THERMAL PROTECTION MATERIALS AND SYSTEMS AT NASA AMES RESEARCH CENTER

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ABSTRACT

Thermal Protection Systems (TPS) are critical for enabling NASA missions involving high-speed atmospheric flight where the entries usually include descending into the atmosphere followed by a trajectory that aims to burn off energy and result in a controlled landing. NASA Ames focuses on qualifying and certifying TPS for current missions, sustaining TPS for future missions, and developing new TPS for upcoming missions where a heritage solution is not viable. More recently there is also a focus on advancing and transferring technologies that can benefit both commercial and government space needs.

Developing mature thermal protection systems is a lengthy process involving advanced tools, extensive research, and testing. Design and analysis tools are used to predict aerothermal environments, aid the design of test and flight hardware, and support the testing for the thermal/mechanical response of thermal protection systems. More recently, advances in computational methods help reduce the time and cost of technological advances, aid in optimized material architecture design, and improve material properties and performance. While high-enthalpy testing that simulates the conditions of space flight remains essential for the evaluation and development of TPS materials, computational tools are already showing promise in reducing the need for widespread testing and can help fast-track the design cycle.

With the exploration of new destinations EDL instrumentation remains an important element of the heatshield and NASA Ames and partners have developed and delivered instrumentation flight hardware in support of recent Mars missions, including Mars Science Lab (MSL) and Mars 2020 (M2020), as well as Artemis Orion. Sensors installed on the heatshield and backshell of spacecraft provide coveted information about the aerodynamic and aerothermal environment during entry.

Over the years NASA Ames has brought several reusable and ablative TPS materials to a level of readiness to hand off to missions and the Thermal Protection Materials branch continues to serve as a TPS steward for the agency.

Index Terms — Thermal Protection Materials and Systems (TPS), ablators, Phenolic Impregnated Carbon Ablator (PICA), woven TPS.

1. INTRODUCTION

NASA Ames has a rich history in TPS development staring in the 1970s providing materials and processing expertise to support TPS for the space shuttle [1]. Shuttle TPS employed reusable materials with a high temperature capability in combination with superior thermal insulation to limit the conduction of heat to the interior of the vehicle. Due to the wide variation of temperatures on shuttle the TPS selected comprised of many different materials including High-temperature and Low Temperature Reusable Surface Insulation tiles (HRSI and LRSI), reinforced carbon-carbon (RCC) for higher temperature areas including the nose and wing leading edges and felt reusable surface insulation (FRSI) for more benign locations. Each material's temperature capability, durability and weight determined the extent of its application on the shuttle vehicle. High-temperature Reusable Surface Insulation tiles are low density fibrous oxide-based systems and are reusable below a certain threshold temperature (~2300 - 2700 °F) dependent on material & exposure duration. To achieve these operating temperatures the tiles are coated with a black coating for high emittance on entry. Tile and coating composition and properties have been augmented over time with early generation tiles being made of high purity silica and recent tiles being composite in nature consisting of aluminoborosilicate, alumina, silica, & silicon carbide. Recent generation composite tiles offer improved dimensional stability and handleability compared to early versions. Reaction Glass Coating (RCG) was the earlier generation tile coating, did not penetrate the tile and was prone to impact damage. More recent surface treatments, such as Toughened Uni-piece Fibrous Insulation (TUFI see Fig. 1), penetrate the tile substrate/ limit impact damage and add toughness. Artemis Orion backshell uses a later generation coated tile system on the capsule backshell (Fig. 2). Commercial space entities are also using variants on shuttle era derived reusable TPS.

Toughened Uni-piece Fibrous Reinforced Oxidation-Resistant Composite (TUFROC) is the state of the art in high-temperature reusable TPS with maximum reusable temperature approaching 2900F. Derived partially from Shuttle era materials, TUFROC is designed to be a dual layer higher temperature capable tile. TUFROC is used on the X-

37B vehicle wind leading edges. As with tile systems, advancements in TUFROC formulations have provided improvements over early formulations.

Fig. 1. 2 TUFI coated tiles provided improved impact damage / toughness compared to RCG coated tiles.

Fig. 2. Artemis 1 Orion spacecraft has a tiled TPS backshell

In the mid ’80s NASA Ames started to explore developing low density ablators under the lightweight ceramic ablator development program [2] and under this effort both Phenolic Impregnated Carbon Ablator (PICA) [3] and Silicone Impregnated Refractory Ceramic Ablator (SIRCA) [4] were developed and have since been adopted by many missions. PICA’s low density coupled with efficient ablative capability at high heat fluxes, made it an enabling technology for the Stardust mission [5] where it was first demonstrated and it has since been used on MSL, M2020, and OSIRIS REx. SIRCA has been used on sections of Mars Pathfinder and Mars Exploration Rover.

More recently NASA has focused on maturing woven TPS systems to develop an alternate to heritage carbon phenolic for NASA’s missions with extreme entry environments including Heatshield for Extreme Entry Environment Technology (HEEET) and 3D Mid-Density Carbon Phenolic (3MDCP) TPS which is baselined for the Mars Sample Return Earth Entry System in a single piece configuration.

2. ACTIVE TPS RESEARCH AND DEVELOPMENT

2.1. PICA-D Sustainability and Capability Extension

PICA is a flight proven TPS material and is baselined for near term missions including Dragonfly and Mars Sample Retrieval Lander (SRL). Although PICA only has two constituents and a relatively straightforward process, it has faced multiple supply chain issues over the years [6]. The most recent supply chain concerns are twofold and relate to the rayon precursor (white goods) used in manufacturing the PICA preform, Fiberform®, becoming unavailable and the vendor fabricating the preform material, Fiber Materials Inc (FMI), ceasing production of their commercial Fiberform® line.

To address the rayon white goods supply chain issue NASA, working with FMI, started to evaluate if a domestically produced Lyocell based PICA, termed PICA-D, would be a viable replacement to heritage rayon-based PICA. The Lyocell Tencel® fiber white goods in PICA-D are used in many different applications including medical products and clothing, are produced domestically and have a large and growing commercial use. Early results, including property and arc jet testing provided high confidence that Lyocell derived PICA-D would be a viable replacement for “heritage” rayon derived PICA as shown in the in-depth thermocouple traces comparing lyocell and rayon derived PICA [7].

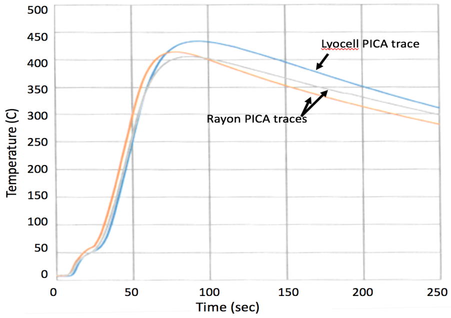

Fig. 3. In-depth thermocouple trace comparing lyocell and rayon derived PICA (220 W/cm^2 and 0.08 atm, 45 second run time)

During the execution of the PICA-D project to establish Lyocell as a replacement, FMI notified NASA they were discontinuing their commercial Fiberform® line at which time NASA Ames ceased further development and testing under the original PICA-D project and in partnership with the

Science Mission Directorate Planetary Science Division (SMD-PSD) funded a new task to maintain FiberForm and PICA manufacturing capabilities at FMI to ensure PICA would be available for the near term needs of Dragonfly and SRL. This new PICA Capability Sustainment (PCS) effort focused on working with FMI to upgrade aging FiberForm® manufacturing facilities and establish a NASA Aerospace grade FiberForm® line and bring improved automation and process controls to PICA material manufacturing. This effort also had Lyocell as the precursor material. The PSC effort just closed out in 2022 with results to be presented at this conference [6] summarizing test results from the PICA-D material production line at FMI. Lot Acceptance Testing of PICA-D billets, compared to heritage PICA, show that thermal, mechanical, and arc-jet tests are in family for both materials, and the project has successfully established PICA-D as a TPS system ready for flight to meet Dragonfly and SRL needs.

Other active efforts under PICA-D include establishing expanded capabilities in terms of single piece heatshield fabrication and expanding the aerothermal design space by completing arcjet testing at heat flux, pressure and shear conditions beyond which PICA has previously been tested or flown. Figure 4 shows a 1.4m, 60-degree sphere cone manufactured as a single piece PICA unit out of domestic Lyocell prior to final machining. This work demonstrated the feasibility of manufacturing larger single piece PICA heatshields, compared to the ~0.8 m diameter Stardust and OSIRIS-REx capsules, to support future NASA opportunities including sample return missions.

NASA is also actively establishing an expanded design space of PICA-D and Figure 5 summarizes recent and future planned testing at expanded heat flux, pressure and shear conditions. Completion of these PICA-D arc jet series will allow future mission proposers to confidently propose utilization of PICA-D and allow sample return missions with higher entry speeds than were considered previously.

Fig. 4: Domestic lyocell 1.4m single piece PICA demonstrated to support future NASA opportunities including sample return missions

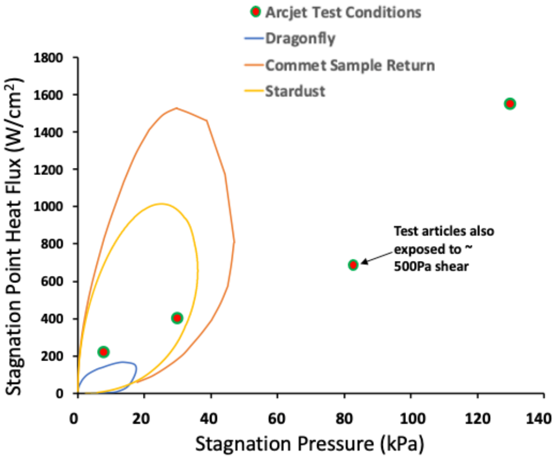

Fig. 5: Target extended heat flux and pressure combinations for PICA-D

2.1. Woven TPS Capability Establishment

Historically carbon phenolic (CP) has been used on both military and NASA atmospheric entry vehicles that must survive the most severe heating conditions. This CP material has been well characterized and successfully used on Pioneer Venus and Galileo Jupiter probes. The Rayon cloth used as the precursor for heritage CP was solely produced by Avtex Fibers Inc., but that supply became obsolete in 1986. In 2010 and 2012 NASA Ames held two workshops concerning supply chain issues with respect to Heritage CP and proposed the development work required to qualify a new rayon-based carbon fiber as well as proposed alternate, more sustainable, materials to CP. Eventually NASA deemed the restart of heritage CP was not a sustainable approach and instead invested in development of 3-D woven TPS materials under the Heatshield for Extreme Entry Environment Technology (HEEET) project. The goal of the HEEET project was to mature a thermal protection system to support NASA Science Mission Directorate robotic entry missions.

The dual-layer HEEET weave, shown in Figure 6 (computerized tomography scan), is a 3-D woven material [8] and is mass efficient [9] compared to heritage CP for missions with very highspeed entries, to deliver probes, landers and higher speed skimmers. The dual layer architecture consists of an outer recession layer, a high density all carbon weave, that is sized sufficiently to manage recession. The recession layer is integrally woven to a lower density weave consisting of a blended yarn composed of carbon and phenolic fibers, the insulation layer. The weave design mechanically interlocks these two layers together. The insulation layer has a lower density and conductivity than the recession layer and is sized to manage the heat load allowing the TPS to be bonded to the underlying structure. HEEET is capable of withstanding extreme entry environments (peak heat-fluxes >3500 W/cm^2; Peak Pressures >5 atm; Peak shear >4000Pa).

Sustainability and scalability were forefront during HEEET development and large volume, established commercial carbon and organic fiber sources were evaluated and downselected. The HEEET project culminated in the manufacturing, integration and testing of a 1-meter Engineering Test Unit (ETU). HEEET TPS was integrated on a flight relevant carrier structure to prove out the manufacturing and integration approaches and the ETU was manufactured with more than 1 row of tiles as would be required for larger entry vehicles, and the seam design and integration approaches were specifically architected to be scalable, with direct traceability to larger heatshields (Fig. 7).

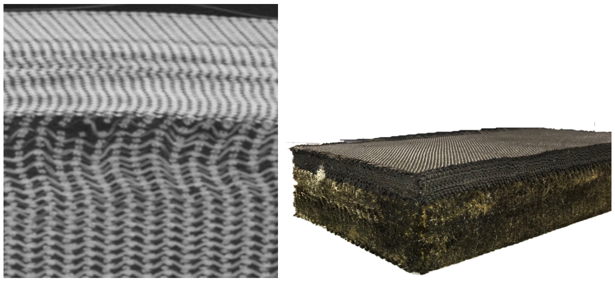

Fig. 6: CT scan of dual layer HEEET weave (left) and image of HEEET dual layer integrally woven TPS

Seams have always been an area of large risk for TPS materials, both aerothermally and structurally, and the most challenging aspect of HEEET from a materials development and integration development perspective. The HEEET gap filler had to perform 2 primary functions (1) provide structural relief for all load cases by increasing compliance in the joint and (2) provide an aerothermally robust joint. The HEEET acreage TPS is a high modulus system and as the carrier structure deflects the HEEET architecture must have sufficient compliance to maintain compatibility with the carrier without inducing excessive stress in the system – that compliance is provided by the gap filler approach established. The HEEET team developed novel approaches for testing and model validation of the structural performance of the seams during entry.

The HEEET project also had a substantial arcjet test campaign to support development and validation of the TPS sizing tools and to evaluate performance of the acreage and seams under mission relevant conditions to establish system capability and look for signs of material failure as summarized in Fig. 8. Ground based test facility limitations did not allow the project to achieve bounding conditions for some steep and high latitude entries at Saturn. However, these testing limitations apply to any TPS concept being evaluated at extreme environments, not just HEEET.

Fig. 7: HEEET dual layer integrally woven TPS Engineering Test Unit (tiles configuration with 2 rings of flank tiles)

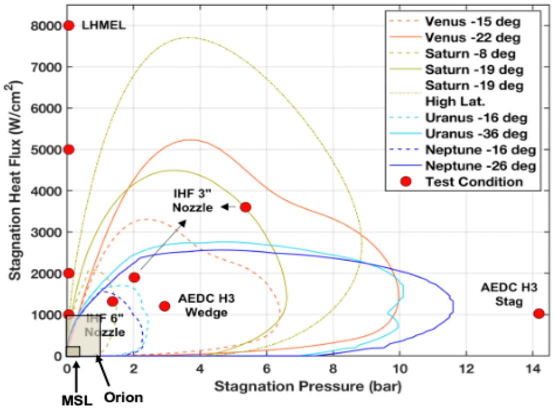

Fig. 8: HEEET arc jet testing completed to support material development and validation

As previously discussed, the seams between the HEEET tiles are the weak point in the overall system. Elimination of seams would improve reliability and reduce risk in the system, and a seamless design is feasible for heatshields under consideration for sample return missions to Earth. NASA Ames has been leading an effort to mature a single piece 3-D woven heat shield for the Mars Sample Return Earth Entry System (MSR-EES). The baseline TPS material for MSR-EES, 3MDCP, is a derivative of HEEET. Elimination of seams for MSR EES TPS also provides confidence in implementing a single piece TPS at very high entry heating environments that require very small sized test articles to achieve desired test conditions. Having seams in such a system raises concerns that small-scale test features are not relevant to flight or cannot be bound in current ground-based test facilities.

2.1. Conformal PICA Capability Establishment

Conformal PICA (C-PICA) is very similar to rigid PICA in fabrication but thermally more efficient and mechanically more complaint, as the substrate is a carbon felt instead of rigid FiberForm®. C-PICA has been matured to TRL 4+ [10] and manufacturing has been demonstrated on ~ 0.75m x 0.75m x thickness on flat and curved parts. Preliminary arc jet testing up to 1850 W/cm^2 (stagnation) and 500 Pa shear @ 400 W/cm^2 has been completed without any concerning model features post-test (figure 9) and an initial property database & thermal/ablation response model have been developed. Current C-PICA tasks are focused on addressing scale up, manufacturing and integration innovation to align with commercial space applications/needs. C-PICA is also an attractive backup solution for PICA.

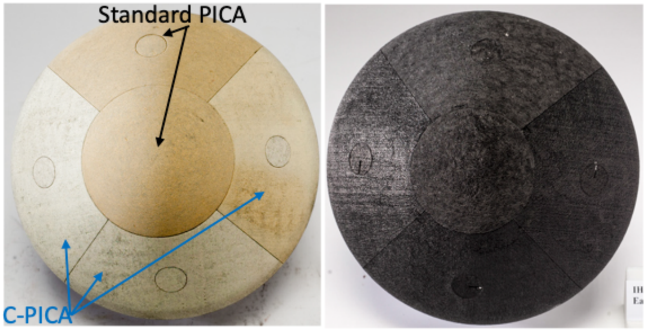

Fig. 9: Pre (left) and post (right) test coupons comparing PICA to C-PICA. Flank heating ~ 400 W/cm2. Shear ~ 200 Pa on flank and 500 Pa on shoulder.

3. TPS TESTING – GROUND AND FLIGHT

The recent Kentucky Re-Entry Probe Experiment (KREPE) [11] is a good example of a low-cost flight experiment to demonstrate the use of small entry capsules to gather TPS data with three instrumented Kentucky Re-entry and Universal Payload System (KRUPS) capsules as shown in Figure 10. These capsules were flown to the International Space Station onboard a Cygnus resupply vehicle in August 2021. The KRUPS capsules were activated and entered Dec 16th, 2021, returning data packages. NASA Ames provided two of the three instrumented heatshields flown on KREPE (Figure 10) and the data collected is currently being analyzed. Small scale units as flown on KREPE allow testing the same geometry capsule in both ground and flight. Such capsule flight experiments and recovery can allow anchoring and validating TPS material models that were calibrated to arc-jet tests to better understand material phenomena not necessarily picked up in ground testing such as coking that was observed in Apollo Avcoat heatshields but not in arc jet coupons. In the future it is expected that low-cost flight testing may reduce the need for large ground testing campaigns in some instances. Flight experiments are already enabling commercial space to more rapidly mature their systems, with Space-X being a prime example.

Fig. 10: NASA Ames delivered instrumented reusable TPS Forebodies for KREPE

In many cases “lower-cost” flight experiments do not achieve conditions needed to expose materials to relevant environments for specific destinations so there is a need to maintain and extend ground test capabilities to address future mission needs. NASAs arc jet complex offers large-scale high heating convective and radiative testing capabilities for TPS materials at conditions that cannot be achieved at any other US facility and is critical to qualifying TPS materials for future planetary missions. Enhancing the capabilities of such facilities is essential for qualifying TPS for future missions, that are pushing to environments not currently achievable in ground-based facilities. Table 1 summarizes typical entry conditions of future destinations of interest to NASA. The capabilities of the Ames arc jet facilities are adequate for supporting many nearer term NASA mission needs including MSR EES, Dragonfly and SRL. However, extended ground test capabilities to allow testing larger sample sizes, accommodate at-scale features of interest such as seams and closeouts, test in flight-relevant atmospheres and pressure/shear combinations are needed to provide enhanced understanding of material performance and identify potential failure mode concerns (thereby reducing TPS uncertainties) for TPS qualification for Ice Giant missions for example.

Table 1 – Estimated Entry Conditions for Destinations of Interest (Design conditions still being refined)

	Mars Sample Return Earth Entry System	Mars Sample Retrieval Lander	Titan (Dragonfly)	Ice Giants
Diameter (m)	~1.25	~4.5	~4.5	-
Entry Mass (kg)	~85	~5500	~2500	-
Relative Entry Velocity (km/sec)	~12	~5.7	~7.3	-
Entry Angle (deg)	-25	-15.6	-48	-
Forebody Peak Convective Heat Flux (W/cm^2)	~3600	~90	~155	2500 - 5500
Forebody Peak Radiative Heat Flux (W/cm^2)	~1100	~20	~165	N/A
Max Stagnation Pressure (kPa)	~230	60	~23	> 500
Peak Shear (kPa)	~6	0.4	-	"high"
Atmospheric Composition	Air	Primarily CO_2, with N_2 and Ar	Primarily N_2, with CH_4	Primarily H_2, He, with CH_4

4. INSTRUMENTATION

NASA has collected EDL data from SMD flagship-class missions in the past, but instrumentation has historically not been included in New Frontiers and Discovery class missions resulting in lost opportunities to gather EDL data about vehicle performance and entry environments that could benefit future missions by reducing uncertainties and validating modeling tools. This is even more important for new destinations where instrumentation allows key measurements to be made for the first time. The Galileo probe entry into Jupiter is an excellent illustration of where TPS instrumentation highlighted shoulder region ablation was not conservative and without margin the TPS thickness would not have been sufficient to meet mission objectives. More recently NASA is requiring that competed missions with an EDL segment propose an Engineering Science Investigation (ESI) plan "to obtain diagnostic and technical data about vehicle performance and entry environments, with minimal impact to mission implementation. The strategic goal for NASA is to utilize these data to improve the designs of all future missions that involve EDL at Solar System bodies with atmospheres" [12]. For crewed spacecraft, there is a requirement that flight instrumentation be evaluated in the early design phase of the mission.

NASA maintains the capability to fabricate multiple TPS sensors and most recently delivered instrumentation in support of the Mars Entry, Descent, and Landing Instrumentation 2 (MEDLI2) project [13]. MEDLI2 provided a suite of sensors installed on the M2020 heatshield and backshell of the spacecraft to collect information about the aerodynamic and aerothermal environment during the entry. For MEDLI2, the data received is already having an impact - the backshell TPS material model for SLA 561V was updated for MEDLI2 to account for low pressure material thermal conductivity resulting in improved accuracy and providing a better match to flight data (Fig. 10). Such lessons learned from MEDLI2 will feed forward to SRL providing more confidence in material models potentially leading to TPS mass reductions.

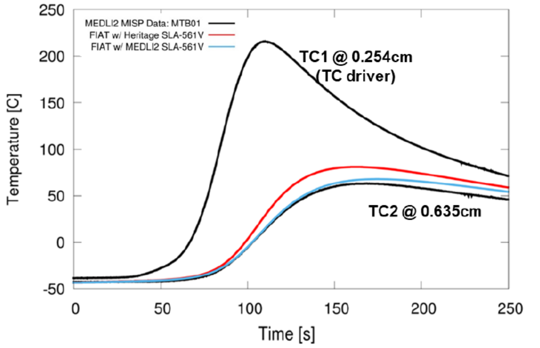

Figure 9 Backshell MISP sensor MTB01 is compared to TC1 driver FIAT results using the Heritage and MEDLI2 flight lot SLA-561V models

Fig. 10 – Backshell MISP sensor highlighting that the MEDLI2 SLA 561V model provides a better match to flight data than the heritage model [14]

4. NUMERICAL MODELING AND PREDICTION

TPS analysis, design and selection efforts at NASA Ames are reinforced by a variety of commercial and in-house-developed software tools for predicting aerothermal environments, designing test and flight hardware, and for performing testing for the thermal/mechanical response of thermal protection systems [15]. The FIAT family of thermal response models [16-17] are essential to NASA missions in ensuring NASA spacecraft have adequate TPS to survive the aerodynamic heating on entry and protect cargo but are sufficiently mass efficient to meet mission goals. Next generation codes including Icarus [18] and PATO [19] are tackling newer material response challenges. Integrated computational materials techniques that span the atomistic and continuum scales have the potential to aid the design and manufacturing of thermal protection materials. Computational methods also help reduce risk, and reduce the time and cost associated with TPS advances and provide early insights in material properties and performance. Examples of early successes with computational materials include process modeling of polymers to provide temperature-time profiles that result in optimal resin thermal-mechanical properties. This has been applied to the 3DMAT (compression pad material on Orion) to optimize processing parameters to achieve target densities during resin transfer molding. Another example is first principles property modeling for high-temperature coatings that can provide formulations optimized for a given behavior, such as low erosion or target optical performance. This is being applied to jet engine coatings to improve oxidation resistance and decrease both maintenance and overall life-cycle costs.

5. LOOKING TO THE FUTURE

With yearly investments in commercial space exceeding $7B (Figure 11 taken from [20]) NASA is actively encouraging collaborations and investing in industry partnerships to decrease development costs and fast-track infusion of emerging space system capabilities. NASA Ames is advancing entry systems technologies including technology transfer of TPS materials in support of commercial space to ensure progress in human exploration and scientific discovery. This is particularly important for thermal protection materials where such systems are not commercially available, and NASA has unique expertise in this area. Additionally, commercial space entities are focused on rapid development with an emphasis on manufacturing and integration innovation with reduced cost and schedule and quick entrance into the market. Performance improvements with large manufacturing and integration cost or schedule are not of priority.

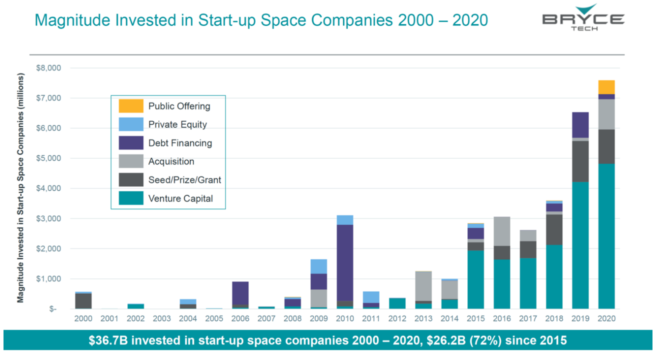

Fig. 11 – Yearly Startup Space Company investments [20]

6. SUMMARY

NASA Ames has a long and successful history in TPS development and has matured several reusable and ablative TPS materials. By inventing and maturing TPS materials and technologies the US government owns the intellectual property and can therefore share the technology with commercial partners and track supply chain concerns. NASA Ames focuses on qualifying and certifying TPS for current missions, sustaining TPS for future missions, and developing new TPS for upcoming missions where a heritage solution is not viable. More recently there is a focus on advancing and transferring technologies that can benefit both commercial and government space needs.

Developing mature thermal protection systems is a lengthy process involving advanced tools, extensive research, and testing. More recently, advances in computational methods help reduce the time and cost of technological advances, aid in optimized material architecture design, and improve material properties and performance. While high-enthalpy testing that simulates the conditions of space flight remains essential for the evaluation and development of TPS materials, computational tools are already showing promise in reducing the need for widespread testing and can help fast-track the design cycle.

With the exploration of new destinations EDL instrumentation remains an important element of the heatshield and NASA Ames and partners continue to explore new EDL sensors.

7. ACKNOWLEDGEMENTS

The author thanks E. Venkatapathy, M. Gasch, D. Ellerby, J. Haskins, J. Santos, J. Monk and J. Feldman.

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