COLUMBIA

ACCIDENT INVESTIGATION BOARD

REPORT VOLUME I

AUGUST 2003

On the Front Cover

This was the crew patch for STS-107. The central element of the patch was the microgravity symbol, µg, flowing into the rays of the Astronaut symbol. The orbital inclination was portrayed by the 39-degree angle of the Earth's horizon to the Astronaut symbol. The sunrise was representative of the numerous science experiments that were the dawn of a new era for continued microgravity research on the International Space Station and beyond. The breadth of science conducted on this mission had widespread benefits to life on Earth and the continued exploration of space, illustrated by the Earth and stars. The constellation Columba (the dove) was chosen to symbolize peace on Earth and the Space Shuttle Columbia. In addition, the seven stars represent the STS-107 crew members, as well as honoring the original Mercury 7 astronauts who paved the way to make research in space possible. The Israeli flag represented the first person from that country to fly on the Space Shuttle.

On the Back Cover

This emblem memorializes the three U.S. human space flight accidents – Apollo 1, Challenger, and Columbia. The words across the top translate to: "To The Stars, Despite Adversity – Always Explore"

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IN MEMORIAM

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Payload Specialist

Jules F. Mier, Jr.
Debris Search Pilot

Charles Krenek
Debris Search Aviation Specialist

This cause of exploration and discovery is not an option we choose; it is a desire written in the human heart …
We find the best among us, send them forth into unmapped darkness, and pray they will return.
They go in peace for all mankind, and all mankind is in their debt.

– President George W. Bush, February 4, 2003

The quarter moon, photographed from Columbia on January 26, 2003, during the STS-107 mission.

VOLUME I

Board Statement

For all those who are inspired by flight, and for the nation where powered flight was first achieved, the year 2003 had long been anticipated as one of celebration – December 17 would mark the centennial of the day the Wright *Flyer* first took to the air. But 2003 began instead on a note of sudden and profound loss. On February 1, Space Shuttle *Columbia* was destroyed in a disaster that claimed the lives of all seven of its crew.

While February 1 was an occasion for mourning, the efforts that ensued can be a source of national pride. NASA publicly and forthrightly informed the nation about the accident and all the associated information that became available. The Columbia Accident Investigation Board was established within two hours of the loss of signal from the returning spacecraft in accordance with procedures established by NASA following the *Challenger* accident 17 years earlier.

The crew members lost that morning were explorers in the finest tradition, and since then, everyone associated with the Board has felt that we were laboring in their legacy. Ours, too, was a journey of discovery: We sought to discover the conditions that produced this tragic outcome and to share those lessons in such a way that this nation's space program will emerge stronger and more sure-footed. If those lessons are truly learned, then *Columbia*'s crew will have made an indelible contribution to the endeavor each one valued so greatly.

After nearly seven months of investigation, the Board has been able to arrive at findings and recommendations aimed at significantly reducing the chances of further accidents. Our aim has been to improve Shuttle safety by multiple means, not just by correcting the specific faults that cost the nation this Orbiter and this crew. With that intent, the Board conducted not only an investigation of what happened to *Columbia*, but also – to determine the conditions that allowed the accident to occur – a safety evaluation of the entire Space Shuttle Program. Most of the Board's efforts were undertaken in a completely open manner. By necessity, the safety evaluation was conducted partially out of the public view, since it included frank, off-the-record statements by a substantial number of people connected with the Shuttle program.

In order to understand the findings and recommendations in this report, it is important to appreciate the way the Board looked at this accident. It is our view that complex systems almost always fail in complex ways, and we believe it would be wrong to reduce the complexities and weaknesses associated with these systems to some simple explanation. Too often, accident investigations blame a failure only on the last step in a complex process, when a more comprehensive understanding of that process could reveal that earlier steps might be equally or even more culpable. In this Board's opinion, unless the technical, organizational, and cultural recommendations made in this report are implemented, little will have been accomplished to lessen the chance that another accident will follow.

From its inception, the Board has considered itself an independent and public institution, accountable to the American public, the White House, Congress, the astronaut corps and their families, and NASA. With the support of these constituents, the Board resolved to broaden the scope of the accident investigation into a far-reaching examination of NASA's operation of the Shuttle fleet. We have explored the impact of NASA's organizational history and practices on Shuttle safety, as well as the roles of public expectations and national policy-making.

In this process, the Board identified a number of pertinent factors, which we have grouped into three distinct categories: 1) physical failures that led directly to *Columbia*'s destruction; 2) underlying weaknesses, revealed in NASA's organization and history, that can pave the way to catastrophic failure; and 3) "other significant observations" made during the course of the investigation, but which may be unrelated to the accident at hand. Left uncorrected, any of these factors could contribute to future Shuttle losses.

To establish the credibility of its findings and recommendations, the Board grounded its examinations in rigorous scientific and engineering principles. We have consulted with leading authorities not only in mechanical systems, but also in organizational theory and practice. These authorities' areas of expertise included risk management, safety engineering, and a review of "best business practices" employed by other high-risk, but apparently reliable enterprises. Among these are nuclear power plants, petrochemical facilities, nuclear weapons production, nuclear submarine operations, and expendable space launch systems.

NASA is a federal agency like no other. Its mission is unique, and its stunning technological accomplishments, a source of pride and inspiration without equal, represent the best in American skill and courage. At times NASA's efforts have riveted the nation, and it is never far from public view and close scrutiny from many quarters. The loss of *Columbia* and her crew represents a turning point, calling for a renewed public policy debate and commitment regarding human space exploration. One of our goals has been to set forth the terms for this debate.

Named for a sloop that was the first American vessel to circumnavigate the Earth more than 200 years ago, in 1981 *Columbia* became the first spacecraft of its type to fly in Earth orbit and successfully completed 27 missions over more than two decades. During the STS-107 mission, *Columbia* and its crew traveled more than six million miles in 16 days.

The Orbiter's destruction, just 16 minutes before scheduled touchdown, shows that space flight is still far from routine. It involves a substantial element of risk, which must be recognized, but never accepted with resignation. The seven *Columbia* astronauts believed that the risk was worth the reward. The Board salutes their courage and dedicates this report to their memory.

Harold W. Gehman, Jr.
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Professor, Massachusetts Institute of Technology

Columbia inside the Orbiter Processing Facility on November 20, 2002.

EXECUTIVE SUMMARY

The Columbia Accident Investigation Board's independent investigation into the February 1, 2003, loss of the Space Shuttle *Columbia* and its seven-member crew lasted nearly seven months. A staff of more than 120, along with some 400 NASA engineers, supported the Board's 13 members. Investigators examined more than 30,000 documents, conducted more than 200 formal interviews, heard testimony from dozens of expert witnesses, and reviewed more than 3,000 inputs from the general public. In addition, more than 25,000 searchers combed vast stretches of the Western United States to retrieve the spacecraft's debris. In the process, *Columbia*'s tragedy was compounded when two debris searchers with the U.S. Forest Service perished in a helicopter accident.

The Board recognized early on that the accident was probably not an anomalous, random event, but rather likely rooted to some degree in NASA's history and the human space flight program's culture. Accordingly, the Board broadened its mandate at the outset to include an investigation of a wide range of historical and organizational issues, including political and budgetary considerations, compromises, and changing priorities over the life of the Space Shuttle Program. The Board's conviction regarding the importance of these factors strengthened as the investigation progressed, with the result that this report, in its findings, conclusions, and recommendations, places as much weight on these causal factors as on the more easily understood and corrected physical cause of the accident.

The physical cause of the loss of *Columbia* and its crew was a breach in the Thermal Protection System on the leading edge of the left wing, caused by a piece of insulating foam which separated from the left bipod ramp section of the External Tank at 81.7 seconds after launch, and struck the wing in the vicinity of the lower half of Reinforced Carbon-Carbon panel number 8. During re-entry this breach in the Thermal Protection System allowed superheated air to penetrate through the leading edge insulation and progressively melt the aluminum structure of the left wing, resulting in a weakening of the structure until increasing aerodynamic forces caused loss of control, failure of the wing, and breakup of the Orbiter. This breakup occurred in a flight regime in which, given the current design of the Orbiter, there was no possibility for the crew to survive.

The organizational causes of this accident are rooted in the Space Shuttle Program's history and culture, including the original compromises that were required to gain approval for the Shuttle, subsequent years of resource constraints, fluctuating priorities, schedule pressures, mischaracterization of the Shuttle as operational rather than developmental, and lack of an agreed national vision for human space flight. Cultural traits and organizational practices detrimental to safety were allowed to develop, including: reliance on past success as a substitute for sound engineering practices (such as testing to understand why systems were not performing in accordance with requirements); organizational barriers that prevented effective communication of critical safety information and stifled professional differences of opinion; lack of integrated management across program elements; and the evolution of an informal chain of command and decision-making processes that operated outside the organization's rules.

This report discusses the attributes of an organization that could more safely and reliably operate the inherently risky Space Shuttle, but does not provide a detailed organizational prescription. Among those attributes are: a robust and independent program technical authority that has complete control over specifications and requirements, and waivers to them; an independent safety assurance organization with line authority over all levels of safety oversight; and an organizational culture that reflects the best characteristics of a learning organization.

This report concludes with recommendations, some of which are specifically identified and prefaced as "before return to flight." These recommendations are largely related to the physical cause of the accident, and include preventing the loss of foam, improved imaging of the Space Shuttle stack from liftoff through separation of the External Tank, and on-orbit inspection and repair of the Thermal Protection System. The remaining recommendations, for the most part, stem from the Board's findings on organizational cause factors. While they are not "before return to flight" recommendations, they can be viewed as "continuing to fly" recommendations, as they capture the Board's thinking on what changes are necessary to operate the Shuttle and future spacecraft safely in the mid- to long-term.

These recommendations reflect both the Board's strong support for return to flight at the earliest date consistent with the overriding objective of safety, and the Board's conviction that operation of the Space Shuttle, and all human spaceflight, is a developmental activity with high inherent risks.

A view from inside the Launch Control Center as Columbia *rolls out to Launch Complex 39-A on December 9, 2002.*

Columbia *sits on Launch Complex 39-A prior to STS-107.*

REPORT SYNOPSIS

The Columbia Accident Investigation Board's independent investigation into the tragic February 1, 2003, loss of the Space Shuttle *Columbia* and its seven-member crew lasted nearly seven months and involved 13 Board members, approximately 120 Board investigators, and thousands of NASA and support personnel. Because the events that initiated the accident were not apparent for some time, the investigation's depth and breadth were unprecedented in NASA history. Further, the Board determined early in the investigation that it intended to put this accident into context. We considered it unlikely that the accident was a random event; rather, it was likely related in some degree to NASA's budgets, history, and program culture, as well as to the politics, compromises, and changing priorities of the democratic process. We are convinced that the management practices overseeing the Space Shuttle Program were as much a cause of the accident as the foam that struck the left wing. The Board was also influenced by discussions with members of Congress, who suggested that this nation needed a broad examination of NASA's Human Space Flight Program, rather than just an investigation into what physical fault caused *Columbia* to break up during re-entry.

Findings and recommendations are in the relevant chapters and all recommendations are compiled in Chapter 11.

Volume I is organized into four parts: The Accident; Why the Accident Occurred; A Look Ahead; and various appendices. To put this accident in context, Parts One and Two begin with histories, after which the accident is described and then analyzed, leading to findings and recommendations. Part Three contains the Board's views on what is needed to improve the safety of our voyage into space. Part Four is reference material. In addition to this first volume, there will be subsequent volumes that contain technical reports generated by the Columbia Accident Investigation Board and NASA, as well as volumes containing reference documentation and other related material.

PART ONE: THE ACCIDENT

Chapter 1 relates the history of the Space Shuttle Program before the *Challenger* accident. With the end looming for the Apollo moon exploration program, NASA unsuccessfully attempted to get approval for an equally ambitious (and expensive) space exploration program. Most of the proposed programs started with space stations in low-Earth orbit and included a reliable, economical, medium-lift vehicle to travel safely to and from low-Earth orbit. After many failed attempts, and finally agreeing to what would be untenable compromises, NASA gained approval from the Nixon Administration to develop, on a fixed budget, only the transport vehicle. Because the Administration did not approve a low-Earth-orbit station, NASA had to create a mission for the vehicle. To satisfy the Administration's requirement that the system be economically justifiable, the vehicle had to capture essentially all space launch business, and to do that, it had to meet wide-ranging requirements. These sometimes-competing requirements resulted in a compromise vehicle that was less than optimal for manned flights. NASA designed and developed a remarkably capable and resilient vehicle, consisting of an Orbiter with three Main Engines, two Solid Rocket Boosters, and an External Tank, but one that has never met any of its original requirements for reliability, cost, ease of turnaround, maintainability, or, regrettably, safety.

Chapter 2 documents the final flight of *Columbia*. As a straightforward record of the event, it contains no findings or recommendations. Designated STS-107, this was the Space Shuttle Program's 113th flight and *Columbia*'s 28th. The flight was close to trouble-free. Unfortunately, there were no indications to either the crew onboard *Columbia* or to engineers in Mission Control that the mission was in trouble as a result of a foam strike during ascent. Mission management failed to detect weak signals that the Orbiter was in trouble and take corrective action.

Columbia was the first space-rated Orbiter. It made the Space Shuttle Program's first four orbital test flights. Because it was the first of its kind, *Columbia* differed slightly from Orbiters *Challenger*, *Discovery*, *Atlantis*, and *Endeavour*. Built to an earlier engineering standard, *Columbia* was slightly heavier, and, although it could reach the high-inclination orbit of the International Space Station, its payload was insufficient to make *Columbia* cost-effective for Space Station missions. Therefore, *Columbia* was not equipped with a Space Station docking system, which freed up space in the payload bay for longer cargos, such as the science modules Spacelab and SPACEHAB. Consequently, *Columbia* generally flew science missions and serviced the Hubble Space Telescope.

STS-107 was an intense science mission that required the seven-member crew to form two teams, enabling round-the-clock shifts. Because the extensive science cargo and its extra power sources required additional checkout time, the launch sequence and countdown were about 24 hours longer than normal. Nevertheless, the countdown proceeded as planned, and *Columbia* was launched from Launch Complex 39-A on January 16, 2003, at 10:39 a.m. Eastern Standard Time (EST).

At 81.7 seconds after launch, when the Shuttle was at about 65,600 feet and traveling at Mach 2.46 (1,650 mph), a large piece of hand-crafted insulating foam came off an area where the Orbiter attaches to the External Tank. At 81.9 seconds, it struck the leading edge of *Columbia*'s left wing. This event was not detected by the crew on board or seen by ground support teams until the next day, during detailed reviews of all launch camera photography and videos. This foam strike had no apparent effect on the daily conduct of the 16-day mission, which met all its objectives.

The de-orbit burn to slow *Columbia* down for re-entry into Earth's atmosphere was normal, and the flight profile throughout re-entry was standard. Time during re-entry is measured in seconds from "Entry Interface," an arbitrarily determined altitude of 400,000 feet where the Orbiter begins to experience the effects of Earth's atmosphere. Entry Interface for STS-107 occurred at 8:44:09 a.m. on February 1. Unknown to the crew or ground personnel, because the data is recorded and stored in the Orbiter instead of being transmitted to Mission Control at Johnson Space Center, the first abnormal indication occurred 270 seconds after Entry Interface. Chapter 2 reconstructs in detail the events leading to the loss of *Columbia* and her crew, and refers to more details in the appendices.

In Chapter 3, the Board analyzes all the information available to conclude that the direct, physical action that initiated the chain of events leading to the loss of *Columbia* and her crew was the foam strike during ascent. This chapter reviews five analytical paths – aerodynamic, thermodynamic, sensor data timeline, debris reconstruction, and imaging evidence – to show that all five independently arrive at the same conclusion. The subsequent impact testing conducted by the Board is also discussed.

That conclusion is that *Columbia* re-entered Earth's atmosphere with a pre-existing breach in the leading edge of its left wing in the vicinity of Reinforced Carbon-Carbon (RCC) panel 8. This breach, caused by the foam strike on ascent, was of sufficient size to allow superheated air (probably exceeding 5,000 degrees Fahrenheit) to penetrate the cavity behind the RCC panel. The breach widened, destroying the insulation protecting the wing's leading edge support structure, and the superheated air eventually melted the thin aluminum wing spar. Once in the interior, the superheated air began to destroy the left wing. This destructive process was carefully reconstructed from the recordings of hundreds of sensors inside the wing, and from analyses of the reactions of the flight control systems to the changes in aerodynamic forces.

By the time *Columbia* passed over the coast of California in the pre-dawn hours of February 1, at Entry Interface plus 555 seconds, amateur videos show that pieces of the Orbiter were shedding. The Orbiter was captured on videotape during most of its quick transit over the Western United States. The Board correlated the events seen in these videos to sensor readings recorded during re-entry. Analysis indicates that the Orbiter continued to fly its pre-planned flight profile, although, still unknown to anyone on the ground or aboard *Columbia*, her control systems were working furiously to maintain that flight profile. Finally, over Texas, just southwest of Dallas-Fort Worth, the increasing aerodynamic forces the Orbiter experienced in the denser levels of the atmosphere overcame the catastrophically damaged left wing, causing the Orbiter to fall out of control at speeds in excess of 10,000 mph.

The chapter details the recovery of about 38 percent of the Orbiter (some 84,000 pieces) and the reconstruction and analysis of this debris. It presents findings and recommendations to make future Space Shuttle operations safer.

Chapter 4 describes the investigation into other possible physical factors that may have contributed to the accident. The chapter opens with the methodology of the fault tree analysis, which is an engineering tool for identifying every conceivable fault, then determining whether that fault could have caused the system in question to fail. In all, more than 3,000 individual elements in the *Columbia* accident fault tree were examined.

In addition, the Board analyzed the more plausible fault scenarios, including the impact of space weather, collisions with micrometeoroids or "space junk," willful damage, flight crew performance, and failure of some critical Shuttle hardware. The Board concludes in Chapter 4 that despite certain fault tree exceptions left "open" because they cannot be conclusively disproved, none of these factors caused or contributed to the accident. This chapter also contains findings and recommendations to make Space Shuttle operations safer.

Part Two: Why the Accident Occurred

Part Two, "Why the Accident Occurred," examines NASA's organizational, historical, and cultural factors, as well as how these factors contributed to the accident.

As in Part One, Part Two begins with history. Chapter 5 examines the post-*Challenger* history of NASA and its Human Space Flight Program. A summary of the relevant portions of the *Challenger* investigation recommendations is presented, followed by a review of NASA budgets to indicate how committed the nation is to supporting human space flight, and within the NASA budget we look at how the Space Shuttle Program has fared. Next, organizational and management history, such as shifting management systems and locations, are reviewed.

Chapter 6 documents management performance related to *Columbia* to establish events analyzed in later chapters. The chapter begins with a review of the history of foam strikes on the Orbiter to determine how Space Shuttle Program managers rationalized the danger from repeated strikes on the Orbiter's Thermal Protection System. Next is an explanation of the intense pressure the program was under to stay on schedule, driven largely by the self-imposed requirement to complete the International Space Station. Chapter 6 then relates in detail the effort by some NASA engineers to obtain additional imagery of *Columbia* to determine if the foam strike had damaged the Orbiter, and how management dealt with that effort.

In Chapter 7, the Board presents its view that NASA's organizational culture had as much to do with this accident as foam did. By examining safety history, organizational theory, best business practices, and current safety failures, the report notes that only significant structural changes to NASA's organizational curlture will enable it to succeed.

This chapter measures the Shuttle Program's practices against this organizational context and finds them wanting. The Board concludes that NASA's current organization does not provide effective checks and balances, does not have an independant safety program, and has not demonstrated the characteristics of a learning organization. Chapter 7 provides recommendations for adjustments in organizational culture.

Chapter 8, the final chapter in Part Two, draws from the previous chapters on history, budgets, culture, organization, and safety practices, and analyzes how all these factors contributed to this accident. The chapter opens with "echoes of *Challenger*" that compares the two accidents. This chapter captures the Board's views of the need to adjust management to enhance safety margins in Shuttle operations, and reaffirms the Board's position that without these changes, we have no confidence that other "corrective actions" will improve the safety of Shuttle operations. The changes we recommend will be difficult to accomplish – and will be internally resisted.

Part Three: A Look Ahead

Part Three summarizes the Board's conclusions on what needs to be done to resume our journey into space, lists significant observations the Board made that are unrelated to the accident but should be recorded, and provides a summary of the Board's recommendations.

In Chapter 9, the Board first reviews its short-term recommendations. These return-to-flight recommendations are the minimum that must be done to essentially fix the problems that were identified by this accident. Next, the report discusses what needs to be done to operate the Shuttle in the mid-term, 3 to 15 years. Based on NASA's history of ignoring external recommendations, or making improvements that atrophy with time, the Board has no confidence that the Space Shuttle can be safely operated for more than a few years based solely on renewed post-accident vigilance.

Chapter 9 then outlines the management system changes the Board feels are necessary to safely operate the Shuttle in the mid-term. These changes separate the management of scheduling and budgets from technical specification authority, build a capability of systems integration, and establish and provide the resources for an independent safety and mission assurance organization that has supervisory authority. The third part of the chapter discusses the poor record this nation has, in the Board's view, of developing either a complement to or a replacement for the Space Shuttle. The report is critical of several bodies in the U.S. government that share responsibility for this situation, and expresses an opinion on how to proceed from here, but does not suggest what the next vehicle should look like.

Chapter 10 contains findings, observations, and recommendations that the Board developed over the course of this extensive investigation that are not directly related to the accident but should prove helpful to NASA.

Chapter 11 is a compilation of all the recommendations in the previous chapters.

Part Four: Appendices

Part Four of the report by the Columbia Accident Investigation Board contains material relevant to this volume organized in appendices. Additional, stand-alone volumes will contain more reference, background, and analysis materials.

This Earth view of the Sinai Peninsula, Red Sea, Egypt, Nile River, and the Mediterranean was taken from Columbia *during STS-107.*

An Introduction to the Space Shuttle

The Space Shuttle is one of the most complex machines ever devised. Its main elements – the Orbiter, Space Shuttle Main Engines, External Tank, and Solid Rocket Boosters – are assembled from more than 2.5 million parts, 230 miles of wire, 1,060 valves, and 1,440 circuit breakers. Weighing approximately 4.5 million-pounds at launch, the Space Shuttle accelerates to an orbital velocity of 17,500 miles per hour – 25 times faster than the speed of sound – in just over eight minutes. Once on orbit, the Orbiter must protect its crew from the vacuum of space while enabling astronauts to conduct scientific research, deploy and service satellites, and assemble the International Space Station. At the end of its mission, the Shuttle uses the Earth's atmosphere as a brake to decelerate from orbital velocity to a safe landing at 220 miles per hour, dissipating in the process all the energy it gained on its way into orbit.

The Orbiter

The Orbiter is what is popularly referred to as "the Space Shuttle." About the size of a small commercial airliner, the Orbiter normally carries a crew of seven, including a Commander, Pilot, and five Mission or Payload Specialists. The Orbiter can accommodate a payload the size of a school bus weighing between 38,000 and 56,300 pounds depending on what orbit it is launched into. The Orbiter's upper flight deck is filled with equipment for flying and maneuvering the vehicle and controlling its remote manipulator arm. The mid-deck contains stowage lockers for food, equipment, supplies, and experiments, as well as a toilet, a hatch for entering and exiting the vehicle on the ground, and – in some instances – an airlock for doing so in orbit. During liftoff and landing, four crew members sit on the flight deck and the rest on the mid-deck.

Different parts of the Orbiter are subjected to dramatically different temperatures during re-entry. The nose and leading edges of the wings are exposed to superheated air temperatures of 2,800 to 3,000 degrees Fahrenheit, depending upon re-entry profile. Other portions of the wing and fuselage can reach 2,300 degrees Fahrenheit. Still other areas on top of the fuselage are sufficiently shielded from superheated air that ice sometimes survives through landing.

To protect its thin aluminum structure during re-entry, the Orbiter is covered with various materials collectively referred to as the Thermal Protection System. The three major components of the system are various types of heat-resistant tiles, blankets, and the Reinforced Carbon-Carbon (RCC) panels on the leading edge of the wing and nose cap. The RCC panels most closely resemble a hi-tech fiberglass – layers of special graphite cloth that are molded to the desired shape at very high temperatures. The tiles, which protect most other areas of the Orbiter exposed to medium and high heating, are 90 percent air and 10 percent silica (similar to common sand). One-tenth the weight of ablative heat shields, which are designed to erode during re-entry and therefore can only be used once, the Shuttle's tiles are reusable. They come in varying strengths and sizes, depending on which area of the Orbiter they protect, and are designed to withstand either 1,200 or 2,300 degrees Fahrenheit. In a dramatic demonstration of how little heat the tiles transfer, one can place a blowtorch on one side of a tile and a bare hand on the other. The blankets, capable of withstanding either 700 or 1,200 degrees Fahrenheit, cover regions of the Orbiter that experience only moderate heating.

Space Shuttle Main Engines

Each Orbiter has three main engines mounted at the aft fuselage. These engines use the most efficient propellants in the world – oxygen and hydrogen – at a rate of half a ton per second. At 100 percent power, each engine produces 375,000 pounds of thrust, four times that of the largest engine on commercial jets. The large bell-shaped nozzle on each engine can swivel 10.5 degrees up and down and 8.5 degrees left and right to provide steering control during ascent.

External Tank

The three main engines burn propellant at a rate that would drain an average-size swimming pool in 20 seconds. The External Tank accommodates up to 143,351 gallons of liquid oxygen and 385,265 gallons of liquid hydrogen. In order to keep the super-cold propellants from boiling and to prevent ice from forming on the outside of the tank while it is sitting on the launch pad, the External Tank is covered with a one-inch-thick coating of insulating foam. This insulation is so effective that the surface of the External Tank feels only slightly cool to the touch, even though the liquid oxygen is stored at minus 297 degrees Fahrenheit and liquid hydrogen at minus 423 degrees Fahrenheit. This insulating foam also protects the tank's aluminum structure from aerodynamic heating during ascent. Although generally considered the least complex of the Shuttle's main components, in fact the External Tank is a remarkable engineering achievement. In addition to holding over 1.5 million pounds of cryogenic propellants, the 153.8-foot long tank must support the weight of the Orbiter while on the launch pad and absorb the 7.3 million pounds of thrust generated by the Solid Rocket Boosters and Space Shuttle Main Engines during launch and ascent. The External Tanks are manufactured in a plant near New

Orleans and are transported by barge to the Kennedy Space Center in Florida. Unlike the Solid Rocket Boosters, which are reused, the External Tank is discarded during each mission, burning up in the Earth's atmosphere after being jettisoned from the Orbiter.

Solid Rocket Boosters

Despite their power, the Space Shuttle Main Engines alone are not sufficient to boost the vehicle to orbit – in fact, they provide only 15 percent of the necessary thrust. Two Solid Rocket Boosters attached to the External Tank generate the remaining 85 percent. Together, these two 149-foot long motors produce over six million pounds of thrust. The largest solid propellant rockets ever flown, these motors use an aluminum powder fuel and ammonium perchlorate oxidizer in a binder that has the feel and consistency of a pencil eraser.

A Solid Rocket Booster (SRB) Demonstration Motor being tested near Brigham City, Utah.

Each of the Solid Rocket Boosters consists of 11 separate segments joined together. The joints between the segments were extensively redesigned after the *Challenger* accident, which occurred when hot gases burned through an O-ring and seal in the aft joint on the left Solid Rocket Booster. The motor segments are shipped from their manufacturer in Utah and assembled at the Kennedy Space Center. Once assembled, each Solid Rocket Booster is connected to the External Tank by bolts weighing 65 pounds each. After the Solid Rocket Boosters burn for just over two minutes, these bolts are separated by pyrotechnic charges and small rockets then push the Solid Rocket Boosters safely away from the rest of the vehicle. As the boosters fall back to Earth, parachutes in their nosecones deploy. After splashing down into the ocean 120 miles downrange from the launch pad, they are recovered for refurbishment and reuse.

The Shuttle Stack

The first step in assembling a Space Shuttle for launch is stacking the Solid Rocket Booster segments on the Mobile Launch Platform. Eight large hold-down bolts at the base of the Solid Rocket Boosters will bear the weight of the entire Space Shuttle stack while it awaits launch. The External Tank is attached to the Solid Rocket Boosters, and the Orbiter is then attached to the External Tank at three points – two at its bottom and a "bipod" attachment near the nose. When the vehicle is ready to move out of the Vehicle Assembly Building, a Crawler-Transporter picks up the entire Mobile Launch Platform and carries it – at one mile per hour – to one of the two launch pads.

An Introduction to NASA

"An Act to provide for research into the problems of flight within and outside the Earth's atmosphere, and for other purposes." With this simple preamble, the Congress and the President of the United States created the National Aeronautics and Space Administration (NASA) on October 1, 1958. Formed in response to the launch of *Sputnik* by the Soviet Union, NASA inherited the research-oriented National Advisory Committee for Aeronautics (NACA) and several other government organizations, and almost immediately began working on options for manned space flight. NASA's first high profile program was Project Mercury, an early effort to learn if humans could survive in space. Project Gemini followed with a more complex series of experiments to increase man's time in space and validate advanced concepts such as rendezvous. The efforts continued with Project Apollo, culminating in 1969 when *Apollo 11* landed the first humans on the Moon. The return from orbit on July 24, 1975, of the crew from the Apollo-Soyuz Test Project began a six-year hiatus of American manned space flight. The launch of the first Space Shuttle in April 1981 brought Americans back into space, continuing today with the assembly and initial operations of the International Space Station.

In addition to the human space flight program, NASA also maintains an active (if small) aeronautics research program, a space science program (including deep space and interplanetary exploration), and an Earth observation program. The agency also conducts basic research activities in a variety of fields.

NASA, like many federal agencies, is a heavily matrixed organization, meaning that the lines of authority are not necessarily straightforward. At the simplest level, there are three major types of entities involved in the Human Space Flight Program: NASA field centers, NASA programs carried out at those centers, and industrial and academic contractors. The centers provide the buildings, facilities, and support services for the various programs. The programs, along with field centers and Headquarters, hire civil servants and contractors from the private sector to support aspects of their enterprises.

The Locations

NASA Headquarters, located in Washington D.C., is responsible for leadership and management across five strategic enterprises: Aerospace Technology, Biological and Physical Research, Earth Science, Space Science, and Human Exploration and Development of Space. NASA Headquarters also provides strategic management for the Space Shuttle and International Space Station programs.

The Johnson Space Center in Houston, Texas, was established in 1961 as the Manned Spacecraft Center and has led the development of every U.S. manned space flight program. Currently, Johnson is home to both the Space Shuttle and International Space Station Program Offices. The facilities at Johnson include the training, simulation, and mission control centers for the Space Shuttle and Space Station. Johnson also has flight operations at Ellington Field, where the training aircraft for the astronauts and support aircraft for the Space Shuttle Program are stationed, and manages the White Sands Test Facility, New Mexico, where hazardous testing is conducted.

The Kennedy Space Center was created to launch the Apollo missions to the Moon, and currently provides launch and landing facilities for the Space Shuttle. The Center is located on Merritt Island, Florida, adjacent to the Cape Canaveral Air Force Station that also provides support for the Space Shuttle Program (and was the site of the earlier Mercury and Gemini launches). Personnel at Kennedy support maintenance and overhaul services for the Orbiters, assemble and check-out the integrated vehicle prior to launch, and operate the Space Station Processing Facility where components of the orbiting laboratory are packaged for launch aboard the Space Shuttle. The majority of contractor personnel assigned to Kennedy are part of the Space Flight Operations Contract administered by the Space Shuttle Program Office at Johnson.

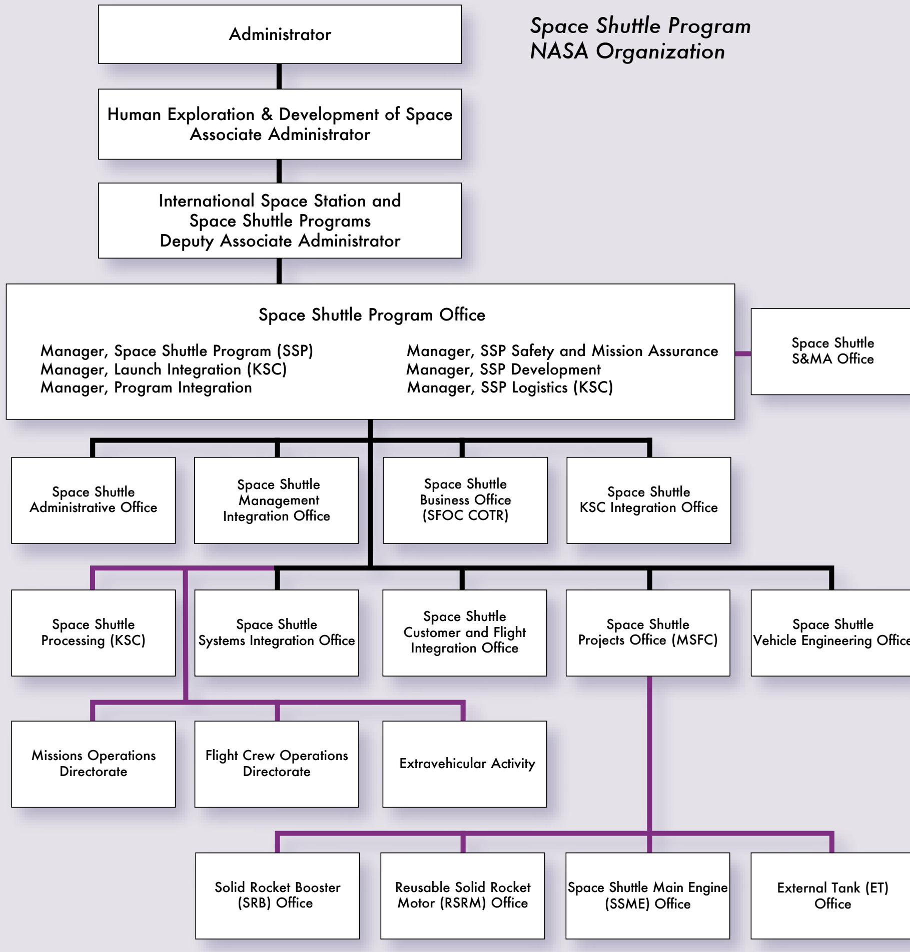
The Marshall Space Flight Center, near Hunstville, Alabama, is home to most NASA rocket propulsion efforts. The Space Shuttle Projects Office located at Marshall—organizationally part of the Space Shuttle Program Office at Johnson—manages the manufacturing and support contracts to Boeing Rocketdyne for the Space Shuttle Main Engine (SSME), to Lockheed Martin for the External Tank (ET), and to ATK Thiokol Propulsion for the Reusable Solid Rocket Motor (RSRM, the major piece of the Solid Rocket Booster). Marshall is also involved in microgravity research and space product development programs that fly as payloads on the Space Shuttle.

The Stennis Space Center in Bay St. Louis, Mississippi, is the largest rocket propulsion test complex in the United States. Stennis provides all of the testing facilities for the Space

Shuttle Main Engines and External Tank. (The Solid Rocket Boosters are tested at the ATK Thiokol Propulsion facilities in Utah.)

The Ames Research Center at Moffett Field, California, has evolved from its aeronautical research roots to become a Center of Excellence for information technology. The Center's primary importance to the Space Shuttle Program, however, lies in wind tunnel and arc-jet testing, and the development of thermal protection system concepts.

The Langley Research Center, at Hampton, Virginia, is the agency's primary center for structures and materials and supports the Space Shuttle Program in these areas, as well as in basic aerodynamic and thermodynamic research.



Space Shuttle Program NASA Organization

THE PROGRAMS

The two major human space flight efforts within NASA are the Space Shuttle Program and International Space Station Program, both headquartered at Johnson although they report to a Deputy Associate Administrator at NASA Headquarters in Washington, D.C.

The Space Shuttle Program Office at Johnson is responsible for all aspects of developing, supporting, and flying the Space Shuttle. To accomplish these tasks, the program maintains large workforces at the various NASA Centers that host the facilities used by the program. The Space Shuttle Program Office is also responsible for managing the Space Flight Operations Contract with United Space Alliance that provides most of the contractor support at Johnson and Kennedy, as well as a small amount at Marshall.

THE CONTRACTORS

The Space Shuttle Program employs a wide variety of commercial companies to provide services and products. Among these are some of the largest aerospace and defense contractors in the country, including (but not limited to):

United Space Alliance

This is a joint venture between Boeing and Lockheed Martin that was established in 1996 to perform the Space Flight Operations Contract that essentially conducts the day-to-day operation of the Space Shuttle. United Space Alliance is headquartered in Houston, Texas, and employs more than 10,000 people at Johnson, Kennedy, and Marshall. Its contract currently runs through 2005.

The Boeing Company, NASA Systems

The Space Shuttle Orbiter was designed and manufactured by Rockwell International, located primarily in Downey and Palmdale, California. In 1996, The Boeing Company purchased the aerospace assets of Rockwell International, and later moved the Downey operation to Huntington Beach, California, as part of a consolidation of facilities. Boeing is subcontracted to United Space Alliance to provide support to Orbiter modifications and operations, with work performed in California, and at Johnson and Kennedy.

The Boeing Company, Rocketdyne Propulsion & Power

The Rocketdyne Division of Rockwell International was responsible for the development and manufacture of the Space Shuttle Main Engines, and continues to support the engines as a part of The Boeing Company. The Space Shuttle Projects Office at Marshall manages the main engines contract, with most of the work performed in California, Stennis, and Kennedy.

ATK Thiokol Propulsion

ATK Thiokol Propulsion (formerly Morton-Thiokol) in Brigham City, Utah, manufactures the Reusable Solid Rocket Motor segments that are the propellant sections of the Solid Rocket Boosters. The Space Shuttle Projects Office at Marshall manages the Reusable Solid Rocket Motor contract.

Lockheed Martin Space Systems, Michoud Operations

The External Tank was developed and manufactured by Martin Marietta at the NASA Michoud Assembly Facility near New Orleans, Louisiana. Martin Marietta later merged with Lockheed to create Lockheed Martin. The External Tank is the only disposable part of the Space Shuttle system, so new ones are always under construction. The Space Shuttle Projects Office at Marshall manages the External Tank contract.

Lockheed Martin Missiles and Fire Control

The Reinforced Carbon-Carbon (RCC) panels used on the nose and wing leading edges of the Orbiter were manufactured by Ling-Temco-Vought in Grand Prairie, Texas. Lockheed Martin acquired LTV through a series of mergers and acquisitions. The Space Shuttle Program office at Johnson manages the RCC support contract.

The launch of STS-107 on January 16, 2003.

Part One

The Accident

"Building rockets is hard." Part of the problem is that space travel is in its infancy. Although humans have been launching orbital vehicles for almost 50 years now – about half the amount of time we have been flying airplanes – contrast the numbers. Since *Sputnik*, humans have launched just over 4,500 rockets towards orbit (not counting suborbital flights and small sounding rockets). During the first 50 years of aviation, there were over one million aircraft built. Almost all of the rockets were used only once; most of the airplanes were used more often.

There is also the issue of performance. Airplanes slowly built their performance from the tens of miles per hour the Wright Brothers initially managed to the 4,520 mph that Major William J. Knight flew in the X-15A-2 research airplane during 1967. Aircraft designers and pilots would slightly push the envelope, stop and get comfortable with where they were, then push on. Orbital rockets, by contrast, must have all of their performance on the first (and often, only) flight. Physics dictates this – to reach orbit, without falling back to Earth, you have to exceed about 17,500 mph. If you cannot vary performance, then the only thing left to change is the amount of payload – the rocket designers began with small payloads and worked their way up.

Rockets, by their very nature, are complex and unforgiving vehicles. They must be as light as possible, yet attain outstanding performance to get to orbit. Mankind is, however, getting better at building them. In the early days as often as not the vehicle exploded on or near the launch pad; that seldom happens any longer. It was not that different from early airplanes, which tended to crash about as often as they flew. Aircraft seldom crash these days, but rockets still fail between two-and-five percent of the time. This is true of just about any launch vehicle – Atlas, Delta, Soyuz, Shuttle – regardless of what nation builds it or what basic configuration is used; they all fail about the same amount of the time. Building and launching rockets is still a very dangerous business, and will continue to be so for the foreseeable future while we gain experience at it. It is unlikely that launching a space vehicle will ever be as routine an undertaking as commercial air travel – certainly not in the lifetime of anybody who reads this. The scientists and engineers continually work on better ways, but if we want to continue going into outer space, we must continue to accept the risks.

Part One of the report of the Columbia Accident Investigation Board is organized into four chapters. In order to set the background for further discussion, Chapter 1 relates the history of the Space Shuttle Program before the *Challenger* accident. The events leading to the original approval of the Space Shuttle Program are recounted, as well as an examination of some of the promises made in order to gain that approval. In retrospect, many of these promises could never have been achieved. Chapter 2 documents the final flight of *Columbia*. As a straightforward record of the event, it contains no findings or recommendations. Chapter 3 reviews five analytical paths – aerodynamic, thermodynamic, sensor data timeline, debris reconstruction, and imaging evidence – to show that all five independently arrive at the same conclusion. Chapter 4 describes the investigation into other possible physical factors that might have contributed to the accident, but were subsequently dismissed as possible causes.

Sunrise aboard Columbia *on Flight Day 7.*