Wings In Orbit
Scientific and Engineering Legacies of the Space Shuttle

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An agency-wide Space Shuttle book project involving contributions from all NASA centers

Space Shuttle book: September 2010
Wings In Orbit

A new, authentic and authoritative book written by the people of the Space Shuttle Program

• Description of the Shuttle and its operations
• Engineering innovations
• Major scientific discoveries
• Social, cultural, and educational legacies
• Commercial developments
• The Shuttle continuum, role of human spaceflight
Overall vision for the book:

*The “so what” factor?*

Our vision is to “inform” the American people about the accomplishments of the Space Shuttle and to “empower” them with the knowledge about the longest-operating human spaceflight program and make them feel “proud” about nation’s investment in science and technology that led to Space Shuttle Program accomplishments.
Focus:

• Science and Engineering accomplishments (not history or hardware or mission activities or crew activities)
• Audience: American public with interest in science and technology (e.g., Scientific American Readership: a chemical engineer, a science teacher, a physician, etc.)

Definition of Accomplishment:

• Space Shuttle Program accomplishments are those “technical results, developments, and innovations that will shape future space programs” or “have affected the direction of science or engineering” with a focus on unique contributions from the shuttle as a platform.

Guiding Principles:

• Honest
• Technically correct
• Capture the passion of the NASA team that worked on the program
“…to review and provide recommendations to the Executive Editor on the contents and the final manuscript…”

Wayne Hale, Chair of Board

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October 2003 saw a period of 29 years, the Orbiter deployed a multitude of satellites for Earth observation and telecommunications, including the Galileo spacecraft, Magellan Venus Radar Mapper, and the Galileo spacecraft, Magellan Venus Radar Mapper, space telescopes, and other observatories that included the Hubble Space Telescope, Compton Gamma Ray Observatory, and Chandra X-ray Observatory. The Orbiter served as a science platform prior to its retirement in 2011.

The Orbiter was the only fully reusable component of the shuttle system. Each Orbiter was designed and serviced for 10 to 15 space missions and required about 5 months once it landed to service the different systems and configure the payload bay to support the requirements for its next mission. NASA replaced the components only when they sustained a system failure and could not be repaired. Even though certified for 100 missions, Discovery, Atlantis, and Endeavour completed 26, 22, and 25 missions, respectively, by the end of the program. Challenger flew 10 missions and Columbia flew 28 missions before its loss on January 28, 1986, and February 1, 2003, respectively.

**Space Shuttle Reusability**

All components of the Space Shuttle vehicle, except for the ET, were designed to be reusable after each flight. The ET was discarded after each mission. The Orbiter, the vehicle where atmospheric heating occurred, was broken up over the ocean.

The SRBs, once jettisoned from the main engines, were recovered by special ships and barges and sent back to KSC. With their solid-propellant spent, the boosters were re-stacked and shipped back to Boeing for re-use. After every mission, the SRBs were thoroughly inspected to ensure that the components were not damaged and could be re-used for another flight. Any damage found was either repaired, or the component was discarded.

**The Orbiter**

The Orbiter was the only fully reusable component of the shuttle system. Each Orbiter was designed and serviced for 10 to 15 space missions and required about 5 months once it landed to service the different systems and configure the payload bay to support the requirements for its next mission. NASA replaced the components only when they sustained a system failure and could not be repaired. Even though certified for 100 missions, Discovery, Atlantis, and Endeavour completed 26, 22, and 25 missions, respectively, by the end of the program. Challenger flew 10 missions and Columbia flew 28 missions before its loss on January 28, 1986, and February 1, 2003, respectively.

**Typical Flight Profile**

The following diagram illustrates the typical flight profile of the Space Shuttle mission. It shows the launch, orbit insertion, mission execution, and re-entry phases. The mission profile includes critical events such as payload deployment and return to Earth. The diagram also highlights the various components of the mission, such as the launch vehicle, payload, and re-entry capsule.
The thermal protection system consisted of various materials applied externally to the outer structural skin of the orbiter to passively maintain the skin within acceptable temperatures, primarily during the re-entry phase of the mission. During this phase, the thermal protection system materials protected the orbiter’s outer skin from exceeding temperatures of 1700°C (3092°F). In addition, they were reusable for 100 missions with refurbishment and maintenance. These materials performed in temperature ranges from -50°C to 2570°F in the vast array of space to re-entry temperatures that reached nearly 1640°C (3000°F). The thermal protection system also withstood the forces induced by deflections of the orbiter airframe as it expanded in various external environments.

At the vehicle surface, a boundary layer developed and was designed to be laminar; however, small gaps and discontinuities on the vehicle surface could cause the flow to transition from laminar to turbulent, thus increasing the overall heating. Therefore, tight fabrication and assembly tolerances were required of the thermal protection system to prevent a transition to turbulence. More early in the flight when heating was at its highest.

Requirements for the thermal protection system extended beyond the normal requirements. For short scenarios, the system had to continue to perform in drastically different environments. These scenarios included: Return-to-Launch Site, Abort Once Around, Transient Abort Landing, and others. Many of these abort scenarios increased heat load to the vehicle and pushed the capabilities of the materials to their limits.

**Thermal Protection System Materials**

Several types of thermal protection system materials were used on the orbiter. Such materials included tiles, advanced flexible reusable surface insulation, reinforced carbon-carbon, and flexible reusable surface insulation. All of these materials used high emissivity coatings to ensure the maximum rejection of incoming convective heat through radiative heat transfer. Selection was based on the temperature on the vehicle. In areas where the temperature fell below approximately 1,200°C (2,192°F), NASA used rigid tiles or fibrous insulation. At temperatures above that point, the agency used reinforced carbon-carbon.

**Tiles**

The background to the shuttle’s tiles is a work dating to the early 1960s at Lockheed Missiles and Space Company (Bethesda, Maryland). A Lockheed patent disclosure of December 1960 gave the first presentation of a reusable surface insulation made of ceramic fibers for use as a re-entry vehicle heat shield. In a phased shuttle thermal protection system development effort, attitude and heat structures were the early competitors. However, light weight and a strong desire to build the orbiter with an aluminum airframe pointed toward an innovative lightweight and reusable insulation material that could be bonded directly to the airframe skins.

NASA studied two categories of thermal protection system tiles on the orbiter—low- and high-temperature reusable surface insulation. Surface coating covered the primary difference between these two categories. High-temperature reusable surface insulation tiles used a black beryllium glass coating, which had an emissivity value greater than 0.9 in all areas. The vehicle is where temperatures reached 1,290°C (2,360°F). Low-temperature reusable surface insulation tiles contained a white coating with the proper optical properties needed to maintain the appropriate on-orbit temperatures for vehicle thermal control purposes. The low-temperature reusable surface insulation covered areas of the vehicle in which temperatures reached up to 649°C (1,202°F).

The orbiter used several different types of tiles, depending on the thermal requirements. Over the years of the program, the tile composition changed with NASA's improved understanding of the thermal conditions. The majority of these tiles, manufactured by Lockheed International, were L-900 and L-12200 B Honeycomb Composite Insulation (BCCI) tiles. Honeycomb Enhanced Thermal Barrier (HETB) tiles helped reduce the overall weight, and later the L-2200 tiles used around the ablator.

As part of the post-Columbia Return to Flight effort, engineers developed Excel Rigid Insulation (ERI), which was used in areas where small pebbles would damage fragile tiles. As part of the post-Columbia Return to Flight effort, engineers developed Excel Rigid Insulation (ERI), which was used in areas where small pebbles would damage fragile tiles. As part of the post-Columbia Return to Flight effort, engineers developed Excel Rigid Insulation (ERI), which was used in areas where small pebbles would damage fragile tiles. As part of the post-Columbia Return to Flight effort, engineers developed Excel Rigid Insulation (ERI), which was used in areas where small pebbles would damage fragile tiles. As part of the post-Columbia Return to Flight effort, engineers developed Excel Rigid Insulation (ERI), which was used in areas where small pebbles would damage fragile tiles. As part of the post-Columbia Return to Flight effort, engineers developed Excel Rigid Insulation (ERI), which was used in areas where small pebbles would damage fragile tiles. As part of the post-Columbia Return to Flight effort, engineers developed Excel Rigid Insulation (ERI), which was used in areas where small pebbles would damage fragile tiles. As part of the post-Columbia Return to Flight effort, engineers developed Excel Rigid Insulation (ERI), which was used in areas where small pebbles would damage fragile tiles. As part of the post-Columbia Return to Flight effort, engineers developed Excel Rigid Insulation (ERI), which was used in areas where small pebbles would damage fragile tiles. As part of the post-Columbia Return to Flight effort, engineers developed Excel Rigid Insulation (ERI), which was used in areas where small pebbles would damage fragile tiles. As part of the post-Columbia Return to Flight effort, engineers developed Excel Rigid Insulation (ERI), which was used in areas where small pebbles would damage fragile tiles. As part of the post-Columbia Return to Flight effort, engineers developed Excel Rigid Insulation (ERI), which was used in areas where small pebbles would damage fragile tiles. As part of the post-Columbia Return to Flight effort, engineers developed Excel Rigid Insulation (ERI), which was used in areas where small pebbles would damage fragile tiles. As part of the post-Columbia Return to Flight effort, engineers developed Excel Rigid Insulation (ERI), which was used in areas where small pebbles would damage fragile tiles. As part of the post-Columbia Return to Flight effort, engineers developed Excel Rigid Insulation (ERI), which was used in areas where small pebbles would damage fragile tiles. As part of the post-Columbia Return to Flight effort, engineers developed Excel Rigid Insulation (ERI), which was used in areas where small pebbles would damage fragile tiles. As part of the post-Columbia Return to Flight effort, engineers developed Excel Rigid Insulation (ERI), which was used in areas where small pebbles would damage fragile tiles. As part of the post-Columbia Return to Flight effort, engineers developed Excel Rigid Insulation (ERI), which was used in areas where small pebbles would damage fragile tiles. As part of the post-Columbia Return to Flight effort, engineers developed Excel Rigid Insulation (ERI), which was used in areas where small pebbles would damage fragile tiles. As part of the post-Columbia Return to Flight effort, engineers developed Excel Rigid Insulation (ERI), which was used in areas where small pebbles would damage fragile tiles. As part of the post-Columbia Return to Flight effort, engineers developed Excel Rigid Insulation (ERI), which was used in areas where small pebbles would damage fragile tiles.
New Results After Servicing Mission 1

Immediately, NASA obtained impressive results. For example, Wide Field Planetary Camera 2 images of the Orion Nebula region revealed tiny areas of compact dust around newly formed stars. These protoplanetary disks, sometimes called protostars, were the first hint that Hubble would contribute in a significant way to the studies of the formation of extrasolar planetary systems. In another observation, Hubble detected a faint galaxy around a luminous quasar (a cheat for an ultradense object) suggesting that luminous quasars and galaxies were fundamentally linked. In our own galaxy, the cores of an extremely dense ancient cluster of stars—the globular cluster 47 Tucanae—were studied, demonstrating definitively to the skeptical scientific community that individual stars in crowded fields could be distinguished with the superb imaging power of Hubble.

Steenek-Huygen

Early Hubble observations of solar system objects included the spectacular occultation of the moon by Earth photographed by the Hubble Space Telescope in 1990. This event was witnessed from start to finish, from the first fragment impact on the moon to the last image of Jupiter's atmospheric composition.

Galaxies on the Horizon

The famous “Pillars of Creation” image of the Eagle Nebula captured the public imagination and contributed to the understanding of star formation processes. The images captured in 1994 with Wide Field Planetary Camera 2 showed several features promulgated from volumes of cold gas and dust. The so-called “columns” of interstellar material collapsed to form young stars. These new hot stars then heat and vaporize the gas and blow it away from the formation sites. The dramatic scene, published in newspapers far and wide, began to redeem the public reputation of Hubble.

Existence of Supermassive Black Holes

From ground-based data, scientists knew that galaxies exhibit jets, and powerful radio emission that extends well beyond their optical boundary. Hubble’s new imaging equipment and the spectroscopic observations of galaxies suggested that some of these objects might contain a large amount of mass near their centers. Even Wide Field Planetary Camera 2 observations of the centers of several galaxies suggested that black holes might lie hidden there. However, it was the observation of the giant elliptical galaxy M87 with the Faint Object Spectrograph that conclusively demonstrated that supermassive black holes exist in large galaxies. This was the turning point in black hole studies, with spectroscopy being the powerful diagnostic tool astronomers could use to begin the humble census of these exotic objects.

Building Blocks of Early Galaxies

One of the planned goals for Hubble research was to understand the nature of the universe and look back in time to the earliest forming galaxies. In December 1995, 2 years after the first servicing mission, Hubble’s Wide Field/Planetary Camera 2 was pointed as a field in Ursa Major for 19 days, accumulating 312 exposures. The first image of the Hubble Deep Field (HDF), at the time, the deepest astronomical image ever acquired. The field probes deep into the universe and contains over 1,500 galaxies at various distances. After the Hubble Deep Fields were published, tremendous new was pointed at the same part of the sky to obtain data in every conceivable way. Besides imaging the idea that galaxies form from building blocks of smaller components, the data was analyzed with the hope it would solve the fundamental problem of the evolution of cosmic structure and the great question of how galaxies work.

Hubble would have been known as one of the great American scientific discoveries of our time. Hubble's observation was due in part to the Space Shuttle Program, and most importantly, to the astronauts who flew the shuttle and all the heroic work of building and maintaining that we never thought could be done in space. Hubble became a symbol of excellence in technology and science, and the shuttle made it happen.

“I've spent 34 years as a builder in one way or another. I was on top of Mount Everest at the launch, with all of those astronauts who had never done an interview. I was on the Today Show and Nightline. We were on the same page when the young man in the suit... In that sense, we knew we could do it. We promised the press we would do it by December of 1985. That was February 23, 1995. We flew the first thing that came back. It was spectacular. I was proud. And that was a first in history. We went from the bottom of the sea back to the top of Mount Everest and beyond... we made history.”

Subsequent Servicing Missions

Servicing Mission 2

By the end of 1996, Hubble was a productive scientific tool, with instruments for optical and ultraviolet astronomy. During the second servicing mission, in February 1997, the STS-82 crew installed two new scientific instruments: the Near Infrared Camera and Multi-Object Spectrograph, extensively Hubble’s capabilities in the infrared; and the Space Telescope Imaging Spectrograph, offering ultraviolet spectroscopic capability. Astronomers now expanded their research to probe astrophysical phenomena using the excellent imaging performance of Hubble coupled with new capability over a larger range of wavelengths.
Ellen Ochoa, PhD
Astronaut at STS-58 (1991),
STS-69 (1994),
STS-96 (1999),
and STS-110 (2002).

Atmospheric
Observations and
Ozone Assessments

“The three Atmospheric Laboratory for Applications and Science missions in the early 1990s illustrated the collaborative role that the shuttle could play with unmanned science satellites. While the satellites had the advantage of staying in orbit for years at a time, providing a long term set of measurements of ozone and chemicals related to the creation and destruction of ozone, their optics degraded over time due to interaction with ultraviolet light. The Space Shuttle carried up freshly calibrated instruments of the same design, and took simultaneous measurements over a period of 9 or 10 days; the resulting data comparison provided correction factors that improved the accuracy of the satellite data and greatly increased their scientific value.

“One of the fortunate requirements of the mission was to videotape each sunrise and sunset for use by the principal investigator of the Forerier transform spectrometer, an instrument that used the sunlight peaking through the atmosphere as a light source in collecting chemical information. Thus, one of the crew members needed to be on the flight deck to start and stop the recordings, a job I lived as it gave us the opportunity to view the incredible change from night to day and back again. I would usually pick up our pair of gyro-stabilized binoculars and watch, fascinated as the layers of the atmosphere changed in number and color in an incredible spectacle that repeated itself every 45 minutes as we orbited the Earth at 28,200 km per hour (17,500 miles per hour).”

Michael Coats
Pilot on STS-41D (1984),
Commander on STS-29 (1989),

A Balmy Hydrogen Valve
Warms Discovery Lifthoff

“I had the privilege of being pilot on the maiden flight of the Orbiter, Discovery, a hugely successful mission. We deployed three large communications satellites and tested the dynamic response characteristics of an extendable solar array wing, which was a precursor to the much larger solar array wings on the International Space Station.

“But the first launch attempt did not go quite as we expected. Our pulses were racing as the three main engines sequentially began to roar to life, but as we rocked forward on the launch pad it suddenly got deathly quiet and all motion stopped abruptly. With the snagslime screaming in protest outside our windows, it dawned on us we weren’t going into space that day. The first comment came from Mission Specialist Steve Hawley who broke the stunned silence by calmly saying “I thought wind be a lot higher at MECO (main engine cutoff)” So we soon started cracking hourly jokes while waiting for the ground crew to return to the pad and open the hatch. The joking was short-lived when we realized there was a residual fire coming up the left side of the Orbiter, led from the same balmy hydrogen valves that has caused the abort. The Launch Control Center team was quick to identify the problem and initiated the water deluge system designed for just such a contingency. We had to exit the pad elevator through a virtual wall of water. We wore thin blue cotton flight suits back then and were soaked to the bone as we entered the air-conditioned astronaut van for the ride back to crew quarters. The drenched crew shivered and huddled together as we watched the Discovery recede through the rear window of the van, as Mike Mullane wryly observed, “This isn’t exactly what I expected spacecraft to be like.” The entire crew, including Commander Hank Hartfield, the other Mission Specialists Mike Mullane and Judy Resnik, and Payload Specialist Charlie Walker, contributed to an easy camaraderie that made the long hours of training for the mission truly enjoyable.”
Witness Accounts – Key to Understanding Columbia Breakup
Introduction by Charles Bolden

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President George H.W. Bush
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Pam Leestma – Elementary School Teacher
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Leah Jamieson – Dean of Engineering at Purdue University
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**Major NASA Leaders**

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