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The Development of Thermal Protection Systems for Aerospace Vehicle Reentry: A Review

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ABSTRACT

Thermal protection systems (TPS) are a crucial part of spacecraft that intend to reenter the atmosphere. They serve the purpose of preventing the heat of reentry from reaching the structure of the spacecraft, which may cause structural failure and destruction of the spacecraft, as well as loss of scientific equipment, data and possibly life if the mission is manned. This paper seeks to provide a review of current progress made in TPS materials and related technologies, with focus on ablative TPS, reusable TPS, criterion for the evaluation of TPS materials as well as methods both experimental and simulation for the testing of various TPS properties. This paper concludes upon current research that is being conducted in both ablative and reusable TPS categories as well as the direction that research on TPS may progress in the foreseeable future.

Introduction

On some missions, a spacecraft has to reenter Earth's atmosphere, such as crew return missions from the International Space Station (ISS) [1], or enter the atmosphere of another celestial body, such as the Mars Science Laboratory (MSL) mission which entered Mars's atmosphere [2]. The spacecraft penetrates the atmosphere and descends towards the surface of the planet under its gravitational influences. As the spacecraft moves through the atmosphere, it compresses the air in front of it at rapid rates, which makes the molecules in the air move quicker, therefore generating heat due to the kinetic energy of the spacecraft being converted into thermal energy [1]. The amount of heating experienced by spacecraft in these scenarios is immense. Temperatures of up to 1477° C have been observed for space shuttle reentry [3]. This can quickly result in damage to the structure of the spacecraft, causing mission failures and possible loss of life. Therefore, a thermal protection system (TPS) is a necessary part of spacecraft designed for atmospheric entry to ensure that the spacecraft's structure is protected from damage from heat.

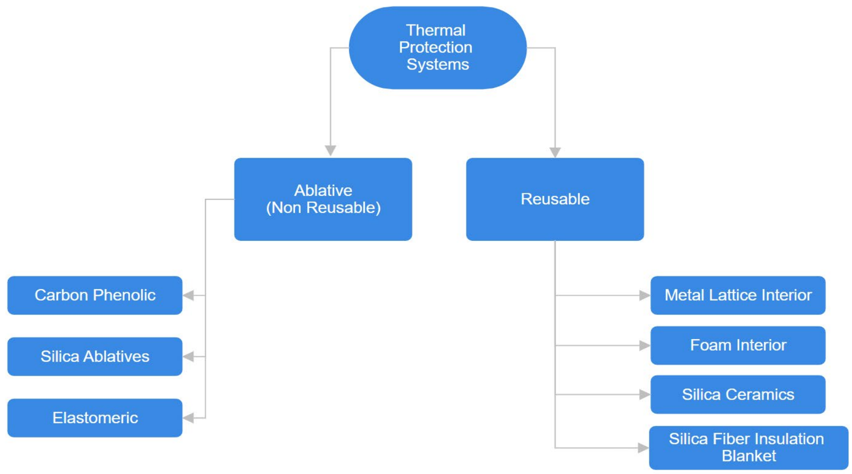

Figure 1. Flowchart of currently existing types of TPS materials discussed throughout this paper.

Throughout history, there have been various types of TPS developed that rely on different materials to suit the specific requirements of different types of missions. These TPS materials can be organized into the following categories: ablative and reusable (Figure 1). Ablative TPSs are made up of resins reinforced with fibers or particle fillers. The outermost layer of an ablative heatshield turns into gas due to reentry heating and carries heat away from the body of the spacecraft, hence undergoing controlled ablation and protecting the spacecraft from damage [4]. As such, they are single use in nature and applicable to missions where a single atmospheric entry is required, which are most of the current spaceflight missions, both manned and unmanned. For ablative TPS materials, there exists carbon- and silica-based ablatives, such as the NASA's phenolic impregnated carbon ablator (PICA), which are used on the exterior of spacecrafts [5], and elastomeric ablatives used to line interiors of solid rocket motors [6]. Missions with reusability in mind utilize reusable TPSs, which absorb the reentry heat without undergoing structural changes. However, reusable TPS materials are limited to protecting against reentry heating via absorption, making them inferior to ablative TPS in terms of thermal performance. As such, reusable TPS materials are limited to missions reentering at a relatively low velocity. Currently, the majority of reusable TPSs are made of silica, either as ceramic tiles or fiber insulation blankets [3]. Multilayered structures with foam and metal lattice interiors have also been designed to absorb and dissipate the heat experienced during reentry [7].

In order to ensure that the spacecraft can survive reentry as intended, TPS materials must undergo rigorous testing of their thermal and mechanical properties to ensure that they meet specifications. Moreover, the development and manufacturing process of TPS is expensive, and as such these processes should be ideally optimized. Researchers focus on the following five key areas in the development of TPS materials:

Density

Mass is one of the most important factors of consideration in every stage of spacecraft design. Every single component of a rocket means added mass, which means that the rocket engines will have to expel more gas out of their engines to reach the same velocity. Since this expelled gas is formed using liquid fuel and oxidizer that is brought aboard the spacecraft [8, the spacecraft can only output a limited amount of change in velocity before the fuel is depleted. As such, rockets and spacecraft are designed to be as light as possible so that the payload weight can be maximized. The TPS of a spacecraft covers a significant area of its exterior section. As such, the density of TPS is a major consideration. TPS that is too dense will add considerable mass to the payload, possibly reducing the features that can be designed into the spacecraft, while a heat shield that is not dense enough may underperform, causing destruction of the spacecraft upon reentry.

Reliability

For missions with the intention of payload return, it is not desirable for the spacecraft to be destroyed due to atmospheric heating upon entry, as this will result in loss of scientific data, samples and human life in the case of manned missions. As such, the reliability TPS is often verified through a series of testing, both experimental and simulated, to ensure it can handle the heat of reentry for the specific mission profile.

Reusability

For some spacecraft where reusability is a concern, such as the Space Shuttle and more recently, SpaceX's Starship, the TPS is also designed to be reusable with minimal servicing between flights. Moreover, currently a choice between lightweight and durable has to be made for current reusable TPS, as there is yet a reusable material that is optimized in both aspects of weight and structural durability. As such, different parts of spacecraft which are subject to different aerodynamic and mechanical forces during operation use different TPS. This increases the complexity of the spacecraft and therefore manufacturing and maintenance costs. As such, a improvement that can be made on current reusable TPS is the optimization of both weight and durability simultaneously.

Scalability

Developing TPS is a complex process that involves repeated experimenting, simulations and rigorous testing. Moreover, many types of TPS also require complex and specialized equipment to make, such as the large oven used by Lockheed Martin to cure the heatshield for the Orion spacecraft [9]. As such, it is both time efficient and cost efficient to make one variant of TPS applicable to multiple mission profiles. However, each mission has spacecrafts of different sizes and geometries, therefore, most TPS are designed so that the manufacturing process allows a certain degree of customizability to the dimensions and geometry of the heatshield, allowing for application across multiple missions.

Safety and Sustainability

Environmental safety and sustainability is a growing concern in the aerospace industry. This includes sustainability considerations for the materials, fuel-efficiency, the output of emissions, and the manufacturing processes. As such the manufacturing processes of TPS is optimized, when possible, to reduce dangers to both the workers involved in the manufacturing process and the environment. This may include actions such as reducing the toxicity of the raw materials and manufacturing process or adjusting supply chains to lessen environmental impact.

This review paper aims to provide an overview on the history and current state of TPS materials in the aerospace industry, covering TPS variants, applications, and both simulation and experimental methods that are utilized to test and develop TPS. This paper also highlights current research occurring for different TPS variants as well as possible future directions.

Methods for Thermal Protection System development

Since thermal protection systems (TPSs) are a complex and critical component of spacecraft, a large amount of simulation and testing is required throughout the design process to ensure that the TPS will function up to standard in an actual mission. In order to function as intended during reentry, the TPS must meet a series of specifications including but not limited to strong thermal and mechanical properties, as well as having an aerodynamic profile that allows for a stable and safe reentry. To ensure that these specifications are met, there are a variety of testing methods used, which can be divided into simulation and experimental.

Simulation

Simulations are computer programs used to model the behavior of TPS in a specific environment. They are used during the design process to gain a preliminary understanding of two different aspects of TPS behavior: the ablative properties of TPS during reentry and the flow of air over the spacecraft caused by the TPS. The two main types of simulation used on TPS are computational fluid dynamics (CFD) and ablative simulation. CFD models the flow of air over the TPS of the spacecraft under different conditions of reentry and is useful for testing and confirming mission-specific TPS designs, such as the shape and geometry of the heat shield. Ablative simulations are used to model the state of ablation in a given type of material under given reentry conditions, and is useful when gaining preliminary understanding of TPS material behavior during reentry.

Computational Fluid Dynamics (CFD)

CFD, or computational fluid dynamics, is using computers to predict the movement of fluid. Since the behaviors of fluid is governed by physical principles, they are predictable and within the capabilities of modern computers to calculate [10]. CFD is most often used when modelling the behavior of airflow around the entire spacecraft during reentry. 4his is usually combined with thermal simulations to model the heating on each area of the spacecraft. CFD is useful for determining the performance of an entire spacecraft during reentry and making structural adjustments to the TPS. There are many variants of different models for CFD, some major models will be discussed below.

CFD Meshes: Since computational fluid dynamics utilizes 3D computer aided design (CAD) models of simulation subjects, mesh construction is an important part of CFD. Meshes, such as ones shown in Figure 2, are a series of faces which form a polygon to represent a shape, they are commonly made up of lines which indicate the vertices in a geometric body and are used in CAD to define geometric forms. The first step of CFD mesh construction is surface grid generation, where a mesh is created over the body of the 3D model [11]. The mesh is of varying densities in different locations and traditionally, the judgement process to determine the appropriate surface grid density is based off the skill and experience of the human analyst regarding the adequate mesh density to simulate flow features of a particular region to appropriate accuracy. Following the construction of the surface grid is the volume grid, which extends away from the surface of the 3D model. The density of cells of each area in the volume grid dictates the level of detail of the airflow simulation occurring in said region [11]. Once again, the generation of the volume grid is traditionally based on the experience of human operators regarding the aerodynamic specifications of the model.

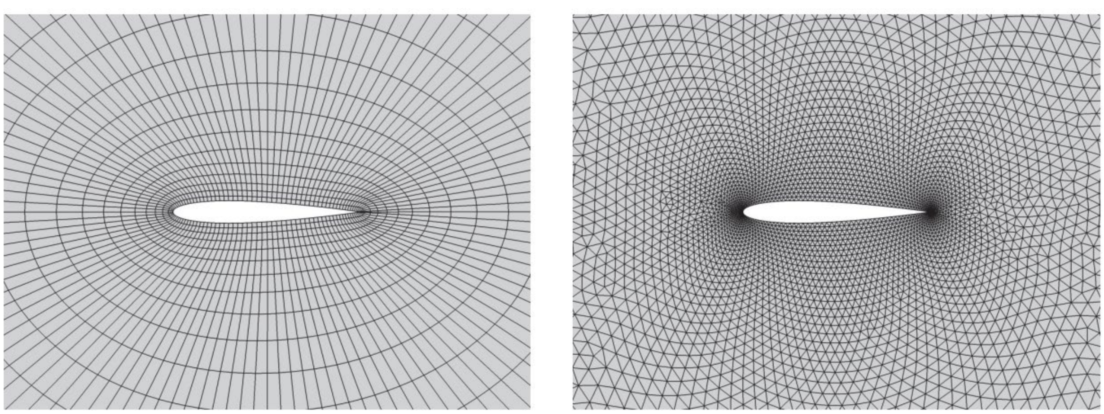

Figure 2. Cross section of an airfoil (white) surrounded with two possible variations of the volume grid. This figure was published by Mani et al. in Annual Review of Fluid Mechanics (2023). [11]

A possible path to further optimize CFD meshing is the development of automatic generation of both surface and volume grids to reduce the necessity of the human element in mesh generation and takes advantage of computers to greatly reduce the time taken for mesh generation, increasing the efficiency of the process. The current hurdle that needs to be overcome to achieve viability of large-scale application of automatic mesh generation is the ability of the computer program to determine the appropriate quantity and location of cells. A lack of cell density will lead to inaccurate simulation results while cells that are too dense greatly increases computation times and decreases the efficiency of the overall CFD procedure. It is expected that efficient methods of automatic mesh generation will be implemented through the use of programs capable of interpreting and applying commonly expected mesh densities for regions of varying distance away from the model and also regions on the model of varying aerodynamic flow. With recent advancements in Artificial Intelligence (AI) technology, it is possible that AI models can be trained on professionally generated CFD meshes in order to emulate such mesh generation behavior. Whether this approach will be effective is an important topic for future studies.

Direct Numerical Simulation (DNS): Direct Numerical Simulation (DNS) is the simplest form of CFD, as it solves the Navier–Stokes equations, which are equations describing the motion of fluids, purely numerically [12]. This means that to simulate fluids accurately, the simulation must work in steps from the smallest scale of turbulence all the way up to the scale of the entire system. This process creates a highly detailed model of aerodynamic behavior down to the smallest scale, but is very computationally taxing and expensive, and therefore rarely used in industrial applications. However, since it is the most basic form of simulation and verifiably correct, it is used to create turbulence models that predict the effects of turbulence.

Turbulence Models: Turbulence models are necessary in other CFD methods that employ the Reynolds-averaged Navier–Stokes (RANS) equations [12], which is a time averaged form of the Navier–Stokes equations designed to reduce computing stress. These turbulence models, which predict the average effect of small-scale turbulent airflow, are introduced to the simulation to reduce computing demands. One such example of a turbulence model used in CFD is large eddy simulation (LES). The LES functions by applying filtering terms to the Navier–Stokes equation to eliminate calculations for smaller scale effects. This approach creates a simulation where small scale effects are time and spatially averaged, also reducing the computing power required [11]. Currently, LESs are applied to a variety of engineering applications, including aerospace.

Ablative Simulation

Ablative simulations are a type of computer simulation where a set of parameters dictating the property of the ablative materials and the properties of the reentry process are entered into the simulation, and the simulation outputs the predicted resultant change in the thickness of the ablative material. Since ablative simulations determine the state of ablative materials after a specific reentry profile, they are useful in the process to design mission specific heat shielding for spacecraft. The current state of art for ablative simulation is the Fully Implicit Ablation Thermal response program version 2 (FIATv2) developed by the NASA Ames Research Center, which is the updated version of FIAT, which evolved from the CMA ablation model developed by the Aerotherm Corporation [13].

Experimental

Experimental methods are generally designed to simulate the flow of heated air particles experienced during reentry, and are as such useful for evaluating both ablation conditions and thermal properties of TPS. However, mechanical properties are not tested using these methods as the stress induced upon TPS by aerodynamic forces during reentry and other forces during the launch process cannot be replicated by these experimental methods.

Arc Jets

An arc jet is a type of thruster where an electrical discharge occurs through a flow of propellent to accelerate the propellent and create thrust [14]. Figure 3 shows an annotated example of an arc jet testing setup for ablative TPS. In TPS development, arc jets are used to accelerate gases to high velocities towards a sample of TPS material to simulate the conditions a TPS material may face during atmospheric reentry. Arc jets are advantageous in that they can burn for extended periods of time and put realistic thermal and mechanical stresses on TPS materials. However, current arc jets are limited in size and can only perform testing on smaller samples of TPS materials, they cannot perform testing on full scale TPS.

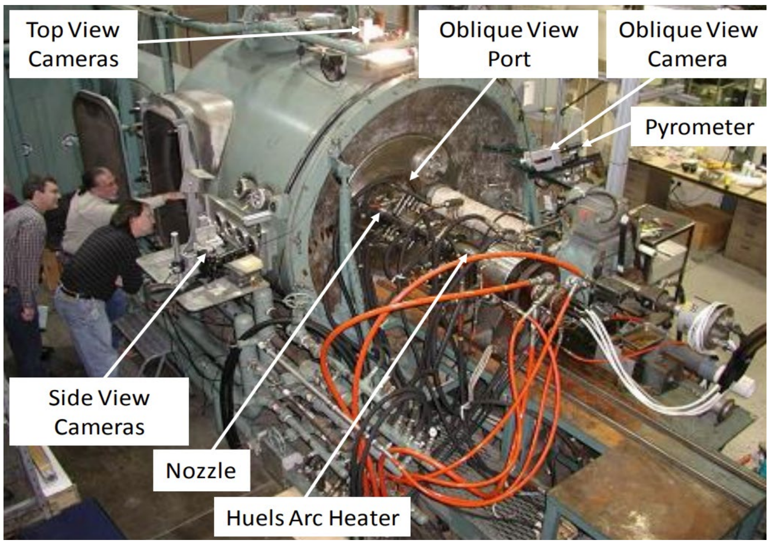

Figure 3. Arc-jet used for testing of TPS materials in the Boeing Large Core Arc Tunnel (LCAT) facility. This figure was published by Beck in a presentation for the Thermal & Fluids Analysis Workshop (TFAWS) 2019. [14]

Solar Tower

Solar towers are an assembly of heliostats, which are mirrors that can angle sunlight onto a predetermined target [15]. All the heliostats in the assembly reflect sunlight onto the central tower, where a TPS can be secured for testing. Solar towers allow testing for full scale Thermal Protection Systems. However, the conditions simulated by a solar tower is not indicative of actual flight conditions, as the heating comes from photons instead of air flow.

CO_2 Lasers

CO_2 lasers are high energy lasers that produce a beam of infrared light. They are currently the most powerful type of laser available and are therefore used to conduct thermal tests on TPS materials by heating the surfaces of testing materials through radiation. One example of currently active CO_2 laser facilities is the Wright-Patterson Air Force Base Laser Hardened Materials Evaluation Laboratory (LHMEL) in the United States of America (Figure 4). This laboratory has a 15-kW which is used to test various TPS materials to validate them for specific missions [16]. Because the source of heat is a laser, the amount of heating the TPS experiences can be adjusted very precisely. Moreover, another significant advantage of CO_2 Laser testing is that the atmospheric environment of the test chamber can be flooded with inter gas [16], preventing surface recession due to chemical reactions of the TPS. This is helpful when comparing multiple types of TPS as not all TPS recede at the same rate in oxygenated and non-oxygenated atmospheres. However, current CO_2 laser facilities are limited in their size, and can only be used to test material samples, not entire heat shields.

Figure 4. Plexiglass test box for containment of test materials within inert atmosphere used at the LHMEL This figure was originally published by Sepka et al. in the proceedings for the 36th International Conference and Expo on Advanced Ceramics and Composites [16]

TPS Materials

Generally speaking, TPS materials can be categorized into reusable and non-reusable sections. With the non-reusable section predominately consisting of ablative materials, which are materials that undergo phase change and turn into gas during reentry, removing heat from the space craft. Reusable materials come in a variety of structures and dissipate reentry heating by absorbing the heat and reducing thermal transfer to the structure of the spacecraft.

Ablative

Ablative TPS are named as such because of the process they undergo during reentry. Due to the heat during reentry, the materials making up the TPS undergo a controlled process of ablation, which involves the surface of the material being worn away. During this process, the material undergoes change from a solid into a gas [4]. The type of change undergone here is dependent on the constituents of the atmosphere the spacecraft is entering. During Earth reentry, chemical reactions occur in the ablatives because Earth's atmosphere contains oxygen [4], which reacts with the ablatives. However, some atmospheric bodies, such as that of Mars, are constituted largely of inert gas [17]. In these cases, the TPS does not undergo chemical reactions, but rather changes phase from solid to gas. Regardless of the type of change, the gas that is formed is carried away from the spacecraft. This change absorbs a significant amount of heat, preventing it from reaching the spacecraft.

Over the years, there have been many iterations of the ablative heat shield. The general design of ablative TPS have remained largely unchanged since their initial development [18]. This type of heatshield typically consists of carbon fiber (or other fibrous materials) reinforced resin [4]. However, research has continued on ablative TPS materials to find better materials and manufacturing methods.

Carbon Phenolics

The current state of the art ablative TPS used by NASA is a phenolic impregnated carbon ablator (PICA)[5]. Carbon phenolics like PICA have significant advantages in terms of excellent thermal performance and decent scalability for current missions, however, as ablatives, those advantages come at the cost of not being reusable. Manufacturing safety concerns have arisen for PICA along with sustainability concerns. Therefore, engineers continue to optimize ablative materials to incorporate updated manufacturing processes, such as seen in the switch NASA conducted from PICA to PICA-D which substituted the originally toxic and nearly obsolete carbon fiber production method with a process that is more sustainable [19]. PICA-D was first conceived as a necessity due to one of the materials used for the manufacturing process of PICA being discontinued. The carbon fiber used in PICA was made from rayon, which is a type of fabric derived from wood pulp. The rayon was chopped and carbonized to create chopped carbon fiber, which was then mixed with phenolic resin to form carbon fiber slurry, cast, and then hardened using a furnace to make PICA TPS [19]. The original manufacturing process to convert wood pulp into rayon carbon fiber was complex and produced toxic products. As a result, the manufacturing methods for this particular type of material was discontinued from production in Europe and the United States of America [19]. Since the manufacturing method to produce PICA was no longer available, NASA developed a type of ablator which substituted the rayon with lyocell, another type of plant-based fiber with a relatively more sustainable and safer manufacturing process [19]. Since lyocell is also a type of fiber, no other significant changes to the manufacturing process were required. Upon testing samples of PICA-D, it was observed that PICA-D exhibited similar thermal performance characteristics to PICA [19] and was deemed satisfactory as a sustainable substitute. Currently, there are multiple variants of PICA that are being utilized by different organizations, such as PICA-D which is being utilized by NASA, and PICA-X which is developed and utilized by private aerospace company SpaceX [20]. For the sake of convenience, all PICA variants will be referred to only as PICA in the following passages.

Ongoing research on PICA works to address limitations that may arise for future, more advanced spaceflight missions. Currently, the focus of most future spaceflight missions is scientific research and sample collection upon Mars. Multiple space agencies have planned and ongoing Mars missions, such as NASA's Mars Perseverance rover, designed to gather scientific data [2], and the Mars Sample Return, which is a joint mission between the European Space Agency (ESA) and NASA to gather samples stored aboard the Perseverance for return to Earth [21] . These missions all utilize ablative heatshields due to their single use nature and excellent thermal performance, specifically PICA. For current and planned missions, PICA TPS is sufficient to suit both mechanical and thermal requirements. However, as scientific research on Mars and other planets progresses, spacecraft will likely need to carry more complex scientific equipment to further progress research. As such, spacecraft size as well as mass will increase. PICA TPS can be cast as single piece for small vehicles smaller than 1.5m in diameter [22] and for larger ones, the TPS is constructed with rectangular PICA tiles [22]. Due to its structure, PICA has excellent thermal performance but has been observed to fracture in a brittle manner upon reaching critical tensile stress [23]. While this structural limitation is not a concern for the TPS of current spacecraft, future spacecraft of larger sizes that require larger heat shielding may see more mechanical stress induced upon the PICA TPS material. This will require researchers to develop methods to further optimize the structural properties of PICA. This could possibly be achieved through further advancements in the structural properties of the ablator itself or improvements to the mounting method of the TPS.

Silica Ablatives

A current direction of research on the further optimization of phenolic ablative heat shielding is with silica ablatives. Silica phenolic ablatives, manufactured in a method similar to that of carbon phenolics, but using silica fabric instead of carbon fibers, have been shown to be more cost effective compared to carbon phenolic ablatives. Research has been conducted on the viability of manufacturing silica ablatives out of chopped silica fibers, phenolic resin and hollow glass microspheres which are filled with inert gas [24]. The hollow glass microspheres have been proven in previous research to enhance the thermal properties of phenolic resin [24] and is expected to do the same for the silica phenolic ablative material. Testing of these silica phenolic ablatives reinforced with hollow glass microspheres proved that the hollow glass microspheres were effective in improving the ablative and thermal properties of the TPS, as well as having the effect of reducing density and therefore mass [24]. As such, experimentation has proved that silica ablatives are a viable, cost-effective alternative that can be applied to spaceflight missions which are designed to enter atmospheres containing oxygen, such as that of Earth's.

Elastomerics

Elastomeric heat shielding materials (EHSMs) are a niche family of ablative TPS materials used exclusively in interior shielding of solid rocket boosters. EHSMs are made of various types of elastomeric resins reinforced with fibers which enhance the thermal properties of the TPS. Common fiber fillers for EHSMs include Kevlar fiber, fiberglass, chopped carbon fiber, and asbestos [6].

EHSMs are designed to have a specific gravity less than one, meaning that they are less dense than water and therefore able to float on it [6]. This is a desirable trait for rocket boosters of some launch systems, such as the space shuttle, because the solid rocket boosters are meant to be recovered for reuse after splashdowns in ocean waters [25]. Since EHSMs are applied to the inner walls of solid motor casings, they contribute to the dry mass (i.e., the mass at full ascent of booster, after the expulsion of all fuel) of the solid rocket motor.
Solid motors are currently still utilized due to their simple design and high thrust to weight ratio (TWR) as rocket boosters on many launch vehicles, such as the European Space Agency's (ESA) Ariane 6 [26], the Japan Aerospace Exploration Agency's (JAXA) H3 [27] and many more. A possible direction for future research is lowering the rate of ablation and the thermal conductivity of ESHMs. This would allow a thinner layer of coating and reductions in dry mass of solid rocket motors, thus further increasing the TWR, and therefore efficiency, of solid rocket motors.

Reusable

Reusable TPSs can absorb the heat of the reentry process but remain both mechanically and chemically unchanged after reentry. This allows reusable heatshields to be used numerous times with minimal servicing. An example of a launch system ideal for the application of a reusable TPS is the Space Shuttle. Not only is the space shuttle designed to be a reusable craft, it is also always returned from Earth orbit, meaning that the reentry heating is comparatively lower than that of crafts reentering from faster orbits, and this heating is within capabilities of current reusable TPS technologies.

Silica Ceramics

High-Temperature Reusable surface Insulation (HRSI) silica ceramic heat shielding is used on most lower surfaces of the Space Shuttle, including the leading edges of the wings [3]. The ceramic heat shielding comprises a multi-layered structure of silica ceramics and is secured onto the Space Shuttle as individual tiles [3]. The black HRSI tiles on the bottom of the space shuttle were designed to have maximum emissivity so that they quickly lose the heat absorbed from the reentry process. The core of the HRSI tiles consists of a type of silica glass fiber called LI-900. LI-900 has incredibly low density and 94% of the volume is made up of air [3], which allows for minimum thermal conductivity thus preventing the heat experienced on the outer surface of the HRSI tile from reaching the inner surface which is attached to the orbiter's structure. The LI-900 is coated with reaction cured glass (RCG), which is silica glass fused with metallic compounds [3]. This fusion strengthens the mechanical properties of RCG and allows it to endure the thermal shock caused by rapidly changing temperatures during reentry. HRSI tiles are machined into shape from blocks of LI-900 and then coated with RCG [28], the tile structure allows for easy swapping of individual tiles if they wear out from reentry.

Silica Fiber Blanket

On areas of the Space Shuttle that experience the most heat during reentry, insulation consisting of silica fiber blankets are used [3]. Silica fiber blankets exhibit low thermal conductivity, resistance to thermal shock, and are also of low density, making them the ideal TPS for aerospace applications where the weight of the spacecraft is a key design consideration. However, the areas of the space shuttle which experience the most heat during reentry, such as the nose cone and wing edges, also happen to be the areas that experiences the highest aerodynamic stress. The silica fiber insulation cannot maintain structural integrity under such aerodynamic stresses and will rip apart, resulting in destruction of the Space Shuttle. To solve this issue, the silica fiber insulation is used in conjunction with an outer plating of Reinforced Carbon-Carbon (RCC), a composite that consists of carbon fibers and other compounds containing carbon [3]. RCC has strong mechanical properties and therefore is used on parts of the shuttle structure that experiences the most mechanical and aerodynamic stress as a structural component to protect the insulation underneath, including the connection points between the structure of the shuttle and its external fuel tank, along with the already mentioned wing leading edges and nose cone. However, because RCC is also thermally conductive, the silica fiber blanket TPS is critical for these structures.

Metal Lattice Sandwich Structures

Sandwich structures are a type of multilayered design for spacecraft TPSs which consists of a core structure positioned between two face sheets, akin to the structure of a sandwich. The face sheet of a sandwich structure TPS is constituted of materials which can withstand the high thermal and mechanical loads of reentry, such as metallic and ceramic composites [29]. The core structure is designed to lower the thermal conductivity of the TPS and prevent the heat on the outer face sheet from reaching the inner face sheet, which is attached to the structure of the spacecraft. Current developments focus mainly on metal lattice structured sandwich TPS, which has a supporting metal lattice structure with gaps that can be filled with highly porous solid materials or utilized as a circulation path for coolant, depending on the method of cooling chosen. [29].

The metal lattice structure is beneficial because it helps to provide additional structural reinforcement to strengthen the TPS tiles. This is useful for spacecraft application systems in order to help reusable TPS withstand the strong aerodynamic and structural forces experienced during both reentry and launch of the spacecraft. Moreover, the metal lattice TPS finds a wider range of applications as the empty core of metal lattice TPS structures can also be used has heat dissipation channels [29] for aerospace applications which require actively cooled TPS, such as hypersonic aircraft and other similar applications. The geometry of actively cooled metal lattice TPS must be designed to allow for maximum heat transfer between the outer face plate and the metal lattice structure, with coolant flowing through the voids in the lattice structure to carry the heat away [29]. The current optimal structure for both passive and active metal lattice TPSs are still being investigated and debated, but the general consensus is that metal lattice TPS are a promising area of development in the future, especially for actively cooled TPS. Examples of geometries being explored are provided in Figure 5 below.

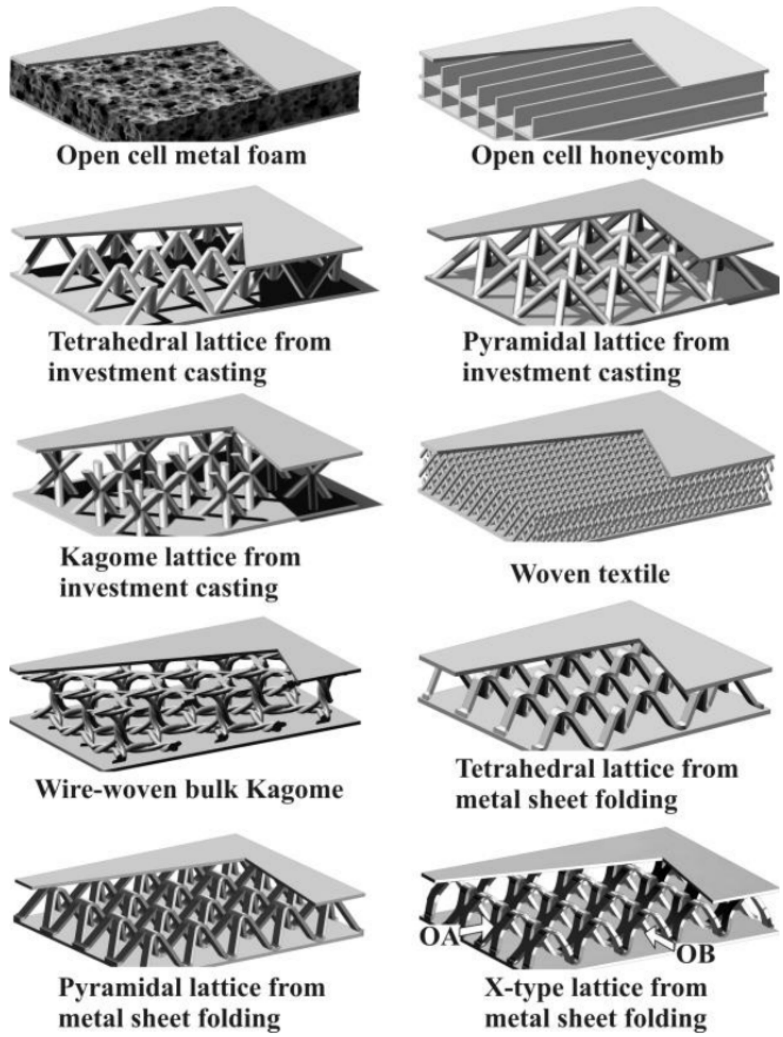

Figure 5. Examples of designs for sandwich structure TPS, with metal foam and lattice variants. This figure was originally published by Yan et al. in Applied Thermal Engineering (2017). [30]

Many types of materials have been explored for application in both the face sheets and metal lattice structures of metal lattice TPS. Carbon fiber reinforced silicon carbide composites (C/SiC) shows significant promise for both applications. C/SiC has been found to be serviceable in temperatures of up to 1873K [31], which is within the range of reentry temperature expected for spacecraft designed for operation in lower Earth orbits, such as the Space Shuttle [3]. Moreover, it also exhibits low density and low thermal conductivity, making it ideal in aerospace applications.

Conclusion

There exists a wide range of thermal protection systems to protect spacecraft from the heat of reentry and therefore prevent damage that may result in destruction of the spacecraft. Different types of TPS are used for different mission profiles. Ablative TPS, which carries heat away from the spacecraft by gradually turning into gas, is used on missions which reenter atmospheres at a higher velocity, and therefore experience higher heat. However, ablative TPS are not reusable since the portion of the TPS that turns into gas is forever lost. For missions with reusability in mind, reusable TPSs which are able to absorb and dissipate the heat from reentry without mechanical changes are used. Current reusable TPS have lower thermal tolerances than ablative TPS and therefore can only be used for reentries at lower velocities.

Future research on ablatives focuses mainly on improving the suitability of ablative TPS to prepare for future missions with spacecraft of larger sizes. This includes improving the mechanical properties of TPS to be able to withstand increased forces during entry into the atmosphere. Research on methods do store ablative TPS in compact form factors and deploy into an extended state before use is also being developed to fit larger TPS onto current launch vehicles. Future research on reusable TPS focuses mainly on improving thermal and mechanical properties to increase the general longevity of TPS to prepare for repeated and extended use aboard future reusable spacecraft. Generally, both types of TPS may be seen to increase focus on sustainability in the future as the exponential growth of the aerospace sector in recent years leads to increased public attention towards the industry.

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References

[1] F. J. Regan, *Re-entry Vehicle Dynamics*. American Institute of Aeronautics and Astronautics, 1984.

[2] mars.nasa.gov, "Overview | Mission," NASA Mars Exploration. Accessed: Feb. 29, 2024. [Online]. Available: https://mars.nasa.gov/msl/mission/overview

[3] NASA Facts,"Orbiter Thermal Protection System," Document FS-2000-06-29-KSC, Kennedy Space Center, FL, Accessed: Feb. 29, 2024. [Online]. Available: https://www3.nasa.gov/centers/kennedy/pdf/91372main_tps.pdf.

[4] O. Uyanna and H. Najafi, "Thermal protection systems for space vehicles: A review on technology development, current challenges and future prospects," *Acta Astronautica*, vol. 176, pp. 341–356, Nov. 2020, doi: 10.1016/j.actaastro.2020.06.047.

[5] P. Agrawal, D. Prabhu, F. S. Milos, and M. Stackpoole, "Investigation of Performance Envelope for Phenolic Impregnated Carbon Ablator (PICA)," presented at the SciTech, San Diego, CA, Jan. 2016. Accessed: Feb. 29, 2024. [Online]. Available: https://ntrs.nasa.gov/citations/20160000305

[6] M. Mosa, M. Mokhtar Kotb, H. Fouda, and M. Gobara, "Study of Elastomeric Heat Shielding Materials for Solid Rocket Motor Insulation," *J. Phys.: Conf. Ser.*, vol. 2305, no. 1, p. 012037, Aug. 2022, doi: 10.1088/1742-6596/2305/1/012037.

[7] V. T. Le, N. S. Ha, and N. S. Goo, "Advanced sandwich structures for thermal protection systems in hypersonic vehicles: A review," *Composites Part B: Engineering*, vol. 226, p. 109301, Dec. 2021, doi: 10.1016/j.compositesb.2021.109301.

[8] G. P. Sutton and O. Biblarz, *Rocket Propulsion Elements*. John Wiley & Sons, 2010.

[9] “NASA Applies Insights for Manufacturing of Orion Spacecraft Heat Shield - NASA.” Accessed: Jan. 09, 2024. [Online]. Available: https://www.nasa.gov/missions/artemis/orion/nasa-applies-insights-for-manufacturing-of-orion-spacecraft-heat-shield/

[10] W. C. Reynolds, “Computation of Turbulent Flows,” *Annual Review of Fluid Mechanics*, vol. 8, no. 1, pp. 183–208, 1976, doi: 10.1146/annurev.fl.08.010176.001151.

[11] M. Mani and A. J. Dorgan, “A Perspective on the State of Aerospace Computational Fluid Dynamics Technology,” *Annu. Rev. Fluid Mech.*, vol. 55, no. 1, pp. 431–457, Jan. 2023, doi: 10.1146/annurev-fluid-120720-124800.

[12] S. A. Orszag, “Analytical theories of turbulence,” *Journal of Fluid Mechanics*, vol. 41, no. 2, pp. 363–386, Apr. 1970, doi: 10.1017/S0022112070000642.

[13] F. S. Milos, Y.-K. Chen, and T. H. Squire, “UPDATED ABLATION AND THERMAL RESPONSE PROGRAM FOR SPACECRAFT HEATSHIELD ANALYSIS.” Accessed: Feb. 29, 2024. [Online]. Available: https://tfaws.nasa.gov/TFAWS06/Proceedings/Aerothermal-Propulsion/Papers/TFAWS06-1008_Paper_Squire.pdf.

[14] R. A. Beck, “Arc Jet Testing: A Short Course - NASA Technical Reports Server (NTRS).” Accessed: Feb. 29, 2024. [Online]. Available: https://ntrs.nasa.gov/citations/20190030274

[15] A. A. Mills, “Heliostats, Siderostats, and Coelostats: A Review of Practical Instruments for Astronomical Applications,” *Journal of the British Astronomical Association*, vol. 95, p. 89, Apr. 1985.

[16] S. Sepka, M. Gasch, R. A. Beck, and S. White, “Testing of Candidate Rigid Heat Shield Materials at LHMEL for the Entry, Descent, and Landing Technology Development Project,” in *Ceramic Engineering and Science Proceedings*, 1st ed., D. Zhu, H. Lin, Y. Zhou, T. Hwang, M. Halbig, and S. Mathur, Eds., Wiley, 2012, pp. 127–155. doi: 10.1002/9781118217474.ch11.

[17] “Mars Fact Sheet.” Accessed: Feb. 29, 2024. [Online]. Available: https://nssdc.gsfc.nasa.gov/planetary/factsheet/marsfact.html

[18] R. B. Erb and S. Jacobs, “Entry Performance of the Mercury Spacecraft Heat Shield,” NASA-TM-X-57097, Jan. 1964. Accessed: Feb. 29, 2024. [Online]. Available: https://ntrs.nasa.gov/citations/19660006061

[19] M. Gasch *et al.*, “Development of Domestic Lyocell Based Phenolic Impregnated Carbon Ablator (PICA-D) for Future NASA Missions,” presented at the Materials Science and Technology 2019, Portland, OR, Sep. 2019. Accessed: Feb. 29, 2024. [Online]. Available: https://ntrs.nasa.gov/citations/20190031963

[20] S. Nowlin, “SURVIVING THE HEAT: THE APPLICATION OF PHENOLIC IMPREGNATED CARBON ABLATORS,” Accessed: Feb. 29, 2024. [Online]. Available: https://spacex.com.pl/files/2017-11/pica-x.pdf.

[21] NASA Facts,“Why Mars Sample Return?,” Document NF-2022-04-622-HQ, Accessed: Feb. 29, 2024. [Online]. Available: https://mars.nasa.gov/internal_resources/1305/.

[22] A. Rajamani, "Heat Shields for Re-Entry Vehicles: A Review," *International Journal of Engineering Research & Technology*, vol. 12, no. 3, Mar. 2023, doi: 10.17577/IJERTV12IS030106.

[23] P. Agrawal and J. F. Chavez-Garcia, "Fracture in Phenolic Impregnated Carbon Ablator," presented at the 42nd AIAA Thermophysics Conference, Honolulu, HI, Jun. 2011. Accessed: Feb. 29, 2024. [Online]. Available: https://ntrs.nasa.gov/citations/20110016513

[24] A. Jithin A J, S. K. Panigrahi, P. Sasikumar, K. S. Rao, and G. Krishnakumar, "Ablative properties, thermal stability, and compressive behaviour of hybrid silica phenolic ablative composites.," *Polymer Degradation and Stability*, vol. 203, p. 110063, Sep. 2022, doi: 10.1016/j.polymdegradstab.2022.110063.

[25] NASA Facts,"Solid Rocket Boosters and Post-Launch Processing," Document FS-2004-07-012-KSC, Kennedy Space Center, FL, Accessed: Feb. 29, 2024. [Online]. Available: http://www.nasa-klass.com/Curriculum/Get_Oriented%202/Solid%20Rocket%20Boosters/RDG_SRB-Additional/SRB-processing.pdf.

[26] "Ariane 6 User's Manual Issue 2 Revision 0 February 2021." Arianespace, Feb. 2021. Accessed: Feb. 29, 2024. [Online]. Available: https://www.arianespace.com/wp-content/uploads/2021/03/Mua-6_Issue-2_Revision-0_March-2021.pdf

[27] "H3ロケット" JAXA, Document JSF170810T, Accessed: Feb. 29, 2024. [Online]. Available: https://www.jaxa.jp/projects/pr/brochure/pdf/01/rocket09.pdf.

[28] H. E. Goldstein, D. B. Leiser, and V. W. Katvala, "Reaction cured glass and glass coatings," Jun. 06, 1978 Accessed: Feb. 29, 2024. [Online]. Available: https://ntrs.nasa.gov/citations/19780024317

[29] V. T. Le, N. S. Ha, and N. S. Goo, "Advanced sandwich structures for thermal protection systems in hypersonic vehicles: A review," *Composites Part B: Engineering*, vol. 226, p. 109301, Dec. 2021, doi: 10.1016/j.compositesb.2021.109301.

[30] H. Yan, X. Yang, T. Lu, and G. Xie, "Convective heat transfer in a lightweight multifunctional sandwich panel with X-type metallic lattice core," *Applied Thermal Engineering*, vol. 127, pp. 1293–1304, Dec. 2017, doi: 10.1016/j.applthermaleng.2017.08.081.

[31] K. Wei, K. Wang, X. Cheng, Y. Peng, M. Li, and X. Yang, "Structural and thermal analysis of integrated thermal protection systems with C/SiC composite cellular core sandwich panels," *Applied Thermal Engineering*, vol. 131, pp. 209–220, Feb. 2018, doi: 10.1016/j.applthermaleng.2017.12.009.