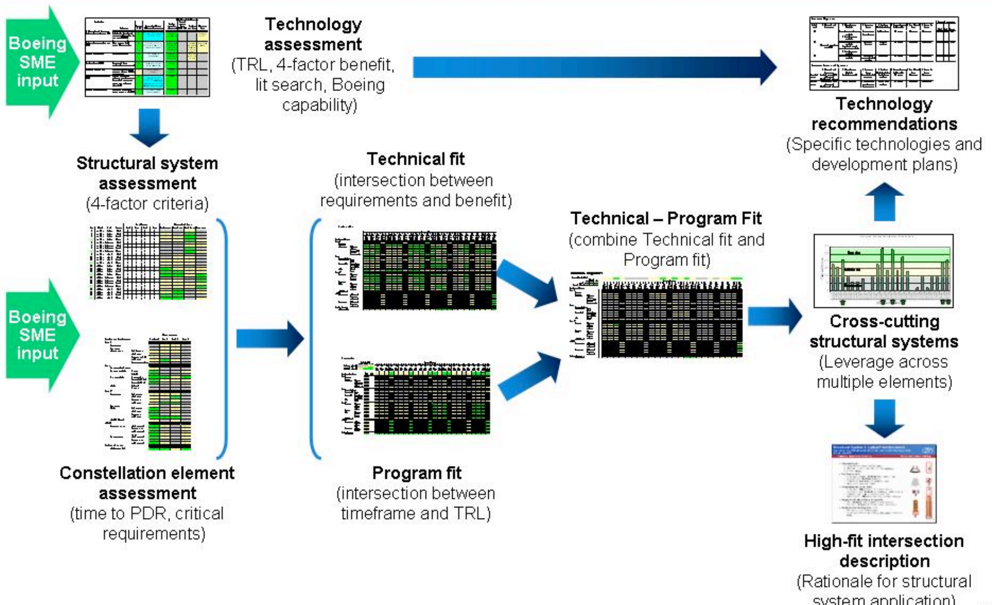

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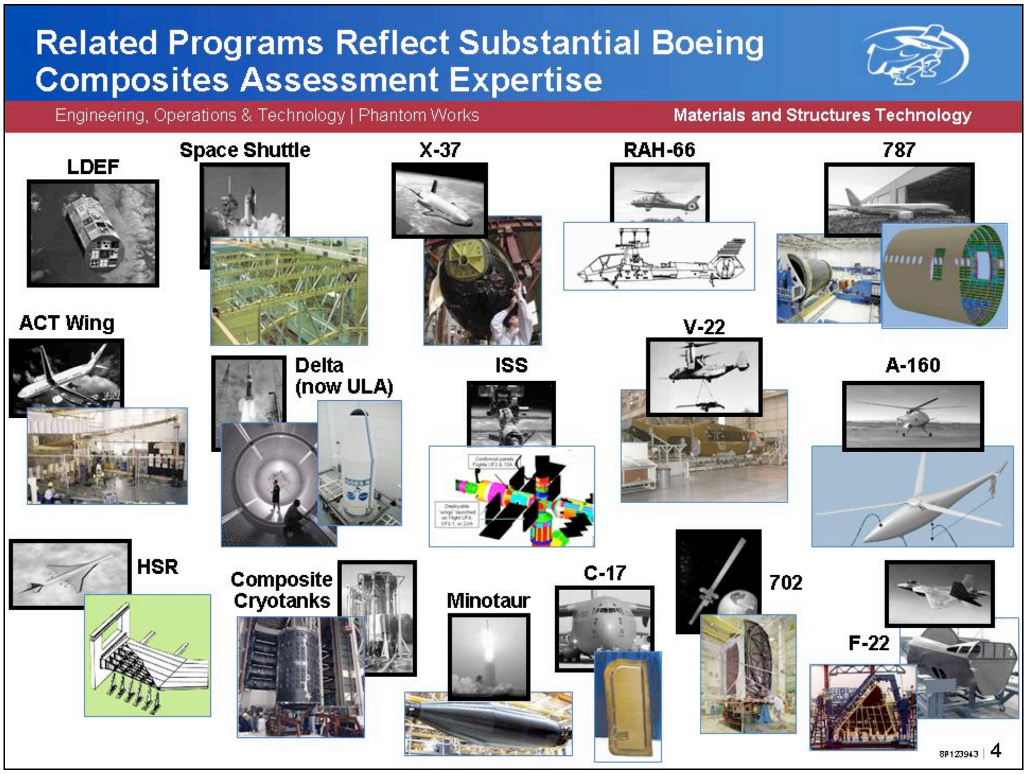
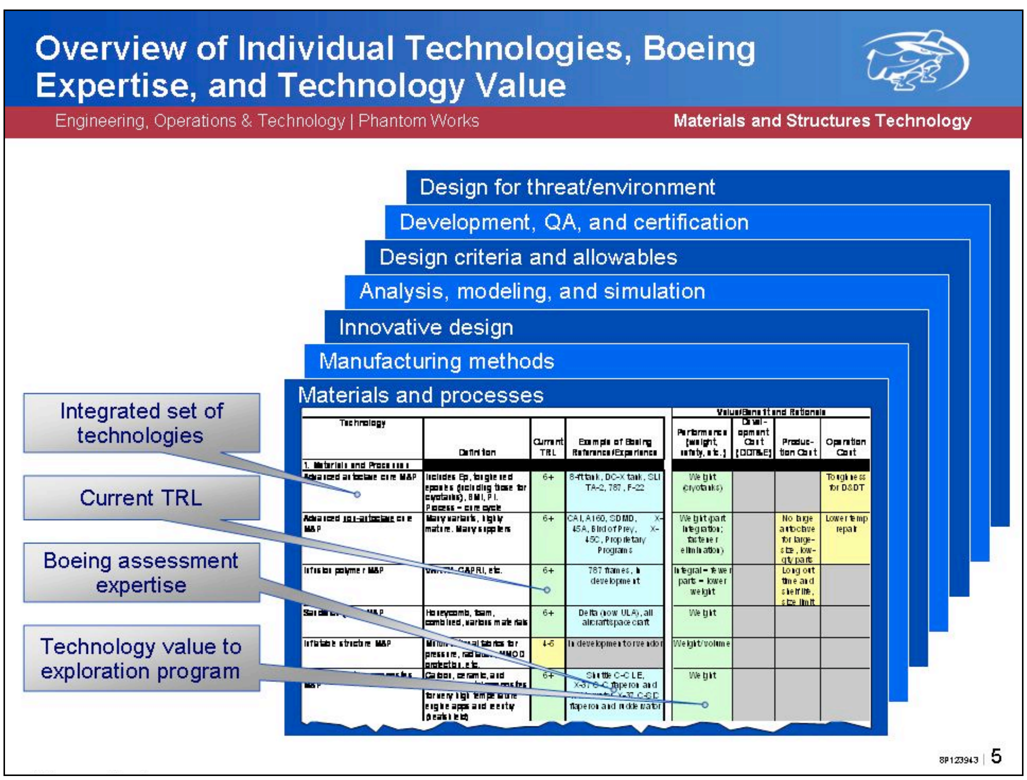

Related Programs Reflect Substantial Boeing Composites Assessment Expertise
Engineering, Operations & Technology | Phantom Works
Materials and Structures Technology
LDEF
Space Shuttle
X-37
RAH-66
787
ACT Wing
Delta (now ULA)
ISS
V-22
A-160
HSR
Composite Cryotanks
Minotaur
C-17
702
F-22
4


Overview of Individual Technologies, Boeing Expertise, and Technology Value
Engineering, Operations & Technology | Phantom Works
Materials and Structures Technology
Design for threat/environment
Development, QA, and certification
Design criteria and allowables
Analysis, modeling, and simulation
Innovative design
Manufacturing methods
Materials and processes
Integrated set of technologies
Current TRL
Boeing assessment expertise
Technology value to exploration program
5

Comprehensive Technology Development Plan Is Basis for Focused Recommendations

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Technology	Definition	Development Plan Options
1. Materials and Processes		
Advanced autoclave cure M&P	Includes Ep, toughened epoxies (including those for cryo tanks), BMI, PI. Process = cure cycle	1. Utilize higher operating temperature toughened Ep and BMI with lower cure temp and pressure 2. Utilize higher operating temp thermoplastics with lower consolidation temp and pressure 3. Improve hydrogen impermeability for cryotanks 4. Employ thin-ply l
Advanced non-autoclave cure M&P	Primarily Epoxy (including those for cryo tanks)	1. Develop material and process with across-the-board autoclave-like properties 2. Acquire epoxies with a lower cure temp and a higher working temp
Infusion polymer M&P	VARTM, CAPRI, etc.	1. Acquire higher temperature resins 2. Develop higher modulus fiber reinforcement 3. Improve rapid preforming
Sandwich (core) M&P	Honeycomb, foam, combined, various materials	1. Design a multifunctional, multicomponent core with strength, thermal, radiation, self-repair, etc., properties 2. Incorporate sandwich panel purge/vent system integration 3. Utilize low permeability co-cured sandwich facesheets
Inflatable structure M&P	Multifunctional fabrics for pressure, radiation, MMOD protection, etc.	1. Evaluate a TransHab-type MMOD protection concept with potential Constellation options; impact data is available
High-temperature composites M&P	Carbon, ceramic, and refractory metal composites for very high temperature engine apps and reentry (heatshield)	1. Develop/characterize one C-C system with balanced processibility, operating temperature, properties, integration, operability, and cross-cutting applicability (including other non-Exploration NASA missions) 2. Develop one well-characterized C-SiC syste
Molding compounds M&P	For fittings, padups, and engine parts (e.g., HexMC)	1. Adapt BCA MCs for space apps
Bonded joining M&P (adhesives)	Co-cure, co-bond, and secondary	1. Develop open air plasma treatment for lower cost and cycle time for cobond/secondary bond applications

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24 Structural Systems Organize a Wide Range of Related Structures Technologies

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	Constituent Type								
	1. Materials and Processes		2. Manufacturing Methods			3. Innovative Design			
	Material System		Fabrication			Design			
Structural System	Low Perf and Cost	High Perf and Cost	Fiber Placement	Resin Infusion	Hand Layup	SSF	Iso/ Orthogrid	Sandwich	Monocoque
1	■		■			■			
2	■		■				■		
3	■		■					■	
4	■		■						■
5	■			■		■			
6	■			■			■		
7	■			■				■	
8	■			■					■
9	■				■	■			
10	■				■		■		
11	■				■			■	
12	■				■				■
13		■	■			■			
14		■	■				■		
15		■	■					■	
16		■	■						■
17		■		■		■			
18		■		■			■		
19		■		■				■	
20		■		■					■
21		■			■	■			
22		■			■		■		
23		■			■			■	
24		■			■				■

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Technical Fit Relates Structural System Values to Constellation Requirements

Engineering, Operations & Technology | Phantom Works — Materials and Structures Technology

Application Score	Technology Score 1	Technology Score 2	Technology Score 3
1	1	1	1
2	1	2	2
3	1	2	3

Structural System

Constellation Element		1 LoMat Fiber SSF	2 LoMat Fiber Grid	3 LoMat Fiber Sand	4 LoMat Fiber Mono	5 LoMat Infus SSF	6 LoMat Infus Grid	7 LoMat Infus Sand	8 LoMat Infus Mono	9 LoMat Hand SSF	10 LoMat Hand Grid	11 LoMat Hand Sand	12 LoMat Hand Mono	13 HiMat Fiber SSF	14 HiMat Fiber Grid	15 HiMat Fiber Sand	16 HiMat Fiber Mono	17 HiMat Infus SSF	18 HiMat Infus Grid	19 HiMat Infus Sand	20 HiMat Infus Mono	21 HiMat Hand SSF	22 HiMat Hand Grid	23 HiMat Hand Sand	24 HiMat Hand Mono
Ares 1																									
First stage					9				9				11				7				9				7
Interstage		11	9	10		10	10	10		11	12	11		9	9	8		8	8	10		8	8	8	
Upper stage	Aft Section	10	10	11		9	9	9		10	11	12		10	10	9		7	9	11		9	9	9	
	LO2 tank	10	10	11		9	9	9		10	11	12		10	10	9		7	9	11		9	9	9	
	Intertank (CB)	9	9	10		8	8	8		11	10	11		11	9	8		8	10	10		10	10	10	
	LH2 tank	9	9	10		8	8	8		9	10	11		9	9	10		6	8	10		10	10	10	
	Instrument Unit	10	10	9	8	9	9	9	8	10	9	10	10	10	8	7	6	7	9	9	8	9	9	9	8
Orion																									
Spacecraft adapter		10	10	9		9	9	9		10	9	10		10	8	7		7	9	9		9	9	9	
Service module	Tanks	8	8	7	8	9	9	7	9	8	7	8	9	10	10	9	7	6	9	9	8	9	9	9	8
	Shell	9	9	8		8	8	8		9	8	9		9	9	8		6	8	8		8	8	10	
Crew module	Crew cabin	6	6	7		7	7	5		6	7	8		8	10	11		5	9	9		9	9	9	
	Aeroshell, fwd	8	8	9		9	9	7		8	9	10		10	12	11		6	9	11		9	9	9	
	Aeroshell, aft	8	8	9		9	9	7		8	9	10		10	12	11		6	9	11		9	9	9	
LAS	Shroud	11	9	8		10	10	10		11	10	9		9	7	6		8	8	8		8	8	8	
	Tower	11	9	8	7	10	10	10	9	11	10	9	9	9	7	6	5	8	8	8	7	8	8	8	7
Ares V																									
First stage	Aft section	10	10	11		9	9	9		10	11	12		10	10	9		7	9	11		9	9	9	
	LO2 tank	9	11	12		8	8	10		9	10	11		9	9	8		6	8	10		8	8	8	
	Intertank	11	11	10		10	10	10		9	10	11		9	9	8		6	8	10		8	8	8	
	LH2 tank	8	10	11		7	7	9		8	9	10		8	8	9		5	7	9		9	9	9	
Interstage		11	11	10		10	10	10		9	10	11		9	9	8		6	8	10		8	8	8	
EDS	Aft section	10	10	9		9	9	9		8	9	10		8	10	9		5	7	9		7	7	9	
	LO2 tank	9	9	10		8	8	8		9	10	11		9	11	10		6	8	10		8	8	10	
	Intertank	10	10	9		9	9	9		8	9	10		8	10	9		5	7	9		7	7	9	
	LH2 tank	7	9	10		6	6	8		7	8	9		7	9	10		4	6	8		8	8	10	
LSAM Shroud		11	11	10		10	10	10		9	10	11		9	9	8		6	8	10		8	8	8	
Altair																									
Descent stage	LO2 tank(s)				9				7				9				9				9				11
	Support str				8				8				8				8				8				10
	LH2 tank(s)				9				7				9				9				9				11
	Legs				9				7				9				9				9				11
Ascent stage	LO2 tank(s)				9				7				9				9				9				11
	Support str				8				8				8				8				8				10
	LCH4 tank(s)				9				7				9				9				9				11
	Crew cabin	6	6	7	8	7	7	5	6	6	7	8	8	8	10	11	12	5	9	9	10	9	9	9	10

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Program Fit Relates Structural System Maturity to Constellation Timeframe

Engineering, Operations & Technology | Phantom Works — Materials and Structures Technology

Application time to tech commitment	TRL 2-3(1)	TRL 45(2)	TRL 6+(3)
<5 yrs (1)	1	1	2
5-10 yrs (2)	1	2	3
>10 yrs (3)	2	3	3

Structural Systems

Constellation Element		Time-frame	TRL	1 LoMat Fiber SSF	2 LoMat Fiber Grid	3 LoMat Fiber Sand	4 LoMat Fiber Mono	5 LoMat Infus SSF	6 LoMat Infus Grid	7 LoMat Infus Sand	8 LoMat Infus Mono	9 LoMat Hand SSF	10 LoMat Hand Grid	11 LoMat Hand Sand	12 LoMat Hand Mono	13 HiMat Fiber SSF	14 HiMat Fiber Grid	15 HiMat Fiber Sand	16 HiMat Fiber Mono	17 HiMat Infus SSF	18 HiMat Infus Grid	19 HiMat Infus Sand	20 HiMat Infus Mono	21 HiMat Hand SSF	22 HiMat Hand Grid	23 HiMat Hand Sand	24 HiMat Hand Mono
				2	2	2	3	2	2	2	3	2	2	2	3	3	2	3	3	2	2	1	2	3	3	3	3
Ares 1																											
First stage		1					2				2				2				2				1				2
Interstage		1		1	1	1		1	1	1		1	1	1		2	1	2		1	1	1		2	2	2	
Upper stage	Aft section	1		1	1	1		1	1	1		1	1	1		2	1	2		1	1	1		2	2	2	
	LO2 tank	1		1	1	1		1	1	1		1	1	1		2	1	2		1	1	1		2	2	2	
	Intertank (CB)	1		1	1	1		1	1	1		1	1	1		2	1	2		1	1	1		2	2	2	
	LH2 tank	1		1	1	1		1	1	1		1	1	1		2	1	2		1	1	1		2	2	2	
	Instrument Unit	1		1	1	1	2	1	1	1	2	1	1	1	2	2	1	2	2	1	1	1	1	2	2	2	2
Orion																											
Spacecraft adapter		1		1	1	1		1	1	1		1	1	1		2	1	2		1	1	1		2	2	2	
Service module	Tanks	1		1	1	1	2	1	1	1	2	1	1	1	2	2	1	2	2	1	1	1	1	2	2	2	2
	Shell	1		1	1	1		1	1	1		1	1	1		2	1	2		1	1	1		2	2	2	
Crew module	Crew cabin	1		1	1	1		1	1	1		1	1	1		2	1	2		1	1	1		2	2	2	
	Aeroshell, fwd	1		1	1	1		1	1	1		1	1	1		2	1	2		1	1	1		2	2	2	
	Aeroshell, aft	1		1	1	1		1	1	1		1	1	1		2	1	2		1	1	1		2	2	2	
LAS	Shroud	1		1	1	1		1	1	1		1	1	1		2	1	2		1	1	1		2	2	2	
	Tower	1		1	1	1	2	1	1	1	2	1	1	1	2	2	1	2	2	1	1	1	1	2	2	2	2
Ares V																											
First stage	Aft section	2		2	2	2		2	2	2		2	2	2		3	2	3		2	2	1		3	3	3	
	LO2 tank	2		2	2	2		2	2	2		2	2	2		3	2	3		2	2	1		3	3	3	
	Intertank	2		2	2	2		2	2	2		2	2	2		3	2	3		2	2	1		3	3	3	
	LH2 tank	2		2	2	2		2	2	2		2	2	2		3	2	3		2	2	1		3	3	3	
Interstage		2		2	2	2		2	2	2		2	2	2		3	2	3		2	2	1		3	3	3	
EDS	Aft section	2		2	2	2		2	2	2		2	2	2		3	2	3		2	2	1		3	3	3	
	LO2 tank	2		2	2	2		2	2	2		2	2	2		3	2	3		2	2	1		3	3	3	
	Intertank	2		2	2	2		2	2	2		2	2	2		3	2	3		2	2	1		3	3	3	
	LH2 tank	2		2	2	2		2	2	2		2	2	2		3	2	3		2	2	1		3	3	3	
LSAM Shroud		2		2	2	2		2	2	2		2	2	2		3	2	3		2	2	1		3	3	3	
Altair																											
Descent stage	LO2 tank(s)	2					3				3				3				3				2				3
	Support str	2					3				3				3				3				2				3
	LH2 tank(s)	2					3				3				3				3				2				3
	Legs	2					3				3				3				3				2				3
Ascent stage	LO2 tank(s)	2					3				3				3				3				2				3
	Support str	2					3				3				3				3				2				3
	LCH4 tank(s)	2					3				3				3				3				2				3
	Crew cabin	3		3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	2	3	3	3	3	3

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Technical-Program Fit Combines Technical Fit and Program Fit

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		Technical Fit		
		Low (4,5,6)	Med (7,8,9)	High (10,11,12)
Program Fit	Low (1)	1	1	2
	Medium (2)	1	2	3
	High (3)	2	3	3

Structural Systems

Constellation Element			1 LoMat Fiber SSF	2 LoMat Fiber Grid	3 LoMat Fiber Sand	4 LoMat Fiber Mono	5 LoMat Infus SSF	6 LoMat Infus Grid	7 LoMat Infus Sand	8 LoMat Infus Mono	9 LoMat Hand SSF	10 LoMat Hand Grid	11 LoMat Hand Sand	12 LoMat Hand Mono	13 HiMat Fiber SSF	14 HiMat Fiber Grid	15 HiMat Fiber Sand	16 HiMat Fiber Mono	17 HiMat Infus SSF	18 HiMat Infus Grid	19 HiMat Infus Sand	20 HiMat Infus Mono	21 HiMat Hand SSF	22 HiMat Hand Grid	23 HiMat Hand Sand	24 HiMat Hand Mono
Ares 1																										
	First stage					1				1				2				1				1				1
	Interstage		2	1	1		1	1	1		2	2	2		1	1	1		1	1	1		1	1	1	
	Upper stage	Aft Section	1	1	2		1	1	1		1	2	2		2	1	1		1	1	2		1	1	1	
		LO2 tank	1	1	2		1	1	1		1	2	2		2	1	1		1	1	2		1	1	1	
		Intertank (CB)	1	1	1		1	1	1		2	1	2		2	1	1		1	1	1		2	2	2	
		LH2 tank	1	1	1		1	1	1		1	1	2		1	1	2		1	1	1		2	2	2	
		Instrument Unit	1	1	1	1	1	1	1	1	1	1	1	2	2	1	1	1	1	1	1	1	1	1	1	1
Orion																										
	Spacecraft adapter		1	1	1		1	1	1		1	1	1		2	1	1		1	1	1		1	1	1	
	Service module	Tanks	1	1	1	1	1	1	1	1	1	1	1	1	2	1	1	1	1	1	1	1	1	1	1	1
		Shell	1	1	1		1	1	1		1	1	1		1	1	1		1	1	1		1	1	2	
	Crew module	Crew cabin	1	1	1		1	1	1		1	1	1		1	1	2		1	1	1		1	1	1	
		Aeroshell, fwd	1	1	1		1	1	1		1	1	1		2	2	2		1	1	2		1	1	1	
		Aeroshell, aft	1	1	1		1	1	1		1	1	1		2	2	2		1	1	2		1	1	1	
	LAS	Shroud	2	1	1		1	1	1		2	1	1		1	1	1		1	1	1		1	1	1	
		Tower	2	1	1	1	1	1	1	1	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Ares V																										
	First stage	Aft section	2	2	2		1	1	1		2	2	3		2	2	2		1	1	2		2	2	2	
		LO2 tank	1	2	3		1	1	2		1	2	2		2	1	1		1	1	1		1	1	1	
		Intertank	2	2	2		2	2	2		1	2	2		2	1	1		1	1	1		1	1	1	
		LH2 tank	1	2	2		1	1	1		1	1	2		1	1	2		1	1	1		2	2	2	
	Interstage		2	2	2		2	2	2		1	2	2		2	1	1		1	1	1		1	1	1	
	EDS	Aft section	2	2	1		1	1	1		1	1	2		1	2	2		1	1	1		1	1	2	
		LO2 tank	1	1	2		1	1	1		1	2	2		2	2	2		1	1	1		1	1	2	
		Intertank	2	2	1		1	1	1		1	1	2		1	2	2		1	1	1		1	1	2	
		LH2 tank	1	1	2		1	1	1		1	1	1		1	1	2		1	1	1		1	1	2	
	LSAM Shroud		2	2	2		2	2	2		1	2	2		2	1	1		1	1	1		1	1	1	
Altair																										
	Descent stage	LO2 tank(s)				2				1				2				2				1				3
		Support Str				1				1				1				1				1				2
		LH2 tank(s)				2				1				2				2				1				3
		Legs				2				1				2				2				1				3
	Ascent stage	LO2 tank(s)				2				1				2				2				1				3
		Support str				1				1				1				1				1				2
		LCH4 tank(s)				2				1				2				2				1				3
		Crew cabin	1	1	1	1	1	1	1	1	1	1	1	1	1	2	3	3	1	2	1	2	2	2	2	2

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Six Structural Systems Have the Greatest Cross-cutting Applicability

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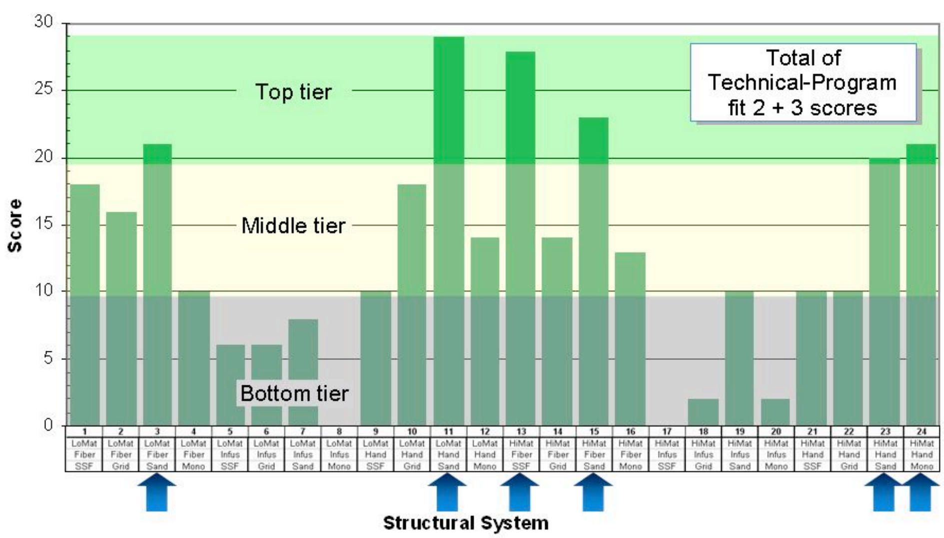

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Technical and Program Fit by Constellation Element Reflects Number of Applicable Structural Systems

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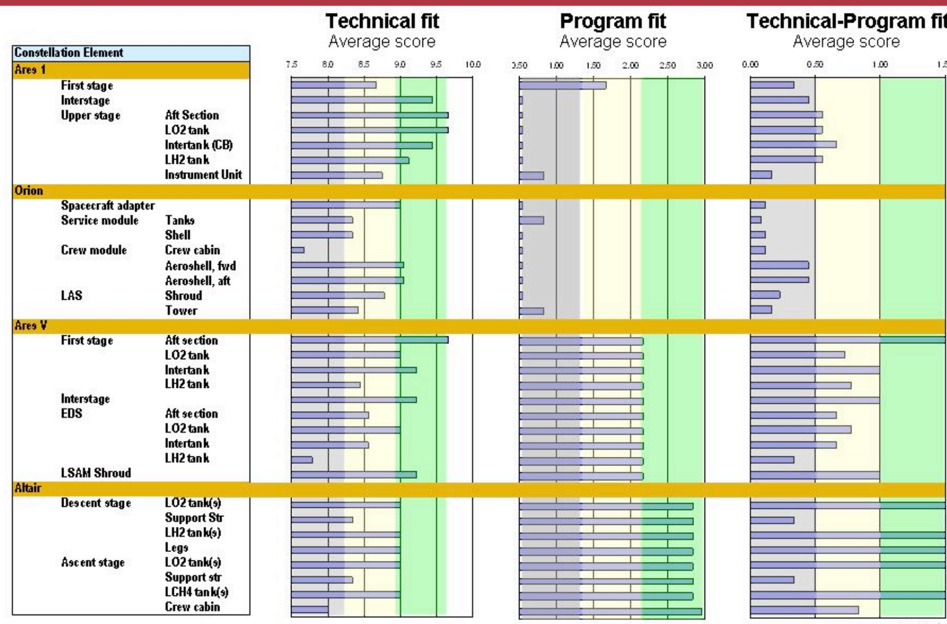

Structural System 13 Has High Technical Maturity and Broad Applicability

EXAMPLE

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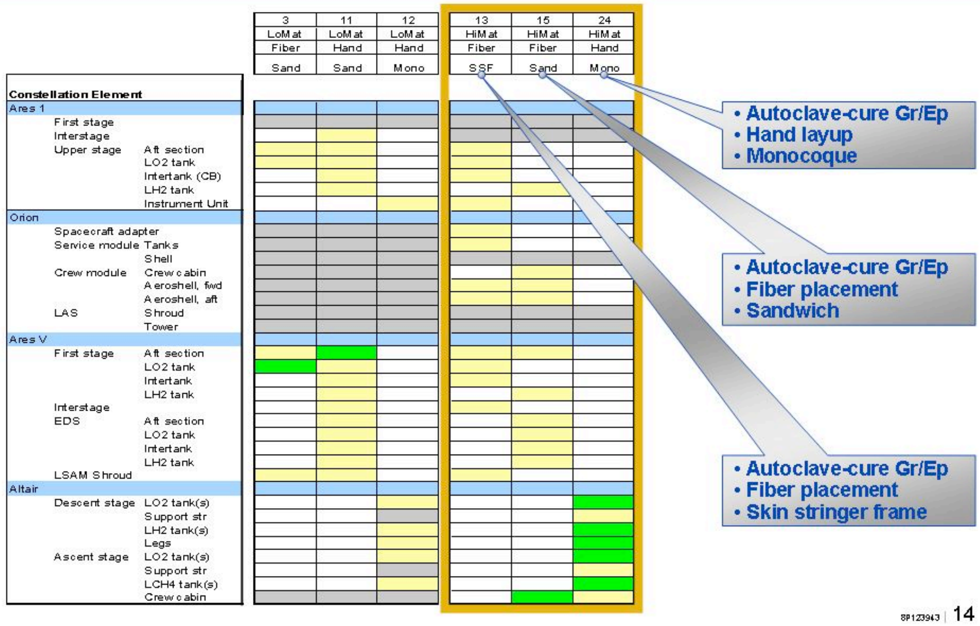
- **Structural system definition**
  - Higher-performance/cost (Gr/Ep) material
  - Fiber/tape placement, autoclave cure fabrication
  - Skin-stringer-frame design
- **Technical fit**
  - Moderate performance matches lower stage requirements
  - Moderate development cost for scale-up
  - Moderate production cost for large scale
  - Moderate operations cost matches expendable elements
- **Program fit**
  - High TRL – 787 production
  - Near-term timeframe (adapt to space)
- **Technical-Program fit**
  - Moderate fit primarily for wide range of dry structure and LO2 tanks

Constellation Element			Structural system 13: Technical Fit	Program Fit	Technical-Program Fit
Constellation Element				3	
Ares 1					
	First stage				
	Interstage		9	2	1
	Upper stage	Aft Section	10	2	2
		LO2 tank	10	2	2
		Intertank (CB)	11	2	2
		LH2 tank	9	2	1
		Instrument Unit	10	2	2
Orion					
	Spacecraft adapter		10	2	2
	Service module	Tanks	10	2	2
		Shell	9	2	1
	Crew module	Crew cabin	8	2	1
		Aeroshell, fwd	10	2	2
		Aeroshell, aft	10	2	2
	LAS	Shroud	9	2	1
		Tower	9	2	1
Ares V					
	First stage	Aft section	10	3	2
		LO2 tank	9	3	2
		Intertank	9	3	2
		LH2 tank	8	3	1
	Interstage		9	3	2
	EDS	Aft section	8	3	1
		LO2 tank	9	3	2
		Intertank	8	3	1
		LH2 tank	7	3	1
	LSAM Shroud		9	3	2
Altair					
	Descent stage	LO2 tank(s)			
		Support str			
		LH2 tank(s)			
		Legs			
	Ascent stage	LO2 tank(s)			
		Support str			
		LCH4 tank(s)			
		Crew cabin	8	3	1

Three related, Single-Material Structural Systems Satisfy Majority of Constellation Program

Engineering, Operations & Technology | Phantom Works — Materials and Structures Technology



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System of Structural Systems includes all Technology Categories and Two Joint Systems

Engineering, Operations & Technology | Phantom Works — Materials and Structures Technology

Rigid shell structural systems

Shells, Rigid	1. Materials and Processes	2. Manufacturing Methods	3. Innovative Design	4. Analysis, Modeling, and Simulation	5. Design Criteria and Allowables	6. Dvt, QA, and Cert	7. Design for Threats	
13	Advanced autoclave cure M&P	Autoclave manufacturing methods Fiber placement methods	Skin-stringer-frame design	SSF analysis	*No unique (Common)*	*No unique (Common)*	*No unique (Common)*	• Autoclave-cure Gr/Ep • Fiber placement • Skin stringer frame
15		Autoclave manufacturing methods Sandwich (core) manufacturing methods Fiber placement methods	Sandwich designs	Sandwich analysis	*No unique (Common)*	*No unique (Common)*	*No unique (Common)*	• Autoclave-cure Gr/Ep • Fiber placement • Sandwich
24		Autoclave manufacturing methods	Lightweight structure for load transfer	*No unique*	*No unique (Common)*	*No unique (Common)*	*No unique (Common)*	• Autoclave-cure Gr/Ep • Hand layup • Monocoque

Joint structural systems

	1. Materials and Processes	2. Manufacturing Methods	3. Innovative Design	4. Analysis, Modeling, and Simulation	5. Design Criteria and Allowables	6. Dvt, QA, and Cert	7. Design for Threats
Bonded Joints	Bonded joining M&P (adhesives) 3-D woven preforms	Bonded assembly	Primarily bonded structures	Bonded joint analysis	*No unique (Common)*	*No unique (Common)*	*No unique (Common)*
Bolted Joints	Bolted joining M&P (fasteners) 3-D woven preforms	Bolted assembly	Efficient bolted joints between large sections	Bolted joint analysis	*No unique (Common)*	*No unique (Common)*	*No unique (Common)*

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Hierarchical Set of Recommendations

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Recommended General Strategy

Engineering, Operations & Technology | Phantom Works — Materials and Structures Technology

- **Adapt commercially available and/or nonunique technologies for exploration applications**
  - Most individual technologies have been developed for aerospace to TRL 6+
  - Minimize development cost/risk with little performance penalty
  - E.g., extend existing autoclave-cure M&P to space environment
- **Develop unique technologies for exploration applications**
  - Multifunctional designs (innovative design category)
    - For extremely weight-critical applications (e.g., Altair)
  - All aspects of threat/environment category
    - MMOD, lunar dust, aging, static charge, thermal cycling, radiation, noise, toxicity, and outgassing
  - Large-scale, expendable, and low-quantity manufacturing
  - Cryotanks

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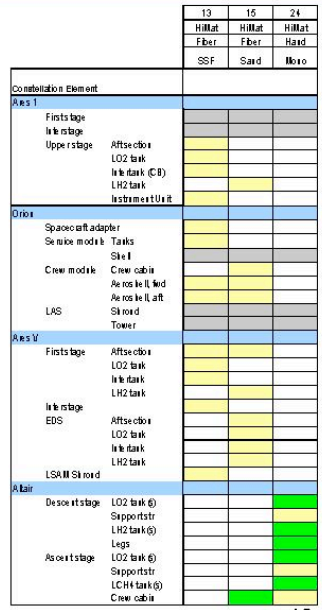
Recommended Constellation-wide Technology Development Program

Engineering, Operations & Technology | Phantom Works — Materials and Structures Technology

1. **Perform selected quantitative trades of system of structural systems for associated Constellation elements**
   - Autoclave-cured Gr/Ep/fiber-placement/skin-stringer-frame (#13)
   - Autoclave-cured Gr/Ep/fiber-placement/sandwich (#15)
   - Autoclave-cured Gr/Ep/hand-layup/monocoque (#24)
   - Bonded joints
   - Bolted joints
   - Common
2. **Select specific structural system constituents and associated technologies**
3. **Prepare development plan for selected Constellation elements using specific structural systems**
4. **Initiate building-block development program of selected specific structural systems for high-payoff Constellation elements**



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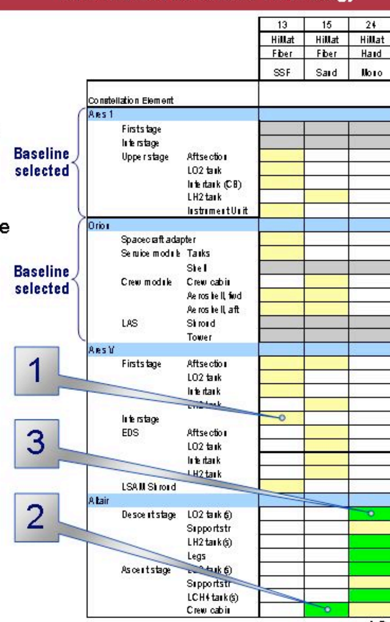
Recommended Integrated Technology Demonstrations

Engineering, Operations & Technology | Phantom Works — Materials and Structures Technology

1. **SS#13 demo (Ares V first stage interstage)**
   - Autoclave-cure Gr/Ep; fiber-place; skin-stringer-frame
   - High performance (weight) payoff for large-scale structure
   - Widely applicable to other dry shell structure
2. **SS#15 demo (habitat module)**
   - Autoclave-cure Gr/Ep; fiber-place; sandwich
   - Extremely high weight payoff using multifunctional structure in extreme environment
3. **SS#24 demo (Altair LO_2 tank)**
   - Autoclave-cure Gr/Ep; hand layup; monocoque
   - Extremely high weight payoff for cryotank in extreme environment
   - Applicable to other cryotanks

	Demo/SS#		
Unique Feature	1 #13	2 #15	3 #24
Multifunctional			
Environment			
Large scale			
Cryotank			
Weight critical			



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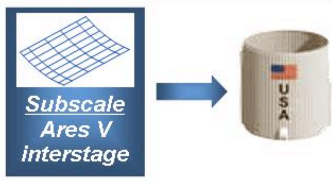
Recommended Task Order Task 1

Engineering, Operations & Technology | Phantom Works — **Materials and Structures Technology**

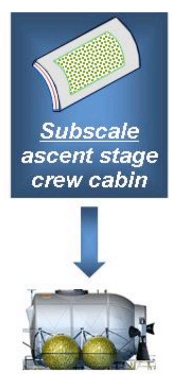
Subtask	Technology	Development Plan	Structural System	Strategy
	2. Manufacturing Methods			
1a	Fiber placement methods	1. Increase material laydown rates with multiple head processes for larger-scale parts 2. Trade hybrid processes that mix 3-inch to 12-inch tape with 1/8 to 1/2 in tow for optimal rates 3. Optimize machine configuration for 5-m parts and for 10-m parts	13	Adapt
1b	Large (reusable) tooling	1. Develop tooling materials and fabrication for large-scale (10 m) cryotanks and dry structure (optimum number of parts and joints) 2. Identify interaction of mass, inertia, and deflection for large-scale part on production equipment and autoclave processes	13	Adapt
	4. Analysis, Modeling, and Simulation			
1c	Cost analysis	1. Validate tools with hardware design, build, and test	Common	Adapt



Recommended Task Order Task 2

Engineering, Operations & Technology | Phantom Works — **Materials and Structures Technology**

Subtask	Technology	Development Plan	Structural System	Strategy
	1. Materials and Processes			
2a	Sandwich (core) M&P	1. Design a multifunctional, multicomponent core and facesheets with strength, thermal, radiation, self-repair, etc., properties 2. Incorporate sandwich panel purge/vent system integration 3. Utilize low-permeability co-cured sandwich facesheets	15	Adapt
	3. Innovative Design			
2b	Multifunctional designs	1. Incorporate MMOD-radiation-acoustic protection in structure for long-duration space apps (ref ISS)	Common	Adapt
2c	Sandwich Designs	1. Minimize weight penalty of openings and joints 2. Develop sandwich for failure-redundant propellant tank and dry structure with multifunctional properties	15	Adapt
	4. Analysis, Modeling, and Simulation			
2d	Optimization methods	1. Develop multifactor (performance and cost) and multifunctional (structure, radiation, MMOD, etc.) optiimization techniques	Common	Adapt
	5. Criteria and Allowables			
2e	Safety factors based on aircraft approach	1. Trade levels of test, analysis, and safety factors 2. Evaluate use of FAA-approved commercial or military aircraft factors of safety	Common	Adapt
	6. Development, QA and Cert			
2f	Accelerated aging and test methods	1. Assess probabilistic aging method (ref Torng) 2. Review HSR methods	Common	Adapt
	7. Design for Threat/Environment			
2g	MMOD (lunar/LEO)	1. Develop ultra high-speed (15 - 20 km/sec) launch capability to characterize meteor impact effects	Common	NASA
2h	Radiation	1. Evaluate radiation effects on electronics parts and crew	Common	NASA



Recommended Task Order Task 3

Engineering, Operations & Technology | Phantom Works — Materials and Structures Technology

Subtask	Technology	Development Plan	Structural System	Strategy
	1. Materials and Processes			
3a	Advanced autoclave cure M&P	3. Improve hydrogen impermeability and LO_2 compatibiity for cryotanks 4. Employ thin-ply laminates to minimize microcracking in cryotanks (ref. Tsai)	24	Adapt
	3. Innovative Design			
3b	Composite pressure vessels (non-integral)	1. Develop tanks with and without liner for (1) short-term, then (2) long-term, storage of cryogenic fluids or gases	24	Adapt
	6. Development, QA, and Certification			
3c	Accelerated aging and test methods	1. Assess probabilistic aging method (ref Torng) 2. Review HSR methods	Common	Adapt
3d	Improved leak detection	1. Develop fiber-optic sensors for low weight and high reliability	Common	NASA

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Summary

Engineering, Operations & Technology | Phantom Works — Materials and Structures Technology

- **Developed comprehensive qualitative (QFD-like) assessment methodology and composite structure technology database from public-domain literature and Boeing expertise on related programs**
- **Recommended one system of structural systems that provides integrated solution for Constellation-wide structure requirements**
- **Defined a comprehensive technology development plan based on recommended system of structural systems**
- **Identified three integrated demonstrations that support the comprehensive technology development plan**
- **Derived focused technology development plans for a Task Order follow-on**

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APPENDIX E ACRONYMS

ACT	Advanced Composites Technology
DC&A	Design Criteria and Allowables
EDS	Earth Departure Stage
Gr/Ep	Graphite/Epoxy
ISS	International Space Station
ITAR	International Traffic in Arms
LAS	Launch Abort System
LCH4	Methane
LDEF	Long Duration Exposure Facility
LEO	Low-Earth Orbit
LH2	Liquid Hydrogen
LO2	Liquid Oxygen
LSAM	Lunar Surface Access Module
M&P	Materials and Processes
MMOD	Micro-Meteorite and Orbital Debris
NASA	National Aeronautics and Space Administration
PDR	Preliminary Design Review
QA	Quality Assurance
QFD	Quality Function Deployment
SMAAA	Structures and Materials and Aerodynamic, Aerothermodynamic, and Acoustics
TRL	Technology Readiness Level
ULA	United Launch Alliance
ELV	Expendable Launch Vehicle
US	Upper Stage
CAI	Composites Affordability Initiative
IU	Instrument Unit
CAD	Computer Aided Design
FEM	Finite Element Model
LBID	Laser-Based Inspection Device
LV	Launch Vehicle
LLO	Low Lunar Orbit
HSR	High Speed Research

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14. ABSTRACT
An assessment was performed to identify the applicability of composite material technologies to major structural elements of the NASA Constellation program. A qualitative technology assessment methodology was developed to document the relative benefit of 24 structural systems with respect to 33 major structural elements of Ares I, Orion, Ares V, and Altair. Technology maturity assessments and development plans were obtained from more than 30 Boeing subject matter experts for more than 100 technologies. These assessment results and technology plans were combined to generate a four-level hierarchy of recommendations. An overarching strategy is suggested, followed by a Constellation-wide development plan, three integrated technology demonstrations, and three focused projects for a task order follow-on.

15. SUBJECT TERMS
Composites; Structurally efficient; Lightweight; Graphite-epoxy

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