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THERMAL PROTECTION SYSTEMS FOR SPACE VEHICLES

Introduction

Thermal protection systems (TPS) for space vehicles are seldom in the public eye. The general public typically hears about heat shields and shuttle tiles only during a manned spacecraft mission. The fact is thermal protection systems are essential for the successful launch and operation of all spacecraft, manned and unmanned.

The obvious goal of a thermal protection system is to keep excessive heat from destroying or damaging a vehicle or its contents. The selection of a system depends upon the mission of the spacecraft. While often the temperature capability is a major concern, the goal remains to protect the internal components at a minimal weight. This may mean extra insulation if the exterior material has a high heat capacity. Thus, TPS is a system of materials working together to protect the vehicle. Vehicles that are expected to function for a short time or that are expendable need much different thermal protection than those vehicles built to function for longer periods of time or for re-usable vehicles. Still greater care is taken with manned spacecraft or for strategic systems.

In order to meet the mission objectives and the design criteria, the thermal protection system must be composed of appropriate materials whose selection is based upon heat dissipation needs and environmental constraints. As a whole, the design cannot be optimized from every point of view, since a compromise must be reached between conflicting requirements. Therefore, one cannot speak of a best thermal protection system or a universal criterion for rating performance.

Mission Environment

Mission environment can be separated into three major regimes: the launch, the space environment, and, if applicable, atmospheric re-entry. The natural and induced environments vary in each scenario and have great influence on the appropriate materials for the thermal protection system.

In the launch environment, the vehicle is subjected to liftoff and ascent acceleration loads, vibration, aerodynamic loads and aerodynamic heating, shock, acoustic loads and loads imposed by flow of liquid fuel and sloshing. Combustion, rocket exhaust plume and aerodynamic heating cause extreme thermal conditions during liftoff and ascent. These are only induced conditions. In addition, vehicles can encounter natural conditions such as wind, rain, hail, lightning strike, and salt water. Contamination or damage during fabrication and storage must also be taken into consideration.[1]

The natural environment of space depends on orbit, time of year and solar activity. The environment includes vacuum, ionizing radiation, spacecraft charging, contamination, degradation due to UV radiation, the existence of atomic oxygen in the upper atmospheric layers, and impact from meteoric debris.[2] Vacuum eliminates convection as a mechanism of heat transfer leaving radiation as the remaining mechanism to eliminate heat from the vehicle. As such, high emissivities are desired in order to dissipate heat.

The re-entry environment imposes the most severe aerodynamic heating in addition to shock and acoustic loads. Like the launch environment, the re-entry environment also includes natural conditions such as wind, rain, hail, sand, and dust.[2, 3]

Mechanisms of Thermal Protection

All thermal protection systems function to keep damaging heat away from spacecraft structures, sensors and payload. Heat is dissipated by several methods:

- Heat sinks. In this method a high thermal conductivity material absorbs the heat and distributes it quickly and uniformly away from the part of the spacecraft it was designed to protect.[4, 5]
- Active cooling. In high heat flux areas, fluids can be used as a liquid or gaseous heat sink when distributed to hot sections via a cooling loop. This mechanism implies a parasitic weight to the system because of the fluid distribution structure. Past proposed cooling fluids include liquid metals like sodium or potassium as well as gaseous hydrogen cooling envisioned under the National AeroSpace Plane (NASP) program.[6]
- Transpiration cooling. Transpiration cooling involves the ejection of a fluid or gas through a porous skin into a boundary layer between the heat flux and the surface, thus reducing the adiabatic wall temperature of the surface. Transpiration cooling can be passive or active, depending on the source of the cooling media. Passive cooling may even involve the use of an ablating material underneath the porous skin that upon heating sublimes to produce the cooling gas. Active cooling involves the injection of a fluid from an interior supply vessel through the porous skin. This mechanism affects both the velocity profile and the frictional drag characteristics. While such cooling schemes are often proposed, they are seldom used in actual hardware.[1, 2, 7]
- Radiation cooling. In radiation cooling, much of the heat flux is reflected back toward the black body of space by a high emissivity coating on the protected substrate. This mechanism is very effective in orbit since the heat transfer rate is proportional to emissivity and the difference between vehicle temperature and space to the fourth power.
- Ablation. Ablation is a very effective mechanism of minimizing the total energy the vehicle absorbs. Ablative cooling occurs when the heat flux changes the state of the surface substrate either by melting, sublimation, or thermal degradation; with the surface mass being carried away in the high-speed flow. Thus, the heat is expended in a material phase change rather than being conducted to the interior of the vehicle. Ablative heat shields were used on the Apollo Command Module.

Types of Thermal Protection Systems

While there are only a handful of basic types of thermal protection, there is a wide variety of materials within each type. All employ one or more of the previously listed protection mechanisms to provide adequate thermal protection.

Blanket insulation is typically a low density, low thermal conductivity material made of high purity silica, high-purity alumina fibers, or some combination of the two. While blanket insulation offers very effective thermal protection, it is not particularly strong and cannot be used as a structural material. In fact, blanket insulation must often be protected from aerodynamic loads. Additionally, blankets often have to be waterproofed to minimize the weight in absorbed water on the launch pad. For example, the space shuttle re-waterproofs its blankets each mission with dimethylethoxysilane. The advantage of blankets is that they are flexible. Thus, they do not need strain isolation pads to ease the mismatch of the thermal expansion coefficient between the structure and the TPS. Also, blankets are often directly bonded to the substructure. Thus, installation costs and time are minimal.

Types of blanket insulation include:

AFRSI – Advanced Felt Reusable Surface Insulation – With a silica base coating for added rigidity, the initial AFRSI materials were quilt-like blankets made with high purity silica fiber between two layers of glass cloth. Subsequent generations of AFRSI employed Nextel 312® instead of glass cloth and alumina fiber insulation to increase the temperature capability of the blanket.[8]

TABI – Tailorable Advanced Blanket Insulation and DURAFRSI – Durable Advanced Reusable Surface Insulation – Both are similar to AFRSI, especially the more advanced AFRSI. TABI and DURAFRSI use high purity silica fibers held together by integrally woven ceramic yarns.[8]

Tile Insulation is similar to blanket insulation. Both tile and blanket insulation are essentially composed of lightweight, low conductivity fibers. Tile insulation differs from blanket insulation because the processing and coating treatments rigidize the tile, making it more resistant to aeromechanical loads. However, because tiles are rigid and are composed of low thermal expansion fibers, they often need to be strain isolated from higher expansion metallic substrates via an aramid fiber felt and RTV silicon. Because tiles are also modular such that individual tiles can be replaced, they require gap fillers between them. Tiles excel in both extreme acoustic environments (165 dB for the shuttle launch) and thermal shock cycling. For example, tiles can be removed from a 2300° F oven and immersed in cold water with no damage. Tiles are also good insulators since by volume they are approximately 90% voids. Because of this porous nature, the tiles used on the shuttle must be waterproofed using a silicone resin.

Typical types of tile insulation include:

LRSI – Low Temperature Reusable Surface Insulation – These are the white tiles of the space shuttle orbiter and are used to protect the areas of the orbiter that experience maximum temperatures between 700 and 1200° F. Several grades of LRSI tile have been developed for shuttle use including LI-900 and LI-2200. LRSI tiles on the shuttle are thin (between .2 – 1.4 in.) and made up of 99.8% pure silica fibers. These tiles are coated with a blend of silica compounds and aluminum oxide to give the tiles their white appearance. The LRSI tiles in fact have a surface emittance of 0.8 and a solar absorbtance of 0.32 enabling them to emit more heat than they absorb from the sun.[8]

HRSI – High Temperature Reusable Surface Insulation – The familiar black-coated shuttle tiles are similar to the LRSI tiles, with the exception that the HRSI tiles are generally thicker (between 1 – 5 in.), hence strain isolation is more important. HRSI tiles are coated with a blend of powdered tetrasilicide and borosilicate glass, which when melted yield an emittance of 0.85 and a solar absorptance of 0.85. Together HRSI and LRSI tiles help control the temperature of the shuttle during orbit just by orienting one side or the other towards the sun. Additionally, HRSI tiles are available in two densities (22 lbm/ft^3 and 9 lbm/ft^3). The dense HRSI tiles are more damage resistant.[8]

FRCI – Fibrous Refractory Composite Insulation – uses 20% alumina-borosilicate fibers and 80% silica fibers to yield a tile with three times the tensile strength, 100° F greater temperature capability and 10% lighter than an HRSI tile. Hence, FRCI is used to replace many of the HRSI 22 lbm/ft^3 tiles.[8]

The tile fabrication process lends itself to a host of additional material variations. As such, many other tiles have been developed with increased moisture resistance and increased durability.

Ablators

Ablative materials work by absorbing a great amount of heat through a phase change. A subset of ablators called charring ablators form a char layer which acts as an insulator while the virgin material underneath continues to decompose and outgas. The gaseous products from decomposition percolate through the char to effectively transpiration cool the surface. The char helps block convection heating. Furthermore, in high heat flux environments, the char will sublime. Thus, charring ablators provide multiple levels of protection. There are a couple of strategies to take when using ablative materials.

First, materials that ablate easily are very effective in removing heat. These low temperature ablators tend to have high drag coefficients and will help slow vehicles down dramatically. As kinetic energy is dissipated high in the atmosphere, the surplus thermal energy is transferred to the shockwave. Of course, slower vehicles are more susceptible to wind and are therefore not as accurate as faster vehicles. When a vehicle exceeds hypersonic speeds in the atmosphere, the air ionizes and creates a plasma sheath which tends to block telemetry and communication. Materials that easily ablate exacerbate this phenomenon with increased gaseous by-products.[9]

Early examples of low temperature ablators include cork, Teflon, Lucite, fiberglass, nylon, and urethane. In 1957, the Jupiter C vehicle demonstrated ablation as an effective thermal protection technique when its 1500 pound payload was recovered close to its target site. This was such a breakthrough that on November 7 of that same year, President Eisenhower appeared on television to show the recovered nosetip.[10] Later, in 1959, the Jupiter nosetip helped two primates, Able and Baker, survive their brief trip to outerspace. Previously, Jupiter missiles used copper, beryllium, and even examined tungsten and molybdenum blunt nosetips as heat sinks.[9, 11]

Scout, the first solid-fuel launch vehicle, launched the United States' first satellite, Discover I, using cork/fiberglass heatshields and cork insulated fins. All told, Scout vehicles flew over one hundred missions from 1957 to May 1994 when the Miniature Sensor Technology Integration (MSTI) program launched its MSTI-2 satellite.[12] Apollo used nylon reinforced with Teflon between fiberglass and cork layers to protect the astronauts.

Today's low temperature ablators use many of the same materials as ingredients. For example, the French are using cork phenolic on an Atmospheric Reentry Demonstrator (ARD) which is intended to transport crewmembers back from the International Space Station.[13] The Pathfinder used a phenolic honeycomb filled with a cork and silica bead filled epoxy, SLA-561, for the Mars entry heatshield. The space shuttle uses several sprayable ablative coatings. MCC-1 is a sprayable cork/polyurethane foam insulation (1/2 in. thick) used on the shuttle solid rocket boosters, Boeing Sea Launch Program and the Titan IV launch vehicle. The large external tank for the shuttle uses layers of a silicon-based elastomeric foam. In addition to providing thermal protection through a 1200° F ablation temperature, this material also insulates the very cold liquid hydrogen tank. This prevents hydrogen boil off while the shuttle is on the launch pad and insures that water does not condense on the tank surface to form ice, which would damage the shuttle tiles on lift off.[14]

Several intermediate temperature ablators are in wide use on higher heat flux applications. Of these, carbon/phenolic and quartz/phenolic are the most significant.

The second ablative strategy is to use materials that ablate very slowly. Although these materials absorb a lot of energy when they ablate, they tend to ablate at higher temperatures. For instance, a carbon to carbon double chemical bond takes a lot of thermal energy to break and begin the ablation process. This often leads to the need for more insulation to protect people and delicate parts. The advantage of high temperature ablators is that they retain their shape in extreme environments. Also, the high temperature capability of the material lets a designer develop more slender, lighter vehicles. Ballistic missile reentry can generate temperatures as high as 20,000° F in the stagnation zone near the nosetip depending upon flight profile and nosetip shape.[15] Additionally, these high temperature ablators do not slow the vehicle down as quickly during reentry – so they are both faster and more accurate.[16] The more renown of these high temperature ablators are 3-D and 4-D carbon-carbon composites used in many ballistic missile nosetips.

In all cases, selecting a set of ablative materials for vehicles is a balancing act between vehicle shape and size, maximum temperature requirements, accuracy and speed.

Hot Structures

Hot structures maintain their aerodynamic load bearing capabilities at high temperatures. Hot structures are selected based on expected temperature regime and mechanical loads. Hot structures protect via the heat sink and radiative mechanisms and generally require insulation to protect underlying components. In general, organic based materials have the lowest temperature capability, followed by metals and metal matrix composites, ceramic matrix composites and finally carbon-carbon composites.

Carbon-Carbon composites consist of a carbon fiber in a carbon matrix. As with all composites, the mechanical and thermal properties are determined by a combination of fiber properties, matrix properties, and processing effects. Carbon-Carbon has one of the highest temperature capabilities of all material systems and actually becomes stronger and stiffer at elevated temperatures. Carbon-Carbon's main disadvantage is its poor oxidation resistance. Carbon-carbon begins to oxidize in air at around 500° C.

For this reason, in applications such as the space shuttle nosecap coated C-C is used. Reinforced Carbon-Carbon (RCC) is C-C with a silicon carbide conversion coating and a tetraethylorthosilicate overcoat to retard oxidation. RCC uses a low conductivity rayon-based fiber and is also found on the wing leading edges and the area around the external tank attachment point. Within the nosecap, RCC uses its high emissivity to radiate heat from the hot stagnation region to cooler areas of the hollow nosecap – thus reducing the stagnation temperature.[8]

Ceramic matrix composites (CMC) used for thermal protection systems include carbon-reinforced silicon carbide (C/SiC) and silicon carbide reinforced silicon carbide (SiC/SiC). C/SiC combines the superior strength and stiffness at elevated temperatures of carbon fibers with a more oxidation resistant matrix. SiC/SiC systems are used where oxidation resistance and high temperature capability are critical. Other composite systems that have been studied for thermal protection or hot structures include SiC/Si_3N_4, SiC/LAS, and Al_2O_3/Al_2O_3.

Hermes, the French version of the space shuttle, was designed with C/SiC nosecaps and leading edges before the program was cancelled. The previously mentioned ARD, shaped similarly to the Apollo capsule, will have four CMC tiles in the large blunt heatshield.[13]

Many planned reusable launch vehicles since 1958's DYNASOAR have examined ultra high temperature ceramics such as Zirconium Diboride and Hafnium Diboride. Recently, NASA-AMES examined ZrB_2/SiC, HfB_2/SiC and $ZrB_2/SiC/C$ materials for a slender leading edge or nose tip application in an effort to reduce vehicle drag and increase payload capability. NASA-Ames, in fact, successfully flew these materials in a May 1997 ballistic test.

Metal and Metal Matrix Composites (MMC) thermal protection materials generally have a lower temperature capability but are more robust and durable than other thermal protection materials. Metallic TPS offers the intrinsic ductility of metals and they are inherently waterproof.

Early metallic TPS were primarily heat sink materials such as the copper nose tips on early Jupiter Intermediate Range Ballistic Missiles (IRBMs). Beryllium nose tips were used on the first submarine launched missile, the Polaris.[9]

Today, metallic TPS found on the X-33 is a hybrid of materials sealed in a panel. For this type of thermal protection system, very thin foils act with a metallic honeycomb and fibrous insulation to form a TPS panel. The approach can provide the durable acreage coverage needed for reusable launch vehicles. The degree of maintenance on these metallic systems should be a fraction of the maintenance that the tiles require on the space shuttle. These metallic systems may require emissive coatings to help cool the vehicle on orbit. If the launch vehicle is orbital, acreage metallic TPS will need a coating with high emissivity in order to cool during orbit. The defunct National AeroSpace Program (NASP) developed such a coating tailored to titanium aluminide.[17]

Choosing a Thermal Protection System

Ok, now what? The analysis has been done, the mission objectives specified, the aerothermal loads have been defined and critical components have been identified. One class of thermal protection is almost never used for the entire vehicle because of weight considerations, upper temperature limitations, and cost.

In addition to these fundamental considerations, TPS must contend with a variety of other environmental and design issues including wind, hail, rain, salt water, acoustic loads, lightning, handling, launch debris, and orbit debris. These environments define the durability of the TPS. Orbital debris can be particularly damaging since the impact is usually hypersonic. It is apparent that selecting TPS materials is a pretty tough balancing act since many of these environmental constraints vary with mission and location on the vehicle.

Just considering aerothermal heating of a typical shuttle mission, temperatures range in excess of 2000° F at the nose cap, leading edges, and near the engines to a low of 200° F on the leeward wing surface (See Figure 1). If a designer were to select one material based solely on the temperature capability, the designer would select C-C. However, cost and weight considerations dictate that a superior design uses a variety of thermal protection materials. In other words, the thermal protection system is designed to be "just good enough" in order to balance performance, weight, and cost considerations.

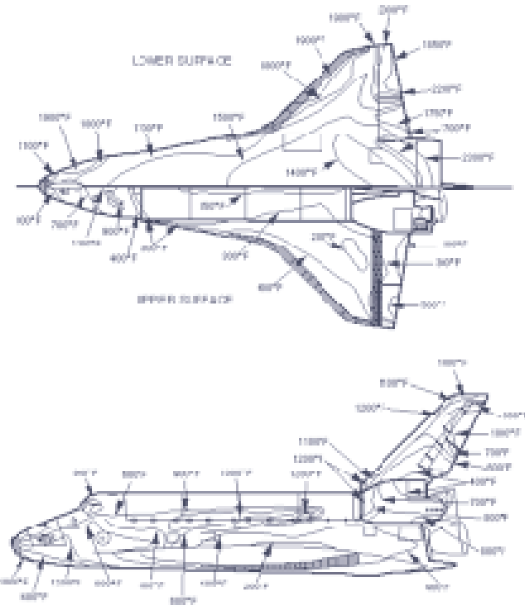

Figure 1. Aerothermal heating profile of space shuttle orbiter. [18]

Although the RCC used on the shuttle is the most durable TPS and has the highest temperature capability, it is also the heaviest and most costly. While it may not be surprising that RCC is the most costly, it is somewhat surprising to learn that on a weight per volume basis, it is also the heaviest material in the thermal protection system. Examining the constituent materials in the shuttle TPS, carbon has a comparable density compared to the silica and borosilicate fibers in the blankets and tiles. However, the open structure of the tiles and blankets make their configuration much lighter than carbon-carbon. For example, the density of silica, one of the primary components of LRSI is 2.2 g/cm^3, similar to that of carbon. Despite the similarities in densities of their primary components, LRSI tiles weigh 9 pounds per cubic foot while RCC weighs over 110 pounds per cubic foot. Again because of their open structure, tiles and blankets are much more insulating than the RCC nose cap which requires an insulating blanket underneath it to protect the structural nose of the shuttle. Figure 2 shows the distribution of TPS materials used on the space shuttle. Here it can be seen that the more costly, heavier materials are applied only where they are needed and the lighter, less expensive materials are used where they can work in concert with the performance, weight and cost requirements.

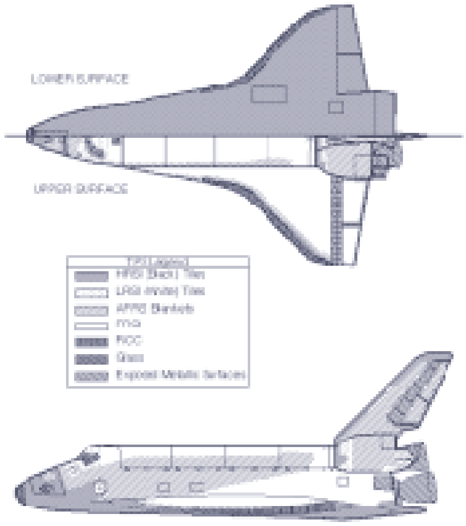

Figure 2. Orbiter thermal protection materials. [18]

Conclusion

John F. Kennedy stated on October 24, 1960 that "...the Nation which controls space controls the Earth."[19] The first step to realizing this statement is in assured access to space. Thermal Protection Materials are, and always have been, among the most crucial critical technologies in access to space. There are not that many areas where materials technology is so visibly enabling.

Thermal protections systems have garnered the attention of the American Public on several occasions. In addition to President's Eisenhower's 1957 television appearance showing the Jupiter C nosetip, John Glenn's reentry after Friendship 7's three orbits around the planet captivated Americans in 1962, when many thought his heatshield was disintegrating.

In short, TPS materials are critical because they represent the outermost protection against some very hostile environments. Even after four decades of research on TPS materials, TPS is still an enabler for tomorrow's missions. Despite the efficiency of the shuttle TPS, an estimated 40,000 hours of maintenance is spent between flights refurbishing and inspecting it. Tomorrow's RLVs will require quicker turn around in a single-stage-to-orbit vehicle.

It is easy to think that TPS is a single material. It is not – TPS is a system of materials working together. A vehicle requires several systems over the aeroshell to protect it in the most efficient manner.

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