Design of a Thermal Protection System (TPS) for NASA's Space Shuttle Program

Analysis of the Columbia Space Shuttle Disaster

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On my honor as a University student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments.

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Introduction

Since 1981, NASA's space shuttle fleet has navigated 135 missions, conducted significant scientific research, and heavily assisted in the construction of the International Space Station (ISS) while transporting satellites as well as crews to space for satellite repair (Loff, 2017). Scientific experiments and observations from the space shuttle program allowed for the creation of a topographical map of Earth and induced the discovery and understanding of the universe. Additionally, space shuttle research has led to the fabrication of non-space-related technologies such as a healthier baby formula and an artificial heart pump (Borenstein, 2011). The space shuttle serves as "humanity's first reusable spacecraft" and requires a tremendous task force to conduct its various advanced operations (Loff, 2017).

In recent years, space travel has become increasingly privatized. NASA has funded companies such as Boeing and SpaceX billions of dollars for the development of cost-effective reusable spacecraft. Despite the rise of this new "space race", these companies tend to have low incentives to pursue space research that does not yield high profits (Martin et al., 2020).

NASA halted missions with its space shuttle program in 2011 due to safety issues, high manufacturing and maintenance costs, and budget cuts. In 2015, former NASA Jet Propulsion Laboratory system engineer Mark Adler wrote, "The shuttle never met its promise for low-cost access to space by virtue of the system's reusability" (Georgiou, 2020). Additionally, in regard to the geopolitical context at the time, Russia held acceptable ties with the United States and agreed to use its Soyuz spacecraft to transport U.S. space crews to the ISS in exchange for billions of dollars. With the shift in geopolitical context over time, the U.S. must now develop its own form of space transport to pursue advanced research and development (Georgiou, 2020). This can be achieved through the continuation of the NASA space shuttle program.

This proposal addresses the challenge of creating a safer and more economical space shuttle to allow for the continuation of space travel, the conduct of scientific research, as well as the transport of resources and crews to and from the ISS. To achieve these objectives, I will develop a design for a lower-cost Thermal Protection System (TPS) with greater structural stability that is more suitable for future missions of NASA's space shuttle program. In the TPS design process, I will address both technical and social factors. I will cover a technical process for redesigning the TPS that better achieves the shuttle's objectives. To address the social factors, I will apply Actor-Network Theory (ANT) to analyze the Columbia Space Shuttle disaster and understand how human and non-human actors played a role in the failure and ultimately led to the halt of future space shuttle missions.

Technical Problem

The Thermal Protection System (TPS) protects the space shuttle, or orbiter, from overheating during reentry into Earth's atmosphere as well as from extremely cold conditions in space. During reentry, a space shuttle travels more than 17,000 mph, causing surface temperatures up to 3,000℉. Without the TPS, atmospheric gases can generate enough friction to cause damage to the orbiter or even result in an explosion. Additionally, the airframe of the orbiter mainly consists of aluminum, which begins to deform or anneal at 350℉. The TPS ensures that the temperature of the airframe does not surpass this limit (Hale et al., 2010).

Four basic materials are used to design the TPS: reinforced carbon-carbon (RCC), low- and high-temperature reusable surface insulation tiles (LRSI and HRSI), and felt reusable surface insulation (FRSI) blankets. RCC is a composite material that is made by curing (toughening a material through a chemical process) graphite fabric and is practical due to its ability to reject heat by radiating it from its surface to its surroundings. This material constructs the nose cap and wing leading edge of the shuttle (Hale et al., 2010). Silica tiles are ideal for use as they have the ability to withstand extremely high temperatures and possess exceptional oxidation resistance to combat reentry environments. They also have high thermal shock resistance, or the ability to endure sudden drastic changes in temperature (NASA, 2006). Since different surfaces of the shuttle experience different temperatures, different tiles are placed on various surfaces of the shuttle (Dino, 2008).

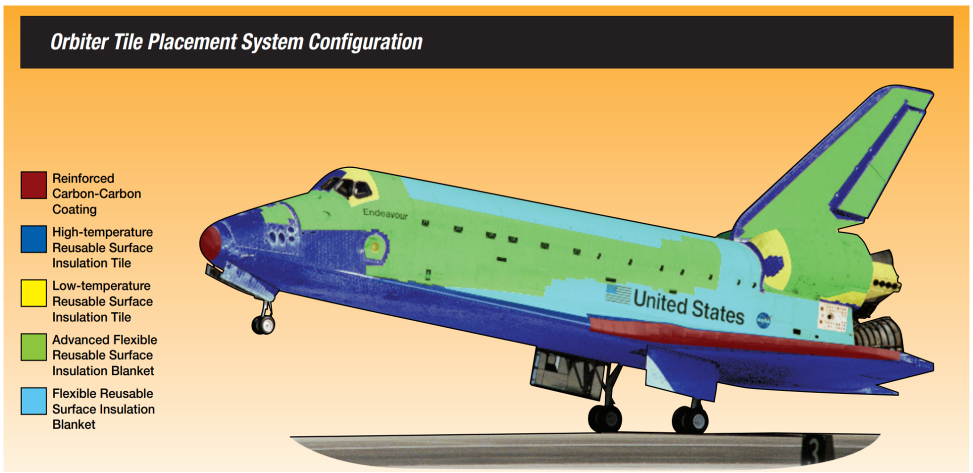

Figure 1. Tile placement on various surfaces of the NASA space shuttle

The surfaces exposed to temperatures up to 2,300℉, such as the underside of the spacecraft, are given a protective black glass coating. These tiles reflect approximately 90% of the heat they are exposed to during reentry, while slowly absorbing the rest. The surface of the shuttle's upper fuselage consists of tiles with a whitewash of silica compounds and aluminum oxide that can withstand temperatures up to 1,200°F (Benningfield, 2006). Each orbiter's TPS is made up of approximately 24,300 tiles and 2,300 FRSI blankets (NASA, 2006).

Strain isolation pads and silicone adhesives are used to bond the tiles to the shuttle. Silicones are ideal for use since they are able to maintain their bond strength at high temperatures and remain flexible at low temperatures (NASA, 2006).

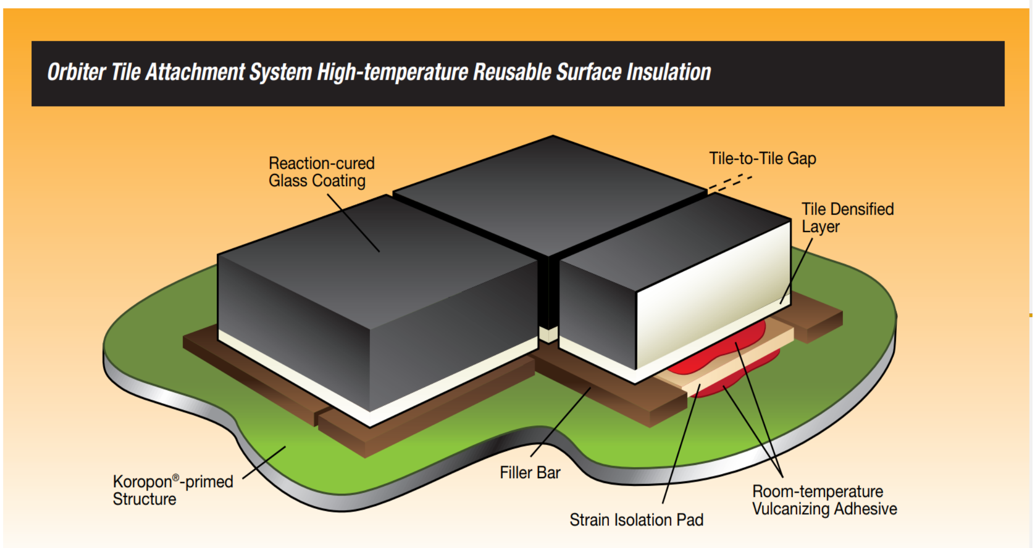

Figure 2. NASA space shuttle tile attachment and bonding mechanism

However, the current materials and design of the TPS lack modern modifications that could enhance structural stability and overall shuttle safety. Every shuttle has returned from its mission with debris-damaged tiles from sources such as ice or insulation protecting the external tank (Paté-Cornell et al., 1994). The bond holding the tiles together can also deteriorate, especially if not applied correctly, which can pose great threats to the system's stability. Furthermore, the maintenance and construction of the tiles constituting the TPS is extremely expensive as each tile is custom-made (Benningfield, 2006). Cracks and pinholes have also been found in the RCC panels that have hindered the system's framework (Hale et al., 2010).

Through this project, I will present a design for a new low-cost TPS with greater structural stability that will allow for the NASA space shuttle program to safely resume missions for space exploration, research, and transportation. To support my new design of the space shuttle TPS, I will produce a proposal that specifically focuses on selecting the best materials for the system as well as cost estimates for production and maintenance. I plan to analyze the stability of the system by determining how various tile materials are affected by different loads and environments.

STS Problem

On January 16th, 2003, NASA's Columbia orbiter was launched into space with the mission to conduct scientific research. However, during liftoff, a piece of foam insulation broke off the shuttle's propellant tank and damaged its left wing. This impact was significantly more severe than determined by NASA engineers and project managers. Nonetheless, on February 1st, 2003, the crew proceeded with normal re-entry procedures, without recognizing that their fate had been predetermined during liftoff. The Columbia disintegrated during reentry over Texas, killing all seven crew members on board (History.com Editors, 2018).

The investigation that followed the disaster determined that several heat-resistant tiles that comprised the Thermal Protection System (TPS) were heavily damaged from the impact incurred during lift-off. As a result of the damage, the system was not able to properly protect the orbiter. Atmospheric gases and heat entered the shuttle's wing upon re-entry, resulting in an explosion (Columbia Accident Investigation Board, 2003).

From a technical approach, the TPS failure caused the shuttle to explode. However, there are several non-technical factors that also contributed to the failure. For instance, the damage was not properly assessed in a timely manner while the Columbia was in orbit and appropriate action was not taken. The impact occurred during the Martin Luther King Jr. holiday weekend, which caused many individuals in project management to take a more relaxed approach, disregard the impact, and refrain from searching for alternatives to mitigate disaster in a timely manner. NASA project managers did not immediately notify the crew of the potential damage and believed that even if there was an issue, nothing could be done (Columbia Accident Investigation Board, 2003).

Additionally, NASA's decisions were strongly influenced by its public relations due to its uncertainty for future funding. As a result, NASA had advertised a higher flight frequency and degree of safety than its actual capabilities. After the space shuttle program was introduced, the organization shifted from its conservative mentality of "launch if proven safe" to "launch unless proven unsafe." This contributed to poor organizational culture as safety concerns were ignored and resulted in severe consequences (Paté-Cornell et al., 1994).

The lack of budget also contributed to an inability to properly assess the damage while the shuttle was in orbit. The cameras that did take photos of the impact site were not able to obtain a clear visual of the severity of the damage. This was due to a lack of necessary equipment and staff cuts. The Department of Defense (DOD) was prepared to use orbital spy cameras to obtain a detailed view of the damage, however, NASA officials declined the offer. Many engineers requested a further investigation into the damage, however, project managers disregarded their concerns. Project managers made many decisions with no factual evidence backing their beliefs (Columbia Accident Investigation Board, 2003). In many previous missions, the foam had detached from the shuttle and collided with its exterior surface with no major issues. Therefore, NASA accepted the impact that the Columbia suffered to be nothing more than a normal occurrence (Sunseri, 2013).

Alongside the TPS failure, I argue that poor project management and organizational culture, a low budget for such an extensive program, and pressure from public relations contributed to the Columbia space shuttle disaster. Actor-Network Theory (ANT) seeks to identify the interactions of human and non-human actors working together in a network to accomplish a common goal (Cressman, 2009). By applying ANT to the shuttle failure and identifying the shuttle as the network, it is evident that there are social and economic factors that influenced the fate of the Columbia shuttle. If the role of human or non-technical actors in the system was overlooked, I would not be able to completely understand why the shuttle failed nor how to prevent similar failures in the future.

Conclusion

To allow for continued space exploration and research through the NASA space shuttle program, I will design a more structurally sound, cost-effective TPS to enhance the safety of space shuttles. This enhanced system will include stronger, yet cheaper materials that ultimately comprise a superior design for NASA's orbiters. My design will be developed alongside an analysis of the Columbia space shuttle disaster, which exposed many flaws within the space shuttle program as well as in the overall construction of the TPS. I will apply Actor-Network Theory in my analysis to identify the roles human and non-human actors played in the shuttle network. By doing so, I will be able to better understand and address the necessity for space shuttles to be able to conduct successful missions in the future and prevent similar failures from recurring.

Word Count: 1,822

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