National Aeronautics and Space Administration

Wings In Orbit

Scientific and Engineering Legacies of the Space Shuttle

1971-2010

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Robert Crippen

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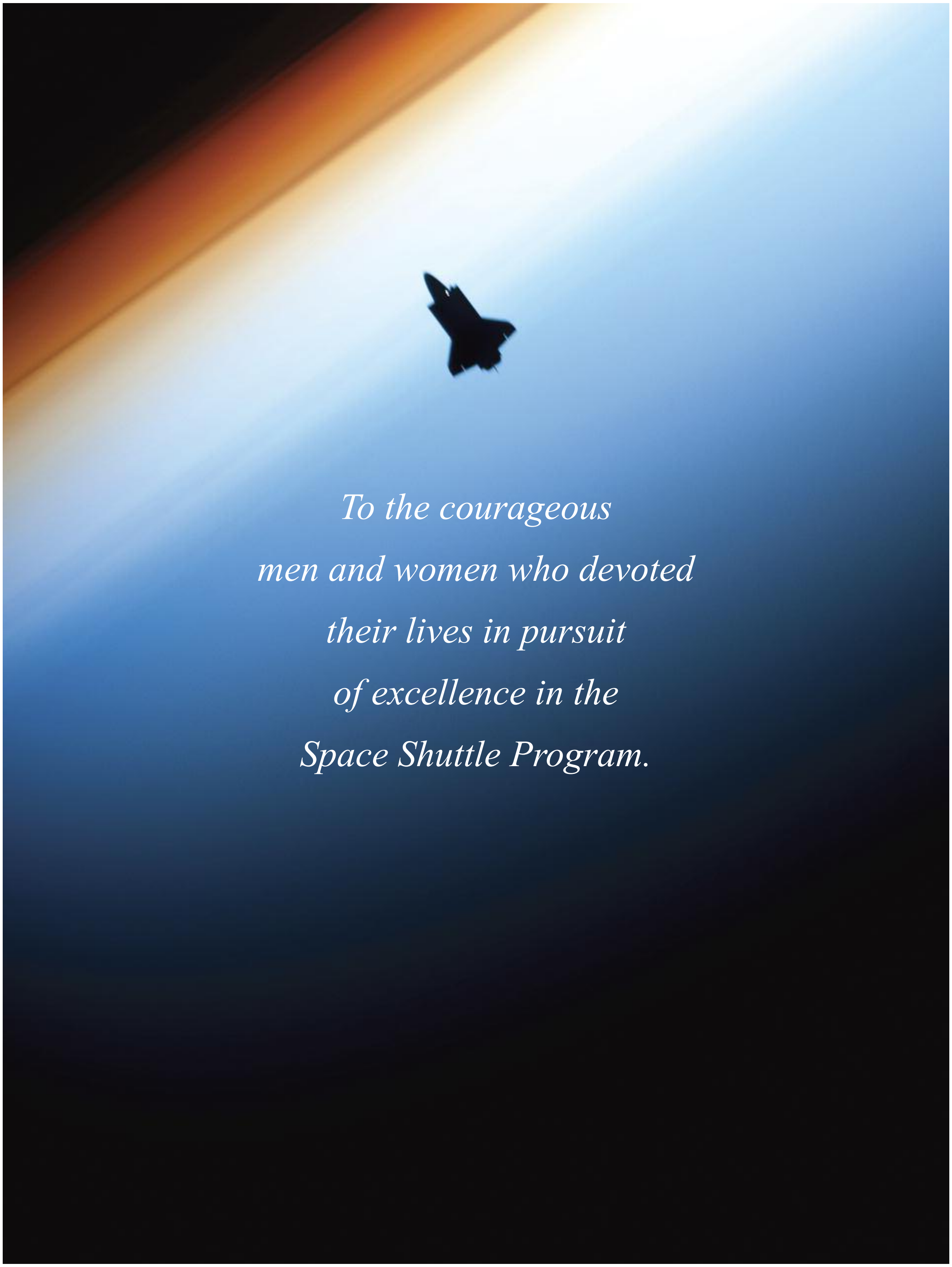
COVER PHOTOS

Front: *View of Space Shuttle Endeavour (STS-118) docked to the International Space Station in August 2007.*

Back: *Launch of Space Shuttle Endeavour (STS-130) during the early morning hours en route to the International Space Station in February 2010.*

Spine: *A rear view of the Orbiter Discovery showing the drag chute deployed during the landing of STS-96 at Kennedy Space Center in May 1999.*


To the courageous
men and women who devoted
their lives in pursuit
of excellence in the
Space Shuttle Program.

Foreword

John Young
STS-1 Commander

Robert Crippen
STS-1 Pilot

We were honored and privileged to fly the shuttle's first orbital flight into space aboard Columbia on April 12, 1981. It was the first time anyone had crewed a space launch vehicle that hadn't been launched unmanned. It also was the first vehicle to use large solid rockets and the first with wings to reenter the Earth's atmosphere and land on a runway. All that made it a great mission for a couple of test pilots.

That first mission proved the vehicle could do the basics for which it had been designed: to launch, operate on orbit, and reenter the Earth's atmosphere and land on a runway. Subsequent flights proved the overall capability of the Space Shuttle. The program went on to deploy satellites, rendezvous and repair satellites, operate as a microgravity laboratory, and ultimately build the International Space Station.

It is a fantastic vehicle that combines human operations with a large cargo capability—a capability that is unlikely to be duplicated in future vehicles anytime soon. The shuttle has allowed expanding the crew to include non-pilots and women. It has provided a means to include our international partners with the Canada arm, the European Spacelab, and eventually the Russians in operation with Mir and the building of the International Space Station. The station allowed expanding that international cooperation even further.

The Space Shuttle Program has also served as an inspiration for young people to study science, technology, engineering, and math, which is so important to the future of our nation.

The Space Shuttle is an engineering marvel perhaps only exceeded by the station itself. The shuttle was based on the technology of the 1960s and early 1970s. It had to overcome significant challenges to make it reusable. Perhaps the greatest challenges were the main engines and the Thermal Protection System.

The program has seen terrible tragedy in its 3 decades of operation, yet it has also seen marvelous success. One of the most notable successes is the Hubble Space Telescope, a program that would have been a failure without the shuttle's capability to rendezvous, capture, repair, as well as upgrade. Now Hubble is a shining example of success admired by people around the world.

As the program comes to a close, it is important to capture the legacy of the shuttle for future generations. That is what "Wings In Orbit" does for space fans, students, engineers, and scientists. This book, written by the men and women who made the program possible, will serve as an excellent reference for building future space vehicles. We are proud to have played a small part in making it happen.

Preface and Acknowledgments

"... because I know also life is a shuttle.
I am in haste; go along with me..."

– Shakespeare, *The Merry Wives of Windsor*, Act V Scene 1

We, the editors of this book, can relate to this portion of a quote by the English bard, for our lives have been entwined with the Space Shuttle Program for over 3 decades. It is often said that all grand journeys begin with a small first step. Our journey to document the scientific and engineering accomplishments of this magnificent winged vehicle began with an audacious proposal: to capture the passion of those who devoted their energies to its success while answering the question "What are the most significant accomplishments?" of the longest-operating human spaceflight program in our nation's history. This is intended to be an honest, accurate, and easily understandable account of the research and innovation accomplished during the era. We hope you will enjoy this book and take pride in the nation's investment in NASA's Space Shuttle Program.

We are fortunate to be a part of an outstanding team that enabled us to tell this story. Our gratitude to all members of the Editorial Board who guided us patiently and willingly through various stages of this undertaking.

Acknowledgments: We are grateful to all the institutions and people that worked on the book. (See appendix for complete list.) Each NASA field center and Headquarters contributed to it, along with many NASA retirees and industry/academic experts. There are a few who made exceptional contributions.

The following generously provided insights about the Space Shuttle Program: James Abrahamson, Arnold Aldrich, Stephen Altemus, Kenneth Baldwin, Baruch Blumberg, Aaron Cohen, Ellen Conners, Robert Crippen, Jeanie Engle, Jack Fischer, William Gerstenmaier, Milton Heflin, Thomas Holloway, Jack Kaye, Christopher Kraft, David Leckrone, Robert Lindstrom, William Lucas, Glynn Lunney, Hans Mark, John Mather, Leonard Nicholson, William Parsons, Brewster Shaw, Robert Sieck, Bob Thompson, J.R. Thompson, Thomas Utsman, Edward Weiler, John Young, and Laurence Young.

We also gratefully acknowledge the support of Susan Breeden for technical editing, Cindy Bush for illustrations, and Perry Jackson for graphic design.

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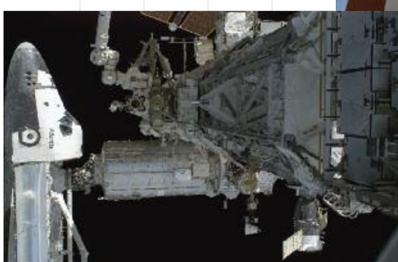
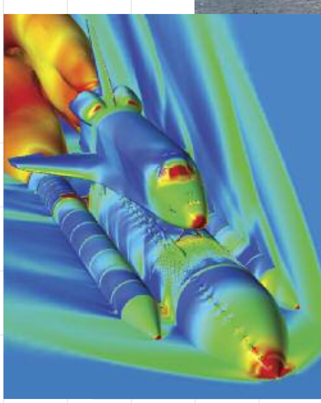
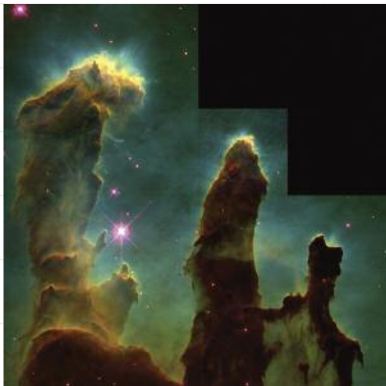






Editorial Board

Witnessing the Launch of the Shuttle Atlantis

Howard Nemerov
Poet Laureate of the United States
1963-1964 and 1988-1990

So much of life in the world is waiting, that
This day was no exception, so we waited
All morning long and into the afternoon.
I spent some of the time remembering
Dante, who did the voyage in the mind
Alone, with no more nor heavier machinery
Than the ghost of a girl giving him guidance;

And wondered if much was lost to gain all this
New world of engine and energy, where dream
Translates into deed. But when the thing went up
It was indeed impressive, as if hell
Itself opened to send its emissary
In search of heaven or "the unpeopled world"
(thus Dante of doomed Ulysses) "behind the sun."

So much of life in the world is memory
That the moment of the happening itself—
So much with noise and smoke and rising clear
To vanish at the limit of our vision
Into the light blue light of afternoon—
Appeared no more, against the void in aim,
Than the flare of a match in sunlight, quickly snuffed.

What yet may come of this? We cannot know.
Great things are promised, as the promised land
Promised to Moses that he would not see
But a distant sight of, though the children would.
The world is made of pictures of the world,
And the pictures change the world into another world
We cannot know, as we knew not this one.

Introduction

Charles Bolden

It is an honor to be invited to write the introduction for this tribute to the Space Shuttle, yet the invitation presents quite an emotional challenge. In many ways, I lament the coming of the end of a great era in human spaceflight. The shuttle has been a crown jewel in NASA's human spaceflight program for over 3 decades. This spectacular flying machine has served as a symbol of our nation's prowess in science and technology as well as a demonstration of our "can-do" attitude. As we face the fleet's retirement, it is appropriate to reflect on its accomplishments and celebrate its contributions. The Space Shuttle Program was a major leap forward in our quest for space exploration. It prepared us for our next steps with a fully operational International Space Station and has set the stage for journeys to deep-space destinations such as asteroids and, eventually, Mars. Our desire to explore more of our solar system is ambitious and risky, but its rewards for all humanity are worth the risks. We, as a nation and a global community, are on the threshold of taking an even greater leap toward that goal.

All the dedicated professionals who worked in the Space Shuttle team—NASA civil servants and contractors alike—deserve to be proud of their accomplishments in spite of the constant presence of skeptics and critics and the demoralizing losses of Challenger (1986) and Columbia (2003) and their dedicated crews. Some of these scientists and engineers contributed to a large portion of this book. Their passion and enthusiasm is evident throughout the pages, and their words will take you on a journey filled with challenges and triumphs. In my view, this is a truly authentic account by people who were part of the teams that worked tirelessly to make the program successful. They have been the heart, mind, spirit, and very soul that brought these amazing flying machines to life.

Unlike any engineering challenge before, the Space Shuttle launched as a rocket, served as an orbital workstation and space habitat, and landed as a glider. The American engineering that produced the shuttle was innovative for its time, providing capabilities beyond our expectations in all disciplines related to the process of launching, working in space, and returning to Earth. We learned with every succeeding flight how to operate more efficiently and effectively in space, and this knowledge will translate to all future space vehicles and the ability of their crews to live and work in space.

The Space Shuttle was a workhorse for space operations. Satellite launching, repair, and retrieval provided the satellite industry with important capabilities. The Department of Defense, national security organizations, and commercial companies used the shuttle to support their ambitious missions and the resultant accomplishments. Without the shuttle and its servicing mission crews, the magnificent Hubble Space Telescope astronomical science discoveries would not have been possible. Laboratories carried in the payload bay of the shuttles provided opportunities to use microgravity's attributes for understanding human health, physical and material sciences, and biology. Shuttle research advanced our understanding of planet Earth, our own star—the sun—and our atmosphere and oceans. From orbit aboard the shuttle, astronaut crews collected hundreds of thousands of Earth observation images and mapped 90% of Earth's land surface.

During this 30-year program, we changed dramatically as a nation. We witnessed increased participation of women and minorities, the international community, and the aerospace industry in science and technology—changes that have greatly benefitted NASA, our nation, and the world. Thousands of students, from elementary school through college and graduate programs, participated in shuttle programs. These students expanded their own horizons—from direct interactions with crew members on orbit, to student-led payloads, to activities at launch and at their schools—and were inspired to seek careers that benefit our nation.

International collaboration increased considerably during this era. Canada provided the robotic arm that helped with satellite repair and served as a mobile crew platform for performing extravehicular activities during construction of the International Space Station and upgrades and repairs to Hubble. The European Space Agency provided a working laboratory to be housed in the payload bay during the period in which the series of space laboratory missions was flown. Both contributions were technical and engineering marvels. Japan, along with member nations of the European Space Agency and Canada, had many successful science and engineering payloads. This international collaboration thus provided the basis for necessary interactions and cooperation.

My personal change and growth as a Space Shuttle crew member are emblematic of the valuable contribution to strengthening the global community that operating the shuttle encouraged and facilitated. I was honored and privileged to close out my astronaut career as commander of the first Russian-American shuttle mission, STS-60 (1994). From space, Earth has no geographic boundaries between nations, and the common dreams of the people of these myriad nations are realizable when we work toward the common mission of exploring our world from space. The International Space Station, the completion of which was only possible with the shuttle, further emphasizes the importance of international cooperation as nations including Russia, Japan, Canada, and the member nations of the European Space Agency join the United States to ensure that our quest for ever-increasing knowledge of our universe continues to move forward.

We have all been incredibly blessed to have been a part of the Space Shuttle Program. The "Remarkable Flying Machine" has been an unqualified success and will remain forever a testament to the ingenuity, inventiveness, and dedication of the NASA-contractor team. Enjoy this book. Learn more about the shuttle through the eyes of those who helped make it happen, and be proud of the human ingenuity that made this complex space vehicle a timeless icon and an enduring legacy.

Magnificent Flying Machine— A Cathedral to Technology

Magnificent Flying Machine— A Cathedral to Technology

Wayne Hale

Certain physical objects become icons of their time. Popular sentiment transmutes shape, form, and outline into a mythic embodiment of the era so that abstracted symbols evoke even the hopes and aspirations of the day. These icons are instantly recognizable even by the merest suggestion of their shape: a certain wasp-waisted soft drink bottle epitomizes America of the 1950s; the outline of a gothic cathedral evokes the Middle Ages of Europe; the outline of a steam locomotive memorializes the American expansion westward in the late 19th century; a clipper ship under full sail idealizes global trade in an earlier part of that century. America's Space Shuttle has become such an icon, symbolizing American ingenuity and leadership at the turn of the 21st century. The outline of the delta-winged Orbiter has permeated the public consciousness. This stylized element has been used in myriad illustrations, advertisements, reports, and video snippets—in short, everywhere. It is a fair question to ask why the Space Shuttle has achieved such status.

The first great age of space exploration culminated with the historic lunar landing in July 1969. Following that achievement, the space policymakers looked back to the history of aviation as a model for the future of space travel. The Space Shuttle was conceived as a way to exploit the resources of the new frontier. Using an aviation analogy, the shuttle would be the Douglas DC-3 of space. That aircraft is generally considered to be the first commercially successful air transport. The shuttle was to be the first commercially successful *space* transport. This impossible leap was not realized, an unrealistic goal that appears patently obvious in retrospect, yet it haunts the history of the shuttle to this day. Much of the criticism of the shuttle originates from this overhyped initial concept.

In fact, the perceived relationship between the history of aviation and the promise of space travel continues to motivate space policymakers. In some ways, the analogy that compares space with aviation can be very illustrative. So, if an unrealistic comparison for the shuttle is the leap from the 1903 Wright Flyer to the DC-3 transport of 1935 in a single technological bound, what is a more accurate comparison?

If the first crewed spacecraft of 1961—either Alan Shepard's Mercury or Yuri Gagarin's Vostok—are accurately the analog of the Wright brothers' first aircraft, the Apollo spacecraft of 1968 should properly be compared with the Wright brothers' 1909 "Model B"—their first commercial sale. The "B" was the product of 6 years of tinkering, experimentation, and adjustments, but were only two major iterations of aircraft design. In much the same way, Apollo was the technological inheritor of two iterations of spacecraft design in 7 years. The Space Shuttle of 1981—coming 20 years after the first spaceflights—could be compared with the aircraft of the mid 1920s. In fact, there is a good analogy in the history of aviation: the Ford Tri-Motor of 1928.

The Ford Tri-Motor was the leap from experimental to operational and had the potential to be economically effective as well. It was a huge improvement in aviation—it was revolutionary, flexible, and capable. The vehicle carried passengers and the US mail.

Top: 1928 Ford Tri-Motor; above: 1909 Wright "Model B." Smithsonian National Air and Space Museum, Washington, DC. (photos by Wayne Hale)

Admiral Richard Evelyn Byrd used the Ford Tri-Motor on his historic flyover of the North Pole. But the Ford Tri-Motor was not quite reliable enough, economical enough, or safe enough to fire off a successful and vibrant commercial airline business; just like the Space Shuttle.

Lower left: 1903 Wright Flyer; right: Douglas aircraft DC-3 of 1935. Smithsonian National Air and Space Museum, Washington, DC. (photos by Wayne Hale)

But here the aviation analogy breaks down. In aviation history, advances are made not just because of the passage of calendar time but because there are hundreds of different aircraft designs with thousands of incremental technology advances tested in flight between the "B" and the Tri-Motor.

Even so, the aviation equivalent compression of decades of technological advance does not do justice to the huge technological leap from expendable rockets and capsules to a reusable, winged, hypersonic, cargo-carrying spacecraft. This was accomplished with no intermediate steps. Viewed from that perspective, the Space Shuttle is truly a wonder. No doubt the shuttle is but one step of many on the road to the stars, but it was a giant leap indeed.

That is what this book is about: not what might have been or what was impossibly promised, but what was actually achieved and what was actually delivered. Viewed against this background, the Space Shuttle was a tremendous engineering achievement—a vehicle that enabled nearly routine and regular access to space for hundreds of people, and a profoundly vital link in scientific advancement. The vision of this book is to take a clear-eyed look at what the shuttle accomplished and the shuttle's legacy to the world.

Superlative Achievements of the Space Shuttle

For almost half a century, academic research, study, calculations, and myriad papers have been written about the problems and promises of controlled, winged hypersonic flight through the atmosphere. The Space Shuttle was the largest, fastest, winged hypersonic aircraft in history. Literally everything else had been a computer model, a wind tunnel experiment, or some subscale vehicle launched on a rocket platform. The shuttle flew at 25 times the speed of sound; regularly. The next fastest crewed vehicle—the venerable X-15—flew at its peak at seven times the speed of sound. Following the X-15, the next fastest crewed vehicle was the military SR-71, which could achieve three times the speed of sound. Both the X-15 and the SR-71 were retired years ago. Flight above about Mach 2 is not practiced today. If the promise of regular, commercial hypersonic flight is ever to come to fruition, the lessons learned from the shuttle will be an important foundation. For example, the specifics of aerodynamic control change significantly with these extreme speeds. Prior to the first flight, computations for the shuttle were found to be seriously in error when actual postflight data were reviewed. Variability in the atmosphere at extreme altitudes would have gone undiscovered except for the regular passage of the shuttle through regions unnavigable any other way. Serious engineering obstacles with formidable names—hypersonic boundary layer transition, for example—must be understood and overcome, and cannot be studied in wind tunnels or computer simulations. Only by flight tests will real data help us understand and tame these dragons of the unknown ocean of hypersonic flight.

The second X-15 rocket plane (56-6671) is shown with two external fuel tanks, which were added during its conversion to the X-15A-2 configuration in the mid 1960s.

Most authorities agree that getting back safely from Earth orbit is a more difficult task than achieving Earth orbit in the first place. All the tremendous energy that went into putting the spacecraft into orbit must be cancelled out. For any vehicle's re-entry into Earth's atmosphere, this is principally accomplished by air friction—turning kinetic energy into heat. Objects entering the Earth's atmosphere are almost always rapidly vaporized by the friction generated by the enormous velocity of space travel. Early spacecraft carried huge and bulky ablative heat shields, which were good for one use only. The Space Shuttle Orbiter was completely reusable, and was covered with Thermal Protection Systems from nose to tail. The thermal shock standing 9 mm (0.3 in.) off the front of the wing leading edge exceeded the temperature of the visible surface of the sun: 8,000°C (14,000°F). At such an extreme temperature, metals don't melt—they boil. Intense heating went on for almost half an hour during a normal deceleration from 8 km (5 miles) per second to full stop. Don't forget that weight was at a premium. A special carbon fiber cloth impregnated with carbon resin was molded to an aerodynamic shape. This was the

This view of the suspended Orbiter Discovery shows the underside covered with Thermal Protection System tiles.

so-called reinforced carbon-carbon on the wing leading edge and nose cone. This amazing composite was only 5 mm (0.2 in.) thick, but the aluminum structure of the Orbiter was completely reliant on the reinforced carbon-carbon for protection. In areas of the shuttle where slightly lower peak temperatures were experienced, the airframe was covered with silica-based tiles. These tiles were mostly empty space but provided protection from temperatures to 1,000°C (2,000°F). Extraordinarily lightweight but structurally robust, easily formed to whatever shape needed, over 24,000 tiles coated the bottom and sides of the Orbiter. In demonstrations of the tile's effectiveness, a technician held one side of a shuttle tile in a bare hand while pointing a blowtorch at the opposite side. These amazing Thermal Protection Systems—all invented for the shuttle—brought 110 metric tons (120 tons) of vehicle, crew, and payload back to Earth through the inferno that is re-entry.

Nor is the shuttle's imaginative navigation system comparable to any other system flying. The navigation system kept track of not only the shuttle's position during re-entry, but also the total energy available to the huge glider. The system managed energy, distance, altitude, speed, and even variations in the winds and weather to deliver the shuttle precisely to the runway threshold. The logic contained in the re-entry guidance software was the hard-won knowledge from successful landings.

So much for re-entry. All real rocket scientists know that propulsion is problem number one for space travel. The shuttle excelled in both solid- and liquid-fueled propulsion elements.

The reusable Solid Rocket Booster (SRB) motors were the largest and most powerful solid rocket motors ever flown. Solid rockets are notable for their high thrust-to-weight ratio and the SRB motors epitomized that. Each one developed a thrust of almost 12 meganewtons (3 million pounds) but weighed only 600,000 kg (1.3 million pounds) at ignition (with weight decreasing rapidly after that). This was the equivalent motive power of 36,000 diesel locomotives that together would weigh 26 billion kg (57 billion pounds). The shuttle's designers were grounded in aviation in the 1950s and thought of the SRB motors as extreme JATO bottles—those small solid rockets strapped to the side of overloaded military transports taking off from short airfields. (JATO is short for jet-assisted takeoff, where "jet" is a generic term covering even rocket engines.) Those small, strap-on solid rocket motors paled in comparison with the SRB motors—some JATO bottles indeed. Within milliseconds of ignition, the finely tuned combustion processes inside the SRB motor generated internal pressure of over 7 million pascals (1,000 pounds per square inch [psi]). The thrust was "throttled" by the shape in which the solid propellant was cast inside the case. This was critical because thrust had to be reduced as the shuttle accelerated through the speed of maximum aerodynamic pressure. For the first 50 years of spaceflight, these reuseable boosters were the largest solid rockets ever flown.

The Solid Rocket Boosters operated in parallel with the main engines for the first 2 minutes of flight to provide the additional thrust needed for the Orbiter to escape the gravitational pull of the Earth. At an altitude of approximately 45 km (24 nautical miles), the boosters separated from the Orbiter/External Tank, descended on parachutes, and landed in the Atlantic Ocean. They were recovered by ships, returned to land, and refurbished for reuse. The boosters also assisted in guiding the entire vehicle during initial ascent. Thrust of both boosters was equal to over 2 million kg (over 5 million pounds).

Development of the liquid-fueled Space Shuttle Main Engine was considered an impossible task in the mid 1970s. Larger liquid-fueled rockets had been developed—most notably the Saturn V first-stage engines, the famous F-1 engine that developed three times the thrust of the shuttle main engines. But the F-1 engines burned kerosene rather than hydrogen and their "gas mileage" was much lower than the shuttle main engines. In fact, no more efficient, liquid-fueled rocket engines have ever been built. Getting to orbit requires enormous amounts of energy. The "mpg" rating of these main engines was unparalleled in the history of rocket manufacture. The laws of thermodynamics define the maximum efficiency of any "heat engine," whether it is the gasoline engine that powers an automobile, or a big power plant that generates electricity, or a rocket engine. Different thermodynamic "cycles" have different possible efficiencies. Automobile engines operating on the Otto cycle typically are 15% of the maximum theoretical efficiency. The shuttle main engines operating on the rocket cycle achieved 99.5% of the maximum theoretical efficiency.

To put the power of the main engines in everyday terms: if your car engine developed the same power per pound as these engines, your automobile would be powered by something about the size and weight of a loaf of bread. And it would cost less than $100.00. More efficient engines have never been made, no matter what measure is used: horsepower to weight, horsepower to cost. Nor is the efficiency standard likely to ever be exceeded by any other chemical rocket.

So far, this has been about the basic problem in any journey—getting there and getting back. But the shuttle was a space truck, a heavy-lift launch vehicle in the same class as the Saturn V moon rocket. In fact, over half of all the mass put in Earth orbit—and that includes all rockets from all the nations of the world from 1957 until 2010—was put there by the shuttle. Think of that. The shuttle lofted more mass to Earth orbit than all the Saturn Vs, Saturn Is, Atlases, Deltas, Protons, Zenits, and Long Marches, etc., combined. And what about all the mass brought safely home from space? Ninety-seven percent came home with the shuttle. The Space Shuttle deployed some of the heaviest-weight upper stages for interplanetary probes. The largest geosynchronous satellites were launched by the shuttle. What a truck. What a transportation system.

And Science?

How much science was accomplished by the Space Shuttle? Start with the study of the stars. What has the shuttle done for astronomy? It brought us closer to the heavens. Shuttle had mounted telescopes operated directly by the crew to study the heavens. Not only did the shuttle launch the Compton Gamma Ray Observatory, the crew saved it by fixing its main antenna. Astronauts deployed the orbiting Chandra X-ray Observatory and the international polar star probe Ulysses. A series of astronomy experiments, under the moniker SPARTAN, studied comets, the sun, and galactic objects. The Solar Maximum Satellite enabled the study of our sun. And the granddaddy of them all, the Hubble Space Telescope, often called the most productive scientific instrument of all time, made discoveries that have rewritten the textbooks on astronomy, astrophysics, and cosmology—all because of shuttle.

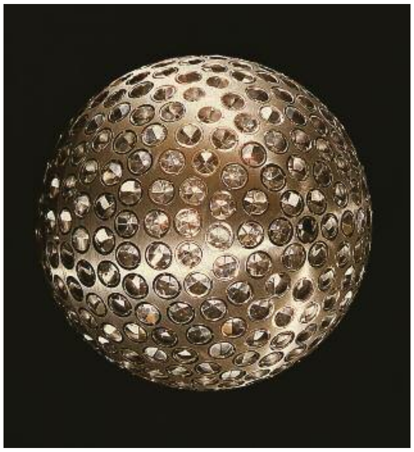
Don't forget planetary science. Not only has Hubble looked deeply at most of the planets, but the shuttle also launched the Magellan radar mapper

Backdropped by a cloud-covered part of Earth, Space Shuttle Discovery approaches the International Space Station during STS-124 (2008) rendezvous and docking operations. The second component of the Japan Aerospace Exploration Agency's Kibo laboratory, the Japanese Pressurized Module, is visible in Discovery's cargo bay.

to Venus and the Galileo mission to Jupiter and its moons.

In Earth science, two Spacelab Atmospheric Laboratory for Applications and Science missions studied our own atmosphere, the Laser Geodynamic Satellite sphere monitors the upper reaches of the atmosphere and aids in mapping, and three Space Radar Laboratory missions mapped virtually the entire land mass of the Earth to a precision previously unachievable. The Upper Atmosphere Research satellite was also launched from the shuttle, as was the Earth Radiation Budget Satellite and a host of smaller nanosatellites that pursued a variety of Earth-oriented topics. Most of all, the pictures and observations made by the shuttle crews using cameras and other handheld instruments provided long-term observation of the Earth, its surface, and its climate.

Satellite launches and repairs were a highlight of shuttle missions, starting with the Tracking and Data Relay Satellites that are the backbone for communications with all NASA satellites—Earth resources,

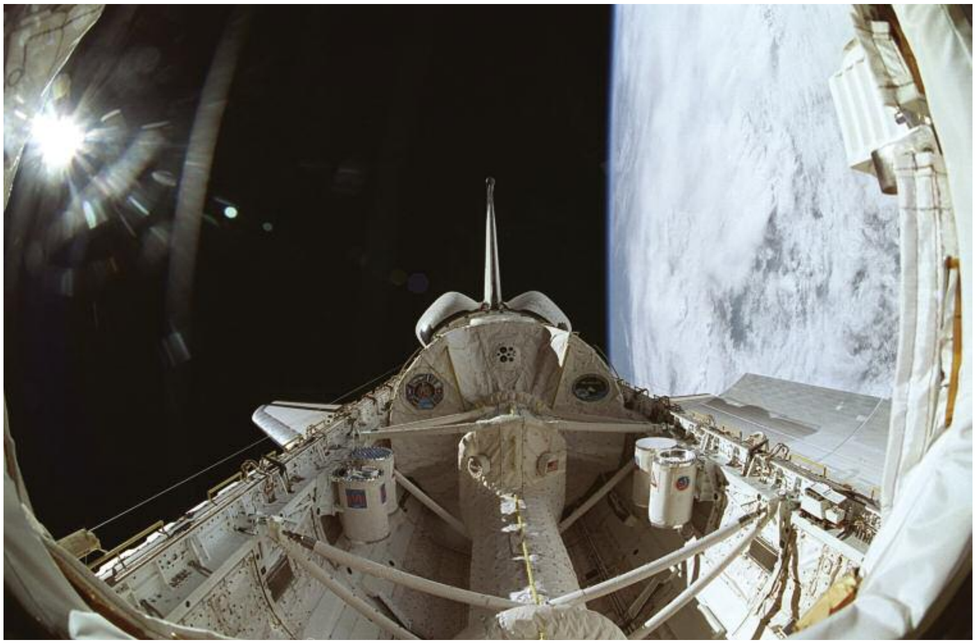


Laser Geodynamic Satellite dedicated to high-precision laser ranging. It was launched on STS-52 (1992).

astronomical, and many more. Communications satellites were launched early in the shuttle's career but were reassigned to expendable launches for a variety of reasons. Space repair and recovery of satellites started with the capture and repair of the Solar Maximum Satellite in 1984 and continued with satellite recovery and repair of two HS-376 communications satellites in 1985 and the repair of Syncom-IV that same year. The most productive satellite repair involved five repetitive shuttle missions to the Hubble Space Telescope to upgrade its systems and instruments on a regular basis.

Biomedical research also was a hallmark of many shuttle missions. Not only were there six dedicated Spacelab missions studying life sciences, but there were also countless smaller experiments on the effects of microgravity (not quite zero gravity) on various life forms: from microbes and viruses, through invertebrates and insects, to mammals, primates, and finally humans. This research yielded valuable insight in the workings of the human body, with ramifications for general medical care and disease cure and prevention. The production of pharmaceuticals in space has been investigated with mixed success, but practical production requires lower cost transportation than the shuttle provided.

Finally, note that nine shuttle flights specifically looked at materials science questions, including how to grow crystals in microgravity, materials processing of all kinds, lubrication, fluid mechanics, and combustion dynamics—all without the presence of gravity.

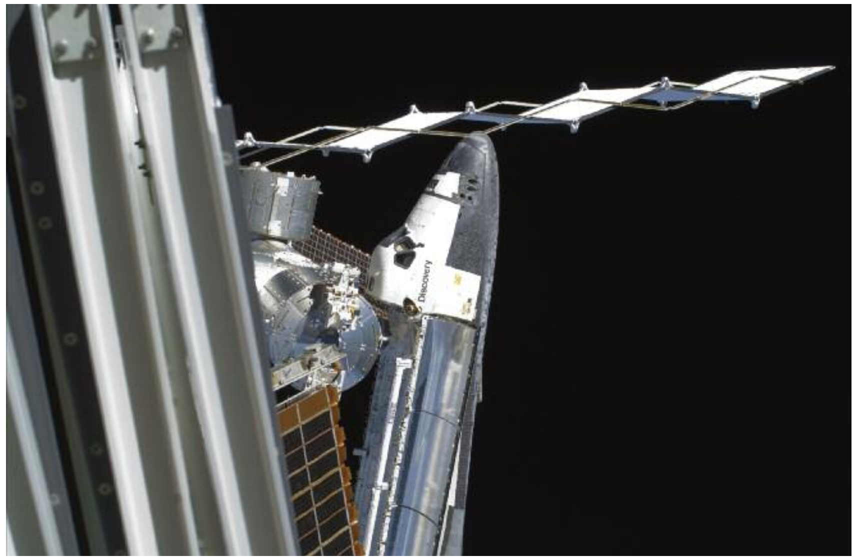


View from the Space Shuttle Columbia's cabin of the Spacelab science module, hosting 16 days of Neurolab research. (STS-90 [1998] is in the center.) This picture clearly depicts the configuration of the tunnel that leads from the cabin to the module in the center of the cargo bay.

Spacewalks

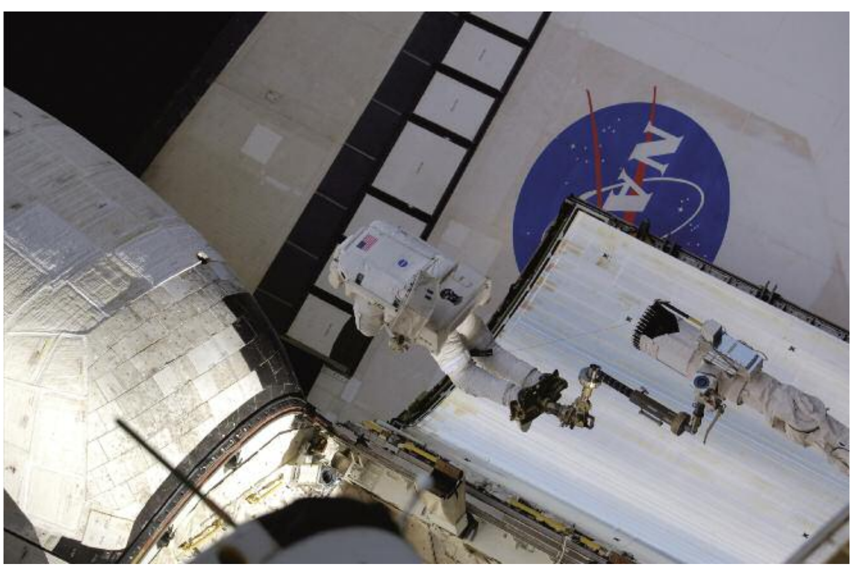
Of all the spacewalks (known as extravehicular activities) conducted in all the spaceflights of the world, more than three-quarters of them were based from the Space Shuttle or with shuttle-carried crew members at the International Space Station (ISS) with the shuttle vehicle attached and supporting. The only "untethered" spacewalks were executed from the shuttle. Those crew members were buoyed by the knowledge that, should their backpacks fail, the shuttle could swiftly come to their rescue.

The final and crowning achievement of the shuttle was to build the ISS. The shuttle was always considered only part of the future of space infrastructure. The construction and servicing of space stations was one of the design goals for the shuttle. The ISS—deserving of a book in its own right—is the largest space international engineering project in the history of the world. The ISS and the Space Shuttle are two sides of the same coin: the ISS could not be constructed without the shuttle, and the shuttle would have lost a major reason for its existence without the ISS. In addition to the scientific accomplishments of the ISS and the engineering marvel of its construction, the ISS is important as one of the shining examples of the power of international cooperation for the good of all humanity. The shuttle team was always international due to the Canadian contributions of the robot arm, the international payloads, and the international spacefarers. But participation in the construction of the ISS brought international cooperation to a new level, and the entire shuttle team was transformed by that experience.



Space Shuttle Discovery docked to the International Space Station is featured in this image photographed by one of the STS-119 (2009) crew members during the mission's first scheduled extravehicular activity.

Anchored to a foot restraint on Space Shuttle Atlantis' remote manipulator system robotic arm, Astronaut John Olivas, STS-117 (2007), moves toward Atlantis' port orbital maneuvering system pod that was damaged during the shuttle's climb to orbit. During the repair, Olivas pushed the turned-up portion of the thermal blanket back into position, used a medical stapler to secure the layers of the blanket, and pinned it in place against adjacent thermal tile.



The Astronauts

In the final analysis, space travel is all about people. In 133 flights, the Space Shuttle provided nearly 850 seats to orbit. Many people have been to orbit more than once, so the total number of different people who have flown to space on all spacecraft (Vostok, Mercury, Voskhod, Gemini, Soyuz, Apollo, Shenzhou, and the shuttle) in the last 50 years is just under 500. Of that number, over 400 have flown on the Space Shuttle. Almost three times as many people flew to space on the

Astronaut Joseph Acaba, STS-119 (2009), works the controls of Space Shuttle Discovery's Shuttle Robotic Arm on the aft flight deck during Flight Day 1 activities.

shuttle than on all other vehicles from all countries of the world combined. If the intent was to transform space and the opening of the frontier to more people, the shuttle accomplished this. Fliers included politicians, officials from other agencies, scientists of all types, and teachers. Probably most telling, these spacefarers represented a multiplicity of ethnicities, genders, and citizenships. The shuttle truly became the people's spaceship.

Fourteen people died flying on the shuttle in two accidents. They too represented the broadest spectrum of humanity. In 11 flights, Apollo lost no astronauts in space—although Apollo 13 was a very close call—and only three astronauts in a ground accident. Soyuz, like shuttle, had two fatal in-flight accidents but lost only four souls due to the smaller carrying capacity. The early days of aviation were far bloodier, even though the altitudes and energies were a fraction of those of orbital flight.

How Do We Rate the Space Shuttle?

Did shuttle have the power of thousands of diesel locomotives? Was it the most efficient rocket system ever built? Certainly it was the only winged space vehicle that flew from orbit as a hypersonic glider. And it was the only reusable space vehicle ever built except for the Soviet Buran ("Snowflake"), which was built to be reusable but only flew once. Imitation is the sincerest form of flattery; the Buran was the greatest compliment the shuttle ever had.

In the 1940s and early 1950s, the world's experimental aircraft flew sequentially faster and higher. The X-15 even allowed six people to earn their astronaut wings for flying above 116,000 m (380,000 ft) in a parabolic suborbital trajectory. If the exigencies of the Cold War—the state of conflict, tension, and competition that existed between the United States and the Soviet Union and their respective allies from the mid 1940s to the early 1990s—had not forced a rapid entry into space on the top of intercontinental ballistic missiles, a far different approach to spaceflight would most likely have occurred with air-breathing winged vehicles flying to the top of the atmosphere and then smaller rocket stages to orbit. But that buildup approach didn't happen. Some historians think such an approach would have provided a more sustainable approach to space than expendable intercontinental ballistic missile-based launch systems. Hypersonic flight continues to be the subject of major research by the aviation community. Plans to build winged vehicles that can take off horizontally and fly all the way to Earth orbit are still advanced as the "proper" way to travel into space. Time will tell if these dreams become reality.

No matter the next steps in space exploration, the legacy of the Space Shuttle will be to inspire designers, planners, and astronauts. Because building a Space Shuttle was thought to be impossible, and yet it flew, the shuttle remains the most remarkable achievement of its time—a cathedral of technology and achievement for future generations to regard with wonder.

The sun radiates on Space Shuttle Atlantis as it is positioned to head for space on mission STS-115 (2006).

The Historical Legacy

Major Milestones

Jennifer Ross-Nazzal
Dennis Webb

Astronauts John Young and Robert Crippen woke early on the morning of April 12, 1981, for the second attempted launch of the Space Shuttle Columbia—the first mission of the Space Shuttle Program. Two days earlier, the launch had been scrubbed due to a computer software error. Those working in the Shuttle Avionics Integration Laboratory at Johnson Space Center (JSC) in Houston, Texas, quickly resolved the issue and, with the problem fixed, the agency scheduled a second try soon after. Neither crew member expected to launch, however, because so much had to come together for liftoff to occur.

That morning, they did encounter a serious problem. With fewer than 2 hours until launch, the crew of Space Transportation System (STS)-1 locked the faceplates onto their helmets, only to find that they could not breathe. To avoid scrubbing the mission, the crew members looked at the issue and asked Loren Shriver, the astronaut support pilot, to help them. Finding a problem with the oxygen hose quick disconnect, Shriver tightened the line with a pair of pliers, and the countdown continued.

At 27 seconds before launch, Crippen realized that this time they were actually going to fly. His heart raced to 130 beats per minute while Young's heart, that of a veteran commander, stayed at a calm 85 beats. Young later joked, "I was excited too. I just couldn't get my heart to beat any faster." At 7:00 a.m., Columbia launched, making its maiden voyage into Earth orbit on the 20th anniversary of Yuri Gagarin's historic first human flight into space (1961).

The thousands who had traveled to the beaches of Florida's coastline to watch the launch were excited to see the United States return to flying in space. The last American flight was the Apollo-Soyuz Test Project, which flew in July 1975 and featured three American astronauts and two cosmonauts who rendezvoused and docked their spacecraft in orbit. Millions of others who watched the launch of STS-1 from their television sets were just as elated. America was back in space.

Like their predecessors, Young and Crippen became heroes for flying this mission—the boldest test flight in history. The shuttle was like no other vehicle that had flown; it was reusable. Unlike the space capsules of the previous generation, the shuttle had not been tested in space. This was the first test flight of the Columbia and the only time astronauts had actually flown a spacecraft on its first flight. The primary objective was to prove that the shuttle could safely launch a crew and then return safely to Earth. Two days later, the mission ended and the goal was accomplished when Young landed the shuttle at Dryden Flight Research Center on the Edwards Air Force Base runway in California. The spacecraft had worked like a "champ" in orbit—even with the loss of several tiles during launch. After landing, Christopher Kraft, director of JSC, said, "We just became infinitely smarter."

Design and Development

It would be a mistake to say that the first flight of Columbia was the start of the Space Shuttle Program. The idea of launching a reusable winged vehicle was not a new concept. Throughout the 1960s, NASA and the Department of Defense (DoD) studied such concepts. Advanced Space Shuttle studies began in 1968 when the Manned Spacecraft Center—which later became JSC—and Marshall Space Flight Center in Huntsville, Alabama, issued a joint request for proposal for an integral launch and re-entry vehicle to study different configurations for a round-trip vehicle that could reduce costs, increase safety, and carry payloads of up to 22,680 kg (50,000 pounds). This marked the beginning of the design and development of the shuttle.

Maxime Faget, director of engineering and development at the Manned Spacecraft Center in 1969, holding a balsa wood model of his concept of the spaceship that would launch on a rocket and land on a runway.

Four contractors—General Dynamics/Convair, Lockheed, McDonnell Douglas, and North American Rockwell—received 10-month contracts to study different approaches for the integral launch and re-entry vehicle. Experts examined a number of designs, from fully reusable vehicles to the use of expendable rockets. On completion of these studies, NASA determined that a two-stage, fully reusable vehicle met its needs and would pay off in terms of cost savings.

On April 1, 1969, Maxime Faget, director of engineering and development at the Manned Spacecraft Center, asked 20 people to report to the third floor of a building that most thought did not have a third floor. Because of that, many believed it was an April Fool's prank but went anyway. Once there, they spotted a test bay, which had three floors, and that was where they met. Faget then walked through the door with a balsa wood model of a plane, which he glided toward the engineers. "We're going to build America's next spacecraft. And it's going to launch like a spacecraft, it's going to land like a plane," he told the team. America had not yet landed on the moon, but NASA's engineers moved ahead with plans to create a new space vehicle.

As the contractors and civil servants explored various configurations for the next generation of spacecraft, the Space Task Group, appointed by President Richard Nixon, issued its report for future space programs. The committee submitted three options: the first and most ambitious featured a manned Mars landing as early as 1983, a lunar and Earth-orbiting station, and a lunar surface base; the second supported a mission to Mars in 1986; and the third deferred the Mars landing, providing no scheduled date for its completion. Included in the committee's post-Apollo plans were a Space Shuttle, referred to as the Space Transportation System, and a space station, to be developed simultaneously. Envisioned as less costly than the Saturn rocket and Apollo capsules, which were expended after only one use, the shuttle would be reusable and, as a result, make space travel more routine and less costly. The shuttle would be capable of carrying passengers, supplies, satellites, and other equipment—much as an airplane ferries people and their luggage—to and from orbit at least 100 times before being retired. The system would support both the civil and military space programs and be a cheaper way to launch satellites. Nixon, the Space Task Group proposals, and NASA cut the moon and Mars from their plans. This left only the shuttle and station for development, which the agency hoped to develop in parallel.

The decision to build a shuttle was extremely controversial, even though NASA presented the vehicle as economical—a cost-saver for taxpayers—when compared with the large outlays for the Apollo Program. In fact, in 1970 the shuttle was nearly defeated by Congress, which was dealing with high inflation, conflict in Vietnam, spiraling deficits, and an economic recession. In April 1970, representatives in the House narrowly defeated an amendment to eliminate all funding for the shuttle. A similar amendment offered in the Senate was also narrowly defeated. Minnesota Senator Walter Mondale explained that the money NASA requested was simply the "tip of the iceberg." He argued that the $110 million requested for development that year might be better spent on urban renewal projects, veterans' care, or improving the environment. Political support for the program was very tenuous, including poor support from some scientific and aerospace leaders.

To garner support for the shuttle and eliminate the possibility of losing the program, NASA formed a coalition with the US Air Force and established a joint space transportation committee to meet the needs of the two agencies. As an Air Force spokesman explained, given the political and economic realities of the time, "Quite possibly neither NASA nor the DoD could justify the shuttle system alone. But together we can make a strong case."

The Space Shuttle design that NASA proposed did not initially meet the military's requirements. The military needed the ability to conduct a polar orbit with quick return to a military airfield. This ability demanded the now-famous delta wings as opposed to the originally proposed airplane-like straight wings. The Air Force also insisted that it needed a larger payload bay and heavier lift capabilities to carry and launch reconnaissance satellites. A smaller payload bay would require the Air Force to retain their expendable launch vehicles and chip away at the argument forwarded by NASA about the shuttle's economy and utilitarian purpose. The result was a larger vehicle with more cross-range landing capability.

Though the president and Congress had not yet approved the shuttle in 1970, NASA awarded preliminary design contracts to McDonnell Douglas and North American Rockwell, thus beginning the second phase of development. By awarding two contracts for the country's next-generation spacecraft, NASA signaled its decision to focus on securing support for the two-stage reusable space plane over the station, which received little funding and was essentially shelved until 1984 when President Ronald Reagan directed the agency to build a space station within a decade. In fact, when James Fletcher became NASA's administrator in April 1971, he wholeheartedly supported the shuttle and proclaimed, "I don't want to hear any more about a space station, not while I am here."

Fletcher was doggedly determined to see that the federal government funded the shuttle, so he worked closely with the Nixon administration to assure the program received approval. Realizing that the $10.5 billion price tag for the development of the fully reusable, two-stage vehicle was too high, and facing massive budget cuts from the Office of Management and Budget, the administrator had the agency study the use of expendable rockets to cut the high cost and determine the significant cost savings with a partially reusable spacecraft as opposed to the proposed totally reusable one. On learning that use of an expendable External Tank, which would provide liquid oxygen and hydrogen fuel for Orbiter engines, would decrease costs by nearly half, NASA chose that technology—thereby making the program more marketable to Congress and the administration.

Robert Thompson, former Space Shuttle Program manager, believed that the decision to use an expendable External Tank for the Space Shuttle Main Engines was "perhaps the single most important configuration decision made in the Space Shuttle Program," resulting in a smaller, lighter shuttle. "In retrospect," Thompson explained, "the basic decision to follow a less complicated development path at the future risk of possible higher operating costs was, in my judgment, a very wise choice." This decision was one of the program's major milestones, and the decreased costs for development had the desired effect.

Presidential Approval

Nixon made the announcement in support of the Space Shuttle Program at his Western White House in San Clemente, California, on January 5, 1972. Believing that the shuttle was a good investment, he asked the space agency to stress that the shuttle was not an expensive toy. The president highlighted the benefits of the civilian and military applications and emphasized the importance of international cooperation, which would be ushered in with the program. Ordinary people from across the globe, not just American test pilots, could fly on board the shuttle.

From the start, Nixon envisioned the shuttle as a truly international program. Even before the president approved the program, NASA Administrator Thomas Paine, at Nixon's urging, approached other nations about participating. As NASA's budget worsened, partnering with other nations became more appealing to the space agency. In 1973, Europe agreed to develop and build the Spacelab, which

Rollout tests of the Solid Rocket Boosters. Mobile Launcher Platform number 3, with twin Solid Rocket Boosters bolted to it, inches along the crawlerway at various speeds up to 1.6 km (1 mile) per hour in an effort to gather vibration data. The boosters are braced at the top for stability. Data from these tests, completed September 2004, helped develop maintenance requirements on the transport equipment and the flight hardware.

would be housed in the payload bay of the Orbiter and serve as an in-flight space research facility. The Canadians agreed to build the Shuttle Robotic Arm in 1975, making the Space Shuttle Program international in scope.

Having the Nixon administration support the shuttle was a major hurdle, but NASA still had to contend with several members of Congress who disagreed with the administration's decision. In spite of highly vocal critics, both the House and Senate voted in favor of NASA's authorization bill, committing the United States to developing the Space Shuttle and, thereby, marking another milestone for the program.

To further reduce costs, NASA decided to use Solid Rocket Boosters, which were less expensive to build because they were a proven technology used by the Air Force in the Minuteman intercontinental ballistic missile program. As NASA Administrator Fletcher explained, "I think we have made the right decision at the right time. And I think it is the right price." Solids were less expensive to develop and cost less than liquid boosters. To save additional funds, NASA planned to recover the Solid Rocket Boosters and refurbish them for future flights.

Contracting out the Work

Two days after NASA selected the parallel burn Solid Rocket Motor propellant configuration, the agency put out a request for proposal for the development of the Orbiter. Four companies responded. NASA selected North American Rockwell, awarding the company a $2.6 billion contract. The Orbiter that Rockwell agreed to build illustrated the impact the Air Force had on the design. The payload bay measured 18.3 by 4.6 m (60 by 15 ft), to house the military's satellites. The Orbiter also had delta wings and the ability to deploy a 29,483-kg (65,000-pound) payload from a due-east orbit.

As NASA studied alternative concepts for the program, the agency issued a request for proposal for the Space Shuttle Main Engines. In the summer of 1971, NASA selected the Rocketdyne Division of Rockwell. Rocketdyne built the large, liquid fuel rocket engines used on the NASA Saturn V (moon rocket). However, the shuttle engines differed dramatically from their predecessors. As James Kingsbury, the director of Science and Engineering at the Marshall Space Flight Center, explained, "It was an unproven technology. Nobody had ever had a rocket engine that operated at the pressures and temperatures of that engine." Because of the necessary lead time needed to develop the world's first reusable rocket engine, the selection of the Space Shuttle Main Engines contractor preceded other Orbiter decisions, but a contract protest delayed development by 10 months. Work on the engines officially began in April 1972.

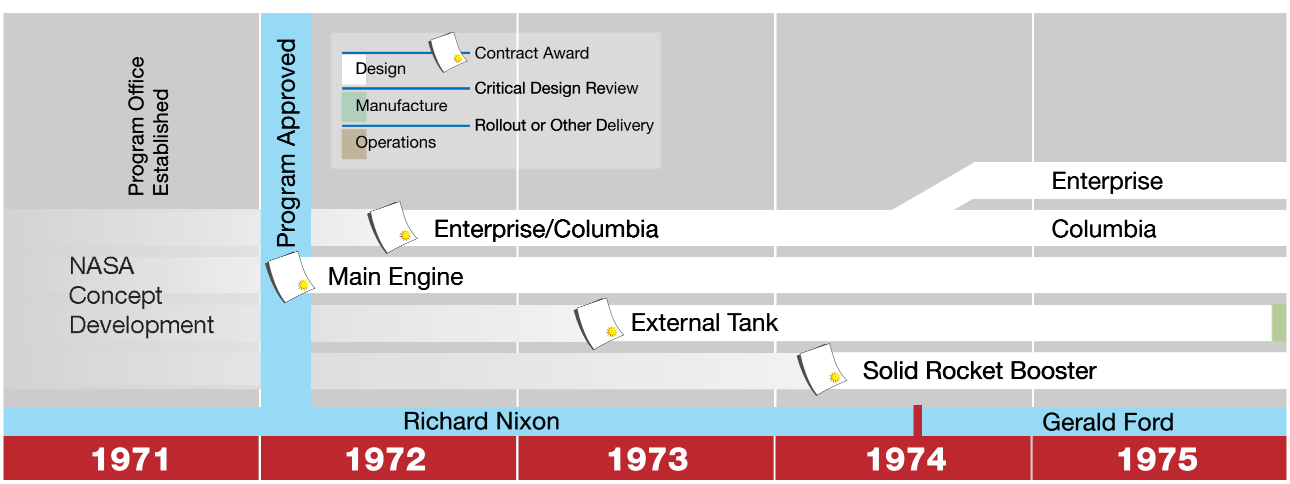
Other large companies benefiting from congressional approval of the Space Shuttle Program included International Business Machines, Martin Marietta, and Thiokol. The computer giant International Business Machines would provide five on-board computers, design and maintain their software, and support testing in all ground facilities that used the flight software and general purpose computers, including the Shuttle Avionics Integration Laboratory, the Shuttle Mission Simulator, and other facilities. Thiokol received the contract for the solid rockets, and NASA selected Martin Marietta to build the External Tank. Although Rockwell received the contract for the Orbiter, the corporation parceled out work to other rival aerospace companies: Grumman built the wings; Convair Aerospace agreed to build the mid-fuselage; and McDonnell Douglas managed the Orbiter rocket engines, which maneuvered the vehicle in space.

Delays and Budget Challenges

Although NASA received approval for the program in 1972, inflation and budget cuts continually ate away at funding throughout the rest of the decade. Over time, this resulted in slips in the schedule as the agency had to make do with effectively fewer dollars each year and eventually cut or decrease spending for less-prominent projects, or postpone them. This also led to higher total development costs. Technical problems with the tiles, Orbiter heat shield, and main engines also resulted in delays, which caused development costs to increase. As a result, NASA kept extending the first launch date.

The shuttle continued to evolve as engineers worked to shave weight from the vehicle to save costs. In 1974, engineers decided to remove the shuttle's air-breathing engines, which would have allowed a powered landing of the vehicle. The engines were to be housed in the payload bay and would have cost more than $300 million to design and build, but

The Space Shuttle Main Engines were the first rocket engines to be reused from one mission to the next. This picture is of Engine 0526, tested on July 7, 2003. A remote camera captures a close-up view of a Space Shuttle Main Engine during a test firing at the John C. Stennis Space Center in Hancock County, Mississippi.



they took up too much space in the bay and added substantial complexity to the design. Thus, the agency decided to go forward with the idea of an unpowered landing to glide the Orbiter and crew safely to a runway.

This decision posed an important question for engineers: how to bring the Orbiter from California, where Rockwell was building it, to the launch sites in Florida, Vandenberg Air Force Base, or test sites in Alabama. NASA considered several options: hanging the Orbiter from a dirigible; carrying the vehicle on a ship; or modifying a Lockheed C-5A or a Boeing 747 to ferry the Orbiter in a piggyback configuration on the back of the plane. Eventually, NASA selected the 747 and purchased a used plane from American Airlines in 1974 to conduct a series of tests before transforming the plane into the Shuttle Carrier Aircraft. Modifications of the 747 began in 1976.

Final Testing

Rollout

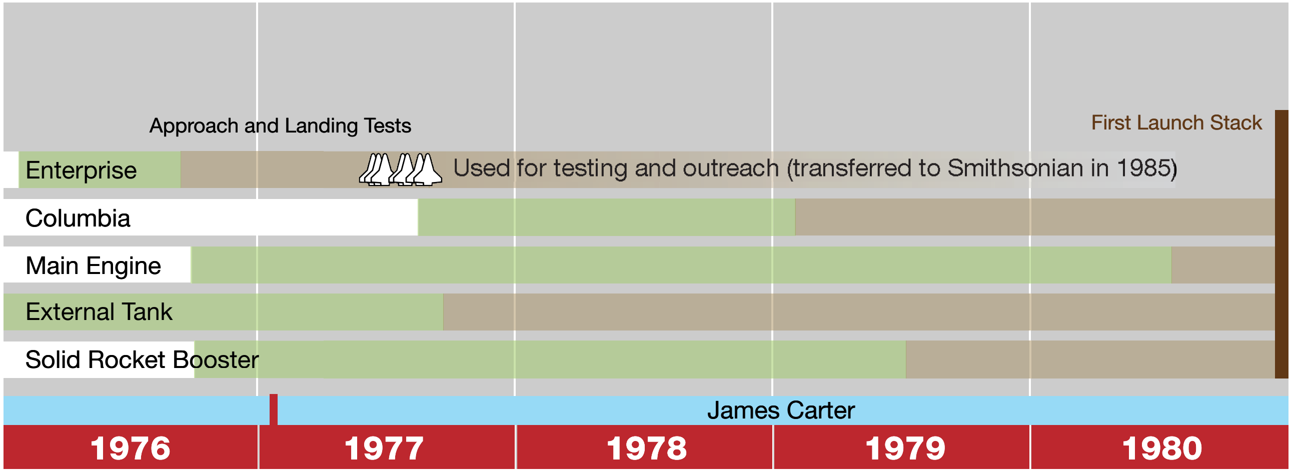
On September 17, 1976, Americans got an initial glimpse of NASA's first shuttle, the Enterprise, when a red, white, and blue tractor pulled the glider out of the hangar at the Air Force Plant in Palmdale, California. Enterprise was not a complete shuttle: it had no propellant lines and the propulsion systems (the main engines and orbital maneuvering pods) were mock-ups. Originally, NASA intended to name the vehicle Constitution in honor of the bicentennial of the United States, but fans of the television show *Star Trek* appealed to NASA and President Gerald Ford, who eventually relented and decided to name the shuttle after Captain Kirk's spaceship. Speaking at the unveiling, Fletcher proclaimed that the debut was "a very proud moment" for NASA. He emphasized the dramatic changes brought about by the program: "Americans and the people of the world have made the evolution to man in space—not just astronauts." The rollout of Enterprise marked the beginning of a new era in spaceflight, one in which all could participate.

In fact, earlier that summer, the agency had issued a call for a new class of astronauts, the first to be selected since the late 1960s when nearly all astronauts were test pilots. A few held advanced degrees in science and medicine, but none were women or minorities. Consequently, NASA emphasized its determination to select people from these groups and encouraged women and minorities to apply.

Approach and Landing Tests

In 1977, Enterprise flew the Approach and Landing Tests at Dryden Flight Research Center using Edwards Air Force Base runways in California. The program was a series of ground and flight tests designed to learn more about the landing characteristics of the Orbiter and how the mated shuttle and its carrier operated together. First, crewless high-speed taxi tests proved that the Shuttle Carrier Aircraft, when mated to the Enterprise, could steer and brake with the Orbiter perched on top of the airframe. The pair, then ready for flight, flew five captive inert flights without astronauts in February and March, which qualified the 747 for ferry operations. Captive-active flights followed in June and July and featured two-man crews.

The final phase was a series of free flights (when Enterprise separated from the Shuttle Carrier Aircraft and landed at the hands of the two-man crews) that flew in 1977, from August to October, and proved the flightworthiness of the shuttle and the techniques of unpowered landings. Most important, the Approach and Landing Tests Program pointed out sections of the Orbiter that needed to be strengthened or made of different materials to save weight.



Enterprise atop the Shuttle Carrier Aircraft in a flight above the Mojave Desert, California (1977).

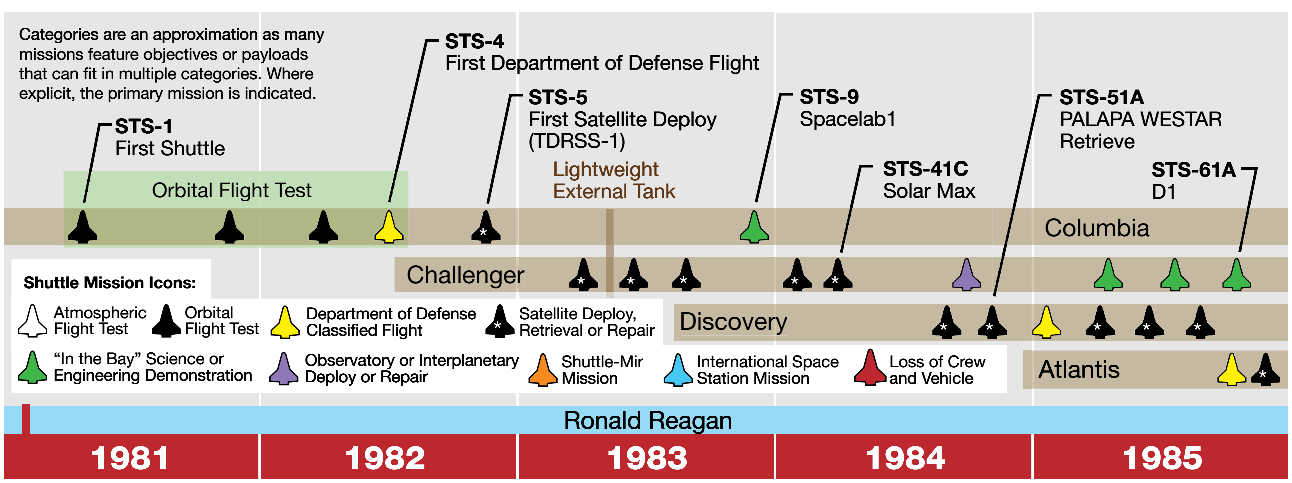
NASA had planned to retrofit Enterprise as a flight vehicle, but that would have taken time and been costly. Instead, the agency selected the other alternative, which was to have the structural test article rebuilt for flight. Eventually called Challenger, this vehicle would become the second Orbiter to fly in space after Columbia. Though Enterprise was no longer slated for flight, NASA continued to use it for a number of tests as the program matured.

Getting Ready to Fly

Concurrent with the Approach and Landing Tests Program, the astronaut selection board in Houston held interviews with 208 applicants selected from more than 8,000 hopefuls. In 1978, the agency announced the first class of Space Shuttle astronauts. This announcement was a historic one. Six women who held PhDs or medical degrees accepted positions along with three African American men and a Japanese American flight test engineer. After completing 1 year of training, the group began following the progress of the shuttle's subsystems, several of which had caused the program's first launch to slip.

The Space Shuttle Main Engines were behind schedule and threatened to delay the first orbital flight, which was tentatively scheduled for March 1979. Problems plagued the engines from the beginning. As early as 1974, the engines ran into trouble as cost overruns threatened the program and delays dogged the modification of facilities in California and the development of key engine components. Test failures occurred at Rocketdyne's California facility and the National Space Technology Laboratory in Mississippi, further delaying development and testing.

Another pacing item for the program was the shuttle's tiles. As Columbia underwent final assembly in California, Rockwell employees began applying the tiles, with the work to be completed in January 1979. Their application was much more time consuming than had been anticipated, and NASA transferred the ship to Kennedy Space Center (KSC) in March, where the task would be completed in the Orbiter Processing Facility and later in the Vehicle Assembly Building. Once in Florida, mating of the tiles to the shuttle ramped up. Unfortunately, engineers found that many of the tiles had to be strengthened. This resulted in many of the 30,000 tiles being removed, tested, and replaced at least once. The bonding process was so time consuming that technicians worked



around the clock, 7 days a week at KSC to meet the launch deadline.

Aaron Cohen, former manager for the Space Shuttle Orbiter Project and JSC director, remembered the stress and pressure caused by the delays in schedule. "I really didn't know how we were going to solve the tile problem," he recalled. As the challenges mounted, Cohen, who was under tremendous pressure from NASA, began going gray, a fact that his wife attributed to "every tile it took to put on the vehicle." Eventually, engineers came up with a solution—a process known as densification, which strengthened the tiles and, according to Cohen, "bailed us out of a major, significant problem" and remained the process throughout the program.

After more than 10 years of design and development, the shuttle appeared ready to fly. In 1979 and 1980, the Space Shuttle Main Engines proved their flightworthiness by completing a series of engine acceptance tests. The tile installation finally ended, and the STS-1 crew members, who had been named in 1978, joked that they were "130% trained and ready to go" because of all the time they spent in the shuttle simulators. Young and Crippen's mission marked the beginning of the shuttle flight test program.

Spaceflight Operations

Columbia's First Missions

Columbia flew three additional test flights between 1981 and 1982. These test flights were designed to verify the shuttle in space, the testing and processing facilities, the vehicle's equipment, and crew procedures. Ground testing demonstrated the capability of the Orbiter, as well as of its components and systems. Without flight time, information about these systems was incomplete. The four tests were necessary to help NASA understand heating, loads, acoustics, and other concepts that could not be studied on the ground.

This test program ended on July 4, 1982, when commander Thomas Mattingly landed the shuttle at Dryden Flight Research Center (DFRC) on the 15,000-ft runway at Edwards Air Force Base in California. Waiting at the foot of the steps, President Reagan and First Lady Nancy Reagan congratulated the STS-4 crew on a job well done. Speaking to a crowd of more than 45,000 people at DFRC, the president said that the completion of this task was "the historical equivalent to the driving of the golden spike which completed the first transcontinental railroad. It marks our entrance into a new era."

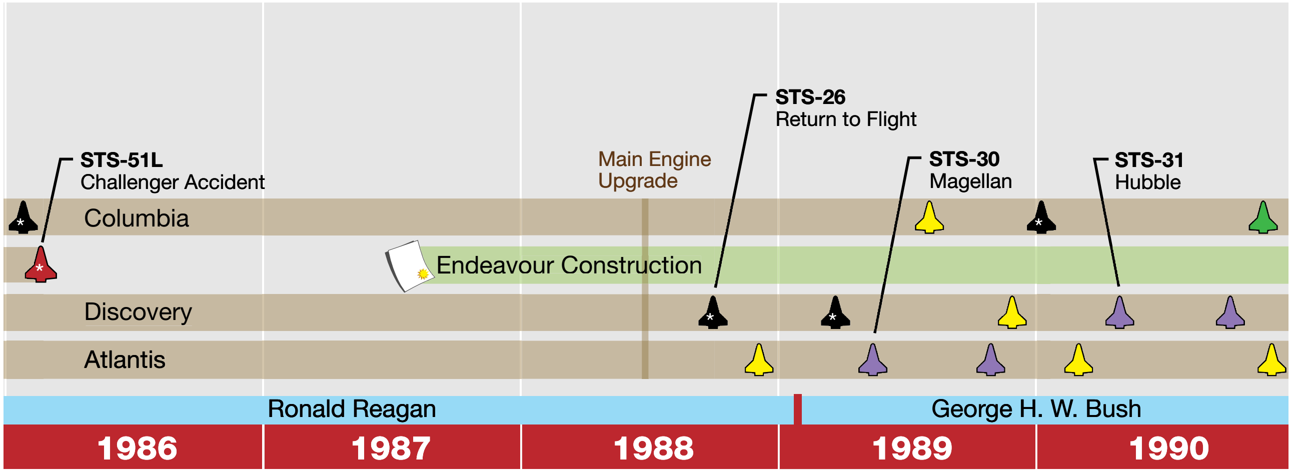
The operational flights, which followed the flight test program, fell into several categories: DoD missions; commercial satellite deployments; space science flights; notable spacewalks (also called extravehicular activities); or satellite repair and retrieval.

To improve costs, beginning in 1983 all launches and landings at KSC were managed by one contractor, Lockheed Space Operations Company, Titusville, Florida. This consolidated many functions for the entire shuttle processing.

Department of Defense Flights

STS-4 (1982) featured the first classified payload, which marked a fundamental shift in NASA's traditionally open environment. Concerned with national security, the DoD instructed NASA Astronauts Mattingly and Henry Hartsfield to not transmit images of the cargo bay during the flight, lest pictures of the secret payload might inadvertently be revealed. STS-4 did differ somewhat from the other future DoD-dedicated flights: there was no secure communication line, so the crew worked out a system of communicating with the ground.

"We had the checklist divided up in sections that we just had letter names like Bravo Charlie, Tab Charlie, Tab



Bravo that they could call out. When we talked to Sunnyvale [California] to Blue Cube out there, military control, they said, 'Do Tab Charlie,' or something. That way it was just unclassified," Hartsfield recalled. Completely classified flights began in 1985.

Even though Vandenberg Air Force Base had been selected as one of the program launch sites in 1972, the California shuttle facilities were not complete when classified flights began. Anticipating slips, the DoD and NASA decided to implement a controlled mode at JSC and KSC that would give the space agency the capability to control classified flights out of the Texas and Florida facilities. Flight controllers at KSC and JSC used secured launch and flight control rooms separate from the rooms used for non-DoD flights. Modifications were also made to the flight simulation facility, and a room was added in the astronaut office, where flight crew members could store classified documents inside a safe and talk on a secure line.

Although the facilities at Vandenberg Air Force Base were nearly complete in 1984, NASA continued to launch and control DoD flights. Two DoD missions flew in 1985: STS-51C and STS-51J. Each flight included a payload specialist from the Air Force. That year, the department also announced the names of the crew of the first Vandenberg flight, STS-62A, which would have been commanded by veteran Astronaut Robert Crippen, but was cancelled in the wake of the Challenger accident (1986).

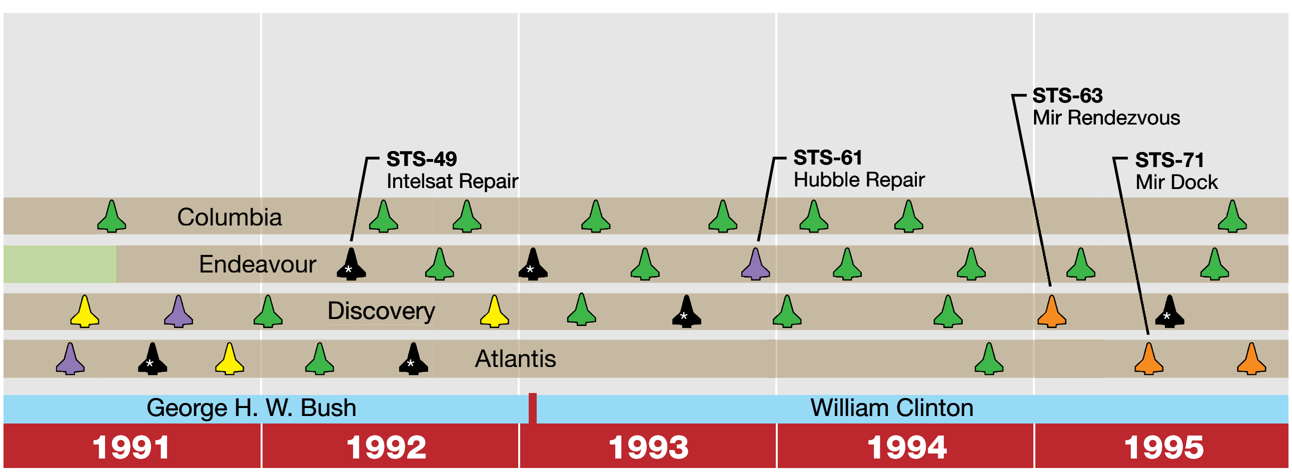
Flying classified flights complicated the business of spaceflight. For national security reasons, the Mission Operations Control Room at JSC was closed to visitors during simulations and these flights. Launch time was not shared with the press and, for the first time in NASA's history, no astronaut interviews were granted about the flight, no press kits were distributed, and the media were prohibited from listening to the air-to-ground communications.

Shuttle Operations, 1982-1986

STS-5 (1982) marked both the beginning of shuttle operations and another turning point in the history of the Space Shuttle Program. As Astronaut Joseph Allen explained, spaceflight changed "from testing the means of getting into space to using the resources found there." Or, put another way, this four-member crew (the largest space crew up to that point; the flight tests never carried more than two men at a time) was the first to launch two commercial satellites. This "initiated a new era in which the business of spaceflight became business itself." Dubbed the "Ace Moving Company," the crew jokingly promised "fast and courteous service" for its future launch services.

Many of the early shuttle flights were, in fact, assigned numerous commercial satellites, which they launched from the Orbiter's cargo bay. With NASA given a monopoly in the domestic launch market, many flight crews released at least one satellite on each flight, with several unloading as many as three communication satellites for a number of nations and companies. Foreign clients, particularly attracted to NASA's bargain rates, booked launches early in the program.

Another visible change that occurred on this, the fifth flight of Columbia was the addition of mission specialists—scientists and engineers—whose job it was to deploy satellites, conduct spacewalks, repair and retrieve malfunctioning satellites, and work as scientific researchers in space. The first two mission specialists—Joseph Allen, a physicist, and William Lenoir, an electrical engineer—held PhDs in their respective fields and had been selected as astronauts in 1967. Those who followed in their footsteps had similar qualifications, often holding advanced degrees in their fields of study.



Christopher Kraft

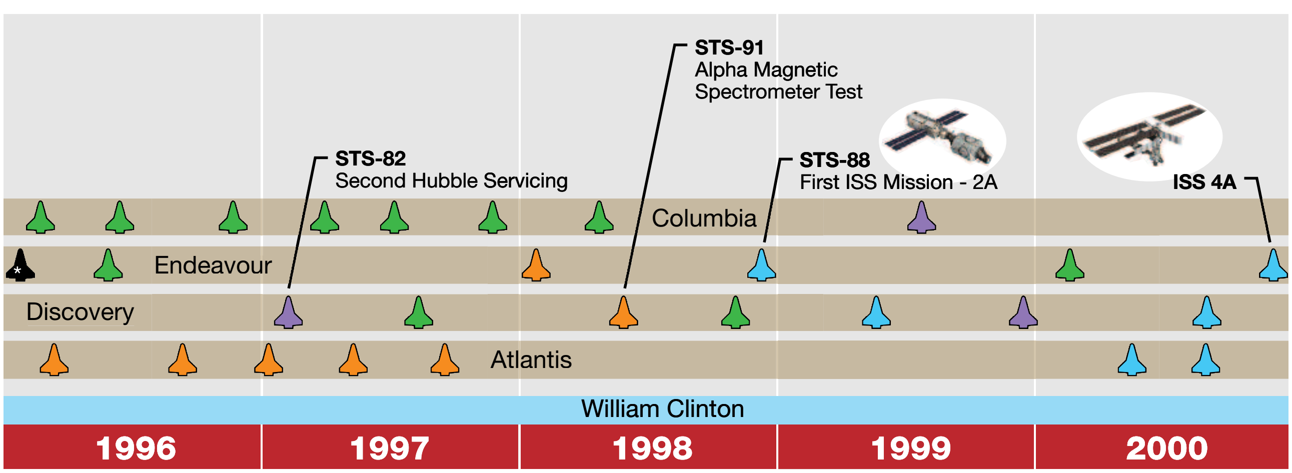
Director of Johnson Space Center during shuttle development and early launches (1972-1982).
Played an instrumental role in the development and establishment of mission control.

"We went through a lot to prove that we should launch STS-1 manned instead of unmanned; it was the first time we ever tried to do anything like that. We convinced ourselves that the reliability was higher and the risk lower, even though we were risking the lives of two men. We convinced ourselves that that was a better way to do it, because we didn't know what else to do. We had done everything we could think of."

With the addition of mission specialists and the beginning of operations, space science became a major priority for the shuttle, and crews turned their attention to research. A variety of experiments made their way on board the shuttle in Get Away Specials, the Shuttle Student Involvement Project, the middeck (crew quarters), pallets (unpressurized platforms designed to support instruments that require direct exposure to space), and Spacelabs. Medical doctors within NASA's own Astronaut Corps studied space sickness on STS-7 (1983) and STS-8 (1983), subjecting their fellow crew members to a variety of tests in the middeck to determine the triggers for a problem that plagues some space travelers. Aside from medical experiments, many of the early missions included a variety of Earth observation instruments. The crews spent time looking out the window, identifying and photographing weather patterns, among other phenomena. A number of flights featured material science research, including STS-61C (1986), which included Marshall Space Flight Center's Material Science Laboratory.

As space research expanded, so did the number of users, and the aerospace industry was not excluded from this list. They were particularly active in capitalizing on the potential benefits offered by the shuttle and its platform as a research facility. Having signed a Joint Endeavor Agreement (a quid pro quo arrangement, where no money exchanged hands) with NASA in 1980, McDonnell Douglas Astronautics flew its Continuous Flow Electrophoresis System on board the shuttle numerous times to explore the capabilities of materials processing in space. The system investigated the ability to purify erythropoietin (a hormone) in orbit and to learn whether the company could mass produce the purified pharmaceutical in orbit. The company even sent one of its employees—who, coincidentally, was the first industrial payload specialist—into space to monitor the experiment on board three flights, including the maiden flight of Discovery. Other companies, like Fairchild Industries and 3M, also signed Joint Endeavor Agreements with NASA.

When the ninth shuttle flight lifted off the pad in November 1983, Columbia had six passengers and a Spacelab in its payload bay. This mission, the first flight of European lab, operated 24 hours a day, featured more than 70 experiments,



William Lucas, PhD
Former director of Marshall Space Flight Center during shuttle operations until Challenger accident (1974-1986).
Played an instrumental role in Space Shuttle Main Engine, External Tank, and Solid Rocket Booster design, development, and operations.

On October 11, 1974, newly appointed Marshall Space Flight Center (MSFC) Director Dr. William Lucas (right) and a former MSFC Director Dr. Wernher von Braun view a model.

"The shuttle was an important part of the total space program and it accomplished, in a remarkable way, the unique missions for which it was designed. In addition, as an element of the continuum from the first ballistic missile to the present, it has been a significant driver of technology for the benefit of all mankind."

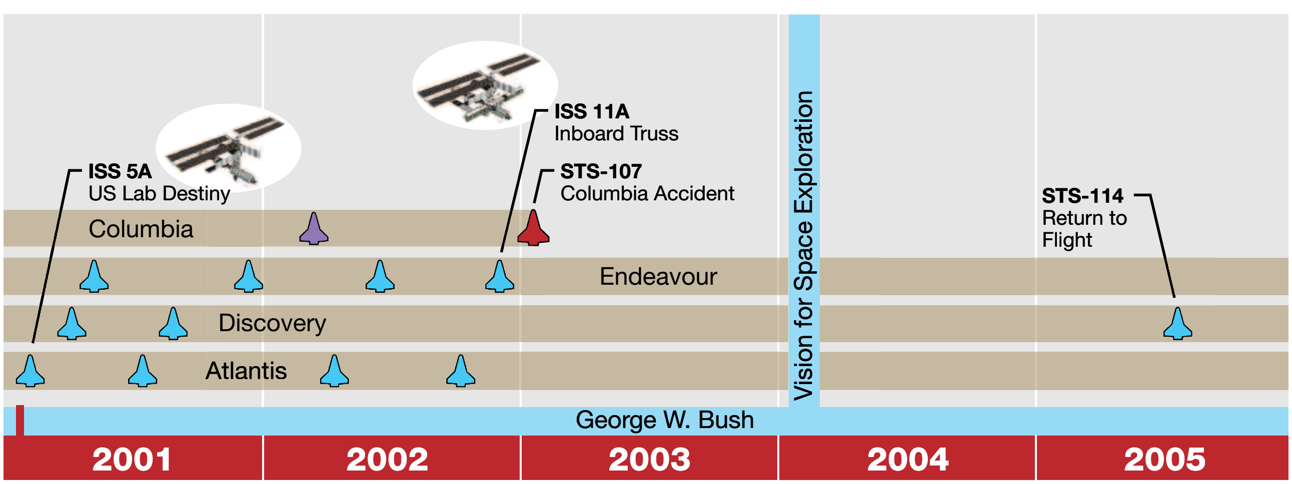
and carried the first noncommercial payload specialists to fly in space.

Three additional missions flew Spacelabs in 1985, with West Germany sponsoring the flight of STS-61A, the first mission financed and operated by another nation. One of the unique features of this flight was how control was split between centers. JSC's Mission Control managed the shuttle's systems and worked closely with the commander and pilot while the German Space Operations Center in Oberpfaffenhofen oversaw the experiments and scientists working in the lab.

By 1984, the shuttle's capabilities expanded dramatically when Astronauts Bruce McCandless and Bob Stewart tested the manned maneuvering units that permitted flight crews to conduct untethered spacewalks. At this point in the program, this was by far the most demanding spacewalk conducted by astronauts. The first spacewalk, conducted just months before the flight of STS-41B, tested the suits and the capability of astronauts to work in the payload bay. As McCandless flew the unit out of the cargo bay for the first time, he said, "It may have been one small step for Neil, but it's a heck of a big leap for me." Set against the darkness of space, McCandless became the first human satellite in space. Having proved the capabilities of the manned maneuvering unit, NASA exploited its capabilities and used the device to make satellite retrieval and repair possible without the use of the Shuttle Robotic Arm.

Early Satellite Repair and Retrievals

Between 1984 and 1985, the shuttle flew three complicated satellite retrieval or repair missions. On NASA's 11th shuttle mission, STS-41C, the crew was to capture and repair the Solar Maximum Satellite (SolarMax), the first one built to be serviced and repaired by shuttle astronauts. Riding the manned maneuvering unit, spacewalker George Nelson tried to capture the SolarMax, but neither he nor the Robotic Arm operator Terry Hart was able to do so. Running low on fuel, the crew backed away from the satellite while folks at the Goddard Space Flight Center in



Maryland stabilized the SolarMax. The shuttle had just enough fuel for one more rendezvous with the satellite. Fortunately, Hart was able to grapple the satellite, allowing Nelson and James van Hoften to fix the unit, which was then rereleased into orbit.

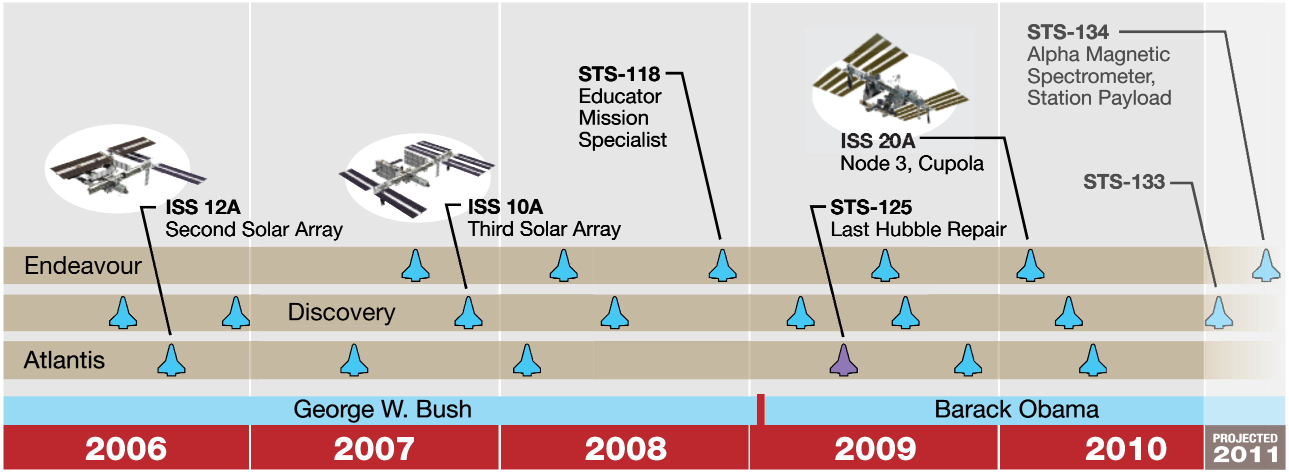
The following retrieval mission was even more complex. STS-51A was the first mission to deploy two satellites and then retrieve two others that failed to achieve their desired orbits. Astronauts Joseph Allen and Dale Gardner used the manned maneuvering unit to capture Palapa and Westar, originally deployed on STS-41B 9 months earlier. They encountered problems, however, when stowing the first recovered satellite, forcing Allen to hold the 907-kg (2,000-pound) satellite over his head for an entire rotation of the Earth—90 minutes. When the crew members reported that they had captured and secured both satellites in Discovery's payload bay, Lloyd's of London—one of the underwriters for the satellites—rang the Lutine bell, as they had done since the 1800s, to announce events of importance. As Cohen, former director of JSC, explained, "Historically Lloyd's of London, who would insure high risk adventures, rang a bell whenever ships returned to port with recovered treasure from the sea." He added that the salvage of these satellites in 1984 "was at that time the largest monetary treasure recovered in history."

The program developed a plan for the crew of STS-51I (1985) to retrieve and repair a malfunctioning Hughes satellite that had failed to power up just months before the flight. With only 4 months to prepare, NASA built a number of tools that had not been tested in space to accomplish the crew's goal. In many ways, the crew's flight was a first. Van Hoften, one of the walkers on STS-41C, recalled the difference between his first and second spacewalk: "It wasn't anything like the first one. The first one was so planned out and choreographed. This one, we were winging it, really." Instead of planning their exact moves, crew members focused instead on skills and tasks. Their efforts paid off when the ground activated the satellite.

Space Station Reemerges

As the Space Shuttle Program matured, NASA began working on the Space Station Program, having been directed to do so by President Reagan in his 1984 State of the Union address. The shuttle would play an important role in building the orbiting facility. In the winter of 1985, STS-61B tested structures and assembly methods for the proposed long-duration workshop. Spacewalkers built a 13.8-m (45-ft) tower and a 3.7-m (12-ft) structure, proving that crews could feasibly assemble structures using parts carried into space by the Orbiter. NASA proceeded with plans to build Space Station Freedom, which in the 1990s was transformed to the International Space Station (ISS).

To fund the space station, NASA needed to cut costs for shuttles by releasing requests for proposals for three new contracts. In 1983, the Shuttle Processing Contract integrated all processing at KSC. Lockheed Space Operations Company received this contract. In 1985, the Space Transportation Systems Operations Contract and the Flight Equipment Contract were solicited. The former contract consolidated 22 shuttle operations contracts, while the latter combined 15 agreements involving spaceflight equipment (e.g., food, clothes, and cameras). NASA Administrator James Beggs hoped that by awarding such contracts, he could reduce shuttle costs by as much as a quarter by putting cost incentives into the contracts. Rockwell International won the Space Transportation Systems Operations Contract, and NASA chose Boeing Aerospace Operations to manage the Flight Equipment Processing Contract.



Challenger Accident

In January 1986, NASA suspended all shuttle flights after the Challenger accident in which seven crew members perished. A failure in the Solid Rocket Booster motor joint caused the vehicle to break up. The investigation board was very critical of NASA management, especially about the decision to launch. For nearly 3 years, NASA flew no shuttle flights. Instead, the agency made changes to the shuttle. It added a crew escape system and new brakes, improved the main engines, and redesigned the Solid Rocket Boosters, among other things.

In the aftermath of the accident, the agency made several key decisions, which were major turning points. The shuttle would no longer deliver commercial satellites into Earth orbit unless "compelling circumstances" existed or the deployment required the unique capabilities of the space truck. This decision forced industry and foreign governments who hoped to deploy satellites from the shuttle to turn to expendable launch vehicles. Fletcher, who had returned for a second term as NASA administrator, cancelled the Shuttle/Centaur Program because it was too risky to launch the shuttle carrying a rocket with highly combustible liquid fuel. Plans to finally activate and use the Vandenberg Air Force Base launch site were abandoned, and the shuttle launch site was eventually mothballed. The Air Force decided to launch future payloads on Titan rockets and ordered additional expendable launch vehicles. A few DoD-dedicated missions would, however, fly after the accident. Finally, in 1987, Congress authorized the building of Endeavour as a replacement for the lost Challenger. Endeavour was delivered to KSC in the spring of 1991.

Post-Challenger Accident Return to Flight

STS-26 was the Space Shuttle's Return to Flight. Thirty-two months after the Challenger accident, Discovery roared to life on September 29, 1988, taking its all-veteran crew into space where they deployed the second Tracking and Data Relay Satellite. The crew safely returned home to DFRC 4 days later, and Vice President George H.W. Bush and his wife Barbara Bush greeted the crew. That mission was a particularly significant accomplishment for NASA. STS-26 restored confidence in the agency and marked a new beginning for NASA's human spaceflight program.

Building Momentum

Following the STS-26 flight, the shuttle's launch schedule climbed once again, with the space agency eventually using all three shuttles in the launch processing flow for upcoming missions. The first four flights after the accident alternated between Discovery and Atlantis, adding Columbia to the mix for STS-28 (1989). Even though the flight crews did not launch any commercial satellites from the payload bay, several deep space probes—the Magellan Venus Radar Mapper, Galileo, and Ulysses—required the shuttle's unique capabilities. STS-30 (1989) launched the mapper, which opened a new era of exploration for the agency. This was the first time a Space Shuttle crew deployed an interplanetary probe, thereby interlocking both the manned and unmanned spaceflight programs. In addition, this flight was NASA's first planetary mission of any kind since 1977, when it launched the Voyager spacecraft. STS-34 (1989) deployed the Galileo spacecraft toward Jupiter. Finally, STS-41 (1990) delivered the European Space Agency's Ulysses spacecraft, which would study the polar regions of the sun.

Astronaut James Voss is pictured during an STS-69 (1995) extravehicular activity that was conducted in and around Endeavour's cargo bay. Voss and Astronaut Michael Gernhardt performed evaluations for space station-era tools and various elements of the spacesuits.

Extended Duration Orbiter Program

Before 1988, shuttle flights were short, with limited life science research. NASA thought that if the shuttle could be modified, it could function as a microgravity laboratory for weeks at a time. The first stage was to make modifications to the life support, air, water, and waste management systems for up to a 16-day stay. There were potential drawbacks to extended stays in microgravity. Astronauts were concerned about the preservation of their capability for unaided egress from the shuttle, including the capability for bailout. Another concern was degradation of landing proficiency after such a long stay, as this had never been done before.

Between 1992 (STS-50) and 1995, this program successfully demonstrated that astronauts could land and egress after such long stays, but that significant muscle degradation occurred. The addition of a new pressurized g-suit provided relief to the light-headedness (feeling like fainting) experienced when returning to Earth. Improvements included the addition of a crew transport vehicle that astronauts entered directly from the landed shuttle in which they reclined during medical examination until they were ready to walk. On-orbit exercise was tested to improve their physical capabilities for emergency egress and landing. The research showed that with more than 2 weeks of microgravity, astronauts probably should not land the shuttle as it was too complicated and risky. In the future, shuttle landing would only be performed by a short-duration astronaut.

The Great Observatories

Months before the Ulysses deployment, the crew of STS-31 (1990) deployed the Hubble Space Telescope, which had been slated for launch in August 1986 but slipped to 1990 after the Challenger accident. Weeks before the launch, astronauts and NASA administrators laid out the importance of the flight. Lennard Fisk, NASA's associate administrator for Space Science and Applications, explained, "This is a mission from which (people) can expect very fundamental discoveries. They could begin to understand creation. Hubble could be a turning point in humankind's perception of itself and its place in the universe."

Unfortunately, within just a few short months NASA discovered problems with the telescope's mirror—problems that generated a great deal of controversy. Several in Congress believed that the telescope was a colossal waste of money. Only 4 years after the accident, NASA's morale plunged again. Fortunately, the flight and ground crews, along with employees at Lockheed Martin, took the time to work out procedures to service the telescope in orbit during the flight hiatus. In 1992, NASA named the crew that would take on this challenge.

The astronauts assigned to repair the telescope felt pressure to succeed. "Everybody was looking at the servicing and repair of the Hubble Space Telescope as the mission that could prove NASA's worth," Commander Dick Covey recalled. The mission was one of the most sophisticated ever planned at NASA. The spacewalkers rendezvoused for the first time with the telescope, one of the largest objects the shuttle had rendezvoused with at that point, and conducted a record-breaking five spacewalks. The repairs were successful, and the public faith rebounded. Four additional missions serviced the Hubble, with the final launching in 2009.

Two other major scientific payloads, part of NASA's Great Observatories including the Compton Gamma Ray Observatory and the Chandra X-ray Observatory, launched from the Orbiter's cargo bay. When the Compton Gamma Ray Observatory's high-gain antenna failed to deploy, Astronauts Jerry Ross and Jay Apt took the first spacewalk in 6 years (the last walk occurred in 1985) and freed the antenna. The crew of STS-93, which featured NASA's first female mission commander, Eileen Collins, delivered the Chandra X-ray Observatory to Earth orbit in 1999.

Satellite Retrieval and Repair

Satellite retrieval and repair missions all but disappeared from the shuttle manifest after the Challenger accident. STS-49 (1992) was the one exception. An Intelsat was stranded in an improper orbit for several years, and spacewalkers from STS-49 were to attach a new kick-start motor to it. The plan seemed simple enough. After all, NASA had plenty of practice capturing ailing satellites. After two unsuccessful attempts, flight controllers developed a plan that required a three-person spacewalk, a first in the history of NASA's space operations. This finally allowed the crew to repair and redeploy the satellite, which occurred—coincidentally—during Endeavour's first flight.

New Main Engine

STS-70 flew in the summer of 1995 and launched a Tracking and Data Relay Satellite. The shuttle flew the new main engine, which contained an improved high-pressure liquid oxygen turbopump, a two-duct powerhead, and a single-coil heat exchanger. The new pumps were a breakthrough in shuttle reliability and quality, for they were much safer than those previously used on the Orbiter. The turbopumps required less maintenance than those used prior to 1995. Rather than removing each pump after every flight, engineers would only have to conduct detailed inspections of the pumps after six missions. A single-coil heat exchanger eliminated many of the welds that existed in the previous pump, thereby increasing engine reliability, while the powerhead enhanced the flow of fuel in the engine.

Space Laboratories

NASA continued to fly space laboratory missions until 1998, when Columbia launched the final laboratory and crew into orbit for the STS-90 mission. The shuttle had two versions of the payload bay laboratory: European Spacelab and US company Spacehab, Inc. Fifteen years had passed since the flight of STS-9—the first mission—and the project ended with the launch of Neurolab, which measured the impact of microgravity on the nervous system: blood pressure; eye-hand coordination; motor coordination; sleep patterns; and the inner ear. Scientists learned a great deal from Spacelab Life Sciences-1 and -2 missions, which flew in the summer of 1991 and 1993, respectively, and represented a turning point in spaceflight human physiology research. Previous understandings of how the human body worked in space were either incomplete or incorrect. The program scientist for the flight explained that the crew obtained “a significant number of surprising results” from the flight.

Other notable flights included the ASTRO-1 payload, which featured four telescopes designed to measure ultraviolet light from astronomical objects, life sciences missions, the US Microgravity Labs, and even a second German flight called D-2. The day before the crew of D-2 touched down at DFRC on an Edwards Air Force Base runway, the Space Shuttle Program reached a major milestone, having accrued a full year of flight time by May 5, 1993.

Spacehab, a commercially provided series of modules similar to Spacelab and used for science and logistics, was a significant part of the shuttle manifest in the 1990s. One of those Spacehab flights featured the return of Mercury 7 Astronaut and US Senator John Glenn, Jr. Thirty-six years had passed since he had flown in space and had become the first American to fly in Earth orbit. He broke records again in 1998 when he became the oldest person to fly in space. Given his age, researchers hoped to compare the similarities between aging on Earth with the effects of microgravity on the human body. Interest in this historic flight, which also fell on NASA’s 40th anniversary, was immense. Not only was Glenn returning to orbit, but Pedro Duque—a European Space Agency astronaut—became the first Spanish astronaut, following in the footsteps of Spanish explorers Hernán Cortés and Francisco Pizarro.

US Senator John Glenn, Jr., payload specialist, keeps up his busy test agenda during Flight Day 7 on board Discovery STS-95 in 1998. This was a Spacehab flight that studied the effect of microgravity on human physiology. He is preparing his food, and on the side is the bar code reader used to record all food, fluids, and drug intakes.

Consolidating Contracts

The Space Shuttle Program seemed to hit its stride in the 1990s. In 1995, NASA decided to consolidate 12 individual contracts under a single prime contractor. United Space Alliance (USA), a hybrid venture between Rockwell International and Lockheed Martin, became NASA’s selection to manage the space agency’s Space Flight Operations Contract. USA was the obvious choice because those two companies combined held nearly 70% of the dollar value of prime shuttle contracts. Although the idea of handing over all processing and launch operations to a contractor was controversial, NASA Administrator Daniel Goldin, known for his “faster, better, cheaper” mantra, enthusiastically supported the sole source contract as part of President William Clinton’s effort to trim the federal budget and increase efficiency within government. NASA awarded USA a $7 billion contract, which went into effect on October 1, 1996. Speaking at JSC about the agreement, Goldin proclaimed, “Today is the first day of a new space program in America. We are opening up the space program to commercial space involving humans. May it survive and get stronger.”

STS-80, the first mission controlled by USA, launched in November 1996. The all-veteran crew, on the final flight of the year and the 80th of the program, stayed in space for a record-breaking 17 days. A failure with the hatch prohibited crew members from conducting two scheduled spacewalks, but NASA considered the mission a success because the crew brought home more scientific data than they had expected to gather with the Orbiting and Retrievable Far and Extreme Ultraviolet Spectrometer-Shuttle Pallet Satellite-II.

The Shuttle-Mir Program

As the Cold War (the Soviet-US conflict between the mid 1940s and early 1990s) ended, the George H.W. Bush administration began laying the groundwork for a partnership in space between the United States and the Soviet Union. Following the collapse of the Soviet Union in 1991, President Bush and Russian President Boris Yeltsin signed a space agreement, in June 1992, calling for collaboration between the two countries in space. They planned to place American astronauts on board the Russian space station Mir and to take Russian cosmonauts on board shuttle flights. Noting the historic nature of the agreement, Goldin said, "Our children and their children will look upon yesterday and today as momentous events that brought our peoples together." This agreement brokered a new partnership between the world's spacefaring nations, once adversaries.

Known as the Shuttle-Mir Program, these international flights were the first phase of the ISS Program and marked a turning point in history. The Shuttle-Mir Program—led from JSC, with its director George Abbey—was a watershed and a symbol of the thawing of relations between the United States and Russia.

For more than 4 years, from the winter of 1994 to the summer of 1998, nine shuttle flights flew to the Russian space station, with seven astronauts living on board the Mir for extended periods of time. The first phase began when Cosmonaut Sergei Krikalev flew on board STS-60 (1994).

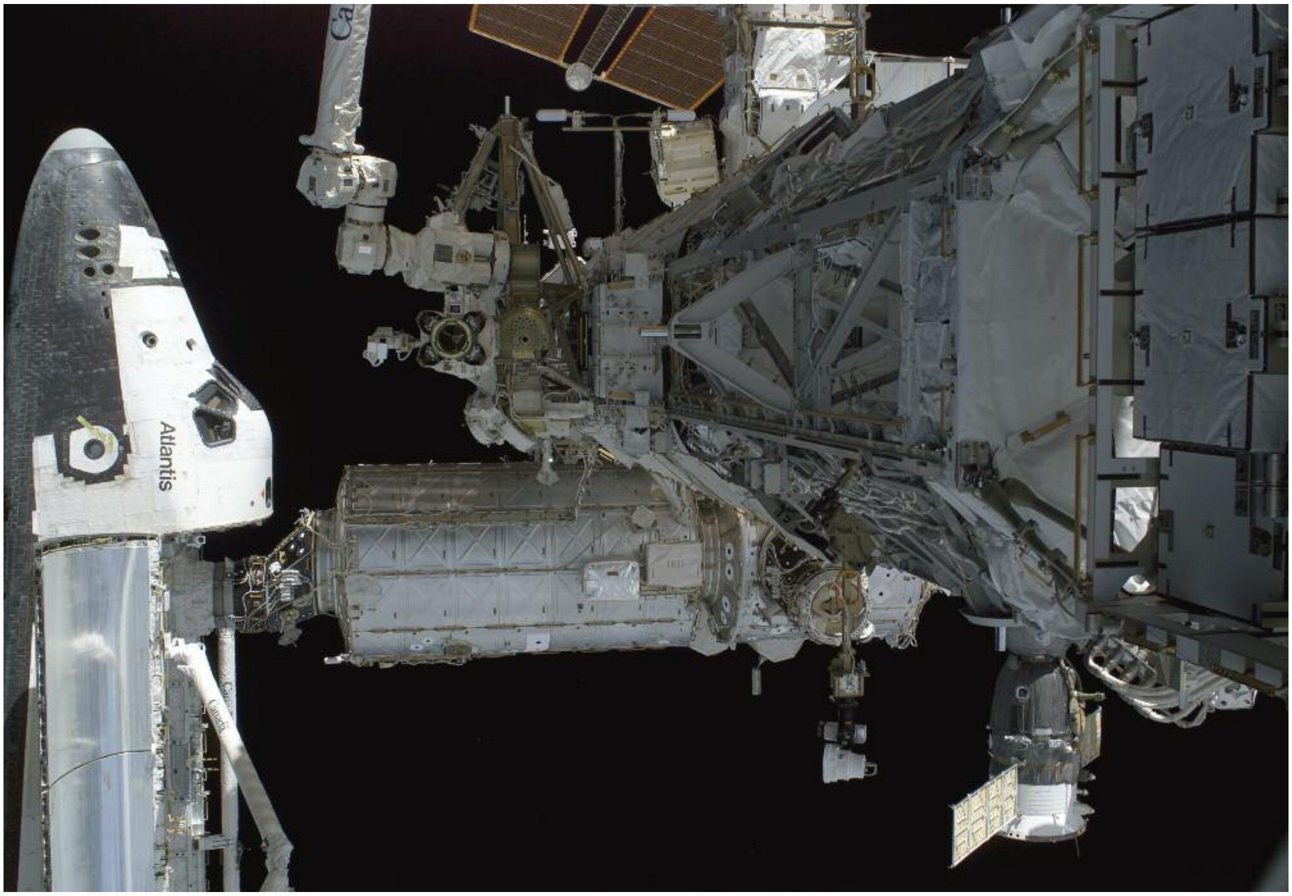
Twenty years had passed since the Apollo-Soyuz Test Project when, in the summer of 1995, Robert Gibson made history when he docked Atlantis to the much-larger Mir. The STS-71 crew members exchanged gifts and shook hands with the Mir commander in the docking tunnel that linked the shuttle and the Russian station. They dropped off the next Mir crew and picked up two cosmonauts and America's first resident of Mir, Astronaut Norman Thagard. Additional missions ferried crews and necessary supplies to Mir. One of the major milestones of the program was the STS-74 (1995) mission, which delivered and attached a permanent docking port to the Russian space station.

In 1996, Astronaut Shannon Lucid broke all American records for time in orbit and held the flight endurance record for all women, from any nation, when she stayed on board Mir for 188 days. Clinton presented Lucid with the Congressional Space Medal of Honor for her service, representing the first time a woman or scientist had received this accolade. Speaking about the importance of the Shuttle-Mir Program, the president said, "Her mission did much to cement the alliance in space we have formed with Russia. It demonstrated that, as we move into a truly global society, space exploration can serve to deepen our understanding, not only of our planet and our universe, but of those who share the Earth with us."

STS-91 (1998), which ended shuttle visits to Mir, featured the first flight of the super-lightweight External Tank. Made of aluminum lithium, the newly designed tank weighed 3,402 kg (7,500 pounds) less than the previous tank (the lightweight or second-generation tank) used on the previous flight, but its metal was stronger than that flown prior to the summer of 1998. By removing so much launch weight, engineers expanded the shuttle's ability to carry heavier payloads, like the space station modules, into Earth's orbit. Launching with less weight also enabled the crew to fly to a high inclination orbit of 51.6 degrees, where NASA and its partners would build the ISS. STS-91 also carried a prototype of the Alpha Magnetic Spectrometer into space. This instrument was designed to look for dark and missing matter in the universe. The preliminary test flight was in preparation for its launch to the ISS on STS-134. The Alpha Magnetic Spectrometer has a state-of-the-art particle physics detector, and includes the participation of 56 institutions and 16 countries led by Nobel Laureate Samuel Ting. By the end of the Shuttle-Mir Program, the number of US astronauts who visited the Russian space station exceeded the number of Russian cosmonauts who had worked aboard Mir.

The International Space Station

With the first phase completed, NASA began constructing the ISS with the assistance of shuttle crews, who played an integral role in building the outpost. In 1998, 13 years after spacewalker Jerry Ross demonstrated the feasibility of assembling structures in space (STS-61B [1985]), ISS construction began. During three spacewalks, Ross and James Newman connected electrical power and cables between the Russian Zarya module and America's Unity Module, also called Node 1. They installed additional hardware—handrails and antennas—on the station. NASA's dream of building a space station had finally come to fruition.



Although no astronauts are visible in this picture, action was brisk outside the Space Shuttle (STS-116)/space station tandem in 2006.

The shuttle's 100th mission (STS-92) launched from KSC in October 2000, marking a major milestone for the Space Shuttle and the International Space Station Programs. The construction crew delivered and installed the initial truss—the first permanent latticework structure—which set the stage for the future addition of trusses. The crew also delivered a docking port and other hardware to the station. Four spacewalkers spent more than 27 hours outside the shuttle as they reconfigured these new elements onto the station. The seven-member crew also prepared the station for the first resident astronauts, who docked with the station 14 days after the crew left the orbital workshop. Of the historic mission, Lead Flight Director Chuck Shaw said, "STS-92/ISS Mission 3A opens the next chapter in the construction of the International Space Station," when human beings from around the world would permanently occupy the space base.

Crews began living and working in the station in the fall of 2000, when the first resident crew (Expedition 1) of Sergei Krikalev, William Shepherd, and Yuri Gidzenko resided in the space station for 4 months. For the next 3 years, the shuttle and her crews were the station's workhorse. They transferred crews; delivered supplies; installed modules, trusses, the Space Station Robotic Arm, an airlock, and a mobile transporter, among other things. By the end of 2002, NASA had flown 16 assembly flights. Flying the shuttle seemed fairly routine until February 2003, when Columbia disintegrated over East Texas, resulting in the loss of the shuttle and her seven-member crew.

Columbia Accident

The cause of the Columbia accident was twofold. The physical cause resulted from the loss of insulating foam from the External Tank, which hit the Orbiter's left wing during launch and created a hole. When Columbia entered the Earth's atmosphere, the left wing leading edge thermal protection (reinforced carbon-carbon panels) was unable to prevent heating due to the breach. This led to the loss of control and disintegration of the shuttle, killing the crew. NASA's flawed culture of complacency also bore responsibility for the loss of the vehicle and its astronauts. All flights were put on hold for more than 2 years as NASA implemented numerous safety improvements, like redesigning the External Tank with an improved bipod fitting that minimized potential foam debris from the tank. Other improvements were the Solid Rocket Booster Bolt Catcher, impact sensors added to the wing's leading edge, and a boom for the shuttle's arm that allowed the crew to inspect the vehicle for any possible damage, among other things.

As NASA worked on these issues, President George W. Bush announced his new Vision for Space Exploration, which included the end of the Space Shuttle Program. As soon as possible, the shuttles would return to flight to complete the ISS by 2010 and then NASA would retire the fleet.

Post-Columbia Accident Return to Flight

In 2005, STS-114 returned NASA to flying in space. Astronaut Eileen Collins commanded the first of two Return to Flight missions, which were considered test flights. The first mission tested and evaluated new flight safety procedures as well as inspection and repair techniques for the vehicle. One of the changes was the addition of an approximately 15-m (50-ft) boom to the end of the robotic arm. This increased astronauts' capabilities to inspect the tile located

Leroy Chiao, PhD
Astronaut on STS-65 (1994), STS-72 (1996), and STS-92 (2000). Commander and science officer on ISS Expedition 10 (2004-2005).

"To me, the Space Shuttle is an amazing flying machine. It launches vertically as a rocket, turns into an extremely capable orbital platform for many purposes, and then becomes an airplane after re-entry into the atmosphere for landing on a conventional runway. Moreover, it is a reusable vehicle, which was a first in the US space program.

"The Space Shuttle Program presented me the opportunity to become a NASA astronaut and to fly in space. I never forgot my boyhood dream and years later applied after watching the first launch of Columbia. In addition to being a superb research and operations platform, the Space Shuttle also served as a bridge to other nations. Never before had foreign nationals flown aboard US spacecraft. On shuttle, the US had flown representatives from nations all around the world. Space is an ideal neutral ground for cooperation and the development of better understanding and relationships between nations.

"Without the Space Shuttle as an extravehicular activity test bed, we would not have been nearly as successful as we have been so far in assembling the ISS. The Space Shuttle again proved its flexibility and capability for ISS construction missions.

"Upon our landing (STS-92), I realized that my shuttle days were behind me. I was about to begin training for ISS. But on that afternoon, as we walked around and under Discovery, I savored the moment and felt a mixture of awe, satisfaction, and a little sadness. Shuttle, to me, represents a triumph and remains to this day a technological marvel. We learned so much from the program, not only in the advancement of science and international relations, but also from what works and what doesn't on a reusable vehicle. The lessons learned from shuttle will make future US spacecraft more reliable, safer, and cost effective.

"I love the Space Shuttle. I am proud and honored to be a part of its history and legacy."

on the underbelly of the shuttle. When NASA discovered two gap fillers sticking out of the tiles on the shuttle's belly on the first mission, flight controllers and the astronauts came up with a plan to remove the gap fillers—an unprecedented and unplanned spacewalk that they believed would decrease excessive temperatures on re-entry. The plan required Astronaut Stephen Robinson to ride the arm underneath the shuttle and pull out the fillers. In 24 years of shuttle operations, this had never been attempted, but the fillers were easily removed. STS-114 showed that improvements in the External Tank insulation foam were insufficient to prevent dangerous losses during ascent. Another year passed before STS-121 (2006), the second Return to Flight mission, flew after more improvements were made to the foam applications.

Final Flights

Educator Astronaut

Excitement began to build at NASA and across the nation as the date for Barbara Morgan's flight, STS-118 (2007), grew closer. Morgan had been selected as the backup for Christa McAuliffe, NASA's first Teacher in Space in 1985. After the Challenger accident, Morgan became the Teacher in Space Designee and returned to teaching in Idaho. She came back to Houston in 1998 when she was selected as an astronaut candidate. More than 20 years after being selected as the backup Teacher in Space, Morgan fulfilled that dream by serving as the first educator mission specialist. NASA Administrator Michael Griffin praised Morgan "for her interest, her toughness, her resiliency, her persistence in wanting to fly in space and eventually doing so." Adults recalled the Challenger accident and watched this flight with interest. STS-118 drew attention from students, from across America and around the globe, who were curious about the flight.

Return to Hubble

In May 2009, the crew of STS-125 made the final repairs and upgrades to the Hubble Space Telescope to ensure quality science for several more years. This flight was a long time coming due to the Columbia accident, after which NASA was unsure whether it could continue to fly to destinations with no safe haven such as the ISS.

With the ISS, if problems arose, especially with the thermal protection, the astronauts could stay in the space station until either another shuttle or the Russian Soyuz could bring them home. The Hubble orbited beyond the ability for the shuttle to get to the ISS if the shuttle was critically damaged. Thus, for several years, the agency had vetoed any possibility that NASA could return to the telescope.

At that point, the Hubble had been functioning for 12 years in the very hostile environment of space. Not only did its instruments eventually wear out, but the telescope needed important upgrades to expand its capabilities. After the Return to Flight of STS-114 and STS-121, NASA reevaluated the ability to safety return astronauts after launch. The method to ensure safe return in the event of shuttle damage was to have a backup vehicle in place. So in 2009, Atlantis launched to repair the telescope, with Endeavour as the backup.

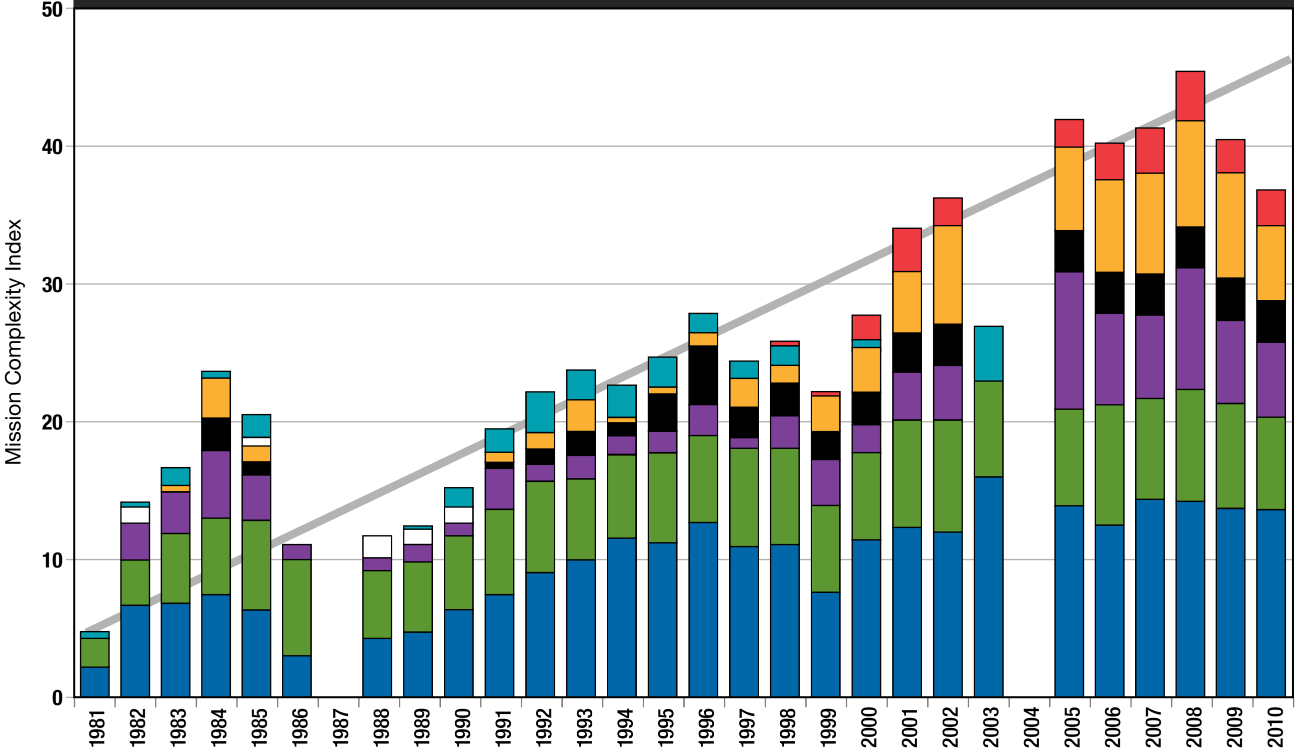
Improvements on the International Space Station Continued

Discovery flight STS-128, in 2009, provided capability for six crew members for ISS. This was a major milestone for ISS as the station had been operating with two to three crew members since its first occupation in 1999. The shuttle launched most of the ISS, including Canadian, European, and Japanese elements, to the orbiting laboratory. In 2010, Endeavour provided the final large components: European Space Agency Node 3 with additional hygiene compartment; and Cupola with a robotic work station to assist in assembly/maintenance of the ISS and a window for Earth observations.

As of December 2010, NASA manifested two more shuttle flights: STS-133 and STS-134.

This Commemorative Patch celebrates the 30-year life and work of the Space Shuttle Program. Selected from over 100 designs, this winning patch by Mr. Blake Dumesnil features the historic icon set within a jewel-shape frame. It celebrates the shuttle's exploration within low-Earth orbit, and our desire to explore beyond. Especially poignant are the seven stars on each side of the shuttle, representing the 14 lives lost—seven on Columbia, seven on Challenger—in pursuit of their dream, and this nation's dream of further exploration and discovery. The five larger stars represent the shuttles that made up the fleet—each shuttle a star in its own right.

Changes in Mission Complexity Over Nearly 3 Decades



Components of Mission Complexity

- *Length of flight as mission days. Early flights lasted less than 1 week, but, as confidence grew, some flights lasted 14 to 15 days.*
- *Crew size started at two—a commander and pilot—and grew to routine flights with six crew members. During the Shuttle-Mir and International Space Station (ISS) Programs, the shuttle took crew members to the station and returned crew members, for a total of seven crew members.*
- *Deploys occurred throughout the program. During the first 10 years, these were primarily satellites with sometimes more than one per flight. Some satellites, such as Hubble Space Telescope, were returned to the payload bay for repair. With construction of the ISS, several major elements were deployed.*
- *Rendezvous included every time the shuttle connected to an orbiting craft from satellites, to Hubble, Mir, and ISS. Some flights had several rendezvous.*
- *Extravehicular activity (EVA) is determined as EVA crew days. Many flights had no EVAs, while others had one every day with two crew members.*
- *Secret Department of Defense missions were very complex.*
- *Spacelabs were missions with a scientific lab in the payload bay. Besides the complexity of launch and landing, these flights included many scientific studies.*
- *Construction of the ISS by shuttle crew members.*

Over the 30 years of the Space Shuttle Program, missions became more complex with increased understanding of the use of this vehicle, thereby producing increased capabilities. This diagram illustrates the increasing complexity as well as the downtime between the major accidents—Challenger and Columbia.

The Accidents: A Nation's Tragedy, NASA's Challenge

Randy Stone
Jennifer Ross-Nazzal

The Crew
Michael Chandler
Philip Stepaniak

Witness Accounts—Key to Understanding Columbia Breakup
Paul Hill

Who heard the whispers that were coming from the shuttle's Solid Rocket Boosters (SRBs) on a cold January morning in 1986? Who thought the mighty Space Shuttle, designed to withstand the thermal extremes of space, would be negatively affected by launching at near-freezing temperatures? Very few understood the danger, and most of the smart people working in the program missed the obvious signs. Through 1985 and January 1986, the dedicated and talented people at the NASA Human Spaceflight Centers focused on readying the Challenger and her crew to fly a complex mission. Seventy-three seconds after SRB ignition, hot gases leaking from a joint on one of the SRBs impinged on the External Tank (ET), causing a structural failure that resulted in the loss of the vehicle and crew.

Most Americans are unaware of the profound and devastating impact the accident had on the close-knit NASA team. The loss of Challenger and her crew devastated NASA, particularly at Johnson Space Center (JSC) and Marshall Space Flight Center (MSFC) as well as the processing crews at Kennedy Space Center (KSC) and the landing and recovery crew at Dryden Flight Research Center. Three NASA teams were primarily responsible for shuttle safety—JSC for on-orbit operation and crew member issues; MSFC for launch propulsion; and KSC for shuttle processing and launch. Each center played its part in the two failures. What happened to the "Failure is not an option" creed, they asked. The engineering and operations teams had spent months preparing for this mission. They identified many failure scenarios and trained relentlessly to overcome them. The ascent flight control team was experienced with outstanding leadership and had practiced for every contingency. But on that cold morning in January, all they could do was watch in disbelief as the vehicle and crew were lost high above the Atlantic Ocean. Nothing could have saved the Challenger and her crew once the chain of events started to unfold. On that day, everything fell to pieces.

Seventeen years later, in 2003, NASA lost a second shuttle and crew—Space Transportation System (STS)-107. The events that led up to the loss of Columbia were eerily similar to those surrounding Challenger. As with Challenger, the vehicle talked to the program but no one understood. Loss of foam from the ET had been a persistent problem in varying degrees for the entire program. When it occurred on STS-107, many doubted that a lightweight piece of foam could damage the resilient shuttle. It made no sense, but that is what happened. Dedicated people missed the obvious. In the end, foam damaged the wing to such an extent that the crew and vehicle could not safely reenter the Earth's atmosphere. Just as with Challenger, there was no opportunity to heroically "save the day" as the data from the vehicle disappeared and it became clear that friends and colleagues were lost. Disbelief was the first reaction, and then a pall of grief and devastation descended on the NASA family of operators, engineers, and managers.

The Challenger Accident

Pressure to Fly

As the final flight of Challenger approached, the Space Shuttle Program and the operations community at JSC, MSFC, and KSC faced many pressures that made each sensitive to maintaining a very ambitious launch schedule. By 1986, the schedule and changes in the manifest due to commercial and Department of Defense launch requirements began to stress NASA's ability to plan, design, and execute shuttle missions. NASA had won support for the program in the 1970s by emphasizing the cost-effectiveness and economic value of the system. By December 1983, 2 years after the maiden flight of Columbia, NASA had flown only nine missions. To make spaceflight more routine and therefore more economical, the agency had to accelerate the number of missions it flew each year. To reach this goal, NASA announced an ambitious rate of 24 flights by 1990.

NASA flew five missions in 1984 and a record nine missions the following year. By 1985, strains in the system were evident. Planning, training, launching, and flying nine flights stressed the agency's resources and workforce, as did the constant change in the flight manifest. Crews scheduled to fly in 1986 would have seen a dramatic decrease in their number of training hours or the agency would have had to slow down its pace because NASA simply lacked the staff and facilities to safely fly an accelerated number of missions.

By the end of 1985, pressure mounted on the space agency as they prepared to launch more than one flight a month the next year. A record four launch scrubs and two launch delays of STS-61C, which finally launched in January 1986, exacerbated tensions. To ensure that no more delays would threaten the 1986 flight rate or schedule, NASA cut the flight 1 day short to make sure Columbia could be processed in time for the scheduled ASTRO-1 science mission in March. Weather conditions prohibited landing that day and the next, causing a slip in the processing schedule. NASA had to avoid any additional delays to meet its goal of 15 flights that year.

The agency needed to hold to the schedule to complete at least three flights that could not be delayed. Two flights had to be launched in May 1986: the Ulysses and the Galileo flights, which were to launch within 6 days of each other. If the back-to-back flights missed their launch window, the payloads could not be launched until July 1987. The delay of STS-61C and Challenger's final liftoff in January threatened the scheduled launch plans of these two flights in particular. The Challenger needed to launch and deploy a second Tracking and Data Relay Satellite, which provided continuous global coverage of Earth-orbiting satellites at various altitudes. The shuttle would then return promptly to be reconfigured to hold the liquid-fueled Centaur rocket in its payload bay. The ASTRO-1 flight had to be launched in March or April to observe Halley's Comet from the shuttle.

On January 28, 1986, NASA launched Challenger, but the mission was never realized. Hot gases from the right-hand Solid Rocket Booster motor had penetrated the thermal barrier and blown by the O-ring seals on the booster field joint. The joints were designed to join the motor segments together and contain the immense heat and pressure of the motor combustion. As the Challenger ascended, the leak became an intense jet of flame that penetrated the ET, resulting in structural failure of the vehicle and loss of the crew.

Prior to this tragic flight, there had been many O-ring problems witnessed as early as November 1981 on the second flight of Columbia. The hot gases had significantly eroded the STS-2 booster right field joint—deeper than on any other mission until the accident—but knowledge was not widespread in mission management. STS-6 (1983) boosters did not have erosion of the O-rings, but heat had impacted them. In addition, holes were blown through the putty in both nozzle joints. NASA reclassified the new field joints Criticality 1, noting that the failure of a joint could result in "loss of life or vehicle if the component fails." Even with this new categorization, the topic of O-ring erosion was not discussed in any Flight Readiness Reviews until March 1984, in preparation for the 11th flight of the program. Time and again these anomalies popped up in other missions flown in 1984 and 1985, with the issue eventually classified as an "acceptable risk" but not desirable. The SRB project manager regularly waived these anomalies, citing them as "repeats of conditions that had already been accepted for flight" or "within their experience base," explained Arnold Aldrich, program manager for the Space Shuttle Program.

Senior leadership like Judson Lovingood believed that engineers "had thoroughly worked that joint problem." As explained by former Chief Engineer Keith Coates, "We knew the gap was opening. We knew the O-rings were getting burned. But there'd been some engineering rationale that said, 'It won't be a failure of the joint.' And I thought justifiably so at the time I was there. And I think that if it hadn't been for the cold weather, which was a whole new environment, then it probably would have continued. We didn't like it, but it wouldn't fail."

Each time the shuttle launched successfully, the accomplishment masked the recurring field joint problems. Engineers and managers were fooled into complacency because they were told it was not a flight safety issue. They concluded that it was safe to fly again because the previous missions had flown successfully. In short, they reached the same conclusion each time—it was safe to fly another mission. "The argument that the same risk was flown before without failure is often accepted as an argument for the safety of accepting it again. Because of this, obvious weaknesses are accepted again and again, sometimes without a sufficiently serious attempt to remedy them or to delay a flight because of their continued presence," wrote Richard Feynman, Nobel Prize winner and member of the presidential-appointed Rogers Commission charged to investigate the Challenger accident.

Operational Syndrome

The Space Shuttle Program was also "caught up in a syndrome that the shuttle was operational," according to J.R. Thompson, former project manager for the Space Shuttle Main Engines. The Orbital Flight Test Program, which ended in 1982, marked the beginning of routine operations of the shuttle, even though there were still problems with the booster joint. Nonetheless, MSFC and Morton Thiokol, the company responsible for the SRBs, seemed confident with the design.

Although the design of the boosters had proven to be a major complication for MSFC and Morton Thiokol, the engineering debate occurring behind closed doors was not visible to the entire Space Shuttle Program preparing for the launch of STS-51L. There had been serious erosions of the booster joint seals on STS-51B (1985) and STS-51C (1985), but MSFC had not pointed out any problems with the boosters right before the Challenger launch. Furthermore, MSFC failed to bring the design issue, failures, or concern with launching in cold temperatures to the attention of senior management. Instead, discussions of the booster engines were resolved at the local level, even on the eve of the Challenger launch. "I was totally unaware that these meetings and discussions had even occurred until they were brought to light several weeks following the Challenger accident in a Rogers Commission hearing at KSC," Arnold Aldrich recalled. He also recalled that he had sat shoulder to shoulder with senior management "in the firing room for approximately 5 hours leading up to the launch of Challenger and no aspect of these deliberations was ever discussed or mentioned."

Even the flight control team "didn't know about what was lurking on the booster side," according to Ascent Flight Director Jay Greene. Astronaut Richard Covey, then working as capsule communicator, explained that the team "just flat didn't have that insight" into the booster trouble. Launch proceeded and, in fewer than 2 minutes, the joint failed, resulting in the loss of seven lives and the Challenger.

Looking back over the decision, it is difficult to understand why NASA launched the Challenger that morning. The history of troublesome technical issues with the O-rings and joint are easily documented. In hindsight, the trends appear obvious, but the data had not been compiled. Wiley Bunn noted, "It was a matter of assembling that data and looking at it [in] the proper fashion. Had we done that, the data just jumps off the page at you."

Devastated

The accident devastated NASA employees and contractors. To this day Aldrich asks himself regularly, "What could we have done to prevent what happened?" Holding a mission management team meeting the morning of launch might have brought up the Thiokol/MSFC teleconference the previous evening. "I wish I had made such a meeting happen," he lamented. The flight control team felt some responsibility for the accident, remembered STS-51L Lead Flight Director Randy Stone. Controllers "truly believed they could handle absolutely any problem that this vehicle could throw at us." The accident, however, "completely shattered the belief that the flight control team can always save the day. We have never fully recovered from that." Alabama and Florida employees similarly felt guilty about the loss of the crew and shuttle, viewing it as a personal failure. John Conway of KSC pointed out that "a lot of the fun went out of the business with that accident."

Rebounded

Over time, the wounds began to heal and morale improved as employees reevaluated the engineering design and process decisions of the program. The KSC personnel dedicated themselves to the recovery of Challenger and returning as much of the vehicle back to the launch site as possible. NASA spent the next 2½ years fixing the hardware and improving processes, and made over 200 changes to the shuttle during this downtime. Working on design changes to improve the vehicle contributed to the healing process for people at the centers.

The Crew

Following the breakup of Challenger (STS-51L) during launch over the Atlantic Ocean on January 28, 1986, personnel in the Department of Defense STS Contingency Support Office activated the rescue and recovery assets. This included the local military search and rescue helicopters from the Eastern Space and Missile Center at Patrick Air Force Base and the US Coast Guard. The crew compartment was eventually located on March 8, and NASA officially announced that the recovery operations were completed on April 21. The recovered remains of the crew were taken to Cape Canaveral Air Force Station and then transported, with military honors, to the Armed Forces Institute of Pathology where they were identified. Burial arrangements were coordinated with the families by the Port Mortuary at Dover Air Force Base, Delaware. Internal NASA reports on the mechanism of injuries sustained by the crew contributed to upgrades in training and crew equipment that supported scenarios of bailout, egress, and escape for Return to Flight.

Following the breakup of Columbia (STS-107) during re-entry over Texas and Louisiana on February 1, 2003, personnel from the NASA Mishap Investigation Team were dispatched to various disaster field offices for crew recovery efforts. The Lufkin, Texas, office served as the primary area for all operations, including staging assets and deploying field teams for search, recovery, and security. Many organizations had operational experience with disaster recovery, including branches of the federal, state, and local governments together with many local citizen volunteers. Remains of all seven crew members were found within a 40- by 3-km (25- by 2-mile) corridor in East Texas. The formal search for crew members was terminated on February 13, 2003. Astronauts, military, and local police personnel transported the crew, with honors, to Barksdale Air Force Base, Louisiana, for preliminary identification and preparation for transport. The crew was then relocated, with military honor guard and protocol, to the Armed Forces Institute of Pathology medical examiner for forensic analysis. Burial preparation and arrangements were coordinated with the families by the Port Mortuary at Dover Air Force Base, Delaware. Additional details on the mechanism of injuries sustained by the crew and lessons learned for enhanced crew survival are found in the Columbia Crew Survival Investigation Report NASA/SP-2008-565.

Reconstruction of the Columbia from parts found in East Texas. From this layout, NASA was able to determine that a large hole occurred in the leading edge of the wing and identify the burn patterns that eventually led to the destruction of the shuttle.

Making the boosters and main engines more robust became extremely important for engineers at MSFC and Thiokol. The engineers and astronauts at JSC threw themselves into developing an escape system and protective launch and re-entry suits and improving the flight preparation process. All of the improvements then had to be incorporated into the KSC vehicle processing efforts.

All NASA centers concentrated on how they could make the system better and safer. For civil servants and contractors, the recovery from the accident was not just business. It was personal. Working toward Return to Flight was almost a religious experience that restored the shattered confidence of the workforce.

NASA instituted a robust flight preparation process for the Return to Flight mission, which focused on safety and included a series of revised procedures and processes at the centers. At KSC, for instance, new policies were instituted for 24-hour operations to avoid the fatigue and excessive overtime noted by the Rogers Commission. NASA implemented the NASA Safety Reporting System. Safety, reliability, maintainability, and quality assurance staff increased considerably.

JSC's Mission Operations Director Eugene Kranz noted that Mission Operations examined "every job we do" during the stand down. They microscopically analyzed their processes and scrutinized those decisions. They learned that the flight readiness process prior to the Challenger accident frequently lacked detailed documentation and was often driven more by personality than by requirements. The process was never identical or exact but unique. Changes were made to institute a more rigorous program, which was well-documented and could be instituted for every flight.

Astronaut Robert Crippen became the deputy director of the National Space Transportation System Operations. He helped to determine and establish new processes for running and operating the flight readiness review and mission management team (headed by Crippen), as well as the launch commit criteria procedures, including temperature standards. He instituted changes to ensure the agency maintained clear lines of responsibility and authority for the new launch decision process he oversaw.

Retired Astronaut Richard Truly also participated in the decision-making processes for the Return to Flight effort. Truly, then working as associate administrator for spaceflight, invited the STS-26 (1988) commander Frederick Hauck to attend any management meetings in relation to the preparation for flight. By attending those meetings, Hauck had "confidence in the fixes that had been made" and "confidence in the team of people that had made those decisions," he remarked.

Return to Flight After Challenger Accident

As the launch date for the flight approached, excitement began to build at the centers. Crowds surrounded the shuttle when it emerged from the Vehicle Assembly Building on July 4, 1988. The Star-Spangled Banner played as the vehicle crawled to the pad, while crew members and other workers from KSC and Headquarters spoke about the milestone. David Hilmers, a member of the crew, tied the milestone to the patriotism of the day. "What more fitting present could we make to our country on the day of its birth than this? America, the dream is still alive," he exclaimed. The Return to Flight effort was a symbol of America's pride and served as a healing moment not only for the agency but also for the country. Tip Talone of KSC likened the event to a "rebirth."

Indeed, President Ronald Reagan, who visited JSC in September 1988, told workers, "When we launch Discovery, even more than the thrust of great engines, it will be the courage of our heroes and the hopes and dreams of every American that will lift the shuttle into the heavens."

Without any delays, the launch of STS-26 went off just a few days after the president's speech, returning Americans to space. The pride in America's accomplishment could be seen across the country. In Florida, the Launch Control Center raised a large American flag at launch time and lowered it when the mission concluded. In California, at Dryden Flight Research Center, the astronauts exited the vehicle carrying an American flag—a patriotic symbol of their flight. Cheering crowds waving American flags greeted the astronauts at the crew return event at Ellington Field in Houston, Texas. The launch restored confidence in the program and the vehicle. Pride and excitement could be found across the centers and at contract facilities around the country.

The Columbia Accident

NASA flew 87 successful missions following the Return to Flight effort. As the 1990s unfolded, the post-Challenger political and economic environment changed dramatically.

Environment Changes

As the Soviet Union disintegrated and the Soviet-US conflict that began in the mid 1940s came to an end, NASA (established in 1958) struggled to find its place in a post-Cold War world. Around the same time, the federal deficit swelled to a height that raised concern among economists and citizens. To cut the deficit, Congress and the White House decreased domestic spending, and NASA was not spared from these cuts. Rather than eliminate programs within the agency, NASA chose to become more cost-effective. A leaner, more efficient agency emerged with the appointment of NASA Administrator Daniel Goldin in 1992, whose slogan was "faster, better, cheaper."

The shuttle, the most expensive line item in NASA's budget, underwent significant budget reductions throughout the 1990s. Between 1993 and 2003, the program suffered from a 40% decrease in its purchasing capability (with inflation included in the figures), and its workforce correspondingly decreased. To secure additional cost savings, NASA awarded the Space Flight Operations Contract to United Space Alliance in 1995 to consolidate numerous shuttle contracts into one.

Pressure Leading up to the Accident

As these changes took effect, NASA began working on Phase One of the Space Station Program, called Shuttle-Mir. Phase Two, assembly of the ISS, began in 1998. The shuttle was critical to the building of the outpost and was the only vehicle that could launch the modules built by Europe, Japan, and the United States. By tying the two programs so closely together, a reliable, regular launch schedule was necessary to maintain crew rotations, so the ISS management began to dictate NASA's launch schedule. The program had to meet deadlines outlined in bilateral agreements signed in 1998. Even though the shuttle was not an operational vehicle, the agency worked its schedules as if the space truck could be launched on demand, and there was increasing pressure to meet a February 2004 launch date for Node 2. When launch dates slipped, these delays affected flight schedules.

On top of budget constraints, personnel reductions, and schedule pressure, the program suffered from a lack of vision on replacing the shuttle. There was uncertainty about the program's lifetime. Would the shuttle fly until 2030 or be replaced with new technology? Ronald Dittemore, manager of the Space Shuttle Program from 1999 to 2003, explained, "We had no direction." NASA would "start and stop" funding initiatives, like the shuttle upgrades, and then reverse directions. "Our reputation was kind of sullied there, because we never finished what we started out to do."

This was the environment in which NASA found itself in 2003. On the morning of January 16, Columbia launched from KSC for a lengthy research flight. On February 1, just minutes from a successful landing in Florida, the Orbiter broke up over East Texas and Louisiana. Debris littered its final path. The crew and Columbia were lost.

Recovering Columbia and Her Crew

Recovery of the Orbiter and its crew began at 9:16 a.m., when the ship failed to arrive in Florida. The rapid response and mishap investigation teams from within the agency headed to Barksdale Air Force Base in Shreveport, Louisiana. Hundreds of NASA employees and contractors reported to their centers to determine how they could help bring the crew and Columbia home. Local emergency service personnel were the first responders at the various scenes. By that evening, representatives from local, state, and federal agencies were in place and ready to assist NASA.

The recovery effort was unique, quite unlike emergency responses following other national disasters. David Whittle, head of the mishap investigation team, recalled that there were "130 state, federal, and local agencies" represented in the effort; but as he explained, we "never, ever had a tiff. Matter of fact, the Congressional Committee on Homeland Security sent some people down to interview us to figure out how we did that, because that was not the experience of 9/11." The priority of the effort was the recovery of the vehicle and the astronauts, and all of these agencies came together to see to it that NASA achieved this goal.

While in East Texas and Louisiana, the space agency came to understand how important the Space Shuttle Program was to the area and America. Volunteers traveled from all over the United States to help in the search. People living in the area opened their arms to the thousands of NASA employees who were grieving. They offered their condolences, while some local restaurants provided free food to workers. Ed Mango, KSC launch manager and director of the recovery for approximately 3 months, learned "that people love the space program and want to support it in any way they can." His replacement, Jeff Angermeier, added, "When you work in the program all the time, you care deeply about it, but it isn't glamorous to you. Out away from the space centers, NASA is a big deal."

As volunteers collected debris, it was shipped to KSC where the vehicle was reconstructed. For the center's employees, the fact that Columbia would not be coming back whole was hard to swallow. "I never thought I'd see Columbia going home in a box," said Michael Leinbach of KSC. Many others felt the same way. Working with the debris and reconstructing the ship did help, however, to heal the wounds.

As with the loss of Challenger, NASA employees continue to be haunted by questions of "what if." "I'll bet you a day hardly goes by that we don't think about the crew of Columbia and if there was something we might have been able to do to prevent" the accident, admitted Dittemore. Wayne Hale, shuttle program manager for launch integration at KSC, called the decisions made by the mission management team his "biggest" regret. "We had the opportunity to really save the day, we really did, and we just didn't do it, just were blind to it."

Causes

Foam had detached from the ET since the beginning of the program, even though design requirements specifically prohibited shedding from the tank. Columbia sustained major damage on its maiden flight, eventually requiring the replacement of 300 tiles. As early as 1983, six other missions witnessed the left tank bipod ramp foam loss that eventually led to the loss of the STS-107 crew and vehicle. For more than 20 years, NASA had witnessed foam shedding and debris hits. Just one flight after STS-26 (the Return to Flight after Challenger), Atlantis was severely damaged by debris that resulted in the loss of one tile.

Two flights prior to the loss of Columbia and her crew, STS-112 (2002) experienced bipod ramp loss, which hit both the booster and tank attachment ring. The result was a 10.2-cm- (4-in.)-wide, 7.6-cm- (3 in.)-deep tear in the insulation. The program assigned the ET Project with the task of determining the cause and a solution. But the project failed to understand the severity of foam loss and its impact on the Orbiter, so the due date for the assignment slipped to after the return of STS-107.

Foam loss became an expected anomaly and was not viewed as risky. Instead, the issue became one the program had regularly experienced, and one that engineers believed they understood. It was never seen as a safety issue. The fact that previous missions, which had experienced severe debris hits, had successfully landed only served to reinforce confidence within the program concerning the robustness of the vehicle.

After several months of investigation and speculation about the cause of the accident, investigators determined that a breach in the tile on the left wing led to the loss of the vehicle. Insulation foam from the ET's left bipod ramp, which damaged the wing's reinforced carbon-carbon panel, created the gap. During re-entry, superheated air entered the breach. Temperatures were so extreme that the aluminum in the left wing began to melt, which eventually destroyed it and led to a loss of vehicle control. Columbia experienced aerodynamic stress that the damaged airframe could not withstand, and the vehicle eventually broke up over East Texas and Louisiana.

Senior program management had been alerted to the STS-107 debris strike on the second day of the flight but had failed to understand the risks to the crew or the vehicle. No one thought that foam could create a hole in the leading edge of the wing. Strikes had been within their experience base. In short, management made assumptions based on previous successes, which blinded them to serious problems. "Even in flight when we saw (the foam) hit the wing, it was a failure of imagination that it could cause the damage that it undoubtedly caused," said John Shannon, who later became manager of the Space Shuttle Program. Testing later proved that foam could create cracks in the reinforced carbon-carbon and holes of 40.6 by 43.2 cm (16 by 17 in.).

Aside from the physical cause of the accident, flaws within the decision-making process also significantly impacted the outcome of the STS-107 flight. A lack of effective and clear communication stemmed from organizational barriers and hierarchies within the program. These obstacles made it difficult for engineers with real concerns about vehicle damage to share their views with management. Investigators found that management accepted opinions that mirrored their own and rejected dissent.

Changes

The second Return to Flight effort focused on reducing the risk of failures documented by the Columbia Accident Investigation Board. The focus was on improving risk assessments, making system improvements, and implementing cultural changes in workforce interaction. In the case of improved risk assessments, Hale explained, "We [had] reestablished the old NASA culture of doing it right, relying more on test and less on talk, requiring exacting analysis, doing our homework." As an example, he cited the ET-120, which was to have been the Return to Flight tank for STS-114 and was to be sent to KSC late in 2004. But, he admitted, "We knew there [were] insufficient data to determine the tank was safe to fly." After the Debris Verification Review, management learned that some minor issues still had to be handled before these tanks would be approved for flight.

During the flight hiatus, NASA upgraded many of the shuttle's systems and began the process of changing its culture. Engineers redesigned the boosters' bolt catcher and modified the tank in an attempt to eliminate foam loss from the bipod ramp. Engineers developed an Orbiter Boom Sensor System to inspect the tiles in space, and NASA added a Wing Leading Edge Impact Detection System. NASA also installed a camera on the ET umbilical well to document separation and any foam loss.

Finally, NASA focused on improving communication and listening to dissenting opinions. To help the agency implement plans to open dialogue between managers and engineers, from the bottom up, NASA hired the global safety consulting firm Behavioral Science Technology, headquartered in Ojai, California.

Return to Flight After Columbia Accident

When the crew of STS-114 finally launched in the summer of 2005, it was a proud moment for the agency and the country. President George W. Bush, who watched the launch from the Oval Office's dining room, said, "Our space program is a source of great national pride, and this flight is an essential step toward our goal of continuing to lead the world in space science, human spaceflight, and space exploration." First Lady Laura Bush and Florida

Witness Accounts—Key to Understanding Columbia Breakup

The early sightings assessment team—formed 2 days after the Space Shuttle Columbia accident on February 1, 2003—had two primary goals:

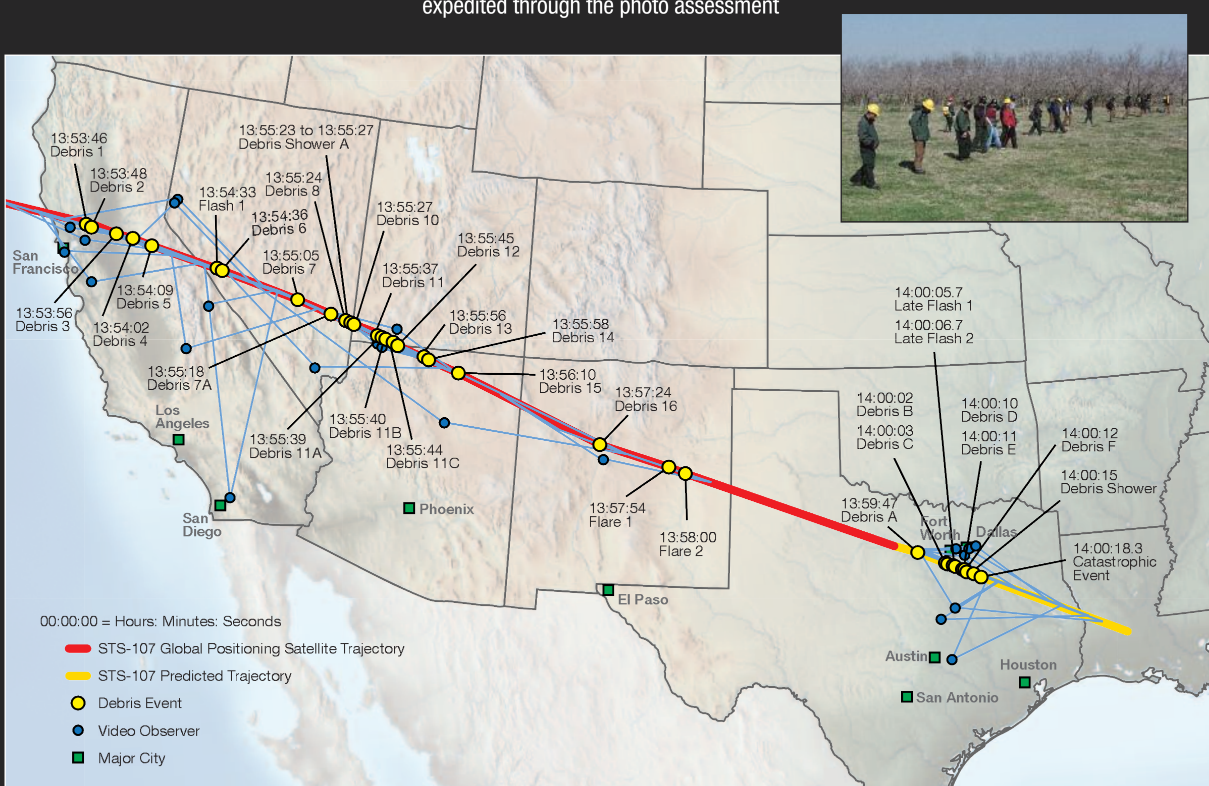
- Sift through and characterize the witness reports during re-entry.
- Obtain and analyze all available data to better characterize the pre-breakup debris and ground impact areas. This included providing the NASA interface to the Department of Defense (DoD) through the DoD Columbia Investigation Support Team.

Of the 17,400 public phone, e-mail, and mail reports received from February 1 through April 4, more than 2,900 were witness reports during re-entry, prior to the vehicle breakup. Over 700 of those included photographs or video. Public imagery provided a near-complete record of Columbia's re-entry and video showed debris being shed from the shuttle. Final analysis revealed 20 distinct debris shedding events and three flashes/flares during re-entry. Analysis of these videos and corresponding air traffic control radar produced 20 pre-breakup search areas, ranging in size from 2.6 to 4,403 square km (1 to 1,700 square miles) extending from the California-Nevada border through West Texas.

To facilitate the trajectory analysis, witness reports were prioritized to process re-entry imagery with precise observer location and time calibration first. The process was to time-synchronize all video, determine the exact debris shedding time, measure relative motion, determine ballistic properties of the debris, and perform trajectory analysis to predict the potential ground impact areas or footprints. Key videos were hand carried, expedited through the photo assessment team, and put into ballistic and trajectory analysis as quickly as possible. The Aerospace Corporation independently performed the ballistic and trajectory analysis for process verification.

The public reports, which at first seemed like random information, were in fact a diamond in the rough. This information became invaluable for the search teams on the ground. The associated trajectory analyses also significantly advanced the study of spacecraft breakup in the atmosphere and the subsequent ground impact footprints.

After the Columbia broke apart over East Texas, volunteers from federal agencies, as well as members of the East Texas First Responders, participated in walking the debris fields, forest, and wetlands to find as many parts as possible. This facilitated in determining the cause of the accident.



Governor Jeb Bush were among the guests at KSC. Indeed, the Return to Flight mission had been a source of pride for the nation since its announcement. For instance, troops in Iraq sent a "Go Discovery" banner that was hung at KSC. At the landing at Dryden Flight Research Center, the astronauts exited the vehicle carrying an American flag. When the crew returned to Ellington Field, a huge crowd greeted the crew, waving flags as a symbol of the nation's accomplishment. Houston Mayor Bill White declared August 10, 2005, "Discovery STS-114 Day." Standing on a stage, backed by a giant American flag, the crew thanked everyone for their support.

Impact of the Accidents on NASA

The two shuttle tragedies shook NASA's confidence and have significantly impacted the agency in the long term. At the time of both accidents, the Space Shuttle Program office, astronauts, and flight and launch control teams were incredibly capable and dedicated to flying safely. Yet, from the vantage point of hindsight, these teams overlooked the obvious, allowing two tragedies to unfold on the public stage.

Many of the people directly involved in those flights remain haunted by the realization that their decisions resulted in the loss of human lives. NASA was responsible for the safety of the crew and vehicles, and they failed. The flight control teams who worked toward perfection with the motto of "Failure is not an option" felt responsible and hesitant to make hard decisions. Likewise, the engineering communities at JSC and MSFC, and the KSC team that prepared the vehicles, shared feelings of guilt and shaken confidence.

The fact that these tragedies occurred in front of millions of spectators and elected officials made the aftermath even more difficult for the NASA team. The American public and the elected officials expected perfection. When it was not delivered, the outcry of "How could this have happened?" made the headlines of every newspaper and television newscast and became a topic of concern in Congress. The second accident was harder on the agency because the question was now: "How could this have happened *again*?"

Because of the accidents, the agency had a more difficult challenge in convincing Congress of NASA's ability to safely fly people in space. That credibility gap made each NASA administrator's job more difficult and raised doubts in Congress about whether human spaceflight was worth the risk and money. To this day, doubts have not been fully erased on the value of human spaceflight, and the questions of safety and cost are at the forefront of every yearly budget cycle.

In contrast with American politicians, the team of astronauts, engineers, and support personnel that makes human spaceflight happen believes that space exploration must continue. "Yes, there is risk in space travel, but I think that it's safe enough that I'm willing to take the risk," STS-114 (2005) Commander Eileen Collins admitted before her final flight. "I think it's much, much safer than what our ancestors did in traveling across the Atlantic Ocean in an old ship. Frankly, I think they were crazy doing that, but they wanted to do that, and we need to carry on the human exploration of the universe that we live in. I'm honored to be part of that and I'm proud to be part of it. I want to be able to hand on that belief or enthusiasm that I have to the younger generation because I want us to continue to explore."

Without this core belief, the individuals who picked up the pieces after both accidents could not have made it through those terrible times. All of the human spaceflight centers—KSC, MSFC, and JSC—suffered terribly from the loss of Challenger and Columbia. The personnel of all three centers recovered by rededicating themselves to understanding what caused the accidents and how accidents could be prevented in the future. Together, they found the problems and fixed them.

Did the agency change following these two accidents? The answer is absolutely. Following the Challenger accident, the teams looked at every aspect of the processes used to prepare for a shuttle mission. As a result, they went from the mentality that every flight was completely new with a custom solution to a mindset that included a documented production process that was repeatable, flight after flight. The flight readiness process evolved from a process of informally asking each element if all was flight ready to a well-documented set of processes that required specific questions be answered and documented for presentation to management at a formal face-to-face meeting. A rigorous process emerged across the engineering and the operations elements at the centers that made subsequent flights safer.

Yet in spite of all the formal processes put in place, Columbia was still lost. These procedures were not flawed, but the decision-making process was flawed with regard to assessing the loss of foam. Tommy Holloway, who served for several years as the Space Shuttle Program manager, observed that the decision to fly had been based on previous success and not on the analysis of the data.

Since 2003, NASA has gone to great lengths to improve the processes to determine risk and how the team handles difficult decisions. A major criticism of NASA following the Columbia accident was that managers did not always listen to minority and dissenting positions. NASA has since diligently worked toward transforming the culture of its employees to be inclusive of all opinions while working toward a solution.

In hindsight, NASA should not have made an “OK to fly” decision for the final missions of Challenger and Columbia. NASA depended on the requirements that went into the Launch Commit Criteria and Flight Rules to assure that the shuttle was safe to fly. Since neither flight had a “violation” of these requirements, the missions were allowed to proceed even though some people were uncomfortable with the conditions. As a result, NASA has emphasized that the culture should be “prove it is safe” as opposed to “prove it is unsafe” when a concern is raised. The process is better, and the culture is changing as a result of both of these accidents.

As a tribute to the human spirit, teams did not quit or give up after either accident but rather pressed on to Return to Flight each time with a better-prepared and more robust vehicle and team. Some individuals never fully recovered, and they drifted away from human spaceflight. The majority, however, stayed with a renewed vigor to find ways to make spaceflight safer. They still believe in the creed “Failure is not an option” and work diligently to meet the expectation of perfection by the American people and Congress.

NASA has learned from past mistakes and continues on with ventures in space exploration, recognizing that spaceflight is hard, complex, and—most importantly—will always have inherent risk. Accidents will happen, and the teams will have to dig deep into their inner strength to find a way to recover, improve the system, and continue the exploration of space for future generations.

On an Occasion of National Mourning

Howard Nemerov
Poet Laureate of the United States
1963-1964 and 1988-1990

It is admittedly difficult for a whole
Nation to mourn and be seen to do so, but
It can be done, the silvery platitudes
Were waiting in their silos for just such
An emergent occasion, cards of sympathy
From heads of state were long ago prepared
For launching and are bounced around the world
From satellites at near the speed of light,
The divine services are telecast
From the home towns, children are interviewed
And say politely, gravely, how sorry they are,
And in a week or so the thing is done,
The sea gives up its bits and pieces and
The investigating board pinpoints the cause
By inspecting bits and pieces, nothing of the sort
Can ever happen again, the prescribed course
Of tragedy is run through omen to amen
As in a play, the nation rises again
Reborn of grief and ready to seek the stars;
Remembering the shuttle, forgetting the loom.

National Security

Jeff DeTroye
James Armor
Sebastian Coglitore
James Grogan
Michael Hamel
David Hess
Gary Payton
Katherine Roberts
Everett Dolman

To fully understand the story of the development of the Space Shuttle, it is important to consider the national defense context in which it was conceived, developed, and initially deployed.

The Cold War between the United States and the Union of Soviet Socialist Republics (USSR), which had played such a large role in the initiation of the Apollo Program, was also an important factor in the decisions that formed and guided the Space Shuttle Program. The United States feared that losing the Cold War (1947-1991) to the USSR could result in Soviet mastery over the globe. Since there were few direct conflicts between the United States and the USSR, success in space was an indicator of which country was ahead—which side was winning. Having lost the tactical battles of first satellite and first human in orbit, the United States had recovered and spectacularly won the race to the moon. To counter the successful US man-on-the-moon effort, the USSR developed an impressive space station program. By the early 1980s, the USSR had launched a series of space stations into Earth orbit. The Soviets were in space to stay, and the United States could not be viewed as having abdicated leadership in space after the Apollo Program.

The need to clearly demonstrate the continued US leadership in space was an important factor in the formation of the Space Shuttle Program. While several other programs were considered, NASA ultimately directed their planning efforts to focus on a reusable, crewed booster that would provide frequent, low-cost access to low-Earth orbit. This booster would launch all US spacecraft, so there would have to be direct interaction between the open, civilian NASA culture and the Defense-related National Security Space (NSS) programs. Use of the civilian NASA Space Shuttle Program by the NSS programs was controversial, with divergent goals, and many thought it was a relationship made for political reasons only—not in the interest of national security. The relationship between these two very different cultures was often turbulent and each side had to change to accommodate the other. Yet it was ultimately successful, as seen in the flawless missions that followed.

National Security Space Programs

The Department of Defense uses space systems in support of air, land, and sea forces to deter and defend against hostile actions directed at the interests of the United States. The Intelligence community uses space systems to collect intelligence. These programs, as a group, are referred to as National Security Space (NSS). Despite having a single name, the NSS did not have a unified management structure with authority over all programs.

Since the beginning of the space era, these defense-related space missions had been giving the president, as well as defense and intelligence leadership in the United States, critical insights into the actions and intents of adversaries. In 1967, President Lyndon Johnson said, "I wouldn't want to be quoted on this—we've spent $35 or $40 billion on the space program. And if nothing else had come out of it except the knowledge that we gained from space photography, it would be worth 10 times what the whole program has cost. Because tonight we know how many missiles the enemy has and, it turned out, our guesses were way off. We were doing things we didn't need to do. We were building things we didn't need to build. We were harboring fears we didn't need to harbor." Due to these important contributions and others, the NSS programs had a significant amount of political support and funding. As a result, both the NSS program leadership and the NASA program leadership often held conflicting views of which program was more important and, therefore, whose position on a given issue ought to prevail.

These two characteristics of the NSS programs—lack of unified NSS program management and a competing view of priorities—would cause friction between NASA and the NSS programs management throughout the duration of the relationship.

1970-1981: Role of National Security Space Programs in Development of the Shuttle

The National Security Space (NSS) is often portrayed as having forced design requirements on NASA to gain NSS commitment to the Space Shuttle Program. In reality, NASA was interested in building the most capable (and largest) shuttle that Congress and the administration would approve. It is true that NSS leaders argued for a large payload bay and a delta wing to provide a 1,600-km (1,000-mile) cross range for landing. NASA, however, also wanted a large payload bay for space station modules as well as for spacecraft and high-energy stage combinations. NASA designers required the shuttle to be able to land at an abort site, one orbit after launch from the West Coast, which would also require a delta wing. Indeed, NASA cited the delta wing as an essential NASA requirement, even for launches from the East Coast. NASA was offered the chance to build a smaller shuttle when, in January 1972, President Richard Nixon approved the Space Transportation System (STS) for development. The NASA leadership decided to stick with the larger, delta wing design.

National Space Policy: The Shuttle as Sole Access to Space

The Space Shuttle Program was approved with the widely understood but unstated policy that when it became operational it would be used to launch all NSS payloads. The production of all other expendable launch vehicles, like the reliable Titan, would be abandoned. In 1981, shortly after the launch of STS-1, the National Space Transportation Policy signed by President Ronald Reagan formalized this position: "The STS will be the primary space launch system for both United States military and civil government missions. The transition to the shuttle should occur as expeditiously as practical. . . . Launch priority will be provided to national security missions, and such missions may use the shuttle as dedicated mission vehicles."

This mandated dependence on the shuttle worried NSS leaders, with some saying the plan was "seriously deficient, both operationally and economically." In January 1984, Secretary of Defense Caspar Weinberger directed the purchase of additional expendable boosters because "total reliance upon the STS for sole access to space in view of the technical and operational uncertainties, represents an unacceptable national security risk." This action, taken 2 years before the Challenger accident, ensured that expendable launch vehicles would be available for use by the NSS programs in the event of a shuttle accident. Furthermore, by 1982 the full costs of shuttle missions were becoming clearer and the actual per-flight cost of a shuttle mission had risen to over $280 million, with a Titan launch looking cheap in comparison at less than $180 million. With the skyrocketing costs of a shuttle launch, the existence of an expendable launch vehicles option for the NSS programs made the transition from the shuttle inevitable.

Military "Man in Space"

To this day, the US Air Force (USAF) uses flight crews for most of their airborne missions. Yet, there was much discussion within the service about the value of having a military human in space program. Through the 1960s, development of early reconnaissance satellites like Corona demonstrated that long-life electronics and complex systems on the spacecraft and on the ground could be relied on to accomplish the crucial task of reconnaissance. These systems used inexpensive systems on orbit and relatively small expendable launch vehicles, and they proved that human presence in space was not necessary for these missions.

During the early 1960s, NSS had two military man in space programs: first the "Dyna Soar" space plane, and then the Manned Orbiting Laboratory program. Both were cancelled, largely due to skepticism on the part of the Department of Defense (DoD) or NSS leadership that the programs' contributions were worth the expense as well as the unwanted attention that the presence of astronauts would bring to these highly classified missions.

Although 14 military astronauts were chosen for the Manned Orbiting Laboratory program, the sudden cancellation of this vast program in 1969 left them, as well as the nearly completed launch facility at Vandenberg Air Force Base, California, without a mission. With NASA's existing programs ramping down, NASA was reluctant to take the military astronauts into its Astronaut Corps. Eventually, only the seven youngest military astronauts transferred to NASA. The others returned to their military careers. These military astronauts did not fly until the 1980s, with the first being Robert Crippen as pilot on STS-1. The Manned Orbiting Laboratory pad at Vandenberg Air Force Base would lie dormant until the early 1980s when modifications were begun for use with the shuttle.

The Space Shuttle Program plans included a payload specialist selected for a particular mission by the payload sponsor or customer. Many NSS leadership were not enthusiastic about the concept; however, in 1979, a selection board made up of NSS leadership and a NASA representative chose the first cadre of 13 military officers from the USAF and US Navy. These officers were called manned spaceflight engineers. There was considerable friction with the NASA astronaut office over the military payload specialist program. Many of the ex-Manned Orbiting Laboratory astronauts who had been working at NASA and waiting for over a decade to fly in space were not enthusiastic about the NSS plans to fly their own officers as payload specialists. In the long run, NASA astronauts had little to be concerned about. When asked his opinion of the role of military payload specialists in upcoming shuttle missions, General Lew Allen, then chief of staff of the USAF, related a story about when he played a major role in the cancellation of the Manned Orbiting Laboratory Military Man in Space program. In 1984, another NSS senior wrote: "The major driver in the higher STS costs is the cost of carrying man on a mission which does not need man. . . . It is clear that man is not needed on the transport mission. . . ." The NSS senior leadership was still very skeptical about the need for a military man in space. Ultimately, only two NSS manned spaceflight engineers flew on shuttle missions.

Launch System Integration: Preparing for Launch

The new partnership between NASA and the NSS programs was very complex. Launching the national security payloads on the shuttle required the cooperation of two large, proud organizations, each of which viewed their mission as being of the highest national priority. This belief in their own primacy was a part of each organization's culture. From the very beginning, it was obvious that considerable effort would be required by both organizations to forge a true partnership. At the beginning of the Space Shuttle Program, NASA focused on the shuttle, while NSS program leaders naturally focused on the spacecraft's mission. As the partnership developed, NASA had to become more payload focused. Much of the friction was over who was in charge. The NSS programs were used to having control of the launch of their spacecraft. NASA kept firm control of the shuttle missions and struggled with the requests for unique support from each of the many programs using the shuttle.

Launch system integration—the process of launching a spacecraft on the shuttle—was a complex activity that had to be navigated successfully. For an existing spacecraft design, transitioning to fly on the shuttle required a detailed engineering and safety assessment. Typically, some redesign was required to make the spacecraft meet the shuttle's operational and safety requirements, such as making dangerous propellant and explosive systems safe for a crewed vehicle. This effort actually offered an opportunity for growth due to the shuttle payload bay size and the lift capacity from the Kennedy Space Center (KSC) launch site. Typically flying alone on dedicated missions, the NSS spacecraft had all the shuttle capacity to grow into. Since design changes were usually required for structural or safety reasons, most NSS program managers could not resist taking at least some advantage of the available mass or volume. So many NSS spacecraft developed during the shuttle era were much larger than their predecessors had been in the late 1960s.

National Security Space Contributions to the Space Shuttle Program

The NSS programs agreed to provide some of the key capabilities that the Space Shuttle Program would need to achieve all of its goals. As the executive agent for DoD space, the USAF funded and managed these programs.

One of these programs, eventually known as the Inertial Upper Stage, focused on an upper stage that would take a spacecraft from the shuttle in low-Earth orbit to its final mission orbit or onto an escape trajectory for an interplanetary mission. Another was a West Coast launch site for the shuttle, Vandenberg Air Force Base, California. Launching from this site would allow the shuttle to reach high inclination orbits over the Earth's poles. Although almost complete, it was closed after the Challenger accident in 1986 and much of the equipment was disassembled and shipped to KSC to improve or expand its facilities. Another program was a USAF shuttle flight operation center in Colorado. This was intended to be the mission control center for NSS shuttle flights, easing the workload on the control center in Houston, Texas, for these classified missions. USAF built the facility and their personnel trained at Johnson Space Center; however, when the decision was made to remove NSS missions from the shuttle manifest after the Challenger accident, the facility was not needed for shuttle flights and eventually it was used for other purposes.

Space Shuttle Enterprise on Space Launch Complex 6 during pad checkout tests at Vandenberg Air Force Base in 1985. Enterprise was the Orbiter built for the Approach and Landing Tests to prove flightworthiness. It never became part of the shuttle fleet.

Flying National Security Space Payloads on the Shuttle

The NSS program leadership matured during a period when spacecraft and their ground systems were fairly simple and orbital operations were not very complex. In the early 1980s, one senior NSS program director was often heard to say, “All operations needs is a roll of quarters and a phone booth.” This was hyperbole, but the point was clear: planning and preparing for orbital operations was not a priority. It wasn’t unheard of for an NSS program with budget, schedule, or political pressures to launch a new spacecraft before all the details for how to operate the spacecraft on orbit had been completely worked out.

Early on, NASA flight operations personnel were stunned to see that the ground systems involved in operating the most critical NSS spacecraft were at least a decade behind equivalent NASA systems. Some even voiced concern that, because the NSS systems were so antiquated, they weren’t sure the NSS spacecraft could be operated safely with the shuttle. In NASA, flight operations was a major organizational focus and had been since the days of Project Mercury. NASA flight operations leaders such as John O’Neil, Jay Honeycutt, Cliff Charlesworth, and Gene Kranz had an important voice in how the Space Shuttle Program allocated its resources and in its development plans. Line managers in NASA, including Jay Greene, Ed Fendell, and Hal Beck, worked closely with the NSS flight operations people to merge NSS spacecraft and shuttle operations into one seamless activity. Many of the NASA personnel, especially flight directors, had no counterpart on the NSS government team.

To prepare for a mission, NASA flight operations employed a very thorough process that focused on ensuring that flight controllers were ready for anything the mission might throw at them. This included practice sessions in the control centers using spacecraft simulators that were better than anything the NSS personnel had seen. NSS flight operations personnel thought they had died and gone to heaven. Here, finally, was an organization that took “ops” seriously and committed the resources to do it right. As the partnership developed, NASA forced, cajoled, and convinced the NSS programs to adopt a more thorough approach to the shuttle integration and operations readiness processes. Over time, NASA’s approach caught on within the NSS. It was simply a best practice worth emulating.

Another component of NASA human spaceflight—the role of the astronaut—was initially very foreign to NSS personnel. Astronauts tended to place a very personal stamp on the plans for “their” mission, which came as a shock to NSS program personnel. Some NSS personnel chafed at the effort required to satisfy the crew member working with their payload. On early missions, the commander or other senior crew members would not start working with the payload until the last 6 months or so prior to launch and would want to make changes in the plans. This caused some friction. The NSS people did not want to deal with last-minute changes so close to launch. After a few missions, as the relationship developed, adjustments were made by both sides to ease this “last-minute effect.”

1982-1992: National Security Space and NASA Complete 11 Missions

The first National Security Space (NSS) payload was launched on Space Transportation System (STS)-4 in June 1982. This attached payload (one that never left the payload bay), called “82-1,” carried the US Air Force (USAF) Space Test Program Cryogenic Infrared Radiance Instrumentation for Shuttle (CIRRIS) telescope and several other small experiments. This mission was originally scheduled for the 18th shuttle flight; but, as the Space Shuttle Program slipped, NSS program management was able to maintain its schedule and was ready for integration into the shuttle early in 1982. Since the first two shuttle missions had gone so well, NASA decided to allow the 82-1 payload to fly on this flight test mission despite the conflicts this decision would cause with the mission’s test goals. This rather selfless act on the part of NASA was characteristic of the positive relationship between NASA and the NSS programs once the shuttle began to fly. For the NSS programs, a major purpose of this mission was to be a pathfinder for subsequent NSS missions. This payload was controlled from the Sunnyvale USAF station in California. This was also the only NSS mission where the NSS flight controllers talked directly to the shuttle crew.

Operational Missions

The next NSS mission, STS-51C, occurred January 1985, 2½ years after STS-4. STS-51C was a classified NSS mission that included the successful use of the Inertial Upper Stage. The

Inertial Upper Stage had experienced a failure during the launch of the first NASA Tracking and Data Relay Satellite mission on STS-6 in 1983. The subsequent failure investigation and redesign had resulted in a long delay in Inertial Upper Stage missions. With the problem solved, the shuttle launched into a 28.5-degree orbit with an altitude of about 407 km (220 nautical miles). The first manned spaceflight engineer, Gary Payton, flew as a payload specialist on this 3-day mission. This was also the first use of the "Department of Defense (DoD) Control Mode"—a specially configured Mission Operations Control Room at Johnson Space Center that was designed and equipped with all the systems required to protect the classified nature of these missions.

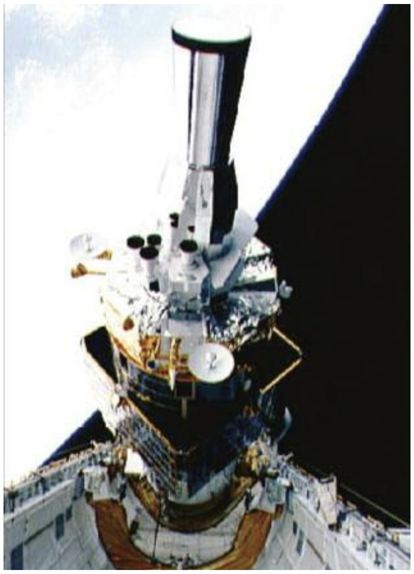
Gary Payton, US Air Force (USAF) Lieutenant General (retired), flew on STS-51C (1985) as a payload specialist. He was part of the USAF manned spaceflight engineering program and served as USAF Deputy Under Secretary for Special Programs.

The second and final manned spaceflight engineer, William Pailes, flew on the 4-day flight of STS-51J in October 1985. This shuttle mission deployed a defense communications satellite riding on an Inertial Upper Stage, which took the satellite up to geosynchronous orbit.

The Challenger and her crew were lost in a tragic accident the following January. After launching only three spacecraft payloads on the first 25 missions, the NSS response to the Challenger accident was to move all spacecraft that it could off shuttle flights. The next NSS spacecraft flew almost 2 years after the Challenger accident on the 4-day mission of STS-27 in December 1988. This mission was launched into a 57-degree orbit and had an all-NASA crew, as did the subsequent NSS spacecraft payload missions with only one exception (STS-44 [1991]). No other details on the STS-27 mission have been released.

The launch rate picked up 8 months later with the launch of STS-28 in August and STS-33 in November (both in 1989), followed by STS-36 in February and STS-38 in November (both in 1990). The details of these missions remain classified, but the rapid launch rate—four missions in 15 months—was working off the backlog that had built up during the delays after the Challenger accident. This pace also demonstrated the growing maturity of the NSS/NASA working relationship.

In April 1991, in a departure from the NSS unified approach to classification of its activities on the shuttle, the USAF Space Test Program AFP-675 with the CIRRIS telescope was launched on STS-39. This was the first time in the NSS/NASA relationship that the details of a dedicated DoD payload were released to the world prior to launch. The focus of this mission was Strategic Defense Initiative research into sensor designs and environmental phenomena. The details of this flight and STS-44 in November 1991 were released to the public. Their payloads were from previously publicized USAF programs.



Defense Support Program spacecraft and attached Inertial Upper Stage prior to release from Atlantis on STS-44 (1991). This spacecraft provides warning of ballistic missile attacks on the United States.

STS-44 crew members included an Army payload specialist, Tom Hennan. This mission marked the end of flights on the shuttle for non-NASA military payload specialists. Ironically, Warrant Officer Hennan performed experiments called "Military Man in Space." The spacecraft launched on this mission was the USAF Defense Support Program satellite designed to detect nuclear detonations, missile launches, and space launches from geosynchronous orbit. This satellite program had been in existence for over 20 years. The satellite launched on STS-44 replaced an older satellite in the operational Defense Support Program constellation.

Space Test Program

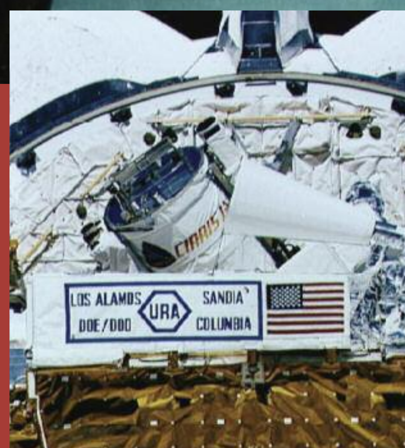
Another series of experiments, called "M88-1," on STS-44 was announced as an ongoing series of tri-service experiments designed to assess man's visual and communication capabilities from space. The objectives of M88-1

Michael Griffin, PhD
Deputy for technology at the Strategic Defense Initiative Organization (1986-1991).
NASA administrator (2005-2009).

Strategic Defense Initiative Test

"STS-39 was a very complex mission that led to breakthroughs in America's understanding of the characteristics of missile signatures in space. The data we gathered enhanced our ability to identify and protect ourselves from future missile threats. This is one of the most under-recognized achievements of the shuttle era."

View of the Aurora Australis—or Southern Lights—taken by Air Force Program-675 Uniformly Redundant Array and Cryogenic Infrared Radiance Instrumentation during STS-39 (1991). One of the equipment's objectives was to gather data on the Earth's aurora, limb, and airglow.



STS-39's Air Force Program-675 equipment mounted on the experiment support system pallet in Discovery's payload bay.

overlapped those done by Hennan with his experiments; however, NASA Mission Specialist Mario Runco and the rest of the NASA crew performed the M88-1 experiments. This activity used a digital camera to produce images that could be evaluated on orbit. Observations were to be radioed to tactical field users seconds after the observation pass was complete. Emphasis was on coordinating observations with ongoing DoD exercises to fully assess the military benefits of a spaceborne observer. The policy implications of using NASA astronauts to provide input directly to military forces on the ground during shuttle missions have long been debated. This flight and the following mission (STS-53) are the only acknowledged examples of this policy.

A year later in December 1992, STS-53 was launched with a classified payload called "DoD-1" on a 7-day mission. Marty Faga, assistant secretary of the USAF (space), said: "STS-53 marks a milestone in our long and productive partnership with NASA. We have enjoyed outstanding support from the Space Shuttle Program. Although this is the last dedicated shuttle payload, we look forward to continued involvement with the program with DoD secondary payloads."

With the landing of STS-53 at Kennedy Space Center, the NSS/NASA partnership came to an end. During the 10 years of shuttle missions, 11 of the 52 missions were dedicated to NSS programs. The end of NSS-dedicated shuttle missions resulted from the rising costs of shuttle missions and policy decisions made as a result of the Challenger accident. There were few NSS-dedicated missions relative to the enthusiastic plans laid in the late 1970s; however, the Space Shuttle Program had a lasting impact on the NSS programs. While the number of NSS-dedicated missions was small, the partnership between the NSS programs and NASA had a lasting impact.

Legacy of the Space Shuttle Program and National Security Space

The greatest legacy of the NASA/National Security Space (NSS) partnership was at the personal level for NSS engineers and managers. Working on the Space Shuttle Program in the early 1980s was exciting and provided just the sort of motivation that could fuel a career. NSS personnel learned new and different operational and engineering techniques through direct contact with their NASA counterparts. As a result, engineering and operations practices developed by NASA were applied to the future complex NSS programs with great success.

Another significant legacy is that of leadership in the NSS programs. The manned spaceflight engineer program in particular was adept at selecting young officers with potential to be future leaders of the NSS programs. A few examples of current or recent NSS leaders who spent their formative years in the manned spaceflight engineer program include: Gary Payton, Mike Hamel, Jim Armor, Kathy Roberts, and Larry James. Others, such as Willie Shelton, were US Air Force (USAF) flight controllers assigned to work in Houston, Texas.

Many military personnel working with NASA returned to the NSS space programs, providing outstanding leadership to future programs. Several ex-astronauts, such as Bob Stuart, John Fabian, and Kevin Chilton, have held or are now holding senior leadership roles in their respective services.

The role that the NASA/NSS collaboration played in the formation of Space Command also left a legacy. While the formation of the USAF Space Command occurred late in the NASA/NSS relationship, close contact between the NSS programs and the shuttle organizations motivated the Department of Defense to create an organization that would have the organizational clout and budget to deal with the Space Shuttle Program on a more equal basis.

The impact on mission assurance and the rigor in operations planning and

US Air Force Space Test Program—Pathfinder for Department of Defense Space Systems

The US Air Force (USAF) Space Test Program was established as a multiuser space program whose role is to be the primary provider of spaceflight for the entire Department of Defense (DoD) space research community. From as early as STS-4 (1982), the USAF Space Test Program used the shuttle to fly payloads relevant to the military. The goal of the program was to exploit the use of the shuttle as a research and development laboratory. In addition to supplying the primary payloads on several DoD-dedicated missions, more than 250 secondary payloads and experiments flew on 95 shuttle missions. Space Test Program payloads flew in the shuttle middeck, cargo bay, Spacelab, and Spacehab, and on the Russian space station Mir during the Shuttle-Mir missions in the mid 1990s.

A Department of Defense pico-satellite known as Atmospheric Neutral Density Experiment (ANDE) is released from the STS-116 (2006) payload bay. ANDE consists of two micro-satellites that measure the density and composition of the low-Earth orbit atmosphere while being tracked from the ground. The data are used to better predict the movement of objects in orbit.

preparation could be the most significant technical legacy the Space Shuttle Program left the NSS programs. NASA required participation by the NSS spacecraft operators in the early stages of each mission's planning. NSS operations personnel quickly realized that this early involvement resulted in improved operations or survivability and provided the tools and experience necessary to deal with the new, more complex NSS spacecraft.

The impact of the Space Shuttle Program on the NSS cannot be judged by the small number of NSS-dedicated shuttle missions. The policy decision that moved all NSS spacecraft onto the shuttle formed a team out of the most creative engineering minds in the country. There was friction between the two organizations, but ultimately it was the people on this NSS/NASA team who made it work. It is unfortunate that, as a result of the Challenger accident, the end of the partnership came so soon. The success of this partnership should be measured not by the number of missions or even by the data collected, but rather by the lasting impact on the NSS programs' personnel and the experiences they brought to future NSS programs.

Another Legacy: Relationship with USSR and Its Allies

In 1972, with the US announcement of the Space Shuttle as its primary space transportation system, the USSR quickly adapted to keep pace. "Believing the Space Shuttle to be a military threat to the Soviet Union, officials of the USSR Ministry of Defense found little interest in lunar bases or giant space stations. What they wanted was a parallel deterrent to the shuttle." Premier Leonid Brezhnev, Russian sources reported, was particularly distraught at the thought of a winged spacecraft on an apparently routine mission in space suddenly swooping down on Moscow and delivering an unthinkably dangerous cargo.

Russian design bureaus offered a number of innovative counter-capabilities, but Brezhnev and the Ministry of Defense were adamant that a near match was vital. They may not have known what the American military was planning with the shuttle, but they wanted to be prepared for exactly what it might be. The Soviets were perplexed by the decision to go forward with the Space Shuttle. Their estimates of cost-performance, particularly over their own mass-produced space launch vehicles, were very high. It seemed to make little practical sense until the announcement that a military shuttle launch facility at Vandenberg Air Force Base was planned; according to one Soviet space scientist, "… trajectories from Vandenberg allowed an overflight of the main centers of the USSR on the first orbit. So our hypothesis was that the development of the shuttle was mainly for military purposes." It was estimated that a military payload could reenter Earth's atmosphere from orbit and engage any target within the USSR in 3 to 4 minutes—much faster than the anticipated 10 minutes from launch to detonation by US nuclear submarines stationed off Arctic coastlines. This drastically changed the deterrence calculations of top Soviet decision makers.

Indeed, deterrence was the great game of the Cold War. Each side had amassed nuclear arsenals sufficient to destroy the other side many times over, and any threat to the precarious balance of terror the two sides had achieved was sure to spell doom. The key to stability was the capacity to deny any gain from a surprise or first strike. A guaranteed response in the form of a devastating counterattack was the hole card in this international game of bluff and brinksmanship. Any development that threatened to mitigate a full second strike was a menace of the highest order.

Several treaties had been signed limiting or barring various anti-satellite activities, especially those targeted against nuclear launch detection capabilities (in a brute attempt to blind the second-strike capacity of the other side). The shuttle, with its robotic arm used for retrieving satellites in orbit, could act as an anti-satellite weapon in a crisis, expensive and dangerous as its use might be. Thus, the shuttle could get around prohibitions against anti-satellite capabilities through its public image as a peaceful NASA space plane. So concerned were the Soviets

Buran/Energiya shuttle and heavy-lift booster, built by the USSR, flew once—uncrewed—in 1988.

with the potential capability of the shuttle, they developed designs for at least two orbiting "laser-equipped battle stations" as a counter and conducted more than 20 "test launches" of a massive ground-launched anti-satellite weapon in the 1970s and 1980s.

In the 1978-1979 strategic arms limitation talks, the Soviets asked for a guarantee that the shuttle would not be used for anti-satellite purposes. The United States refused. In 1983, the USSR offered to prohibit the stationing of any weapons in space, if the United States would agree. The catch was the shuttle could not be used for military activities. In exchange, the Soviets would likewise limit the Mir space station from military interaction—an untenable exchange.

So a shuttle-equivalent space plane was bulldozed through the Soviet budget and the result was the Buran/Energiya shuttle and heavy-lift booster. After more than a decade of funding—and, for the cash-strapped Soviet government, a crippling budget—the unmanned Buran debuted and flew two orbits before landing flawlessly in November 1988. Immediately after the impressive proof-of-concept flight, the Soviets mothballed Buran.

James Moltz, professor of national security at the Naval Postgraduate School, commented that the "self-inflicted extreme cost of the Buran/Energiya program did more to destabilize the Soviet economy than any response to the Reagan administration's efforts in the 1980s." If so, the Space Shuttle can be given at least partial credit for winning the Cold War.