Conference Session B9
Paper #3131

SURVIVING THE HEAT: THE APPLICATION OF PHENOLIC IMPREGNATED CARBON ABLATORS

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Abstract - *As society reaches farther into the cosmos, one constant obstacle stands in the way of every manned mission. This obstacle is to return crew, cargo, and the spacecraft to Earth safely even as spacecraft experience temperatures upwards of 1500 degrees Celsius during re-entry through Earth's atmosphere [1]. To make this return trip without harm to the craft or its contents, considerable heat shielding is necessary. This heat shielding is provided in a number of different ways, depending on the craft, but the most recent of Space-X's line of spacecraft, The Dragon Capsule, uses a Phenolic Impregnated Carbon Ablator (PICA) designed to enable Space-X to completely reuse capsules for future missions [2]. Ablators are specific types of heat shielding that are made to turn to gas during re-entry, which causes the heat to be dissipated through the process of convection [3]. In this paper, we are going to examine PICA, its manufacturing, and its testing, as well as explore the other options of heat shielding such as the space shuttle thermal protection system and NASA's new Inflatable Re-entry Vehicle Experiment (IRVE). We will also discuss the successes and failures of some heat shielding mechanisms to date, namely the Colombia disaster. PICA's structure will be examined on both a microscopic and macroscopic level to gain an understanding of the properties of the material, possible advancements and where the industry is headed. PICA-X is a huge progression for heat shielding that was designed to take new, larger spacecraft to Mars.*

Key Words- Ablator, Dragon capsule, Heat shield, NASA, PICA, Space-X

THE NEED FOR EFFECTIVE HEAT SHIELDING

Today, space exploration is a field of rapidly growing interest. As the space industry is expanding, the need for returnable vehicles and vehicles that are able to land on other bodies is growing. During re-entry or landing on another body, a tremendous amount of heat is generated. Upon re-entry into Earth's atmosphere spacecraft experience temperatures of up to 1,600 degrees Celsius [1]. If any vehicle is expected to remain intact and operating after re-entry, significant heat protection becomes a necessity.

In the era of space exploration there have existed two preeminent types of heat shielding. The familiar space shuttles from NASA employed an aluminum skin covered in silicon tiles. These tiles are used along with a carbon composite on the wings to insulate the shuttle. The Russian Soyuz, the Chinese Shenzhou along with all early NASA spacecraft, however, used ablative heat shields [4]. Rather than acting solely as an insulator, an ablative heat shield slowly burns off and uses convection to keep the spacecraft within a safe temperature. This type of heat shield actually erodes under re-entry conditions, instead of simply absorbing heat. Ablative heat shields take advantage of the hypersonic flow of atmospheric gases, which creates a boundary layer of low pressure against the vehicle. Within this boundary the ablated gases circulate and convey heat away from the vehicle. Because of the properties of hypersonic flow during re-entry, ablative heat shields are an efficient option for thermal shielding. See Figure 1.

FIGURE 1

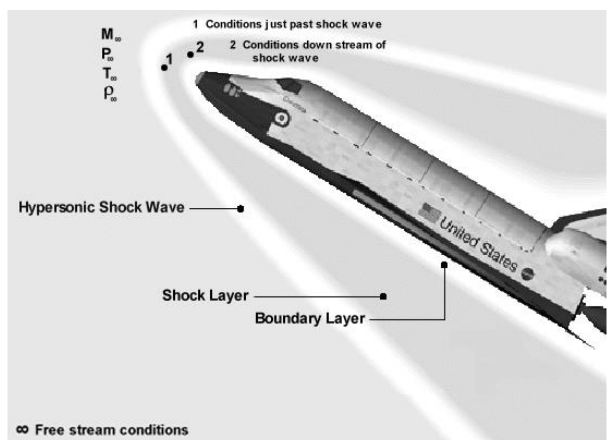


Illustration of hypersonic flow [5]

THE TECHNOLOGY OF HEAT SHIELDS

Although thermal protection systems (TPS) are a necessity, there are essentially only a few types of TPS in use today or that have been used in the current area of space travel. These include NASA's Space Shuttle Thermal Protection System, a few different ablation based thermal protection systems, and NASA's newest TPS, the Inflatable Re-entry Vehicle Experiment, or IRVE. It should be noted that the Space Shuttle TPS was used exclusively on the Space Shuttles, which are now retired, and the IRVE is still in its experimental stages. This leaves mostly ablative based TPS species being currently used and they are being used on some of the most high-profile missions in the history of spaceflight. Missions such as NASA's Mars Science Laboratory, which has been collecting some of the most monumental data from the Martian surface [6] and Space-X's Dragon Capsules, which were the first, and currently only, commercially developed space craft to dock with the International Space Station [7].

In depth on PICA and ablation

It has been established that ablative based TPS species are the way most spaceflight agencies are choosing to go, but what exactly is an ablative based TPS species and what is ablation? The answer to those questions, unfortunately, requires a good amount of background knowledge on its fundamental processes, so we will explain those first. Another bit of information that might help to understand the process of ablative heat shielding is the definition of ablation, which is defined as the corrosion of the outer layer of a spacecraft's skin due to heating from hypersonic speed [8].

Now, armed with the definition of the process itself, a greater understanding of it can be created. It was stated that the outer layer corrodes away in order to shield the vehicle from intense heat. It does this through the process of convection, that is, heat transfer by a flow or current of fluid, just the same way a radiator heats a room. This convection occurs because the corroding, or pyrolysizing layer, made of reinforced composites impregnated with organic resins, diffuses towards the heated area of the shield where a boundary layer, caused by the low pressure of re-entry, allows for the heat to be transferred away from the shield. As the composite pyrolysizes, it usually produces a carbonaceous residue called char. A layer of char is eventually formed creating a second level of heat protection [8]. See figure 2.

FIGURE 2

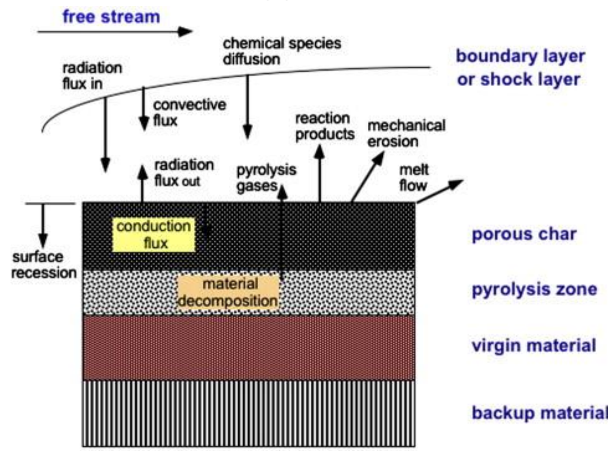


Diagram of ablation process [8]

More details on the technical aspects of PICA-X will be given later in the paper. Let's now examine the technical processes of the other two TPS species, the Space Shuttle TPS and the IRVE.

In Depth on the Space Shuttle TPS

The Space Shuttle Thermal Protection System was the proprietary system that NASA developed and used on their Space Shuttles from 1981 until the retirement of the Shuttles in 2011. The system proved over its thirty year life-span to be extremely effective, only causing one failure out of 134 successful launches. Unfortunately, even that success rate is not high enough when creating manned spacecraft. The only failure of the TPS caused the complete destruction of an orbiter and the death of seven astronauts during re-entry, but this will be discussed in depth later.

The Shuttle's TPS consists of seven main materials meant to protect the orbiter and its payload from the extreme heat of re-entry, while being reusable for up to 100 missions. These materials were reinforced carbon-carbon tiles, high-temperature reusable surface insulation tiles, fibrous refractory composite insulation tiles, low-temperature reusable surface insulating tiles, a flexible reusable surface insulation, blankets of coated Nomex surface insulation, and some additional materials needed for special areas such as the windows [9].

The reinforced carbon-carbon, or RCC, tiles, which are colored black on the Shuttles, appear on the nose cap and the leading edge of the wings. These tiles are made to protect the orbiter from temperatures above 1260 degrees Celsius. Also colored black, are the high-temperature reusable surface insulation (HRSI) tiles. These tiles are fastened to the forward fuselage and the underside of the orbiter where RCC is not used and can withstand temperatures below 1260 degrees Celsius. Fibrous refractory composite insulation tiles serve the same purpose as the HRSI tiles, but have a higher strength and weigh less, thus replaced the HRSI in some key areas of the orbiter. The white tiles that coat the upper part of the fuselage as well as the top of the wings are low-temperature reusable surface insulating tiles. These tiles are used for areas where the temperature does not exceed 650 degrees Celsius. They were eventually mostly replaced with flexible reusable surface insulation, which was essentially a quilt of composite fabric between two layers of white fabric. This new surface insulation comes with greater ease of production and durability as well as reduced installation time and cost. White blankets of coated Nomex surface insulation are used on the very upper part of the fuselage and other lower heat areas, and can withstand temperatures of about 370 degrees Celsius [9].

In Depth on the IRVE

These materials were developed over the time of development of the Shuttles and some were even implemented long after the Shuttle flights began, but one technique of heat shielding is just in its beginning stages of development, and that is the IRVE. To quote NASA's own reports on it, “The heat shield is a cone of inflatable rings, which when filled with nitrogen look a little like a giant stacking ring toy or a mushroom. The rings are covered by a high-tech blanket or thermal protection system that is made up of layers of heat resistant materials. [10]” The inflatable cone will be deployed about 280 miles above the Earth's surface because of the potential for extreme heating before the cone is deployed [10].

Right now, this system is being tested on a three stage Black Brant XI rocket with numerous cameras, ready to record and stream the re-entry to the control room in Wallops Flight Facility in Eastern Virginia. Carrie Rhoades, a flight systems engineer, said this of the new heat shield: “We like it when it looks simple. It actually took quite a bit of work to get to where we are now. We have to do all kinds of different testing -- in wind tunnels, high temperature facilities and laboratories [10].” According to engineers at NASA, inflatable heat shields such as IRVE, “could offer more flexibility for future missions by reducing size and weight restrictions that are part of the rigid aeroshells we currently use for planetary exploration [10].”

Why Ablative TPS?

Of these three separate TPS species, why an ablative TPS? More specifically, why PICA? The answers to these questions come down to efficiency; faster reentries, the ability to shield from higher temperatures, and overall ease of production. Robin Beck, an engineer at NASA's Ames Research center, where PICA was developed had this to say about the TPS: “The MSL PICA heat shield was designed to withstand more than five times the highest heating encountered anywhere on the space shuttle and we expect that it will perform beautifully,[6]” and indeed it did, landing on the surface of Mars successfully on August 6, 2011 [10]. Another advantage of PICA and other lightweight ceramic ablator shields is that they are only slightly denser than balsa wood, a rather low density type of wood. It can weigh as little as one fifth as much as other shields, and yet protects vehicles from temperatures upwards of 2760 degrees Celsius [11]. S. Pete Worden explains the future of ablative shields in NASA's press release after PICA won NASA's Government Invention of 2007: “This material will play a key role in NASA's future space missions as we mount human and robotic missions to the moon, asteroids, Mars and throughout the solar system [11].”

As if these statistics and projections weren't enough evidence to believe that PICA and ablators are the future of TPS, PICA holds the honor of enabling the fastest re-entry of a spacecraft to Earth. It was used on NASA's Stardust Capsule which brought back samples of comet particles and interstellar dust faster than any man-made object to reenter Earth's atmosphere. It is also planned to be used on NASA's Orion Crew Vehicle and was used on their recent Mars Science Laboratory, carrying the Curiosity Mars Rover [11].

NASA-Space-X COLLABORATION

In the 1980's NASA developed a light-weight heat shielding material at its AMES Research Center which was the basis for NASA's new PICA heat shield [12]. This heat shield was first employed on NASA's Stardust mission upon re-entry into Earth's atmosphere. The ablative heat shielding material was a breakthrough in the field, offering an extremely low density, high performance alternative to other traditional heat shielding options. Even today the PICA material remains a viable and highly effective heat shielding option for spacecraft re-entry. In recent years, however, the PICA heat shield was redesigned by the private corporation Space-X for use on its Dragon capsules. Though the original PICA heat shield was very effective, it had one major drawback that Space-X could not overlook. After deciding to use PICA on its vessels Space-X looked to NASA's manufacturer for the original PICA heat shield. The price of PICA heat shielding from the manufacturer, however, was far more than Space-X was willing to pay, and so the private corporation took to creating its own version of the

PICA heat shield.

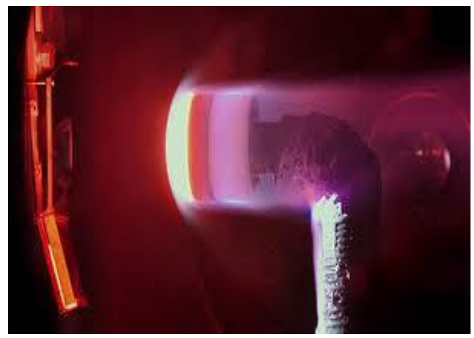
This updated heat shield would not only focus performance improvements over its predecessor, but would emphasize reusability and sustainable design. Spacecraft have never been designed to be reused over multiple missions, but this is something that Space-X has made one of its greatest goals. Eliminating the need to build entirely new vehicles with every flight will allow for vast expansion of the spaceflight industry. With the goal of sustainable spaceflight in mind, Space-X took on the task of remaking NASA's revolutionary PICA heat shield.

Contributions from NASA and Space-X

Lacking the specialized facilities needed to develop and test such a vital component of its spacecraft, however, Space-X turned to NASA and its breadth of resources. NASA and Space-X worked very closely throughout the development of the new heat shield, known now as PICA-X. In 2008 NASA even sent Dan Rasky, one of the original developers of the PICA heat shield and a twenty year veteran at NASA to work with Space-X in the design of this new heat shield [13]. With its long history of space exploration, its advanced facilities and its seasoned researchers; NASA had a lot to offer Space-X and played a vital role in the development of PICA-X. Space-X, however, took the project to new levels, bringing the project the high level of efficiency necessary for private enterprise. The rapid development style Space-X took is made clear by Dan Rasky and Andrew Chambers in their article "*Nasa + SpaceX Work Together*" when they recall an early design meeting headed by Space-X CEO Elon Musk. " ...Musk turned to Rasky during the discussion of options for producing PICA and asked, 'Dan, what do you think?' When Rasky described his preference and the reasons for it, Musk said, 'OK. That's what we're going to do,'. [13]"

This type of sudden decision making is something which a government agency such as NASA cannot employ. In a small corporation such as Space-X, however, speed and efficiency cannot be compromised. In order to remain in business and to secure contracts, Space-X has no choice but to be exceptionally efficient. That speed of the design process, however, though vital to the success of the project, would not have been possible without NASA's expertise and resources at hand. NASA offered Space-X its fifty years of space exploration experience [14] and the wealth of knowledge that comes with that experience. The engineers at NASA knew better than anyone how heat shielding was designed produced and most importantly how it behaved in flight. In addition to its experience, NASA provided Space-X with one of the most crucial tools of the entire project. This key contribution from NASA was the Atmospheric Re-entry Materials and Structures Evaluation Facility (Arc-Jet) at the Ames Research Center (ARC) [15] , to which Space-X was given full access during the course of the project. In this highly specialized facility, the Arc-jet, capable of generating heated gas up to 7,000 K [1] is used to test heat shielding materials under re-entry conditions. See figure 3.

FIGURE 3



A sample if PICA-X being tested at NASA's Arc-Jet Facility [13]

Without access to the Arc-jet facility Space-X would have had no means of properly testing the PICA-X heat shield material and the project would have floundered.

Collaboration Results

The collaboration between NASA and Space-X was a resounding success, the entire Dragon project from initial design its first mission taking only 4 years [16]. The result of the project was a reusable high performance heat shield which, according to Musk could withstand hundreds of reentries to earth [24]. The project marked a huge step forward in Space-X's mission toward sustainable spaceflight. The efficiency of the private corporation Space-X coupled with the experience and resources of NASA allowed for the development of new PICA heat shield, PICA-X, which improved on all aspects of its predecessor. In Andrew Chaikin's article "*Is SpaceX changing the rocket equation?"* Space-X propulsion Chief Tom Mueller admits, "We're standing on the shoulders of giants...with the Apollo program they learned so much. And we can get access to all that. We use that tremendously. A private company in a vacuum could not do what we did. [17]"

THE ADVANTAGES OF PICA-X

The collaboration between NASA and SpaceX played a major part in ushering in a new era of space exploration, one led by commercial institutions rather than governments. There are so many advantages to this new direction that space exploration is taking, especially for the case of the American government and NASA. In the years since NASA's conception in 1958, the funding they've received from the government has dwindled to nearly nothing. At its peak during the Apollo program, just before landing men on the moon with Apollo 11 , NASA received nearly four and a half percent of the federal budget. Today, they receive less than half of a percent. This meager budget has put major constraints on the power of NASA and thus has made privatized space flight a necessity [18].

This particular collaboration has brought major improvements in SpaceX's TPS technologies. At the time, their Dragon Capsule, soon to be the first private capsule to dock with the International Space Station, needed a suitable TPS to prevent it and its cargo from burning up during re-entry. Yes, NASA had already developed their PICA shield for Stardust and MSL but Dragon was to be the first vehicle using a PICA based shield to enter the Earth's atmosphere from low Earth orbit rather than deep space. For this reason, the Dragon capsule would not need to have as heavy protection as it would be going only half the speed of Stardust and will only experience a tenth of the heating [13].

The PICA-X shield that resulted was tested at the Ames Research Center's Arc Jet Complex. It withstood temperatures of up to 1850 degrees Celsius, the projected temperature of Dragon during re-entry, with only a few inches of PICA-X needed. Elon Musk, had this to say of the testing, “The arc jet tests represent the culmination of an aggressive six-month development effort, and our goals have been met or exceeded.” The overall performance of the shield is important, but also important is the ease of production of the shield, and in Space-X's own press release on PICA-X, it was said that, “[PICA-X] has several improved properties and greater ease of manufacture, [13]” when compared to the original PICA [13].

Space Shuttle Disaster

A question that might be looming is: why improve upon PICA and not another TPS such as that on the Space Shuttle? One short and simple way to answer that question is to look at the track record of the Space Shuttle TPS, in which one grim accident in 2003 forever tainted the reputation of the Shuttles and their heat shields [19].

On February 1, 2003, seven astronauts lost their lives in a disastrous breakup of the Space Shuttle Columbia. During re-entry, the heat shield keeping the vehicle and its cargo intact, failed, causing it to completely disintegrate in the skies over Texas and Louisiana. This led to NASA suspending the Space Shuttle program while a full investigation took place [19].

The investigation found that during lift-off, a piece of foam from the left bipod ramp had separated and impacted the leading edge of the left wing. This impact was able to create a hole in the Reinforce Carbon-Carbon tiles on the leading edge of the wing that measured nearly sixteen by sixteen inches which allowed hot atmospheric gasses to flow under the shield on the left wing. These hot gasses caused failures of many instruments, the first of which were temperature sensors in the wing and then tire pressure sensors in the left tires. These failures raised concerns at mission control, who called Columbia to discuss them. Mission commander, Rick Husband, had enough time to reply with “roger,” a cut off word and then silence. It was later revealed to Mission Control that the Shuttle had broken up. It was found that the break up was caused by the hole in the RCC tiles on the wing, and analysts had previously estimated that a hole only ten inches wide would have been capable of destroying the vehicle during re-entry [20].

The Columbia disaster had a profound impact on the public's view of the Shuttles and their heat shielding and while it may be possible for such a disaster to occur with a vehicle using a PICA TPS, it is yet to happen. This gives PICA an ethical advantage over the Space Shuttle TPS. Would you rather use and work on advancing a TPS that has already failed and caused the loss of seven lives rather than one with accolades such as the fastest re-entry, that has never caused loss of life? Neither would I, and this seems to be a major contributor to the continued development of PICA-X and the retirement of the Shuttles.

PICA-X STRUCTURE AND PRODUCTION

In order to understand why PICA-X has such beneficial properties we will investigate the structure of the heat shield material as well as look into its manufacturing. First we will look at PICA-X from a macroscopic viewpoint, inspecting its readily observable physical properties and applications. With knowledge on the physical aspects of PICA-X, we will move onto its structure on a microscopic level as well as observing its chemical properties which make it such an effective heat shield.

PICA-X Macrostructure

The PICA-X heat shield, once applied to a spacecraft, consist of a number of smaller sheets of the material fitted closely together and attached to an adhesive substrate. See figure 4.

FIGURE 4

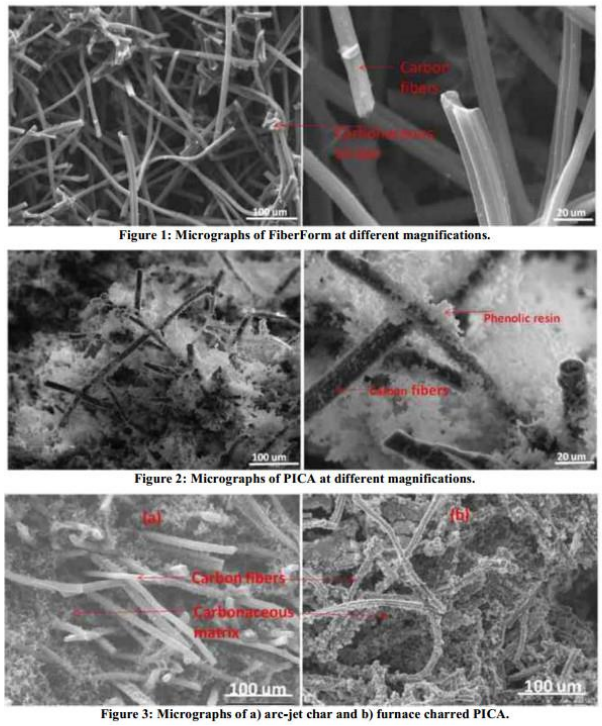
Tiled PICA-X being applied to the Dragon's heat-shield carrier [13]

The material is not flexible and not easily manufactured into very large curved sheets, so this piecemeal type of construction is necessary for application to any curved surface, such as that of a spacecraft designed for atmospheric re-entry. The lack of flexibility of the material, however, is of no consequence once applied to the substrate. The greatest advantage of PICA-X is its low thermal conductivity as well as its very low density. When sending vehicles into space, weight is a major concern. Space-X has managed to trim launch costs to around $1000 per pound [17], a vast improvement from NASA's $10,000 per pound price tag [21]. With numbers so high, though Space-X has lowered cost greatly, any weight reduction is not only very beneficial, but it is a necessity. Space-X's new PICA-X heat shield material boasts a density of only 0.27 g/ cm^3, near the density of solid cork (0.24 g/cm3) [22]. The material needs only be a few centimeters thick (typically around 6 cm) in order to protect the spacecraft from the intense heat experienced during re-entry. According to Space-X a few inches PICA-X heat shield will protect against temperature of up to 1850 ^oC keeping the interior of the capsule at room temperature [23]. This material is also designed to be reusable, as a part of Space-X's push for reusable spacecraft. In the words of Space-X CEO Elon Musk, "This is the most advanced heat shield ever to fly. It is so powerful that it can potentially be used hundreds of times for Earth orbit re-entry with only minor degradation each time and can even withstand the much higher heat of a moon or Mars velocity re-entry.[24]" In order to understand why PICA-X is such a sustainable and reusable heat shield, we will examine the structure now on a microscopic level.

PICA-X Microstructure

Looking at the microstructure of PICA-X, we can gain an understanding why it has the ablative properties that it does and why it is such an excellent option for heat shielding. We can learn a lot about the heat shield by investigating the naming of the material. PICA is short for Phenolic Impregnated Carbon Ablator. By breaking down the components of the name and looking at each of the mentioned substances, we can understand just what the PICA-X material is. First, we will discuss what makes PICA-X an ablator. From our earlier exploration of ablators, we know that an ablator heat shield works by eroding during re-entry and allowing some of its material to pyrolyze. This is the process by which PICA protects spacecraft during re-entry. PICA is made up of two major components both mentioned in the material name, a carbon fiber insulator and a phenolic resin [25]. These two substances are bonded together to form PICA's very low density, porous structure. The substance which undergoes the pyrolysis is the phenolic resin. The resin is initially dispersed among the carbon fibers, bonding the material and pushing the fibers apart, creating a porous structure. Once the extreme heats of re-entry are encountered, the phenolic resin undergoes pyrolysis, altering the microstructure of the PICA heat shield. Under very high temperatures the phenolic resin sublimates, leaving behind a carbon matrix, within which the carbon fibers remain bonded [25]. In this new carbon matrix, the fibers are significantly closer together, resulting in the char layer. The material for the PICA heat shield begins as a simple carbon fiber insulator, which lacks ablative properties. Through the addition of the phenolic resin, the material attains ablator status, while retaining the carbon fiber's original insulating properties. See Figure 5.

FIGURE 5



Various magnifications of PICA during a heat test [25]

PICA-X Production

Though we do not know the precise methods employed by Space-X to create the PICA-X heat shield, we do know that is produced in much the same way as the original PICA; PICA-X being only a modification of the original PICA [24] . PICA production begins with a material called Fiberform [24]. Fiberform is a carbon fiber insulator designed for use under extremely high temperatures. This material provides the carbon fibers which make up the main body of the heat shield. As the name of the heat shield suggests, the carbon fiber material is impregnated with a phenolic resin. The impregnation results in a material in which carbon fibers are bonded by the organic bonds made possible by the introduced phenolic resin. The development of PICA-X stemmed from the high price of PICA from other manufacturers. In developing and creating PICA-X in house, Space-X was able to create a cheaper and more effective heat shield. According to Meuller, Space-X's PICA-X material is 10 times less expensive to produce than NASA's original PICA and he adds, "…and the stuff we made actually was better. [17]"

PIONEERING SUSTAINABLE DESIGN

PICA-X is designed to be resistant to extremely high temperatures as well as resistant to the extreme forces exerted on it during reentry. The high standards to which PICA-X was held during design and construction ensure that the shield remains structurally sound and safe to reuse over multiple flights. After reentry it can be observed that less than a centimeter of the heat shield pyrolyzes [26]. To prepare for reuse on a future launch the charred material is removed leaving untouched materials ready to protect another vehicle during reentry. The shield, being over 3 inches thick, is not negatively affected by the removal of less than a centimeter of outer material. The process of pyrolysis and char removal can be repeated multiple times allowing for the reuse of the PICA-X heat shield over the span of many missions.

This ongoing mission toward reusable and sustainable spaceflight echoes throughout Space-X in the designs of virtually all of its other ventures. Space-X recently designed and built an autonomous rocket called the grasshopper [27]. The purpose of this rocket is to test the viability of a landable rocket. The grasshopper is able to launch and land itself autonomously and is the first rocket to achieve this feat. With this achievement Space-X is pioneering a new generation of completely reusable spacecraft. During its development, the altitude that the grasshopper has been able to reach has shown exponential growth. " Last September, Grasshopper flew to 2.5 meters (8.2 feet), in November, it flew to 5.4 meters (17.7 feet) and in December, it flew to 40 meters (131 feet).[27]" With continued testing the grasshopper project shows great promise and marks a huge step forward in sustainable rocketry.

The stretch for sustainability by Space-X is apparent after a brief examination if its CEO, Elon Musk, who also runs Tesla Motor Company. His drive to remain green, reusable, and sustainable shows in the endeavors of both of his companies.

In contrast to the PICA-X heat shield, the shields on the Space Shuttles and the IRVE are less reusable. After every launch of a Space Shuttle, a process of re-waterproofing was required before subsequent launches. A waterproofing substance had to be injected under each tile through holes in the tiles and into the insulation blankets with needles [9]. After a launch of a rocket using the IRVE, the inflated shield would need to be deflated and repacked, which is one of the most painstaking processes in the development of the project [10]. Neil Cheatwood, principal investigator for the project had this to say about the packing process, “Packing actually turns out to be quite a challenge. One reason is because the IRVE-3 thermal protection system has this insulating layer of pyrogel -- an aerogel -- that is largely air. That makes it very difficult to compress. It's like trying to compress a sponge [10]." PICA-X avoids such difficulties needing only the minor modification of surface char removal to be ready for another flight. Due to its high performance heat shielding and its ease of reuse we will very likely see PICA-X being utilized on many more missions in the future and we will certainly continue to see development of increasingly sustainable spaceflight technology. PICA-X and other innovation by Space-X, such as their merlin engines, are early steps toward Space-X’s ultimate goal of highly sustainable spaceflight [13].

CURRENT AND FUTURE APPLICATIONS

PICA and PICA-X are currently being used in some of the most high profile space flights in the history of space exploration as stated before. Less than a year ago, NASA landed its fourth and most advanced rover on Mars. This mission could potentially turn up traces of water or life, permanently changing our view of the solar system, and one of life's ultimate questions: are we alone? This monumental achievement of engineering, rivaling Apollo 11 landing men on the moon for most important achievement in space exploration, was made possible in part by the PICA heat shield on board the lander. Only a few inches of material separated the outer skin of the lander from the hypersonic flow and extreme heat of the atmosphere rushing by, and yet, the Curiosity Rover stayed at operating temperature throughout landing.

Another recent achievement of aerospace engineering was the docking of Space-X's Dragon Capsule with the International Space Station [27]. This docking marks the first time that any vehicle created by a private enterprise has interfaced with the Space Station. It has now done this twice, exemplifying a definite shift in the space exploration market from governments to private companies. For the first time in the space age, the huge funding of a government wasn't needed to explore space. This is also an achievement made possible by PICA and its successor PICA-X. During re-entry to Earth, carrying valuable experiments, data, and equipment from the ISS, the Dragon Capsule uses PICA-X to keep its cargo from burning up or disintegrating [2].

Without PICA and PICA-X, these modern miracles of engineering might not have been successful. By using a less efficient heat shield, perhaps the MSL would have burned up in the Martian atmosphere, causing a complete loss of the rover, or maybe Dragon would have disintegrated on its way back to Earth, losing all data and expensive equipment from the ISS. If a more costly shield would have been used, NASA might not have gotten funding for MSL, as the project might have been too expensive for the American Government and the Dragon Capsule might never have left the ground as the heat shield broke the bank for Space-X. Who knows what could have happened provided PICA and PICA-X were never developed? All that is known is that with them, these agencies and companies are paving the way for the future of space flight and exploring the last frontier: space.

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ACKNOWLEDGEMENTS

We would like to thank our writing instructor Dianne Kerr for providing us with feedback and helping us to improve our paper. We would also like to our section co-chair for meeting with us and taking the time to make sure we had the tools to succeed in writing this paper.