Modifications

In 1996-1997, *Endeavour* underwent her first OMDP after completion of STS-72 in May 1996; OMDP-1 was partially conducted at Palmdale and partially at KSC. Sixty-three modifications were made at Palmdale, thirty-three at KSC, and ten were shared between the two facilities. The orbiter left KSC for Palmdale on July 30, 1996, and returned on March 27, 1997. The most notable improvement was the installation of an external airlock and ODS. In addition, the AFRSI blankets on the midfuselage, aft fuselage, payload bay doors, and upper wings were replaced by the thinner and lighter FRSI blankets. Also, doublers were added to several wing spars to eliminate load restrictions.

Beginning in December 2003, *Endeavour* underwent an almost two-year OMDP-2 at KSC. One hundred and twenty-four modifications were made, including safety measures and the new MEDS "glass cockpit."[269] In addition, the first station-to-shuttle power transfer system (SSPTS) was installed, as was the 3-string GPS. About 2,000 tiles were replaced, and seventy-two tiles were added to the wing leading edges and main and landing gear doors. Furthermore, approximately 2,000 TPS blankets were replaced or repaired.[270]

IC. Orbiter Thermal Protection System Development and Testing

Introduction

A variety of TPS materials were used to protect the orbiter vehicle, mostly from the extreme heat of reentry. Among the materials applied externally to the structural skin of the orbiter were reinforced carbon-carbon (RCC), high temperature reusable surface insulation (HRSI), fibrous refractory composite insulation (FRCI), low-temperature reusable surface insulation (LRSI), advanced flexible reusable surface insulation (AFRSI), and felt reusable surface insulation (FRSI), as well as strain isolator pads (SIPs) and gap fillers. In general, the type and placement of TPS materials on the orbiter was related to temperature. A description of the TPS materials which characterized the "end-state" orbiters *Discovery*, *Atlantis*, and *Endeavour* is provided in Part IIB.

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[269] Boeing, *OV-105, Volume II*, 65; "NASA's Space Shuttle Endeavour Comes to Life," NASA News Release, October 6, 2005, http://www.nasa.gov/home/hqnews/2005/oct/HQ_05336_Endeavour_comes_to_life.html.

[270] Laura Herridge, "STS-118 crew members proud of modified Endeavour," *Spaceport News*, August 10, 2007, 1 and 4.

Early Research and Development

> "*We knew it would be hot in the nose and the wings and not as hot on the top side. That's what we started out with.*"[271]

As captured in the statement of Wendell D. Emde, former supervisor of North American Rockwell's TPS group, there was no precedent for the thermal protection system required by the STS. NASA first experimented with ablative heat shields for the Mercury, Gemini, and Apollo programs, but by 1970, for the future space shuttle, the agency sought a type of heat shield that was reusable. In early 1971, NASA MSC awarded contracts to three companies for the development of new orbiter "surface materials." The recipients of the contracts, valued at about $320,000 each, were McDonnell Douglas Corporation; General Electric Company, Aerospace Group; and the Lockheed Missiles and Space Company. The contracts covered the design, development and testing of a ceramic insulator class of materials, including the delivery of sample tiles sized to 12" x 12" x 2".[272]

One of the alternate reusable heat shields under consideration was known as reusable surface insulation (RSI). RSI, in turn, led directly to the development of thermal ceramic tiles. Lockheed's research center in Palo Alto, California, had undertaken research and development for this type of thermal protection shield, beginning in the early 1960s. By 1970-1971, Lockheed had a functioning pilot plant to manufacture silica RSI tiles. Experimentation for improved tile materials continued, and in late 1972, NASA ran a series of tests at several of its centers. At the MSC (now JSC) in Houston, Lockheed RSI tiles were the only ones that survived the final series of thermal-acoustic tests.[273] The final tiles had two different coatings, as well as size and thickness dimensions, dependent on which area of the shuttle they were to cover. NASA testing and evaluation of the tiles continued through the 1970s, most notably at Ames.

Manufacture

Following their award as the orbiter and shuttle integration prime contractor, North American Rockwell selected the Lockheed Missile and Space Company as the subcontractor for the manufacture of most of the shuttle's TPS. Production of the insulating tiles which covered the orbiter's surface was initiated at Lockheed's new facility in Sunnyvale, California, on September 15, 1976.[274] The first shipment of HRSI was delivered to Rockwell in early 1977. Subsequently, in the mid-1980s, Rockwell took over the manufacture of TPS materials at Palmdale, where

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[271] Wendell D. Emde, interview by Jennifer Ross-Nazzal, *NASA STS Recordation Oral History Project,* August 27, 2010, http://www.jsc.nasa.gov/history/oral_histories/STS-R/EmdeWD/EmdeWD_8-27-10.htm
[272] "MSC Awards Three Contracts For Shuttle Surface Materials," *Roundup*, July 16, 1971, 1.
[273] Joan Lisa Bromberg, *NASA and the Space Industry* (Baltimore: Johns Hopkins University Press, 1999), 100.
[274] "Orbiter insulation production begins," *Roundup*, September 24, 1976, 2.

NASA constructed Building 154 for work on protective tile adhesives, gap fillers, thermal barriers, and foam, during 1983-1984.[275] Rockwell fabricated FRSI in various thicknesses.

Supplementing the tile assembly and manufacturing capabilities at Lockheed's Sunnyvale plant and at Rockwell's Palmdale plant was the Thermal Protection System Facility (TPSF) at KSC, completed in 1988. The first tiles made at KSC were produced in the OPF-2. Later, the manufacture and repair of the Space Shuttle's tiles, gap fillers, and insulation blankets, as well as coatings and adhesives, were moved to the TSPF. Each unique tile underwent a process which took it from raw materials through finished product; the gap fillers and blankets were assembled from pre-made fabrics. Following their manufacture, TPS products were delivered to the OPF for installation on the orbiter. The first tiles produced at KSC flew on *Columbia* in January 1990.[276]

NASA encountered major challenges in the tile adhesive process. The tiles were fragile and required an intermediate, flexible layer next to the skin of the shuttle. A SIP, made of Nomex nylon felt, served this purpose. Rockwell individually bonded the tiles to SIPs. Workmen glued them to the shuttle in arrays, with small gaps set between the tiles. At their Palmdale plant, Rockwell workers painted the exterior of the shuttle with a green epoxy corrosion inhibiter at the start of the tile application process. Rockwell also used a blueprint-like guide printed on Mylar to assist in tile layout. Typically, the tiles also required extensive post-mission reworking after each shuttle flight.

TPS Testing

Qualifying a new TPS material required extensive testing. Critical to the testing process were NASA's arc jet facilities at both Ames and JSC; the arc jets simulated flight entry conditions. Ames also played a leading role in the development and testing of plugs, patches, pastes, and other materials used to repair damage to the shuttle's TPS while in orbit.

Between December 1979 and November 1980, approximately sixty flights were flown during a 12-month flight test program at NASA's DFRC. Both the F-15 and F-104 aircraft were used to test some of the TPS tiles from the orbiter to demonstrate tile performance up to 104 percent of the dynamic pressure planned for shuttle operations.[277] Six different tile articles were constructed identical to the areas of the orbiter surface being represented. The tested locations were the closeout tile aft of the wing leading edge area; the forward wing glove area; the vertical tail leading edge; the window post area; and the elevon leading edge and elevon hinge areas. As a

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[275] Boeing, *Space Exploration – Palmdale, CA: AF Plant 42, Site 1 North* (Palmdale, California: The Boeing Company, 2006).
[276] Patricia Slovinac, "Cape Canaveral Air Force Station, Launch Complex 39, Thermal Protection System Facility (John F. Kennedy Space Center)," HAER No. FL-8-11-L. Historic American Engineering Record (HAER), National Park Service, US Department of the Interior, April 2011, 13.
[277] "Dryden to Participate in More Shuttle Tests," *X-Press*, October 5, 1979, 2-3; "Tile Tests Continued," *X-Press*, August 22, 1980, 2.

result, several design changes were made to the TPS in several areas.[278] "These changes consisted of revision of attachment techniques to improve binding forces, modified gap filler assemblies to prevent detachment, and improved installation and testing techniques to ensure satisfactory compliance with design requirements."[279] These changes were later incorporated into the orbiter.

Beginning in late 1982, DFRC conducted tests of AFRSI, as part of Ames' investigation of new thermal protection materials. Following initial wind tunnel tests conducted at Ames, the baseline test program at DFRC used the F-140 aircraft to subject the AFRSI to air loads that were equal and up to 1.4 times those experienced in actual flights. Variations in the materials tested in the baseline series included insulation fabricated using heavy and light surface fabric, felt layers of differing thicknesses, and varying joint configurations. Later tests at DFRC, in early 1983, investigated the drag characteristics of the insulation materials, as well as more severe thermal and aerodynamic environments to help determine the long-term durability.[280]

TPS Evolutionary Changes

Throughout the SSP, the TPS that safeguarded the shuttle's frame from the intense heat of space was regularly modified. Changes were both in response to technological advances as well as to correct problems detected after flight. Early in the SSP, for example, plasma flow was discovered where the wings and elevons met. Hence, the LRSI tiles on *Discovery* and *Atlantis* were replaced by FRCI and HRSI tiles and gap fillers.[281] In other areas not exposed to high temperatures, the LRSI tiles were replaced by AFRSI blankets, developed after *Columbia* was delivered to KSC in 1979. The blankets were stronger, lighter, quicker to install, and cheaper than the LRSI tile alternative. After its seventh flight, *Columbia* was modified to replace most of the LRSI tiles with AFRSI, and AFRSI blankets gradually replaced most of the LRSI tiles on *Discovery* and *Atlantis*. The LRSI tiles on *Columbia*'s mid-fuselage, payload bay doors, and vertical stabilizer were also replaced, and *Endeavour* was built with many AFRSI blankets already in place.[282] Damaged HRSI tiles were replaced by the more durable FRCI tiles, which were developed after the construction of the Space Shuttle. Furthermore, in 1988, the HRSI tiles near the nose cap were regularly damaged upon reentry, so they were replaced with a RCC chin. TUFI tiles successfully debuted in 1994 on *Endeavour*'s base heat shield between the three SSMEs. From then on, TUFI tiles were used to replace damaged HRSI tiles on the base heat shield and lower body flap surface, because the TUFI tiles were more likely to dent than break when struck.

[278] "Shuttle Tile Tests Being Completed," *X-Press*, November 21, 1980, 2; "Shuttle Tile Test Completed," *X-Press*, January 16, 1981, 2.
[279] "Shuttle Tile Test Completed."
[280] "Dryden Starts Shuttle Insulation Tests," *X-Press*, January 7, 1983, 2; "Space Shuttle Insulation Tested Here for Air Load Data," *X-Press*, March 18, 1983, 2 and 4.
[281] Jenkins, *Space Shuttle*, 400.
[282] Jenkins, *Space Shuttle*, 401.

As a result of the trend to replace some tiles with Flexible Insulation Blankets (FIBs), while the earlier orbiters used as many as 34,000 tiles, the last addition to the orbiter fleet, *Endeavour*, was protected by approximately 26,000 tiles. Beginning in 1996, AFRSI blankets were replaced by the lighter FRSI tiles to reduce weight in preparation for flights to the ISS. During major modification periods, the FRSI tiles were added to the shuttle midfuselage and aft fuselage, payload bay doors, and upper wing surfaces.[283]

The wing leading edge RCC upper panels were designed to withstand up to 1”-long penetrations and still block plasma flow. However, some of the lower panels could not suffer any damage without letting heat from the plasma flow reach the leading attach fittings and front spar in the wings. Starting in 1998, during major modifications, insulation was added to the lower panels.[284]

The *Columbia* accident demonstrated that the shuttle’s TPS design was vulnerable to impact damage from the existing debris environment. As a result, NASA initiated a program to harden the orbiter against impacts.[285] In 2003, spar sneak flow protection was added to the wing leading edges to prevent hot gas flow from potentially reaching the RCC tiles. In addition, the horse collar gap fillers were redesigned to prevent hot gas from passing into the wing leading edges in case a tile broke off.[286] Beginning with STS-121 in July 2006, NASA replaced the existing FRCI belly tiles with the more impact-resistant Boeing Rigid Insulation (BRI) tiles around the main landing gear door, nose landing gear door, ET umbilical doors, wing leading edge carrier panels, and windows. These changes were made during orbiter processing between flights.[287]

ID. Shuttle Carrier Aircraft

Two NASA-owned SCAs, N905NA and N911NA, supported the SSP. These aircraft were modified four-engine intercontinental range Boeing 747 jetliners, originally manufactured for commercial use (Figure Nos. A-34, A-35).

Historical Overview

In 1973, early in the SSP, NASA considered both the C-5A cargo aircraft, manufactured by Lockheed,[288] and the Boeing 747 “jumbo jet” as potential vehicles to ferry the orbiter cross country. In August and October 1973, contracts were awarded to Boeing and Lockheed, respectively, to conduct preliminary feasibility studies to evaluate whether the orbiter could

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[283] Jenkins, *Space Shuttle*, 398-401.
[284] Jenkins, *Space Shuttle*, 398-401.
[285] NASA, *NASA’s Implementation Plan for Space Shuttle Return to Flight and Beyond*, vol. 1 (Washington, DC: NASA Headquarters, 2007), 1-21.
[286] Boeing, *Atlantis OV-104, Volume II*, 74.
[287] NASA, *NASA’s Implementation Plan*, 1-25.
[288] The original version of the C-5A was manufactured by Lockheed between 1968 and 1973. This large military transport aircraft, which featured a heavy airlift capacity, was used primarily by the US Air Force.