Orbiter Thermal Protection System

At the end of a mission, 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 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.

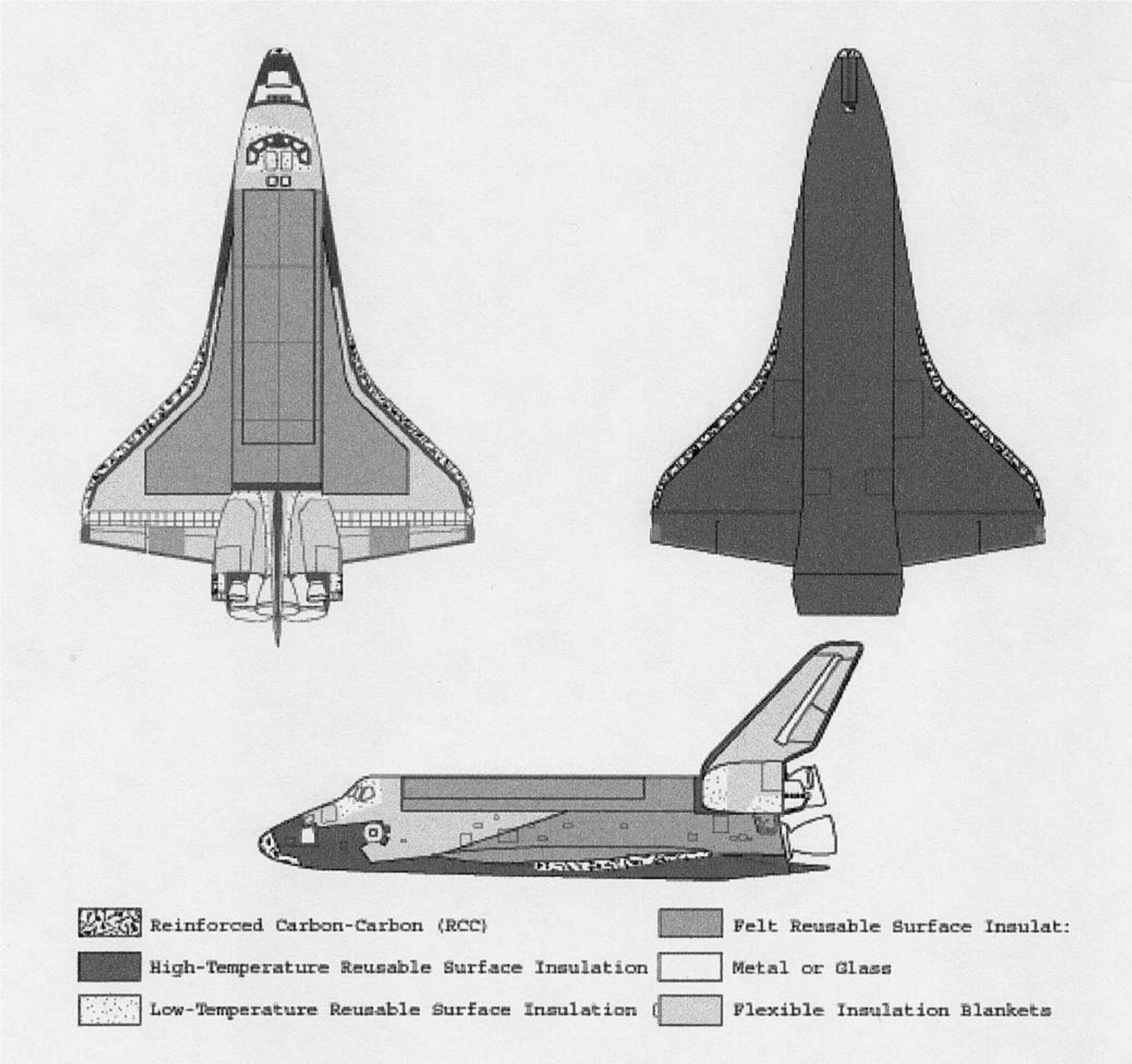
Earlier manned spacecraft, such as Mercury, Gemini and Apollo, were not maneuverable and followed ballistic re-entry trajectories, parachuting to a watery landing in the ocean. The space capsules were protected during re-entry by a heat shield constructed of phenolic epoxy resins in a nickel-alloy honeycomb matrix. The heat shield was capable of withstanding very high heating rates.

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

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



High-Temperature Reusable Surface Insulation (HRSI) tiles

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

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.

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.

Felt Reusable Surface Insulation

FRSI blankets protect orbiter surfaces from temperatures between 350 F and 700 F. The insulation is coated with a white silicone rubber paint. FRSI once covered about 25 percent of the vehicle. Now, the material is used only on the upper section of the payload bay doors and the inboard sections of the wing upper surface.

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 towards 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.

Both white and black tiles are all made of the same base materials. These materials 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 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 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 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.

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.

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. 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 Material

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.

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 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.

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 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 F, thus exposing the outer surface of the thermal system to water absorption.

RCC Panels

The RCC panels are used on the orbiter's wing leading edges; the nose cap and an area immediately aft of the nose cap on the lower surface (chin panel); and the area immediately around the forward orbiter/external tank structural attachment point. The panels are manufactured by Lockheed-Martin's Missile and Fire Control Facilities in Dallas, Texas.

The leading edges of each of the orbiters' wings have 22 RCC panels. They are light gray and made entirely of carbon composite material. The molded components are

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 United Space Alliance worker positions a reinforced-carbon carbon panel on the table to perform flash thermography.

approximately 0.25-inch to 0.5-inch thick. During fabrication, the RCC panels are treated so they are resistant to oxidation and covered with a silicon carbide coating and a final coating of a glass sealant. They can withstand temperatures up to 3,220 F.

Although the RCC panels are strong and capable of withstanding extreme temperatures, they are thermally conductive. This brings a need to extensively use insulating blankets and tiles behind the RCC panels to protect the structure and attach fittings from heat radiated from the backside.

Prior to each space shuttle mission, the RCC panels undergo three inspections to ensure their integrity. The first is a post-flight, visual micro-detail inspection of the thermal protection system, which includes the RCC. During this inspection, all exterior surfaces of the orbiter are closely examined and any damage is documented for repair.

The second is a pre-rollout inspection of thermal protection system that also includes the RCC. This visual inspection checks again for any external damage. The third is a "tactile test," or hands-on test, that examines the hottest panels (panels 6-17) for evidence of loose or separated coating. These inspections are required and performed for every flight.

If damage is seen, the RCC section is removed and returned to the vendor for repair and refurbishment. Also, after a specified number of missions, the RCC panels are sent back to the vendor for recoating.

During processing for return to flight, all RCC panels undergo extensive nondestructive inspections (NDI) and nondestructive evaluations (NDE). NDI inspections include the use of thermography and a CAT scan to detect imperfections or cracks in the structures on and below the surface. Thermography, a relatively new procedure at KSC, uses high-intensity light to heat areas of the panels. The panels are then immediately scanned with an infrared camera. As the panels cool, internal flaws are revealed. This form of NDI is in the development stage at KSC as RCC panel testing proceeds.

A computer-aided CAT scan uses magnetic resonance to scan the internal structure of the RCC panels. Panels are sent to a lab in Canoga Park, Calif., where a much larger machine is used to detect flaws.

NDE methods include eddy current, ultrasound and X-ray. Eddy current is a technique that measures coating thickness and density properties of the panels. An electronic field detects disturbances in the panels, such as cracks and imperfections.

During an ultrasound inspection, sound pulse waves are sent out to the component. As they are received back, defects and discontinuities are detected. X-rays of panels are performed at Lockheed Martin facilities in Dallas.

In addition, several inspections of the metal components behind the RCC panels are performed. First, a visual inspection reveals any flaws to the naked eye. A dye-pen test, using a dye of red or purple, is applied to the component. Then a black light is used to reveal any liquid that has penetrated the components, indicating cracks on or deeper than the surface. Current requirements state KSC will inspect all of the thermal protection system and RCC to verify integrity before flight.

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.

For more information about spinoffs from space, go to the Web site:

http://www.thespaceplace.com/nasa/spinoffs.html

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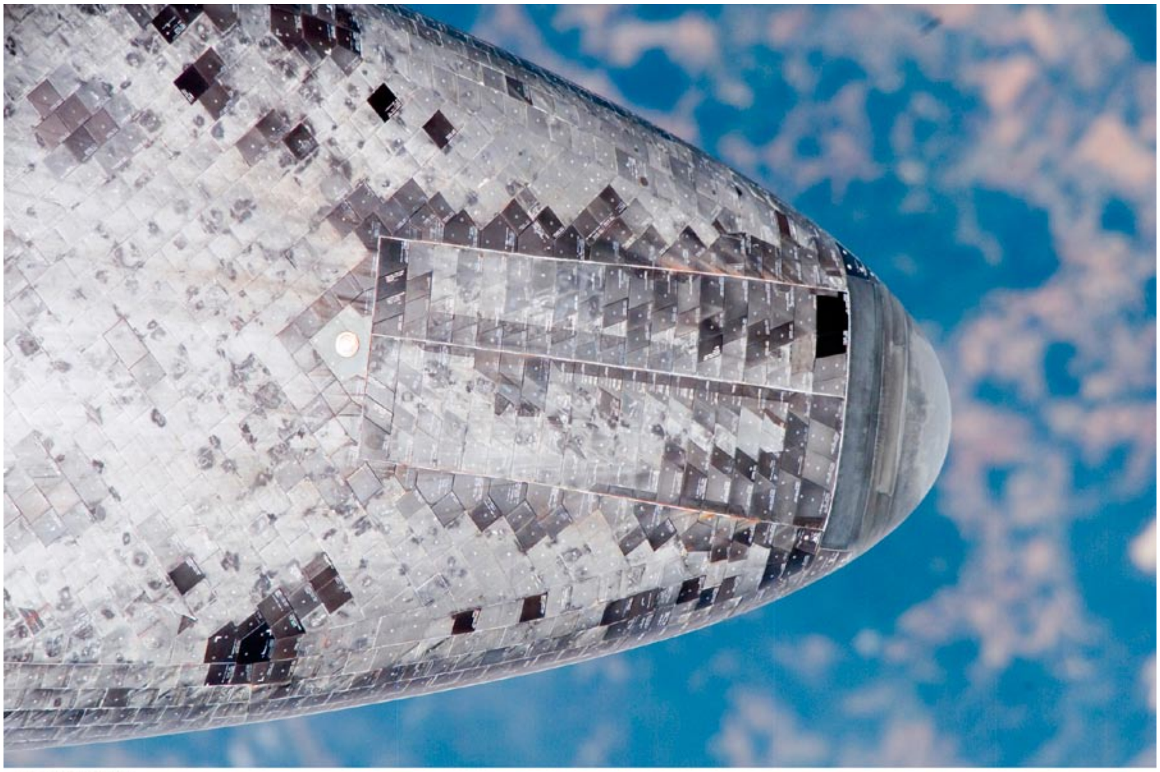

Part of the bottom of Discovery's crew cabin and a number of its thermal protection system tiles are visible in this image photographed July 6, 2006, by one of the Expedition 13 crewmembers onboard the International Space Station.

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