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Introduction. It is uncertain whether the next, new launch vehicle developed in the United States will focus on commercial access to space - a “Reusable Launch Vehicle -focus” - or military access to space - a “Space Operations Vehicle -focus”. However, it is clear that both the RLV-focus and the SOV-focus benefit from design approaches which have the simplicity and robustness needed to reduce costs and meet rapid-response mission needs. An innovative fuselage design approach that combines many desirable operational features with a simple and efficient structural approach is being developed by NASA. The approach, named METAShield for MEtallic TransAtmospheric Shield, utilizes lightly loaded, hot aeroshell structures surrounding integral propellant tanks that carry the primary structural loads. The aeroshells are designed to withstand the local pressure loads, transmitting them to the tanks with minimal restraint of thermal growth. No additional thermal protection system protects the METAShield, and a fibrous or multilayer insulation blanket, located in the space between the aeroshell and the tanks, serves as both high temperature and cryogenic insulation for the tanks. The concept is described in detail, and the performance and operational features are highlighted. Initial design results and analyses of the structural, thermal, and thermal-structural performance are described. Computational results evaluating resistance to hypervelocity impact damage, as well as some supporting aerothermal wind tunnel results are also presented. Future development needs are summarized.

Outline

- Concept Introduction
- Heritage/Technology Impacts
- Design Features
- Preliminary Structural Analyses
- Cryogenic Insulation Predictions
- Hypervelocity Impact Calculations
- Expansion Joint Aerothermal Leakage Tests
- Additional Needs for Concept Validation

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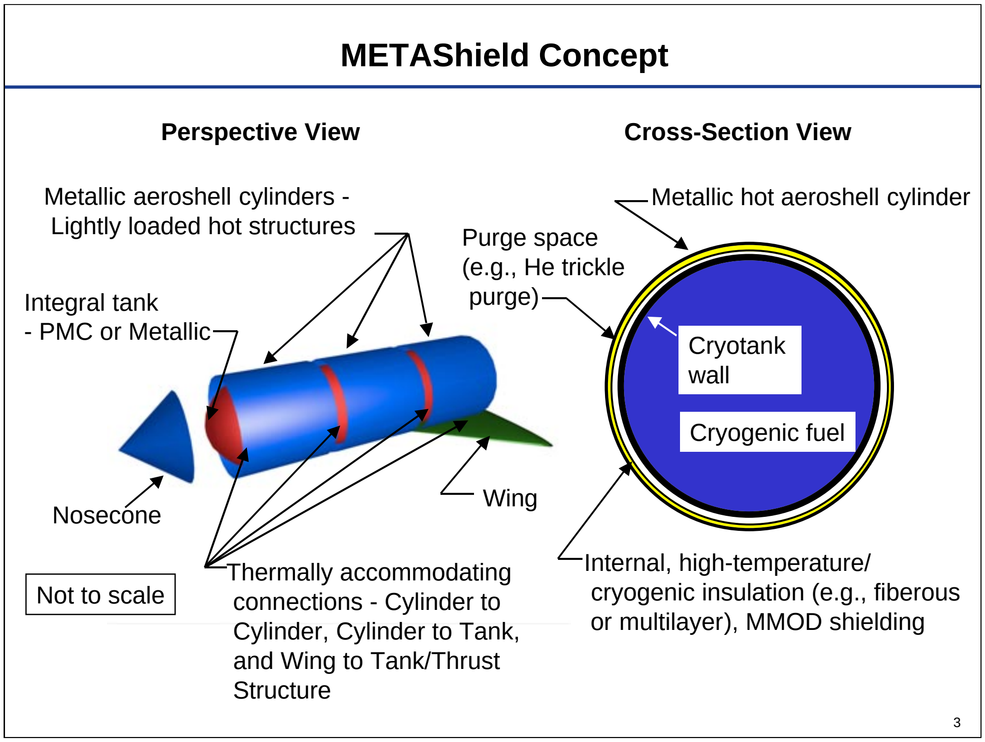
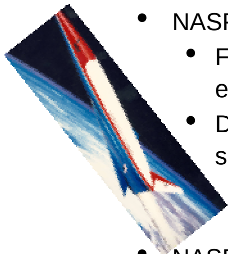
The research effort described herein was initiated under the Second Generation RLV Airframe project (2GRLV, now Next Generation Launch Technologies). The goal of this NASA-led task was to take an independent approach to studying thermal-structural designs for the airframe structures in an integrated manner. Design concepts were required to address as wide a range of vehicle architectures as possible and to focus on the greatly improved cost (driven by operations) and safety goals. The METAShield concept was studied as an attractive alternative with significantly higher potential to meet these program goals than the various Thermal Protection System (TPS) - Tank approaches widely adopted by 2GRLV Industry Airframe team members. The results presented subsequently follow the outline shown in this figure.

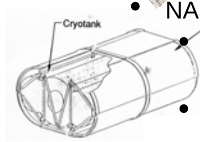


The METAShield is comprised of several large structural shells ("aeroshells") suspended over an integral tank primary fuselage structure. Circular cylinders provide structurally efficient shells, but other shapes can be accommodated with the design. Each shell is lightly loaded by local aerodynamic pressures and its own inertial loads. It transmits these loads to the tank structures through thermally accommodating connections at the two ends and at a few other discrete locations. Because of the low internal structural loads, these shells are essentially sized at the minimum gauges normally accepted for aircraft structures (depending on wall construction), forming very durable, structurally efficient hot structures. The initial aerothermal loads predicted by 2GRLV contractors have indicated that peak radiation equilibrium fuselage surface temperatures past the nosecone area will be less than 2000˚F. Therefore, state-of-the-art superalloys are viable options, and their replacement by more advanced, lower weight materials as they mature is relatively simple. The primary structures within the aeroshells are thermally protected using efficient, low-density fibrous insulation blankets. This insulation performs several functions, it protects against high temperature reentry aerothermal loads, it maintains propellant conditioning during ground hold using a low-flow-rate helium purge, and it, along with the shell, act to protect the primary structure from orbital debris. This insulation can also be replaced as more advanced insulations, such as Multi Layer or aerogel-based insulations, are developed.

Heritage



- NASP Program - Government Baseline
  - Features adopted: Multiple hot cylindrical fuselage shells w/ expansion joints over an integral tank primary structure
  - Differences: A purge space (nominally 6 in.) instead of an evacuated space, thermally accommodating connections to tank



- NASP Program - Task D fuselage test article
  - Features adopted: Purged High Temperature insulation as cryoinsulation
  - Differences: lightly loaded fuselage shell -> Titanium Matrix Composite structure not needed

- Future Space Transportation System Study - Integral tank/thrust structure - Wing/Fuselage Aeroshell
  - Features adopted: Bellows thermal accommodation connection between tank and aeroshell

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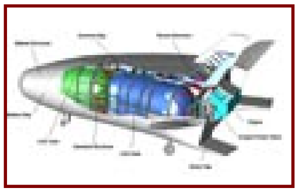
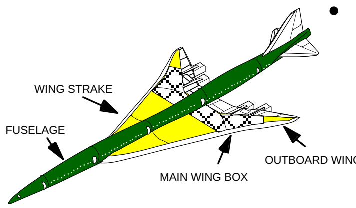
As with most new ideas, the METAShield concept was developed building on a heritage of prior approaches from other advanced NASA research projects. The salient features adopted, as well as those features which were intentionally omitted, are summarized in this and the subsequent chart. Aeroshell-like structures were proposed as a design feature of the original “government baseline” vehicle in the National Aerospace Plane (NASP) program. Helium-purged insulations were used as cryogenic insulations in large-scale tests during NASP, and would only be needed for ground hold conditions with rocket-propelled launch vehicles. Thermal accommodation concepts have been key features for several space access vehicles studied by NASA. Practical design features and fabrication features for high-temperature metallic structures were developed during the High Speed Research (HSR) program. The development of the METAShield benefited from this research heritage.

Heritage - continued



- X-33 program
  - Features adopted: Torsionally rigid, thermal accommodation hinges for proposed X-33 TPS-to-Aluminum-H2-tank support structure redesign
  - Differences: Hinge plates redesigned for simplified fabrication and more commonality of parts



- HSR program
  - Features adopted: Operability design features for hot metallic structure (e.g., gauges for damage tolerance, lightning strike, etc.), design and fabrication approaches for lightly loaded stiffened and sandwich fuselage structures (e.g., joints, doors, other structural details)

Technology Impacts

Technology Impact Areas	Positive Impacts	Negative Impacts
Performance	• Hot aeroshell structure saves weight due to elimination of most/all external TPS	• Limited temperature capability compared to ceramic (e.g., shuttle-derived) external TPS tiles
	• Lightly-loaded aeroshell structure more efficient than non-integral tank airframe	
	• Dual-use internal insulation saves mass since no cryoinsulation system needed	• Heat short to tank at tank attachment sites
	• Non-structural internal insulation more efficient than load bearing insulations (e.g., Shuttle-Derived TPS)	
	• Can substitute lighter-weight, high-temperature (e.g., aluminide) alloys as desired	
	• Can substitute lighter-weight, more efficient Multi Layer Insulation internal insulations as desired	
	• Smooth outer shell more aerodynamic/reduced heating vs TPS-covered system	• Uncertain aeroheating effect of discrete steps at aeroshell Interfaces
	• Inherent capability to purge hydrogen leakage from tanks allows tank design for maximal structural efficiency and not to low-leak strain limits	
	• Can be used with either composite or metallic integral cryotanks, Storable, LH2, and LOX tanks	
Safety	• Robust aeroshell gives durability and damage tolerance similar to commercial airline airframe:	• Limited metallic temperature capability may limit abort options
	- inherent lightning strike resistance	
	- resistance to bird-strike, hail, FOD, etc.	
	• Robust aeroshell and purge space combine to give maximal protection from hypervelocity MMOD	
	• Purge space allows for:	
	- Ability to safely remove hydrogen leakage from tanks	
	- Ability to include additional Whipple shields for hypervelocity MMOD	
	• Few aerothermal seals that could fail compared with systems using external TPS	

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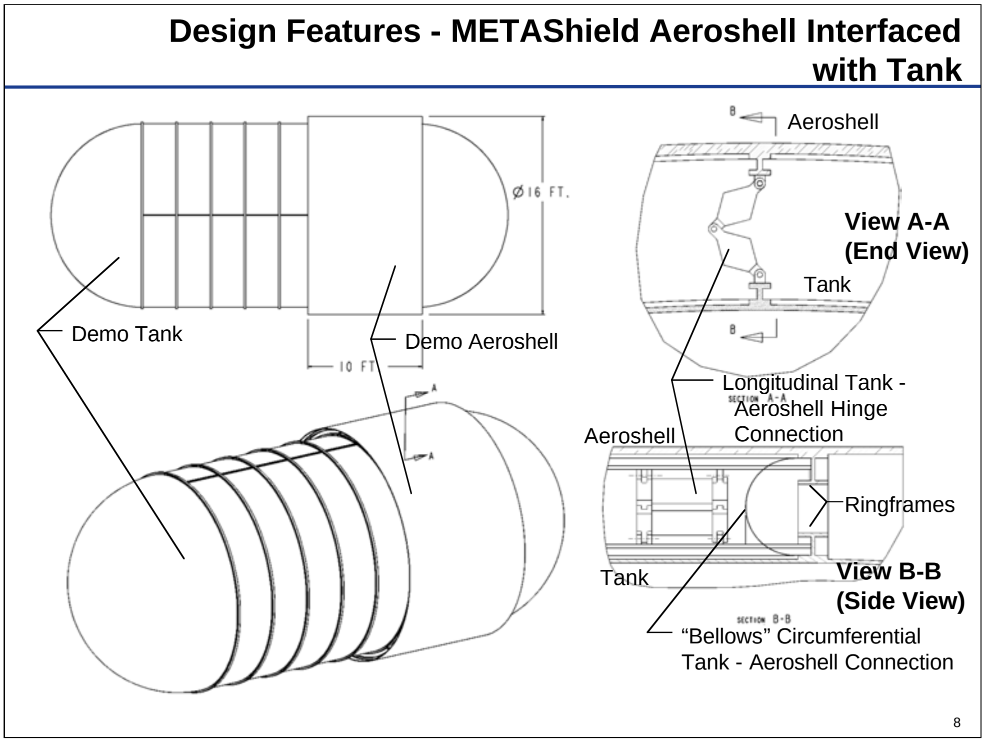
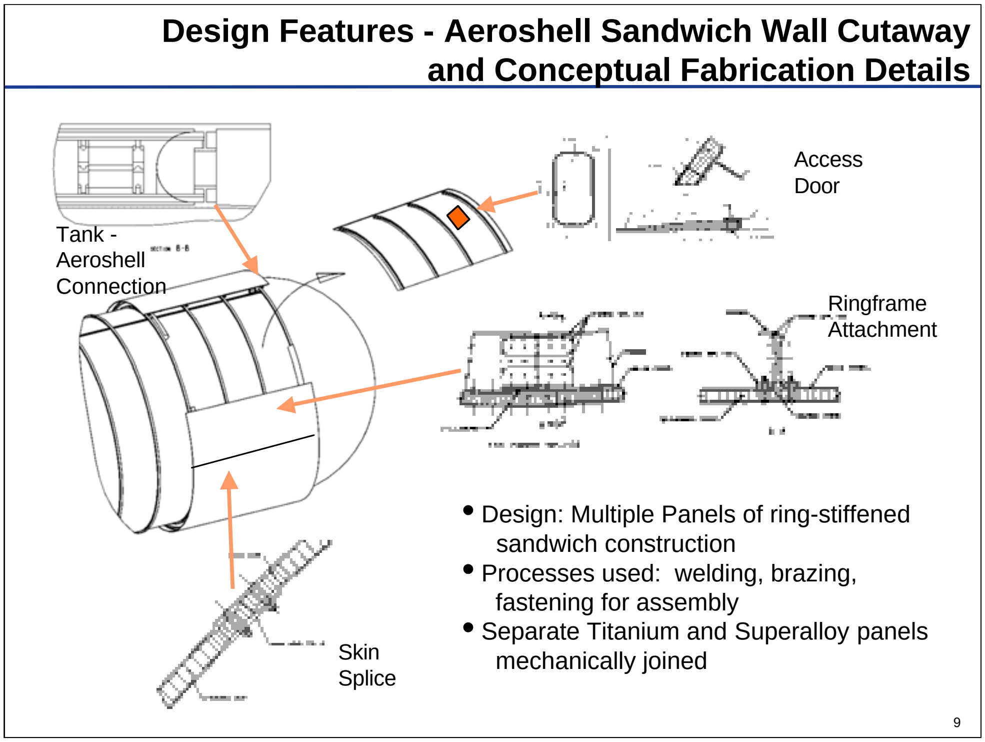
A qualitative assessment of the “impacts” of the METAShield concept on the reusable launch vehicle goals are shown in this and the subsequent chart. Because this approach is substantially different than the more traditional approach to thermal protection using discrete tiles (metallic or ceramic) and blankets, but less challenging than a hot, primary airframe structure it has a unique and attractive set of performance, safety, reliability, cost, and operations impacts. It combines the durability and damage tolerance of traditional aircraft airframe structures with an integrated approach to managing the effects of the aerothermal loads that are unique to an RLV. It’s maintainability is closer to aircraft because the tank and outer structural shells are more easily inspectable during routine maintenance (the latter using access doors into the purge space). The number of expansion joints for this concept is vastly reduced compared to an airframe structure with discrete TPS tiles. In addition, the METAShield concept eliminates systems such as a separate cryoinsulation system that must be maintained. As previously mentioned, it is also readily upgraded by fielding improved shell structures and insulations. An added safety benefit for hydrogen-fueled vehicles is that the inert purge outside the tanks (but inside the METAShield) will allow for a larger acceptable leakage of H2 from cryogenic tanks than many alternate approaches for integration of the tanks with a TPS.

Technology Impacts - continued

Technology Impact Areas	Positive Impacts	Negative Impacts
Reliability	• Incorporates positive mechanical/metallurgical attachments (e.g., aeroshell to tank, subcomponents, etc.) compared to adhesive attachments having uncertain reliability	• Tank attachment complexity - transmit mechanical loads and accommodate thermal growth
	• Ability to design for level of Durability/Damage Tolerance (e.g., MMOD, FOD,…) desired	
	• Fewer on-board systems that could fail (I.e., no external TPS, no separate cryoinsulation)	
	• Large Aeroshell sections mean fewer aerothermal seals that could fail compared to systems with external TPS	• Seal gaps: size larger than external TPS tiles, and must also limit rain ingestion and purge loss
Cost	• Maintenance requirements/expertise closer to Commerial Civil Airframes than Shuttle	• Metallic systems acquisition costs higher than PMC structures
	• No long TPS turnaround timeline and maintenance "army" needed	
	• Fewer systems to develop (I.e., no external TPS, no separate cryoinsulation)	
	• Design/fabrication practices needed can be adapted from NASA High Speed Transport (HSR) Program	
Operations	• Robustness leads to improved ground processing (e.g., fewer restrictions on access, tool drop, fluid spills, etc.)	
	• Reduced part count compared to systems with external TPS	
	• Tank and aeroshell surfaces are bare and inspectable using SOA methods	
	• Major servicing by removal of access panels and/or large shell sections	
	• No waterproofing required	
	• Potential for All-weather operations (I.e., vehicle can fly through rain, hail, lightening, etc.)	
	• Improved airframe turnaround times, and launch and landing	

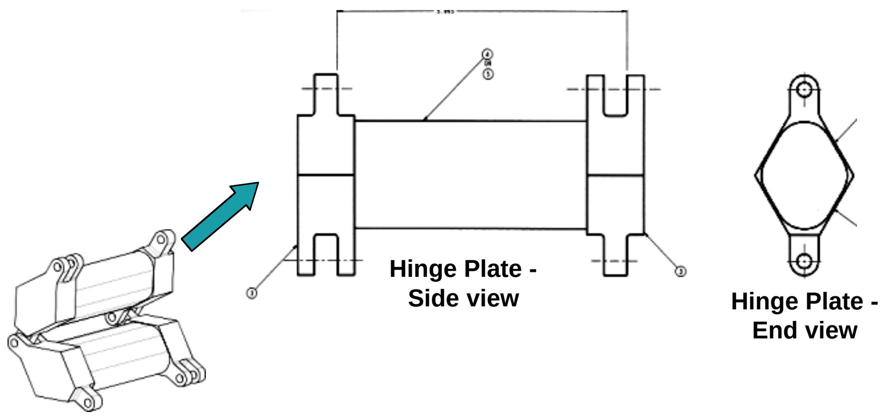


Some preliminary design approaches for the thermal accommodation interfaces that constrain rigid-body motion between an aeroshell structure and a tank structure are shown in this chart. The relative longitudinal motion between the aeroshell and the tank is constrained with a set of bifold hinges. Though shown in this cutaway as located at the end of the aeroshell, the thermal-structural analyses indicate a more optimal location of these hinges is at the midsection of the shell. Although a single connection is sufficient to restrain this motion, a series of hinges arranged around the shell circumference is envisioned to better distribute the load. At each end of a aeroshell cylinder, the other five degrees of relative motion between the aeroshell and the tank are restrained with shear webs, in this figure shown as circumferential bellows. Any static local pressure or normal inertial load on the aeroshell will follow a loadpath that converts the load to an inplane shear within the shell structure which is then transmitted through the bellows into the tank. Although the bellows have high flexibility along the vehicle axis and somewhat less flexibility in the radial direction, they are very stiff in shear and can transmit this load to the tank at low stress levels for even minimum gauge bellows designs.



Some potential approaches to fabrication of a honeycomb sandwich aeroshell wall are shown in this chart. These fabrication details were initially developed by U. S. commercial airframe companies (Boeing, Northrop-Grumman, Lockheed) for the NASA HSR program to support development of a commercial supersonic transport. Thus, they represent the result of a significant design effort that 1) developed affordable approaches to fabrication, 2) developed advanced structures that would have damage tolerance characteristics and good potential to satisfy FAA certification requirements, and 3) would be acceptable to the commercial airlines in terms of durability and ability to be maintained in a cost effective manner. The approach shown here is to use multiple honeycomb sandwich panels that are formed by metallurgical brazing or welding. These panels and other components such as ringframes, bellows, etc. are joined using mechanical fasteners to form the shell structures. This approach allows for final assembly and maintenance using traditional aerospace practices, and also simplifies the transitions between higher-temperature alloys for windward-surface panels and lower-temperature alloys for leeward-surface panels. Also shown in the chart is a conceptual approach for access doors. Access doors aid in final assembly, provide an internal inspection capability, and provide access to internal systems.

Design Features - Longitudinal Tank - Aeroshell Hinge Connection Demonstration Hardware



- Closed-section hinge plates for high torsional rigidity
- Design, fabrication, and assembly drawings for hinge connection completed
- Fabrication of hinge hardware having two barrel lengths initiated

This chart shows some design details for the bifold hinge that constrains relative axial motion between an aeroshell and a tank. The design was developed from a proposed approach to attach TPS support ringframes to an aluminum cryotank in the X-33 hydrogen tank redesign effort. The hinges primarily transmit a shear load through the hinge plates, but this shear induces a moment that becomes a torsion within the hinge plates. Because of the large forces, and the need to maintain low rotations (I.e., keep the hinge pins parallel), closed section hinge plates were required to maintain adequate torsional rigidity. A common hinge-plate design is used for both bifold hinge plates, thus reducing design, manufacturing, and maintenance costs.

Preliminary Structural Analyses

- Non-linear, thermal-structural analyses were performed for single, 30 ft diameter aeroshell cylinder with thermally accommodating attachments (bellows)
- Estimated temperatures (based on aerothermal data from prior studies) and pressures utilized
- Sandwich aeroshell having MA754 (2000˚F) and Ti1100 (1100˚F) material mix analyzed for “representative” circumferential temperature and pressure loading distributions. Studied effects of varying:
  - Bellows gauges and support constraints at tank interface
  - Location of thermally accommodation hinges
  - Sandwich core thickness
- Stiffened skin aeroshell allowing for near-term fabrication processes analyzed using only Ti1100 material properties, a “representative” circumferential temperature distribution, but a severe step change in pressure loading. Studied effects of varying:
  - Bellows gauges and attachment constraints at tank interface
  - Location of thermal accommodation hinges
  - Stiffener geometry, gauges, and stabilization structure
- Design considerations included global instability as well as maximum radial displacements, longitudinal displacements, and stresses

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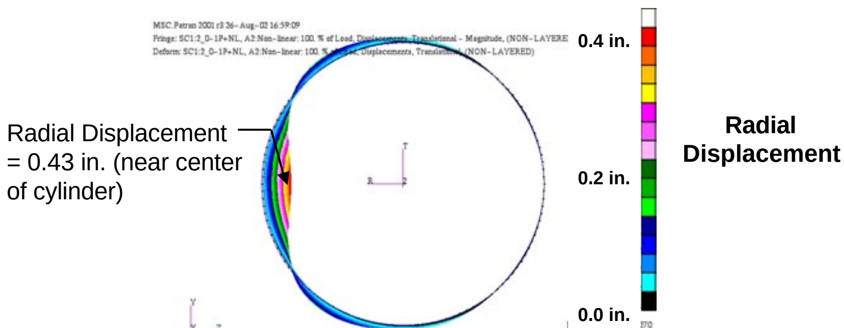
Nonlinear analyses have been performed to determine the thermal-structural performance of the basic aeroshell/bellows structural system. Representative pressure and temperature load cases were developed from prior studies for reusable launch vehicles. Both sandwich and stiffened-skin design were analyzed for an aeroshell that was nominally 30 ft diameter and 30 ft long. Because the peak temperatures were below 2000˚F on the shell windward side, a state-of-the-art powder metallurgy nickel alloy MA 754 (European designation PM1000) was utilized for this region. For the lower temperature leeward side, a titanium alloy (Ti6242 or Ti1100) was utilized. Parametric studies were performed to investigate variations of displacements and stresses with sandwich and stiffened skin design parameters as shown in the chart. In addition, the thermally induced longitudinal displacement that would be accommodated by expansion joints, and the global stability due to pressure loading were studied. Dynamic loads and acoustic loading effects have not been included in the analysis and sizing of the structure.

Example Honeycomb Sandwich Results - Maximum Radial Displacement, Pressure Load



- Material utilization: 50% Ti1100, 50% Ma754
- Single Center Ringframe
- Bellow diameter is 6 in., skin gauge is 30 mils.
- Ti Honeycomb Sandwich dimensions: 15 mil facesheets, 0.5 inch thick Honeycomb core
- Ma754 Honeycomb Sandwich dimensions: 15 mil facesheets, 1.2 inch thick Honeycomb core
- Maximum Von Mises Stress 17.6KSI (in 30 mil bellows)
- Average structure unit weight - 1.7 lbm/sqft (ideal weight)

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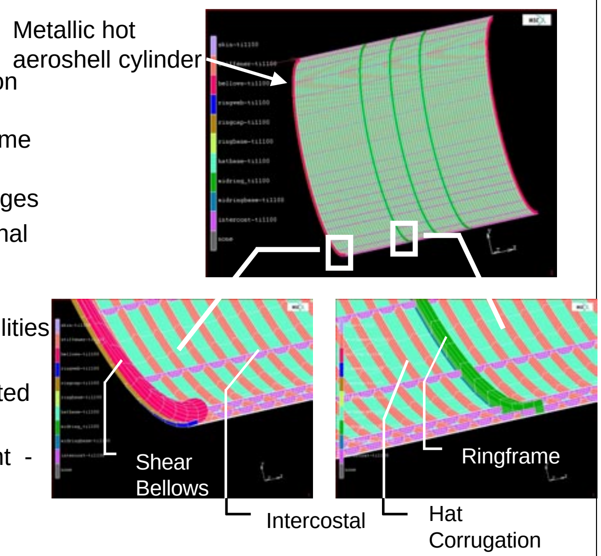
This chart shows a sample set of results for the sandwich aeroshell design under a pressure load case which peaked at 2 psi on the windward surface. The geometry of the sandwich structure is described in the chart. The color contour plot of radial displacement is superimposed on an exaggerated deflection plot. In this case, the maximum radial deflection is only 0.43 inches and the maximum Von Mises stress is within the bellows and is only 17.6KSI. Thus the anticipated effectiveness of the bellow connection for transmitting mechanical loads is demonstrated by this calculation. The sandwich structure stresses, even at minimum gauge (15 mil facesheets), are very low for both this pressure load case and the thermal load case. Additional weight savings could be achieved by reducing the thickness of the Ma 754 honeycomb core. However, the bellows stresses for the thermal load case (not shown) were unsatisfactorily high, and this load case will be described in more detail in the subsequent chart for stiffened skin aeroshell construction. The ideal structural unit weight for this design, including only the structural elements modeled for the analysis, was only 1.7 lbm/sqft.

Stiffened Aeroshell Structural FE Model

Structural analysis and sizing using MSC-Marc

- Over 103000 elements
- Sizing by iterative modification of skin gauge, corrugation gauge and geometry, ringframe locations and gauges, and intercostal locations and gauges
- Sizing loadcase: 2 PSI external pressure (over half cylinder)
- Criteria used: gross stresses below yield, no global instabilities
- Preliminary thermal stress analysis using same estimated temperatures as H/C case
- Average structural unit weight - 1.5 lbm/sqft (ideal weight)



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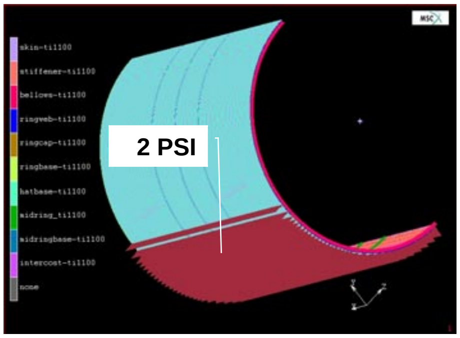
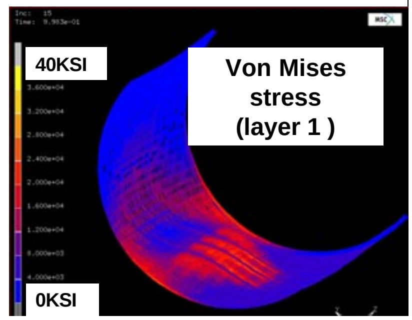
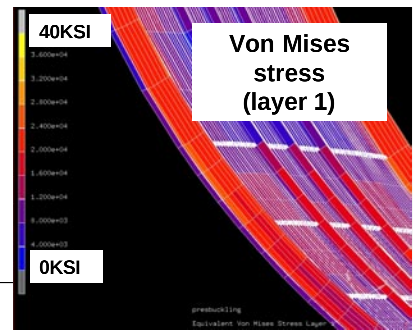
Metallic honeycomb-sandwich construction is theoretically a very efficient design, but it requires an advanced manufacturing capability available at few sites, and the panel sizes which can be manufactured are also limited. The latter observation implies that even though the individual panels are structurally efficient, a large number of panels would need to be fabricated, and a significant number of structural joints would be required to form a single aeroshell cylinder, potentially reducing the overall structural efficiency. A stiffened skin alternative design has been studied to allow for a more readily manufacturable design using less expensive fabrication techniques. A number of analysis models for various titanium stiffened-skin approaches were generated and analyzed. Since only the feasibility of stiffened skin was of interest, the pressure load condition previously utilized was simplified, and no attempt was made to mix high and low temperature alloys. The design shown in the figure is comprised of a corrugated skin attached to the outer-mold-line skin, intercostals to stabilize the corrugations, and three intermediate ringframes. The load path induced by pressure loads favored the approach of having the stiffeners oriented circumferentially. A nonlinear structural analysis model was generated to study the response for the simplified pressure load, and the thermal load case previously used for the sandwich structure to provide qualitative insights on the performance of this design. The structural parameters (e.g., skin gauges, stiffener dimensions, etc.) were found to be sized primarily to preclude general instability, and the ideal structural weight, including only the structural elements modeled for the analysis, was about 1.5 lbm/sqft.

Example Stiffened Skin Results - Pressure Load



Pressure Distribution Assumed

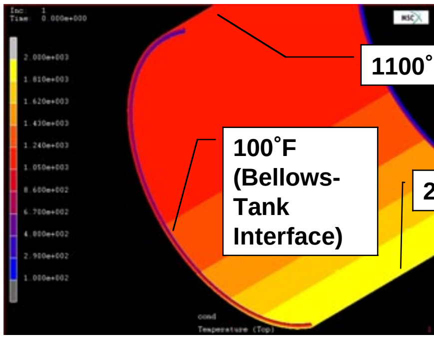




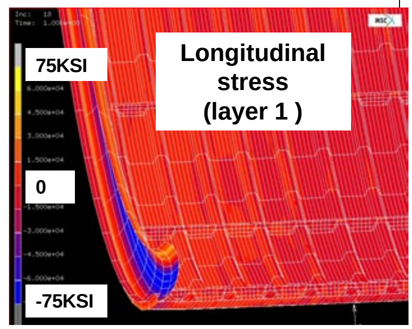
- No global instability, but some skin buckling locally (below hat under intercostal)
  - Initates at ~1.2 psi
  - Local doublers can be used if buckling exists using refined loads and models
- In general, stresses << 40KSi
- Maximum radial deflection in center is 1.3 in.

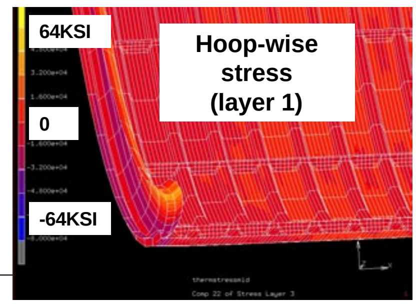
This chart shows example results for the stiffened skin aeroshell design for a half-symmetric model. The analyzed loadcase utilized a simplified local pressure distribution, a constant 2 PSI over half the aeroshell circumference. This condition was more severe than that analyzed for the honeycomb sandwich shell design, and thus the stresses induced were higher than those for the sandwich structure. The skin gauges and other geometric parameters were selected to preclude general instability, but a true optimization was not performed. Some local instabilities (I.e., local skin buckling) were found to be present as the load increased beyond the 1.2 PSI level, but it is believed this result would be moderated for a more realistic pressure distribution. The peak stresses were near 40 KSI however, from the contour plots it can be seen that stresses were generally much lower than the peak stress. The maximum radial deflection for this load condition was 1.3 inches, and as for the sandwich wall construction, the bellows were very effective in transmitting the load to the tank interface location.

Example Stiffened Skin Results - Thermal Load



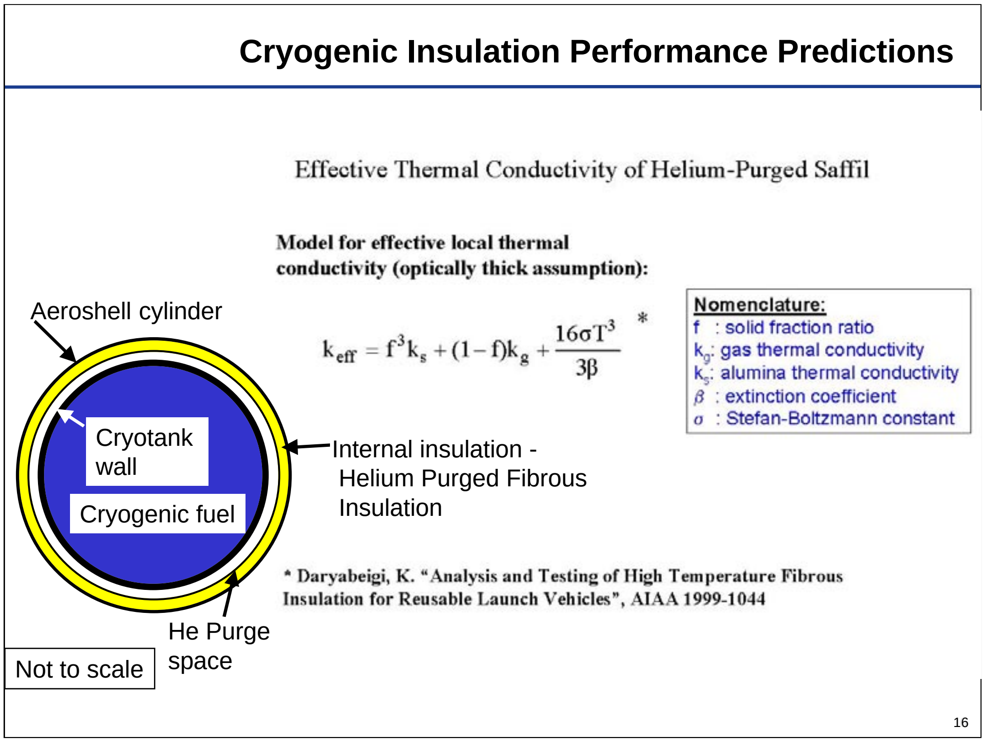
Temperature Distribution Assumed





- Structural design from preliminary sizing
- Primary stresses of concern in bellows
  - Modification of bellow shape and skin needed

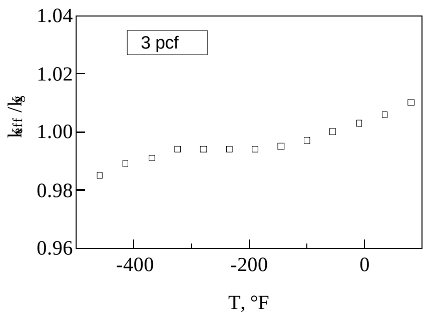
This chart shows thermal-stress analysis results for the stiffened skin aeroshell design for a half-symmetric model. The assumed temperature distribution on the shell is based on surface temperatures calculated previously for RLV's with cylindrical fuselages. At each shell circumferential location, the temperatures assumed along the bellows arc varied linearly between the shell temperature and the 100˚F tank temperature. Thermal stresses for the "longitudinal" direction and the aeroshell circumferential direction are shown. The stresses in the aeroshell were generally low and acceptable, however significant thermal stresses in the bellows were developed. The bellows longitudinal stress shown is a bending stress induced by the large shell displacement. This stress can most readily be reduced by reducing the bellows gauge and/or by reducing the aeroshell length. The hoop-wise stress in the bellows is essentially constant through the bellows skin thickness and is primarily due to the differential hoop-wise growth of the inboard and outboard edges of the bellows. The strains induced by this hoop-wise growth are relatively insensitive to the gauge variations utilized as parameters in traditional structural sizing, and a redesign that reduces hoop-wise stiffness in the microscale (e.g., skin dimpling) and/or the macroscale (e.g., gross shape change) is required. Stresses in the bellows for the previously discussed honeycomb shell construction showed similar characteristics.



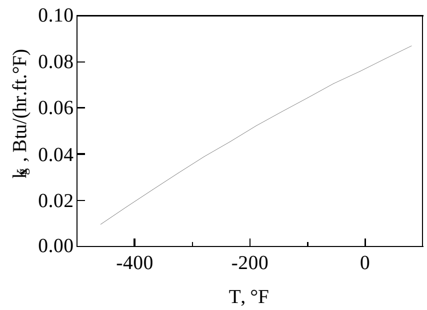
A cryoinsulation approach using a fibrous insulation combined with a low-flow-rate helium purge to avoid cryopumping was successfully demonstrated in the NASP task D fuselage test. To determine if the METAShield cryoinsulation concept was adequate for typical RLV operations, an analytical comparison of it's insulation capability to the present Shuttle External Tank was performed. An analytic prediction of the effective thermal conductivity of the purged insulation was made using techniques developed under the X-33 program for high-temperature fibrous insulations (reference 1). The interacting modes of solid and gaseous conduction, and radiation were studied in that program and a verified technique was developed to model the effective conductivity of fibrous insulation (see reference 1). The assumption of essentially static gaseous conduction behavior in the purge space, and the effectiveness of the models at cryogenic temperatures both require validation.

Cryogenic Insulation Performance Predictions - continued

Ratio of effective to gas thermal conductivity



Helium thermal conductivity



- Effective thermal conductivity is dominated by gas thermal conductivity in the temperature range of interest
- Ground hold heat flux for 6 inch purge space - 0.012 BTU/Sqft-s (-420˚F to 40˚F)
- Shuttle-derived requirement (Ref. AIAA 2002-0504) - 0.01 BTU/Sqft-s
- Purged fiberous insulation appears feasible as cryoinsulation approach

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The result of the modeling of a helium purged fiberous insulation is shown in this chart. The effective thermal conductivity over the cryogenic to room temperature range is dominated by the conductivity of the helium gas as seen on the left of the chart. Using the temperature dependent thermal conductivity of helium shown on the right of the figure, the heat leak into a cryotank during ground hold for a nominal 6 in. purge space going from 40˚F outer surface temperature to -420˚F hydrogen temperature is 0.012 BTU/Sqft-s. This compares favorably with the Shuttle-derived value of 0.01 BTU/Sqft-s in reference 2, so the purged insulation approach for ground hold conditions appears feasible.

Hypervelocity Impact Calculations
Study Overview

- Preliminary calculations using CTH hydrocode performed to assess hypervelocity impact resistance

- Calculation assumptions:
  - Simplified axisymmetric geometry
  - Titanium aeroshell model - Sandwich (2 bumpers) and stiffened skin (1 bumper)
  - 0.35 in. Diameter spherical Aluminum projectile - normal incidence at 7 km/s
  - 0.1 in. Aluminum tank wall
  - No other intermediate bumpers, insulation, etc. in model

- Aeroshell gauges investigated to date:
  - Two 15 mil Ti sheets spaced 6 in. from tank wall
  - One 30 mil Ti sheet spaced 6.75 in. from tank wall
  - One 52 mil Ti sheet spaced 6.75 in. from tank wall

- Results of interest:
  - Aeroshell wall puncture diameter
  - Characteristics of debris cloud
  - Tank wall puncture diameter

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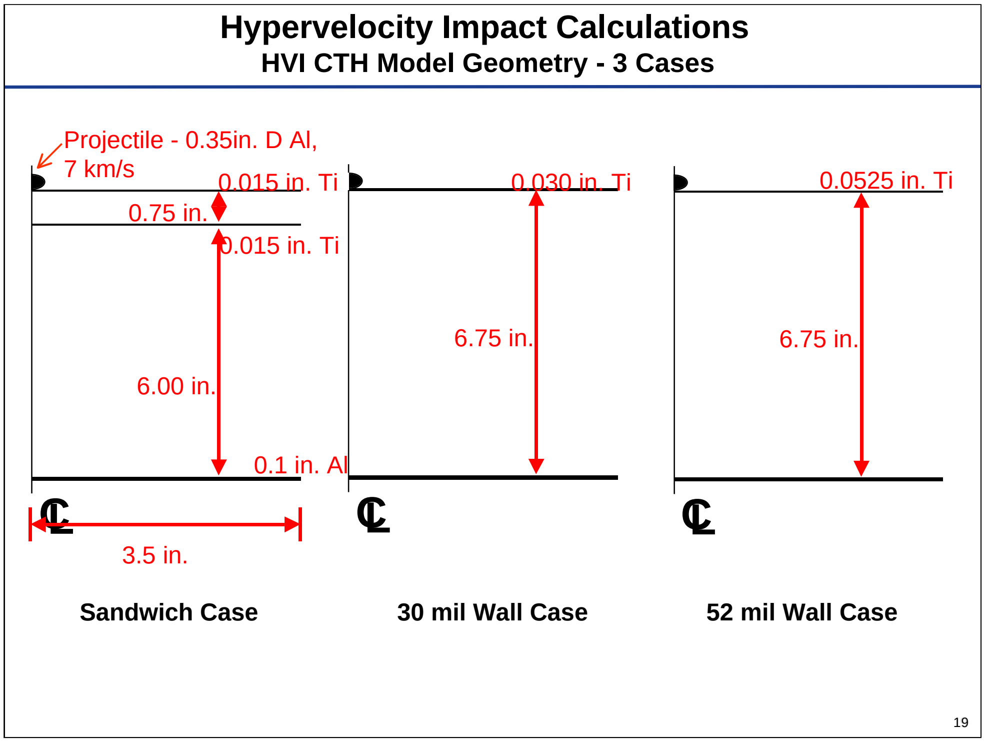
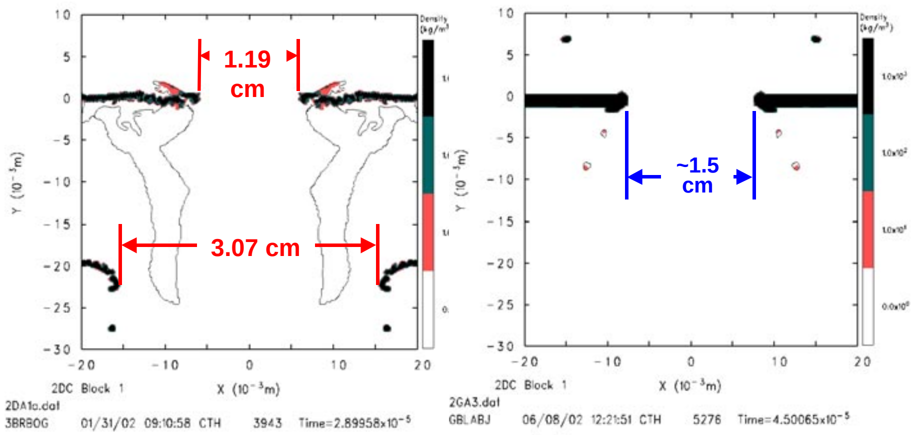
The METAShield concept offers the potential for significantly improved protection from orbital debris compared to TPS protected tanks. An analytic study using the CTH hydrocode (reference 3) was performed to quantify the METAShield's resistance to hypervelocity impact damage. To make the problem more tractable, an axisymmetric geometry was assumed. Three cases were studied using the geometric design parameters developed from the thermal-structural sizings presented previously. Titanium material models were used in analyses representing both honeycomb and stiffened skin because no models for superalloys were available. Results are believed to be conservative because intermediate core, insulation, and other materials were neglected in the model.



In prior studies of hypervelocity impact resistance of metallic thermal protection systems, it was assumed that a significant portion of the orbital debris threat could be accommodated by a system that could withstand the impact of a 0.1875 in. diameter aluminum ball arriving at a 7 KM/s normal velocity (reference 4). In the present study a much more severe impact situation, a 0.35 in. diameter aluminum ball arriving at a 7 KM/s normal velocity, was analyzed. Aeroshell models for the three cases were analyzed: 1) Two 15 mil titanium skins, spaced 0.75 in apart, and spaced 6 in. from a 0.1 in. aluminum skin - representing a titanium honeycomb sandwich aeroshell above an aluminum tank wall. 2) A single 30 mil skin, spaced 6.75 in. from a 0.1 in. aluminum skin to compare single vs double wall aeroshells having similar mass. 3) A single 52 mil skin spaced 6.75 in. from a 0.1 in. aluminum skin representing the stiffened skinaeroshell design at a location where the stiffening corrugation meets the OML skin. The responses of interest included the diameter of the puncture in the aeroshell skin, the characteristics of the debris cloud formed after impact, and the diameter and character of the puncture of the aluminum skin representing the tank wall. These three cases will be termed 1) the Sandwich Case, 2) the 30-mil Wall Case, and 3) the 52-mil Wall Case.

Hypervelocity Impact Calculations

HVI Aeroshell Wall Puncture - 3 Cases



Sandwich Case **30 mil and 52 mil Wall Cases**

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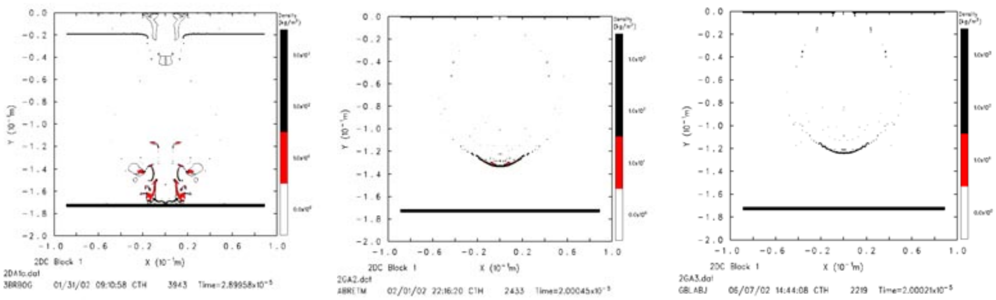
The diameters of the punctures in the aeroshell skins calculated using the CTH code are shown in this chart. The Sandwich case shows the punctures for each “facesheet” of the aeroshell sandwich skin. Recall that honeycomb core material was not included in the model. The outer facesheet puncture for the 0.35 in. (0.89 cm) diameter impactor had a 0.47 in. (1.19 cm) diameter, and the inner facesheet puncture was slightly larger than 1.2 in. (3 cm). For both the 30-mil and 53-mil Wall cases, the aeroshell skin punctures were slightly larger than the Sandwich case at about 0.6 in. (1.5 cm). Only results for one of these single wall cases is presented because the differences between the two aeroshell skin puncture results were small.

Hypervelocity Impact Calculations

HVI Debris Cloud - 3 Cases

Sandwich Case **30 mil Wall Case** **52 mil Wall Case**



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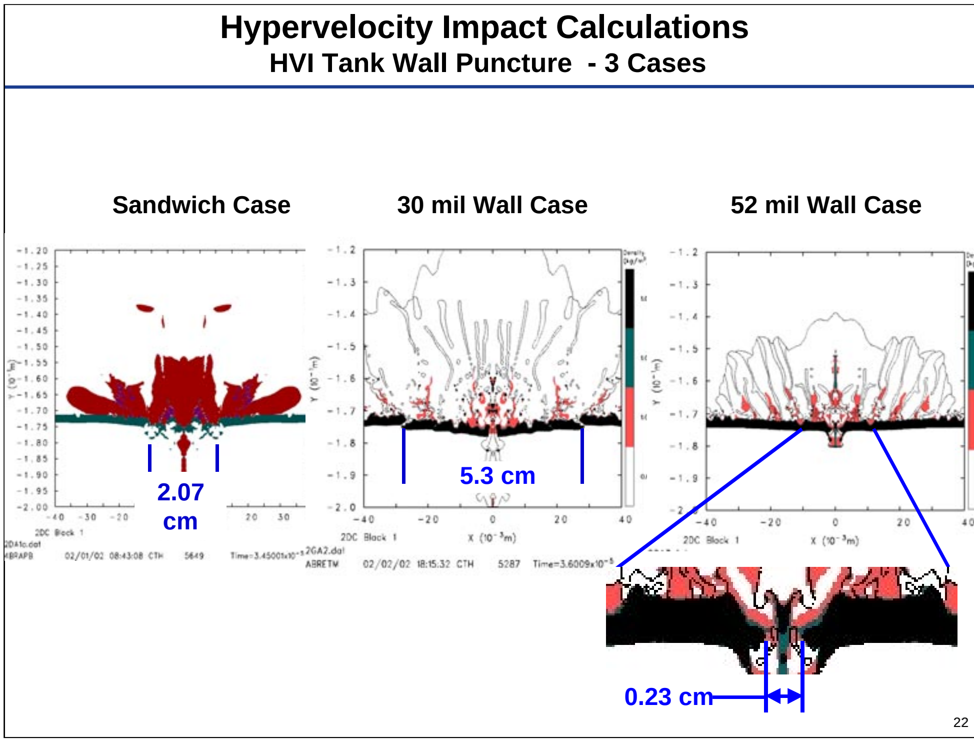
The character of the debris cloud for the three CTH cases analyzed is shown in this chart. Unfortunately, the times from initial impact shown vary for the three cases, however the characters of the debris clouds are clearly seen. The Sandwich case had a much tighter debris cloud with a narrow cone angle, while the two single wall cases had much wider debris clouds with larger cone angles. The debris from thicker single wall case also had a “less solid” character than the case with the thinner wall, although this result is difficult to see in the figure.



The character of the puncture of the aluminum skin representing the tank wall is shown in the chart for the three CTH cases analyzed. The character of the puncture varied for the three cases. The small cone angle of the debris cloud from the Sandwich case caused significant and widespread damage to the aluminum skin where it impacted, but the puncture was only slightly larger than 0.8 in. (2 cm). The wider debris cloud from the single Wall cases resulted in a more distributed damage on the aluminum skin. In the 30-mil Wall case, the debris cloud sheared through the aluminum skin locally removing a 2.1 in. (5.3 cm) plug from the skin. This result is somewhat artificial and results from the axisymmetric analysis assumption. The damage to the aluminum skin for the 53-mil Wall case was similar to the other single-wall case, but the only penetration that resulted in this case was a small central hole 0.09 in. (0.23 cm) in diameter. An aluminum skin hole size of 0.31 in. (0.78 cm) was reported for a metallic honeycomb TPS panel utilizing two 5 mil titanium facesheets plus an intermediate bumper impacted with a 0.1875 in. diameter aluminum ball in reference 4. Thus, the METAShield, having less aluminum skin damage from a more energetic projectile, is significantly more robust than discrete metallic TPS.

Hypervelocity Impact Calculations
Conclusions

- Aeroshell puncture diameters the same order as the projectile (1.3 - 1.7 X)
- Debris cloud from aeroshell with 2 facesheets appears to have smaller cone angle than single sheet aeroshell wall
- Mechanism for tank puncture varied significantly for 3 cases analyzed - large-area damage, localized annular shearing, small puncture
- Using preliminary design gauges, aeroshell wall provides significant hypervelocity impact resistance with no additional design features (e.g., intermediate bumpers)
- Recent parametric calculations using design of experiments (Ref. AIAA-2002-0912) indicate that use of higher temperature (higher density) alloys on aeroshell lower surface should significantly improve damage tolerance

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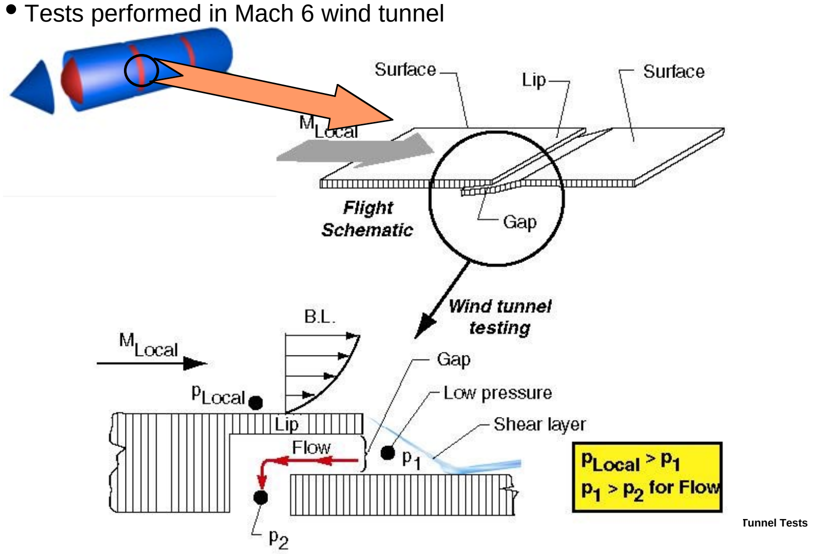
This chart summarizes the hypervelocity impact analysis results described on previous charts. The significant hypervelocity impact resistance of the METAShield aeroshell is clearly seen in these results. The damage threat assumed was extremely severe with impact projectile diameters nearly twice those assumed in 2GRLV TPS studies, and the calculated damage to the underlying structure was less. Also, the benefits of intermediate materials in the METAShield purge space - the thermal insulation and Nextel and glass encapsulation bags - were not considered in the analyses. In addition, titanium material properties were used to represent the aeroshell structure skins. Prior studies on parameters affecting hypervelocity impact damage tolerance (see reference 4) indicated that increasing the mass of the outer shield can reduce impact damage, so high-temperature, high-density alloys that would be used for windward aeroshell surfaces should have improved damage tolerance over titanium alloys.

Expansion Joint Leakage Flow Study

- Parametric data (vs. gap height and flow angle) for joint leakage flow to aid in expansion joint design
- Tests performed in Mach 6 wind tunnel



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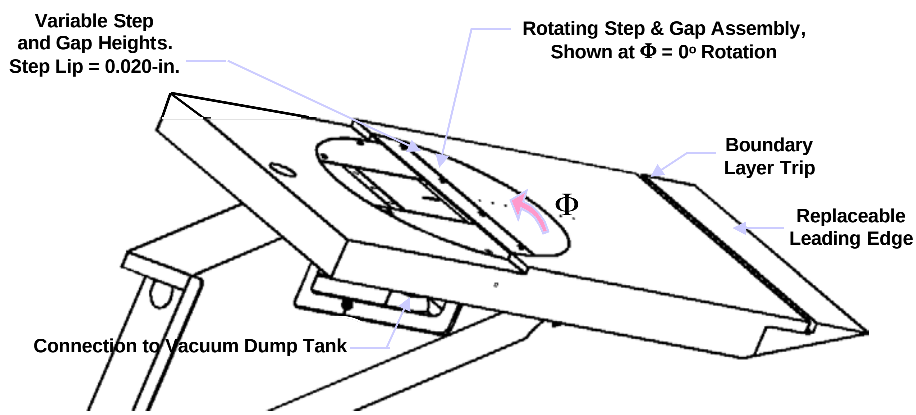
A significant challenge in developing the METAShield aeroshell is the expansion joints that span sequential aeroshells and accommodate their longitudinal growth. Prior approaches for expansion joints for metallic TPS emphasized maintaining smooth, continuous surfaces using overlapping seals to prevent hot gas ingress. However, an alternate approach to seals for the METAShield aeroshell expansion joints is being studied. Aerothermal studies have been recently performed to understand the flow mechanics of rearward facing steps at hypersonic speeds. These studies were motivated by the surprisingly good performance of the BF Goodrich-designed X-33 metallic TPS when the overlapping expansion joint seals were damaged. A wind tunnel model (shown schematically in the bottom of the chart) was built and tested to produce parametric data on pressure and leakage flow into the entrance gap of a cavity with a rearward facing step as a function of the gap height and cross flow angle.

Wind Tunnel Model for Leakage Flow into Cavity through Gaps Having Backward Facing Steps



Instrumentation
- 17 pressure taps
- Temperature of Gap Gas
- Global Pressure from Paint

Parameters
- Angle of attack = 15 deg.
- Freestream Re/ft = 8×10^6
- Rotation Angle, Φ: 0 to 95°
- Step Height: 0.027 to 0.225 in.
- Gap Height: 0.007 to 0.205 in.

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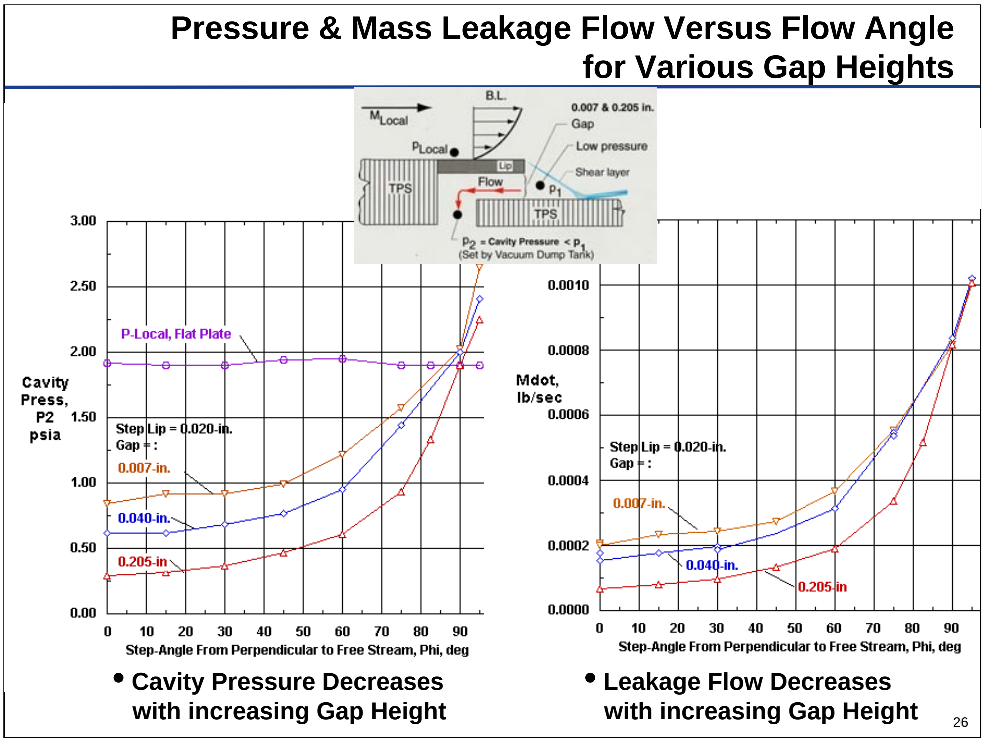
This chart shows the model that was developed for tests in the LaRC 20-Inch Mach 6 tunnel to generate the parametric data. The chart shows the salient feature of the model, the instrumentation utilized and the parameters studied in the tests. Not shown is the connection to the vacuum dump tank that was utilized in measuring the leakage flowrates. The turntable in the model could be rotated to set the cross flow angle, and step height was adjustable at any cross flow angle. Effects of the cross flow (rotation) angle and gap height were studied parametrically.



Summaries of cavity pressure and leakage flow data are shown in this chart. The independent axis is the flow angle relative to the step, with zero being flow perpendicular to the edge of the step, and 90 degrees being parallel to the edge of the step. In addition, curves corresponding to three gap heights are shown (the total step height is the gap height plus a 0.020 step lip thickness). In the chart on the left, the gap pressure decreases monotonically as the gap height increases. However the variation of gap pressure is very insensitive to flow angle over a large range and does not increase significantly until the flow angle exceeds 45 degrees. In the chart on the right, the leakage flow behaves in a manner very similar to the gap pressure. As the gap height increases the leakage flow, already very low, decreases monotonically. In addition, the leakage flow is very insensitive to cross flow, and does not increase significantly until it the flow angle exceeds 45 degrees. The largest step tested was nearly 0.23 in. These results, if similar behavior occurs at full scale, have important ramifications in the design of the expansion joints for the METAShield. Expansion joint designs taking advantage of this flow phenomenon would incorporate discrete steps between the aeroshells with large step-height tolerances. Large joint tolerances would simplify the design, the fabrication, and the ground maintenance for these joints thus reducing costs and turnaround time. However, though these aerothermal results are encouraging, a detailed design of an expansion joint would also need to consider step effects on aeroheating, design features for limiting rain ingestion and purge leakage as well as consider joint producibility and maintenance.

Additional Needs for Concept Development

- Continued Development of Thermally Accommodating Attachments from Aeroshell to Tank to Reduce Thermal Stresses
- Development of Expansion Joints between Aeroshell Cylinders
  - Designs that Links Radial Movements while not Restraining Axial Motion
  - Study Boundary Layer Thickness Effects on Gap Leakage Flows
- Refined Analysis of Concept, Integrated with Rest of Airframe and Applied to an Architecture using a “Good” Set of Design Requirements and Design Loads.
- Building-Block Fabrication and Test Validation of Critical Design Features (thermal, mechanical, structural, thermal-structural, low velocity and hypervelocity impact damage tolerance)
- Development of Specific Designs to Allow Integrated Test with a Cryotank

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In summary, the METAShield integrated airframe concept utilizing several large “aeroshell” structural shells suspended over an integral tank primary fuselage structure shows significant promise for achieving the Next Generation RLV goals. Additional design and analysis efforts are required to improve the bellows connecting the aeroshell to the tank. In addition, the expansion joints between aeroshells have not been adequately defined, but designs utilizing the advantageous flow mechanics of rearward facing steps appear promising. Additional aerothermal testing coupled with CFD to study boundary layer thickness effects will determine if the leakage behavior from wind tunnel tests also applies at full scale. Evaluation of the METAShield concept compared to more traditional TPS-on-tank concepts needs to be performed in a systematic and consistent manner using a common set of design conditions and the program performance, safety and cost goals as metrics. Satisfactory evaluations would be a prelude to progress to higher Technology Readiness levels through a systematic, “Building Block” fabrication and test validation of the critical design features of the METAShield concept culminating with the design and fabrication of components for integrated tests with acryotank.

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14. ABSTRACT
An innovative fuselage design approach that combines many desirable operational features with a simple and efficient structural approach is being developed by NASA. The approach, named METAShield for MEtallic TransAtmospheric Shield, utilizes lightly loaded, hot aeroshell structures surrounding integral propellant tanks that carry the primary structural loads. The aeroshells are designed to withstand the local pressure loads, transmitting them to the tanks with minimal restraint of thermal growth. No additional thermal protection system protects the METAShield, and a fibrous or multilayer insulation blanket, located in the space between the aeroshell and the tanks, serves as both high temperature and cryogenic insulation for the tanks. The concept is described in detail, and the performance and operational features are highlighted. Initial design results and analyses of the structural, thermal, and thermal-structural performance are described. Computational results evaluating resistance to hypervelocity impact damage, as well as some supporting aerothermal wind tunnel results, are also presented. Future development needs are summarized.

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