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Orbiter Thermal Protection System

When the orbiter re-enters the Earth's atmosphere, it is traveling in excess of 17,000 mph. To slow down to landing speed, friction with the atmosphere produces external surface temperatures as high as 3,000 degrees Fahrenheit – well above the melting point of steel. Special thermal shields are required to protect the vehicle and its occupants. Although the orbiters were constructed using highly advanced construction methods and materials, the airframe is formed primarily from aluminum and can only withstand 350 degrees F without the material annealing, or softening. The primary purpose of the thermal protection system is to ensure that the aluminum airframe does not exceed this 350-degree limit.

Earlier manned spacecraft, such as Mercury, Gemini and Apollo, were not maneuverable and followed ballistic re-entry trajectories, parachuting to a watery landing in the ocean. The space capsules were protected during re-entry by a heat shield constructed of phenolic epoxy resins in a nickel-alloy honeycomb matrix. The heat shield was capable of withstanding very high heating rates. This was particularly necessary during the Apollo moon missions where the capsule, returning from the moon, entered the atmosphere at more than 25,000 mph. During the reentry, the heat shield would ablate, or controllably burn with the char layer protecting the layers below. Despite the advantages, ablative heat shields had some major drawbacks. They were bonded directly to the vehicle, they were heavy, and they were not reusable.

For the Space Shuttle orbiter, a different kind of heat protection system was needed. With a design life of 100 missions, this revolutionary new space vehicle required a lightweight, reusable Thermal Protection System composed of entirely new materials.

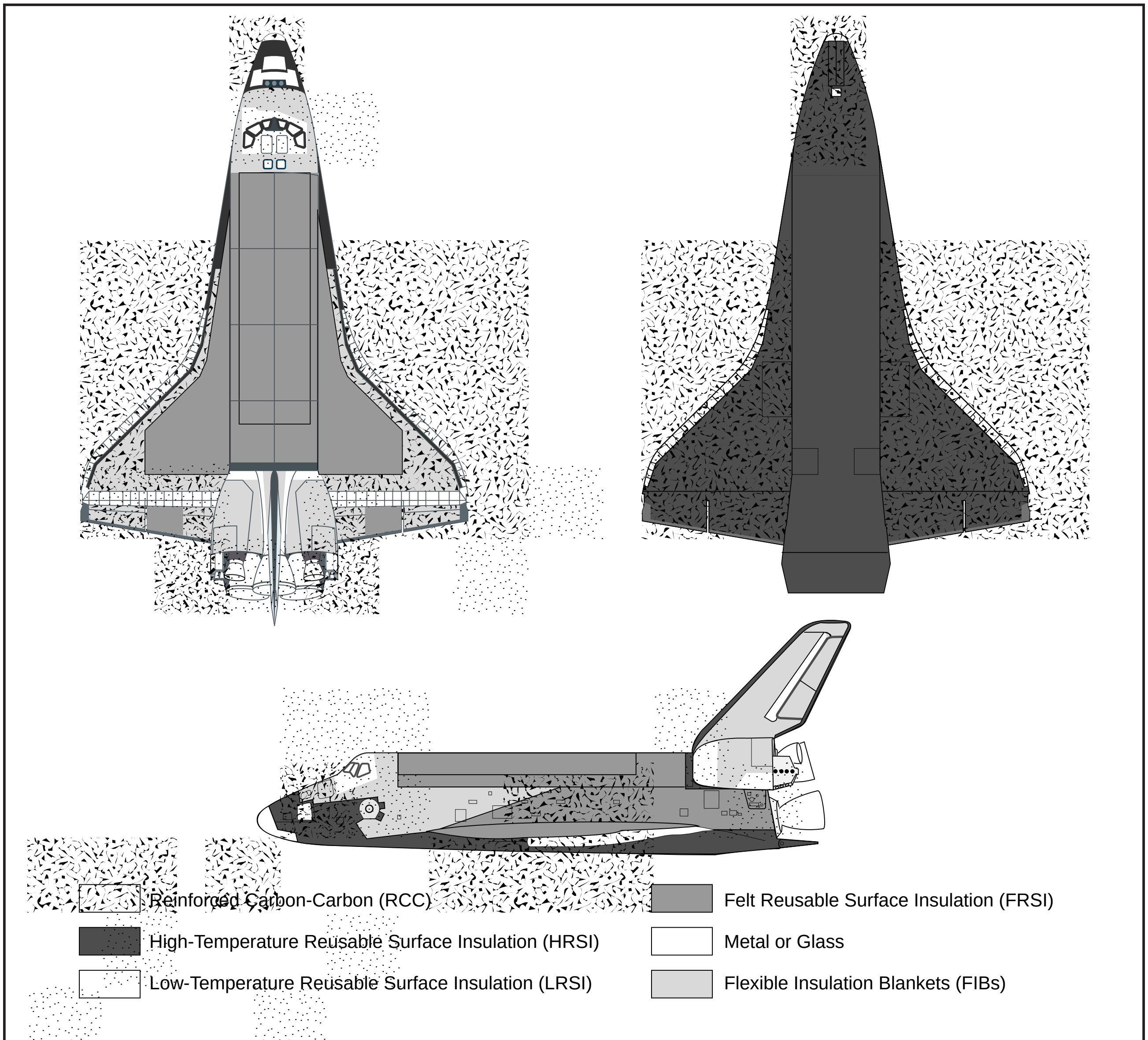
The purpose of the thermal protection system is not only to protect the orbiter from the searing heat of reentry, but also to protect the airframe and major systems from the extremely cold conditions experienced when the vehicle is in the night phase of each orbit. The external temperature fluctuates from -200 degrees F to +200 degrees F during each 90-minute orbit.

Thermal Materials

NASA selected four basic materials for the original design used on Columbia, the first operational orbiter. The basic materials were Reinforced Carbon-Carbon (RCC), Low- and High-Temperature Reusable Surface Insulation tiles (LRSI and HRSI, respectively), and Felt Reusable Surface Insulation (FRSI) blankets. For the development flights, Columbia had more than 32,000 individual tiles covering the lower and upper surfaces, with FRSI covering the upper payload bay where peak temperatures were less than 600 degrees F.

Reinforced Carbon Carbon (RCC)

RCC is a light gray, all carbon composite. It has sufficient strength to withstand the aerodynamic forces experienced during launch and reentry, which can reach as high as 800 pounds per square foot. These molded components are approximately 0.25-inch to 0.5-inch thick. RCC, although strong and capable of withstanding extreme temperatures, is also thermally conductive. This necessitates extensive use of insulating blankets and tiles behind the RCC panels to protect the structure and attach fillings from heat radiated from the back side. Combinations of Nextel/silica fiber blankets and internal tiles protect the area behind the nose cap, and Inconel foil (metal) wrapped ceramic insulators protect the wing leading edge. RCC also is used in the arrowhead area at the forward external tank attach point. RCC is used there for shock protection during pyrotechnic separation of the external tank from the orbiter.



Thermal Protection System Materials

High-Temperature Reusable Surface Insulation (HRSI) Tiles

22-pounds-per-cubic-foot =	525
9-pounds-per-cubic-foot =	20,000

Fibrous Refractory Composite Insulation (FRCI) Tiles

12-pounds-per-cubic-foot =	2,950

Low-Temperature Reusable Surface Insulation (LRSI) Tiles

9-pounds-per-cubic-foot =	725
12-pounds-per-cubic-foot =	77*

Flexible Insulation Blankets (FIB's) = 2,300

Felt Reusable Surface Insulation (FRSI) = 975**

*Columbia (OV-102) will have a slight variation in the number of tiles because of the Shuttle infrared leeside temperature sensing pod atop the vertical stabilizer. There is a slight variation in the number of tiles per vehicle. Some orbiters also have no 12-pounds-per-cubic-foot (LRSI) tiles.

**The FRSI sheets will vary slightly in number for each orbiter. An average of 1,860 square feet of FRSI sheets are used on an orbiter.

Reusable Surface InsulationTiles

Black or white tiles are used to protect the orbiter against temperatures between 1,200 and 2,500 degrees F. The necessity for both black and white tiles lies in the requirement to control the temperature of the vehicle while on orbit.

The white tiles, known as Low-Temperature Reusable surface Insulation (LRSI), on the upper surface of the vehicle have higher thermal reflectivity (tend to absorb little heat) maximizing solar gain when the orbiter is on the illuminated part of the orbit.

The black tiles, known as High-Temperature Reusable surface Insulation (HRSI), are optimized for maximum emissivity, which means they lose heat faster than white tiles. This property is required to maximize heat rejection during the hot phase of reentry.

Both white and black tiles are all made of the same base materials. These materials are manufuctured in blocks (or billets) that are machined into the precise shape of the tile before application of the coating. The reaction cured glass (RCG) coatings are made from blended glass powders mixed with thickeners and pigments. The coatings are applied with conventional spray equipment, dried, and are then fired in a kiln at 2,200 degrees Fahrenheit for 90 minutes. The coatings are approximately 0.01 inch thick.

The majority of the tiles on the lower surface are made from a material called LI-900, which has a bulk density of 9 pounds per cubic foot. They are made from 99.9 percent pure silica glass fibers, and consist of 94 percent by volume of air . The material was developed and manufactured by Lockheed Missiles and Space Company in Sunnyvale, Calif.

LI-900 was designed to minimize thermal conductivity and weight, while providing the maximum thermal shock resistance. An LI-900 tile can be heated to 2,200 degrees F and plunged into cold water without damage. Unfortunately, in optimizing these properties, overall strength was compromised and the material was not suitable for use in high stress areas such as the tiles surrounding the landing gear doors and windows.

To address this problem, a higher-strength version of the LI-900 material, known as LI-2200 (22 pounds per cubic foot bulk density) was used in these areas. LI-2200 tiles provided the strength and insulating properties needed in these areas, but not without an undesirable weight penalty. This prompted the development, by NASA, of FRCI-12, a 12-pound-per-cubic-foot bulk density material.

The FRCI-12 composition contained 22 percent by weight of Nextel fiber, an amorphous aluminoborosilicate fiber. The resultant material was considerably lighter than LI-2200, but had thermal conductivity only slightly higher than LI-900 and was compatible with the existing RCG glass coatings. It also had lower thermal shock resistance than the pure silica compositions, but remained within flight limits.

Since its introduction in 1981, FRCI-12 tiles have been used to replace both LI-900 and LI-2200 tiles in penetrating and leading edge areas of the vehicle.

White tiles insulate the spacecraft from temperatures up to 1,200 degrees F. They are typically used where aerodynamic contour has to be maintained. Although they have almost entirely been replaced with Advanced Flexible Reusable Surface Insulation blankets, they are still used on the upper surface of the forward fuselage above the crew windows and on some parts of the OMS pods, where temperatures do not exceed 1,200 degrees F.

Improvements to the Thermal Protection System repair processes have reduced the amount of maintenance required after each mission. In most cases, scratches and gouges on the tiles can be repaired with specially developed coatings and cements.

Tile Bonding

The tiles are bonded to the orbiter with a silicone adhesive. Silicones, unlike many adhesives, remain very flexible at low temperatures (experienced during the cold part of orbit) and retain good bond strength at the high temperatures experienced during reentry.

The tiles are first bonded to a Strain Isolator Pad (SIP), a needled Nomex felt material, before bonding directly to the aluminum airframe (or graphite epoxy composite in the case of the OMS pods and payload bay doors). The purpose of the SIP is to allow the tiles to "float" very slightly to limit vibration-induced damage during the ascent to orbit and also to provide a means of compensating for the differences in thermal expansion between the tiles and the airframe.

Upgrades

As flight and operational requirements became better understood, and as new material technologies became available, systematic upgrades were performed on the thermal protection system.

Fibrous Insulation Blankets

The first upgrade concerned the introduction of Advanced Flexible Reusable Surface Insulation (AFRSI—also known as Fibrous Insulation Blankets or FIB). AFRSI blankets were used to replace the majority of the white (LRSI) tiles on the upper surface. A single blanket could replace as many as 25 individual tiles although the size and shape of the individual blankets vary considerably.

The blankets consist of layered, pure silica felt sandwiched between a layer of silica fabric (the hot side) and a layer of S-Glass fabric. The blanket is through-stitched with pure silica thread in a 1-inch grid pattern. After fabrication, the blanket is bonded directly to the vehicle structure and finally coated with a high-purity silica coating that improves erosion resistance. The blankets are semi-rigid and can be made as large as 30 inches by 30 inches. In the current configuration, each orbiter has approximately 24,300 tiles and 2,300 Flexible Insulation Blankets installed.

Tile Upgrades

In 1996 NASA introduced a fourth tile material called AETB-8. AETB-8 (Alumina Enhanced Thermal Barrier) took FRCI technology further by introducing small quantities of alumina (Al2O3) fiber into the composition. This change increased the thermal stability and conductivity of the material without significantly affecting the strength or weight.

In conjunction with the development of AETB-8, a new coating became available, which, when used in conjunction with the new substrate, produced tiles known as Toughened Unipiece Fibrous Insulation (TUFI). These tiles exhibit much higher strength than earlier tiles with minimal weight impact. They have been used extensively on the orbiter in high impact areas, such as the base heat shield (around the main engines) and the upper body flap; however, their higher thermal conductivity has limited their further use.

Thermal Barriers

There are a total of 88 opening doors on the orbiter. Some are used for access during turnaround processing, like those to the payload bay midbody. Others are fixed in place during launch and open after reentry, such as the landing gear doors to allow deployment of the landing gear. Others, such as the external tank (ET) doors and vent doors, actively open and close during the ascent cycle. Each of these doors is typically provided with a silicone pressure seal that must be protected from the high heat experienced during launch and reentry.

There are over 800 individual sizes and shapes of thermal barriers on the orbiter, specifically designed for each individual application. Construction varies widely, but the general design consists of a knitted tubular spring, woven from nickel alloy wire and then tempered to provide resilience. This central spring core is overwrapped with one to five layers of braided ceramic sleeving (Nextel) and subsequently bonded either directly to the orbiter, or to a metal carrier panel which is then mechanically attached to the orbiter.

This approach is used for thermal barriers that are replaced regularly, such as those protecting the main landing gear doors and external tank fuel and oxidizer doors. Several different coatings (ceramic and silicone) are used to increase the durability of the thermal barriers. The coatings are generally applied after the thermal barriers are installed.

Thermal barriers are also extensively used to seal the interfaces between removable modules such as the Orbital Maneuvering System (OMS) pods and the Forward Reaction Control System (FRCS).

Gaps and Gap Fillers

The gaps between the tiles, which range from 0.028 inch to 0.200 inch are necessary for two important reasons. The first reason concerns the difference in thermal expansion properties between the tiles and the orbiter airframe. When in orbit, the external temperature fluctuates by as much as 400 degrees F. The tiles contract much less than the airframe, due to differences in the thermal expansion; thus, the gaps are required to accommodate the difference. During reentry the gap dimensions are also critical. As the orbiter descends through the ever-thickening atmosphere, pressure gradients cause the plasma surrounding the orbiter to flow. If the gaps are too large, hot gases can flow through the gaps and can cause damage to the backup surface seals (filler bar). Gap fillers are used extensively to control the gap dimensions between the individual tiles in many areas of the orbiter and in some areas to provide mechanical 'padding' between the tiles.

After each flight, the orbiter's external Thermal Protection System is rewaterproofed. Dimethylethoxysilane is injected with a needleless gun through an existing hole in the surface coating, and the blankets are injected by a needle gun. The procedure must be done each time because the waterproofing material burns out at 1,050 degrees F, thus exposing the outer surface of the thermal system to water absorption.

Spinoffs

There are numerous and far-ranging possibilities for spinoffs or commercial applications of Thermal Protection System materials. For example, tiles can be ideal as a jeweler's soldering base because they absorb so little heat from a torch, do not contaminate precious metals, and are soft enough to hold items to be soldered. Because of their purity, tiles can be an excellent high-temperature filter for liquid metals. Carbon-carbon pistons have been shown to be lighter than aluminum pistons and increase the mechanical and thermal efficiencies of internal combustion engines.

High costs at this time are a deterrent to widespread application of the techniques and materials of the Thermal Protection System. A single coated tile can cost as much as $2,000. But technological advances may make these pure, lightweight thermal materials the new insulators of the future.