National Aeronautics and Space Administration

Orbiter Thermal Protection System

At the end of a mission, when the space shuttle 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 built using highly advanced construction methods and materials, the airframe is formed primarily from aluminum and can only withstand 350 F without the material annealing, or softening. The 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.

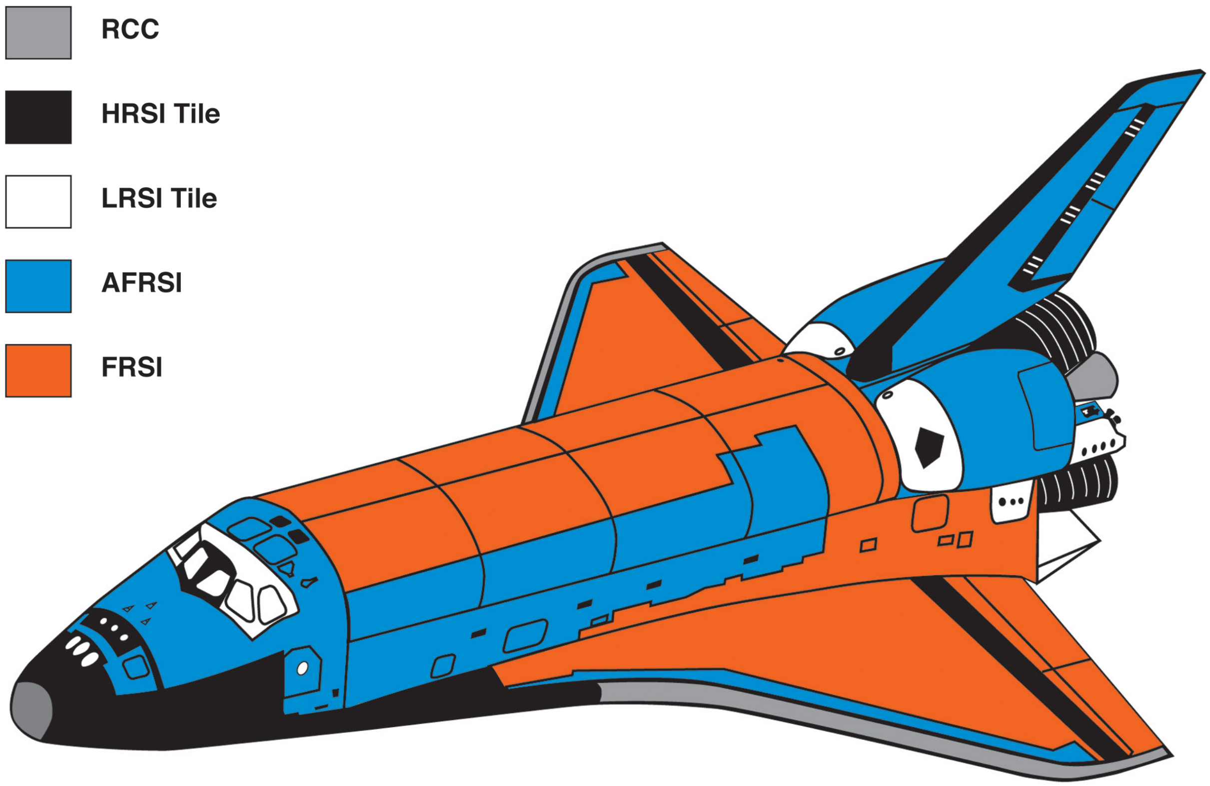
This was particularly necessary during the Apollo moon missions where the capsule, returning from the moon, entered the atmosphere at more than 25,000 mph. During the re-entry, the heat shield would ablate, or controllably burn with the char layer protecting the layers below. Despite the advantages, 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 re-entry, 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 F to +200 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 F.



High-Temperature Reusable Surface Insulation (HRSI) tiles

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

Reinforced Carbon-Carbon (RCC) panels or segments 57

Fibrous Refractory Composite Insulation (FRCI) tiles*

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

Low-Temperature Reusable Surface Insulation (LRSI) tiles

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

Flexible Insulation Blankets (FIBs) = 2,300

Felt Reusable Surface Insulation (FRSI) = 975***

* Not shown is FRCI. The tiles are limited to isolated areas.

** There is a slight variation in the number of tiles per vehicle. Some orbiters also have no 12-pound-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.

Felt Reusable Surface Insulation

FRSI blankets protect orbiter surfaces from temperatures up to 600 F. FRSI is a felt-like material made from needled polyaramid fibers. The needled felt is heat treated and coated on the outer surface with a white silicone membrane. FRSI ranges in thickness from 0.16 to 0.32 inches in thickness and covers about 25 percent of the vehicle. The material is naturally water resistant and is used extensively in areas of the vehicle where temperatures do not routinely exceed 600 F. These areas include the payload bay doors, the rear of the fuselage sidewalls and the upper wings.

Reusable Surface Insulation Tiles

Black or white tiles are used to protect the orbiter against temperatures between 1,200 F and 2,500 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 LRSI, on the upper surface of the vehicle have higher thermal reflectivity (they tend to absorb little heat) and are pointed toward the sun to minimize solar gain when the orbiter is on the illuminated part of the orbit.

The black tiles, known as 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 re-entry.

White and black tiles are all made of the same base materials, which are manufactured in blocks (or billets) that are machined into the precise shape of the tile before application of the coating. The reaction-cured glass coatings are made from blended glass powders mixed with thickeners and pigments. The coatings are applied with conventional spray equipment and dried, and then are fired in a kiln at 2,200 F for 90 minutes. The coatings are between 0.01- and 0.1-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 1-3 micron diameter pure silica glass fibers (about 1/25th of the diameter of a human hair) and consist of 6 percent solid phase and 94 percent air by volume. 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 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.

A gap test is being performed on the tiles below the windshield on the orbiter Atlantis.

LI-2200 tiles provided the strength and insulating properties needed in these areas, but not without an undesirable weight penalty. This prompted NASA to develop fibrous refractory composite insulation, or FRCI-12, a 12-pound-per-cubic-foot bulk density material.

Twenty-two percent of the weight of the FRCI-12 composition was Nextel fiber, an amorphous alumino-boro-silicate 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 reaction-cured glass coatings. It also had lower thermal shock resistance than the pure silica compositions, but remained within flight limits.

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

White tiles insulate the spacecraft from temperatures up to 1,200 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 orbiter maneuvering system pods, where temperatures do not exceed 1,200 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. An average of 50 tiles are replaced after each mission, either due to handling damage or accumulated repairs.

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 re-entry. The tiles are first bonded to a strain isolator pad, a needled Nomex felt material, before bonding directly to the aluminum airframe (or graphite epoxy composite in the case of the orbiter maneuvering system pods and payload bay doors). The purpose of the isolator pad 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.

Gaps and Gap Fillers

The gaps between the tiles, which range from 0.028 inch to 0.2 inch, are necessary for two important reasons. The first 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 F. The tiles contract much less than the airframe, due to differences in the thermal expansion; thus, the gaps are required to expand and contract to accommodate the difference.

In Orbiter Processing Facility bay 1 at NASA's Kennedy Space Center, a United Space Alliance technician uses a laser tool to take step and gap measurements on Thermal Protection System tiles on the underside of orbiter Atlantis.

In the Orbiter Processing Facility, a technician prepares the blanket insulation to be installed on the body flap on orbiter Discovery. The blankets are part of the Orbiter Thermal Protection System's, thermal shields to protect against temperatures as high as 3,000° Fahrenheit, which are produced during descent for landing.

During re-entry, 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 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

In the Orbiter Processing Facility, a United Space Alliance worker positions a reinforced-carbon carbon panel on the table to perform flash thermography.

be done each time because the waterproofing material burns out at 1,050 F, thus exposing the outer surface of the thermal system to water absorption.

RCC Panels

Reinforced carbon-carbon, or RCC, is one of the principle components of the thermal protection system of the orbiter. It is used as a high-temperature aerodynamic structure on the leading-edge structural subsystem, which consists of the nose cap, chin panel, wing leading edge and associated seals and access panels. In addition, the external tank forward attach point adjacent structure is protected by an RCC arrowhead component due to the pyrotechnic shock environment of the external tank's separation mechanism.

RCC consists of a carbon fiber/matrix composite substrate for rigidity and strength, a silicon carbide fiber/matrix conversion coating for high-temperature oxidation protection, tetraethylorthosilane impregnation, and a sodium silicate sealant for additional oxidation protection. The impregnation is the process of surface densification of the tile materials by brush coating with a hydrolyzed tetraethylorthosilane solution.

RCC has a multi-mission, maximum-use temperature of more than 3000 F. The material, having a relatively high thermal conductivity with respect to other thermal protection system components, promotes the internal cross-radiation from the hot stagnation region at the apex to cooler areas of the component. This cross-radiation reduces the temperatures near the apex and increases the temperatures of the cooler regions that, in turn, reduce the thermal gradients around the component. The radiation network allows for cooling of the part. The hot lower surface radiates to the upper surface, which, in turn, radiates to cold space.

The attach and support structure must be protected by the use of internal insulation. The nose cap and chin panel use an uncoated flexible blanket fabricated from Nextel fabric and Saffil or Cerachrome insulation to protect the structure. In addition, high-temperature reusable surface insulation, known as HRSI, tiles are bonded to the forward bulkhead to offer additional thermal protection behind the nose cap. An uncoated flexible blanket fabricated with quartz fabric and Q-Felt batting is used as the insulation under the arrowhead. The radiation from the wing leading edge RCC to the wing spar is protected by rigidized 0.004-inch-thick Inconel 601 foil-covered Cerachrome batting.

Although the intent of the internal insulation is to protect the structure, it consequently retards the cooling rate of the RCC lugs. This prolonged time at temperature contributes to the undesirable oxidation rate of the RCC, which, in turn, reduces the mission life of the component.

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, or AFRSI — also known as fibrous insulation blankets. 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 Materials

In 1996, NASA introduced a fourth tile material called AETB-8 (alumina-enhanced thermal barrier). This 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. 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 use to the upper surface.

In 2005, NASA introduced a fifth tile material called BRI-18, an acronym for Boeing Rigid Insulation-18 pounds per cubic foot density. BRI-18 is the strongest material used to date and, when coated to produce toughened unipiece fibrous insulation, provides a tile with extremely high-impact resistance. BRI-18 was tested extensively in the wake of the Columbia accident in 2003 and is currently being used to replace LI-2200 and FRCI-12 tiles areas of the vehicle where impact risk is high. These areas include the landing gear doors, the wing leading edge and the external tank doors. Installation of these BRI tiles has increased the tolerance of the thermal protection system to impacts in these critical areas.

In the Thermal Protection System Facility, Tim Wright, engineering manager with United Space Alliance, tests a new tile, called "Boeing replacement insulation" or "BRI-18." The new tiles have replaced older tiles around main landing gear doors, external tank doors and nose landing gear doors.

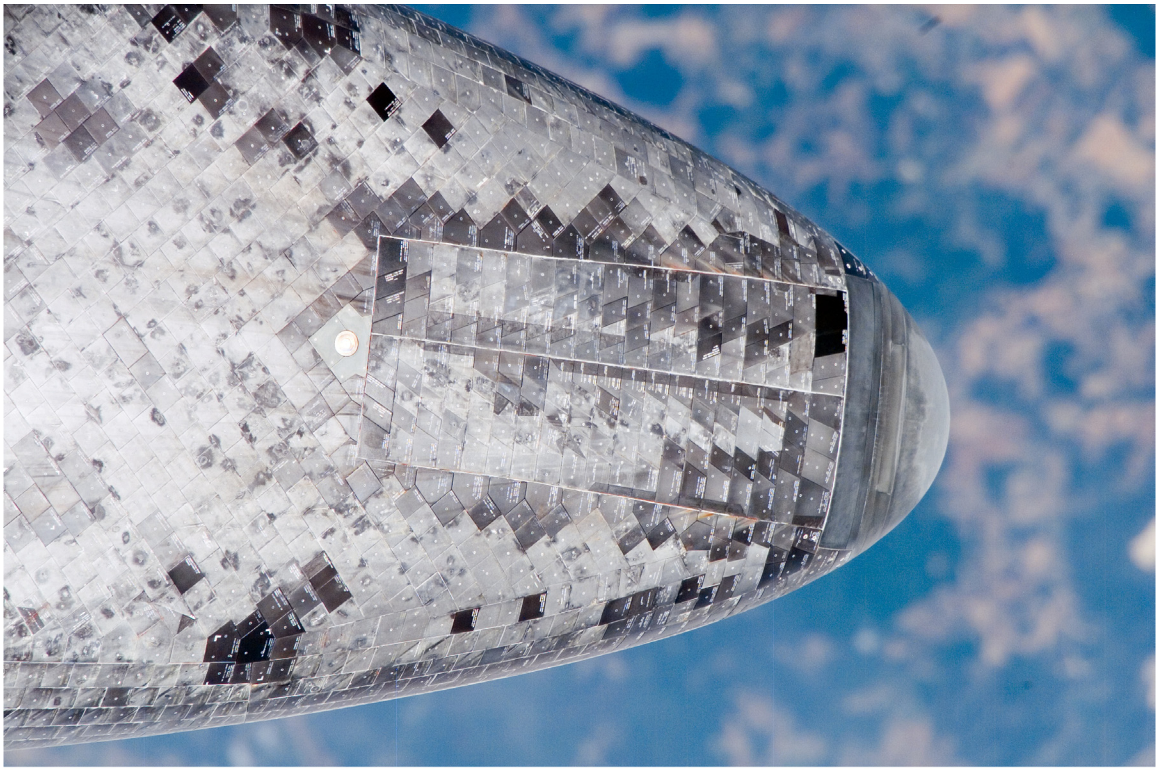
Spinoffs

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.

Fire-resistant materials include chemically treated fabric for sheets, uniforms for hazardous material handlers, clothing, furniture, interior walls of submersibles and auto racer and refueler suits.

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 $1,000. But technological advances may make these pure, lightweight thermal materials the new insulators of the future.



Part of the bottom of Discovery's crew cabin and a number of its thermal protection system tiles are visible in this image photographed July 6, 2006, by one of the Expedition 13 crewmembers onboard the International Space Station.

A low-angle view of the nose and underside of the Space Shuttle Atlantis' crew cabin was provided by Expedition 16 crewmembers. Before docking with the International Space Station, STS-122 Commander Steve Frick flew the shuttle through a roll-pitch maneuver, or basically a backflip, to allow the space station crew a good view of Atlantis' heat shield.

During a backflip maneuver during the STS-120 mission, the underside of the space shuttle Discovery is featured in this image photographed by an Expedition 16 crewmember. Visible are a landing gear door (large square at center) and an external tank umbilical door (lower left).

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