

COMPOSITE PAYLOAD FAIRING STRUCTURAL ARCHITECTURE ASSESSMENT AND SELECTION

Thomas M. Krivanek
NASA Glenn Research Center
21000 Brookpark Rd.
Cleveland, OH 44135

Bryan C. Yount
NASA Ames Research Center
Moffett Field, CA 94035

ABSTRACT

This paper provides a summary of the structural architecture assessments conducted and a recommendation for an affordable high performance composite structural concept to use on the next generation heavy-lift launch vehicle, the Space Launch System (SLS).

The Structural Concepts Element of the Advanced Composites Technology (ACT) project and its follow on the Lightweight Spacecraft Structures and Materials (LSSM) project was tasked with evaluating a number of composite construction technologies for specific Ares V components: the Payload Shroud, the Interstage, and the Core Stage Intertank. Team studies strived to address the structural challenges, risks and needs for each of these vehicle components. Leveraging off of this work, the subsequent Composites for Exploration (CoEx) effort is focused on providing a composite structural concept to support the Payload Fairing for SLS.

This paper documents the evaluation and down selection of composite construction technologies and evolution to the SLS Payload Fairing. Development of the evaluation criteria (also referred to as Figures of Merit or FOMs), their relative importance, and association to vehicle requirements are presented. A summary of the evaluation results, and a recommendation of the composite concept to baseline in the Composites for Exploration (CoEx) project is presented. The recommendation for the SLS Fairing is a Honeycomb Sandwich architecture based primarily on affordability and performance with two promising alternatives, Hat stiffened and Fiber Reinforced Foam (FRF) identified for eventual program block upgrade.

1. INTRODUCTION

The Advanced Composites Technologies (ACT) and follow on Lightweight Spacecraft Materials and Manufacturing (LSSM) Projects were implemented to help enable the Constellation Program to support a manned lunar mission via mass reduction of vehicle dry structures through the use of composite materials. (Ref. 1, Sumrall). The ACT project was formulated to advance the Technology Readiness Level (TRL) of large scale composite structures from TRL 3-4 (Proof of concept / validated in lab environment) to TRL 6. (System/subsystem demonstrated in a relevant environment) (Ref. 2, Mankins).

The objective of the Structural Concepts Studies was to identify, optimize, and evaluate composite construction technologies for use as dry structures on the Ares V Heavy Lift Launch Vehicle. This information was to be applied toward the definition of the new Space Launch System (SLS) Heavy Lift Launch Vehicle (Fig. 1). An agency-wide team with members from ARC, GRC, GSFC, KSC, LaRC, and MSFC was assembled to perform these structural concept studies.



Figure 1. SLS heavy lift launch vehicle.

The Structural Concepts Team identified eight composite construction technologies that met the initial feasibility ground rule of having a TRL of three or higher. These construction technologies (or concepts) were then analyzed and sized for use on the Payload Shroud per the project requirements and ground rules. (The payload fairing element was referred to as “Shroud” during the Ares V project). The concepts were then rated with respect to the Figures of Merit (FOMs). Some of the key figures of merit included mass, development risk (due to TRL maturity), damage tolerance, cost, acoustic transmissibility, thermal tolerance, joining, and inspectability. Weighting factors were applied to each FOM based on their relative importance to the project, and a modified Analytical Hierarchy Process (AHP) was used to rank the proposed composite construction technologies. This process was used to determine the top two candidate construction concepts to be recommended for possible use.

2. PAYLOAD FAIRING REQUIREMENTS AND CONFIGURATION

Requirements for the Structural Concept studies were extracted from the Ares V vehicle requirements. A total of 29 requirements were identified, but many of these have negligible effect on the structural concept studies. The remaining requirements could be identified as subsets of the following five categories.

- Payload protection and environmental control (Ground, launch and flight ops)
- Payload access (During integration and on-pad)
- Structural integrity (For all ground, launch and flight environments – includes inertial, aerodynamic, vibration, thermal and acoustic loads)
- Separation from launch vehicle (As commanded)
- System Telemetry (Including Structural Health Monitoring (SHM))

The structural concept studies focused on meeting the structural integrity requirements for a specified set of launch and flight loads. Each of the composite construction technology concepts was evaluated quantitatively for the primary structural mass figure of merit, while FOMs that addressed most of the other requirements were evaluated qualitatively. The configuration baselined for the structural concept studies has a 10 m diameter tangent ogive nose cone that is 14 m long, plus a barrel section that is 9.7 m long. Loads were derived from the Ares V LV 57.01.14 vehicle configuration and flight trajectory.

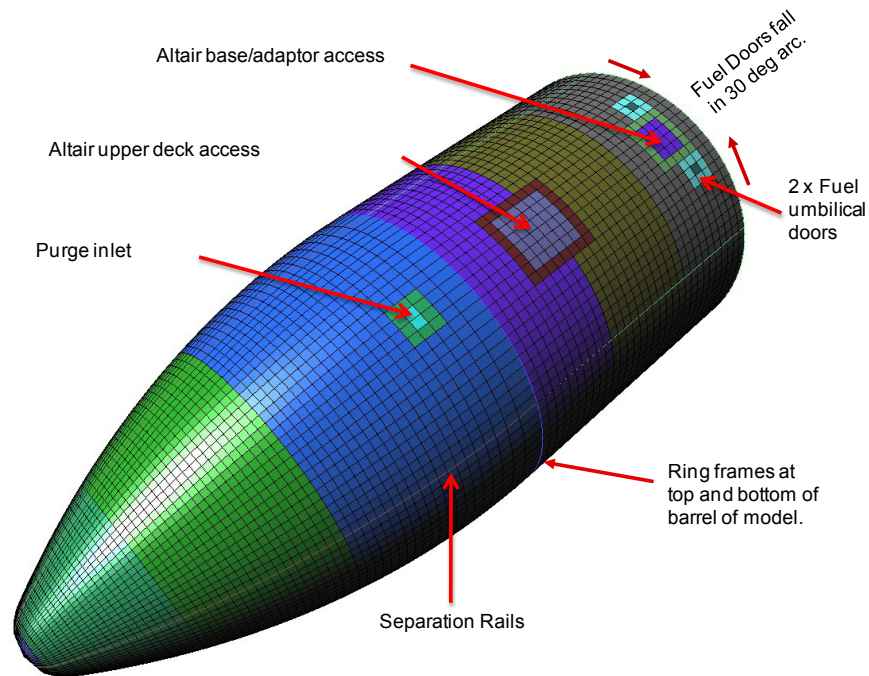


Figure 2. Payload shroud PS-02 finite element model.

Consistency in the evaluation of the structural concepts was facilitated by the use of a master Finite Element Model (FEM) (Fig. 2). The master model was used to define the shroud Outer Mold Line (OML) geometry, access openings, split-lines, and load cases. HyperSizer[®] structural sizing software from Collier Research Corporation was then used in conjunction with the master FEM to define the structural concept properties, analyze and optimize each concept. Eight composite construction technologies (concepts) were chosen for assessment and these candidates are shown in Figure 3, where PRSEUS stands for “Pultruded Rod Stitched Efficient Unitized Structure” concept.

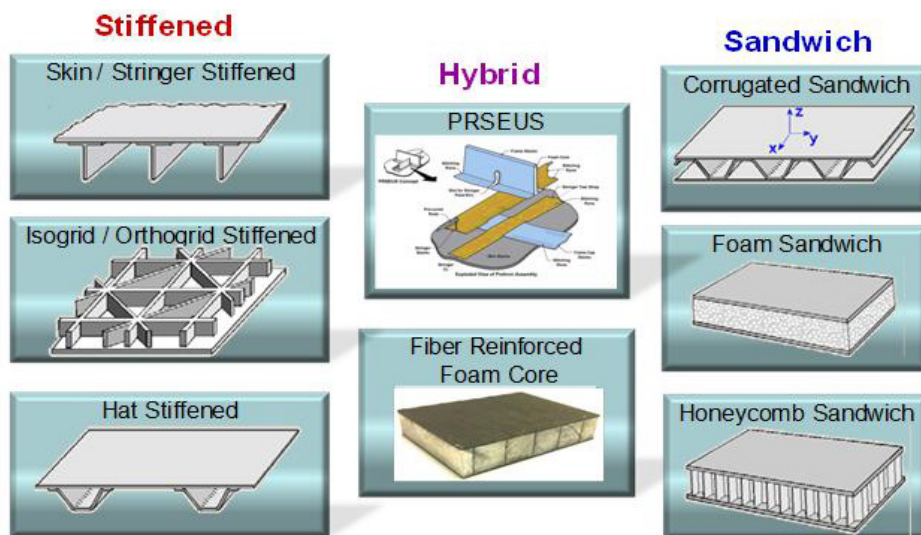


Figure 3. Composite construction technologies for evaluation.

3. EVALUATION CRITERIA AND PRIORITY

The success criteria were defined as meeting mission requirements with demonstrated improvements in Key Performance Parameters (KPPs) over current state-of-the-art technology. The central KPP for which this study was formulated was the reduction of dry structure mass. Minimal structural mass on its own, however, cannot be used to determine the best overall structural concept. Other performance requirements needed to be considered, and the overall trade space also required the inclusion of cost and schedule. The key functions of the Payload Fairing is to provide protection for the payload from thermal, aerodynamic, acoustic, and environmental conditions during vehicle processing, liftoff and ascent. In addition to the primary structure, subsystems functions must provide for acoustic treatment, environmental control, thermal protection, and separation from the launch vehicle.

The DAC1 baseline quad petal design is of nearly equivalent surface area to several large commercially flown launch vehicle fairings. It is considered to be a relatively lightly loaded, stiffness driven structure. From a mass summary the structure is expected to be the largest contributor to the total mass (45%). But the Thermal Protection System (TPS: 19%) and the Environmental Control Systems (comprised mostly of acoustic blankets: 26%) are also significant contributors to the total mass. This emphasizes the need to maintain a system-level perspective when evaluating construction technologies and not to focus solely on the mass of the primary structure. Structural concepts that can operate at higher temperatures (thus needing less TPS) or have more intrinsic acoustic damping (allowing for a reduction in acoustic blankets) may produce an optimum design even if they are not the minimum structural mass option.

Based on the requirements, knowledge from early design studies, and input from industry partners and the USAF, the Team put significant effort into defining a complete set of Figures of Merit to encompass the trade space. This was a collaborative effort between the Structural Concepts Team, the Materials & Manufacturing Team, the Test & Evaluation Team, and the Ares V Shroud Team. Importance with respect to the requirements and KPPs, relevance to the structural concepts, influence on operations, and independence with respect to each other were all considered while defining the FOMs. In cases where FOMs were clearly dependent on each other, those FOMs were redefined and combined. Other FOMs that were considered to be unaffected by differences in structural concepts were excluded from the study. The result was the selection of 13 Figures of Merit with weightings that reflect the team's assessment of their importance. The selected FOMs and their relative weightings are shown in Figure 4.

3.1 Basic Mass

Basic Mass was given the highest weighting, and was the focus of much of the work performed by the Structural Concepts team during this set of studies. Basic Mass was defined as the mass of the Shroud primary structure as predicted by sizing analysis performed using NASTRAN and HyperSizer. All concepts were sized using the same guidelines, load cases, and factor of safety requirements. The Basic Mass number includes all of the Shroud surface structure, any vertical or circumferential stiffeners needed, plus reinforcing structure around the specified access holes. The mass of joints, separation system, thermal protection, and acoustic blankets is not included in the Basic Mass. The concepts with the lowest primary structural mass received the highest rankings for Basic Mass.

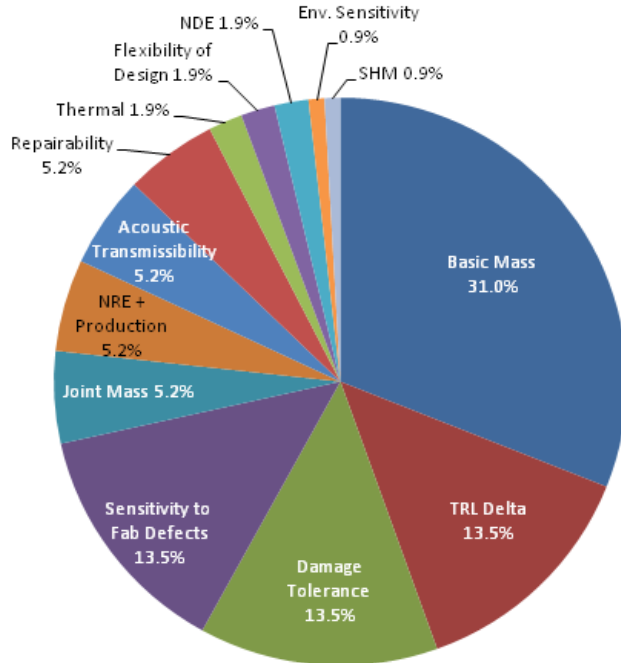


Figure 4. Relative FOM weightings.

3.2 TRL Delta

TRL Delta is a FOM defined for this study that is intended to describe a concept's likelihood of reaching a Technology Readiness Level of six by PDR in 2013. The TRL scale itself is used to define the maturity of a given technology. The TRL scale was taken from the NASA Systems Engineering Handbook (NASA/SP-2007-6105 Rev1) - Page 296 (Ref. 3). A TRL of 9 is given only if the system has already been flown successfully in the configuration being evaluated. The goal of TRL 6 means that a prototype shroud needs to be demonstrated in a simulated (or actual) space environment. The team also looked at the amount of effort likely needed to raise the TRL of each concept to six by the time of the PDR. Concepts expected to have the best chance of achieving TRL 6 by 2013 received the highest TRL Delta scores.

3.3 Damage Tolerance During Use

The Damage Tolerance During Use (Reliability) FOM evaluated a concept's ability to withstand a damage causing event during ground or flight operations without experiencing a failure. Subject matter experts ranked the concepts with regards to their capacity to function with sustained damage.

3.4 Sensitivity to Fabrication Defects

This figure of merit considers how well a concept can tolerate fabrication defects without a substantial loss in strength. Inspectability is a separate FOM, but the ability to detect defects in each concept was given some consideration when ranking concepts for sensitivity to defects. Again, subject matter experts reviewed and ranked the concepts with regards to their ability to maintain strength despite the presence of flaws.

Due to the figure of merit weightings, nearly three quarters of the concept evaluation scoring comes from the first four FOMs just discussed. The remaining quarter of the concept evaluation scoring is distributed amongst the nine remaining FOMs such that the individual FOMs only have a small impact on the overall concept scoring, but collectively, they can affect the order of the overall concept rankings.

The nine Figures of Merit with weightings of 5.2% or less each are described below.

3.5 Joint Mass

Joint Mass was given its own FOM (separate from basic mass) because it was determined that detailed joint mass estimates would not be available for all of the concepts during the course of the study. The Structural Concepts Team evaluated the concepts with regards to their expected longitudinal and circumferential joint mass (Refs. 4 and 5). Concepts that were identified as likely to have low joint mass were given a high ranking for Joint Mass.

3.6 Non-Recurring Cost + 20 Production Units

This FOM represents a measure of the total life-cycle cost for each of the concepts. Based on the information available, cost estimates were generated for each concept. Development, facilities, tooling, materials, labor and expected production rates were all considered. Concepts with the lowest expected total cost were given the highest rankings for the NRE+20 FOM.

3.7 Acoustic Transmissibility

Acoustic Transmissibility was selected as a FOM for the shroud concepts due to the important role of protecting payloads from the harsh acoustic environments experienced during launch and ascent. Concepts with good intrinsic acoustic attenuation are expected to require less acoustic blanket treatment to achieve the required internal sound pressure levels, thus saving mass. The structural concepts were analyzed for acoustic transmissibility and ranked by their performance. Concepts with low acoustic transmissibility (high attenuation) were given high rankings for this FOM.

3.8 Repairability

This FOM was used to rank the concepts with regards to their likelihood of being recovered for use after moderate to significant damage during fabrication, shipping, or ground operations. Subject matter experts reviewed and ranked all of the concepts for their ease of repair. Concepts that were considered easy to repair received the highest rankings.

3.9 Thermal Tolerance

Similar to the Joint Mass and Acoustic Transmissibility FOMs, the Thermal Tolerance FOM is a mass performance measurement. As mentioned earlier, thermal protection systems typically are a significant contributor to the overall mass. Structural concepts that can withstand elevated temperatures may be able to save mass in the TPS resulting in a lower overall mass. A basic thermal sizing analysis was performed for each concept to determine the amount of TPS to maintain the temperature of the primary structure below the maximum allowable material temperature. Concepts that required the least amount of TPS received the highest FOM scores.

3.10 Flexibility in Design

This FOM was defined as a measure of how well a concept can accommodate changes in requirements or the addition of features such as attachment points or access hatches late in the design/analysis/fabrication cycle. These were essentially the profiles with minimal discrete reinforcements or discontinuities and more homogeneous structure. The structural concepts team reviewed the different construction technologies and high scores were given to the concepts that were deemed to be the most adaptable to feature changes or additions.

3.11 Non-Destructive Evaluation and Inspectability

The NDE/Inspectability FOM was used to rank the concepts with respect to their ease and effectiveness of inspection. Subject matter experts reviewed all of the concepts and ranked them for their ability to be inspected by radiography, shearography, thermography, or ultrasound.

3.12 Environmental Sensitivity

This FOM was selected to rank the concepts regarding their ability to maintain their material properties when exposed to the pre-launch environment. The primary consideration for this FOM is moisture absorption and its impact on strength, stiffness, density, and cohesion between materials. The team reviewed the concepts and high rankings were given to the concepts that were expected to experience very little degradation due to moisture.

3.13 Structural Health Monitoring

Compatibility with Structural Health Monitoring (SHM) was the final figure of merit used for evaluating the concepts in this study. This technology allows an entire structure to be continuously monitored for impact or structural damage via an array of embedded sensors. Subject matter experts reviewed the concepts and gave the highest rankings to the concepts that were deemed to be most compatible with SHM.

4. TRADE PROCESS

With the structural concepts selected and the weighted figures of merit established, the trade space was defined. The trade process then involved consistently sizing and evaluating each of the concepts with respect to all of the FOMs and performing a sensitivity study to check the robustness of the results.

Consistent with the high FOM weighting, assessment for basic mass was given the most in-depth analysis. The basic mass assessment involved a complete finite element analysis with optimization in order to provide a quantitative mass estimate for each structural concept.

Analysis ground rules and assumptions were established to assure that each concept was analyzed with the same methodology in order to eliminate bias. The analysis was performed using NASTRAN finite element analysis and HyperSizer (Ref. 6) structural sizing and optimization software to determine the optimum construction for each concept while satisfying the defined load cases. A single master finite element model was used for consistency in geometry, constraints, and load cases (Ref. 7). HyperSizer was used to define the concept materials and dimensional parameters which were then implemented as element properties into

NASTRAN. (Note that the PRSEUS concept, which did not have a suitable concept definition in HyperSizer was sized using the ANSYS software package while following the analysis ground rules and assumptions as best as possible.)

The PS-02 finite element model (Fig. 2) was provided as the master model for the structural concept studies. One of its four petals contains several access penetrations with beams (frames) reinforcing each penetration. The penetrations have covers that are used to accept, map, and transfer aerodynamic loading to the surrounding structure but are assumed to be non-load bearing and are not sized. The shell elements of the shroud surface geometry are approximately one foot on each edge at the base while tapering down in size as they approach the nose cap in order to maintain a low aspect ratio. Ring frames are located at the base, the nose cone to barrel junction, and mid-way up the ogive nose cone geometry.

Model elements were assigned properties and grouped into a handful of HyperSizer “components” for use in the sizing and optimization runs. Each “component” is subjected to independent design-to loads statistically derived from NASTRAN analysis and is analyzed independently in HyperSizer. Groups used included: forward nose, mid nose, aft nose, upper barrel, mid barrel, aft barrel, individual ring frames, and the frames and panels for each penetration (Fig. 5). Component grouping was used to maintain model symmetry, limit the number of structural variations for manufacturability, and to reduce computation time. The separation rails and penetration panels were not sized as part of the basic mass evaluation. They were purposely set to be very weak such that the surrounding structure was sized to carry the load in those areas.

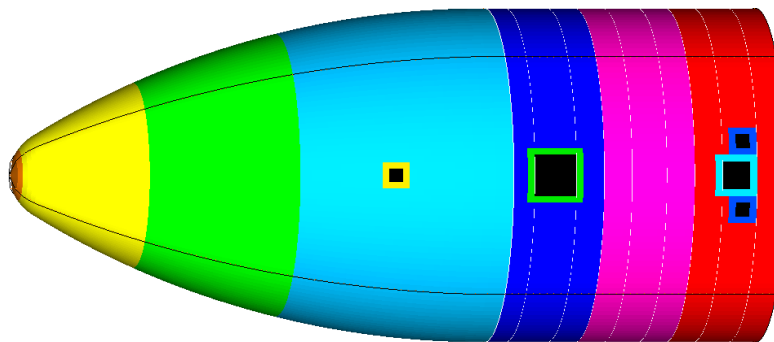


Figure 5. Model HyperSizer component groups.

Based on interactions between the team, industry and the DoD, the composite material selected for face sheets and stiffeners was IM7/977-3 graphite/epoxy prepreg. This aerospace grade material combination was selected for its strength and toughness as well as to leverage its available material databases. Layups were allowed to vary as dictated by the design and load conditions as long as minimum gage (6 ply face sheets) and layup symmetry requirements were met. Foam and honeycomb core material properties were obtained from the HyperSizer materials database for the concepts that use a core. Further evaluation of material properties will be required if either the Fiber Reinforced Foam sandwich or the PRSEUS concepts are selected since neither of these concepts use a manufacturing process that is compatible with IM7/977-3.

All of the structural concepts were sized for load cases intended to represent the flight envelope. They included Max Q, Max Q-alpha, and Max G with an elevated temperature (220 °F) thermal load. The model used rigid constraints at the aft end of the barrel where it attaches to the launch vehicle upper stage forward skirt. All sizing was performed to achieve factors of safety of 1.0 on yield and 1.4 on ultimate strength while using a knockdown factor of 0.65 on global buckling.

Numerous failure criteria were used to determine the failure mechanisms of the structure and to size the concept components to avoid these failure mechanisms. The following HyperSizer version 5.6.38 failure criteria were used to size the structure: composite strength for max strain and max stress in the 11, 22, and 12 directions, composite strength for Tsai-Hill, Tsai-Wu, Tsai-Hahn, and Hoffman criteria, as well as for LaRC03 composite strength matrix cracking and fiber failure. Other composite strength structural sizing checks were for crippling from Mil-Hdbk-17-3E including D_{ij} terms, global buckling of a curved panel, and local buckling in the longitudinal, transverse, and shear directions (Fig. 6). Concept optimization was performed using HyperSizer software. The software uses element force and moment loads imported from NASTRAN to create statistically determined (mean plus two standard deviations) loads for the component groups. HyperSizer then does a brute force optimization to find the lightest structural configuration within the dimensional bounds specified by the user that meets all of the failure criteria. The mass of the sized and optimized component groups was obtained from HyperSizer for each structural concept (Table 1). A 25% “fastener and build-ups” non-opt factor (Ref. 8, Wu & Cerro) was added to all of the component masses and the results were totaled. This total mass from the concept analysis process provided a quantitative result that was used in the Basic Mass FOM rating. The full scale from 1 (heaviest) to 9 (lightest) was used, while the remaining concepts were given real number rankings scaled between 1 and 9 based on their mass value within the range between the lightest and heaviest concepts.

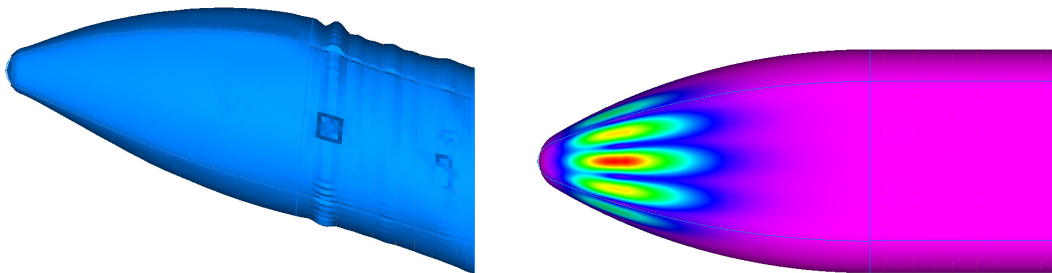


Figure 6. Exaggerated deformed and 1st buckling mode shape at Max Q-alpha.

The rating and ranking approach for the remaining 12 figures of merit were somewhat less rigorous, partly due to time constraints and because the remaining figures of merit were given lower weightings.

The Damage Tolerance and the Sensitivity to Fabrication Defects figures of merit were scored based on face sheet thickness, (thicker skins can resist external damage and punctures) likelihood of stiffener or core de-bonding, and capacity to redistribute loads around small flaws.

Table 1. Panel sizing results summary for the hat stiffened concept

Component	Area (m²)	Unit Mass (kg/m²)	Mass (kg)	Lowest MS	Controlling Failure Mode
Tip	1.99	1.28	2.54	2.539	Composite Strength, Tsai-Wu
Ogive Fwd	46.48	3.91	181.66	0.02121	Local Buckling
Ogive Mid	100.06	3.93	393.13	0.08008	Curved Panel Buckling
Ogive Aft	185.99	3.73	694.45	0.0417	Local Buckling
Barrel Fwd	81.54	2.46	200.71	0.007769	Local Buckling
Barrel Mid	84.27	2.96	249.52	0.0316	Curved Panel Buckling
Barrel Aft	81.37	3.58	291.48	0.009815	Curved Panel Buckling
Ogive Buildup	0.46	7.70	3.54	0.04347	Curved Panel Buckling
Barrel Fwd Buildup	1.19	13.22	15.73	0.001398	Curved Panel Buckling
Barrel Aft Big Buildup	0.85	13.64	11.59	0.02598	Curved Panel Buckling
Barrel Aft Small Buildup	1.02	14.49	14.78	0.02739	Curved Panel Buckling

The Cost of Non-Recurring Engineering (NRE) plus 20 Production Units was evaluated for each concept for capital equipment needs, manufacturing processes, assembly processes including labor, and material costs. ROM cost estimates were generated and then the results were checked against each other. The concepts with lower costs were given higher NRE+20 Cost FOM rankings. The evaluators did not use the full 1-9 FOM ranking range due to lack of concept detail that limited discrimination between the concepts.

Acoustic Transmissibility was evaluated quantitatively from an FEA based acoustic transmissibility analysis on a virtual panel portion of each concept. The concepts were ranked based on their calculated acoustic properties. The ranking range used for this FOM was between two and seven (rather than 1-9) because the difference in acoustic transmissibility between the concepts was not that extreme, and there were several ties. High rankings indicate good acoustic attenuation (low acoustic transmissibility).

Evaluation of the concepts for the Repairability FOM was performed by assessing each technology for compatibility with existing repair methods. This included how concept complexity may affect repairability, and accessibility to likely damage areas. Limited information caused the team to use a small ranking range (3-6).

Thermal Tolerance was evaluated quantitatively for this FOM by performing a quick thermal analysis based on structural information from the Basic Mass sizing effort. TPS thicknesses were calculated so that shroud structural temperatures would remain below the material allowable for each concept. The thermal load case was based on the specified ascent trajectory. Since TPS material volume can be equated to mass added for thermal control, the rankings for Thermal Tolerance are in the inverse order of the reported TPS volumes.

The rankings for the Flexibility in Design FOM were assigned by the Structural Concepts team. Each concept was reviewed and discussed regarding its capacity to accommodate changes to the design. The design concepts that rely on a pattern of discrete stiffeners generally received low scores due to concerns regarding terminating or relocating stiffeners and the potential difficulty in re-routing load paths. FOM scoring of the concepts for Non-Destructive Evaluation and Inspection was determined by reviewing for compatibility with current inspection technology and methods as well as for the potential use of developing technology. Accessibility and complexity were key factors in the scoring. Concepts with embedded or out of plane features are difficult to access for inspection, while concepts with many intersecting features or joints are difficult to inspect due to the many signal variations picked up by the inspection equipment within a given region.

The Environmental Sensitivity (Hygroscopic Absorption) characteristics of each concept were evaluated for their tendency to gain significant mass, lose strength or corrode due to water absorption. Concepts prone to environmental degradation were given low scores for this FOM.

Structural Health Monitoring (SHM) FOM scoring was performed for the primary states of health intended to be detected by the SHM system. These were assumed to be overstress, debonds, and delaminations. Crack detection and monitoring for buckling were thought to be of lesser interest due to the nature of the structure and the load conditions. Factors influencing the rankings for each concept included: signal sensitivity for sensors (likelihood of a quality signal reaching a sensor), reliability of sensor types for a given concept, SHM system complexity required, and number of sensors required. The pros and cons for each concept were considered prior to assigning scores. A score of 5 was considered a neutral ranking for concepts that have a reasonable chance of implementing a functional SHM system.

A sensitivity analysis was performed on FOM scoring to evaluate the robustness of the results. If moderate changes to the FOM weighting factors or to individual FOM scores (especially those in question) do not change the overall results, then the decision model is considered to be robust. If the “best options” indicated by the overall FOM results vary significantly with moderate changes to the FOM scores or weighting, very little confidence can be placed in the study results.

5. RISK AND UNCERTAINTY ISSUES

A number of areas of risk and uncertainty were identified as part of the concept down select study. The evaluation results and concept recommendations could be altered by changes or variations in the following areas: the maturity of the concept designs, the completeness of the analysis/optimization, the applied loads, the requirements or assumptions, and the FOM scores that are based on engineering judgment. The lack of concept detail for this level of study presented a number of uncertainties for the mass analysis as well as a number of other FOM categories. Design and manufacturability details of the concepts dealing with complex geometry, tapers, transitions, lay-ups and ply drop-offs could impact the Basic Mass estimates as well as other FOM rankings such as Cost (NRE+20 Units), Repairability, and Inspectability. Uncertainties in the analysis results included the typical and generally accepted effects of boundary conditions, sharp corners, and possible computational errors associated with the finite element method. These issues were common to the concept models and considered unlikely to influence the ranking results. The analysis method did not model concept details, but rather

relied on HyperSizer to apply statistically derived loads from the greater finite element model and calculate margins of safety for the concept elements based on built-in closed-form solutions. Previous software verification and validation efforts have shown this approach to have good accuracy beyond the level of detail needed for this study. The PRSEUS concept was analyzed and sized using a different software package (ANSYS) than the other concepts. This is a source of uncertainty in the Basic Mass ranking for PRSEUS, but it is unlikely that its estimated mass could improve enough to make it a top contender considering its many other poor FOM rankings.

A single set of material properties was used to try to eliminate uncertainty in material allowables when comparing the concepts. Due to manufacturing processes, however, the FRF and PRSEUS concepts aren't compatible with the prescribed material. It isn't clear that out-of-autoclave materials compatible with these concepts' manufacturing processes can be obtained that will provide the assumed material properties. The load carrying capacity of the FRF Core ribs was ignored in order to offset the likely difference in achieved vs. assumed material properties. There is some risk that this approach didn't capture the actual difference in material properties and that the FRF concept won't perform as well as expected.

The loading conditions used in the analysis may have influenced the selection of the preferred concepts as well. Some of the architectures are better suited for directional loading than others. If the flight trajectory changes significantly or a new load case (such as ground handling) is introduced, the ratio of load orientations could change, which could favor a different concept architecture. Changes in the thermal load cases could have a similar effect. The Structural Concepts Team used the best information available regarding loads, requirements and assumptions for the structural concept studies. Considering the limited level of detail to which the concepts could be developed for the study, the team tried to maintain a consistent approach to the evaluation process such that a reasonable level of confidence can be placed on the down select results.

6. RESULTS OF STUDY

Each of the eight proposed shroud structural concepts was evaluated with respect to the 13 figures of merit selected by the team in order to rate their performance.

6.1 Basic Mass

The final result of the Basic Mass FOM analysis process was a mass estimate for the concept's primary structure. The final mass estimate included a roll-up of the individual component group mass estimates determined by HyperSizer. Component group mass estimates were combined into three categories for reporting to the FOM scoring table: Nose Mass, Barrel Mass, and Misc./Adhesive Mass. Values reported to the FOM scoring table included a 1.25x non-opt factor to account for the coarseness of the analysis modeling. The reported mass for the nose region contains the nose cap (or tip) mass, the mass of all three ogive sections, and any build-ups and ring frames in the ogive region. The reported mass for the barrel region contains the mass of all three barrel sub-regions, the build-ups within the barrel region, plus all the ring frames (to prevent buckling) in the barrel region. Separation rail and access door panel mass numbers are not reported. The total mass for nose and barrel including the non-opt factor is the value used for FOM ranking (Fig. 7). The Dark Horse concept is a hybrid that uses stringer stiffened construction in the barrel section and honeycomb construction in the ogive.

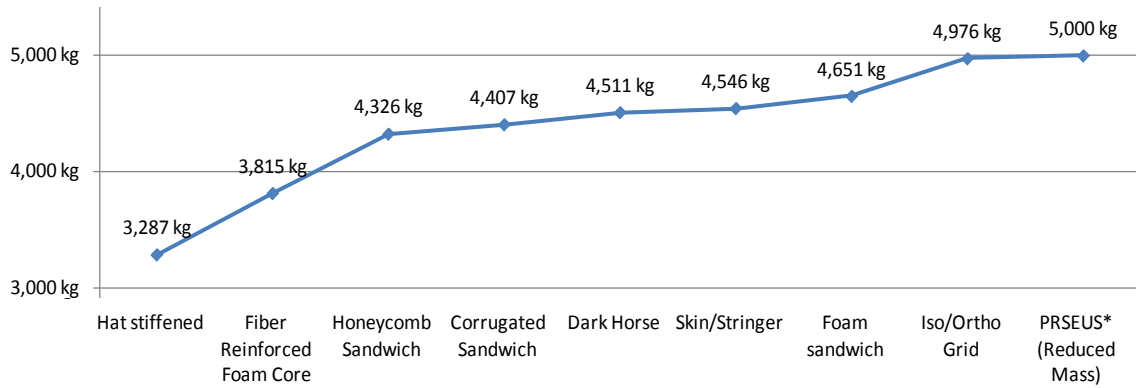


Figure 7. Shroud concept basic mass results.

The results show that the Hat Stiffened and Fiber Reinforced Foam Core concepts are significantly lighter than the other concepts.

Table 2. Concept overall FOM scoring results.

Design Consideration:	Points of Contact	Weighting Factor	Skin/Stringer	Hat stiffened	Corrugated Sandwich	Honeycomb Sandwich	Foam sandwich	Fiber Reinforced Foam Core	Iso/Ortho Grid	PRSEUS	Dark Horse
Basic Mass	Concepts Team	3.104	3.12	9.00	3.77	4.15	2.63	6.53	1.11	1.00	3.29
TRL Delta (Cost & Schedule Risk)	Concepts Team	1.349	4	4	4	9	9	4	1	4	4
Damage Tolerance During Use (Reliability)	Alan Nettles, John Thesken, James Reeder	1.349	5	5	4.5	4.5	4.5	6	4.5	6.5	4.5
Sensitivity to Fab Defects/Damage	Larry Pelham (06/25/09)	1.349	5	5	5	3	4	6	5	8	4
Joint Mass (Ver. & Hor. + Diff Concepts = Diff joints)	Sandy Walker	0.524	2	2	8	8	8	8	2	4	1
NRE + 20 Production Units	Larry Pelham & Tom Parkey	0.524	5.79	5.45	5.08	6.61	6.64	4.35	3.94	1.05	6.08
Acoustic Transmissibility	Anne McNeilis	0.524	3	6	7	4	5	5	7	2	4
Repairability (Defects, Accidents, etc..)	Alan Nettles, John Thesken, James Reeder	0.524	5	5	4	6	6	4	4	3	5.5
Thermal Tolerance	Sandy Walker & Marcus Studmire	0.192	1.00	2.51	1.51	9.00	3.96	2.50	1.00	1.00	3.34
Flexibility in Design (Secondary Att. & Penetrations)	Concepts Team	0.192	4	4	4	8	8	7	2	1	6
NDE Ability / Inspection	Don Roth, Pat Johnston, James Walker	0.192	6	5	2	9	8	4	4	2	6
Environmental Sensitivity (Hygroscopic Absorption)	Jim Sutter & Mark Nurge	0.089	6	4	6	3	1	2	5	9	8
Structural Health Monitoring (SHM)	Jim Miller & Curtis Banks	0.089	6	6	3	7	4	5	4	1	5
Total Figures of Merit =			39.57	59.13	44.32	53.91	49.48	55.81	28.64	34.53	39.4
The top two designs with the highest total figure of merit are highlighted in blue.											

6.2 Concept Overall Scoring

Total scores for the concepts are determined by summing all of the weighted Figure of Merit scores. The results of the total FOM scoring for the concepts is shown in Table 2. The two concepts with the highest overall scores are the Hat Stiffened concept and the Fiber Reinforced Foam Core concept with total scores of 59.13 and 55.81 respectively. The Honeycomb Sandwich concept received a total score of 53.91, putting it in a close third place. The remaining concepts all earned total FOM scores below 50, creating a reasonable separation between the concepts that lends confidence to the selection of a few concepts and the elimination of others. Prior to making

the final concept down select, the robustness of the FOM scoring and ranking system was checked by performing a sensitivity analysis. The FOM weighting factors were varied to see how they influence the overall concept scores. It was found that when the FOM weighting factors were varied up and down by a reasonable amount, the top three concepts remained in the top three positions. In some cases, the ranking order of the concepts changed, but the Hat Stiffened, the Fiber Reinforced Foam Core, and the Honeycomb Sandwich concepts were consistently the top three options. The same result was found when some of the individual FOM scores were adjusted to reflect uncertainty or scoring suggestions made by other team members.

7. CONCLUSIONS

Eight different composite construction concepts plus a ninth combined technology option were identified as candidates. The team analyzed and evaluated these concepts for their expected performance with respect to 13 Figures of Merit. The FOMs were given weighting factors representative of their relative importance as determined by the team. Primary structural mass (Basic Mass) was given the highest weighting at 31% of the overall score. The FOMs with the next highest weighting were TRL Delta, (indicating development risk) Damage Tolerance, and Sensitivity to Fabrication Defects, with each of these categories given a weighting factor worth 13.5% of the overall score.

After completing all 13 FOM evaluations for each of the nine composite construction concepts, overall scores were tallied for the options. It was determined that the Hat Stiffened Panel Concept, the Fiber Reinforced Foam Core Concept, and the Honeycomb Sandwich Concept were the options with the best overall scores. The Honeycomb Sandwich Concept is the Point of Departure design and the results of this study reaffirm that selection as a good choice. The study results, however, indicate that there are other composite construction options that may provide better overall performance than the POD design.

The Structural Concepts Team recommends that the Hat Stiffened Panel and Fiber Reinforced Foam Core concepts be given further study and consideration as potential high-performance alternates to Honeycomb Sandwich construction. Detailed documentation of the analysis, optimization and evaluation of the two recommended alternate concepts can be found in “ACT Payload Shroud Structural Concept Analysis and Optimization” (Ref. 9, Zalewski & Bednarcyk). The use of advanced composites technology to create lightweight, reliable and affordable structures is considered to be an important enabler of the next generation of manned space systems. The ability to predict composite structure performance and capability with consistent results is essential to their widespread use on man-rated systems. A building block approach can be used as a key to develop the needed confidence in the design, analysis and manufacturing of large composite structures such that their performance can be fully utilized.

The incorporation of a multi-disciplinary approach with a strong link to program requirements to provide foundational elements needed to develop large-scale, man-rated composite structures has been demonstrated. The Structural Concepts Team includes groups focusing on Composite Construction Architectures, Damage Tolerance, Composite Joints, and Repair while working closely with the Materials & Manufacturing Team, and the Testing & Evaluation team. This integrated approach provides the building blocks necessary to advance the TRL of large composite structures toward their acceptance for space applications.

8. ACKNOWLEDGEMENTS

The authors are grateful to Bob Draper, Dr. Lloyd Eldred, John Lucero, Dr. Ted Johnson, Dr. Alan Nettles, Ken Segal, Dr. Mark Shuart, Dr. LaNetra Tate, Scott Thomas, Dr. Sandy Walker and many others for providing the analysis, guidance, team leadership, and insight vital to the implementation of this task.

9. REFERENCES

1. Sumrall, P., Creech, S., Refinements in the Design of the Ares V Cargo Launch Vehicle for NASA's Exploration Strategy, AIAA-2008-4981, 44th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, 21-23 July 2008, Hartford, CT.
2. Mankins, J.C., Research & Development Degree of Difficulty (R&D3): A White Paper, March 10, 1998.
3. NASA/SP-2007-6105, Rev 1, NASA Systems Engineering Handbook, December 2007.
4. Johnson, T., ACT Segmented and Full Barrel Study Results and Recommendations for an Ares V Vehicle Interstage, 2010 National Space and Missiles Materials Symposium, June 28 – July 1, 2010, Scottsdale, Arizona.
5. Walker, S., Lightweight Composite Joints Development, 2010 National Space and Missiles Materials Symposium, June 28 – July 1, 2010, Scottsdale, Arizona.
6. HyperSizer Structural Sizing Software User's Manual, version 5.3, Collier Research Corporation, Hampton, Virginia, <http://www.hypersizer.com>, 2008.
7. Eldred, L., Ares V Shroud - PS-02 Finite Element Model Usage Guidelines, October 10, 2008.
8. Wu, C., Cerro, J., Hardware-Based Non-Optimum Factors for Launch Vehicle Structural Design, 2010 National Space and Missiles Materials Symposium, June 28-July 1, 2010, Scottsdale, Arizona.
9. Zalewski, B., Bednarczyk, B., ACT Payload Shroud Structural Concept Analysis and Optimization, 2010 National Space and Missiles Materials Symposium, June 28-July 1, 2010, Scottsdale, Arizona.