THE BLOCK-ABLATOR-IN-A-HONEYCOMB HEAT SHIELD ARCHITECTURE OVERVIEW

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ABSTRACT

An atmospheric-entry heat shield architecture is presented that employs cured ablator blocks bonded into a structural honeycomb lattice. This architectural approach provides the flexibility to tailor the distribution of thermal protection materials; both, over the surface area of the vehicle, and at depth. This approach may provide higher atmospheric entry reliability due to the structural attachment integrity provided by the honeycomb lattice in the ablative material layer. The architecture is described using the NASA Orion Crew Module's 5.0m diameter heat shield configuration as an example case. In general, this architecture has broad potential application for future missions that involve large-vehicle entries into planetary atmospheres.

1. INTRODUCTION

The primary challenge faced by thermal protection system (TPS) designers for relatively large (>3m diameter) atmospheric entry vehicles is to provide reliable protection for the crew or payload, within a limited fraction of the available vehicle mass. This fundamental trade between reliability and mass often raises the TPS to the top of space vehicle development risk list. This is especially the case when human occupants are involved with the vehicle entry since TPS is a sub-system that usually has no redundancy for failure.

The development of heat shield preliminary designs for the 5.0m dia. Orion Crew Module (CM) provided an opportunity to consider alternate architectures for the thermal protection material (TPM) layer. A three-year Advanced Development Project (ADP) for the Orion heat shield was led by NASA Ames Research Center from 2005 to early 2009. This ADP was tasked with developing the preliminary designs for a primary and alternate heat shield to accommodate both lunar-return and low-earth-orbit atmospheric entries. The block-ablator-in-a-honeycomb heat shield architecture was conceived and considered for use on Orion during early system design trades. Subsequently, two "flight-proven" TPM solutions were selected for the Orion CM (Fig. 1). The block-ablator-in-a-honeycomb heat shield architecture was provided resource support for a technical feasibility study to determine if the approach had merit for future applications.

This paper presents how block-ablator-in-a-honeycomb heat shield architecture was conceived, how it was envisioned for the Orion CM, and how it could be adapted for future mission applications. A case is made for the perceived strengths of the architecture relative to the current state-of-the-art. A description of the work accomplished to establish the feasibility of the architecture is provided, along with a description of current work that is underway.

Fig. 1. Orion Crew Module with Heat Shield

2. THE CHALLENGE OF THERMAL PROTECTION MATERIAL INTEGRATION

TPM materials capable of protecting entry vehicle from the heating environment in a mass-efficient way are relatively low in density and robustness. This results in the TPM layer rarely being counted on as a structural strength element. It is most often viewed as a component that is "along for the ride" with a singular requirement to protect the vehicle during entry. This lack of TPM layer robustness also necessitates extensive processes to avoid and identify structural damage. It also makes the integration of the TPM layer on the vehicle a significant challenge.

The thermal protection material (TPM) layer must be integrated with a space vehicle in a way that provides reliable attachment through all phases of the mission, from launch to post-entry landing. Some of the key forces challenging the TPM layer attachment integrity include:

- static deflections caused by aerodynamics, vehicle element separations, and other mission operations
- thermal expansion/contraction of vehicle components during entry and other the mission phases
- vibrations during launch and other mission phases
- off-nominal events during the mission such as impacts, severe accelerations, high local heating

Assuring TPM attachment integrity for the full spectrum of load cases is accomplished with a combination of sound design practices, testing, and verification methodology. Two successful Earth-entry vehicles that provide important lessons for TPM layer attachment assurance are the Apollo crew module (CM) and the Space Shuttle Orbiter.

The Apollo CM heat shield [1], capable of a single lunar-return Earth entry, employed a mid-density ablative TPM supported in a structural honeycomb lattice (Fig. 2). This TPM layer was realized by first bonding the honeycomb to the vehicle hard external surface. Attachment integrity was then verified by pull testing the honeycomb lattice at many locations over the heat shield surface. Uncured TPM was then packed into the ~1 cm diameter honeycomb cells (Fig. 3) and the assembly was cured in a large oven. The final vehicle shape was then obtained by removing residual TPM material to the desired external geometric coordinates. This TPM-in-a-honeycomb architecture provided a robust solution to the challenge of attachment, and attachment verification. Each small cell of TPM was well supported in a flexible structural lattice that had been pull tested to confirm attachment to the vehicle. The primary challenge with this architecture is the labor-intensive, time constrained, manual filling of each honeycomb cell; and the challenge of assuring that no voids or ablator material property variations are present after curing of the entire heat shield in an oven.

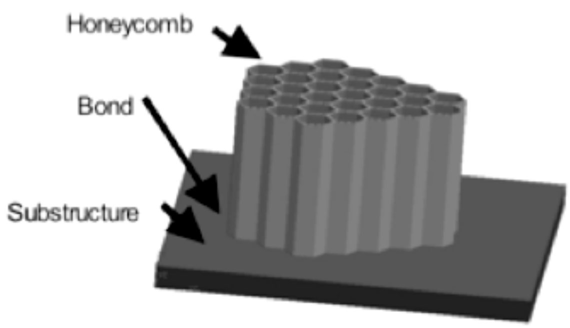

Fig. 2. ~1 cm Diameter Cell Honeycomb Bonded to the Apollo Substructure Prior to Filling

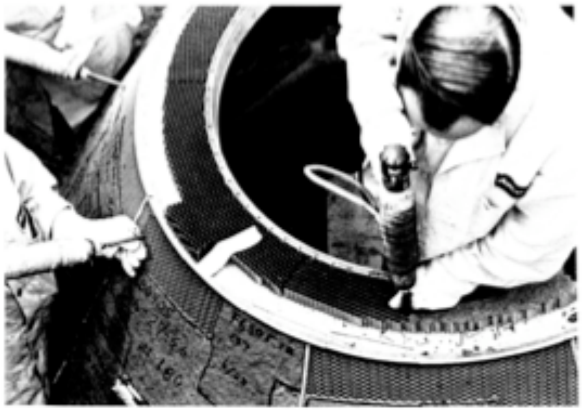

Fig. 3. Uncured Ablator Being Packed into ~300,000 Honeycomb Cells on the Apollo CM

The Space Shuttle Orbiter heat shield [2], capable of multiple low-Earth-orbit-return entries, employs ceramic tiles bonded to the vehicle (Fig. 4). The tiles are bonded to a strain isolation pad (SIP), which is then bonded to the vehicle's hard surface. A gap is maintained around each tile to allow for deflections and thermal expansion. This gap is filled with a compressible material that rejects hot flow in the gap, while not exerting loads on the tiles that could damage them. This floating-TPM-tile-with-flexible-gap-filler architecture also provided a relatively robust solution to the challenge of attachment, and attachment verification. Each TPM tile is structurally isolated from both adjacent tiles, and the vehicle hard surface. The tiles are also pull-tested to verify the integrity of tile-to-SIP, and SIP-to-vehicle bonds. The primary integration challenge with of this type of architecture is assuring that stresses do not build up in the tiles to a level that causes failures that lead to hot gas ingestion.

Fig. 4. Ceramic Tiles Being Mounted on the Shuttle Orbiter

3. THE ORION CREW MODULE HEAT SHIELD

The Orion CM was conceived with a requirement to survive a lunar-return ballistic entry back to Earth. A Thermal Protection System (TPS) Advanced Development Project (ADP), led by NASA Ames Research Center, was assigned responsibility for identifying a preliminary design for the vehicle's primary heat shield in late 2005. NASA's objective was to assemble the limited thermal protection system expertise across the agency, and industry, to tackle this significant design challenge. No comparable heat shield design effort, from a vehicle size and severity of environments standpoint, had been undertaken since Apollo, about 4 decades ago.

The Orion heat shield can be simply described as a 5 meter diameter shallow bowl comprised of a section of a sphere with a relatively abrupt shoulder (Fig. 1). This heat shield attaches to the "aft" end of the capsule and is oriented on the windward side during entry into the atmosphere. It experiences the most severe heating and heat loads on the vehicle. Heating occurs at the surface of the heat shield due friction generated as the vehicle encounters the atmosphere at high speeds. Heat load is used to describe the accumulation of energy in the heat shield as the vehicle is exposed to the heating over the duration of the entry. For example, a very steep, high-speed entry can result in high heating and a low heat load due to the short duration of the entry. Conversely, a shallow, longer duration entry can result in lower relative heating with a greater heat load. The heat shield must be designed to withstand both peak heating and the exposure to a heat load.

A limited timeframe to define a heat shield design, combined with a relatively limited budget allocation, necessitated an ADP focus on the TPM architectures with a flight heritage and an established industrial manufacturing base. The search was thus on for a heat shield design with a high technology readiness level (TRL), a 10-point scale used by NASA to measure the maturity of technology applied to missions. This narrowed the focus of the design team to TPM solutions that had flown on recent planetary missions and those that form the heritage of manned spaceflight. The field of solutions was also focused on ablative thermal protection systems, where the exposed materials are consumed in the process of protecting the vehicle from entry environments. Re-usable TPM architectures, like the ceramic-based tiles used on the Space Shuttle Orbiter heat shield were determined to be either incapable, or at too low of a TRL level to satisfy the lunar-return requirement.

The TPS ADP converged on two heat shield TPM architectures with a high potential to satisfy the Orion CM requirements. The first architecture employed Phenolic Impregnated Carbon Ablator (PICA) panels attached to the heat shield sub-structure using SIP material in a manner similar to what was done with Shuttle tiles. This architecture requires some mechanical isolation between the discrete tiles to address thermal expansion/contraction, as well as heat shield surface deflection loads. This isolation is possible with structurally compliant gap fillers that provide adequate thermal protection. The flight heritage for the PICA material came from the successful Stardust heat shield atmospheric entry.

The second TPM architecture chosen was essentially the heritage Apollo heat shield solution. This approach provides a "monolythic" solution without gaps that must be filled. It also has an embedded structural lattice in the form of a phenolic honeycomb that is attached directly to the heat shield sub-structure in a manner that provides direct attachment verification. The honeycomb also provides flexibility to accommodate thermal expansion & contraction, and surface deflection loads with a much lower concern about ablator cracking or delaminating. The challenges faced by these two architectures were described in Section 2.

4. DESCRIPTION OF THE BLOCK-ABLATOR-IN-A-HONEYCOMB HEAT SHIELD ARCITECTURE

As is often the case when two capable options are being explored, a solution can be constructed between the two that employs the advantages of both, while also eliminating some of the disadvantages of both. Unfortunately, this hybrid cannot fully claim the heritage of its parents and must be evaluated as a new, unproven system. This situation occurred with the identification of the block-ablator-in-a-honeycomb heat shield architecture during the TPS ADP. The purpose of this paper is to present this new TPM architectural option and efforts to obtain the technical evidence necessary to raise the TRL of this approach.

The block-ablator-in-a-honeycomb approach [3] employs pre-inspected blocks of fully cured TPM bonded into a large-cell honeycomb structural lattice. This architecture has the potential to provide a structurally robust, monolithic TPM layer in a way that allows for attachment integrity verification. It also enables tailoring of the TPM over the surface of the vehicle to match predicted entry environments. The architecture, as envisioned, could be both lighter weight and easier to manufacture than the current state of the art. Of course, these claims must be supported by sound technical evidence.

Using the Orion CM heat shield as a test case, a block-ablator-in-a-honeycomb configuration was defined that could be used for comparative purposes and to uncover unknown technical issues with the approach. The narrative below explains the steps that led to the heat shield TPM configuration presented in this paper.

4.1 Honeycomb Configuration

The honeycomb used for this new architecture must serve as a structural lattice, holding uniformly shaped, pre-cured ablator blocks in position. The solution employs faceted TPS attachment surfaces as shown in Figure 5. Each facet provides a flat surface to attach un-deflected, empty honeycomb panels (Fig. 6). Un-deflected honeycomb cells allow the use of standardized TPM blocks with a flat bottom surface. Unfilled, flexible honeycomb "wrapped" around curved surfaces (Apollo approach) prior to insertion of the TPM results in complex cell internal volumes and negates a key manufacturability advantage of this architecture. Note that the figure shows a shoulder consisting of straight cylindrical sections. These shoulder segments will also have a uniform foundation that employs standard TPM block shapes.

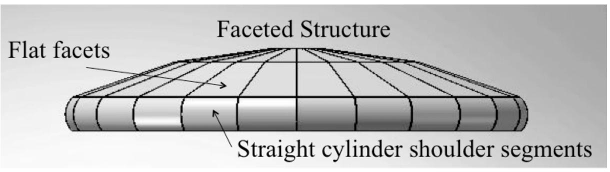

Fig. 5. Faceted TPS Attachment Surface

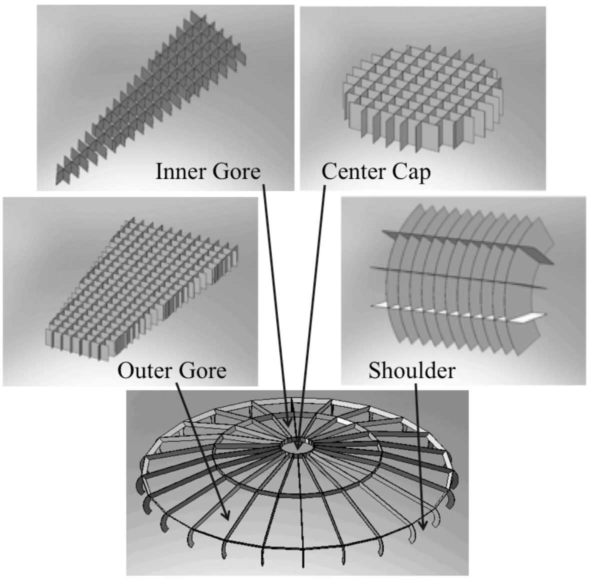

Fig. 6. Empty Honeycomb Panels with ~5 cm Cells

Facet frames, made of the same material as the honeycomb, will ring each facet and form a transition to adjacent facets. Figure 7 shows an exploded view of a heat shield assembly. Heritage heat shield TPS designs that employ honeycomb bond the empty honeycomb to the TPS attachment substrate with high temperature adhesives. This then allows for a critical TPS attachment verification pull-test prior to TPM insertion.

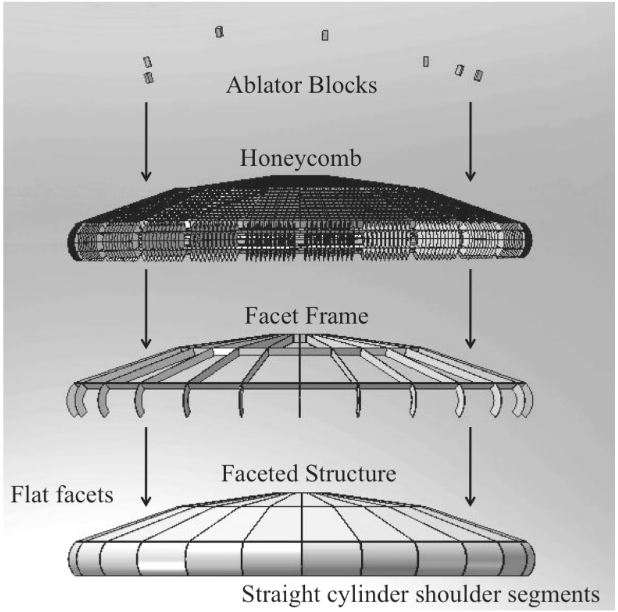

Fig. 7. Exploded View of Heat Shield Assembly

The assembled heat shield depicted in Figure 8 represents the Orion Crew Module maximum diameter of 5.0 m with honeycomb cell sizes of roughly 5 cm by 5 cm. This is the "pallet" that the TPS designer will use to tailor a solution for the predicted atmospheric entry environments for the vehicle mission. Cured TPM blocks with varying materials, densities, and in-depth compositions can be distributed over this surface as required to optimize mass and thermal performance.

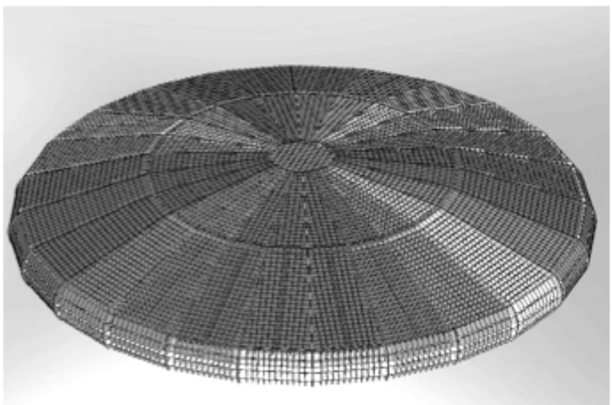

Fig. 8. Assembled Block-ablator Heat Shield

4.2 Honeycomb Cell Size and Shape

The size of the honeycomb cells chosen to evaluate the feasibility of the block-ablator architecture was driven primarily by the desire to have a practical block size for fabrication and testing. The authors acknowledge that the honeycomb cell size should be optimized to provide structural strength or thermal performance advantages for mission applications. For feasibility purposes, a key dimension of 5.1 cm (2 inches) was chosen to allow a full honeycomb cell to be evaluated in standard arc jet thermal test samples at NASA Ames. A drawing of a stagnation and shear test coupon are shown in Figure 9.

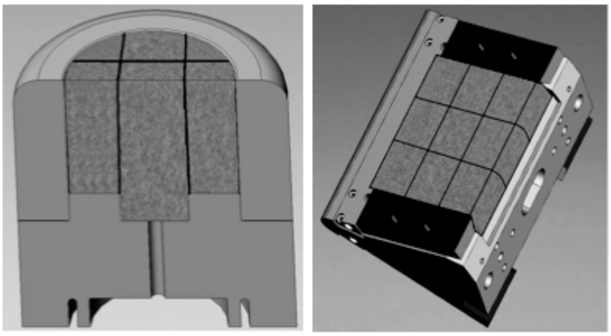

Fig. 9. Stagnation (left), and Shear (right) Arc Jet test Coupons - Note that the stagnation coupon is a ½ cross-section view.

A square honeycomb cell shape was chosen for feasibility assessment purposes. This decision was made after a search for commercially available "large-cell" honeycomb sheets yielded no suppliers. It became clear that custom honeycomb would need to be built and a square-cell configuration was thought to be easier to fabricate. Square cells also resulted in a simpler ablator block shape that could be cut to fit the flat honeycomb panel edge interfaces. The "cylindrical" shoulder honeycombs would also be custom fabricated with flat sides and a circular arch in one dimension. These standardized blocks are described in the next section.

4.3 Ablator Blocks

Four standard TPM block shapes are envisioned for this embodiment of the block-ablator architecture. Two will be the majority of the blocks used on the "acreage" and shoulder of the heat shield (Fig. 10). These blocks have a nominal dimension of 5 cm by 5 cm by the depth of TPM required. The other two blocks shapes are roughly twice as wide (nominally 10 cm) versions of each of the nominal blocks shown in Figure 10, and represent blocks that can be cut to fit the transition cells between the honeycomb panels. These modifications to standard blocks are expected to be simple, oblique cuts and represent approximately 20% of the total blocks on a heat shield as envisioned in Figure 8. Figure 6 illustrates how the honeycomb panels can be tailored, by removing honeycomb cell walls, to avoid blocks cut into small slivers. Figure 11 illustrates how the blocks would be bonded into the honeycomb.

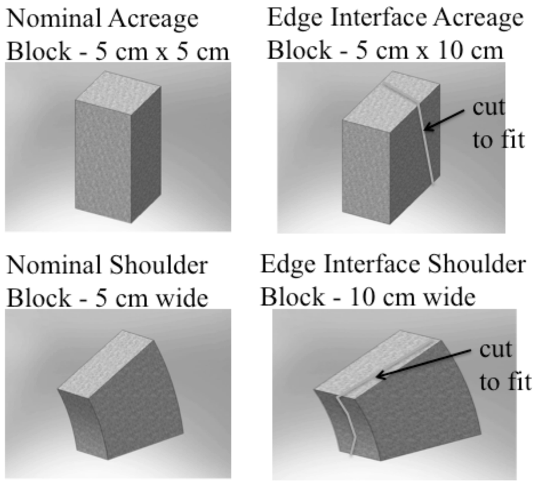

Fig. 10. Ablator Block Configurations

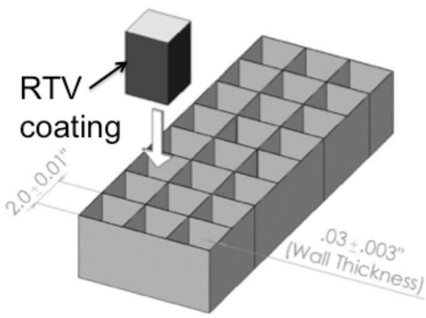

Fig. 11. Ablator Block Bonding into Honeycomb

4.4 Heat Shield TPM Layer Assembly

The block-ablator heat shield assembly is envisioned as follows:

1. Prepare the facetted heat shield substructure for honeycomb attachment.
2. Bond the honeycomb facet frames into position.
3. Cut and bond the center cap, inner gore, outer gore, and shoulder honeycomb panels between the facet frames.
4. Pull test the honeycomb and facet frames to confirm desired attachment strength.
5. Prepare the substructure and honeycomb surfaces as required for ablator block insertion and bonding.
6. Coat the standard ablator blocks and/or cell internal surfaces with bonding agent.

7. Bond the standard ablator blocks into the common flat surface and shoulder cells.
8. Cut and fit the facet edge blocks as required.
9. Bond the facet edge blocks into the honeycomb.
10. Machine the heat shield surface to the desired outer mold line shape.

5. GATHERING OF TECHNCIAL EVIDENCE TO SUPPORT THE ARCHITECTURE

Several key questions were raised by experts in the field of thermal protection systems with regard to the block-ablator approach. Answering these questions was the goal that drove the feasibility efforts following the architecture conception.

Key Questions

1. Can "large-cell" honeycomb be fabricated with a uniform cell geometry that allows the use of standard-geometry ablator blocks?
2. Can the TPM blocks be inserted into the honeycomb for bonding in a reliable fashion?
3. Will the block-ablator-in-a-honeycomb TPM layer have comparable thermal protection performance in arc jet tests to uniform (no honeycomb) ablator coupons?
4. Will the honeycomb recede at a similar rate to the ablator material (i.e. without fencing due to slower recession or gaps due to faster recession)?
5. Can panels of honeycomb on a heat shield surface and shoulder section be filled and machined to a desired surface shape?
6. Will the block-ablator-in-a-honeycomb TPM layer have comparable or improved structural performance in coupon bend tests to uniform (no honeycomb) ablator coupons?

Answering some of these Key Questions (3, 4 & 6) was made easier because the Orion Crew Module TPS ADP established the benchmark TPM material test designs and obtained results for the uniform ablator case. The ADP sponsored the fabrication of TPM demonstration panels that employed similar machining challenges (Key Question 5). The ADP also conducted trade studies on bonding agents and the thermal-structural performance of bond seams that helped guide decisions about the block-ablator architecture for feasibility assessment.

A contract with Applied Research Associates (ARA) Ablatives Laboratory was established in May of 2008 to evaluate the feasibility of the architecture. This one-year duration contract involved focused trade studies, test coupon fabrications, demonstrator panel fabrications, and test executions with the final focus on an overall architecture feasibility assessment report. Reference 4 presents an overview of this feasibility study and the preliminary test results.

ARA began the contract with a focus on designing and fabricating a ~5 cm cell honeycomb suitable for use with two mid-density ablator materials (PICA and Phencarb 28) evaluated during the early phases of the TPS ADP. ARA has built honeycomb with smaller cell sizes for filling with uncured ablator material and employed this experience in their solution. The novel, "trapezoidal" cell, honeycomb ARA designed and built for the block-ablator architecture fulfilled the requirement for uniform cell geometries. ARA fabricated the honeycomb using a silica-based fabric and resin combination with applications in previously tested ablative systems. A photo of an empty trapezoidal cell honeycomb segment is shown in Figure 12. The segments shown are approximately 5 cm thick. The photo also shows trapezoidal ablator blocks (Phencarb) inserted into the honeycomb for fit checks (un-bonded). Note that the honeycomb cell wall thickness is approximately 0.05 cm.

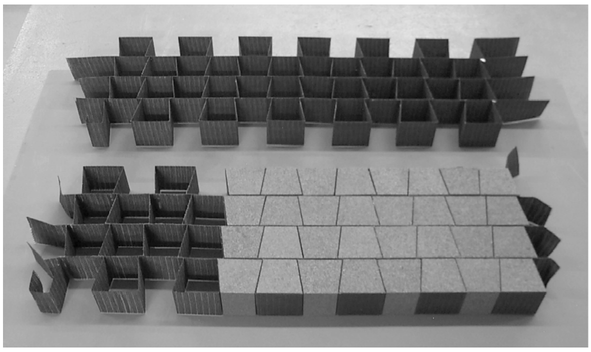

Fig. 12. Trapezoidal-cell Honeycomb

With a honeycomb configuration defined (Key Question 1), the feasibility study effort moved to the fabrication and testing of thermal performance coupons for testing in the NASA Ames arc jet facilities. ARA bonded trapezoidal ablator blocks into the honeycomb using RTV-560, a commercially available high-temperature adhesive used for many past and present heat shield TPS applications. Tests were performed to evaluate bonding of the ablator blocks into the honeycomb. These tests defined the correct RTV uncured viscosity to avoid wiping off the bonding agent during block insertion (Key Question 2). These tests showed that surface roughness and porosity in the honeycomb cell walls provided a beneficial feature for bonding of the blocks by holding the uncured RTV in place.

Using test coupon designs employed during the TPS ADP, ARA was able to employ existing test support equipment and test planning documentation. Figure 13 shows the resulting 5-inch diameter stagnation coupons, and the "swept-cylinder" shear performance coupons [4] that were fabricated for tests in the arc jet at conditions comparable to TPS ADP testing done on uniform-ablator coupons without honeycomb.

Fig. 13. Stagnation and Shear Arc Jet Coupons (PICA)

Exploratory arc jet tests were conducted in April 2009. These architecture feasibility test results indicated ablator recession rates and in-depth temperature profiles comparable to what was observed without honeycomb in earlier testing (Key Question 3). There was also no evidence a problem with differential recession between the honeycomb and ablator for the conditions evaluated (Key Question 4). More details about these tests are presented in Reference 4.

The next challenge was to fabricate some demonstration panels to show that the concept could be built for large-scale applications. The contract called for the construction of a 60 cm by 60 cm flat panel (144 cells), and a roughly 30 cm by 40 cm shoulder panel (40 cells). These panels were bonded to metallic substrates that were representative of a heat shield substructure. ARA chose to attached the honeycomb to the metal substrates with HT-424 adhesive paste using a process they have employed on past projects. Figure 14 shows the resulting flat panel with a machined top surface. Figure 15 shows the resulting shoulder panel demonstration. These demonstrations showed that the shape of the block-ablator–in-a-honeycomb architecture top surface could be machined to match the curvature of a heat shield section as required (Key Question 5).

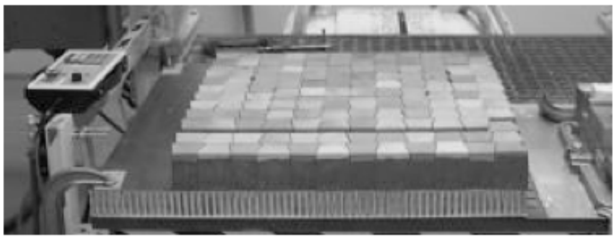

Fig. 14. Acreage Panel Demonstration (PICA)

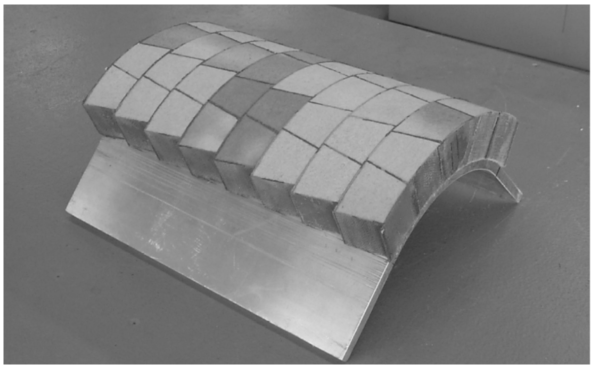

Fig. 15. Shoulder Panel Demonstration (PICA)

The next phase of the feasibility contract was to fabricate structural bend test coupons that would be tested at NASA Langley Research Center (LaRC) using the same test technique employed during the TPS ADP. These coupons have a 15 cm by 75 cm, 1.3 cm thick, aluminium plate substrate that is compatible with a 4-point bend apparatus in the LaRC structural test lab. The ablator panel is approximately 15 cm by 40 cm and is attached to the substrate using the same process employed for the demonstration panels described above. Figure 16 is a photo of the six structural test coupons tested at LaRC.

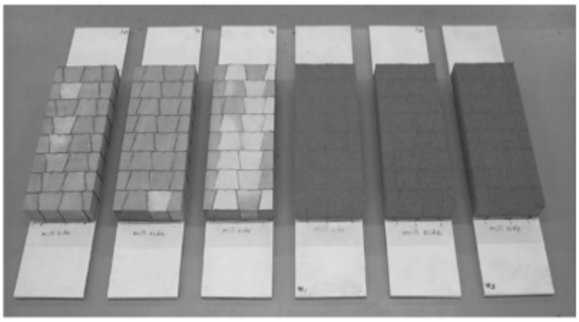

Fig. 16. Structural Test Coupons (3 PICA, 3 Phencarb)

The structural test coupons were deflected to curvature levels similar to what was used during TPS ADP tests of uniform ablator (no honeycomb) panels. Test results showed some localized cracking of the ablator blocks within a cell, however did not show any large scale cracks running across the coupon (Key Question 6). The ablator eventually separated from the aluminum plate at the free ends, as expected. This structural feasibility test result showed that the segmented ablator worked to remove almost all of the contribution of the TPM layer to the overall bending stiffness. This flexibility means that the TPM layer has a good chance to be integrated in way that does not cause a build-up of high stresses in the ablator material. It is also interesting to note that the local damage within a cell did not result in any large, open gaps that could result in the ingestion of hot gases during atmospheric entry.

6. DISTRIBUED AND DUAL-LAYER TPS

It was stated in Section 3 that the block-ablator-in-a-honeycomb architecture enables tailoring of the TPM over the surface of the vehicle to match predicted entry environments. This involves distributing ablator blocks, for example with varying density, into the honeycomb to match local peak-heating and heat-load levels. Realizing this architectural advantage will involve selecting honeycomb and ablator materials that are compatible and distributing them over the surface of an envisioned entry vehicle. These material selections and distributions will need to be verified with a wide range of analytical and testing methods to assure that the vehicle will be protected through the full spectrum of entry environments. Of particular concern is the possibility of differential ablation at ablator-to-ablator boundaries; and, dealing with the ablator-to-ablator thickness variations.

Another flexibility that the block-ablator-in-a-honeycomb architecture enables is the tailoring of the TPM in-depth to match predicted entry environments. This concept (US patent pending) involves using blocks that consist of multiple layers of ablators; or, an ablator layer with a lightweight insulator material layer (Fig. 17). The ablator-over-lightweight insulator block concept has analytically been shown to have significant mass advantages over a traditional, through-the-thickness ablator approach. Reference 5 presents analytical and experimental work that is underway to evaluate this TPS option for a large Mars vehicle entry heat shield. Structural bend coupons employing dual-layer blocks are shown in Figure 18.

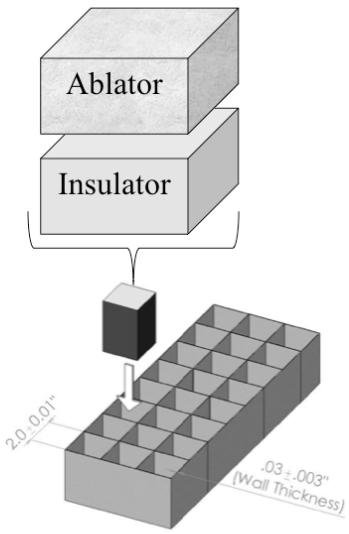

Fig. 17. Dual-layer Block Insertion

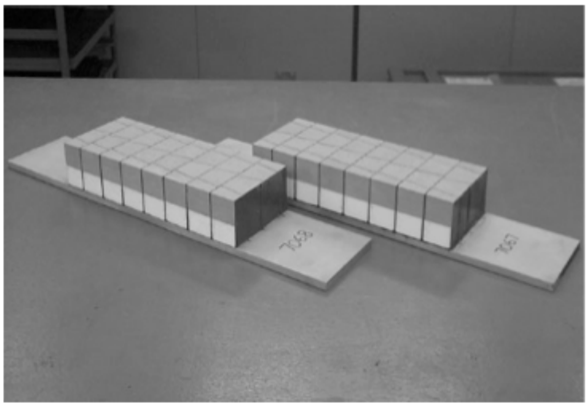

Fig. 18. Dual-layer Structural Bend Coupons (PICA over LI-900 ceramic insulator)

7. CONCLUSION

This paper has presented the origination of, and technical evidence gathered to date for, the block-ablator-in-a-honeycomb TPS architecture. The architecture is illustrated as it could be applied on the Orion Crew Module's 5.0-meter heat shield. Technical evidence presented from coupon tests indicates that the architecture has thermal/structural performance and manufacturing/vehicle integration advantages that make it a feasible solution to consider for future entry vehicle missions. Future work on the architecture will enable the ability of TPS designers to tailor the heat shield design over the surface of the vehicle, and in-depth through the TPM layer. This is a significant departure from the current state-of-the-art; which typically employs single ablative materials, distributed over large areas and through the thickness, serving as both an ablator and as an insulator.

8. ACKNOWLEDGEMENTS

The authors wish to acknowledge the TPS ADP team that established most of the testing methodology, TPM materials, and background data used for this investigation. The TPS ADP team also spent many hours evaluating challenges involved with integrating this layer of complex material that serves as a critical barrier between the vehicle, and the incredibly harsh environments of atmospheric entry. Their work was the inspiration behind this TPS architecture. The TPS ADP also provided principle funding for the feasibility study contract to explore this solution for future mission applications.

The authors also wish to acknowledge a group of summer interns that contributed to the illustrations, analysis, testing, and general improvement of the architecture. They include: Kristen John, Jessica Juneau, Brandon Smith, Austin Howard, and Kellie

Norton. The technical team at ARA also deserves a focused acknowledgement for their creativity developing both the trapezoid honeycomb, and the process to bond the ablator blocks into the honeycomb.

The NASA Ames (TS) Space Technology Division deserves acknowledgement for their support of this TPS technology; in particular, by providing arc jet test services and the support of the thermal protection material lab to prepare test specimens. The NASA Langley team that performed structural tests of the concept is also acknowledged for their focused and timely efforts.

9. ABBREVIATIONS AND ACRONYMS

ADP Advanced Development Project
ARA Applied Research Associates
ARC NASA Ames Research Center
CM crew module
H/S heat shield
LaRC NASA Langley Research Center
NASA National Aeronautics and Space Administration
SIP strain isolation pad
TPM thermal protection material
TPS thermal protection system
TRL technology readiness level

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