National Aeronautics and Space Administration

Wings In Orbit

Scientific and Engineering Legacies of the Space Shuttle

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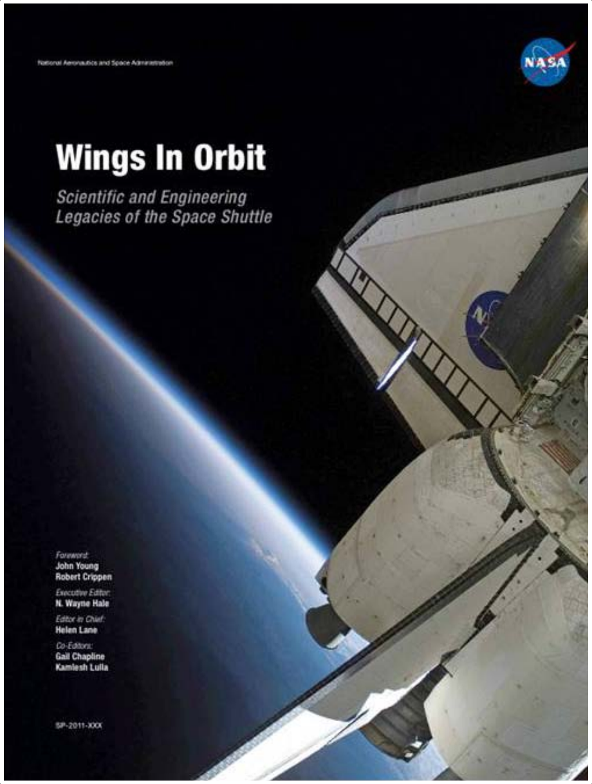
An agency-wide Space Shuttle book project involving contributions from all NASA centers

Space Shuttle book: September 2010



Wings In Orbit

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

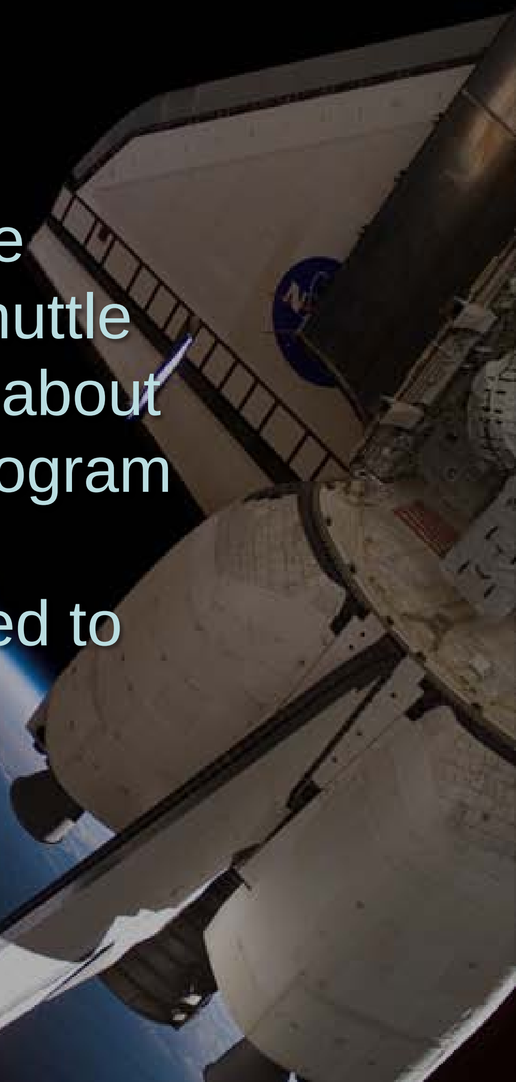
- Description of the Shuttle and its operations
- Engineering innovations
- Major scientific discoveries
- Social, cultural, and educational legacies
- Commercial developments
- The Shuttle continuum, role of human spaceflight

Vision

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.



Vision *(continued)*

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

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Example Page Layout – Flight Ops

October 2010) over a period of 29 years, the Orbiter deployed a multitude of satellites for Earth observation and telecommunications, interplanetary probes such as Galileo/Jupiter spacecraft, Magellan/Venus Radar Mapper, great observatories that included the Hubble Space Telescope, Compton Gamma Ray Observatory, and Chandra X-ray Observatory. The Orbiter even functioned as a science platform/laboratory; e.g., Spacelab, Astronomy Ultraviolet Telescope, US Microgravity Laboratory, US Microgravity Payload, etc. Aside from the experiments and satellite deployments that the shuttle performed, the most important accomplishment was the delivery and assembly of the ISS.

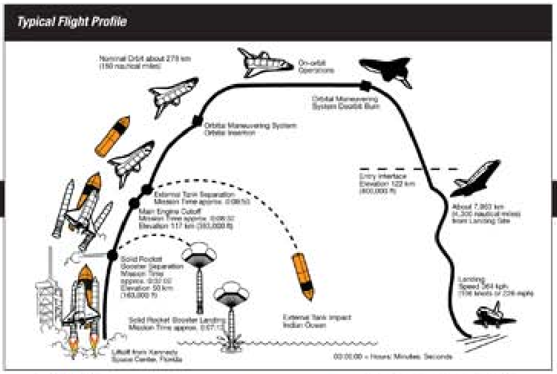
Space Shuttle Reusability

All components of the Space Shuttle vehicle, except for the ET, were designed to be reusable, flight after flight. The ET, once jettisoned from the Orbiter, fell to Earth where atmospheric heating caused the tank to break up over the ocean.

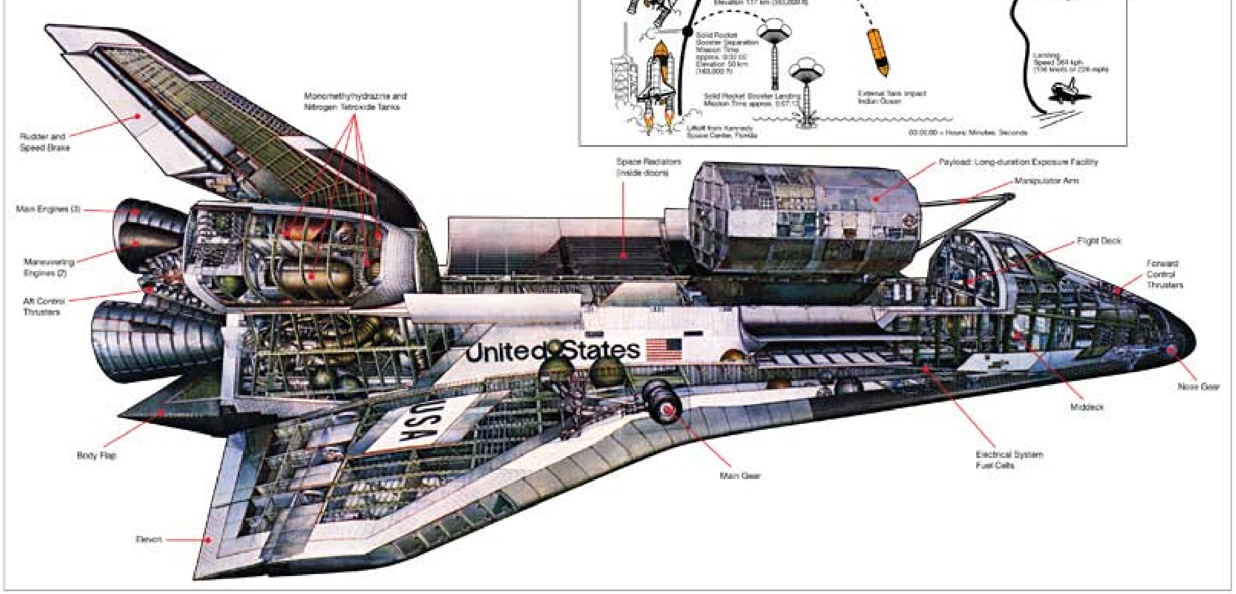
The SRBs, once jettisoned from the tank, parachuted back to the ocean where they were recovered by special ships and brought back to KSC. With their solid propellant spent, the boosters were de-stacked and shipped back to aerospace and defense company Thiokol—now ATK—in Utah for refurbishment and re-use. After every mission, the SRBs were thoroughly inspected to ensure that the components were not damaged and could be refurbished for another flight. Any damage found was either repaired, or the component was discarded.

The Orbiter was the only fully reusable component of the shuttle system. Each Orbiter was designed and certified for 100 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 39, 32, and 25 missions, respectively, by the end of the program. Challenger flew 10 missions and Columbia flew 28 missions before their loss on January 28, 1986, and February 1, 2003, respectively.

Typical Flight Profile



The Orbiter



Example Page Layout – Engineering

form the contours of these structural components. NASA made an exhaustive effort to ensure that these materials would operate over a large spectrum of environments during launch, ascent, on-orbit operations, re-entry, and landing.

Environments

During re-entry, the orbiter's external surface reached extreme temperatures—up to 1,648°C (3,000°F). The thermal protection system was designed to provide a smooth, aerodynamic surface while protecting the underlying metal structure from excessive temperature. The loads endured by the system included launch acoustics, aerodynamic loading and associated structural deflections, and on-orbit temperature variations, as well as natural environments such as salt fog, wind, and rain. In addition, the thermal protection system had to resist pyrotechnic shock loads as the orbiter separated from the ET.

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 176°C (350°F). In addition, they were reusable for 100 missions with refurbishment and maintenance. These materials performed in temperatures that ranged from -156°C (-250°F) in the cold soak of space to re-entry temperatures that reached nearly 1,648°C (3,000°F). The thermal protection system also withstood the forces induced by deflections of the orbiter airframe as it responded to various external environments.

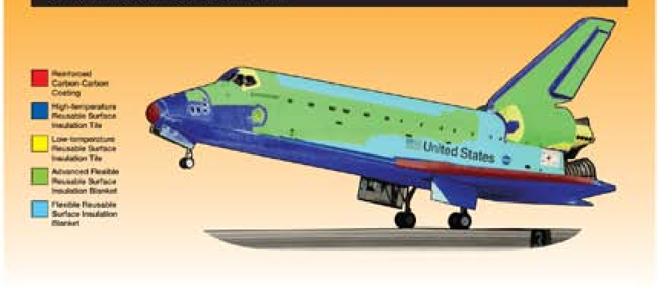
At the vehicle surface, a boundary layer developed and was designed to be laminar; however, small gaps and discontinuities on the vehicle surface could cause the flow to transition from laminar to turbulent, thus increasing the overall heating. Therefore, tight fabrication and assembly tolerances were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

Requirements for the thermal protection system extended beyond the nominal trajectories. For abort scenarios, the systems had to continue to perform in drastically different environments. These scenarios included: Return-to-Launch Site; Abort Once Around; Transatlantic 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.

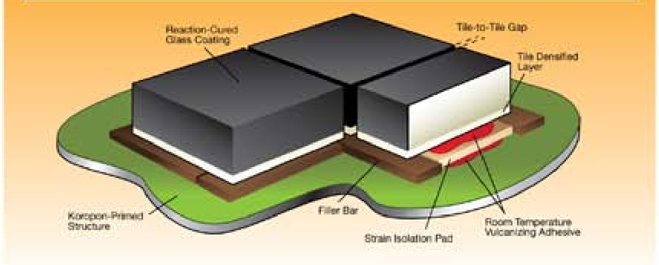
Thermal Protection System Materials

Several types of thermal protection system materials were used on the orbiter. Such materials included: tiles; advanced flexible reusable surface

Orbiter Tile Placement System Configuration



High-temperature Reusable Surface Insulation Tile Attachment System



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 temperatures fell below approximately 1,260°C (2,300°F), NASA used rigid silica tiles or fibrous insulation. At temperatures above that point, the agency used reinforced carbon-carbon.

Tiles

The background to the shuttle's tiles lay in 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 insulation made of ceramic fibers for use as a re-entry vehicle heat shield. In a phased shuttle thermal protection system development effort, ablatives and hot structures were the early competitors. However, tight cost constraints 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 skin.

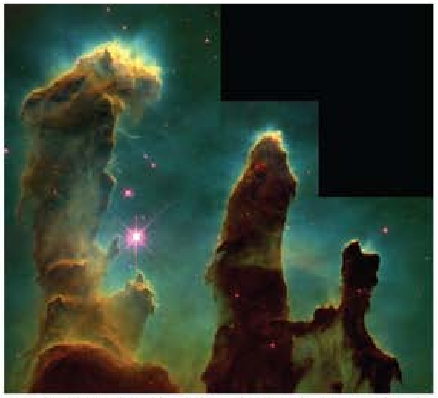
NASA used two categories of thermal protection system tiles on the orbiter—low- and high-temperature reusable surface insulation. Surface coating constituted the primary difference between these two categories. High-temperature reusable surface insulation tiles used a black borosilicate glass coating, which had an emittance value greater than 0.8 and covered areas of the vehicle in which temperatures reached up to 1,260°C (2,300°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 tiles covered areas of the vehicle in which temperatures reached up to 649°C (1,200°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 LI900 and LI2200. Fibrous Refractory Composite Insulation (FRCI-12) tiles helped reduce the overall weight, and later replaced the LI2200 tiles used around door penetrations. Alumina Enhanced Thermal Barrier (AETB-8) was used in areas where small particles would damage fragile tiles. As part of the post-Columbia Return to Flight effort, engineers developed Boeing Rigidized Insulation (BRI-18). Overall, the major improvements included reduction of weight, vulnerability to orbital debris, and minimal thermal conductivity.

Example Page Layout – Science

New Results After Servicing Mission 1

Immediately, NASA obtained impressive results. For example, Wide Field Planetary Camera 2 images of the Orion Nebula region resolved tiny areas of compact dust around newly formed stars. These protoplanetary disks, sometimes called *proplyds*, 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 (short for quasi-stellar object), suggesting that luminous quasars and galaxies were fundamentally linked. In our own galaxy, the core of an extremely dense ancient cluster of stars—the globular cluster 47 Tucanae—was resolved, demonstrating definitively to the skeptical scientific community that individual stars in crowded fields could be distinguished with the superb imaging power of Hubble.



Gas pillars in the Eagle Nebula: Pillars of Creation in star-forming region captured by the Wide Field Planetary Camera 2 in 1995. The region is trillions and trillions of miles away in the constellation Serpens. The tallest pillar is 4 light-years long and the colors show emissions from different atoms.

Shoemaker-Levy

Early Hubble observations of solar system objects included the spectacular crash of Comet Shoemaker-Levy 9 into Jupiter in 1994. This event was witnessed from start to finish, from the first fragment impact to the aftermath on the Jovian atmosphere. Images were also taken in visible blue light and ultraviolet light to determine the depth of the impacts and the nature of Jupiter's atmospheric composition.

Color image of Jupiter showing the affect of the several impacts of Comet Shoemaker-Levy 9 after its multiple fragments impacted the planet in 1994.

Pillars of Creation

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 1995 with Wide Field Planetary Camera 2 showed narrow features protruding from columns of cold gas and dust. Inside the gaseous "towers," interstellar material collapses to form young stars. These new hot stars then heat and ionize 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 periphery. Huge x-ray emissions and 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 innards of several galaxies suggested that black holes might be 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 Hubble 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 at a field in Ursa Major for 10 days, accumulating 342 exposures. The final image—the Hubble Deep Field—was, 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 Field data were produced, telescopes were pointed at the same part of the sky to obtain data in every conceivable way. Besides bolstering the idea that galaxies form from building blocks of smaller components that are irregularly shaped and that the rate of star and galaxy formation was much higher in the past, analysis of the data pushed the observable universe back to approximately 12 billion years. Papers written on Hubble Deep Field data alone number in the hundreds and document the new understanding of cosmological and astrophysical phenomena.

The immediate release of Hubble Deep Field data represented a watershed in astronomical research as well. A new method was born for concentrating astronomical facilities and the collective brainpower of the scientific community on a specific research problem. Thus, the Hubble Deep Field represents not only a leap forward in scientific understanding of the universe, but a significant alteration in the way astronomy was conducted.

Edward Weller, PhD
Chief scientist for the Hubble Space Telescope (1979-1998)
NASA associate administrator, Science Mission Directorate

"It's fair to say that Hubble, today, would be a piece of orbiting space debris if it hadn't been for the Space Shuttle Program. If Hubble had been launched on an expendable launch vehicle, we would have discovered the optical problem, yet been unable to fix it. Hubble would have been known as one of the great American scientific disasters of our time. Hubble's redemption is due to the Space Shuttle Program and, most importantly, to the astronauts who flew the shuttle and did things (in repairing Hubble) that we never thought could be done in space. Hubble became a symbol of excellence in technology and science, and the shuttle made that happen.

"I've spent 34 years on Hubble in one way or another. I was on top of Mount Everest at the launch, with all of us astronomers who had never done an interview. I was on the Today Show and Nightline on the same day. I experienced the ecstasy in April of 1990, to the bottom of the Dead Sea 2 months later when a spherical aberration was detected in the Hubble. In our hearts, we knew we could fix it. We promised the press we would fix it by December of 1993, and nobody believed us. Then, on December 20, 1993, we saw the first image come back. It was spectacular. It was fixed. And the rest is history. We went from the bottom of the Dead Sea back to the top of Mount Everest and beyond…we were elated!"

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 Spectrometer, extending Hubble's capabilities to 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.

Astronaut Quote Boxes Examples

Ellen Ochoa, PhD
Astronaut on STS-56 (1993), STS-66 (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 Fourier transform spectrometer, an instrument that used the sunlight peeking 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 we loved 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)."

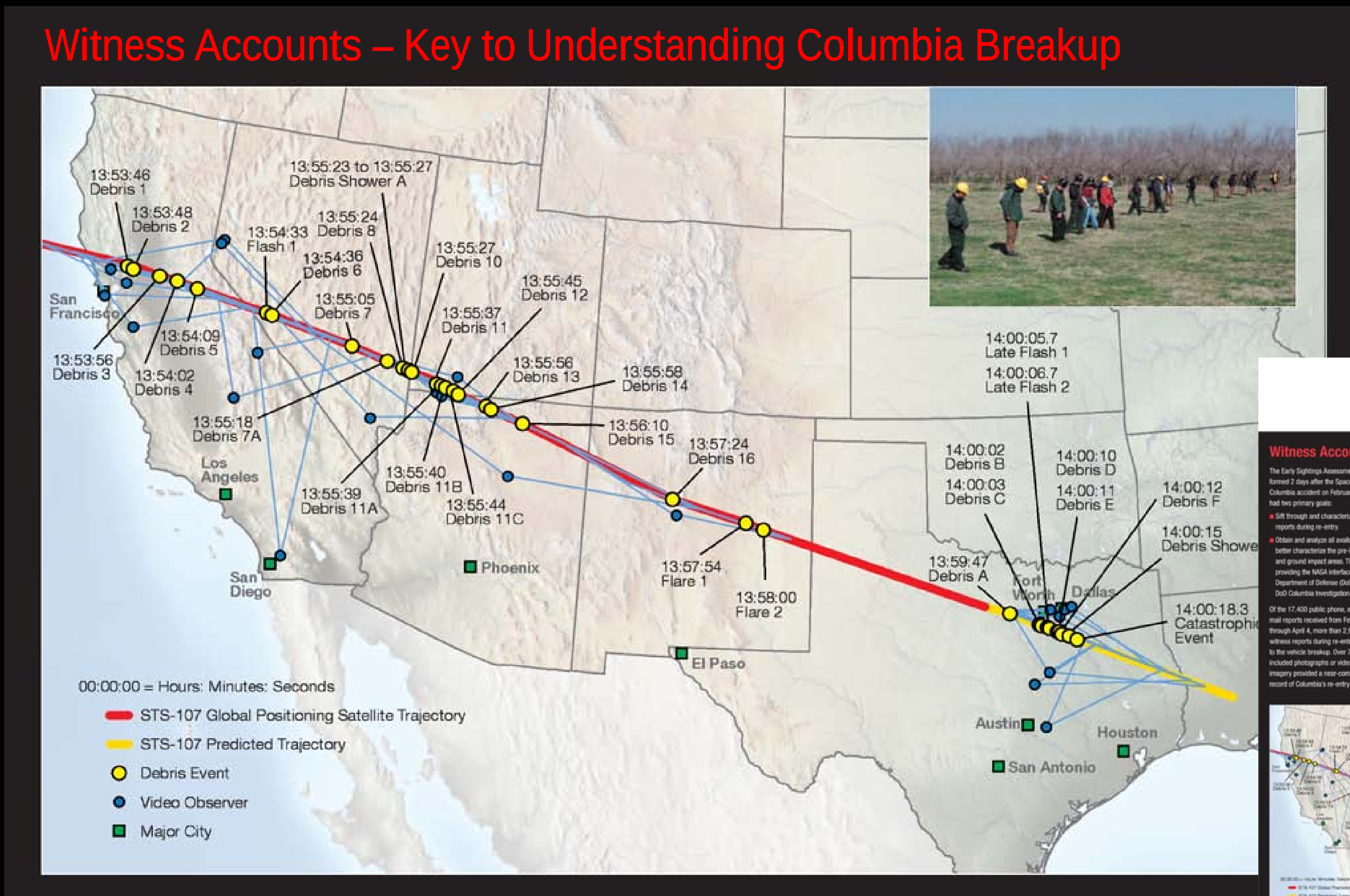
Michael Coats
Pilot on STS-41D (1984). Commander on STS-29 (1989) and STS-39 (1991).

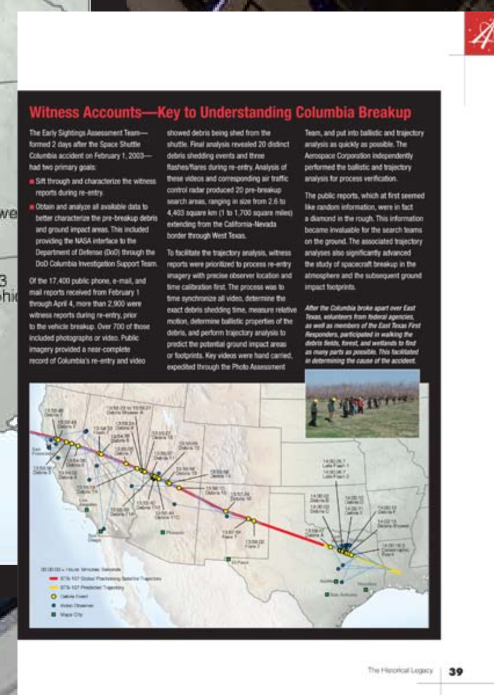
A Balky Hydrogen Valve Halts Discovery Liftoff

"I had the privilege of being the 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 seagulls 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 we'd be a lot higher at MECO (main engine cutoff)." So we soon started cracking lousy 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, fed from the same balky hydrogen valve that had 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, and as Mike Mullane wryly observed, "This isn't exactly what I expected spaceflight to be like." The entire crew, including Commander Hank Hartsfield, 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."

Example of Side Bars




Witness Accounts—Key to Understanding Columbia Breakup

Introduction by Charles Bolden

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President George H.W. Bush

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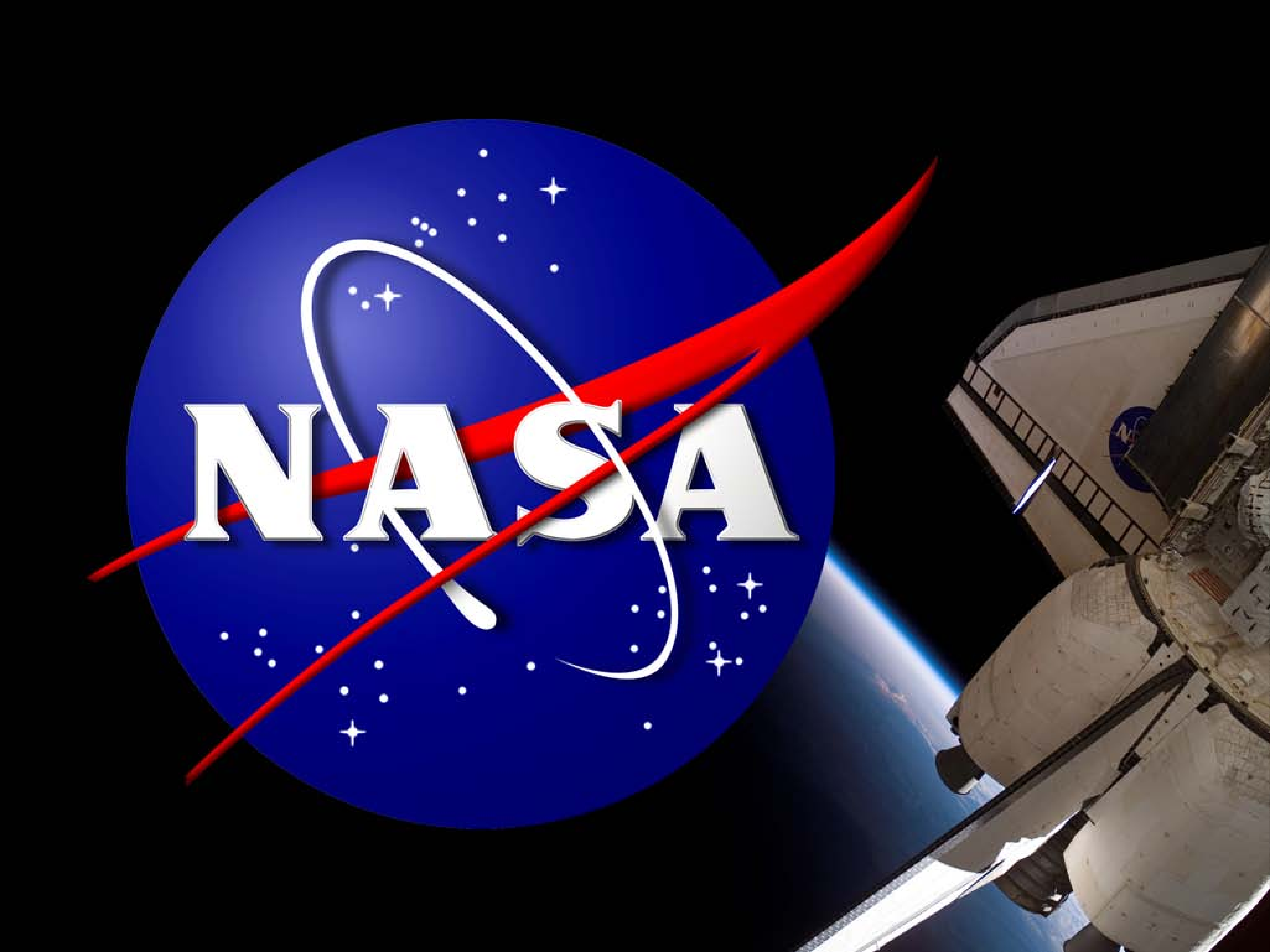
NASA

Backup

Interviewees as of January 2010

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Ken Baldwin
Barry Blumberg
Bob Crippen
Aaron Cohen
Jack Fischer
Bill Gerstenmaier
Milt Heflin
Ernie Hilsenrath
Tommy Holloway
Dick Kohrs
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JR Thompson
Bob Thompson
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Perspectives Inputs as of January 2010

Astronaut quote boxes

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Tom Jones
Chiaki Mukai
Barbara Morgan
Ellen Ochoa
Ken Reightler
Richard Searfoss
Brewster Shaw
Gene Trinh
Don Thomas
Bill Thornton
Mary Ellen Weber
Dave Williams

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Mark Kelly
Shannon Lucid
Sally Ride

Two Nobel Prize Winners

Major NASA Leaders

World Renowned Scientists

Written by people of the Space Shuttle Program

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