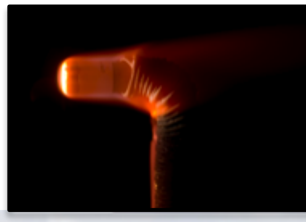
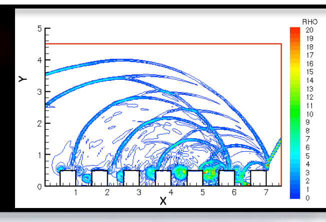
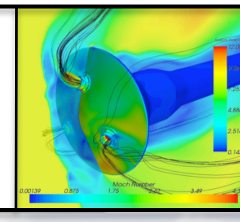
National Aeronautics and Space Administration

Optimization and Fabrication Studies in the Development of Structurally Integrated Thermal Protection System Technology

Mr. Craig Stephens, Element Lead







2009 Annual Meeting
September 29-October 1, 2009

Outline

- **Overview of near- and far-term structurally integrated thermal protection system (SITPS) efforts**
  - Process for vehicle level airframe analysis and design
  - Hypersonic vehicle acreage TPS options
    - Insulated, stand-off, SITPS characteristics
    - Comparison and implications of the various options
  - Background on the current SITPS efforts under HYP M&S
    - SITPS-0: Testing
    - SITPS-1: Design, manufacturing and test
    - SITPS-2: Design
    - SITPS Alternate Core: Development
  - Conclusions

Acknowledgements

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Process for Vehicle Level Airframe Analysis and Design

Hypersonic Vehicle Airframe Analysis and Design Methodology

- **Vehicle FEA model incorporating a representation of both the airframe substructure and acreage TPS are developed**
  - Vehicle acreage TPS is modeled (e.g. build an equivalent plate model) to produce effective stiffnesses for use in vehicle level model
  - **Nature of the TPS (insulated, stand-off, or SITPS) dictates the modeling of the load transfer from panel-to-panel (PtoP) and panel-to-airframe substructure (PtoAS)**

- **Vehicle global loads (aerodynamic, aerothermal, and aerostructural) are applied to vehicle FEA model to produce nodal {U}, {Q}, and temperature vectors for entire vehicle**
  - Areas of high deformations, high temperatures, high thermal gradients are candidate areas for submodel investigation

Hypersonic Vehicle Airframe Analysis and Design Methodology

- **For a specific critical region, submodels are constructed and subjected to appropriate temperatures, loads and displacement boundary conditions for these regions**
  - Detailed 3D FEA submodels of the specific elements (corrugated core, sandwich structures, etc.) are used
  - Stresses within individual elements are determined and Margin-of-Safety (MOS) values are calculated
  - Negative MOS and / or high MOS require changes to the acreage design elements
- **When submodel designs are obtained with all positive MOS, updated [A], [B] and [D] matrices of acreage regions are used in full vehicle model to produce new {U}, {Q}, and temperature vectors for entire vehicle**
  - Submodels are re-analyzed with new {U} and {Q} to check that all MOS are still positive

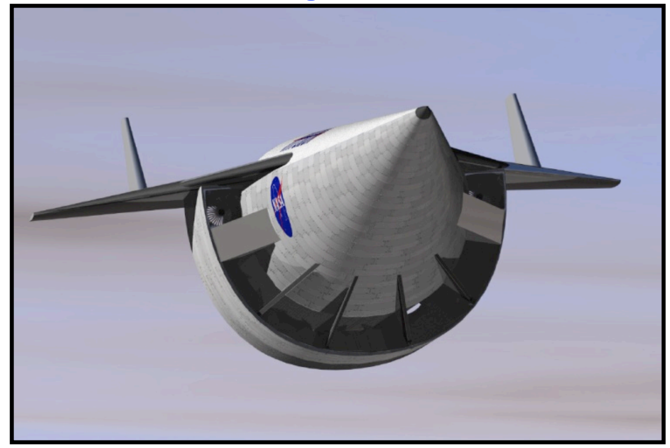
Hypersonic Vehicle Acreage TPS Options

Vehicle Trajectory Impact on TPS Needs

Re-Entry Vehicles

- Higher peak heating rates over shorter time periods
  - Yields higher surface temperatures
- Lower integrated heat loads
  - Vehicle thermal management systems typically not required
  - Vehicle cooling provided by ground support equipment soon after landing
- Mechanical / thermal loads out-of-phase

Trans-Atmospheric Vehicles



- Lower peak heating rates over longer time periods
  - Yields lower surface temperatures
- Higher integrated heat loads
  - Vehicle thermal management a critical consideration in vehicle design and operation
- Mechanical / thermal loads in-phase

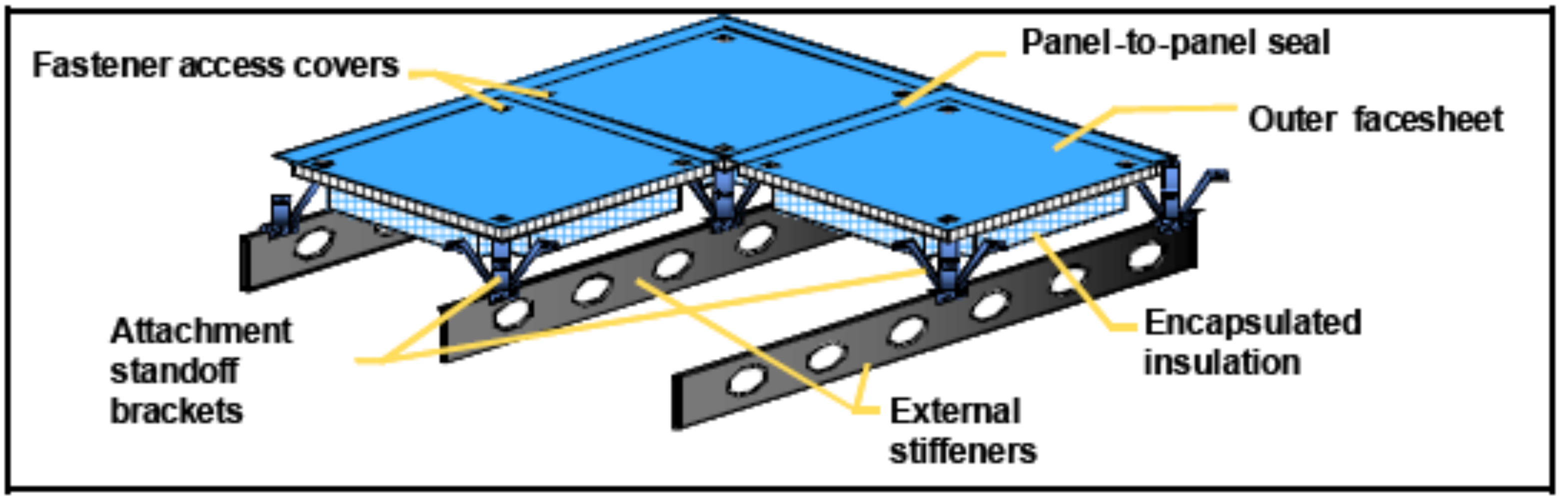
TPS Options – Vehicle Acreage*

- **Insulated Structure**
  - **Insulators (tiles or blankets) are attached directly to the cold structure to form the outer mold line (OML) of the vehicle**
    - Insulators are for thermal performance and transfer some aerodynamic (pressure only) loads to the inner structure, but no thermal loads
    - Inertial loads are carried by the internal vehicle structure
    - Example: Space Shuttle acreage TPS

*Glass, David E., "Ceramic Matrix Composite (CMC) Thermal Protection Systems (TPS) and Hot Structures for Hypersonic Vehicles," AIAA-2008-2682, 2008.

TPS Options – Vehicle Acreage*

- **Stand-off TPS**
  - **TPS system is "isolated" so aerodynamic (pressure only) loads and not thermal loads can be directly transferred to the internal vehicle structure**
    - Typically consist of more parts but can form an OML of a different contour than the internal vehicle structure
    - Insulation is required on the panel inner mold line (IML)
    - Example: X-33



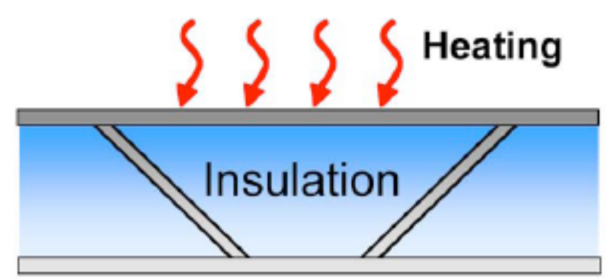
*Glass, David E., "Ceramic Matrix Composite (CMC) Thermal Protection Systems (TPS) and Hot Structures for Hypersonic Vehicles," AIAA-2008-2682, 2008.

Vehicle Trajectory and TPS

- **Vehicle Design Level**
  - Internal systems need to be thermally protected in a volumetric efficient manner
    - Vehicle design options
      - **Application of external insulation (i.e. insulated structure)**
      - **Less external insulation but additional internal insulation and / or thermal management systems**
  - Design option becomes insulating at the OML only <u>or</u> insulating at both the OML and at the individual internal systems?
  - Is there another option? Can you develop a method for insulation application that is <u>both structurally and volumetrically efficient</u>?
    - **This goal is the driver for NASA's SITPS development**
      - **The development of an advanced TPS that is <u>both structurally and volumetrically</u> efficient using high-temperature ceramic matrix composite and light-weight insulation materials**

TPS Options – Vehicle Acreage*

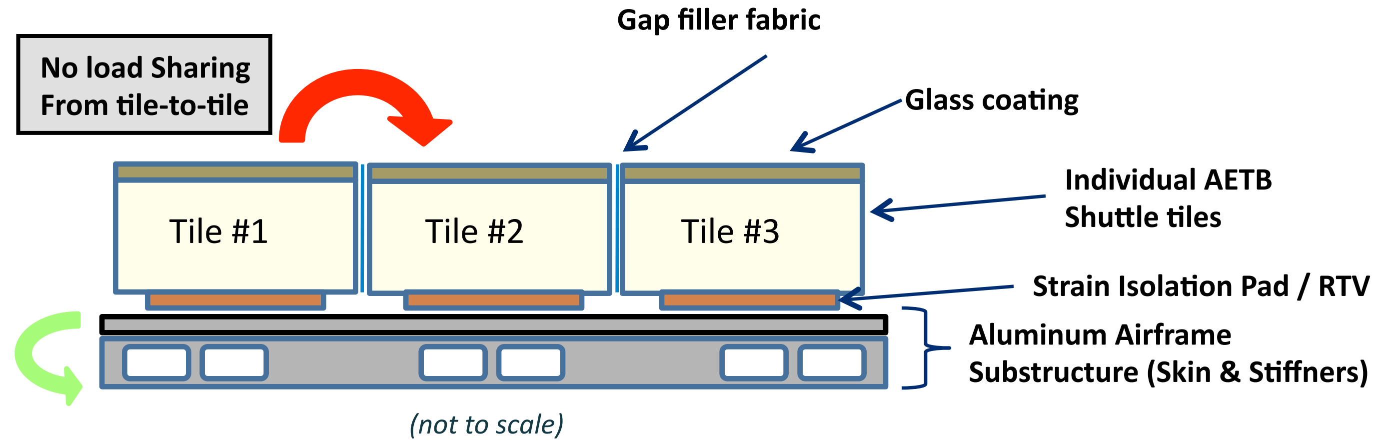
- **Structurally Integrated Thermal Protection Systems**
  - **"A TPS that has both an integrated (mechanical and thermal) load carrying capability and an ability to share mechanical loads with adjacent TPS structures"**
    - SITPS is designed to carry both aerodynamic (pressure & shear) and inertial loads
    - Outer and inner walls carry airframe loads, with outer wall operating hot and the inner wall insulated
    - For SITPS panels to be structurally efficient, mechanical loads (i.e. bending moments, shear, and torques) must occur across adjacent panels
      - If this does not occur, all panels behave as "simply supported," thus behaving like a stand-off TPS
    - Potential Benefits of SITPS
      - Lower weight TPS, higher structural efficiency
      - Larger panel sizes possible, fewer seals, reduced gaps, and lower parts count
      - More durable TPS, lower maintenance
    - SITPS Design Options
      - Sandwich (e.g. honeycomb, foam filled, etc.)
      - Hat-stiffened
      - Rib-stiffened shell
    - Example: None (low TRL technology)

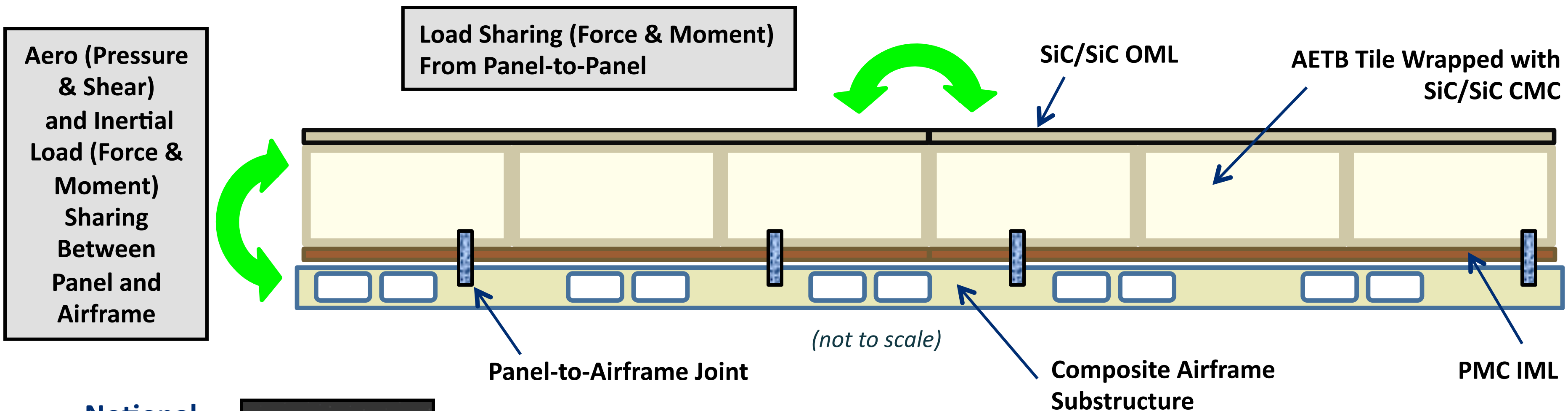


*Glass, David E., "Ceramic Matrix Composite (CMC) Thermal Protection Systems (TPS) and Hot Structures for Hypersonic Vehicles," AIAA-2008-2682, 2008.

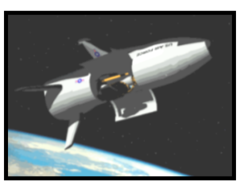
TPS Options – Vehicle Acreage Comparison

Space Shuttle





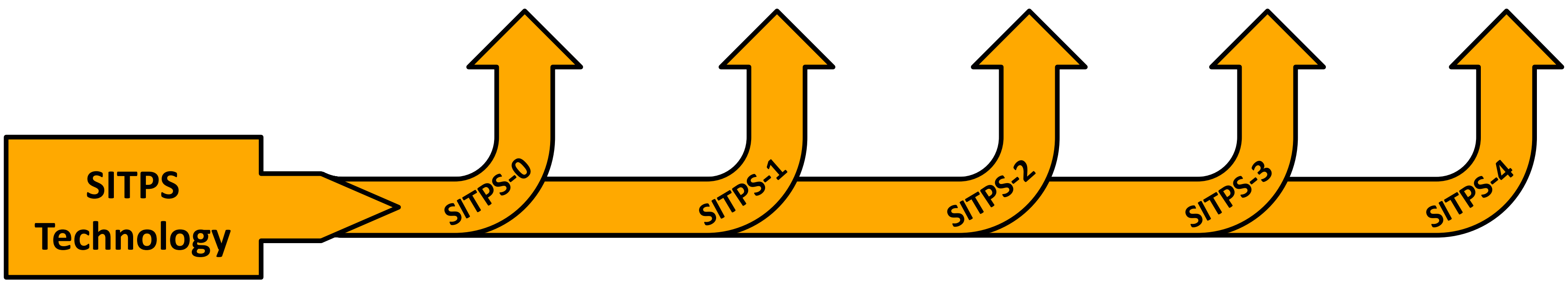
Notional Space Operations Vehicle



SITPS Roadmap

- **ARMD Hypersonics Materials & Structures (M&S) Approach**
  - Incrementally develop the required SITPS technology
  - Continually integrate and test SITPS technology as it becomes available
  - Document technology for future efforts

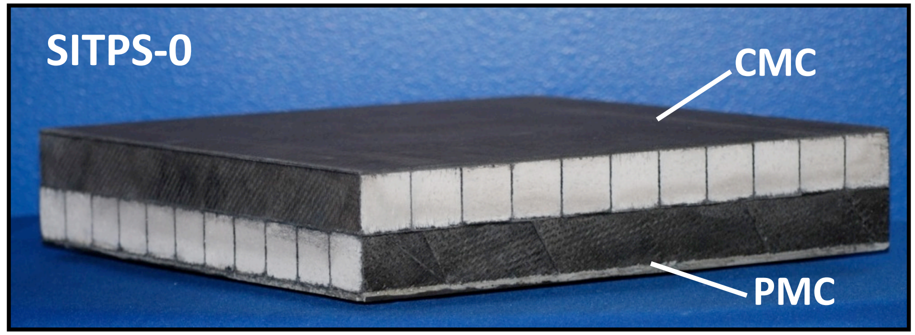
FY09				FY10				FY11				FY12				FY13			
Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4

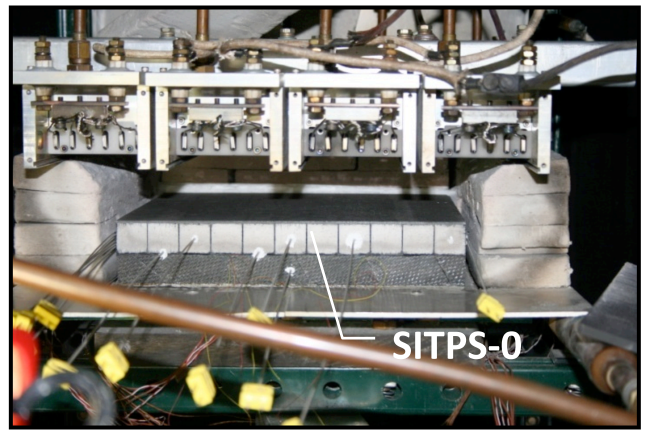


HYP M&S SITPS Development Effort: SITPS-0

SITPS-0 Overview
Manufacturing Demonstration Article

- **Goal**
  - Develop manufacturing capabilities (ATK-COIC)
- **SITPS-0 Details**
  - Panel has no detectable defects
  - 11.5 in. x 11.5 in. x 2.2 in. thick (approx.)
  - Insulation core – AETB 16
  - OML: S200H PIP SiC/SiC
  - IML: M55J/954-3 Cyanate Ester
  - Weight ~ 5.8 lb_m/ft^2
- **Panel is currently at NASA LaRC for thermal characterization testing**
  - Steady-state measurements of "through-thickness" effective thermal conductivity (K_{eff})
    - OML CMC side: isothermal conditions from 250°F to 2000°F
    - IML CE side: mounted to a water cooled plate
    - Pressure varied from 0.001 Torr to 760 Torr (10^{-6} to 1 atm)
  - Transient measurements
    - Simulated re-entry pressure and surface temperature profiles
    - Used to validate (1) the K_{eff} data collected and (2) validate the thermal model developed for SITPS-0





SITPS-0 in the LaRC Steady-State Thermal Test Apparatus

HYP M&S SITPS Development Effort: SITPS-1

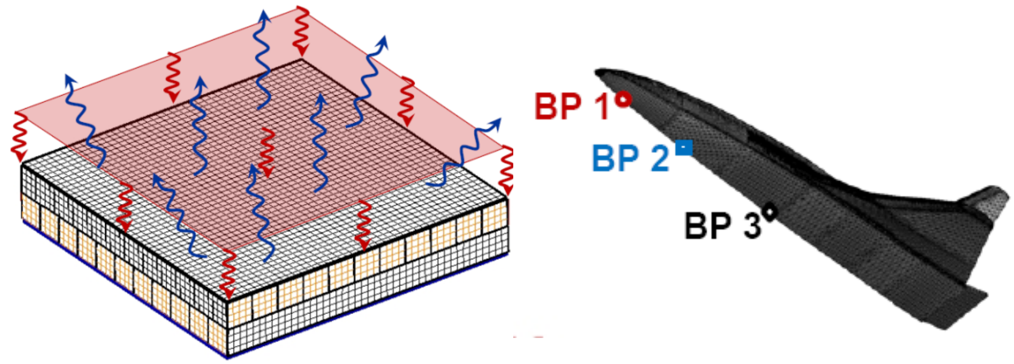
SITPS-1 Overview

- **Goal**
  - Scale-up the SITPS-0 manufacturing capability
  - Fabricate a panel for structural testing
    - Generate data to validate a model of the SITPS-1 concept
- **Process**
  - Optimize the SITPS-0 Design
    - Reduce the panel area weight – goal is approximately 3 lb_m/ft^2
    - Reduce the disparities between failure loads between the OML and IML materials
  - Address manufacturing issues with scaling up the optimized design to larger panel areas
  - Develop a database of SITPS material strength and thermal performance
- **Results – SITPS-1 Panel Design Based on Optimization of SITPS-0**
  - Thermal analysis of the SITPS-0 performance for NASA HRRLS re-entry trajectory
    - Switched from AETB-16 to AETB-8 to help reduce area weight
    - Modified the IML temperature allowables from 400°F to 600°F
    - Modified AETB “bar” sizes to reduce area weight
  - Structural analysis of the OML and IML to modify the ply layups to reduce the disparities between failure loads

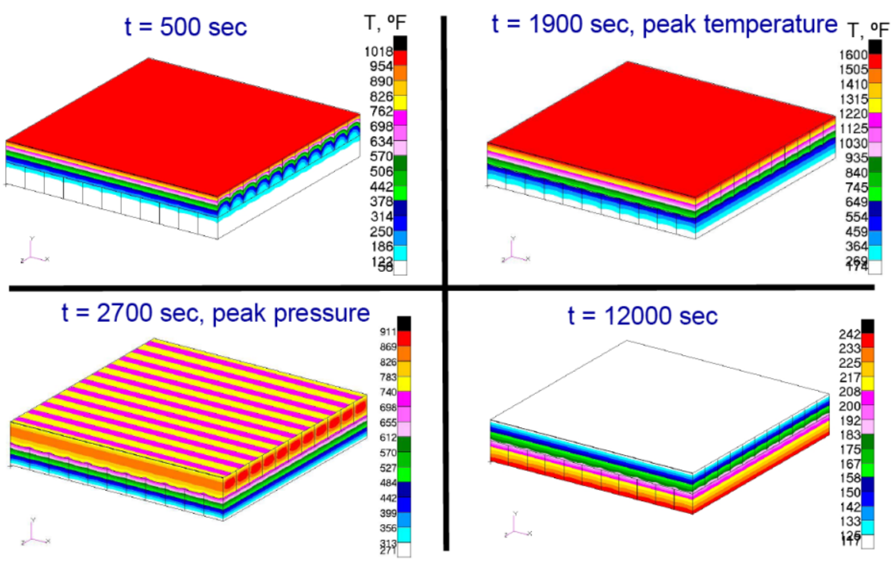
SITPS-0 Modeling*

Original Thermal Analysis

- **Original SITPS-0 configuration**
- **Boundary Conditions**
  - Uniform heat flux corresponding to a particular body point
  - Radiation to space
  - Insulated sides and bottom
- **Material Temperature Limit Criteria**
  - **PMC and bondline ≤ 400°F**



- **BP-2 maximum outer surface temperature ~ 1590°F**

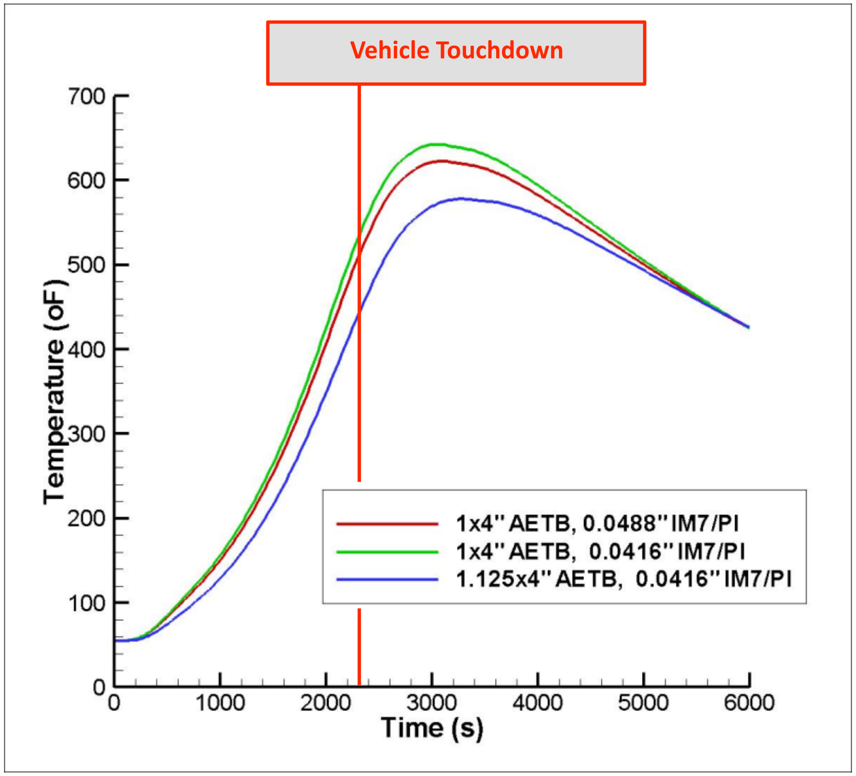


- **Concluding Remarks**
  - The SITPS concept was sized for HRRLS upper stage re-entry heating, resulting in overall insulation thickness of ~3.7, 3.25, and 3 inches at 10, 25, and 50% of vehicle length (respectively)
  - Thermal-stress analysis of the 3-inch thick panel indicates that the concept is viable at the fabricated panel scale

* Bey, K., Butcher, K., and Easler, T., "Fabrication and Thermal Analysis of a Structurally-Integrated Thermal Protection System Concept," 33rd Annual Conference on Composites, Materials, and Structures, Cocoa Beach, FL, Jan. 26-29, 2009.

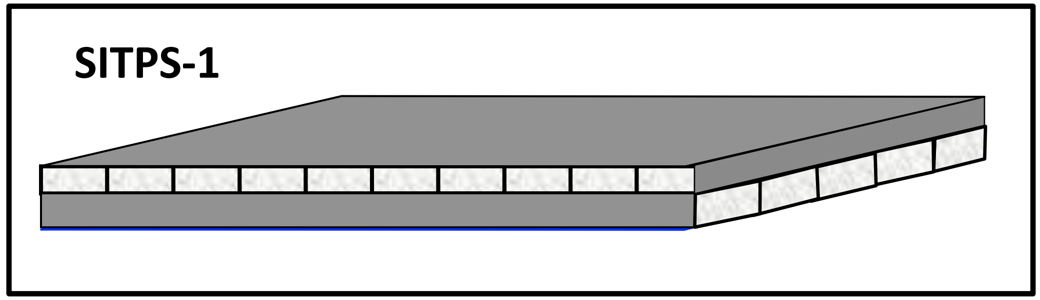
SITPS-1 Optimization
Thermal / Structural Analysis

- **SITPS analysis changes**
  - Switched from AETB-16 to AETB-8 to help reduce area weight
  - Modified the IML temperature allowables from 400°F to 600°F
  - Modified AETB "bar" sizes to reduce area weight
  - Laminate analysis resulted in tailoring the OML and IML ply layups to reduce the disparities between failure loads
- **"Optimized" SITPS-1 Design**
  - 4 plies of S200H as top facesheet
  - 2 layers (thicker and wider) of AETB-8 core / insulation (alternating directions)
  - 4 plies of T650-35/PI for the bottom facesheet
- **Area weight estimate = 3.1 lb_m/ft^2**



SITPS-1 Status

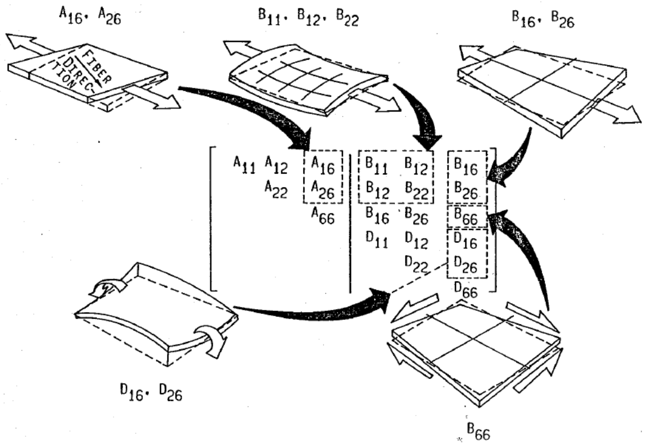
- **ATK-COIC to manufacture larger panel for structural testing**
  - 20 in. wide x 36 in. long x ~ 2.15 in. thick
  - Insulation core – AETB 8
  - OML: S200H PIP SiC/SiC
  - IML: T650-35 Woven Polyimide



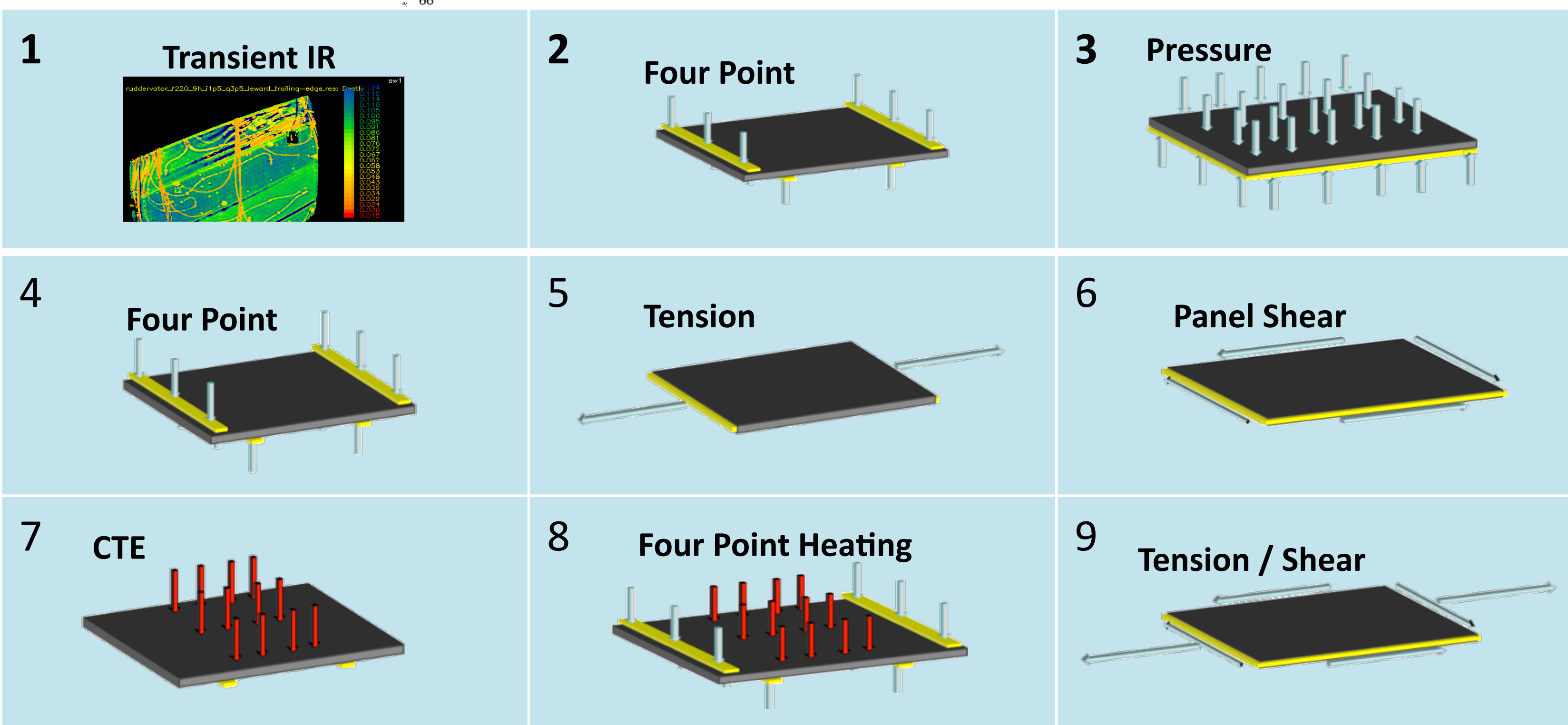
- **SITPS-1 panel fabrication initiated**
  - Numerous panel fabrication issues have been addressed by the team
    - Estimate panel fabricated January 2010
  - SITPS-1 to be structurally tested by September 2010
    - Currently working the design details of the structural tests
  - Material database for the SITPS-1 components to be completed September 2010
    - Materials will be available November 2009
    - Thermal / structural testing to be completed by September 2009 and will be posted on the HYP M&S CMC Wiki site

SITPS-1 Testing

Acquisition of Compliance Coefficient Information



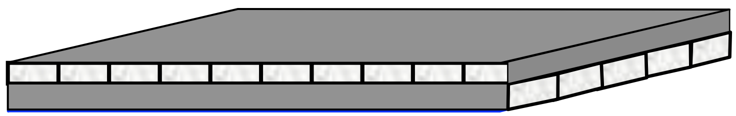
- Coupling Phenomena in the SITPS-1 design
  - In-plane normal loads produce in-plane shear and bending and twisting curvatures
  - Bending loads produce in-plane distortions as well as bending & twisting curvatures



SITPS Structural Test Plans

Current Effort

Single-Panel Characterization Tests
(Near-Term Goal)



Measured A, B, D compliance coefficients

M&S Vehicle Level Analysis

MDAO Analysis Using SITPS

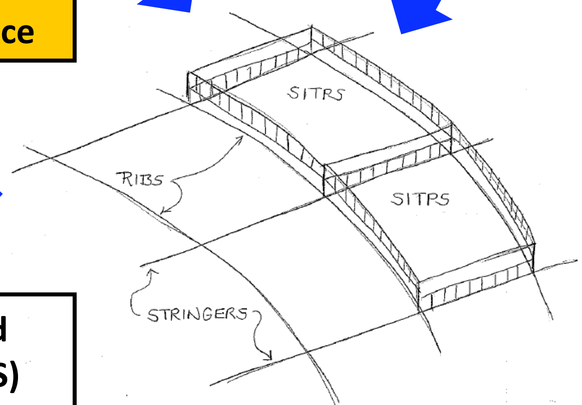
Future Effort

Multi-Panel Performance Tests
(Long-Term Goal)

M&S development of generic PtoP and PtoAS attachment option(s)

MDAO provides "vision vehicle" loads

M&S development of structural test methods to evaluate panel performance



- **Quantified effective load transfer (PtoP and PtoAS)**
- **SITPS overall performance**

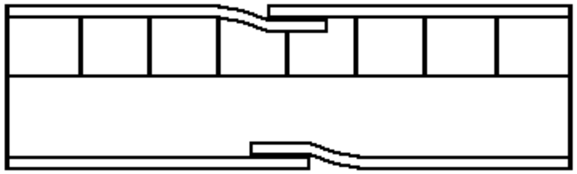
<u>Improved</u> M&S Vehicle Level Analysis

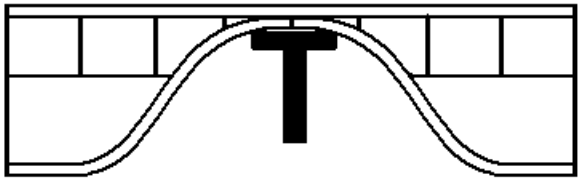
<u>Improved</u> MDAO Analysis Using SITPS

HYP M&S SITPS Development Effort: SITPS-2

SITPS-2 Overview

- **Goal**
  - SITPS-2A: Initiate the development of panel closeouts and panel-to-panel joints
  - SITPS-2B: Develop manufacturing capability for curved SITPS panels
- **Process**
  - SITPS-2A
    - Formulate panel-to-panel joint concepts that allow load and moment transfer between panels
    - Structurally test three sub-elements of potential joint designs
    - Down select to the most promising joint design for a larger panel development and testing
  - SITPS-2B
    - Address manufacturing issues associated with the fabrication of a large-scale SITPS panel with single-direction curvature
- **Results – SITPS-2**
  - Planning for SITPS-2A and SITPS-2B to begin in Oct 2009
    - Initiate the design discussion focusing on the development of SITPS-2A panel-to-panel attachment designs for

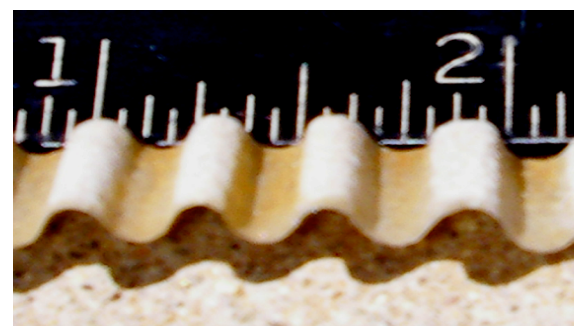


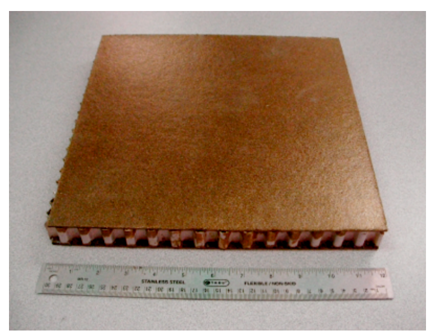


HYP M&S SITPS Development Effort: SITPS Alternate Cores

SITPS Alternate Core Overview

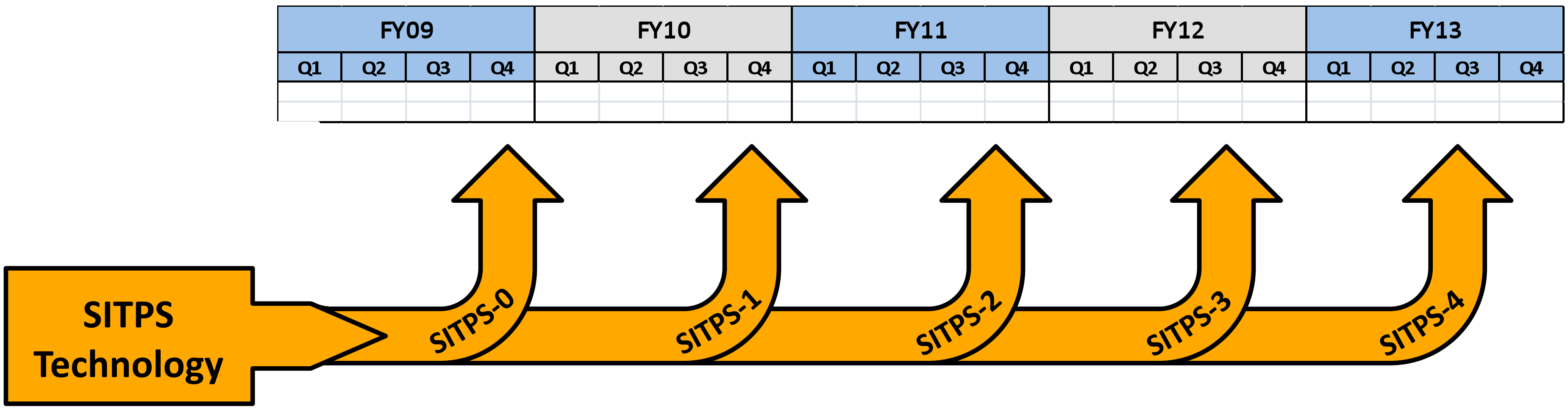
- **Goal**
  - Development of high-temperature core technology (i.e. honeycomb) for use with alternate SITPS designs
- **Process**
  - Identify core materials and evaluate the materials for potential honeycomb fabrication
  - Thermal / structural evaluation testing of candidate honeycomb sub-elements
  - Conduct analytical study to examine the different core geometries (i.e. wall thickness, shape, height, etc.) and its effect on core thermal / structural properties
    - Goal is to define the best core geometry for SITPS applications
  - Assess what material, core geometries, etc. that lend themselves to be scaled up to larger panels and ultimately vehicle use
- **Results – SITPS Alternate Cores**
  - Current NRA has been re-directed to focus on SITPS requirements





Conclusions

Conclusions



- **NASA HYP M&S is pursuing the development of SITPS**
  - Working with HYP MDAO to formulate methodology to incorporate SITPS into hypersonic vehicle design trades
  - SITPS-0 to SITPS-1 (FY10)
    - Manufacturing development and weight reduction (5.8 to 3.1 lb_m/ft^2)
    - Structural testing to mature SITPS model
  - SITPS-2 (FY11)
    - Focus on panel closeout, panel-to-panel load transfer, and panel curvature
  - Extend fabrication technology to include alternate cores and insulations (FY12)