Thermal Protection and Control

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Abstract

During all phases of a spacecraft's mission, a Thermal Protection System (TPS) is needed to protect the vehicle and structure from extreme temperatures and heating. When designing TPS, low weight and cost while ensuring the protection of the vehicle is highly desired. There are two main types of TPS, ablative and reusable. The Apollo missions needed ablators due to the high heat loads from lunar reentry. However, when the desire for a reusable space vehicle emerged, the resultant Space Shuttle program propelled a push for the development of reusable TPS. With the growth of reusable TPS, the need for ablators declined, triggering a drop off of the ablator industry. As a result, the expertise was not heavily maintained within NASA or the industry. When the Orion Program initiated a few years back, a need for an ablator reemerged. Yet, due to of the lack of industry capability, redeveloping the ablator material took several years and came at a high cost. As NASA looks towards the future with both the Orion and Commercial Crew Programs, a need to preserve reusable, ablative, and other TPS technologies is essential. Research of the different TPS materials alongside their properties, capabilities, and manufacturing process was performed, and the benefits of the materials were analyzed alongside the future of TPS. Knowledge of the different technologies has the ability to help us know what expertise to maintain and ensure a lack in the industry does not occur again.

Nomenclature

AETB	=	Alumina Enhanced Thermal Barrier
AFRSI	=	Advanced Flexible Reusable Surface Insulation
BRI	=	Boeing Rigid Insulation
CCP	=	Commercial Crew Program
CM	=	Crew Module
FRCI	=	Fibrous Refractory Composite Insulation
FRSI	=	Felt Reusable Surface Insulation
HETC	=	High Efficiency Tantalum-based Composite
HRSI	=	High-Temperature Reusable Surface Insulation
IML	=	Inner Mold Line
ISS	=	International Space Station
LEO	=	Low Earth Orbit
LRSI	=	Low-Temperature Reusable Surface Insulation
MLI	=	Multi-Layer Insulation
MMOD	=	Micrometeoroids and Orbital Debris
OML	=	Outer Mold Line
PICA	=	Phenolic Impregnated Carbon Ablator
RCC	=	Reinforced Carbon-Carbon
RCG	=	Reaction Cured Glass
RTV	=	Room Temperature Volcanized (Silicon Adhesive)
SIP	=	Strain Isolation Pads
SPAM	=	SpaceX Proprietary Ablative Material
TPS	=	Thermal Protection System
TPSF	=	Thermal Protection System Facility
TUFI	=	Toughened Unipiece Fibrous Insulation
TUFROC	=	Toughened Unipiece Fibrous Reinforced Oxidation-resistant Composite
SNC	=	Sierra Nevada Corporation
SpaceX	=	Space Exploration Technologies Corporation

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I. Introduction

The National Aeronautics and Space Administration (NASA) has been a chief developer in Thermal Protection Systems (TPS) since the beginning of the Apollo program in 1958. The John F. Kennedy Space Center (KSC) has many capabilities for producing TPS. In 1988 the Thermal Protection System Facility (TPSF) was opened to bring the capability of producing TPS on a manufacturing scale to KSC. Cutting edge materials have been developed and produced over the years in conjunction with other NASA centers, with the TPSF making KSC known as the "capability" center.

Early development of TPS was influenced by ballistic missile designs. With developing missile designs, the idea of a blunt body design arose. A blunt body deflects heat away via a strong bow shock wave; this concept can be seen in the shape of our heat shield designs today. When considering a new TPS design it is important to know the different types of TPS. They can be categorized as leading edge, acreage, and internal thermal control. Within those categories it can be classified reusable or ablative. Reusable TPS is that which after a mission, no changes in the properties of the material have occurred. Reusable is usually limited to milder entry environments such as Low Earth Orbit (LEO). The ending of the shuttle program marked a renaissance back to using ablative TPS as well as the continuation of reusable TPS, which is still being used today for the Commercial Crew Program (CCP) and Orion. Ablative TPS is used for higher heating rates and loads because they experience phase changes and shed heat through mass loss. Combining an ablator with the blunt body was an early breakthrough in TPS development. This concept deflected, rejected, and reradiated the heat load instead of absorbing it. Ablative TPS was used in the Apollo era and can be seen again in the Orion and CCP.

II. Early TPS

A. Apollo

With the race of to the moon in full swing, the start of the Apollo program marked the need for TPS able to withstand the return from lunar orbit. The TPS also needed to be able to protect from micrometeoroids and orbital debris (MMOD), and withstand vacuum and ultraviolet exposure. An ablative heat shield is required to endure the heat produced from lunar orbit reentry and provide the protection needed. An ablator dissipates heat by means of a melting heat shield, resulting in a single use TPS system. The crew module (CM) needed to have limit temperature at the ablator-steel interface of 600°F during reentry. The material chosen for the Apollo missions was an Avcoat 5026-39, an epoxy novolac resin with special additives in a fiberglass honeycomb matrix. The heat shield had a slip-stringer strain isolation system to accommodate the differential expansions between the two shells and was bonded to a honeycomb (Figure 1). The honeycomb technique was chosen over bonded tile because doubts were raised over the ability to attach tiles.

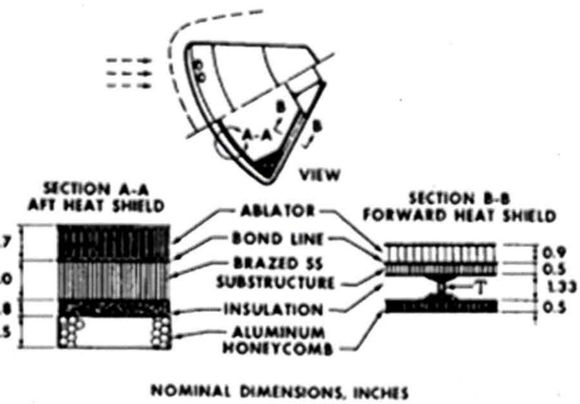

Figure 1. Structure of the Apollo thermal protection system

The avcoat heat shield was made by machining holes into the core material in the shape of a honeycomb, contoured to the Outer Mold Line (OML) of the heat shield. The empty holes were filled with avcoat using a grease gun like device to tampen the material into the cells. The assembly would be x-rayed for voids. If a void was found, the faulty cell would be refilled before curing. The cured heat shield is then sanded and painted or a temperature control coating added. The development of the Apollo TPS system provided NASA with the technology for reentry speeds associated with lunar return and a technology base to build off of.

B. Shuttle

Consisting of over 24,000 tiles individually bonded, the shuttle presented a whole new type of TPS. For the shuttle, the TPS design needed to be reusable and lightweight; this meant new materials needed to be considered. Because the vehicle would be entering from a Low Earth Orbit (LEO) instead of a lunar orbit, an ablator would not be required. The shuttle TPS system features three main components and materials: Reinforced Carbon-Carbon (RCC), insulation tiles, and insulation blankets.

Different considerations need to be taken into account when designing reusable TPS verses ablative. Reusable TPS has a significant amount of energy re-radiated from the surface with the rest conducted into the material. This is a result of radiative and convective heating. It is beneficial to have a coating with high emissivity and low catalyticity so as to maximize the amount of energy reradiated and minimize the amount of convective heating. Low surface catalyticity minimizes convective heating by suppressing the recombination of dissociated boundary layer species at the heated surface. External surface roughness was minimized in order to prolong laminar flow during reentry, as turbulent flow collapsed the boundary layer and intensified convective heat load on the structure.

TPS Materials

The shuttles tiles consisted of two densities LI-900, 9 pound per cubic foot, and LI-2200, 22 pound per cubic foot. The bulk of the tiles were LI-900, which were designed for minimal thermal conductivity and weight. LI-2200 was a higher strength version of the tile for use in high stress areas such as around windows and doors. Both have maximum thermal shock resistance; however LI-2200 had an undesirable weight drawback. The tiles were composed mostly of silica and had either a low or high temperature resistant coating on them. The tiles blocks were machined into the exact shape needed and then coated with Reaction Cured Glass (RCG), a coating made from blended glass powders mixed with thickeners and pigments.

The High Temperature Reusable Surface Insulation (HRSI) tiles were black and used principally on the lower surface and aft base heat shield of the shuttle, while the Low Temperature Reusable Surface Insulation (LSRI) tiles were white and used on the upper part of the shuttle. The use of both black and white tiles had to do with temperature control while on orbit. White tiles on the top of the vehicle are pointed towards the sun to minimize solar gain. Black tiles lose heat a lot faster than the white ones because they are optimized for high emissivity. This makes them ideal for the bottom of the shuttle and reentry purposes. Eventually, the low temperature tiles were mostly replaced by Felt Reusable Surface Insulation (FRSI) blankets and Advanced Flesible Reusable Surface Insulation (AFRSI). FRSI blankets are composed of Nomex felt coated with silicone rubber paint and protects the shuttle from temperatures between 350°F and 700°F, perfect for the top of the shuttle which usually reached around 600°F. FRSI was usually located on the upper surface of payload bay doors and wings. AFRSI also known as Flexible Insulation Blanket (FIB) have a core of pure silica felt between a layer of silica fabric and a layer of glass fabric. These blankets are used on used on the upper wings and sides of the shuttle as well as parts of the upper fuselage. Even though the white tiles were mostly replaced by FRSI and AFRSI, they were still used on upper parts of the shuttle around crew windows.

In 1981, the weight drawbacks of the LI-2200 tiles prompted the development of Fibrous Refractory Composite Insulation (FRCI-12), which weighed less but was comparable in strength. The tiles had slightly higher thermal conductivity than LI-900 tiles and had lower thermal shock resistance that was still within the required limits. FRCI-12 tiles have been used to replace both LI-900 and LI-2200.

In 1996 the FRCI technology was advanced further to introduce a new tile material, Alumina Enhanced Thermal Barrier (AETB-8). This technology introduced small amounts of Alumina into the FRCI to increase thermal stability and conductivity. At the same time a new coating was developed, Toughened Unipiece Fibrous Insulation (TUFI). This provided much higher strength with a low impact on weight. TUFI was used on high impact areas around engines and body flaps. Boeing Rigid Insulation (BRI-18) was developed to be used around main landing gear doors, external tank doors, and nose landing gear doors. The tiles are more rigid than previous tiles and are impact resistant. The tile is mainly silica mixed with other proprietary ingredients. The BRI-18 tiles undergo the same densification, machining, and ceramic coating as the other types of tiles.

The wing leading edge and nose cap required a material with higher heating capabilities. RCC panels are strong and can withstand temperatures up to 3220°F. RCC is a carbon composite made of carbon fiber in a graphite matrix. 22 RCC panels were used on each wing's leading edge. The caveat to RCC panels is that they are thermally conductive, however insulating blankets and tiles could be used behind them to protect the structure.

Another type of insulation used was Multi-Layer Insulation (MLI) was used on the inside of the shuttle and around fuel tanks. It is a passive thermal control system that primarily protects against radiation. It also stabilizes air flow inside the crew cabin.

TPS Attachment

Space Shuttle Orbiter tiles needed to be protected from both the stresses on the orbiter's structure and the shrinking and expanding of the structure during temperature changes. To avoid damage to the tiles, a Strain Isolation

Pad (SIP) made of Nomex was bonded between the tile and the structure. The SIP limited vibration induced damage and protected from the different thermal expansion between tiles and vehicle frame. In order to bond the SIP, the tile was densified to add tensile strength to the surface for bonding (Figure 2). This process was done by adding a slurry coating to the underside of the tile. Filler bar is bonded to the vehicle structure beneath the tile gaps. The filler bar provides thermal insulation from hot plasma flow in the tile gaps and acts as a seal between the structure and tile Inner Mold Line (IML).

Gaps were left between the tiles to accommodate the different thermal expansions between the tiles and the airframe. Gap dimensions are a critical part of TPS. If the gaps are too big during reentry hot gasses will bleed into the cracks and damage the filler bar and the seal it provides. Gap fillers, comprised of Nomex felt, were used to provide mechanical padding between tiles and control gap dimensions (Figure 2). Thermal barriers are similar to gap fillers but they are used to provide thermal seals in openings in the orbiter structure, such as external tank and landing gear doors.

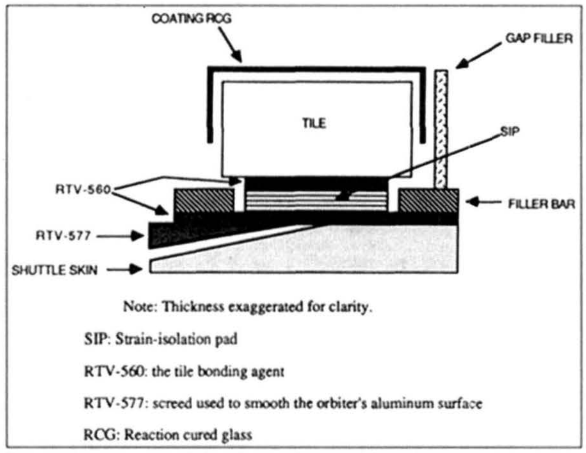

Figure 2. Diagram of the Shuttle Tile and TPS Attachments

A Room Temperature Vulcanized (RTV) adhesive under vacuum pressure is used to bond all of the major TPS items to the orbiter's structure. A silicone adhesive was chosen because silicones retain their strenght at cold and hot temperatures. An RTV screed is used to fill voids and provide a smooth surface for bonding (Figure 2).

III. Current TPS

A. Commercial Crew Program

To redevelop the America's capability of flying humans into space, NASA has partnered with three commercial companies to help design and build a vehicle capable of taking our Astronauts to the International Space Station (ISS). The Boeing Company, Space Exploration Technologies Corporation (SpaceX), and Sierra Nevada Corporation (SNC) are competing to be the commercial provider of transportation to the ISS. With private companies taking over the job of transportation to the ISS and LEO, NASA can look ahead to traveling to the moon and beyond with the Orion Program.

i. The Boeing Company

Boeing is developing the CST-100, a capsule capable of transporting 7 (Figure 3). The capsule will consist of a single use heat shield with a backshell that is reusable for up to 10 flights. The backshell will have BRI-18 tiles and FRSI/AFRSI blankets. Unlike the Apollo capsule, the CST-100 will land on land with parachutes and airbags. The material for Boeings heat shield is still being deliberated. Because the capsule will be coming from the space station, more options can be considered than a lunar orbit return. Avcoat has been considered along with Boeing Phenolic Ablator (BPA) and Boeing Lightweight Ablator (BLA), two ablative materials that are specific to the Boeing Company.

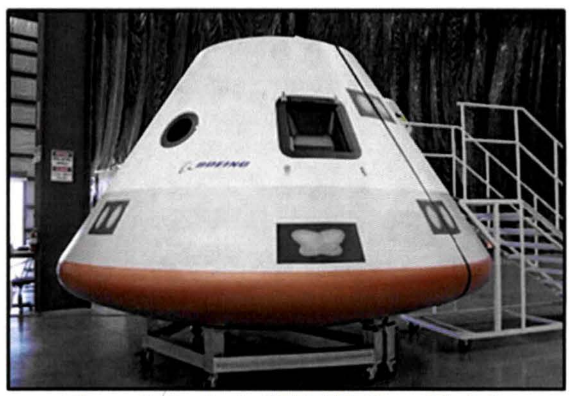

Figure 3. Boeing's CST-100 Crew Module (Taken from http://aeroexperience.blogspot.com)

ii. SpaceX

The SpaceX Dragon capsule is another CCP vehicle that sticks with the capsule design (Figure 4). The current design consists of parachutes for a water landing. The current cargo design employs water landings; however, the manned version is looking to land on land instead of in the water. This will make more parts of the capsule reusable. Nonetheless, the heat shield is still a single use system. The SpaceX heat shield will use PICA-X, which is their version of Phenolic Impregnated Carbon Ablator (PICA).

Figure 4. SpaceX Dragon Capsule (Taken from nbc.news.com)

PICA is a low density ablator that was used on the Mars Science Laboratory (MSL) and StarDust. It has an effective ablative capacity at high heat fluxes. PICA has the capability of both Low Earth Orbit (LEO) returns and lunar returns, which made it a contender for Orion. With CCP only going to the ISS, PICA was an appropriate choice with many advantages. PICA can be purchased directly from FMI or the carbon base block can be purchased from FMI and made from that. SpaceX gets the carbon block from FMI and produces PICA-X themselves, which is a variant on PICA. The back shell of the Dragon capsule will use SpaceX Proprietary Ablative Material (SPAM).

iii. Sierra Nevada Corporation

Instead of a capsule design, SNC is designing the Dreamchaser, a lifting body that looks like a miniature shuttle to most (Figure 5). At about forty feet long, this ship will carry seven astronauts to the space station and LEO. The ship will land on two back wheels and a skid plate. The TPS on the Dreamchaser is designed to be reusable. Similar to shuttle, the bottom of the Dreamchaser will have black AETB tiles; however, these will be 17 pound density. Due to the high heat loads on those areas, the leading edge of the wings, nose chine, and body flaps are currently set to be Toughened Unipiece Fibrous Reinforced Oxidation-resistant Composite (TUFROC). The top will consist of white AETB tiles and FRSI because they are in a lower heat area.

Figure 5. Sierra Nevada Dream Chaser (Taken from www.spacedev.com)

B. Orion Multi-Purpose Crew Vehicle

With CCP focusing on the space station, NASA is able to focus on greater undertakings. NASA's new vehicle Orion, designed by Lockheed Martin, is a multi-purpose crew vehicle intended for beyond LEO missions. Entering from a lunar orbit the vehicle experiences higher speeds and greater heating. It is useful to think of Orion as analogous to Apollo in its capsule design and constraints. As learned with Apollo, coming in from a lunar orbit or beyond requires an ablative heat shield. Orion will be thirty percent larger than Apollo, but will still be a single use system with nominal water landings.

The Apollo heritage heat shield will be Avcoat and produced by Textron Defense Systems. When choosing a heat shield material, many different types were considered, but was eventually narrowed down to Avcoat and PICA. Unlike the avcoat honeycomb matrix, PICA is tiled onto the heat shield. The lack of a development of appropriate gap fillers produced concern because of the heat that is produced from lunar or beyond reentry. In the end, avcoat was chosen. The avcoat heat shield is produced roughly the same way, with the exception of a titanium structure. Each honeycomb cell is gunned in by hand individually, just like the Apollo days.

The backshell of Orion consists of 10 panels made of composite laminate face sheets with a titanium honeycomb core. For added protection from heat and MMOD, they are covered in TUFI coated AETB-8 tiles. The forward bay cover also consists of TUFI coated AETB-8 tiles, FRSI blankets, and is a six panel composite laminate structure. Tiles are attached similar to how they were on orbiter. The tiles will undergo densification and SIP will be bonded to them with RTV, and filler bar and gap fillers will be used between the tiles. MLI will also be used to protect from over heating and cooling due the solar and deep space effects.

C. Thermal Protection Systems Facility

In 1988 KSC opened the TPSF for tile manufacturing for shuttle orbiters. In 2004 blanket manufacturing started taking place as well. The TPSF provides a facility at KSC where TPS components can be repaired or new ones manufactured. The TPSF has capabilities that are crucial to maintaining the production of TPS at KSC. The facility has the capability to manufacture a tile from start to finish and prepare it for installation. The facility contains milling machines, both manual and automatic, that are used for the sculpting and shaping the tiles. There are also rooms for heat cleaning, tile painting, waterproofing and densification, and chemical application. The capabilities in the TPSF have the capability to provide support to both present and future programs.

IV. The Future of TPS

As long as missions to space continue, TPS will always be around. The future of TPS is centered around maintaining capabilities and technologies as well as developing new ones. NASA Ames Research Center has developed a new material to replace RCC. Capable of up to 3000°F, TUFROC is an advanced material able to withstand leading edge and nose cap heating. Because RCC is no longer produced, TUFROC is filling a gap in the market for leading edge materials.

TUFROC is a two piece, reusable TPS material that consists of a treated, carbonaceous cap for heat resistance and OML stability and a fibrous silicon base for thermal insulation. The cap is a low density; high temperature capability material known was Refractory Oxidation-resistant Ceramic Carbon Insulation (ROCCI). It is produced by impregnating a porous carbon substrate with a siloxane gel. The gel is then dried on the carbon substrate to form a ceramic carbon precursor. Finally, the precursor is pyrolyzed in an inert atmosphere, usually argon. The result of this process is a porous, fibrous, carbon ceramic tile that is lightweight and ideal for spacecraft use. A High Efficiency Tantalum-based Composite (HETC) treatment is added near the surface to slow oxidation and keep the emissivity high.

The base block of TUFROC is easy to produce because it is the AETB tile but at 17 pound density. The two halves of TUFROC are attached by both mechanical attachments and a high temperature adhesive. The adhesive is about a 1.2 mm layer thick of RCG. The RCG acts not only as an adhesive, but also a non-abrupt transition between thermal gradients. If temperatures exceed 3700°F due to a failure, the ROCCI cap continues to provide thermal protection through ablation at a controlled rate. The AETB base ablates at a faster rate than the ROCCI. However, most abort scenarios are short and the ROCCI would likely last long enough.

Currently TUFROC is being developed on small scales at AMES and also by Boeing. However, it is in the works to bring the manufacturing of TUFROC to the TPSF at KSC. It is extremely advantageous for this to happen because it would allow TUFROC to be produced for current and future programs on a large scale. The TPSF already has the majority of the technology available, with few upgrades needed to be made. Developing this capability provides many benefits in its affordability and short lead time. The manufacturing of TUFROC represents breakthrough in reusable TPS and a positive move forward for the future of TPS.

V. Conclusion

Because it is a single point failure, TPS is considered a critical subsystem. TPS protects a vehicle from the hazardous heating of reentry into the atmosphere in addition to serving as protection from MMODS and the extreme environments in space. It is critical to keep up the current technologies as well as continue the advancement of newer ones. An understanding of the different types of TPS is crucial in knowing what type is needed for different missions. Maintaining multiple options for the same situation ensures that there is always a TPS option readily available. KSC has the technology and capability to produce many different TPS types. The TPSF has capability to manufacture, process, and apply TPS to the vehicle, making it a critical component in keeping KSC on the leading edge of TPS development.

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Even though my time at KSC was only 10 weeks, I received an enormous amount support and assistance while I was there. First and foremost I would like to thank my mentor, Dan Keenan, for this summer internship. Dan was extremely helpful, always available, and easy to work with. I would also like to thank another member of the TPS group, Joy Huff. Joy was always ready to answer my questions and show me cool things. Both Joy and Dan

were there to guide me around showing me interesting things, and describing all they had worked to really help me make the most of my experience. They were not only teaching me, but including me in discussions. I cannot thank both of them enough for their support and providing and awesome experience.

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Lastly, I would like to thank NASA KSC and USRP for giving me the opportunity. I couldn't be more grateful for the experience I had this summer and all that I have learned.

USRP Internship

As a mechanical engineering student, my passion for space and in particular NASA has always been strong. I was fortunate enough to be given the amazing opportunity for a summer internship at NASA's Kennedy Space Center in the Thermal Protection Systems division. I was provided with unique and informative tours, challenging work, and an excellent mentor and many other engineers ready to offer me valuable information. I was introduced to the history of TPS in NASA from Apollo to Shuttle. I also was given the opportunity to learn about both Orion and the Commercial Crew Programs. Learning about the history of TPS helped me to understand the current state of TPS more and has given me the ability to think about the future state. My internship also gave me a better understanding of NASA as a whole and how the centers work together. The skills and experience I gained this summer will benefit me in school and throughout my life. I am thankful to USRP for being given the opportunity to have been part of such an excellent program.

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