The high temperatures that were to be encountered by the Space Shuttle were simulated in the wind tunnels at Langley in this 1975 test of the thermal insulation materials that were used on the Space Shuttle Orbiter.

The Space Shuttle Orbiter is an amazing technological achievement. It is the world's first and so far only reusable spacecraft. It is immensely complicated and certainly does not achieve the reusability of an airplane, requiring extensive (and expensive) overhaul and checkout after each flight. But the Orbiter still flies again and again using much of the same equipment, something that no other space vehicle has done.

One of the keys to this reusability is the Orbiter's Thermal Protection System, or TPS. The most visible aspect of the TPS is the Orbiter's external tiles. But in reality, the TPS consists of a combination of materials and technologies that work together to protect the spacecraft and its human occupants. The TPS represents significant advances in aerodynamic design, metallurgy, and the understanding and manufacture of materials, a discipline known as materials science. Underneath its protective layer of tiles and other materials, the Space Shuttle is of rather ordinary aluminum construction, similar to many large aircraft.

Early vehicles that had to reenter the Earth's atmosphere used a variety of techniques to keep from burning to a crisp. Some used heat sinks to absorb the heat. Others used ablative material that charred and vaporized. But none of the early vehicles had to be reusable and so they could use materials and techniques that protected the vehicle but rendered it essentially unusable afterwards. Some spacecraft designers did propose developing heat shields for spacecraft that could be completely replaced after flight, allowing a space capsule, such as the Apollo Command Module, to be reused, but these proposals never advanced very far. When spacecraft designers started thinking about reusable vehicles, they figured that they would have to use some combination of metals and ceramics that could survive high temperatures. Such an approach was considered for the canceled X-20 Dyna Soar spaceplane of the early 1960s.

When the Space Shuttle was first proposed in the late 1960s, planners from the National Aeronautics and Space Administration (NASA) wanted a vehicle that would be much larger than any that had flown in space before. But the amount of high-temperature metal required to protect a large vehicle would have been very heavy and this would have affected vehicle performance. Designers chose to use conventional aluminum for the main body and to protect it with a layer of heat resistant material.

The properties of aluminum demand that the maximum temperature of the Orbiter's structure be kept below 350 degrees Fahrenheit (175 degrees Celsius) in operations. But aerothermal heating during liftoff and reentry (in other words, heating caused by friction with the air) will create surface temperatures high above this level and in many places will push the temperature well above the melting point of aluminum (1,220 degrees Fahrenheit or 660 degrees Celsius). Clearly an effective insulator was needed.

Fortunately, during the 1960s, Lockheed developed a silica-based insulation material for NASA. NASA designers decided to use this and similar materials to manufacture heat-resistant tiles and other coverings to protect the Orbiter's airframe.
Typical Thermal Protection System gap fillers and thermal barriers.

Fused silica insert and plug locations on Orbiter.

Rockwell technician Pat Klose make repairs to Thermal Protection System (TPS) tile on the rim of one of Columbia's windows before launch of STS-4.

Thousands of tiles of various sizes and shapes cover a large percentage of the Space Shuttle Orbiter's exterior surface, although over the two decades of Shuttle operation, many tiles have been removed from the upper wings and fuselage of the Orbiter and replaced with a lighter and less expensive material. Some tiles have a side dimension of six inches (15 centimeters) or less; others are about eight inches (20 centimeters) on a side. There are two main types of tiles, referred to as Low-temperature Reusable Surface Insulation (LRSI) and High-temperature Reusable Surface Insulation (or HRSI).

LRSI tiles cover relatively low-temperature areas of one of the orbiters, the Columbia, where the maximum surface temperature runs between 700 and 1,200 degrees Fahrenheit (370 and 650 degrees Celsius), primarily on the upper surface of fuselage around the cockpit. These tiles have a white ceramic coating that reflects solar radiation while in space, keeping the Columbia cool. HRSI tiles cover areas where the maximum surface temperature runs between 1,200 and 2,300 degrees Fahrenheit (650 and 1,260 degrees Celsius). They have a black ceramic coating, which helps them radiate heat during reentry. Most of these tiles cover the bottom of the Orbiter. Both LRSI and HRSI tiles are manufactured from the same material and their primary difference is the coating.

Two other types of tiles, known as FRCI and TUCI (Fibrous Refractory Composite Insulation and Toughened Unipiece Fibrous Insulation), which protect against temperatures between 1,200 and 2,300 degrees Fahrenheit (650 and 1,260 degrees Celsius), are also used in small numbers. FRCI is used in a few areas and TUCI is used on the extreme back of the Orbiter, near the engines. The forward nose cap is made of a material called Reinforced Carbon Carbon, or RCC. RCC covers the highest temperature areas of the Shuttle and is also used on the leading edges of the wings.

All of the tiles are brittle and can crack if stressed. Because the aluminum structure of the Orbiter expands and contracts due to temperature changes, the tiles could not be mounted directly to the aluminum or they would shatter and crack as the Orbiter heated up. So the tiles have to be mounted to a felt pad using a silicone adhesive and then the tile and pad combination are bonded to the aluminum skin. This proved to be a difficult process to perfect and many of the tiles did not adhere properly. Partially as a result of this, the Space Shuttle's launch was delayed for over a year.

Over the years, many of the tiles have been replaced by a material known as Flexible Reusable Surface Insulation, or FRSI, and Advanced Flexible Reusable Surface Insulation, or AFRSI. FRSI and AFRSI are lighter and less expensive than the conventional tiles and using them has enabled the Shuttle to lift heavier payloads to orbit. FRSI and AFRSI cover areas of the Shuttle Orbiter that do not exceed 700 degrees Fahrenheit (370 degrees Celsius) during entry or 750 degrees Fahrenheit (400 degrees Celsius) during ascent. This includes the fuselage sides and top, the payload bay doors, the tops of the wings, and the Orbiter Maneuvering System (OMS) pods near the tail. The FRSI/AFRSI is soft and is sometimes referred to as a “thermal blanket.”

Other parts of the Orbiter that are exposed to intense heat, such as the hinges for the flight control surfaces, are made of Inconel, a high-temperature alloy first perfected for the X-15 research aircraft program. An important lesson learned from the X-15 was that small gaps or protrusions on the surface of the aircraft can get extremely hot and can act like a blowtorch, channeling high-temperature gas into areas that could be damaged, like the wells around the landing gear. Shuttle designers paid close attention to this when designing...
the Orbiter, and use filler materials in some areas to fill in the gaps. They also use ablative materials in a few areas. These burn away during reentry and have to be replaced after each flight.

Space Shuttle flights occasionally lose tiles during liftoff. This is because of the incredibly loud noise that the Shuttle engines generate as well as aerodynamic forces during ascent. The sound waves actually shake the tiles loose. None of these losses have endangered the astronauts, but engineers developed stronger adhesive materials and procedures to ensure that the tiles stayed attached. Because of this as well as weight concerns, many of the fuselage tiles were also replaced by FRSI blankets.

In addition to the external tiles, the Orbiter also has a lot of internal insulation, in particular a material known as Q-felt. This prevents any residual heat from the tiles from seeping into the vehicle where it could damage electronics or structures.

During both liftoff and landing, tiles can become damaged and chipped. This can happen because of pieces of ice flying off the Shuttle's External Tank and striking the Orbiter during liftoff, or because of debris on the runway getting kicked up from the landing gear tires during landing. Before every landing, a group of people walks the length of the runway looking for any stones, twigs, or other debris that might have been carried onto the runway by birds or animals. At Kennedy Space Center in Florida, they also remove the occasional alligator that wanders onto the runway. After the Orbiter has landed and been taken indoors for inspection, any damaged tiles are removed and replaced for the next flight.

Some of the blanket material is already used on other space vehicles, and internal insulation material like the Q-felt is used by other industries. For instance, it is used in NASCAR racing cars. But the tiles have their limitations. For other reusable vehicles, like the canceled X-33 vehicle or the National Aerospace Plane, the tiles would not provide sufficient protection and some other solution would be necessary. Most other proposed reusable thermal protection systems have involved some kind of advanced high-temperature metal.

--Dwayne A. Day

Sources and further reading:


