National Aeronautics and
Space Administration

Loss of Signal

Aeromedical Lessons Learned from the STS-107 Columbia Space Shuttle Mishap

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Foreword
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Cover photos:

Front: *An overall view of the shuttle flight control room in Houston's Mission Control Center (MCC) at the Johnson Space Center (JSC). At the time this photo was taken, flight controllers had just lost contact with the Space Shuttle Columbia at 08:59:32 CST, February 1, 2003.*

Back: *The Space Shuttle Columbia is just about to clear the tower at Launch Pad 39A for STS-107. Following a flawless and uneventful countdown, liftoff occurred on-time at 10:39 EST, January 16, 2003.*

Spine: *The United States flag, in front of the Johnson Space Center's (JSC) Project Management Facility (Bldg. 1), is flown at half-staff in memory of the seven Space Shuttle Columbia crewmembers who lost their lives on February 1, 2003.*

DEDICATED TO THE CREW OF COLUMBIA STS-107

From the left (bottom row), wearing red shirts to signify their shift's color, are astronauts Kalpana Chawla, mission specialist; Rick D. Husband, mission commander; Laurel B. Clark, mission specialist; and Ilan Ramon (Israeli Space Agency), payload specialist. From the left (top row), wearing blue shirts, are astronauts David M. Brown, mission specialist; William C. McCool, pilot; and Michael P. Anderson, payload commander.

Foreword

Jeffrey R. Davis

On the morning of February 1, 2003, the Space Shuttle Columbia underwent a high-altitude, high-velocity breakup during the entry-to-landing phase of flight. The external investigation by the Columbia Accident Investigation Board (CAIB) provided the overall causes of the accident in a report that included an analysis by the Crew Survivability Working Group to determine the cause of the crewmembers' deaths and the lessons learned. The next year the Space Shuttle Program commissioned the Spacecraft Crew Survival Integrated Investigation Team to perform a comprehensive analysis of the accident, focusing on factors and events affecting crew safety and developing recommendations for improving crew survival for future human space flight. This report was published in December 2008.

Loss of Signal presents the aeromedical lessons learned from the Columbia accident that will enhance crew safety and survival on human space flight missions. These lessons were presented to limited audiences at three separate Aerospace Medical Association (AsMA) conferences: in 2004 in Anchorage, Alaska, on the causes of the accident; in 2005 in Kansas City, Missouri, on the response, recovery, and identification aspects of the investigation; and in 2011, again in Anchorage, Alaska, on future implications for human space flight. As we are embarking on the development of new spacefaring vehicles through both government and commercial efforts, the NASA Johnson Space Center Space Life Sciences Directorate (SLSD)[1] proceeded to make this information available to a wider audience engaged in the design and development of future space vehicles.

Historically, the SLSD has always prepared for space flight mishaps. From the beginning of the Space Shuttle Program with the launch of the first Space Shuttle mission in 1981 through the Challenger accident in 1986, the SLSD interfaced with the Department of Defense Manned Space Flight Program Support Office (DOD DDMS), Patrick Air Force Base, Florida, with preparation for launch and landing emergencies. After the Challenger accident, these efforts were upgraded by enhancing crew safety including improved egress, escape, and bail-out procedures with the new Launch Entry Suit. In preparation for return to flight in 1988, the SLSD developed a flight surgeon training program, the Space Operations Medical Support Training Course. These improvements led to a more direct interface of NASA with DOD DDMS in training medical personnel and trauma teams at landing sites in the United States and international locations on equipment, procedures, and communications for response, search, rescue, and recovery operations. In 1998, the SLSD Medical Operations Branch formed a Contingency Medical Group, a cadre of flight surgeons that specialized in preparation for any aviation and spacecraft mishap. This group met with the Office of Armed Forces Medical Examiner and Armed Forces Institute of Pathology[2] in 1999 to renew and improve the SLSD relationships with these organizations for mishap investigations. This coordination greatly assisted the recovery and identification efforts during the Columbia tragedy.

Loss of Signal summarizes and consolidates the aeromedical impacts of the Columbia mishap process—the response, recovery, identification, investigative studies, medical and legal forensic analysis, and future preparation that are needed to respond to spacecraft mishaps. The goal of this book is to provide an account of the aeromedical aspects of the Columbia accident and the investigation that followed, and to encourage aerospace medical specialists to continue to capture information, learn from it, and improve procedures and spacecraft designs for the safety of future crews.

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[1] The Space Life Sciences Directorate was renamed the Human Health and Performance Directorate in 2012.

[2] Armed Forces Institute of Pathology was disestablished in 2011 as part of the Base Realignment and Closure Act.

Preface and Acknowledgments

The editors of *Loss of Signal* wanted to document the aeromedical lessons learned from the Space Shuttle Columbia mishap. The book is intended to be an accurate and easily understood account of the entire process of recovering and analyzing the human remains, investigating and analyzing what happened to the crew, and using the resulting information to recommend ways to prevent mishaps and provide better protection to crewmembers.

We organized this book into 5 sections—

- The Mission
- The Response
- The Investigation
- The Analysis
- The Future

Our goal is to capture the passions of those who devoted their energies in responding to the Columbia mishap. We have reunited authors who were directly involved in each of these aspects. These authors tell the story of their efforts related to the Columbia mishap from their point of view. They give the reader an honest description of their responsibilities and share their challenges, their experiences, and their lessons learned on how to enhance crew safety and survival, and how to be prepared to support space mishap investigations.

As a result of this approach, a few of the chapters have some redundancy of information and authors' opinions may differ. In no way did we or they intend to assign blame or criticize anyone's professional efforts. All those involved did their best to obtain the truth in the situations to which they were assigned.

Our gratitude goes out to all members of the editorial board who guided us patiently through the various sections of this undertaking. We thank the NASA/Johnson Space Center Space and Clinical Operations Division and NASA Human Research Program that provided the financial resources.

We want to acknowledge the multitude of local, state, and federal government agencies as well as civilian agencies, especially citizen volunteers, whose organizational efforts were a great achievement despite the magnitude of this tragedy.

By going forward with these aeromedical lessons learned to enhance crew safety and survival, we honor the families of the crewmembers, who have lost their loved ones. We pay tribute to the crewmembers themselves for their courage. Their efforts and sacrifice of their lives will benefit survival of future fliers in the exploration of space.

Executive Editor
Philip C. Stepaniak

Editor in Chief
Helen W. Lane

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Editorial Board

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Mr. Hale retired from NASA in 2010 as the Deputy Associate Administrator of Strategic Partnerships at NASA Headquarters in Washington, DC. Mr. Hale served in the senior leadership of NASA's Space Shuttle Program from 2003 to 2008 including Launch Integration Manager at the Kennedy Space Center and then assignments as Deputy Program Manager and finally as Program Manager during the post-Columbia return to flight effort. From 1988 to 2003, he was a Space Shuttle Flight Director for 40 Space Shuttle flights, and prior to that as an orbiter systems flight controller in Mission Control for 15 early Space Shuttle flights.

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Introduction

Michael Barratt

Seated in front are astronauts Rick D. Husband (left), mission commander; Kalpana Chawla, mission specialist; and William C. McCool, pilot. Standing are (from the left) astronauts David M. Brown, Laurel B. Clark, and Michael P. Anderson, all mission specialists; and Ilan Ramon, payload specialist representing the Israeli Space Agency.

On the morning of February 1, 2003, the US Space Shuttle Columbia broke apart during reentry into Earth's atmosphere at the end of a highly productive 16-day science mission. The usual upbeat anticipation associated with the return of a ship and its crew from space was utterly shattered with this loss. Mourning for Columbia's seven-member crew was followed by a 2½-year stand down of Shuttle flights, in spite of NASA and its international partners being in the midst of a flight-intensive period of constructing the International Space Station.

NASA Administrator Sean O'Keefe commissioned the Columbia Accident Investigation Board (CAIB) within hours of the accident. This board worked diligently to produce a report, released in August of 2003, that detailed the causal factors, from hardware failures to organizational and technical oversight anomalies, that contributed to the mishap. The CAIB offered a set of recommendations for actions to be taken before Shuttle flights were resumed. A constituent group of the CAIB, the Crew Survivability Working Group (CSWG), concentrated their analysis on the

T-38s flying over Johnson Space Center during the Columbia memorial service on February 4, 2003.

crew environment, the forces inflicted on crewmembers, and cause of death. They released their final report in October 2003 as an appendix to the CAIB report. In 2004 NASA established the Spacecraft Crew Survival Integrated Investigation Team to complete the work of the Crew Survivability Working Group with more extensive resources. Their report, published in 2008, provided comprehensive understanding of the forces and factors that directly affected crew survival. They analyzed performance and failures of structures and crew equipment designed to protect human space flyers, with a deliberate aim to improve these for future flights and vehicles.

The Columbia accident was the second loss of a US Space Shuttle and its crew. As was true for the previous US space tragedies, the Columbia mishap sparked fundamental questions and vigorous public debate about flight safety, mission planning and oversight, and the very justification of human space flight. Fortunately our nation's resolve to continue to explore won over; Shuttle flights resumed in 2005, and the International Space Station was completed without mishap.

The methodical investigation of a vehicle accident is one of the most important responses to such a tragedy, and its contribution to progress is well established. The rapid pace of aviation development in the 1940s and '50s, during which significant advances in aircraft speed, altitude, and maneuverability were realized, was unfortunately punctuated by spectacular accidents and significant loss of life. But the rigorous analysis of mishaps provided valuable lessons that were applied directly to ongoing development programs and led to future successes. An implicit understanding was that a mishap investigation must be as disciplined and documented as any other aspect of a flight. Aircraft accident investigation is now a well-developed discipline. The return from this discipline is seen in the realities of modern-day high-performance aviation and civil jet transport, with expectations of safe operations and exceedingly low rates of accidents per mile.

In many respects, human space flight is analogous to the aviation test programs of decades ago. Hardware and systems operate near the limits of their performance specifications, space crews are highly trained and fit individuals, and each launch may be considered a test flight. The space flight environment, however, is decidedly different from the aviation environment.

The two most dangerous phases of space flight are launch and reentry into Earth's atmosphere; during these phases a spacecraft requires enormous energies to overcome gravity and attain orbital velocity, and then to shed that velocity upon return to Earth. The space flight environment is really three different environments, and all contain many hazards to human health. The outer space environment is a near-vacuum, with highly reactive monatomic oxygen, radiation (ionizing and solar ultraviolet), acceleration forces, extreme temperature shifts, and hypervelocity and shock wave interactions; near the spacecraft are hazards such as propellants and coolants; and the weightless environment deconditions crewmembers. After every mission, engineers methodically analyze data on these environmental factors along with the flight's performance, and subsequently brief mission managers on these aspects.

All spacecraft mishaps will invariably involve combinations of these factors. Thoroughly understanding the environmental factors, and determining which of them led to specific hazards and injuries, is of paramount importance in understanding a mishap event for causation, timing, and sequence. The loss of Columbia constituted the first high-altitude hypersonic breakup, exposing crew and hardware to an unprecedentedly hostile environment.

Reflecting current efforts and understanding, *Loss of Signal* aims to present the story of Columbia from an aerospace medical angle, focusing holistically on what is important for future investigations and analysis of spacecraft mishaps. This book is written by those who participated in the crew recovery and analysis and is written from their first-hand perspective of the events. The loss of a human crew implies sensitivities that must be balanced against the public and industry need to know, with the guiding principle being prevention of further mishaps and enhanced protection for crewmembers.

Two factors prompted the production of this book. First, the passage of time has caused some of the sensitivities to ease. Second, and critically important, are the vigorous activities now underway in the design and production of new human space vehicles. It is a unique time in human space flight, in that there have never been so many new human-rated spacecraft in design and production. These are meant for low Earth orbit and space station servicing, exploration beyond Earth orbit, and a burgeoning suborbital tourist industry. This activity drastically increases the benefits of disseminating lessons learned from such events.

Human space flight is a very public endeavor, with high-profile operators and continual open debate about the balance between cost and benefit. There is a great sense of public ownership and of sharing the adventures and successes; in turn, our tragedies and losses are keenly felt on a nearly global level. However, it is a truism that we are defined as much or more by how we respond to our failures as by how we respond to our successes. In the long run this is what moves us forward, as individuals, as nations, and as a civilization. In particular when technology progresses and boundaries are pushed, the learning curve is steep. We cannot anticipate the mishaps that may occur in the future, and thus it is vital to study every aspect of a current mishap to prepare and prevent, to learn the lessons and apply them. Aside from prevention, developing a methodical approach to spacecraft mishaps ensures a rapid and aggressive response to future events.

Loss of Signal and other works before it contain knowledge that has been given to us at a very high price, and the space medical community is morally and professionally bound to make the best use of it. Educating our community enables these facts and observations to be integrated into every relevant aspect of human space flight. With this information and with every subsequent flight, we continue down a path toward safer and more routine access to space, ultimately making space flight similar to jet transport today.

Section 1 – The Mission

The Mission and The Crew

The Mishap

The Mission and The Crew

Helen W. Lane, Smith Johnston, and John B. Charles

NASA dedicated a majority of the Space Shuttle missions to science with focus on the effects of microgravity on biological, chemical, and physical systems. These included cellular, animal, and human types of experiments as well as atmospheric sciences, combustion, fluid mechanics, crystal growth, protein properties, and basic physics. After 20 years, NASA along with her international partners and commercial organizations had developed expertise in conducting these types of experiments during Space Shuttle flights. STS-107 was the final Space Shuttle flight totally dedicated to science to provide the foundation for future ISS research programs. It was the 113th mission of the Space Shuttle Program and the 28th flight of the Shuttle orbiter Columbia, launched on January 16, 2003, at 10:39 a.m. EST for a 16-day mission. At 11:20 a.m. EST, a 2-minute burn of the orbital maneuvering system engines began to position Columbia in its proper orbit, an inclination of 39° to the equator and about 175 miles above the Earth.

Before we recount the mission's purposes and the skills of the crewmembers who made it possible, we will briefly describe the structure of the Space Shuttle, emphasizing the capabilities of the orbiter Columbia, and the environment at NASA at the time of the mission.

Photo of Columbia STS-1 on the launch pad at Kennedy Space Center, ready for the historic first launch on April 12, 1981. Columbia, the first orbiter in the Shuttle fleet, was named after the Boston, Massachusetts-based sloop captained by American Robert Gray. On May 11, 1792, Gray and his crew maneuvered the Columbia past the dangerous sandbar at the mouth of a river (now named Columbia River, extending more than 1,000 miles through what is today southeastern British Columbia, Canada, and the Washington-Oregon border). Gray also led Columbia and its crew on the first American circumnavigation of the globe, carrying a cargo of otter skins to Canton, China, and then returning to Boston. Other sailing ships have further enhanced the luster of the name Columbia. The first US Navy ship to circle the globe bore that title, as did the Command Module for Apollo 11, the first lunar landing mission.

The Vehicle

The Space Shuttle had three major components: the two solid rocket boosters, the external tank, and the orbiter. Each of the six orbiters was slightly different from the others, and each was given a name: Atlantis, Challenger, Columbia, Discovery, Endeavour, Enterprise. Each orbiter contained three Space Shuttle main engines and the orbiter thrusters, crew compartment, and payload bay. The crew compartment included the flight deck, from which the commander and pilot controlled the spacecraft, and the middeck, the location of some research and the crew facilities such as sleep stations, galley, waste collection system, crew supplies, and environmental control system supplies. The crew compartment structure “floated” inside the forward fuselage and was attached to it at four discrete points. This construction provided greater thermal isolation and potentially ensured pressure integrity even if the orbiter aluminum shell cracked.

Columbia was the first space flight-worthy orbiter and therefore unique in several ways. (The first orbiter, Enterprise, was built to perform approach and landing tests and was never converted to a spacecraft with rockets such as the Orbiter Maneuvering System and Reaction Control System engines). In 1981 and 1982 Columbia flew the first five Space Shuttle flights—the first three were test flights, the fourth was a test and Department of Defense flight, and the fifth was the first operational flight, which included an expanded crew of four. These test flights were successful and they allowed NASA to begin flying payloads sooner than anticipated. Columbia’s early flights as a test platform validated the concepts and techniques for the fledgling Shuttle program.

Columbia was built to carry a laboratory for scientific research in its payload bay. The first laboratory to occupy Columbia’s payload bay was Spacelab, which was first flown in space in 1983 on the STS-9 mission. For the STS-107 flight, Spacehab, Inc provided the last of these pressurized payload laboratories, the SPACEHAB Research Double Module.

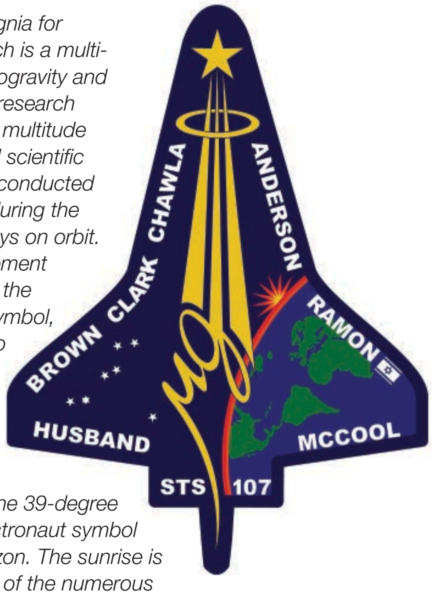
The NASA Environment

The climate at NASA during the time leading up to the Columbia launch was rapidly changing in response to political and financial pressures on the agency. A growing federal deficit led to a push for reductions in government spending, and NASA’s budget, like that of other federal agencies, was reduced. Budget constraints reduced the Space Shuttle Program workforce and operations budget by an estimated 40% relative to the previous decade. At the same time, however, Shuttle operations were essential for continuing support of development, assembly, and operation of the International Space Station (ISS). The Space Shuttle Program was under significant pressure to meet launch dates to ensure the timely construction of the ISS. The STS-107 Columbia flight, unique in its purpose and significance, had a limited budget in this environment of reduced federal spending. NASA science managers were forced to constantly justify the role of a science-dedicated flight in an otherwise ISS-focused agency.

The STS-107 mission was delayed many times from the announced launch date in 2000 to the final launch in 2003. These delays occurred because higher priority was given to launches for ISS construction and for repair and upgrades of the Hubble Space Telescope, and because at different times damaged insulated wiring and damage in the main engines of Columbia had to be repaired. Finally, in early 2003, Columbia was slated for launch. By this time the crew, who had been training together for the better part of 3 years, functioned as an organized and integrated team, and close friendships had been formed among crewmembers, family members, and support staff.

The Mission

When STS-107’s flight was announced, the Space Shuttle Program was focused on assembling the ISS. However, NASA decided to have this one last research-dedicated Space Shuttle mission using the SPACEHAB laboratory. STS-107 research focused on the consequences of microgravity on physical and living systems. The underlying goals were to enhance the well-being of people on Earth, using microgravity for basic scientific understanding; this knowledge might enable scientists to build better spacecraft and to understand the human system. Also, the goal was to develop countermeasures to allow astronauts to stay healthy during long duration missions such as those on the ISS or beyond low Earth orbit. With a large set of submitted proposals, NASA and its international and commercial partners conducted peer review to determine the best scientific studies that could be implemented during this Space Shuttle flight. Once the science was selected, NASA mission managers and the STS-107 crew worked with the investigators to ensure the highest quality of research. The crew trained diligently to ensure they could conduct the research at the highest levels.



This is the insignia for STS-107, which is a multi-discipline microgravity and Earth science research mission with a multitude of international scientific investigations conducted continuously during the planned 16 days on orbit. The central element of the patch is the microgravity symbol, μg, flowing into the rays of the astronaut symbol. The mission inclination is portrayed by the 39-degree angle of the astronaut symbol to Earth's horizon. The sunrise is representative of the numerous experiments that are the dawn of a new era for continued microgravity research on the International Space Station and beyond. The breadth of science conducted on this mission will have widespread benefits to life on Earth and our continued exploration of space illustrated by Earth and stars. The constellation Columba (the dove) was chosen to symbolize peace on Earth and the space shuttle Columbia. The seven stars also represent the mission crewmembers and honor the original astronauts who paved the way to make research in space possible. The Israeli flag is adjacent to the name of the payload specialist who is the first person from that country to fly on the Space Shuttle.

This science mission had a mixed complement of experiments that had been selected through competition. The mission had 32 payloads, 40% of which were international or commercial. Sponsoring organizations ranged from multiple NASA research divisions to military research organizations, educational institutions, and international partners. The research was proposed by 59 separate investigators and represented numerous scientific fields, including biology, medicine, materials science, physics, and atmospheric sciences. The astronauts served as researchers and test subjects for experiments related to astronaut health, including respiratory monitoring and bone physiology studies, and an investigation of circadian rhythms and light exposure.

International payloads were from Canada, Germany, the European Space Agency, and Israel. The Israeli Space Agency sponsored a payload bay project called Mediterranean-Israeli Dust Experiment (MEIDEX), and it was designed to study atmospheric dust over Africa and the Mediterranean to provide important understanding of dust and weather, and thus climate changes. As part of this project, the first Israeli payload specialist flew, causing the flight to have significant attention from the international community and, of course, Israel.

The Crew

The complex payloads on this mission required an exceptionally qualified crew with strong scientific, medical, and research backgrounds. Also, because the astronauts would function as both scientists and test subjects, NASA asked for volunteers from the astronaut corps who would be dedicated to successful accomplishment of scientific goals.

Rick Husband, an Air Force test pilot, embraced his role as the commander of the STS-107 mission. His pilot was William McCool, a Navy test pilot. Both Husband and McCool had engineering backgrounds, and both were active participants in multiple research projects during the flight. Michael Anderson, the payload commander, had a background in physics and astronomy, and was well suited to lead research efforts on orbit. The mission's flight engineer, Kalpana Chawla, had a background in aerospace engineering. The crew had two Navy flight surgeons: David Brown, a naval aviator, physician, and scientist, and Laurel Clark, a naval commander, physician, and zoologist. Ilan Ramon, a colonel in the Israeli Air Force and a fighter pilot, had a background in computer engineering. Ramon, the first Israeli astronaut to take the ride into orbit, worked with the Israeli Space Agency MEIDEX investigation.

This crew's rigorous preparation included about 5,000 hours of general training, as well as an additional 3,500 hours of training specific to the research payloads and the objectives and procedures for each experiment. Some of the research was dedicated to biological and medical sciences, and thus required consultation with the crew flight surgeons throughout training and the mission itself. The medical impact of this mission, which included a wide variety of experiments, was important.

Research

Crew research activity was planned for every hour of the day, and called for crewmembers to work in two shifts, called the Blue Team and the Red Team, on opposite schedules during the mission. This required careful preparation of schedules to ensure that crewmembers had enough time to rest. The Red Team comprised Commander Richard Husband, Flight Engineer and Mission Specialist 2 Kalpana Chawla, Mission Specialist 4 Laurel Clark, and Payload Specialist Ilan Ramon. The Blue Team consisted of Pilot William McCool, Mission Specialist 1 David Brown, and Mission Specialist 3 and Payload Commander Michael Anderson.

During their flight on January 28, the STS-107 crew honored those who lost their lives in the Apollo 1 fire and the Challenger accident. The Columbia crew never anticipated the danger that was awaiting them, or that, ironically, they too would be honored and never forgotten.

At the end of their final research day, the crew had completed all the experiments. By all indications at this time, the STS-107 crew and the researchers on the ground had had a highly successful science mission, and all were ecstatic over completion of the mission objectives. On February 1, 2003, the Columbia and its crew would make preparations to reenter the Earth's atmosphere and return home.

Commander
Rick D. Husband

(Colonel, US Air Force)

A native of Amarillo, Texas, Rick earned a BS degree in mechanical engineering from Texas Tech University and an MS degree in the same discipline from California State University, Fresno. Rick served as the Astronaut Office representative for Advanced Projects and served as Chief of Safety for the Astronaut Office. He served as pilot for STS-96 (1999), a 10-day mission during which the crew performed the first docking with the International Space Station. STS-107 was Rick's second Space Shuttle mission and his first as Commander.

Pilot
William C. "Willie" McCool

(Commander, US Navy)

Willie was born in San Diego, California. He held a BS degree in applied science from the US Naval Academy, an MS degree in computer science from the University of Maryland, and an MS degree in aeronautical engineering from the US Naval Postgraduate School. Willie logged over 3,000 hours of flight experience in 24 aircraft and more than 400 carrier arrestments before NASA selected him as an astronaut candidate in 1996. STS-107 was Willie's first Space Shuttle mission.

Mission Specialist
Michael "Mike" P. Anderson

(Lieutenant Colonel, US Air Force)

Mike was born in Plattsburgh, New York, but called Spokane, Washington, home. He received a BS degree in physics/astronomy from the University of Washington and an MS degree in physics from Creighton University. With over 4,000 hours in various models of the KC-135 and the T-38 aircraft, Mike served as an aircraft commander, an instructor pilot, and a tactics officer before he was selected as an astronaut for NASA in 1994. He flew on STS-89 (1998), the eighth Shuttle-Mir docking mission. STS-107 was Mike's second Space Shuttle mission.

Mission Specialist
Kalpana "K.C." Chawla, PhD

K.C. was born and raised in Karnal, India. She received a BS in aeronautical engineering from Punjab Engineering College, Chandigarh, India, an MS in aerospace engineering from the University of Texas, and a PhD in aerospace engineering from the University of Colorado. In 1988, she started work at NASA Ames Research Center, and she was selected as an astronaut candidate by NASA in December 1994, reporting to the Johnson Space Center in March 1995 as an astronaut candidate in the 15th group of astronauts. K.C. flew as a mission specialist on STS-87 (1997). STS-107 was K.C.'s second Space Shuttle mission.

Mission Specialist
David "Dave" Brown, MD

(Captain, US Navy)

Dave was born in Arlington, Virginia. He received a BS degree in biology from the College of William and Mary and a doctorate in medicine from Eastern Virginia Medical School. Brown joined the Navy and completed flight surgeon training. In 1988, he was the only flight surgeon in a 10-year period to be chosen for pilot training. He was ultimately designated a naval aviator, ranking number one in his class. Dave logged over 2,700 flight hours, with 1,700 hours in high-performance military aircraft, and was qualified as first pilot in NASA T-38 aircraft. NASA selected him as an astronaut candidate in 1996. STS-107 was Dave's first Space Shuttle mission.

Mission Specialist
Laurel Blair Salton Clark, MD

(Commander, US Navy)

Laurel was born in Ames, Iowa, but called Racine, Wisconsin, her hometown. She received both a BS degree and a doctorate in medicine from the University of Wisconsin-Madison. Prior to her selection as an astronaut candidate in 1996, she served as a flight surgeon for the Naval Flight Officer advanced training squadron (VT-86) in Pensacola, Florida. While at NASA, Laurel worked on International Space Station and Space Shuttle medical systems and payload operations and development. STS-107 was Laurel's first Space Shuttle mission.

Payload Specialist
Ilan Ramon

(Colonel, Israel Air Force)

Ilan was born in Tel Aviv, Israel. He received a BS degree in electronics and computer engineering from the University of Tel Aviv, Israel. He graduated as a fighter pilot from the Israel Air Force Flight School. In 1997, Ilan was selected as a Payload Specialist. He was designated to train for a Space Shuttle mission carrying an Israeli payload (MEIDEX) that included a multispectral radiometric camera for recording atmospheric desert aerosols from space. In August 1998, he started basic Shuttle training at Johnson Space Center. In August 2000, he was assigned as one of the seven crewmembers for this flight. STS-107 was Ilan's first Space Shuttle mission, and he was the first Israeli to fly in space.

Crew Activities During Flight of STS-107, Representing Research and Education Outreach

STS-107 Commander Rick D. Husband works the controls on the support hardware for the European Research in Space and Terrestrial Osteoporosis experiment located in the SPACEHAB Research Double Module.

STS-107 Mission Specialist David "Dave" Brown, holding papers, smiles for the camera from orbiter Columbia's flight deck/ middeck access way. Beside him is a spare mission specialist seat in stowed configuration.

STS-107 Pilot William C. "Willie" McCool views data on a laptop computer at a workstation on Columbia's aft flight deck. He holds a checklist in one hand and a portable communications system in the other.

STS-107 Mission Specialist 4 Laurel Blair Salton Clark looks over her shoulder as she enters data on a Payload General Support Computer at a workstation on Columbia's aft flight deck.

STS-107 Payload Commander and Mission Specialist Michael P. "Mike" Anderson works with the Laminar Soot Processes experiment in the Combustion Module -2 in the SPACEHAB Research Double Module.

STS-107 Payload Specialist Ilan Ramon works with the Space Technology And Research Students (STARS) educational payload housed in an Isothermal Containment Module (ICM) in the SPACEHAB Research Double Module. The STARS payload included the following experiments: "The Chemical Garden," sponsored by Israel; "Astrospiders — Spiders in Space," sponsored by Australia; "Silkworm Lifecycle During Space Flight" sponsored by China; "Flight of the Medaka Fish," sponsored by Japan; "Carpenter Bees in Space," sponsored by Liechtenstein; and "Ant Colony," sponsored by the United States.

STS-107 Mission Specialist Kalpana "KC" Chawla at work in the SPACEHAB Research Double Module.

The Mishap

Stevan Gilmore and Charles Campbell

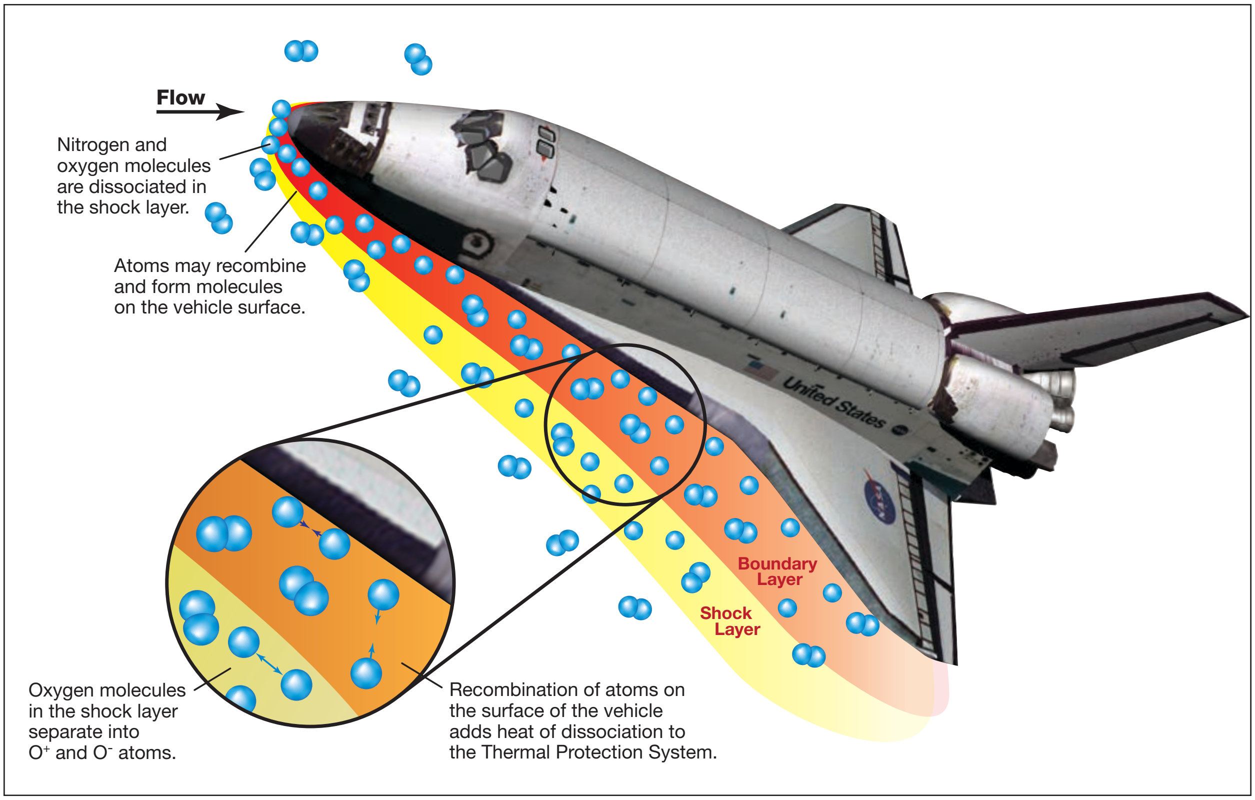
Normal Launch and Reentry Dynamics

The process of launching an object into low Earth orbit and then returning it to Earth is an energetic and dynamic process. To understand the nature of the Columbia mishap and the ballistic effects that produced the debris field, it is important to understand launch and reentry dynamics.

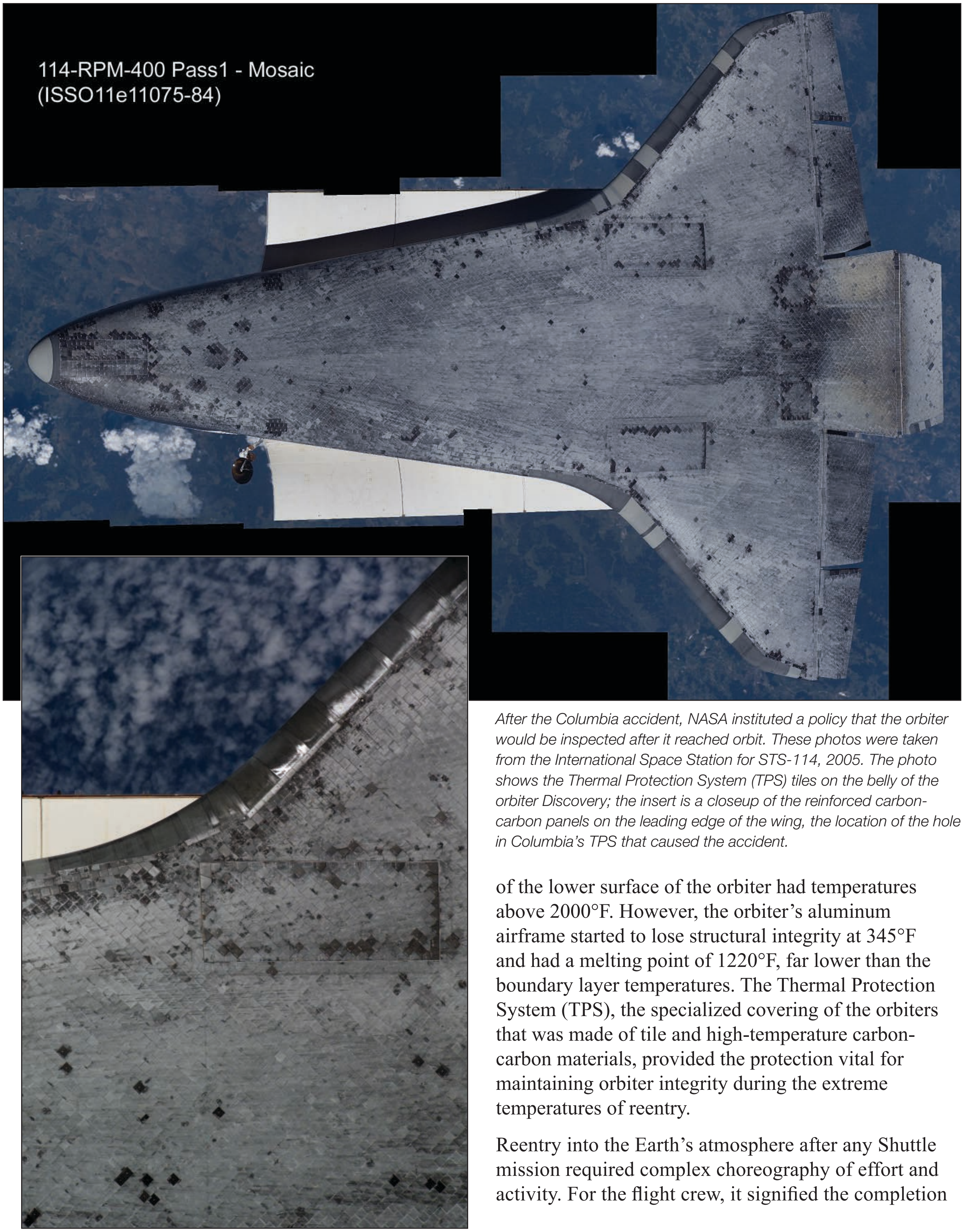
The launch of the Shuttle demanded a dynamic expenditure of energy as the vehicle accelerated from rest to an orbital velocity of 17,500 miles per hour (mph). Including crew and cargo, a typical Shuttle with a complete payload weighed about 110 metric tons, and the acceleration of such a mass to orbital velocity required nearly one million watts of energy, or enough energy to power the average house for 41 years.

Before landing, the energy of the vehicle in orbit had to be dissipated; this was accomplished by converting kinetic energy into heat. As the orbiter reentered the atmosphere, the vehicle slammed into air particles in the atmosphere, creating a shock layer where the kinetic energy of the Shuttle was transferred to molecules of air, ripping these molecules apart.

Within the shock layer, temperatures reached over 10,000°F, an environment with characteristics approaching those of plasma-phase matter. In a true plasma, free electrons significantly affect the gas dynamic properties and involve significant electromagnetic effects. During reentry from low Earth orbit, however, the main effect of the large number of free electrons is the loss of radio communications. The orbiter surface did not make contact with this superheated gas in the shock layer but instead was protected with a thin boundary layer of atmosphere that limited heat transfer. The temperature of the orbiter surface, which was protected from these very high temperatures because of this boundary layer, normally had peak temperatures approaching 3000°F. Most



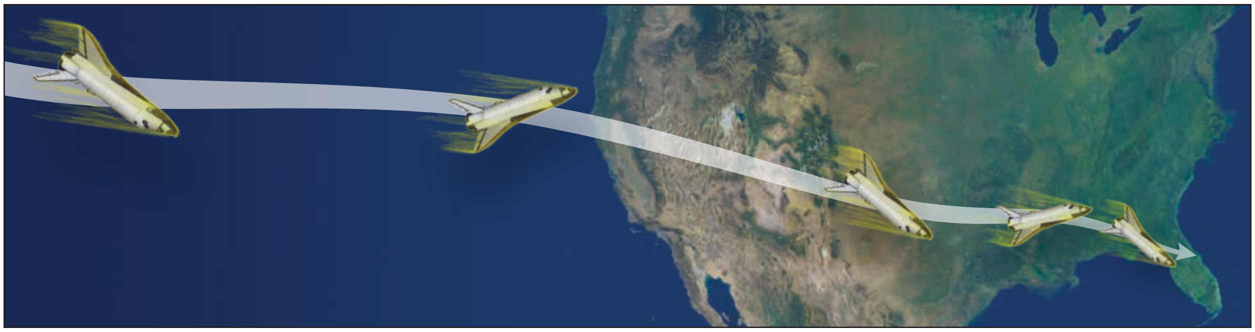
This image illustrates how the Thermal Protection System protected the orbiter's aluminum shell.



After the Columbia accident, NASA instituted a policy that the orbiter would be inspected after it reached orbit. These photos were taken from the International Space Station for STS-114, 2005. The photo shows the Thermal Protection System (TPS) tiles on the belly of the orbiter Discovery; the insert is a closeup of the reinforced carbon-carbon panels on the leading edge of the wing, the location of the hole in Columbia's TPS that caused the accident.

of the lower surface of the orbiter had temperatures above 2000°F. However, the orbiter's aluminum airframe started to lose structural integrity at 345°F and had a melting point of 1220°F, far lower than the boundary layer temperatures. The Thermal Protection System (TPS), the specialized covering of the orbiters that was made of tile and high-temperature carbon-carbon materials, provided the protection vital for maintaining orbiter integrity during the extreme temperatures of reentry.

Reentry into the Earth's atmosphere after any Shuttle mission required complex choreography of effort and activity. For the flight crew, it signified the completion



This image illustrates the angle of the orbiter as it enters the Earth's atmosphere beginning with the belly facing the atmosphere. Flying through the atmosphere decreases the speed due to aerodynamic drag. By rolling the orbiter left and right, the guidance brings the crew to a precision unpowered touchdown on the runway.

of on-orbit mission objectives and required a sudden focus of activity to reconfigure the orbiter from a work and science platform back into a flying machine. In Mission Control, analysts, flight controllers, and management teams had to prepare for the reentry to Earth's atmospheric operations with the deployment of personnel to landing sites and the active analysis of orbiter systems, reentry weather, and landing conditions.

Flight controllers divided the orbiter reentry profile into three phases for tracking: reentry, terminal area energy management (TAEM), and approach through landing. The reentry phase began with entry interface, arbitrarily determined to occur at an altitude of 400,000 ft. Entry interface signifies the beginning of reentry, where the atmosphere is about to begin exerting drag on the orbiter. During reentry, Shuttle computers commanded the orbiter to perform a series of banks and roll-reversals, decelerating the orbiter from the initial reentry speed of Mach 25. At the same time, these maneuvers protected the TPS surfaces, limiting surface heating and surface temperatures to within operational performance range. The flight software running on the computer was designed to carefully control the reentry path such that the orbiter would achieve TAEM with enough energy to reach the runway. TAEM would typically occur at 83,000 ft and a speed of Mach 2.5, about 52 nautical miles from the runway. The distinctive "double sonic boom" would thunder from the vehicle until it slowed to subsonic speeds at an altitude of 49,000 ft, about 22 nautical miles from the runway. TAEM would transition into the approach and landing phase below 10,000 ft after the Shuttle attained the appropriate glide slope and air speed for landing.

The Columbia Reentry Mishap

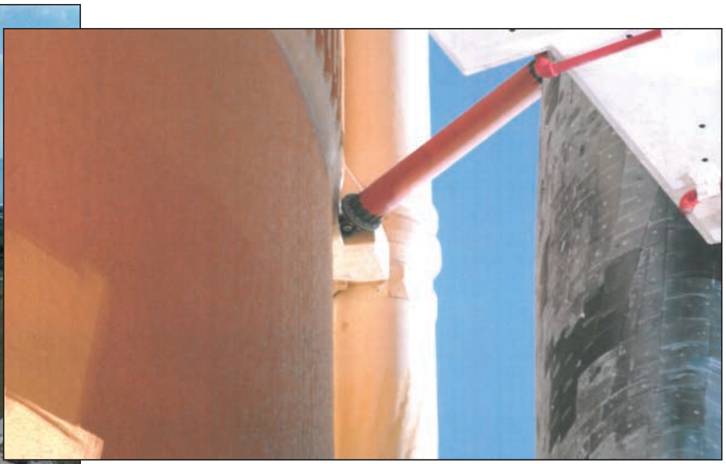
Damage to the Columbia Orbiter

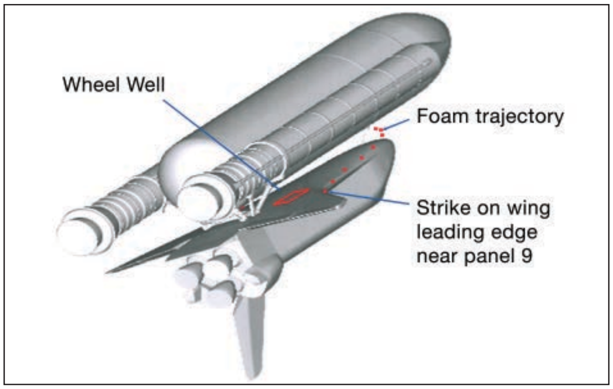
By the time of reentry, the Columbia crew had completed 16 days of rigorous scientific endeavors and they eagerly anticipated their return trip to Earth. Columbia's crew busily prepared to return home. Beginning on January 31, 2003, members of the night-shift Blue Team (Anderson and Brown) woke up about 3:30 p.m. CST. McCool, also a member of the Blue Team, earned a slightly longer sleep period and was awakened 2 hours later than his teammates so that he could be well rested for performing his flight duties associated with reentry. The team began their final day of activities, including configuration of the SPACEHAB and orbiter middeck and flight deck in preparation for reentry. The Red Team awakened shortly before 1:00 a.m. CST February 1 for final deorbit preparations.

However, the launch 2 weeks before this day had included significant events that would ultimately lead to disaster during reentry. As with all Shuttle missions, numerous videos of Columbia's launch and ascent sequence were thoroughly analyzed by engineering experts during and after launch. These experts promptly recognized that an anomaly had occurred during launch: foam debris from the external tank had shed during the extreme conditions of launch and struck the left wing of Columbia exactly 81.9 seconds into the flight. In the context of operations in early 2003, foam strikes were not particularly unexpected or unusual. In fact, foam debris was shed on every launch before STS-107, and resultant debris strikes had become a regular occurrence.

When it was recognized that Columbia had suffered a debris strike, analysis and engineering experts worked to identify the significance of this event for vehicle integrity. The videos of launch showed that the foam


Launch of STS-107 at Kennedy Space Center on January 16, 2003.


Left Bipod Foam Ramp where the loss of debris occurred on STS-107. Left side is the external tank, and right side is the orbiter.



The foam strike on the leading edge of the wing at 81.9 seconds after lift-off.

struck Columbia's left wing on or near a leading edge, an area covered in reinforced carbon-carbon panels because of the extreme heating of this region during reentry. Some analysts expressed concern about this event, given the limited analysis available and the possible implication of such a strike on the TPS and vehicle integrity. Because operational experience with previous foam debris strike events had shown that such strikes had never caused significant structural damage, this event ultimately was not considered mission critical and the flight continued uninterrupted.

Reentry Sequence

In Houston, responsibility for the mission was handed over to the reentry Mission Control team at about 2:30 a.m. CST, February 1, and this team began monitoring crew activities and vehicle telemetry, coordinating reentry and landing site weather assessments, and relaying entry parameter updates to the crew for entry into the flight computers. At 8:10 a.m., members of the reentry team were polled for "Go/No-Go" status for final approval of the reentry procedure. At 8:16 the capsule communicator (CAPCOM) informed the commander that he was cleared for reentry and a landing at the Kennedy Space Center (KSC).

Five minutes after receiving clearance for landing, as the Shuttle orbit passed above the Indian Ocean, Husband and McCool initiated a deorbit burn that lasted 2 minutes 38 seconds. This procedure fires the engines against the direction of the orbital trajectory so that engine thrust works to slow the vehicle. The action slowed Columbia by only about 250 mph, but the new trajectory created by this deceleration placed the orbiter in a path that would contact the upper regions of the atmosphere. As they finished this maneuver, Husband and McCool reoriented the vehicle from the inverted orbital position (with the payload bay pointed down toward the Earth's surface) to an upright, nose-forward, pitched-up orientation, maximizing exposure of the vehicle's heat-resistant surfaces to the atmosphere.

Entry interface, the entry of the orbiter into the atmosphere, occurred on time and as expected at 08:44:09 CST over the Pacific Ocean. On board and in the Mission Control Center, the crew and the ground team monitored the performance of the digital autopilot as it commanded flight maneuvers. At 08:49:32 CST, Columbia executed the first in a series of energy-management maneuvers designed to reach the landing site with the appropriate conditions for an aerodynamic landing. The initial move in this energy management choreography, a bank to the right, occurred without incident. At 08:50:53 CST, Columbia was gliding roughly 300 nautical miles west of the California coast and entered a 10-minute period of peak heating on the TPS as it was slowed by the atmosphere. At 08:53:25 CST, Columbia crossed the west coast of California at 231,600 ft and traveling at Mach 23. All procedures and events appeared to be normal.

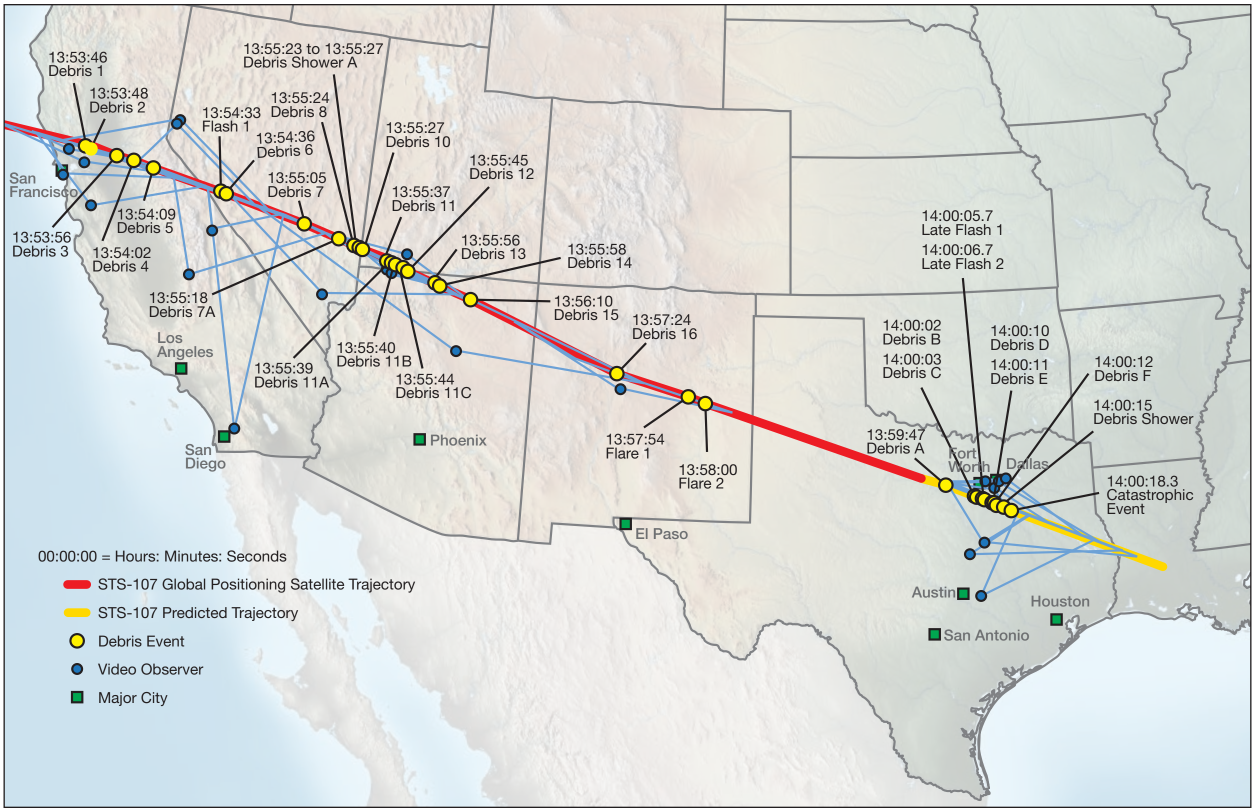
The orbiter Columbia had the heaviest airframe of the orbiter fleet, and that frame had a multitude of integrated sensors for accurate measurements of vehicle performance and the flight environment. The inclusion of these sensors, so important for the first Shuttle flights by Columbia, ultimately contributed significantly to the reconstruction and understanding of the events that were to unfold during its last mission. At 08:54:24 CST, as Columbia crossed from California into Nevada, flight controllers in Mission Control received the first nonstandard telemetry from the vehicle. The maintenance, mechanical, and crew systems (MMACS) officer, who was responsible for monitoring all of the orbiter structural and mechanical systems, reported to the flight director that four hydraulic sensors in the left wing were indicating off-scale low. As Mission Control specialists analyzed the telemetry signature and discussed possible causes, Columbia continued along its reentry path over the western United States. At 08:56:30 CST, while transiting over northern Arizona, Columbia executed its nominal roll-reversal from a right to left bank as the flight-control computers continued the reentry energy-management choreography.

At 08:58:20 CST, Columbia entered the skies over Texas, traveling at Mach 19.5 and at an altitude of 209,800 ft. Shortly after this, CAPCOM received a broken call from Columbia, "And, uh, Hou…" At 08:59:15 CST, MMACS reported a second unexpected telemetry signature, the loss of tire pressure reading data from both left main gear tires, to the flight director. CAPCOM relayed the receipt of these telemetry signals to the crew and requested a repeat of the crew's interrupted transmission. Shortly thereafter, CAPCOM announced to the crew that a fault message about backup tire pressure had been registered by ground telemetry; this fault message may have been the reason the commander had initiated the final voice communication.

At 08:59:32 CST, loss of signal occurred with a mid-sentence interruption of the final voice call from Commander Husband: "Roger, …" At this time the orbiter was in the vicinity of Dallas, TX, at an altitude of 200,700 ft and traveling at Mach 18. Although the significance was only recognized in retrospect, the time at which loss of signal occurred coincided with an expected transition between West coast communication assets tracking the Shuttle to those positioned on the East coast and on the ground at KSC. Unknown to those in Mission Control at the time, 08:59:32 CST would mark the time at which no further useful telemetry was received from Columbia. This moment would come to be known as the Loss of Signal.

Flight controllers continued to discuss the possible causes of the unexpected tire pressure and telemetry signatures received from the orbiter. Additionally, the instrumentation and communications officer, responsible for monitoring communication systems and telemetry links between the vehicle and the ground, reported that the communications drop-out was rather longer than expected. The mission control team began to step through processes to confirm the last known configuration of communication assets and then reacquire communication with the orbiter.

Unknown to Mission Control, observers located in the vicinity of the orbiter's ground track across the western and central United States witnessed unexpected events as they watched Columbia's reentry. A series of separate observers on the ground were filming the orbiter, using a variety of modalities ranging from amateur video to advanced optics from government assets. Starting near the coast of California, these observers documented discrete debris-shedding events as well as irregularities in Columbia's wing profile. At 09:00:18 CST, as Mission Control began its series of steps to reacquire communications, military assets located in the Dallas and Fort Hood areas documented this catastrophic event. State and local authorities began to be inundated by calls from witnesses reporting a loud sonic boom followed shortly thereafter on the ground by falling debris. This visual confirmation of the catastrophic reentry event was part of the information that was eventually relayed



This graphic illustrates the sightings by amateurs and the Department of Defense during the reentry of Columbia. These videos and photos allowed NASA to better characterize the pre-breakup debris and ground impact areas. Time is represented as Greenwich Mean Time (GMT).

to the Mission Control team in Houston as the team searched for the cause of the extended loss of signal from Columbia.

At 09:02:21 CST, when Columbia was expected to be within range of communication with KSC, personnel at the Merritt Island Launch Annex (MILA) in Florida reported to the Houston team that they were unable to contact the crew on the radio. CAPCOM attempted to regain communication with the orbiter by means of an ultra-high-frequency antenna. The ground control officer reported that ground assets at the MILA were not in radio contact with the orbiter.

At 09:09:29 CST, when Columbia was expected to enter TAEM, the flight dynamics officer again reported that they were not receiving any tracking data. A few minutes later, when Columbia was expected to be entering the third phase of reentry and the characteristic double sonic boom was conspicuously absent, the flight director was informed of events as witnessed by the public. Private citizens, news media, military personnel, and others were already witnessing and videotaping the significant events taking place over the skies of Texas and Louisiana.

At 09:12:39 CST the flight director instructed that the control room doors be locked and that control team members begin securing their stations and the data within.

Recovery Operations

Once the Control Team became aware of the situation, the Shuttle contingency action plan was activated. This plan was made up of a number of actions including notification, through the NASA chain of command, of members of the astronauts' families and members of the government. At Johnson Space Center (JSC), the Mission Management Team (MMT) convened a meeting in the action center of Mission Control at 9:30 a.m. CST. One of their first actions was to prepare responders for immediate deployment to the disaster site. By 10:30 a.m. CST, the NASA administrator had named Admiral Harold W. Gehman, Jr., Chair of the Columbia Accident Investigation Board (CAIB). Soon after, President Bush informed the Israeli Prime Minister of the mishap and then declared the affected areas Federal disaster areas, mobilizing government relief and recovery resources for assistance.

Reconstruction of the Columbia from parts found in East Texas and western Louisiana. 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 orbiter.

At 11:30 a.m. CST, a second meeting of the MMT occurred at which the management team presented information from local state agencies and the Department of Defense about the approximate coordinates of the orbiter breakup. Team members from a number of disciplines at the JSC were assigned to the Mishap Investigation Team (MIT), whose task was to spearhead NASA's efforts in conjunction with other federal, state, and local entities to locate, preserve, and protect the hardware debris and human remains. The MIT deployed to Barksdale Air Force Base (AFB) in Louisiana from Ellington Field in Houston, Texas, at 3:30 p.m. CST to coordinate the recovery of the Columbia vehicle and her crew. Other members of the MIT deployed to Disaster Field Offices that were subsequently established in Lufkin, Texas; Fort Worth Naval Air Station, Texas; and other areas throughout northeastern Texas and western Louisiana. This initial response was vital in locating the Columbia vehicle and its crew and in preserving and protecting evidence for the mishap investigations conducted by the CAIB.

Federal agencies including the Federal Emergency Management Agency (FEMA), the Environmental Protection Agency (EPA), the National Transportation Safety Board (NTSB), and the Federal Bureau of Investigation (FBI) worked together with state and local agencies in what was to be the largest recovery effort ever undertaken anywhere. More than 25,000 people participated in recovery efforts. Over 700,000 acres of land were walked in a grid pattern to locate debris, and more than 37 helicopters and 7 airplanes were used to search 1.6 million acres by air. Even scuba divers searched a number of lakes in the affected areas.

Debris Recovery

In total, 83,013 debris pieces weighing 84,900 pounds were recovered, equaling roughly 39% of the weight of the orbiter. The Modular Auxiliary Data System recorder that contained critical data needed for the accident analyses was found near Hemphill, Texas. It recorded data about the local flight environment and dynamics, including data recorded for an additional 14 seconds after the loss of signal to Mission Control in Houston. Searchers photographed and geo-tagged recovered debris in the field, then sent the items to designated sites across Texas for archiving and identification. Much of the recovered hardware debris was forwarded to KSC from February 12 to May 6, 2003, and assembled on a full-scale grid for further analysis and reconstruction efforts.

President George W. Bush spoke at the Columbia memorial service at the Johnson Space Center on February 4, 2003. The President was accompanied by NASA Administrator Sean O'Keefe (left) and Chief of the Astronaut Corps Captain Kent Rominger.

Memorials

A memorial service to honor the crew occurred on February 4, 2003, at JSC and was televised worldwide. President George W. Bush was accompanied by NASA Administrator Sean O'Keefe and Chief of the Astronaut Corps Captain Kent Rominger. President Bush stated to the assembled group of employees, retirees, crew families, and other dignitaries, "Their mission was almost complete, and we lost them so close to home…. For these seven, it was a dream fulfilled. Each of these astronauts had the daring and discipline required of their calling. Each of them knew that great endeavors are inseparable from great risks. And each of them accepted those risks, even joyfully, in the cause of discovery."

On February 7, at KSC the orbiter Columbia was memorialized. Robert Crippen, Columbia's first pilot, remembered the great matriarch of the Space Shuttle fleet with these touching words during the KSC memorial service: "Just as her crew has, Columbia has left us quite a legacy."

NASA and contractor employees attended the Columbia memorial service at the Johnson Space Center on February 4, 2003.

A Columbia Crew Memorial Service was held at the Shuttle Landing Facility for KSC employees and invited guests on February 7, 2003. Columbia's first pilot and former KSC Director Robert Crippen is at the podium. Seated to his right are NASA Associate Deputy Administrator for Institutions and Asset Management James L. Jennings, Florida Gov. Jeb Bush, and NASA Administrator Sean O'Keefe. The Columbia and her crew of seven were lost on February 1, 2003, over East Texas as they returned to Earth after a 16-day research mission. Taking part in the service were NASA Administrator Sean O'Keefe, former KSC Director Robert Crippen, astronaut Jim Halsell, several employees, area clergymen, and members of Patrick Air Force Base. The service concluded with a "Missing Man Formation Fly Over" by NASA T-38 jet aircraft.

Section 2 – The Response

Search and Recovery Team Operations

Mishap Investigation Team Medical Efforts for Crew Recovery and Identification

Mishap Response and Lessons Learned:
The Role of the Office of the Armed Forces Medical Examiner and the Armed Forces Institute of Pathology

Johnson Space Center Space Life Sciences Response and Crew Survival Investigation

Kennedy Space Center Operations – Commitment to Safety and Preparedness

Crew Medical and Psychological Support Operations

Search and Recovery Team Operations

James D. Wetherbee

A difficult but essential component of aerospace accidents is the recovery of human remains. Members of the teams that participated in the search and recovery of the human remains of the Columbia crew felt a personal responsibility to succeed for the crewmembers' immediate family members, the workers of NASA, the citizens of the United States, and the international space community. The participants had the guiding principle to recover the remains of the astronauts with dignity, honor, and reverence. The purpose of this chapter is to describe this noble recovery effort, its organizational structure, and the leadership that met this guiding principle.

Immediately after confirmation of the Columbia mishap, NASA initiated its contingency action plan. The NASA Flight Crew Operations Directorate, which includes the Astronaut Office at the Johnson Space Center (JSC), was responsible for the search and recovery of the human remains of the Columbia crew. More than two thousand people contributed to this effort with inspiring and humbling self-sacrifice. The work was dangerous and the terrain was challenging; sometimes it rained and sometimes temperatures were just above freezing. Recognizing the complexity of the task, the number of teams working, and the speed required, the leaders of the search and recovery effort rapidly developed a centralized plan to guide the work and coordinate the teams involved. Over the two weeks that followed, the leaders adjusted the plan and refined the operations, based on valuable input from personnel in the field.

Organizations involved in the effort were extraordinarily helpful. However, operational leaders quickly faced the challenge of knowing how much help to accept and how to coordinate effectively the valuable external assistance that was offered into a comprehensive and cohesive operational plan. Overcoming this challenge required the establishment of a clear and organized hierarchy of leadership.

Initial Organizational Development

The Federal Bureau of Investigation (FBI) was responsible for managing the investigation of this mishap. The location of the debris pattern on the ground in East Texas led to joint jurisdiction being shared by the Dallas and Houston Field Divisions of the FBI. Soon after the accident, when the FBI learned that possible human remains were being discovered on the ground, the FBI and NASA jointly decided to draw on the valuable experience of the FBI's Evidence Response Teams (ERTs), which follow established protocols to recover all human remains with dignity. Members of these teams had previously participated in the Oklahoma City bombing investigation in 1995 and the September 11, 2001, events at the World Trade Center and the Pentagon. The Dallas Field Division of the FBI assumed the lead and FBI Special Agents

Multiple Organizations Contributed to the Search for and Recovery of the Human Remains of the Columbia Crew

- Federal Bureau of Investigation (FBI)
- Federal Emergency Management Agency (FEMA)
- Environmental Protection Agency (EPA)
- White House Liaison Office
- NASA Centers (including Ames Research Center, NASA Headquarters, Johnson Space Center, Kennedy Space Center, and Marshall Space Flight Center)
- Texas Army National Guard
- Texas A&M Forest Service
- Native American search teams
- Air Land Emergency Resource Team
- Local citizens of Sabine and San Augustine Counties (including the cities of Hemphill, San Augustine, and Lufkin)
- Department of Public Safety (Texas Police)
- Local Fire Departments
- Lufkin Civic Center
- Lufkin Mortuary
- Carroway-Claybar Funeral Home
- The Salvation Army
- McDonald's Restaurant (Lufkin)

from Dallas, Houston, and Lufkin were the principal field operatives. Special Agent Mike Sutton from the Houston Field Division coordinated the ERT operations. With knowledge and experience in disaster recovery, these ERTs made effective decisions in organizing and conducting the recovery operations. The FBI provided a well-functioning operation with exceptional personnel. NASA will always remember their valuable, selfless, and dedicated contributions.

The Federal Emergency Management Agency (FEMA) was responsible for managing the crisis. Through mutual assistance agreements, FEMA provided funding and logistical support to enable the FBI to conduct the investigation and multiple agencies to recover the debris.

The Environmental Protection Agency (EPA) was responsible for the safe recovery of hardware debris. EPA officials postponed hardware recovery to allow time for each piece of hardware to be assessed for contamination with toxic fuel and oxidizer from the propulsion systems in the Space Shuttle. For three days after the mishap, local sheriff, police, and fire department personnel guarded the locations of debris until each item was determined by EPA officials to be uncontaminated and safe for collection. Initially, NASA search leaders decided that, although the contamination analysis might delay the recovery of human remains, the delay was acceptable to reduce risk to personnel.

On the third day of the search (February 3), the search leaders determined that the contamination-analysis process was inefficient and that the officials who were guarding the hardware were needed to accelerate the search for human remains. Because NASA personnel could accurately identify which items of debris were not part of the propulsion systems and were free from contamination, the EPA agreed to allow NASA personnel in the field to designate the debris items that were safe for collection by the search teams. The efforts to recover hardware debris and human remains safely proceeded in parallel without waiting for contamination analyses.

Selecting Command Centers

Three types of command centers—strategic, tactical and forward—were established according to operational requirements and locations. First, a strategic command center was created at Barksdale Air Force Base (AFB) in Shreveport, Louisiana. This became the center of operations for FEMA management activities and the hardware-debris recovery, and the mortuary for the human remains. Barksdale AFB was located close to the debris field, and the US Air Force personnel on site provided the logistical, operational, and medical support for the recovery team.

On the first day of operations (February 1), the recovery team determined that the planning and coordination of the search and recovery activities should take place much closer to the field operations. They chose the Lufkin Civic Center as the tactical command center for the human-remains recovery operation.

On the basis of their extensive past experience with large-scale disaster operations, FBI personnel recommended that the operational team use a large, open room for the managers to establish the search and recovery planning and coordination activities.

Command Centers

According to the operational requirements, three types of command centers were needed in the locations described:

Strategic Command Center – Barksdale Air Force Base (AFB), Shreveport, Louisiana, was chosen as the major command center for the hardware-debris recovery operations. This was a large base located near the debris field, chosen because the US Air Force personnel on site were able to provide logistical, operational, and medical support for the recovery team.

Tactical Command Center – The directors of the search needed to be close to the search teams that would be deployed into the recovery field, so the Lufkin Civic Center was selected as the Tactical Command Center for the human remains recovery operation. The large, open space in the building was quickly arranged to allow the organizational leaders of the various agencies to have line-of-sight and direct physical access to each other while decisions were made in the early stages of team formation.

Forward-Deployed Execution Posts – Two smaller forward posts were needed in the field for staging and briefing the search and recovery personnel. These were the areas where the operational plan, generated at the Lufkin Tactical Command Center, was disseminated to the search team leaders before the teams deployed into the field to execute the search and recovery operations.

The Lufkin Civic Center was the Tactical Command Center for the human remains recovery operation.

The Lufkin Civic Center had an acceptable area on the main floor and this space was configured quickly. The team arranged multiple tables to allow the organizational leaders of the various agencies to have line-of-sight and direct physical access to each other while decisions were made in the early stages of team formation. NASA installed a computer local area network and telephones to improve communication and coordination early in the operation. The leaders developed and directed the operational plan for the search and recovery of human remains at this tactical command center in Lufkin, Texas.

Early in the search effort (February 3) the leaders decided that two forward-deployed execution posts were needed in the field for the personnel performing the search and recovery operations in the two Texas counties of Sabine and San Augustine. As the third type of command center, these forward posts became staging and briefing areas for the thousands of volunteer workers involved in the search efforts. The Lufkin Tactical Command Center generated the operational plan for the field leaders at these sites, who then created field plans which were given to individual teams before they deployed into the field to conduct the search and recovery.

Communications were challenging at the beginning of the operation, as coverage for cellular phones was intermittent in the remote and hilly areas of the search corridor. Local mobile transmitters for radios were transported to San Augustine and Hemphill, Texas, to create improved and nearly continuous radio communications coverage for the search teams in the field.

Establishment of the Operational Leadership Team

The senior NASA official at the Lufkin Tactical Command Center was David King, from the NASA Marshall Space Flight Center. King became the Search Director and was accountable for all aspects of the recovery of the human remains, including coordination with executives at NASA and other federal agencies. To execute the operational aspects of the mission, King appointed astronaut and US Navy Captain James Wetherbee as the Operational Search Director to be responsible for creating and executing the search and recovery plan. Wetherbee was the senior representative from the Flight Crew Operations Directorate at NASA, and was responsible for operational decisions involving the activation and deployment of the recovery teams, the methods used and locations designated for the search, the process and procedures used for the recovery and transportation of the human remains, the termination of the search, and the post-search activities for transition and closeout of operations.

Management Positions

A military style of leadership, management, command, and control contributed to the success of this mission, which had simultaneous needs for centralized and decentralized decisions. The following managerial positions were created to lead the teams in the search and recovery effort:

Search Director – responsible for establishing the organization and accountable for all aspects of the recovery of the human remains, including coordination with executives in NASA and other federal agencies.

Operational Search Director – responsible for creating and executing the search and recovery plan, including the associated operational decisions involving the activation and deployment of the recovery teams, the methods used and locations designated for the search, the process and procedures used for the recovery and transportation of the human remains, the termination of the search, and the post-search activities for transition and closeout of operations.

Ground Operations Officer – responsible for developing an operational plan for ground search, and coordinating with the different search groups to execute the plan each day.

Air Operations Officer – responsible for developing and coordinating an operational plan with all the organizations that were offering airborne platforms and sensors for use in the search efforts.

Forward Coordinator – responsible for disseminating the operational plan to the search team leaders at the Forward Deployed Posts before the teams went into the field to execute the search and recovery.

Administrative Officer – responsible for decisions regarding the assignment of astronaut support personnel, local transportation, lodging, and supplies. This officer developed a file system for records and arranged the installation of a computer network and printer.

At the start of the operations, the NASA Search Directors established a military style of leadership, management, command, and control. Astronaut John Grunsfeld, PhD, became the Ground Operations Officer in the Lufkin Tactical Command Center, and was responsible for developing the tactical ground-search plans from the operational plan and coordinating with the different ground-search teams that executed the plans each day. He received field observation information, which was used as planning feedback each night to allow the Operational Search Director and the leadership team in the Lufkin Tactical Command Center to refine the operational plan. The Ground Operations Officer also developed the statistical analysis tool that was used to refine the search area and predict the location of the human remains during the search efforts.

An Air Operations Officer had the responsibilities of developing an airborne-search plan and coordinating the flight activities of the organizations that offered aircraft and sensors for the search operations. Astronaut and US Air Force Colonel Scott Horowitz, PhD, filled this position. Horowitz also used his extensive computer applications skills to develop an independent mapping tool that provided data used in the analysis to narrow the search corridor.

On the third day of the search (February 3), when the NASA team created the forward-deployed execution posts in Hemphill and San Augustine, Texas, astronaut and US Navy Captain Brent Jett became the Forward Coordinator in the field. He disseminated the operational plan and the tactical field plans from the leadership team in the Lufkin Tactical Command Center to the search team leaders in the field before the teams deployed to execute their search and recovery tactical operations.

For the support of the astronaut operations in the Lufkin Tactical Command Center, astronaut Marsha Ivins was designated as Administrative Officer. She was responsible for decisions regarding assignment of astronaut support personnel, local transportation, lodging, and supplies. Ivins organized a system for collection and identification of crew-equipment debris and a file system for records, and she generated the rotational schedule for the field-deployed personnel.

Security personnel from NASA Headquarters and the Marshall Space Flight Center provided protection for all facets of the operation, including security of human remains in the field, record keeping and protection of sensitive medical and operational data, and the dignified transportation of remains to the temporary mortuary at Barksdale. In addition, the security personnel from Marshall Space Flight Center supplied the cellular phones that were needed to ensure that secure communications were always available to participating agencies.

Readiness of Astronaut Support Personnel

As the recovery plan took shape, the NASA Search Directors decided that astronauts would provide leadership support to the deployed teams in the field. Because of the expected psychological difficulties of recovering the human remains of fellow astronauts, the Operational Search Director established a requirement that all astronauts directly involved in the recovery operations should return to Houston after a maximum of three continuous days of operations in the field. The Administrative Officer developed the schedule and coordinated with the Astronaut Office at Johnson Space Center for personnel rotation into and out of the field. Astronauts filling management positions were needed to stay in the Lufkin area and support the effort for periods longer than three days. Because of the stressors involved, these management astronauts were prohibited from participating in the search and recovery operations in the field.

When support astronauts arrived for duty at the Lufkin Tactical Command Center, the Operational Search Director provided briefings on personnel safety, the organizational structure, chain of command, responsibilities in the field, and potential psychological effects, and a description of the coordination required

Briefing for Arriving Astronauts

The readiness of newly assigned astronauts to support the search and recovery mission was enhanced by setting clear expectations. To set expectations effectively while verifying understanding, and to create a common framework for operating, the Operational Search Director provided a briefing to astronauts arriving for duty at the Lufkin Tactical Command Center. The briefing contained the following items:

Organization – A description of the organizational structure and chain of command, and an explanation of the various organizations that were supporting the search.

Operations – A description of the search operations and what to expect after receiving tasking orders. This included a safety briefing for operations in the field, a description of the search teams, tasking that might be expected, transportation to the search area, search methods, description of terrain and weather, and cleanliness precautions for eating in the field.

Responsibility – A statement of the search and recovery team's responsibility to recover the human remains of the Columbia crew with dignity, honor, and reverence, and guidance detailing the methods and procedures used during recovery and transportation to the temporary morgue.

Psychological Support – A brief description of what the astronaut would likely see in the field, and some suggested psychological techniques to use upon recovery of human remains.

Communications – The communications protocols, including cell phone or radio operations, call signs and personnel, information required and desired, check-in and periodic status reports, and the methods used to rigorously control the transmission of information because of the highly sensitive nature of the search results.

Administrative Items – Information on lodging, transportation, meals, search and debriefing times, possible press coverage, and tour of duty length (three days maximum).

Out-briefing – An explanation of the requirement to check in with the Johnson Space Center space medicine psychiatrist after returning to Houston at the completion of the astronaut's three-day tour of duty, regardless of self-perceived psychological fitness.

Security – A description of the security protocols used and personnel assigned to help with transportation of suspected human remains.

for the various organizations supporting the search. Each astronaut team leader was made aware of individual responsibilities and orders within the operation as a whole. The safety briefings included information about field operations and hazards, a description of the terrain, and precautions for working, eating, and operating in the field environment. Significant effort was spent in the orientation briefings on the safety, decision-making, and emotional aspects of the search, to prepare newly arriving astronauts for the challenges of search and recovery of the human remains of fellow crewmembers that had been subjected to hypersonic reentry of the Earth's atmosphere from space.

The astronaut team leader provided each team member a clear statement of responsibility for the dignified recovery of all human remains, particularly detailing methods and procedures used during recovery and transportation of remains. This statement included communications protocols such as mobile phone and radio etiquette, call signs of teams and personnel, information required and desired, status reports, and methods used to transmit highly sensitive information. All astronaut volunteers also received a briefing on the nature of the psychological stressors involved in such an operation. Early in the recovery efforts, to reduce potential emotional stress, the Operational Search Director suggested to the support astronauts (as well as other volunteers) that they try not to think about identifying the remains but rather try to think of all the remains as being part of the Columbia crew. Many of the support astronauts appreciated this technique and found it helpful.

All personnel who supported the human remains recovery operations had to make critical decisions while demonstrating great composure and distinction in their actions. They accomplished their mission under difficult environmental, physiological, and psychological conditions. The tireless efforts and leadership skills displayed by the astronauts who participated in the search and recovery process led to the success of the search and recovery operation.

Development of the Search and Recovery Plan

The initial phase of developing the search and recovery plan consisted of the activation of the command centers, the identification of available personnel and other assets, and the establishment of communication and protocols for transferring information. Immediate concerns for the safety of all personnel were identified and addressed before further actions were taken. In this initial phase, personnel were deployed to multiple locations in the predicted debris field to gather intelligence information to help shape the development of the operational plan.

On the basis of what was observed in the field, the operational leaders at the Lufkin Tactical Command Center developed the search and recovery plan and filled management positions within the organizational

Guidelines for Making Decisions

To succeed in this demanding and complex search and recovery effort, which extended over thousands of square miles, leaders had to make correct decisions. Some operational decisions were centralized, whereas others needed to be decentralized and made quickly by distributed field leaders. The following guidelines helped the search and recovery leaders to make effective decisions:

Mission Statement – We must recover the human remains of the Columbia crew with dignity, honor, and reverence.

Timeliness – We must find the human remains quickly, because of the dual responsibilities we feel to satisfy the shared human value of recovering remains and to preserve the possibility of learning forensic information that might benefit future spaceflight crews through designing improvements in space vehicles.

Integrity – To inspire the highest integrity in decision-making, we will follow an *"8, 8, 8 Rule"* a reminder that "8 days, 8 months, and 8 years from now, we must be able to live with the consequences of the decisions that we will make in the field, so every decision must be based on our highest judgment using our greatest professionalism and human values."

Search Area Collapse – We will not reduce the size of the search area until all members of the leadership team are confident, on the basis of technical analysis and justifiable rationale, that the reduced area still contained all the human remains.

Data – To prevent being misled by any theories about how Columbia broke apart in the upper atmosphere, only the *ground-truth data* of confirmed locations of human remains will be used to reduce the size of the search area.

hierarchy. Simultaneously, the leaders designed a continuous improvement process for the plan. As information was reported from the field to the command centers, the search and recovery plan was adjusted and refined for more effective operations. Planning sessions were held each evening after sunset when the field team leaders returned, and tasking was revised for the operations on the next day. The field team leaders provided valuable feedback to improve the quality of the plan. A great deal of trust and respect developed among the operational management team. Over the 12 days after the mishap, this integrated and dedicated team led 2,000 people in successfully recovering the human remains of the Columbia crew.

Defining the Search Area

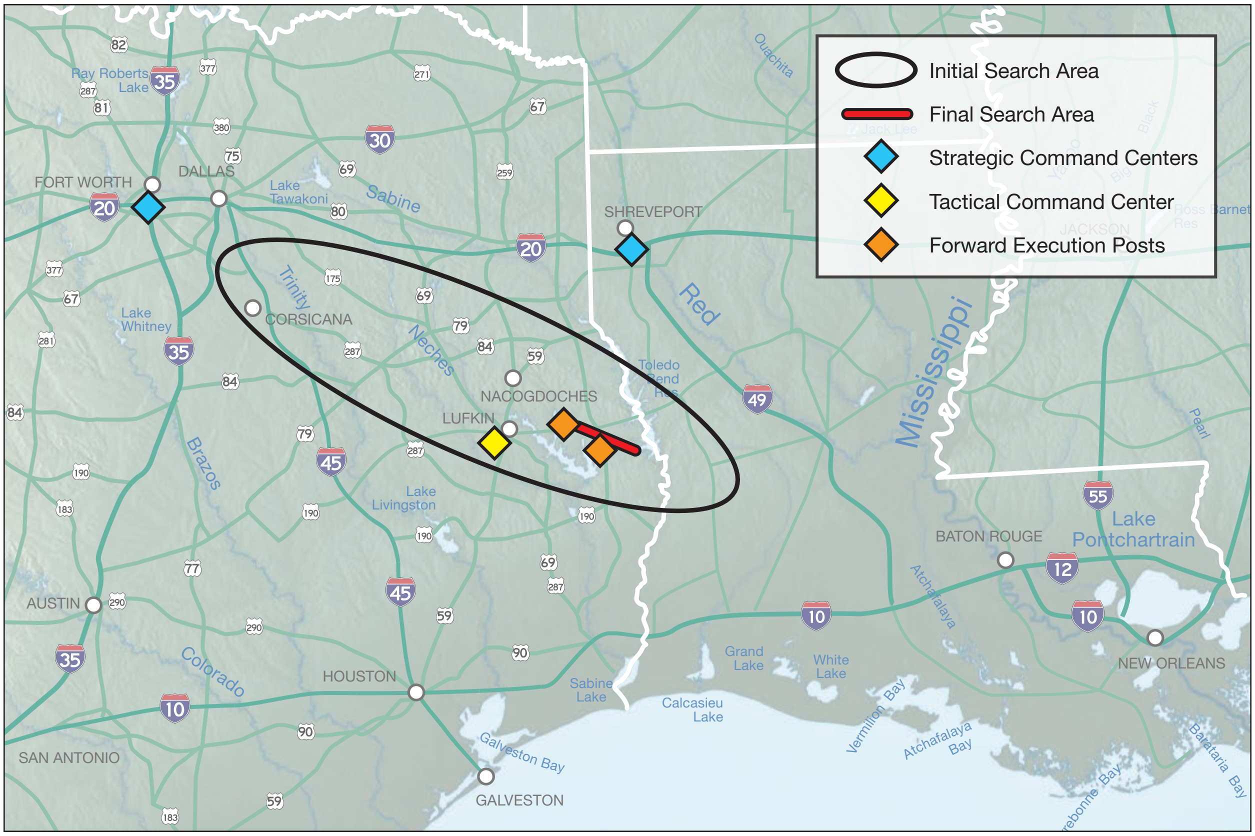
The impact pattern of Columbia debris was predicted by radar tracking of the falling debris. The prediction covered an area that was 200 miles long and 50 miles wide, designated as the initial search area. Local citizens reported several sightings of suspected human remains at sites in an eastern part of this initial search area. Local authorities were dispatched to each of these sites to provide security, and the FBI immediately deployed their ERTs to document the location and condition of any suspected remains.

On the second day of the recovery effort (February 2), the Search Directors concluded that the 10,000-square-mile search corridor was too large to search expeditiously. The designated search area had to be reduced to a manageable size that still contained all the human remains.

Guidelines for Making Decisions

The Operational Search Director developed several guiding principles to help the leaders make the correct decisions and to maximize the chances for successfully recovering the human remains of the Columbia crew.

Above all, the recovery of the human remains was to be accomplished with dignity, honor, and reverence. Timeliness of searching was of great importance, not only to satisfy the human emotional need to recover the remains quickly, but also to preserve the possibility of learning forensic information that might benefit future



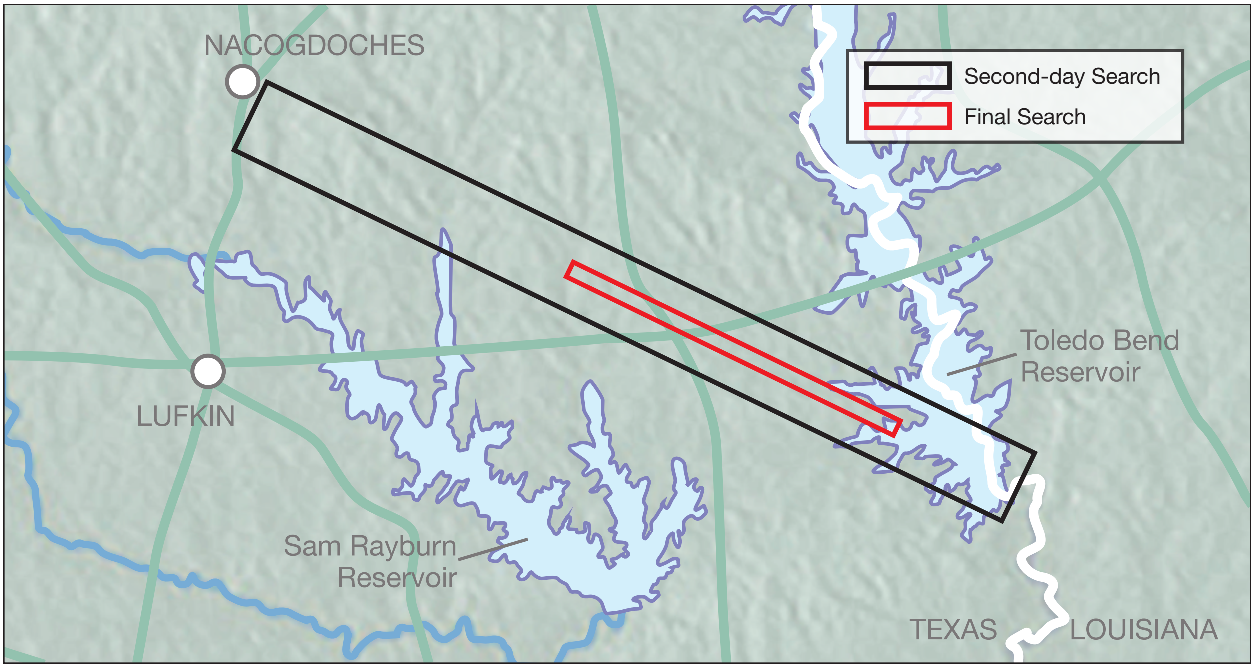
Initial Search Area (200 mi × 50 mi). Also shown are the locations of the Strategic Command Centers, the Tactical Command Center, and the two Forward Execution Posts.

space flight crews through design improvements in space vehicles. A deliberate reduction in the size of the search area was necessary. This reduction should be accomplished only if all members of the operational leadership team were confident, based on technical analysis and justifiable rationale, that the reduced area still contained all of the remains. Also, reduction of the search area size should not be based on yet unproven theories of how Columbia broke apart and the postulated trajectory of human remains. To prevent being misled by these theories, only the *ground-truth data* of confirmed locations of human remains was used to reduce the size of the search area. Finally, to inspire the highest integrity in decision-making, the Operational Search Director formulated what was briefed as the "*8, 8, 8 Rule,*" a reminder that "8 days, 8 months, and 8 years from now, we must be able to live with the consequences of the decisions that we will make in the field, so every decision must be based on our greatest judgment using our best professionalism and human values."

Statistical Analysis Used to Reduce the Size of the Search Area

Several hundred suspected remains were found during the search. The majority of suspected remains that were found were later determined to be from animals. Although the DNA results of suspected remains might have provided conclusive data during the initial search operations to determine accurate search areas, these DNA results required several days to generate. At the same time, some of the suspected remains had the distinctive appearance of human tissue that had been exposed to hypersonic descent to Earth. The team plotted on a map the locations of these known-human remains. Though all potential human remains were collected and sent for DNA analysis, those that appeared to be from animals were not used in the mapping analysis. This statistically based analysis allowed the leaders to identify a narrow search corridor within the larger hardware-debris field. By the second day of search and recovery efforts (February 2), the operational leaders made the decision to reduce the defined search area to a corridor that was 5 miles wide and 60 miles long, centered on a statistically averaged straight line along the path of distinctive remains recovered in the field.

For the following two days (February 3–4), teams searched designated areas with the highest probability of finding human remains expeditiously. These were areas with easy terrain, which enabled large regions to be covered quickly within the 5-mile-wide corridor. Search areas were chosen near previously sighted human remains. Because of logistical constraints, the search patterns were not changed daily. It took two days to redirect the extensive search teams effectively to new locations or new strategies. A great deal of effort was



Second-day Search Area (60 mi × 5 mi) and Final Search Area (25 mi × 1 mi).

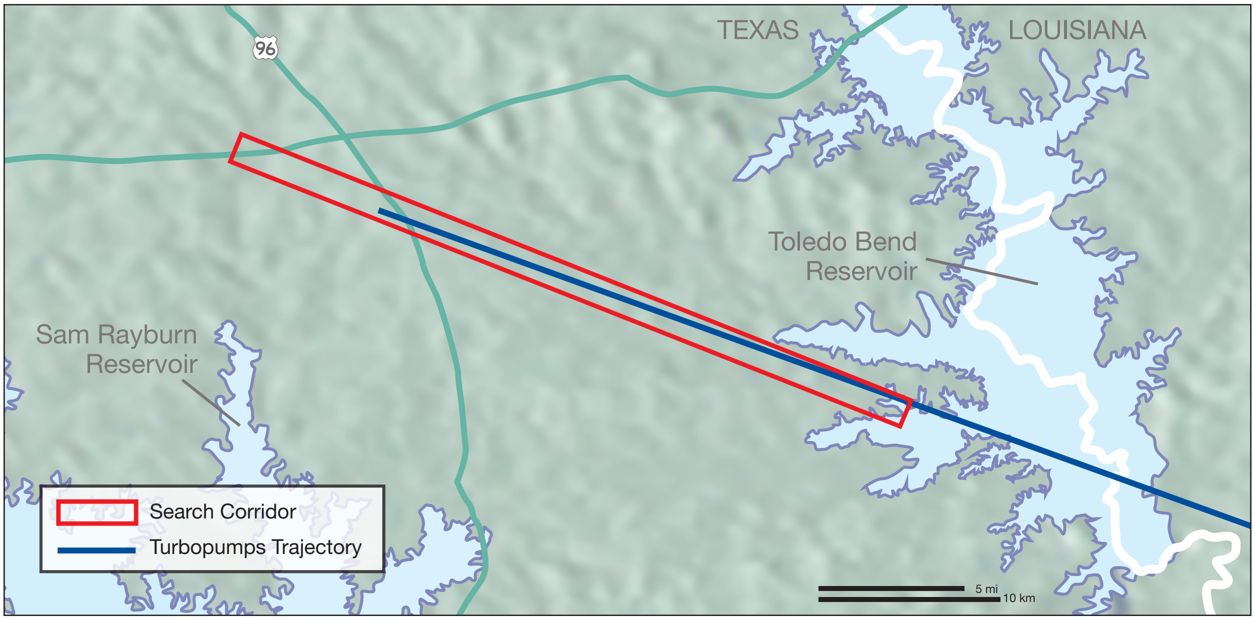
made to ensure that team tasking and search directions would not lead to wasted time in incorrect recovery areas.

After DNA results became available, the operational leaders of the search developed higher confidence in defining the search corridor. A statistical analysis was used to reduce the size of the search corridor to only 1 mile wide and 25 miles long. The analytical reduction was accomplished by using two independent mapping models that provided a 95% statistical confidence that all remains found in the future would be located within the 1-mile-wide corridor.

Final Adjustment of the Search Corridor

Several days after the accident, the mishap team determined the coordinates of the impact sites for the densest parts of the Space Shuttle, the three high-pressure turbopumps from the main engines. With their high ballistic coefficients and therefore their greater ability to overcome air resistance, these turbopumps traveled the farthest and were found along the debris trajectories farthest east in Fort Polk, Louisiana. These locations, and the locations of the human remains that had been found to the west, were plotted on a map. The next step in the mapping analysis was to connect the statistical centroid of the location of human remains to the impact points of the turbopumps. In a gnomonic projection, all great circle lines are depicted as straight, so the connecting line represented the accurate ballistic trajectory of the high-speed debris and human remains. There was a slight angular misalignment between this new accurate ballistic trajectory and the previously defined search corridor (shown as a red box in the figure), which was based on a less accurate mapping analysis using a Mercator projection. Without moving the centroid of the previously defined search corridor, the azimuth of the search corridor was rotated so that it was parallel to the accurate trajectory of the high-density turbopumps using the gnomonic projection. After this final analysis was completed by rotating the search corridor using the accurate ballistic trajectory, the operational leaders had high confidence that any other human remains would likely be found in this final search corridor. Search teams were directed to different locations corresponding to the slight rotation.

No further analytical refinement of the search corridor was possible statistically. Analyses of the locations of human remains resulted in reducing the size of the corridor to 1 mile wide and 25 miles long. The ballistics analysis fixed the proper azimuth of the corridor. At this time, the strategy for the search was changed from a targeted search of specific areas within the corridor to a comprehensive search of the entire corridor. The Texas Army National Guard assisted with the comprehensive search strategy by providing necessary additional resources in the search and recovery.



Misalignment of Search Corridor Azimuth. The known trajectory of the turbopumps (blue line) was used to make a final adjustment to the misaligned search corridor (red box).

Search Methods

The fundamental search plan was to use line searches with large teams of volunteers, using Global Positioning System (GPS) coordinates for tracking and documenting the location of any suspected human remains. This search method, which used the skills and judgment of humans, proved to be the most effective. During 12 days of searching, as many as 2,000 volunteers and Texas Army National Guard troops engaged in the line searches. These volunteers and troops maintained professional demeanors at all times and were dedicated to accomplishing the goal. The teams faced difficult challenges during the search and recovery effort, including hazardous terrain with rocky hills, dense forest, and thicket. In some areas, the branches and bushes were so dense that the searchers walked no farther than an arm's length away from each other to search the underbrush reliably. When these conditions were encountered, the progress of the line search slowed significantly. The operational leaders appreciated the dedication displayed and personal sacrifices made by the search teams.

Dog teams that specialized in human cadaver searches were also used. These teams were sometimes successful, but the dogs were occasionally confused

Volunteers and Texas Army National Guard troops conducted line searches for crewmember remains.

Dense forest and thicket were two of the many challenges encountered by searchers.

with false indications from other humans in the area. The operational leaders had more confidence in the reliability and greater numbers of the human search teams operating in long lines to search large areas. To develop confidence that human remains were not overlooked, the search directors used the dog teams effectively to search in expanding spirals around the sites of suspected human remains after the recovery teams had left the area.

Horse teams were used to search open areas. Because they could cover large areas of territory quickly, this search method was used effectively in open areas just outside the defined corridor to verify that human remains had not fallen outside the boundaries.

Helicopter spotters were used to identify areas of the forest where broken branches in the tops of trees indicated possible high-speed impacts of remains. Though successful initially in identifying the location of some human remains, this technique eventually became ineffective after high winds in the area led to extensive branch damage unrelated to the Columbia mishap.

Search helicopters operated from the Angelina County Airport, six miles south of Lufkin, Texas.

After 10 days of searching, a significant amount of human remains had not yet been found from one of the seven crewmembers. Emotions were strained and volunteers felt a strong desire to recover the remains of each crewmember successfully and bring closure to the search effort. On the tenth day of the recovery effort (February 10), more human remains were discovered. The team leaders attempted to counsel the ground-search teams to manage their emotions and wait for identification that might confirm the recovery of the remains of the seventh crewmember. Unfortunately, the erroneous belief had already spread among the search teams that the search effort had been completed successfully. This created an emotional release that had to be reversed after it was communicated to the team members that the remains of the seventh crewmember had not been recovered. The remains of that crewmember were recovered successfully on the eleventh day of the search.

Care of Crew Remains

Each recovery team included members of the FBI ERTs, an astronaut, a religious member (minister, priest, or rabbi), a NASA security person, and a pathologist, if one was available. Ceremonial last rites were administered with reverence in the field. The teams recovered the human remains with dignity and used appropriate medical precautions. The astronaut and security personnel escorted the human remains with honor from the field to the Lufkin collection point. At this Lufkin facility a medical doctor from JSC Space Medicine accepted the crew remains. At the end of each day astronaut and security personnel escorted the remains to a temporary morgue at Barksdale AFB.

In the morgue at Barksdale AFB, NASA flight surgeon Philip Stepaniak, MD, accepted the human remains. Dr. Stepaniak provided leadership for the development of a NASA medical contingency plan using lessons learned from the NASA Challenger accident in 1986 and the TWA-800 airliner accident in 1996. At the Barksdale AFB morgue, Dr. Stepaniak and his team enacted this contingency plan and made arrangements for identification and transportation of the crew remains to the Armed Forces Institute of Pathology at Dover AFB. With the appropriate honor-guard protocol, the initial human remains were placed in seven transfer cases to be accepted by the US Air Force and transported to Dover AFB on February 5, 2003. The seven transfer cases were draped with the national flags of the Columbia crewmembers, six Americans and one Israeli.

The decision of when these initial remains would be transported to Dover AFB was challenging, as opposing considerations had to be balanced carefully. There was a desire to wait until the human remains of all seven crewmembers were recovered so that seven transfer cases could be sent one time to minimize the grieving process for the families and the international community. At the same time, there was a conflicting desire to transport the recovered human remains as soon as possible to the Armed Forces Institute of

Pathology to retrieve forensic information before tissue breakdown occurred by natural decomposition. This decision was further complicated by the fact that it was difficult to know if representative human remains had been recovered from all seven crewmembers. This information would be available only after DNA or dental record analyses could be completed and verified, a process that might span several days. Four days after the accident, a joint decision was reached by Operational Search Director Wetherbee and Dr. Stepaniak to send the human remains in seven transfer cases, despite the fact that not all human remains had been recovered and some had not yet been identified. This decision, though difficult, was based on shared human values with cognizance of the difficulties faced by the grieving families, the NASA community, and the public at large.

Analysis of Remains and Dissemination of Data

On arrival at Dover AFB, the remains were transferred to the Armed Forces Medical Examiner. The medical examiner and his team performed the forensic analyses and transmitted the results of the DNA analyses to the NASA Space Life Sciences Directorate at JSC for immediate dissemination to the families of the Columbia crew.

The medical examiner also provided the DNA findings to Dr. Stepaniak and Director Wetherbee to assist in field analysis, planning for search operations, and establishment of tasks for the search teams to locate additional human remains. The dissemination of these results was controlled rigorously. Using a code generated by Dr. James Bagian, a former astronaut and an advisor to the Columbia Accident Investigation Board, encoded results of the DNA findings were transmitted by means of a landline telephone from Dr. Stepaniak to the Lufkin Tactical Command Center. Each specimen was identified using a two-letter random code array, which enabled the locations of human remains to be plotted on a map without crewmember identity. Only Drs. Bagian and Stepaniak along with Director Wetherbee possessed the key to the code array and knowledge of the identity of all human remains. All coded data of human remains were tightly controlled, with the location information being separated from any database containing hardware or debris information. Maintaining confidentiality was not an easy task to accomplish; in one instance, a potential breach of security was identified when a volunteer-generated map containing coded data and location of human remains was exposed briefly to the Internet. Data security personnel acted quickly to secure the breach, and to increase security and control over data release.

Many search team members, including members of the leadership team, expressed a desire to remain insulated from identity information about the human remains, as they felt that they could not operate effectively if they were aware of the location of the identified human remains. Among the leadership and search teams, only Operational Search Director Wetherbee knew this information. But this isolation of information introduced a risk that an erroneous decision made by Wetherbee in developing the plan would be unchecked by his insulated leadership team. To mitigate the potential consequences of such an error in decision-making, Wetherbee presented the comprehensive search plan to Dr. Bagian and included the identities of the human remains and how this information was used to refine the plan and search for additional human remains. Dr. Bagian had performed a similar role as the director of the search and recovery efforts for the human remains from the Challenger accident 17 years earlier. His valuable experience and insightful analysis provided the necessary confidence in the Columbia search and recovery plans and operations.

Termination of Recovery Efforts

The decision to terminate the search for human remains of the Columbia crew was difficult. After careful consideration, this decision was made according to the following rationale. Although the recovery teams had not found 100% of the crew remains, a high percentage of remains of all seven crewmembers had been found and identified. Statistical data indicated that any remains that had reached the surface of the Earth would likely be located within the 1-mile-wide search corridor. After 12 days, the corridor was searched extensively, along with many of the marginal areas in the larger 5-mile-wide corridor. The only part of the final search corridor that was not searched extensively was a small area of particularly dangerous wetlands containing potentially dangerous snakes. The search leaders decided this area presented an unacceptable risk to the volunteers, and the small area was left unsearched. Finally, after observing the intense dedication and willingness of 2,000 volunteers to risk personal safety to help accomplish the goal, and because the search efforts had been so successful until that time, the Operational Search Director made the decision to terminate the official search for human remains on February 13, 2003.

After conferring with the Armed Forces Medical Examiner and the Mortuary Affairs specialists, who had relevant experience investigating aircraft accidents, the search leaders anticipated that small amounts of human remains might be discovered more than a year after this accident. The NASA medical group at the Barksdale AFB Strategic Command Center arranged with NASA Headquarters, the Office of the Armed Forces Medical Examiner, the Armed Forces Institute of Pathology, and Armed Forces Mortuary Affairs to have a plan, with a contract in effect, for future recovery and transportation of suspected human remains that might be found. One hour before the active search for human remains was officially terminated on February 13, FEMA disseminated the forward plan to the local law enforcement agencies in the State of Texas. The plan provided reporting procedures to follow in the event any suspected human remains were found, with procedures for the delivery of any specimen to the Armed Forces Institute of Pathology.

Because ground and airborne search teams remained in the Lufkin area to search for hardware debris, the plan contained a recovery process for human remains that was similar to the process that had been in effect. If suspected human remains were found by the hardware search teams, the Lufkin FBI ERTs would be notified immediately and deployed to the field site. If they thought it was likely that the remains were from the Columbia crew, the Lufkin FBI would call the Astronaut Office and a medical doctor would deploy to the site to recover and transport the remains to JSC in Houston. The Emergency Operations Center medical representative and the Flight Medicine Clinic at JSC would make arrangements with the Aircraft Operations Division at JSC to transport the human remains to Andrews AFB, where the remains would be received by the Armed Forces Medical Examiner.

On March 7, 2003, teams that were searching the area for hardware debris found a small amount of human remains from the Columbia crew, less than one-half mile north of the northern boundary of the 1-mile-wide search corridor. These were the only human remains to be found outside this final search corridor. The remains were recovered and transported to Andrews AFB with an astronaut escort. Teams searching for hardware debris completed their search of the adjacent areas up to two miles north of the boundary of the final corridor. No other human remains were found.

Psychological Readiness and Support for Astronauts

Profound psychological consequences must be anticipated for search and recovery personnel after an event such as the Columbia mishap. In light of initial reports of the condition of the human remains found by local citizens, the recovery process was predicted to be difficult for all involved. Compartmentalization was embraced as the best coping mechanism for the task, and concentrating on the operational task rather than considering the tragic nature of the mishap allowed volunteers to operate effectively. Some of those who participated in the recovery operation decided not to initiate their personal grieving process or to attend speeches or memorial services, to help them maintain compartmentalization of the psychological stress involved.

Personal Commitment of Volunteers

Throughout the operation many people made flawless decisions and displayed remarkable leadership, demonstrating the integrity of the individuals involved. Many personal sacrifices were made, and the overwhelming dedication and motivation of all involved was astounding. The personal commitment and selfless efforts of the volunteers will long be remembered.

Acting on a recommendation from Special Agent Sutton, coordinator of the FBI ERTs, the Chief of the Astronaut Office directed all deployed astronauts who supported the recovery operations to have a psychological debriefing session with Dr. Chris Flynn, JSC space medicine psychiatrist, after returning to Houston. Making this debriefing session mandatory provided support to all deployed astronauts regardless of their self-perceived psychological fitness or willingness to request support. Some astronauts did not foresee that the session would be valuable. Other astronauts may have desired psychological support but chose not to request such support because they felt embarrassed. Ultimately, most of the deployed astronauts considered the psychological debriefing to be a positive experience.

Some members of the space community had advised against using active astronauts in the recovery process. Leaders of the search effort after the Challenger accident had found that adverse psychological effects could occur and linger in an astronaut long after the operation had concluded, and that these psychological impacts might decrease the performance of the individual during future flight operations. At the beginning of the search operation for the Columbia crew, the potential disadvantages were weighed against the value of having astronauts with considerable experience, dedication, and compassion conduct the challenging mission. NASA managers decided that it would be best to allow the volunteer involvement of active astronauts in the recovery process. If faced with a similar situation in the future, managers likely would make the decision to use active astronauts in the same way.

Conclusions

Because of the momentous nature of the Columbia accident, the people who supported this search and recovery effort arrived with an innate and clear sense of the mission. More importantly, volunteers understood that the recovery mission transcended their individual desires and motivations, and they came with a pure selfless intention to help. Although these factors created powerful conditions for success, the leaders of this effort nevertheless communicated an explicit mission statement to the people and teams. The mission was to recover the human remains of the seven astronauts of the Space Shuttle Columbia with dignity, honor, and reverence. Ultimately, the remains of the seven crewmembers of space flight STS-107 were found, ceremonial last rites were administered with reverence in the field, and astronaut and military personnel escorted the remains with honor to the medical examiner at the Armed Forces Institute of Pathology at Dover AFB.

From the beginning of the recovery efforts, the leaders of the search and recovery operations observed that those who volunteered for this mission embraced the highest of personal values. These values were reflected in conversations and behaviors conducted with great respect and professionalism. The operational leaders made explicit the values that were expected of team members, with the intention that such personal values would be used collectively to guide actions and decisions made by all team leaders and individual volunteers. Emphasis was placed on the safety of personnel and clear communications between leaders and team members. Information gathered from the field was recognized for its importance and was used to improve the quality of the plan, which led to the success of the recovery operation.

Throughout the operation many people made flawless decisions and displayed remarkable leadership, demonstrating the integrity of the individuals involved. While they were in East Texas and Louisiana, NASA personnel came to understand how important the Space Shuttle Program was to the local area volunteers. Many personal sacrifices were made, and the overwhelming dedication and motivation of all involved was astounding. Out of tragedy came greatness.

Mishap Investigation Team Medical Efforts for Crew Recovery and Identification

Philip C. Stepaniak, Michael R. Chandler, and Robert Patlach

The Space Shuttle Program established procedures for the Columbia Mishap Investigation Team (MIT) with the purpose to gather, guard, and preserve all evidence pertinent to the incident; the MIT was not responsible for determination of the cause. Team members included a NASA flight crew surgeon. This chapter describes the NASA flight surgeon's relationship to the Columbia MIT and the team's efforts to complete the recovery of crewmember remains, identify the crewmembers, establish accurate communication with the crewmembers' families, and assist the forensic teams.

Background

During the advent of the Space Shuttle Program, the flight surgeons of the Medical Operations Branch at the Johnson Space Center (JSC) in Houston worked together with the emergency medical services (EMS) personnel at the Kennedy Space Center (KSC), Florida, and the Department of Defense (DOD) Manned Space Flight Program Support Office (DDMS) at Patrick Air Force Base (AFB), Florida, in preparation for a spacecraft mishap that could occur during launch or landing. After the Challenger accident in 1986 the JSC Space Life Sciences Directorate provided an internal report on the cause of death of the Challenger crewmembers. The lessons learned included the determination that the crew should be protected from the possibility of rapid decompression and have a means for bailout.

The Medical Operations Branch assisted the Space Shuttle Program in upgrading crew egress, escape, and bailout equipment and procedures. For return to flight after the Challenger accident, these modifications involved the use of a launch and entry partial pressure suit and the addition of an emergency mode procedure for crew bailout. In 1994, NASA began using the more capable fully pressurized advanced crew escape suits that were worn by the STS-107 astronauts.

These additional upgrades in equipment and procedures required further training for EMS personnel during launch and landing activities. As a result, the Medical Operations Branch provided a training course that began in 1988. This course was originally taught at JSC; but in response to student feedback, the course was later moved and taught at each of the primary landing sites within the United States. The course was also taught at military bases in Europe that supported the Transoceanic Abort Landings at the following air bases: Moron or Zaragoza in Spain; Istres, France; Ben Guerir, Morocco; or Banjul, The Gambia. The primary reason for the change was to provide more specific, detailed training that was needed for each particular site.

Since the Medical Operations Branch had additional responsibilities related to spacecraft contingency operations, they decided to consolidate these efforts into a single Contingency Medical Group (CMG) that was formed in January 1998. The CMG, serving under the direction of the JSC Space Medicine Division of the Space Life Sciences Directorate, selected a group of flight surgeons involved in space flight operations to develop contingency plans and responses, and to investigate any NASA aviation or spacecraft mishaps.

In May 1998, the Aerospace Medical Association (AsMA) held its annual conference in Seattle, Washington. During this conference, a panel presentation and discussion was held on the 1996 crash of TWA flight 800 (Boeing 747) in the Atlantic Ocean. The panel members specifically discussed the medical and legal challenges of the mishap investigation and the interaction of the many federal and local agencies involved. Participants in this discussion were members of the National Transportation Safety Board (NTSB), the FBI, the US Coast Guard, the US Navy, and New York State authorities from the Suffolk County medical examiner's office. The Joint Committee on Aviation Pathology of the Armed Forces Institute of Pathology (AFIP) provided detailed forensic analysis. At this lecture they discussed the recovery of wreckage and human remains from the ocean, processing of remains, and DNA identification of fragmented and decomposed tissues. Members of the CMG attended this session and were impressed by the efforts that had gone into the TWA 800 investigation, recognizing their relevance to space flight operations.

Upon hearing of the efforts of the AFIP after the TWA 800 crash, the CMG brought this information to the attention of the Medical Operations Branch, which subsequently arranged a tour of the AFIP Port Mortuary at Dover AFB, Delaware, in 1999. NASA flight surgeons, an astronaut representative, contingency personnel from both JSC and KSC, and medical personnel from the DDMS attended this meeting, which included the Office of the Armed Forces Medical Examiner (OAFME) and the Office of Mortuary Affairs at Dover AFB.

During this visit, CMG personnel toured the facilities in which the processing of human remains occurred as well as areas where the deceased were prepared for burial. Over the course of the visit, discussions with the AFIP included spacecraft contingency scenarios that could occur during launch, on orbit, and during reentry and landing, and how such scenarios could be handled with the resources at the OAFME. Services discussed included air transportation of remains to Dover AFB, postmortem examinations, reprocessing of remains, and air transportation to a location designated by the next of kin or other legal authority. JSC's Space Medicine Division would provide all support materials including medical, dental, and DNA records as well as radiographs and consent forms. Although no formal written agreements were produced at this meeting, oral agreements were reached to include the assistance of the AFIP in the case of a space-related disaster. At the same time, contingency medical team members were able to coordinate their efforts and skills to develop an enhanced approach for any future spacecraft mishap.

The Mishap – Initial Activation of the MIT

On February 1, 2003, the Mission Control Center (MCC) in Houston lost the signal from Columbia at 08:59:32 a.m. CST during its reentry over Texas. Shortly thereafter, the entry flight director had the MCC secured and in lockdown. All calls from inside the MCC to outside lines were disabled, but incoming calls were allowed. Richard McCluskey, MD, was the flight surgeon on console in the MCC at the time of the mishap. Members of the CMG reported to the Action Center in the MCC, where the Space Shuttle Mission Management Team (MMT) was meeting, to quickly begin preparations to activate the MIT for search and recovery efforts led by David Whittle. The atmosphere at that meeting was solemn, with conjecture regarding the mishap very much present. As the formal meeting began, managers called for an end to speculation, requesting that all involved focus instead on the recovery of the crew and the vehicle. It was at this time that team members officially learned that the crew had perished during the high-altitude breakup of the orbiter Columbia over Texas. Exact details of the altitude, speed of the breakup, and location of the debris field were later provided by the Department of Defense (DOD).

Barksdale Air Force Base, home of the Eighth Air Force, was the strategic site for the Columbia Mishap Investigation Team.

During this initial meeting of the MMT, managers discussed potential staging of the recovery operation at various locations in Texas and Louisiana. Multiple locations around the debris field were discussed, with security and transportation constituting the major concerns. Staffing of the MIT was also discussed and decisions had to be made, particularly regarding the choice of the medical support team members. Standard operating procedure called for the primary and deputy mission crew surgeons (Smith Johnston, MD, and Stephen Hart, MD), the physicians assigned to the crew throughout their training, to act as the primary medical members of the MIT. However, these physicians were at KSC with the crew families at the time of the mishap and were occupied by caring for family members in the wake of the disaster. Since these physicians were well known to the families and had close personal bonds with the crew, the Space Life Sciences Directorate recommended that these physicians remain at KSC with the crew relatives. Instead, members of the CMG, Philip Stepaniak, MD, NASA flight surgeon, and Michael Chandler of Wyle Laboratories Inc., Houston, space flight medical contingency coordinator, were appointed as medical representatives to the MIT. Space Medicine Division management, with concurrence from the Space Life Sciences Director, provided a single point of contact to disseminate information to all levels of management, thus releasing the flight surgeon at the MIT location to focus on recovery and identification.

By 11:30 a.m. CST, the MMT decided to stage recovery efforts at Barksdale AFB, Louisiana. This location was north of the main debris field, but was selected as the best choice because of its security and capabilities for rapid air transportation in multiple types of aircraft.

Medical members of NASA MIT at Barksdale Air Force Base confer with military officers of the DDMS.

At the same time, NASA established a Disaster Field Office (also called the Tactical Command Center, headed by astronaut James D. Wetherbee) in Lufkin, Texas, for the recovery of human remains because of its proximity to reports of remains in the area. By 3:30 p.m. CST that day, the advance MIT members were flying from Ellington Field in Houston to Barksdale AFB. During the flight to Barksdale AFB, Stepaniak and Chandler carefully reviewed the contingency action plans for space operations while preparing for the recovery effort ahead. The 2nd Bomb Wing Vice Commander, Col. Charles McGuirk, met with the MIT members around 4:30 that afternoon. Despite concurrent operations at the base, specifically ongoing preparations for an international conflict with Iraq, Col. McGuirk informed the MIT that the base would offer full support for their efforts. Barksdale AFB personnel immediately provided resources for the establishment of MIT operations, including office space, transportation, local lodging, communications, and computers.

The MIT medical representatives were next introduced to members of the Barksdale Flight Surgeons Office, US Air Force flight surgeon Col. Jerry Owens and the Squadron Services Mortuary Affairs Officer, Maj. John Ogden. Representatives from the NTSB and OAFME flight surgeon US Navy CAPT Douglas Knittel, MD, were also present for assistance, given the extreme nature of the accident and the extensive debris field. The medical representatives discussed the operational plan with these individuals, particularly regarding personnel, equipment, procedures, and communications. These discussions took place amid a nearly continuous stream of incoming calls from the Lufkin Disaster Field Office and JSC, as team members at these locations raced to establish an operational plan.

One of the first challenges faced was the designation of a hierarchy, particularly as medical team members were acutely aware of the need to control the flow of information regarding human remains recovery. Jeffrey Davis, MD, the director of the JSC Space Life Sciences Directorate, became a single point of contact for the medical teams, to avoid confusion and the inadvertent release of private crew-related information. Throughout this period, local citizens made multiple calls about possible human remains and toxic debris sightings. It was quickly realized that search and recovery team members and civilians alike would need clear information about procedures for handling both human remains and toxic debris.

On the evening of February 1, Dr. McCluskey, NASA flight surgeon and pathologist, and Robert Patlach, space flight medical contingency coordinator, deployed to Lufkin. They met with astronaut physician Dafydd (Dave) Williams, MD, and FBI Evidence Response Team members at the office of local pathologist James Bruce, MD. Bruce's office became the initial collection point for all recovered Columbia crewmember remains. Facility security was provided by the Texas Department of Public Safety, the US Marshals Service, and the

DOD Criminal Investigative Service. Plans called for remains recovered in the field to be transported to the collection point in Lufkin. After preliminary review and assignment of tracking numbers, the remains were transported to Barksdale AFB. The Batesville Casket Company, Batesville, Indiana, donated caskets for crewmembers, and the Carroway–Claybar Funeral Home in Lufkin donated hearse services.

Crew Remains Recovery

As the news media presence grew exponentially the next day, Barksdale AFB established enhanced security measures at the base to maintain privacy and allow operations to proceed unhindered. Simultaneously the number of MIT personnel numbers increased since team members had arrived late the night before. The atmosphere at the morning operational meeting was increasingly intimidating as high-ranking members of federal and local government agencies arrived to oversee operations. The Federal Emergency Management Agency (FEMA), the Environmental Protection Agency (EPA), and the NTSB provided a number of personnel to support NASA's recovery efforts. The lead of the MIT, David Whittle, began the meeting by stating that the primary mission of the field teams was to collect all human remains, vehicle debris, and evidence for transport to the MIT at Barksdale AFB and from there, to final locations for analysis.

As the meeting concluded, medical team members gathered with all personnel participating in human remains recovery activities. This medical assembly consisted of personnel from the AFIP; DOD; NTSB; EPA; FEMA; FBI; KSC Security; the Barksdale Flight Surgeon's Office, Mortuary Affairs Office, Security Office; JSC Public Affairs Office, Legal Affairs Office, Photography, and Aircraft Operations. This initial meeting served the important purpose of ensuring that all team members were known to one another for the difficult operation ahead. Working with the Lufkin Tactical Command Center, Stepaniak defined the plan for the recovery of crew remains in the field and transportation of the remains to an initial collection post in Lufkin, then to a temporary morgue facility at Barksdale AFB for identification, and finally to Dover AFB for analysis and for release of remains to the crewmembers' families.

Afterward, the day was filled with multiple activities needed to prepare Barksdale AFB for the receipt of remains. First, Stepaniak contacted the JSC Flight Medicine Clinic to request the crewmembers' medical, dental, and DNA records that were essential for identification; these records were delivered to the Barksdale AFB Mortuary Affairs Office for safekeeping. Later that afternoon, two Blackhawk helicopters provided by the Texas National Guard transferred the initial set of remains from the Lufkin collection point to Barksdale AFB. These helicopters arrived at Barksdale AFB about 5:00 p.m. CST on February 2, with the remains being escorted by the OAFME advance team under the lead of US Navy CDR Craig Mallak, MD, Armed Forces Medical Examiner, and accompanied by US Navy CDR James Caruso, MD. A military honor guard protocol was instituted for the transfer of these remains to the temporary morgue facility.
All subsequent remains were transported by ground convoy with a security escort from Lufkin to Barksdale AFB at the conclusion of each search day. Stepaniak also met with Dr. James Bagian, the medical consultant to the Columbia Accident Investigation Board, who was briefed on NASA MIT medical operations. Bagian, together with Wetherbee, later revised the plan for locating and recovering the crewmember remains.

February 2, 2003 – First recovered remains transfer from Lufkin, Texas, to Barksdale Air Force Base in Louisiana.

This facility at Barksdale Air Force Base served as the temporary morgue.

Public Misconceptions

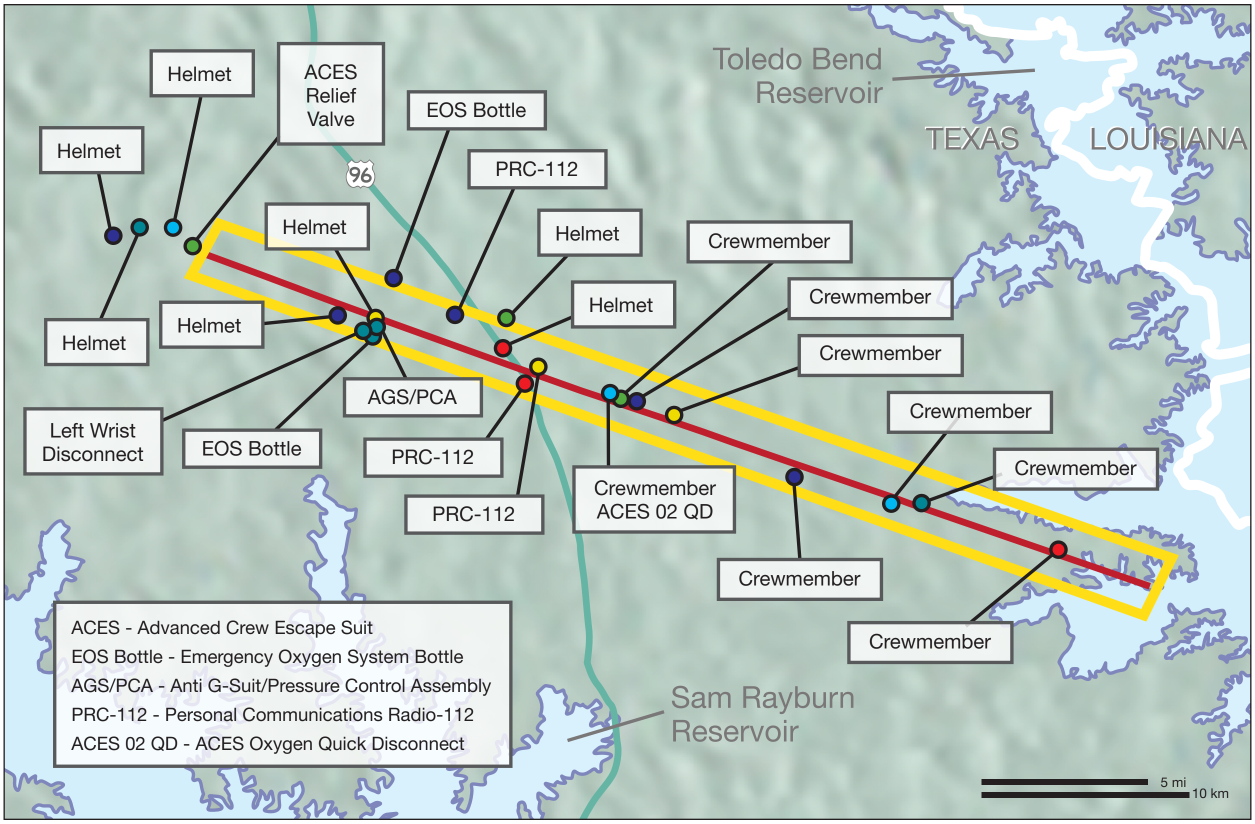
On the evening of February 2, Whittle and other senior management of the MIT told Stepaniak that they had received a call from the Governor's Office of the State of Texas about concerns that remains had not yet been recovered, requesting an explanation for the apparent delay. It became known that the Governor's Office was receiving numerous calls from citizens regarding their willingness to help with recovery efforts. The Governor's office was concerned that these reports did not seem to generate an immediate response from NASA officials. It was clear that the public was unaware of the scope of the operation. Because the initial debris field included an area of about 10,000 square miles with dense foliage and hazardous terrain, recovery team efforts were simply dwarfed by the magnitude of the mission.

At the same time in various offices, misunderstandings occurred about the nature of the mishap, with concern that foul play or acts of terror were involved in the orbiter's destruction. NASA was forced to recognize the need for better distribution of information, and set about reassuring the public that Columbia had been destroyed because of a mechanical accident with no acts of terror involved, and that recovery teams were exerting every effort to promptly and appropriately recover all remains and debris while ensuring the safety of those searching.

Recovery and Identification of Human Remains

The primary mission of the MIT medical team was to receive, identify, preserve, and transport human remains to the AFIP at Dover AFB. At the same time, the recovery of initial remains gave significant insight into the nature of the accident and provided some understanding of the forces involved in the crewmembers' deaths. First, it was noted that none of the remains were recovered with any donned life-support equipment, such as their reentry suits. From this observation, it became clear that the shear forces involved at the speed and altitude of the breakup caused all life support equipment to be torn away from the bodies.

Patterns of injury were observed, including multiple-force trauma. It was later determined that these patterns



Crewmember remains and life-support equipment were found within a corridor in East Texas that was approximately 30 statute miles long and 2 statute miles wide.

were caused by seating arrangements on the two decks of the crew compartment, with crewmembers being exposed to certain types of injuries according to their location within the compartment. It was also noted that all remains had a pachydermic appearance, indicating exposure to the severe thermal insults and low pressure conditions of extreme altitude during reentry.

All crewmembers were identified by dental forensics and DNA analysis. Through the use of dental records provided by the JSC medical clinic, the remains of five crewmembers were formally identified by February 4. A sixth crewmember was formally identified by dental records on February 11, and the final crewmember was formally identified on February 12, 2003. All identifications of disassociated crew remains were confirmed by the use of DNA analysis conducted at the OAFME Rockville, Maryland facility.

Throughout the recovery and identification of human remains, it became apparent that the contingency medical group required additional personnel. Peter Bauer, MD, NASA flight surgeon, Mark Swann, space flight medical contingency coordinator, Wyle, and Richard Pettys, advance projects engineer, Wyle, provided operational and data management support.

Providing Information to the Families

Family members returned to Houston from KSC the afternoon of the mishap, and awaited information about their loved ones. The MIT medical representative provided identification information to the mission crew flight surgeons, who had close bonds with both the crewmembers and their families. These mission crew flight surgeons, Drs. Johnston and Hart, coordinated with the Casualty Assistance Calls Officers (CACOs), astronauts assigned to assist the family in the case of a disaster. To prepare for this exchange of information, on February 3, the MIT medical lead and the OAFME lead held a teleconference with Johnston and Wetherbee to discuss the duties of the CACOs and the flow of information to the families. These conferences were repeated daily, and information was provided to the crew flight surgeons and CACOs, who ensured that the families had the most accurate and complete information available regarding recovery efforts and dispelled any rumors reported by the media or the general public.

As crewmembers were identified, the mission crew flight surgeons along with the CACOs notified the families. Once OAFME completed the forensic analysis of the remains, the Dover Mortuary Affairs Office coordinated with family members, again with the help of the crew flight surgeons and CACOs, to prepare the remains for burial or cremation and return them to their families. A unique approach was required for Ilan Ramon, the Israeli astronaut, to respect cultural sensitivities and religious preferences. An Israeli flight surgeon and rabbi, Col. Ahron Zwi Black, MD, arrived at Barksdale AFB on February 3 to observe MIT-OAFME operations and to ensure that cultural and religious customs were followed. US Navy CAPT Rabbi Harold Robinson assisted Black, who later accompanied the remains when they were transported by aircraft to Dover AFB and oversaw the final disposition of this crewmember's remains.

Transfer of Remains

Multiple challenges were involved in the transfer of human remains from Barksdale AFB to Dover AFB. First was the issue of timing since the OAFME staff at Dover AFB needed to receive the remains and tissue samples as quickly as possible to assist with their forensic analysis before valuable evidence was lost to degradation. At the same time, it was important that the remains be transported with dignity, honor, and respect, for the families' sake, in as few shipments as possible.

Pathologists provided tissue samples taken from all recovered remains, and the samples were flown on a NASA T-38 to Andrews AFB for immediate delivery to OAFME at its Rockville, Maryland, facility for DNA analysis. The first shipment occurred on February 3. On February 5, seven transfer cases containing the majority of the recovered remains were sent with military honors by an Air Force C-141 aircraft to Dover AFB. These transfer cases were accompanied by Dr. Black; US Air Force Col. Rex Walheim, NASA astronaut; and Craig

February 5, 2003 – Seven transfer cases containing Columbia crewmember remains were transported to Dover Air Force Base. Israeli Col. Rabbi Black and US Navy CAPT Rabbi Robinson provided a blessing for the fallen astronauts.

Honor guard protocol for the Columbia crewmembers at Barksdale Air Force Base.

Fischer, MD, from JSC Space Life Sciences Directorate, along with the OAFME advance team. OAFME provided duplicates of all reports and photographs on a compact disc to the JSC medical MIT. Astronauts US Navy CAPT Barry Wilmore and US Navy CAPT Kenneth Ham escorted the subsequent transfers to Dover AFB on February 11 and 12, respectively.

In addition to the remains, search teams found debris from parts of crewmembers' reentry suits that they had been wearing. Debris included helmets, suit parts such as wrist rings, suit oxygen bottles, and radios and other equipment. All equipment had identification numbers that associated each piece with a particular crewmember. This crew life-support equipment was kept with the crew remains and transferred to Barksdale AFB and then to Dover AFB. JSC engineers from the Crew and Thermal Systems Division initially reviewed this hardware at Barksdale AFB and then traveled to Dover AFB for comparative analysis of the hardware to provide a better understanding of the crewmembers' injuries.

In addition, the Air Force sent an experienced former NASA flight surgeon, Maj. Hernando (Joe) Ortega, to Dover AFB to assist with the forensic analysis of the human remains and the crew life-support equipment. The JSC engineers also provided a complete reentry suit (advanced crew escape suit) to OAFME as well as technicians and engineers to assist with the functional analysis.

Terminating Operations

Twelve days after the mishap, all crewmembers had been identified and the medical team began the transition toward the termination of recovery operations and the initiation of a sustainable long-term support plan. The MIT management and the JSC Director of Space Life Sciences approved a final long-term plan developed by the MIT medical representatives, which was subsequently distributed to all members of the MIT. This plan also established procedures for the handling of commingled remains that might be discovered with orbiter debris shipped to KSC. The official search for human remains terminated on February 13, 2003. Through the JSC Emergency Operations Center, the CMG supported recovery of human remains until February 22.

Barksdale AFB information technology personnel, in coordination with FEMA personnel, erased all pertinent data from the base medical computers. The MIT medical lead provided updated schematics of crewmembers' remains to the Lufkin Disaster Field Office so that they would have adequate information in case more remains were found. The medical team returned to JSC the following day to brief JSC management on the status of the medical operations and crew recovery efforts.

Summary: Medical Mishap Investigation Team Mission Objectives at Barksdale Air Force Base

The mission objectives at Barksdale AFB were divided into primary and additional issues. This division became obvious as personnel were working in the field and determined that multiple items needed to be addressed by the team. These items needed to be coordinated to keep members of the team informed and management satisfied with the team's efforts. The primary (#1) and additional objectives were as follows:

1. Receive, analyze, identify, and transport human remains to the Armed Forces Institute of Pathology at Dover AFB.
2. Provide assistance in the human remains recovery efforts to the prime Disaster Field Office at Lufkin, Texas.
3. Brief the astronaut CACOs and the crew surgeons for the STS-107 mission daily so they could inform the families with the latest recovery details.
4. Provide information, plans, and guidelines for medical concerns and occupational health care issues associated with spacecraft toxic substances to the search teams, local physicians, and civilians.
5. Receive, store, and transport crew life-support equipment to Dover AFB for analysis. This equipment eventually was transported to Kennedy Space Center.

6. Receive, store, and transport biological payloads from STS-107 to the Kennedy and Johnson Space Centers.
7. Develop long-range plans for human remains recovery and transport after departing the base of the MIT operations at Barksdale AFB.

Lessons Learned

Personnel

Due to the nature of the mishap, it was appropriate to have the mission crew flight surgeons remain with crewmembers' families for medical and psychological support rather than reassigning them to investigative and recovery roles. Personnel in the CMG proved uniquely suited to act as members of the MIT. Initial operations were marked by a significant lack of necessary support personnel needed for operational assistance, record keeping, and similar activities. The identification of contingency teams before a mishap occurs, with associated training of team members, could alleviate much of the burden placed on the MIT medical representatives by providing adequate support for initial operations. Personnel with expertise in computerized mapping and plotting of recovered human remains and crew equipment would have provided great benefit for a more efficient search.

The introductory medical team meeting held at Barksdale AFB for all individuals involved in human remains recovery proved to be extremely valuable. Not only did this meeting provide an opportunity to establish responsibilities for early, clear coordination of efforts, but it also allowed all team members to meet other parties involved and understand their roles, leading to smoother operations once recovery efforts were underway.

It was noted that many of the MIT personnel turned to the MIT medical representatives for routine medical advice. Although this was an understandable occurrence, the primary mission of the MIT medical team was recovery of human remains, not provision of medical care to other team members. Future medical teams must consider the health of team members and identify local medical care facilities, providing this information to their team members.

Equipment

Barksdale AFB personnel were extremely helpful in providing adequate work space and supplies for the initial operations, but it would be desirable in the future for team members to deploy with equipment and supplies sufficient for the first few days of an operation. In particular, dedicated and secure cell phones, a secure computer, and adequate office supplies are essential to early activities. FEMA provided many of these supplies later in the operation, but such supplies are needed from the start.

Procedures

The serendipitous meeting of the JSC CMG and the OAFME and AFIP at Dover AFB in 1999 was extraordinarily valuable. This meeting established familiarity among the various organizations and helped to develop an initial concept of operations. In retrospect, however, specific protocols for the handling of vehicle debris, crew and personal equipment, human remains, and other biohazardous material were lacking. In particular, the type of personal protective gear needed in any recovery operation and how it will be provided should be established so that clear protocols and appropriate equipment can be provided to the team. Contingency medical personnel who may need to respond to a similar future mishap should be aware that they will be part of an integrated team that will include professionals experienced in photographing, coding, and identifying GPS coordinates of any recovered debris or remains.

Chain-of-custody procedures should be well established and controlled. This is important both at field operations collection points and at temporary morgue facilities. Transport of all human remains to the forensic analysis facility needs to occur as soon as possible to prevent tissue decay and loss of toxic materials by off-gassing, so that accurate data can be obtained. Further, procedures should be established for the handling of commingled human remains discovered within spacecraft debris.

Honor and respect guided the coordination of religious and cultural provisions for the international crewmember, and such efforts were greatly appreciated by both the family and the international community. Similarly, the use of an honor guard protocol for the transfer of human remains provided dignity, honor, and respect to crewmembers.

Transitional and long-term plans were carefully considered toward the end of the recovery efforts. These plans proved to be quite useful and will be useful in the future, since additional remains will almost invariably be discovered after search and recovery operations are terminated. These plans should be coordinated with all members of the MIT and supporting agencies.

Communications

It was extremely useful to have identified a single point of contact in the management chain who was responsible for the appropriate dissemination of information. This point of contact relieved field team members of the responsibility of reporting to multiple individuals, ensured that data were not misconstrued or distributed to inappropriate parties, and allowed the team to focus on recovery tasks.

Daily briefings with the Lufkin Tactical Command Center, the mission crew surgeon, and CACOs enabled an effective flow of information to the families provided by individuals whom the families knew and trusted. This process rallied the families and provided comfort in the knowledge that they were receiving accurate and verified information directly from the field.

During the TWA 800 discussion at the AsMA conference in 1998, a panelist was asked to identify the greatest detriment to the investigation of the accident. The panel member responded with the memorable statement that political grandstanding led to the distribution of unsubstantiated information as certain individuals fought for their turn in the media spotlight. This false information led to great emotional disturbance for family members and the public at large, and made the distribution of accurate data even more challenging in an already difficult situation. This lesson was well heeded by the MIT medical team, and they made a considered decision to make information available first to the families to protect privacy and trust. NASA as a whole worked tirelessly to ensure that no false or unsubstantiated information was ever reported to the media during the search and recovery efforts.

Communications were a continuing issue for the individuals working in the cauldron of a major public mishap such as the Columbia accident. Under these stressful conditions, a good rule was to never promise anything that could not be personally delivered. The MIT medical team received multiple questions from the media, senior government officials, and political officials—all wanting immediate answers to questions about the identification and disposition of the crew. The MIT flight surgeon relied on NASA senior managers, such as the Director of Space Life Sciences, and NASA Public Affairs officials to interact with these questioners. This need to make accurate information available while working to recover and identify crewmember remains was difficult. One must always remember to be flexible yet realistic, balancing the need to accomplish objectives with the need to deal with the perception of how well the recovery is going by those in authority who may attempt to inject politics into the accident investigation process.

Conclusions

As long as humans continue to fly in space, mishaps will occur. The monumental risks inherent in space flight guarantee that tragedies, though deplorable, cannot always be prevented. A team involved in search, rescue, recovery, and investigation efforts must have appropriate personnel who are trained to conduct this mission. The coordination of these efforts before a mishap occurs will provide for more efficient operations in the event of a disaster.

Mishap preparations for a spacecraft disaster should include, at a minimum, coordination among NASA, its international partners, the DOD, the NTSB, FEMA, EPA, the FBI, and the Federal Aviation Administration. Medical and legal experts should provide guidance in the coordination of both recovery and communication efforts. Communications must be carefully controlled to ensure appropriate release of accurate and reliable information.

Tragedies of this magnitude impart extreme stress to those involved, yet those who respond are capable of remarkable feats in such times. After the Columbia mishap, the MIT and the medical team demonstrated efficiency and determination, using the lessons learned from the TWA 800 accident and the Challenger disaster to better respond to this contingency. The lessons learned from the Columbia disaster will provide guidance for future operations. It is our responsibility to ensure that the sacrifices made and the knowledge gained by all involved will be available for use by those conducting this type of response in the future.

“We don’t rise to the level of our expectations, we fall to the level of our training.”

Archilochus, Greek Soldier, Poet, c. 650 BC

Mishap Response and Lessons Learned: *The Role of the Office of the Armed Forces Medical Examiner and the Armed Forces Institute of Pathology*

Craig Mallak

The Columbia accident presented a difficult situation for pathologists, because of the unexpected nature of the high-altitude breakup of the space vehicle and the large area in which crewmembers' remains could have been found. East Texas was a difficult terrain in which to manage recovery operations, and methods to ensure an efficient and highly proficient evaluation were necessary. Complicating matters was the issue of chemical toxicity (propellants) as well as the hazards of the spacecraft debris. This chapter is the story of how NASA and the Office of the Armed Forces Medical Examiner (OAFME) worked together to recover and identify the crew remains. This team had methods that worked, to make sure the families of the STS-107 crewmembers received a dignified yet accurate accounting of the deaths as well as to provide the information to NASA and the external investigation teams for an understanding of the mishap. The lessons learned will benefit future space flight accident investigations.

The Office of the Armed Forces Medical Examiner.

Capabilities of the Armed Forces Medical Examiner and the Armed Forces Institute of Pathology

At the time of the incident, the OAFME was a branch of the Armed Forces Institute of Pathology (AFIP), which was disestablished as part of the 2005 Base Realignment and Closure Act. OAFME is now a separate agency within the Department of Defense, known as the Armed Forces Medical Examiner System. The mission of the OAFME, which was established in 1988, was to conduct scientific forensic investigations for determining the cause and manner of death of members of the armed forces and, under special circumstances, civilians in the United States and overseas. In 1999, the jurisdiction of the office was defined by 10 US Code 1471 to include assisting other federal agencies by way of agreement or through requests to the Department of Defense. Before 1988, the AFIP consisted of a forensic science department and an aerospace mishap department that worked in a consulting capacity for military mishaps. With the formation of an Armed Forces Medical Examiner System, these departments were enveloped by the larger system.

In addition to performing multiple autopsies every year, the OAFME is further responsible for conducting medicolegal investigations, particularly regarding medical, dental, forensic, toxicological, laboratory, and DNA analyses. The staff of the OAFME consists of pathologists, anthropologists, investigators, photographers, toxicologists, DNA scientists, and other scientific and administrative personnel. Forensic pathologists are active-duty members of the US Air Force, US Navy, and US Army, and are board certified in anatomic, clinical, and forensic pathology. Many staff members have a variety of other skills in veterinary medicine, legal affairs, and hyperbaric

The Army Medical Museum located in Washington, DC, from 1887 to 1955.

The Army Medical Museum, now named the Armed Forces Institute of Pathology, on the grounds of Walter Reed Army Medical Center, 1955 until it was closed in 2011.

medicine, together with expertise in combat, aviation, and water-related deaths. On the whole, the OAFME was well suited to manage the forensic investigation resulting from the Columbia mishap. The Columbia disaster was not the first time that NASA interacted with the OAFME, as previous generations of military medical examiners investigated the Apollo 1 and Challenger fatalities.

The AFIP was a US government institution concerned with diagnostic consultation, education, and research in the medical specialty of pathology. It was founded in 1862 as the Army Medical Museum and was located in Washington, DC, on Independence Ave until it moved to the grounds of Walter Reed Army Medical Center in 1955.

The unique character of the AFIP rested in the expertise of its civilian and military staff of diagnostic pathologists whose daily work consisted of the study of cases that are difficult to diagnose owing to their rarity or their variation from the ordinary.

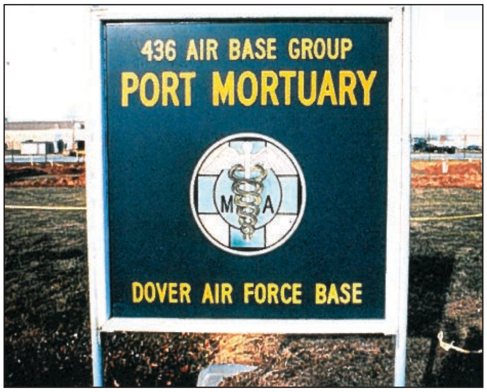
Contingency Planning Between NASA Flight Surgeons and AFIP – OAFME

In 1998 the AFIP presented a panel discussion at the Aerospace Medical Association Annual Conference in Seattle, Washington, on the 1996 TWA 800 in-flight mishap, one of the deadliest US aviation accidents of all time, which occurred in August over the Atlantic Ocean near Long Island, New York. This panel discussed the lessons learned by the recovery and response teams involved in that accident. The lead pathologists of the Joint Committee on Aviation Pathology of the AFIP chaired this discussion. Members of NASA's Space Medicine Division were impressed by the lessons learned presented by this panel and, as a direct result, wanted to put in place a medical contingency plan for use in case of a NASA spacecraft mishap in the future.

In 1999, members of the Johnson Space Center (JSC) Contingency Medical Group, the Kennedy Space Center (KSC) Aerospace Medicine and Occupational Health Branch, and the Department of Defense (DOD) Manned Space Flight Support Office (DDMS) visited the AFIP facility at the Port Mortuary at Dover Air Force Base (AFB) in Delaware. The purpose of this visit was to outline procedures for the handling of crewmember remains after any spacecraft mishap in the future. The visit included a site tour, particularly of the unique fatality processing and autopsy facilities. Dover AFB is the only medical examiner's office that is designed for a multidisciplinary approach that includes an onsite Explosives Ordinance Disposal clearing area, FBI disaster identification component, and radiological and dental identification capability. The team also met with their experts and toured the Mortuary Affairs section of the facility where the deceased are prepared for disposition, including burial and cremation. At this meeting no formal agreement between the OAFME and NASA was put into place; however, a discussion did occur regarding the informal procedure that would be followed in case another spacecraft accident should occur. In 1999, NASA and the OAFME reaffirmed that casualties resulting from the loss of a spacecraft would be ultimately examined by the AFIP at Dover AFB.

Recovery Operations

On February 1, 2003, the STS-107 Columbia accident occurred. Following the loss of signal from the Columbia spacecraft, the medical organizations at both JSC and KSC scrambled into action. At 10:00 a.m. EST



The Dover Port Mortuary is located at Dover Air Force Base, Delaware. In October 2003, the Charles C. Carson Center for Mortuary Affairs replaced this 48-year-old facility that had been in use since 1955 to identify and process the remains of more than 50,000 service members and many victims of numerous fatal incidents of federal interest, as well as the crew of the Space Shuttle Columbia. In 2011 the national mass fatality campus was completed at Dover Air Force Base including the reassignment of the Armed Forces Medical Examiner System and the US Personal Effects Depot, all within a secured compound at the base.

the medical team at OAFME assembled and engaged in a telecommunication consultation with DDMS representatives from Patrick AFB, Florida, and NASA's medical team from the Space Life Sciences Directorate at JSC. During the initial conversations it was unknown whether any human remains would be recovered because of the extreme altitude of the incident, the speed at which the vehicle was traveling, and various forces that would have been applied to the crew. For this reason, operations were suspended at noon while team members awaited further information. By 4:00 p.m. EST, JSC officially requested on-site assistance from the OAFME as reports of significant human remains in the extensive debris field began to emerge. Immediately, OAFME sent an advance team to the primary Disaster Field Office managed by the Tactical Search Director, at Lufkin, Texas, to begin the preliminary examination of recovered remains. At the same time OAFME sent a pathologist to Barksdale AFB, Louisiana, to work with the Columbia Mishap Investigation Team (MIT).

The first remains found were temporarily held in a local pathologist's office in Lufkin, Texas, and this became the main collection point for human remains found at all the search sites. A preliminary review of the remains was completed at this Lufkin facility.

In order for the OAFME staff to complete a preliminary identification, as well as cataloging and initial evaluation of the injuries suffered by the crewmembers, a temporary morgue was set up at Barksdale AFB. The pathologist detailed to Barksdale AFB worked with base leaders to find a space suitable for the work that had to be done. In a matter of a few hours a facility was identified, and with the assistance of base staff was prepared for receiving and evaluating the remains. The Barksdale AFB temporary morgue had sufficient space, lighting, water, electricity, medical support from a local military medical treatment facility, security, and availability for air transportation. This temporary morgue was available within 24 hours of occurrence of the mishap and was fully operational by the time the first human remains arrived at the base on February 2. The MIT from NASA immediately began to coordinate with the Flight Medicine Clinic at JSC to obtain all crewmembers' medical, dental, and DNA records. The MIT flight surgeon, Philip Stepaniak, MD, also set up daily evening dialogues with the crew flight surgeon, Smith Johnston, MD, Casualty Assistance Calls Officers (CACO) from the JSC Astronaut Office, an experienced mortuary affairs officer from the Air Force, and the Tactical Search Director, James Wetherbee, at Lufkin Disaster Field Office. The early coordination of these assets proved vital for ongoing operations.

Recovered remains were temporarily held at the office of a local pathologist in Lufkin, Texas.

Challenges for OAFME and NASA

Once the OAFME was called into action certain challenges became evident. These challenges included jurisdiction; organization and logistics; recovery, analysis and identification of remains; death certificates; and international issues. Initially it was assumed that remains of the crew might be difficult to locate because the accident occurred at high altitude and speed. This type of accident had never occurred before, and considering the nature of the forces and large debris field, the expectations were that not many remains of the crew would be recovered. However, this was not the case.

Jurisdiction

The initial challenge was determining who would have jurisdiction over the remains. The medicolegal jurisdiction is dictated by where death is pronounced. The involvement of the states of Texas and Louisiana, with their numerous counties and municipalities, created a legal challenge. However, the President of the United States federalized the recovery efforts and thus the local authorities ceded jurisdiction to the OAFME, which lessened the burden of negotiations with multiple local medical examiners.

Organization and Logistics

The team that had assembled in Lufkin, Texas, on day 1 (February 1) moved with the remains to Barksdale AFB, providing a full scope of investigative personnel. A team of forensic odontologists and an FBI fingerprint specialist arrived at Barksdale AFB the next day to supplement the team members already in place. A military epidemiologist came on February 4 to catalog and analyze the growing amount of material. This epidemiologist greatly assisted the recovery of the remaining crewmembers by triangulating the coordinates of recovery sites and by plotting and extrapolating geographic data to identify recovery zones. Finally, as the Columbia mishap involved Israeli astronaut Ilan Ramon, a representative of the Israeli Defense Forces, Col. Ahron Zwi Black, a medical doctor and rabbi with forensic experience, came to Barksdale AFB as part of the investigative team.

Recovery, Analysis, and Identification of Remains

The primary objective at the Barksdale AFB facility was to identify crewmembers before their remains were sent to the forensic center at Dover AFB. After the remains were transported to Dover AFB, the OAFME assigned a pathologist to remain at Barksdale AFB on a rotating basis through the remainder of the formal search and recovery effort. NASA transported all recovered remains to Dover AFB for the OAFME evaluations. The Port Mortuary Affairs Office provided the arrangements for disposition of remains in accordance with the wishes of the families.

Recovery

The recovery of crewmember remains involved the tireless efforts of members of the Federal Bureau of Investigation, NASA personnel, local police, emergency medical services personnel, and volunteers from across Texas in a well-coordinated search and recovery process. Initially, recovery efforts were made in response to calls made by civilians reporting potential sightings of human remains. Findings on the ground led to concentric search patterns in the area, but this approach proved to be more cumbersome than necessary, and a more sophisticated pattern was developed as insight was gained into the sequelae of the vehicle breakup. The best approach was to have field personnel recover anything that might be considered human, with analysis performed by forensic professionals for definitive identification. The consequence of this decision was that eight nonhuman specimens arrived at Barksdale AFB and Dover AFB for every recovered human portion. Although this decision resulted in extra hours of work, it was necessary to ensure that the greatest possible representation of the remains of the crewmembers was recovered and all crewmembers were identified.

Analysis and Identification

All remains recovered in the field were sent to the Lufkin collection point and then were escorted by security to Barksdale AFB for further examination by the OAFME investigation team. This team photographed all remains, charted them by recovery location, and provided anatomical schematic outlines of each crewmember. Initial screening of disassociated remains included first an examination by a forensic anthropologist to evaluate whether the remains were human and to determine the part of the body recovered. Any portion of the hands or feet was triaged to the FBI for identification. Likewise, fragments of the jaw or teeth were evaluated by the forensic odontologists on the team. The pathologist took samples from the tissue and bone for DNA analysis. These tissues were flown almost on a daily basis by NASA aircraft to Andrews AFB and then sent to the facilities of the OAFME at Rockville, Maryland, for DNA identification. Most tissue samples were identified within 24–48 hours after their arrival at the Rockville facility. This timely and rapid identification through mitochondrial and nuclear DNA analysis assisted NASA in the search and recovery process. When nuclear DNA was not available from the tissue, OAFME technicians performed mitochondrial DNA analysis. Mitochondrial DNA helped analysts segregate nonhuman tissue from human tissue and bone. At least one portion of each crewmember was positively identified by dental forensics at Barksdale AFB.

During this process, a question quickly arose regarding how long remains should stay at Barksdale AFB. The OAFME requested that all remains be transferred to Dover AFB as soon as possible for a more detailed forensic analysis as there were concerns that tissue decomposition could cause valuable data to be lost if the remains were not evaluated in a timely manner. In response, the MIT made arrangements with the Barksdale AFB Mortuary Affairs Office and the US Air Force Mortuary Affairs Department to coordinate rapid transfer of all remains. The initial formal transfer from Barksdale AFB to Dover AFB occurred on the morning of February 5, with full military honors for the remains in transit. Two other formal transfers were made on February 11 and 12.

The KSC Medical Operations team coordinated with the Barksdale AFB mortuary team concerning any commingled human remains found with the vehicle and crew compartment, which were shipped to KSC for evaluation of the orbiter debris. Processing of these remains underwent the same procedures that were conducted by the MIT at Barksdale AFB, ending with the established protocol for transfer of all human remains to Dover AFB.

Once the remains of the Columbia crew arrived at Port Mortuary, Dover, initial processing of remains began with a screen for any hazardous or toxic items. As tissues were declared safe for processing, subsequent procedures called for the collection and review of relevant documents such as casualty or investigative reports provided by the field teams at Barksdale AFB and the Lufkin facility. Photographs were made of all remains, with assignment of barcodes for tracking. This was followed by postmortem processing of finger- and footprints with comparative pre- and postmortem analysis as well as a dental record review and analysis of dental imaging. Body imaging and skeletal surveys followed, and x-rays were reviewed for basic injuries and the presence of any foreign metallic objects or identifying features. Next, an initial external examination was conducted, with careful documentation of injuries. Technicians collected the appropriate specimens for toxicology findings together with a complete examination of internal organs. A forensic anthropologist assisted with triage and reassociation of any dissociated remains, performed by comparison of DNA profiles as much as possible to account for all recovered tissues. The anthropologist was also instrumental in separating the human from the nonhuman material that arrived daily at Barksdale AFB and Dover AFB. All of the remains and personal effects were then transferred to the Mortuary Affairs section for disposition. Mortuary Affairs coordinated with the families for determination of funeral arrangements according to the family’s wishes. The families received all crewmember personal effects at this time. The whole operation for the Columbia crew, from search and recovery to transport, autopsy, and burial, was completed and accounted for through this process.

Issue: Determination of Injury Patterns

As of 2003, studies had determined that previous techniques used to evaluate injury patterns in aircraft mishaps were less than scientifically sound. Thus, the team could not use their previous experiences with aircraft to determine the factors leading to loss of crew life. The OAFME staff decided that such speculative analyses could not be provided given the now-known lack of accuracy and precision of such opinioned reports. A major complication was the breakup of the orbiter at high altitude, which involved a variety of forces, including the destruction of a highly complex vehicle with metal, glass, and other materials interacting with the astronauts’ bodies in the most extreme of environments.

The OAFME decided not to provide conclusions about the cause and timing of injuries because they would have been speculative and inappropriate.

Recovery and Analysis of Life-Support Equipment

Crew life-support equipment such as helmets and reentry suit oxygen bottles, and suit hardware like wrist rings and suit emergency radios, that were found in the debris field were also sent to the temporary morgue at Barksdale AFB. Members of the JSC Crew and Thermal Systems Team (the organization that is responsible for all crew-worn equipment) initially evaluated the equipment at Barksdale AFB and then sent it to Dover AFB for further analysis of injuries sustained. At the request of NASA, the Department of Defense also sent an experienced, NASA-trained military USAF flight surgeon, Maj. Hernando (Joe) Ortega, to Dover AFB for additional consultation. The JSC Crew and Thermal Systems team and the military flight surgeon reassociated the life-support equipment and remains recovered, providing valuable information used to understand the nature of injuries that occurred at altitude under such extreme conditions.

Death Certificates

Another challenge was the processing of the death certificates. The location of death and municipalities where the death certificates should be filed were debated. The JSC legal team, with the recommendations of the OAFME, resolved this process with the municipalities of Texas and Louisiana. Also, the JSC Flight Medicine Clinic needed to collect additional information that was required for the certificates from the crewmembers' families. The death certificates were prepared at Barksdale AFB and sent to Texas for processing and certification. The recorded cause of death on the certificates issued by the State of Texas was "blunt force and thermal injuries in association with exposure to extreme altitude with underlying cause of spacecraft mishap."

International Affairs

International issues were another factor to consider as an Israeli astronaut was a member of the crew of STS-107. Special religious customs and autopsy procedures needed to be honored and respected. This process was handled with dignity by making sure Israeli flags and proper transfer cases were available during the transfer of the remains. Also, NASA's medical MIT arranged to have a US Navy rabbi and an Israeli flight surgeon rabbi present at Barksdale AFB and Dover AFB to oversee handling of the Israeli astronaut's remains.

Termination of Recovery Efforts

OAFME and the NASA MIT terminated the formal medical operations at Barksdale AFB on February 13 after consultation with the Tactical Search Director at Lufkin, Texas. NASA and the US Air Force Mortuary Affairs Office developed a long-term recovery plan to be implemented for remains recovered after the termination of formal search efforts. OAFME and the AFIP concurred. According to this plan, any crew remains recovered within the debris field after the termination of recovery efforts would be sent to Dover AFB for analysis and disposition. For several years, biological remains found in the debris field were sent to the OAFME facility at Dover AFB for evaluation. The probability of subsequent recoveries was discussed with the families of the crewmembers, and each family controlled the eventual disposition of any scientifically identified remains. This included whether they wished to be notified about such identification of remains and how they wished them to be handled by the Port Mortuary. This backup plan is still in effect today and the families have the opportunity to change their wishes at any time.

Lessons Learned

Lessons learned from the Columbia disaster were developed to make improvements in the response, search, recovery, and investigative process. The main lessons learned for the OAFME and the AFIP during the Space Shuttle Columbia mishap were the following:

1. The preplanning by NASA with the Department of Defense Manned Space Flight Support Office (DDMS) and the OAFME before the accident contributed to strong communication and familiarity among the groups, which prepared them for this mishap.

2. Having single points of contact with the Tactical Search Director at the primary Disaster Field Office site, Lufkin, Texas, and NASA's medical MIT site at Barksdale AFB, during the search, recovery, and transport of remains prevented miscommunications up the chain of command and helped to create a sense of trust among those who were in charge within the field of operations.
3. Having a temporary morgue available at the NASA MIT site with all available equipment to do a preliminary evaluation and preservation of remains within 24 hours after the accident contributed to the timely identification of remains.
4. Having medical and dental records including DNA cards from NASA's Flight Medicine Clinic available contributed to the timely identification of remains.
5. Having a means of rapidly transporting remains with military honors to the Port Mortuary at Dover AFB enabled the team to preserve valuable toxicology evidence.
6. Having daily situation reports with NASA's medical MIT that included passing along accurate information to the search teams and the CACO representatives for the crewmembers' families created a sense of trust and confidence.
7. Recognizing the needs to respect and honor the customs of crewmembers from other countries by having representatives present prevented any misunderstandings by the crewmember's family or the international partner country.

NASA launched a return-to-flight mission, STS-114, in July of 2005. Before this launch, several visits and exchanges of ideas were coordinated between NASA and the OAFME. It was of specific interest that a written memorandum of understanding be developed to detail any future involvement and responsibilities of each party in the event of a future spacecraft mishap with loss of crewmember life. Aeromedical and legal teams at NASA and the OAFME coordinated the details of this agreement. This memorandum is reviewed annually and remains in effect today, and OAFME and NASA teams meet regularly to update plans for responding to any future fatal mishaps.

The Findings

NASA's initial expectation from the OAFME and AFIP was that these offices would provide a formal and in-depth forensic analysis on the factors involved in the loss of crew life during the STS-107 breakup. This expectation was not met for multiple reasons. The first was that reductions in OAFME/AFIP budget and staff occurred in the years before the incident. In addition, the OAFME staff was making preparations for the US military to be potentially engaged in a conflict with Iraq that ultimately began within 2 months of the Columbia mishap. This potential conflict required significant efforts on the part of the OAFME and the AFIP to prepare for casualties of war from a major military operation, and these efforts required the full support of its staff. Most importantly, resolution of many issues that NASA was interested in learning about was beyond the state of the science at the time and would have been mere speculation, especially considering that this very unique mishap occurred at high altitude with aerodynamic and thermal effects.

Although specimens of tissue such as lung, liver, heart, and bone were sent to other departments at the AFIP for evaluation, these consultations proved of little assistance in further defining the effects on the human body of exposure to the conditions that occurred during the breakup of Columbia. As a result, NASA outsourced the development of the detailed forensic analysis to a private contractor to provide additional insight needed to clarify the source of the injuries and the forces that the astronauts sustained during a high-altitude, high-speed thermal event.

Future Recommendations and Summary

The actions taken in response to future spacecraft mishaps will be dictated by the nature of the accident. Preparations and planning for mishaps occurring during launch, on orbit, or during reentry or landing are essential for guiding the actions of response, rescue, recovery, and investigation teams. Many commercial companies are now in the arena of space travel together with the military services and NASA. The details of who will be involved and responsible in handling a mishap need to be predetermined, particularly regarding

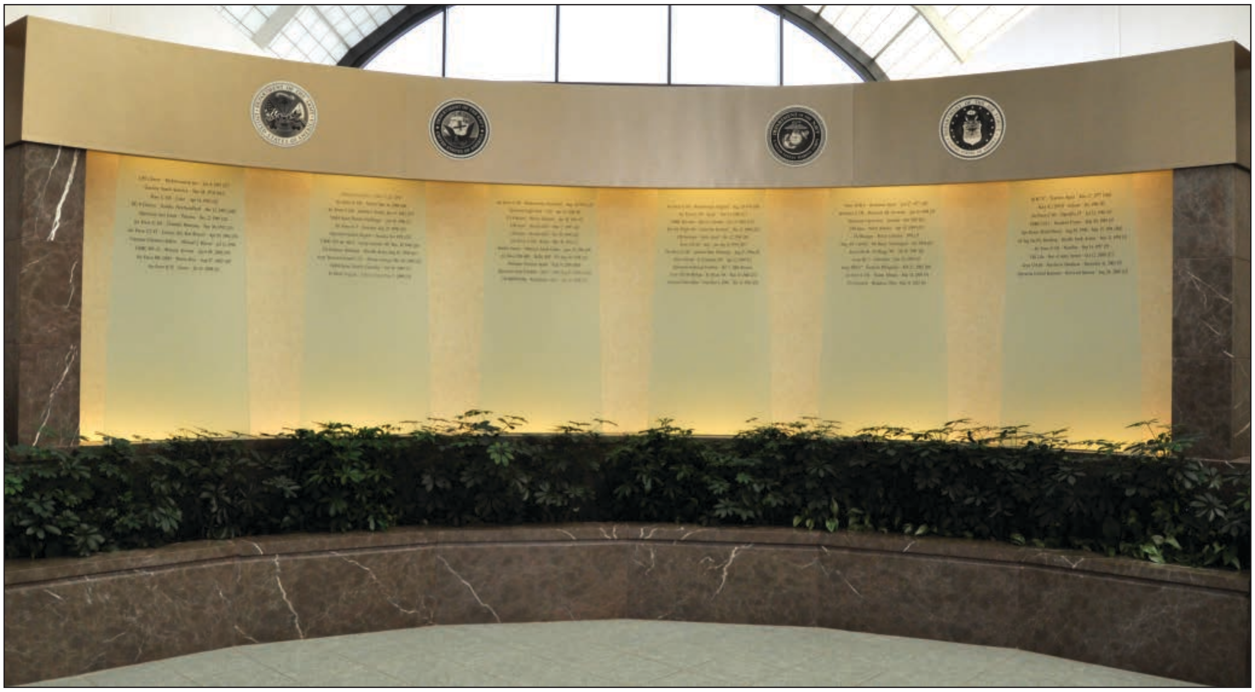


Photo credit: US Air Force/Tech. Sgt. Catherine Carbullido

The Wall of Fallen Heroes greets each visitor as they walk into the Charles C. Carson Center for Mortuary Affairs, Dover AFB, Delaware. Each tragedy is engraved into the glass for remembrance of the date and the number of fallen heroes, including Space Shuttle Challenger and Space Shuttle Columbia.

the authority of each office or agency involved, such as the Federal Aviation Administration, National Transportation Safety Board, Department of Defense, private space flight company, or NASA. An analysis of the causes of any accident must be given priority, to gain insight that can ultimately enhance the safety of vehicles, crews, and space flight as a whole. At the same time, expectations for medical evaluation and analysis must be realistic and within the boundaries of objectivity to best serve the space flight community.

During this time of national tragedy, the OAFME and AFIP proudly conducted this difficult investigation with honor, dignity, and respect for the fallen crewmembers. It was a great privilege for the OAFME and the AFIP to assist NASA during the Columbia mishap. All members of the OAFME and the AFIP were dedicated in their efforts to complete their mission, and conducted their work in remembrance of the crew of STS-107.

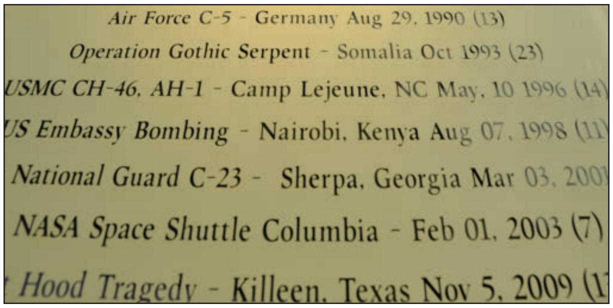


Photo credit: US Air Force/Tech. Sgt. Catherine Carbullido

This panel from the Wall of Fallen Heroes at the Charles C. Carson Center for Mortuary Affairs includes the Space Shuttle Columbia.

Johnson Space Center Space Life Sciences Response and Crew Survival Investigation

Jeffrey R. Davis

The United States, Texas, and NASA flags, in front of the Johnson Space Center's (JSC) Project Management Facility (Bldg. 1), fly at half-staff in memory of the seven Space Shuttle Columbia crewmembers who lost their lives on February 1, 2003.

At the time of the STS-107 flight, the Space Life Sciences Directorate (SLSD) at Johnson Space Center (JSC) was engaged in human space flight operations and research. The directorate worked with the Space Shuttle Program as well as the International Space Station. The directorate included the Space Medicine Division and the Medical Operations Branch, which had responsibility for astronaut health, and this included working with the astronauts before, during, and after their space flight. The flight surgeons assigned to the flight were the crewmembers' advocate for all issues related to health. Besides keeping the astronauts healthy, the directorate set standards and requirements for astronaut selection and retention, and provided behavioral health support for the astronauts and their families. Each flight had two crewmembers trained to provide medical care on orbit, and the SLSD provided such training and supplied the medical kits for each flight. Other support efforts included establishment of aeromedical flight rules, ground rules/constraints such as the wake/sleep cycles, and providing 24/7 support for the mission in the Mission Control Center. Furthermore the directorate set standards and monitored air and water quality and crew consumables such as food. For the STS-107 mission the directorate provided coordination with the scientific payload community including in-house investigators. The directorate was also responsible for occupational health for JSC and had expertise in toxicological hazards.

The purpose of this chapter is to identify all the major phases of activities and interfaces after the STS-107 mishap that involved the SLSD at JSC in Houston, Texas. The discussion is divided into the phases of support for the accident.

Acute Phase, Initial Response to the Accident

On the morning of February 1, 2003, after NASA learned that the Space Shuttle Columbia broke up over the skies of Texas, representative members of the SLSD – Charles Stegemoeller, Associate Director of SLSD, and Sam Pool, MD, Assistant Director of SLSD, attended the Space Shuttle Mission Management team meeting at the Action Center of the Mission Control Center at JSC. The Mission Management Team activated their Mishap Investigation Team (MIT). Immediately, SLSD activated its Contingency Action Plan (CAP) for Space Flight Programs. The SLSD CAP for Space Flight Programs reflects the directorate's response activities and key personnel who would be involved in the event of a space flight contingency. The plan defines the responsibilities and procedures used by SLSD personnel for taking initial action in the event of a mission contingency such as a mishap, investigating and reporting mission failure, accidents, or incidents under the directorate's jurisdiction. The Director of the NASA Johnson Space Center, General Jefferson Howell, USMC (retired), supported this investigation along with NASA headquarters Chief Health and Medical Officer, Richard Williams, MD.

The SLSD assigned several key individuals to the MIT. Generally, these members would be the crew flight surgeons for the mission. However, the crew surgeons were with the crewmembers' families at the Kennedy Space Center (KSC) Shuttle Landing Facility, where Columbia was to have landed. Thus, SLSD appointed members from the Medical Operations Branch: NASA flight surgeon Philip Stepaniak, MD, and the support contractor (Wyle) contingency coordinator, Michael Chandler. They were deployed the afternoon of February 1, 2003, the day of the mishap, to the strategic MIT site at Barksdale Air Force Base (AFB), Louisiana, leaving from Ellington Field, Houston, Texas, and arriving by 4:30 p.m. CST. The purpose of their mission was to gather, guard, preserve, and identify all human remains evidence for analysis of the incident.

At 10:30 a.m. CST the day of the accident, SLSD, through the DOD Manned Space Flight Support Office (DDMS) at Patrick AFB, Florida, had discussions with the Armed Forces Institute of Pathology (AFIP), Rockville, Maryland, to determine how to recover and identify crew remains if any were found. Initially the assumption was made that very small amounts of human remains would be recovered because of the altitude and speed of the breakup. Therefore NASA told the AFIP to stand down for deployment until further notice. Later that afternoon, because members of the public reported significant human remains in the debris field, SLSD recalled the AFIP team to organize the support needed for recovery and identification of the crew. That day an advance team from the AFIP Office of the Armed Forces Medical Examiner (OAFME) went to Lufkin, Texas, as that was the tactical site of the primary Disaster Field Office responsible for the crew recovery. The OAFME also sent a pathologist to the MIT strategic site at Barksdale AFB.

Within hours of the Columbia loss, the NASA administrator, Sean O'Keefe, formed the Columbia Accident Investigation Board (CAIB) under the leadership of Admiral Harold Gehman, USN (retired). The CAIB also contacted a former astronaut, James Bagian, MD, who had provided the medical support for the Challenger accident investigation. Bagian became the medical consultant and chief flight surgeon for the CAIB. By February 2 Bagian was at the search and recovery sites in East Texas to understand those efforts and began the overview of the impacts of the accident on the crewmembers.

During this initial phase, SLSD together with members of the JSC toxicology working group, directed by John T. James, PhD, provided guidelines for the collection of Space Shuttle material in the debris field. The Columbia orbiter had toxic propellants associated with the various propulsion and power systems. The toxic compounds that were potentially present included the hypergolic propellants nitrogen tetroxide and hydrazine. The SLSD toxicology group provided guidance for the safe detection and handling of these propellants. NASA personnel worked with members of local, state, and federal law-enforcement agencies including fire, medical, and emergency medical services, US and Texas forest services, the Federal Emergency Management Agency, and the Environmental Protection Agency. The guidelines given by NASA personnel included information on what to do when encountering hazardous or potentially hazardous materials and procedures for collecting Space Shuttle materials.

MIT Recovery Phase

Over the next 2 weeks the medical members of the MIT at Barksdale AFB worked with the Columbia crew flight surgeons, Smith Johnston, MD, and Stephen Hart, MD, who interfaced with the Casualty Assistance Calls Officers (CACOs) to provide accurate and timely information to the families of the crewmembers about the recovery efforts and identification of the crew. The SLSD always kept the family needs first in their objectives. The SLSD enlisted the services of the JSC Behavioral Health and Performance group to provide psychological support to family members and to NASA civil servants who were involved in the collection of human remains. Crewmember remains were later sent with military honors from Barksdale AFB to Port Mortuary, Dover AFB, Delaware, for further analysis and preparation for eventual burial. During this time, SLSD staff also interacted with the payloads community regarding disposition of the recovered biological payloads, and SLSD worked with KSC on crew compartment components and possible commingled human remains.

Initial Analysis Phase

The CAIB requested the formation of the Crew Survival Working Group (CSWG) to provide needed input to the investigation. General Howell commissioned the CSWG, which was managed by SLSD Director Jeffrey Davis, MD, and Laurie Hansen from the JSC Engineering Directorate. NASA flight surgeon Rainer Effenhauser, MD, US Air Force Lt Col Donald White, and James Bagian, MD, provided medical support to the CSWG. The CSWG initiated a crew-centric investigation of the Columbia mishap. Their charter was to define the fate of the crew module and the crew. Craig Stencil from SLSD led organizational meetings that were attended by representatives of medical forensics, flight crew operations, safety, flight crew equipment, vehicle engineering, flight dynamics, and video analysis. Their results were eventually published in a one-page crew-centric summary in the CAIB report that was published in August 2003. The CSWG published their final report, authored by James Bagian, MD, and Lt Col Donald White, in CAIB Volume 5: Other Significant Documents, Appendix G.12 in October 2003.

Final Analysis Phase

The SLSD director worked to expand this initial CSWG-CAIB report, to have a much more complete analysis that was needed to enable NASA to determine ways to build better spacecraft to mitigate crew risks in the event of a vehicle accident. After its funding was established, the CSWG became the Spacecraft Crew Survival Integrated Investigation Team (SCSIIT), formed in 2004. The leadership of the SCSIIT consisted of project manager Greg Hite, who chaired the team, astronaut Pam Melroy, who served as cochair and was involved with operations and vehicle components, and Craig Fischer, MD, SLSD pathologist, who was involved with medical forensics. Robert Banks, MD, and his team from Biodynamic Research Corp., in San Antonio, Texas, provided the major contribution to the SCSIIT report. The task list for the SCSIIT was the following:

1. Review the CAIB reports.
2. Establish subject expert working groups to locate and analyze all data related to the Challenger and Columbia mishaps.
3. Reconstruct the breakup sequence of the Columbia forward fuselage/crew module complex.
4. Establish a comprehensive archive for manned spacecraft accidents, involving both data and artifacts, for all mishaps both foreign and domestic.
5. Determine the atmospheric pressure, thermal environment, and acceleration forces that the Columbia and Challenger crews experienced.
6. Determine the cause of death of the Columbia crew.
7. Develop lessons learned for application to future spacecraft designs.
8. Develop lessons learned for application to future mishap investigations.
9. Educate managers, engineers, and physicians who support manned space flight (government and civilian) about mishap survival.
10. Periodically review and assess manned space flight projects to make sure that survival goals are addressed.

Crew Team and Consultants for Spacecraft Crew Survival Integrated Investigations Team (SCSIIT)

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To accomplish these assigned tasks, the SCSIIT was organized into the following discipline teams: crew, crew operations, crew equipment, crew module, vehicle, video analysis, and concept evaluation laboratory. Each team was given specific tasks to accomplish. For example, the specific tasks of the crew team were to determine the following:

1. During the mishap, what was the crew situational awareness?
2. What actions if any did the crew take?
3. How did the crew equipment perform?
4. What was the cause of death?

The medical portion of the SCSIIT report contained substantially more technical data than are normally found in an aviation mishap report. The SCSIIT report not only concentrated on crew event awareness and crew actions and response to events, but also on the sequence of crew exposures that led to the potential lethal events. The SCSIIT collected the objective data that included forensic medical findings, onboard recorded data, telemetry, ground-based and recovered video data, air-to-ground communications, and data from examination of debris and materials testing. Analysis also involved derived data from ballistics, thermal analysis, aerodynamic analysis, shock-wave interactions, flail modeling, thermal injury mapping, simulations, structure analysis, and systems analysis.

The SCSIIT's reported goal was to identify problems to aid current and future spacecraft designers in developing safer vehicles and systems and aid in the development of a medical protocol for investigating spacecraft accidents. NASA published the final SCSIIT report in December 2008 for a target audience that included NASA administration, personnel involved in spacecraft design, NASA flight crews, NASA spacecraft operations personnel, space medicine physicians, spacecraft accident investigators, researchers, commercial space flight operators, spacecraft safety professionals, aerospace academics, and members of the US Congress and the general public.

Summary and Lessons Learned

The Columbia accident investigation required preparation and coordination of operations at the directorate level across many technical disciplines of the SLSD, and required effective work with many teams at NASA, the CAIB, and state and federal agencies. The initial key to success was having a contingency action plan that enabled the deployment of a rapid-response team for search, rescue, recovery, and identification of crewmembers, a team that had the appropriate personnel trained in these operations. Equally important was the provision of psychological support to family members.

Communications in real time with the multiple medical organizations from local, state, and federal agencies to define responsibilities and goals produced a team effort in accomplishing the recovery and identification of the crew. Contingency mishap planning requires negotiations with these organizations to produce a clear agreement on roles and responsibilities that results in a written memorandum of understanding. Any future mishap will require the work of a multidisciplinary team to provide a thorough forensic investigation that should enhance crew safety for future spacecraft missions.

The SLSD team served professionally in all phases of the mishap and believes that its contributions will provide the spacecraft requirements and personnel training necessary for future generations that participate in human space flight.

Kennedy Space Center Operations – Commitment to Safety and Preparedness

Philip J. Scarpa

The Vehicle Assembly Building (VAB) is one of the largest buildings in the world. It was originally built for assembly of Apollo/Saturn vehicles and was later modified to support Space Shuttle operations. High Bays 1 and 3 were used for integration and stacking of the complete Space Shuttle vehicle. High Bay 2 was used for external tank (ET) checkout and storage and as a contingency storage area for orbiters. High Bay 4 was also used for ET checkout and storage, as well as for payload canister operations and solid rocket booster contingency handling.

Kennedy Space Center (KSC), located on the central east coast of Florida, hosted all the Space Shuttle launches and a very high percentage of the landings. Launch and landing support teams at KSC were well aware of the potential for aeromedical contingencies during a Shuttle mission. For this reason, they implemented procedures for safe launches and landings, and prepared and practiced for medical contingencies. However, on the morning of February 1, 2003, no one was thoroughly prepared for what was to come. KSC responded immediately and became a part of the major recovery of Columbia and consequential analysis of the Columbia debris. This chapter describes what KSC personnel did and what they learned about this accident.

Description of KSC Medical Support for Space Shuttle Launches and Landings

Initially the future site of KSC was near a US military base, the Cape Canaveral Air Force Station, known for its remoteness, minimal inhabitation, security, year-round summer weather, accessibility by waterways, proximity to the Earth's equator, and access to a chain of Caribbean islands that provided for a network of downrange monitoring stations over the ocean. KSC developed, next to this base, into a large complex for space flight launches and landings along with a large surrounding community of cities and tourist attractions.

A medical emergency could occur at any phase of a Space Shuttle mission, including on the launch pad, during launch, on orbit, reentry, or during landing. Potential sources of injuries included burns, blasts, toxic exposures, deceleration, impact, hypoxia, and hypothermia. For this reason, every launch and landing of the Shuttle was monitored closely by mobile triage forces staged throughout the space center, ready to respond to any potential Shuttle emergency. These triage forces included dedicated fire and rescue responders, environmental health teams, medical personnel (including physicians, nurses, and paramedics), logistics and transport, along with communication personnel. At their disposal were fire decontamination trucks, a supply van, ambulances, helicopters, an all-terrain vehicle, Hagglunds BV 206 Bearcat, and several M-113 armored personnel carriers used for hazardous escape. US Department of Defense physicians, Patrick Air Force Base (AFB) paramedic jumpers, helicopters, as well as crew surgeon(s) from Johnson Space Center (JSC), and community medical personnel further augmented the triage forces. Medical personnel and equipment were also staged at the KSC clinic, biomedical offices, Shuttle Landing Facility (the KSC runway, known as the “SLF”), Environmental Health Facility, KSC fire stations, and logistically throughout the space center for visitor support.

Medical personnel staged in the biomedical offices served as liaisons to area support hospitals, supported the astronaut crew quarters, and provided preflight and postflight medical examinations and experiment data collection. All of these forces were directed by the Emergency Medical Services (EMS) Coordinator, located in the KSC firing room of the Launch Control Center and assisted by a biomedical engineer. During launches, the JSC deputy crew surgeon coordinated closely with this team.

Mission preparation of all aspects of the KSC EMS plan began months in advance with hospital readiness checks, distribution of completed astronaut physical examinations, participation in medical operations readiness reviews, a medical and equipment briefing to physicians and paramedic jumpers, and preparation of a personnel coverage schedule for all EMS positions during all scheduled launch, landing, and mission days.

During normal launches, triage forces were positioned by the EMS Coordinator in a strategic location for maximum geographic coverage response. Crew surgeons and KSC medical personnel provided any needed medical assistance for the crewmembers at the astronaut quarters during quarantine, which began about 3 to 4 days before launch, through crew examinations on launch day. On launch day, medical monitoring began at the time the astronauts were instrumented in crew quarters before they donned their spacesuits, and monitoring continued during all activities on the launch pad and normal launch phases. If the launch was canceled, the EMS forces would monitor crewmembers until they returned to the crew quarters.

During landing operations, EMS forces would again perform a readiness check of all planned medical components before landing day. A few hours before a scheduled landing, triage forces would be strategically placed around KSC to provide coverage concentrated at the Shuttle landing runway. KSC medical personnel would be located in the Crew Transport Vehicle with the crew surgeons, in a convoy on the runway, to provide additional support for returning astronauts.

Upon landing normally, the crew would egress from the Shuttle crew compartment into the Crew Transport Vehicle or down the Shuttle stairs. Most crewmembers chose to then perform an inspection walk around the orbiter while it was positioned on the runway. After this brief excursion, the crew would be transported by the Crew Transport Vehicle or the astronaut van to the KSC astronaut quarters. Triage forces deployed for landing were released only when astronauts were safely returned to quarters. At this time, returning astronauts were able to visit briefly with their families and then were directed through the Baseline Data Collection Facility to undergo postflight medical examination and procedures required for flight experiments. The crew would complete their examinations within a few hours of landing and, after a brief press conference, would spend the rest of the day with their families offsite or in crew quarters. Generally, crewmembers returned to JSC in Houston the day after landing.

Emergency Planning

For any Shuttle emergency, KSC EMS forces were trained to respond with four essential elements: mode declaration, rescue, triage, and medical evacuation. The first element, mode declaration, identified the nature and location of the emergency and initiated a particular response. For Space Shuttle operations there were eight predetermined modes: four for launch and four for landing. The four launch modes consisted of those that could occur during prelaunch contingencies on the launch pad. The four landing modes could occur during any landing contingency or even during postlaunch contingencies such as launch aborts, return to launch sites, abort after one complete orbit around the Earth, or bailouts over the ocean. Launch or landing emergency modes were ranked from low numbers to high numbers by the difficulty of egress and rescue execution and by the potential number of victims involved.

Rescues included the egress of any victims and their transportation to the triage forces, emergency teams located closest to and upwind of the Shuttle contingency. Egress could be assisted by fellow non-injured crewmembers, the Shuttle closeout crew, and fire and rescue personnel. Transportation could be provided by launch pad egress systems, ground vehicles, or helicopters. Transportation by helicopter could also bypass triage forces and deliver victims directly to a hospital if this was determined to be the best option for the victim. In the case of a medical contingency, the medical response plan called for triage forces in the field to receive and evaluate the victim, decontaminate any victim exposed to potential toxins, and provide initial medical stabilization and treatment. Medical evacuation could be provided, if needed, by ground or helicopter to local area hospitals or to the KSC onsite medical clinic as determined by the Triage Officer at the triage site and the EMS Coordinator at the launch control center.

Final disposition of any victim would be influenced by multiple factors, including the specific injuries sustained, the urgency of the medical case, accessible transportation, and resources available. Flight crew and non-flight crew fatalities would be managed by the KSC Medical Code Zero Plan, completed in 1999 with the cooperation and assistance of the DOD Department of Mortuary Affairs and the DOD Armed Forces Institute of Pathology. Psychological care was available on site and could be provided as needed for victims, families, and KSC employees through trained Critical Incident Stress Debriefing (CISD) employee assistance program (EAP) counselors.

KSC Mishap Response: Support on Landing Day

The Plan

The day before STS-107 was to land, the KSC medical team rehearsed and choreographed normal Shuttle egress procedures and medical personnel coverage for postflight experiments scheduled in both the crew transport vehicle and in the Baseline Data Collection Facility. STS-107 was a dedicated science mission, and as such it had multiple experiments on board and an exceptionally full postflight experiment data collection schedule. Special considerations were discussed with the primary investigators: for example, four crewmembers required recumbent positioning for appropriate data collection after landing. These special needs were incorporated into a meticulously planned medical schedule for the returning crew. The scheduled landing was on a weekend; as a result, only essential medical personnel would have been scheduled to be on site at the time of the landing. However, because of the busy post-landing test schedule and the large number of experiments on board this particular flight, several additional medical personnel were on site and available for the landing. In retrospect, this simple coincidence was particularly fortuitous, as each of these medical personnel became essential for the ensuing mishap support.

NASA mission managers were aware of the vehicular debris strike during the launch phase of Columbia's flight. This debris strike had been discussed a few days before the scheduled landing and it was ultimately determined not to be a significant issue to the mission; as a result, landing preparations were normal. On the day of landing, KSC medical forces took position on site about 90 minutes before landing. According to standard practice, all support hospitals were contacted and confirmed ready, and EMS forces took their positions to await Columbia's return.

The Response

At 8:59 CST on the morning of February 1, 2003, loss of signal occurred and no further communications were received from Columbia. Within moments, a contingency was declared and KSC initiated emergency operation procedures. Medical personnel immediately began readying medical kits for rapid response by mishap investigation teams that might be needed for deployment. As information began to reach personnel at KSC, it became clear that there was no local crash scene at which medical responses would be concentrated, and the immediate primary concern became refocused on the astronaut families and KSC employees. At this time, KSC activated the psychological triage support plan. This plan was relatively new, identified as a need during the STS-95 mission in 1998. The plan covered the delivery of psychological support after contingencies to astronauts and their families and friends, as well as to employees, visitors, and witnesses. It called for the establishment of a Psychological Triage Officer to provide CISD within 72 hours of an incident, and to provide additional CISD if needed in the case of a larger disaster.

As soon as KSC knew that a mishap had occurred, medical personnel assisted in the relocation of the astronauts' immediate families from the landing site to the crew quarters as well as the simultaneous relocation of the astronauts' extended families and friends to the KSC training auditorium. KSC medical staff also provided medical treatment for the families and friends as needed. By the early afternoon, KSC staff escorted the families in ground vehicles to air transport at the nearby Cape Canaveral Air Force Station for return to their homes in Houston. CISD was made available by EAP personnel for families, friends, and all KSC employees within 24 hours of the accident.

Recovery Efforts and Occupational Medicine, Environmental and Medical Support

Recovery field operations began within hours of the loss of the orbiter. A rapid response team of about 40 personnel, many from KSC, went to Barksdale AFB in Shreveport, Louisiana, to begin debris search and recovery efforts. At the peak of the recovery effort, a total of about 25,000 recovery personnel, including 1,000 KSC employees, participated at several debris recovery sites. The debris search lasted 3 months and was, to date, the largest organized recovery effort, in terms of both geographic area and number of participants, ever conducted in the world.

The KSC medical team had immediate concerns about adequate and coordinated occupational medicine, environmental health, and medical services for the recovery teams, considering the tremendous number of recovery team members and numerous potential hazards of this operation. There were no physicians or environmental health specialists in the initial response team, and medical capabilities were minimal at best. Work conditions for the recovery teams were not optimal, often including physically demanding outdoor conditions of rough terrain and inclement weather. Team members labored for prolonged work days (typically 12 to 16 hours) over several weeks and months, without interruption for rest or diversion. In addition, there was a reasonable degree of concern about toxic exposure and injury from debris discovery and handling. As is typical for such extreme operations, the urgency in dispatching personnel to the field sites dictated that few to no medical screening exams were performed before deployment, raising concerns about the physical capabilities of those sent to the sites.

Columbia recovery personnel working in central East Texas. Work conditions were a concern.

KSC medical personnel worked with JSC counterparts, the Federal Emergency Management Agency, the Environmental Protection Agency, and the Texas A&M Forest Service to deliver adequate occupational medicine and environmental health services. Policies and procedures were written for the recognition and handling of materials discovered in the field, with associated levels of personal protective equipment. NASA provided a hazard operations briefing tailored to the recovery activity for KSC employees before they left KSC, then again in the field. Eventually, sufficient work rotations and change-outs occurred to limit excessive work times and chronic fatigue. Although medical screening and certification were not performed before deployment of personnel in the recovery effort, NASA team members completed a self-administered medical screening questionnaire. The plan for EMS services was limited but sufficient. It called for first-aid kits or a visit to the Barksdale AFB Medical Clinic for minor injuries, and reporting to the local 9-1-1 EMS provider or to one of the local hospitals for major illnesses and injuries.

During the recovery operations, two major incidents occurred. In the first, a KSC employee lost consciousness and was sent to the local hospital for a cardiac evaluation. His evaluation was ultimately negative, but he was placed on limited duty in the Barksdale AFB hangar and subsequently returned to Florida for rest and recovery. The second incident involved two KSC employees and one Texas A&M Forest Service worker who were seriously injured in a helicopter crash that killed two other Forest Service workers. The two injured KSC employees had chest injuries with resultant pneumothorax (punctured lung), and shoulder and pelvic trauma. A local hospital provided treatment to the injured personnel and after several days they were stable enough to return home to Florida in a fully pressurized medical evacuation aircraft.

KSC and JSC EAPs provided psychological counseling, but some recovery personnel reported that if they had any sadness or depression, the search and recovery work seemed actually “therapeutic.” Many reported that what happened to the vehicle and crew did not seem to truly become real for them until they returned home and had time to reflect, indicating that significant compartmentalization of the grieving process occurred during recovery operations.

Columbia Reconstruction: Overview of Scope and Process in Reconstruction Hangar

Soon after the first recovery teams arrived at the debris field, they began locating orbiter debris. These teams recorded the coordinates and sent the decontaminated debris to a local field center for collection. Debris was then sent to Barksdale AFB for cataloging and preparation to send it to the NASA collection and reconstruction site, and it was subsequently shipped by truck to KSC. The first shipment from Barksdale AFB to KSC arrived on February 12, 2003.

The Reusable Launch Vehicle Hangar, located just off the Shuttle landing runway, was relatively new and unoccupied at the time of the mishap. As a result, KSC designated it as the primary collection and reconstruction site of the Columbia accident investigation. KSC organized and prepared the Columbia Reconstruction Hangar, as it was renamed, for use by February 7, 2003.

Columbia Reconstruction Hangar at the NASA Kennedy Space Center, Florida.

Handling the Debris from the Orbiter

Each truck carrying items from Barksdale AFB stopped in front of the Columbia Reconstruction Hangar for removal of the items, with monitoring for toxic off-gassing. Then employees brought these items inside the hangar for careful cataloging, with photography, barcoding, categorization, and identification. Next the items were analyzed and ultimately placed on organized shelves for storage, or on the floor grid, on a wing-tile grid table, or in a mockup wing display.

Crew effects and cabin debris were handled and assessed separately from the rest of the vehicle to better understand the accident’s effects on the cabin and crew. The crew cabin work analysis was performed in a secure, walled-off corner of the hangar to maintain privacy. NASA evaluated the payload items for potential science return. KSC had strict hangar security access with item tracking and release procedures in place.

A total of 150 individuals worked in the reconstruction hangar, 2 shifts per day, 6 days per week. In total, 27 truckloads of debris items were delivered from February 12 to May 6, 2003. Ultimately 83,013 items and 84,900 pounds (39% of the vehicle) were received, cataloged, and analyzed. The KSC staff laid out about 2,800 pieces on the hangar floor grid during reconstruction phases of the analysis.

Medical Involvement: Screening for Human Remains

Remains from all seven crewmembers were recovered in the field and shipped to the Armed Forces Institute of Pathology (AFIP) for post mortem analysis. However, some of the crew remains were never recovered. For this reason it was thought prudent to inspect any debris in the field or delivered to the reconstruction hangar for evidence of human remains and, if any suspected human remains were present, to send such items to AFIP for analysis. NASA instituted a system with designated points of contact and a logic flow diagram for handling and disposition of these items. In the field, NASA instructed local law enforcement agents to ship all suspected items directly to AFIP. On request, the KSC Medical Office provided written guidance to the recovery teams on handling biological specimens in the field. At the

Inside the Columbia Reconstruction Hangar. Clockwise from top: debris floor grid, wing tile grid table, mockup wing display.

reconstruction hangar, for any item in question the KSC medical officer, Dr. Philip Scarpa, or his designee assessed and evaluated it, especially for evidence of potential human remains and, if such evidence was apparent, sent it to AFIP. Biological items not obviously of human origin or belonging to the scientific payload, but possibly from the Shuttle, were also sent to AFIP. The team sent these items to AFIP by Federal Express next-day shipping unless the item was obvious human remains, in which case the delivery to AFIP was performed by astronaut escort. Guidance for evaluation of the biological and human remains was provided by NASA JSC, the Federal Aviation Administration, the National Transportation Safety Board, and AFIP. All packing and shipping followed AFIP recommendations and each shipment was coordinated with the US Air Force Department of Mortuary Affairs.

Initially, the field recovery team sent the debris of biological interest that was recovered in the field, mostly from payload experiments, to JSC for storage. Through the course of the recovery activities, the decision was made that this debris, as well as any future debris, should be sent to the reconstruction effort at KSC. JSC shipped two debris containers to KSC for disposition and analysis. A designated team inspected all incoming debris of biological interest as it arrived at the hangar from the shipping trucks. This team enabled the expedited sorting and hazard evaluation of material from a biological standpoint. The team consisted of a KSC physician and personnel from the Astronaut Office, Vehicle Integration Test Team Office, Payloads Office, and KSC Environmental Health.

KSC received a total of 370 items that were evaluated for potential biological interest or concern for potential human remains. Of the 370, KSC sent 15 items in 6 shipments (1 by astronaut escort) to AFIP for further analysis over an 8-week period, but none of the samples tested positive for human remains. KSC received the final truckload of debris from Barksdale AFB on May 6, 2003, and it contained no items of biological interest.

KSC used a team approach to meet and inspect all incoming debris of biological interest entering the Columbia Reconstruction Hangar.

Hangar personnel wearing personal protective equipment.

Protection of Hangar Personnel

Several occupational medicine and environmental health concerns for the personnel in the reconstruction hangar required specific attention. These included adequate lighting, indoor air quality, toxic exposure, friable debris, fiber inhalation, sharp edges, lifting concerns, and impact trauma. KSC implemented hangar personal protective equipment (PPE) policies for prevention of hazards associated with these concerns.

As in the recovery effort, the potential for hangar personnel to be emotionally affected by handling of the debris was great. The KSC clinic offered counseling to them as requested.

Early in the reconstruction, hangar personnel were concerned with two biomedical issues: exposure to blood-borne pathogens and discovery of unexpected human remains. KSC medical management quickly and adequately provided blood-borne pathogen and PPE training, and implemented procedures for

Unlike the Challenger accident debris, the Columbia debris is accessible for investigation and research.

screening all items of biological interest that entered the reconstruction hangar. The screening protocol proved very useful because first, it allowed the control of all toxic or biohazardous materials entering the hangar, limiting unnecessary biohazardous handling. Similarly, the protocol provided a point at which all debris could be screened for any potential human remains overlooked in the field. Screening aided in the reconstruction efforts by providing proper categorization of items, particularly by providing the opportunity to isolate crew cabin items from the main flow of debris recovery and reconstruction. The screening protocol also allowed the recovery of payload experiment items for their potential science yield.

Long-Term Recovery Efforts

With the conclusion of the recovery efforts and the last major shipments of debris to the Columbia Reconstruction Hangar in May of 2003, NASA management established a long-term plan to respond to the occasional small shipments received, usually from local residents who might find an unidentified item within the debris field. At first, KSC received about one or two items per week, but that quickly tapered off, and the last known items were received in November of 2005. After the hangar operations concluded, the KSC Medical Office maintained the capability to evaluate and ship to AFIP any received items that it deemed necessary.

The debris from the Challenger accident in 1986 is buried and inaccessible, but NASA decided to honor the Columbia astronauts by allowing the Columbia debris to be readily accessible for investigation and research. In October of 2003, NASA put into effect a plan for long-term storage, designating secure facilities within the KSC Vehicle Assembly Building for the storage and management of recovered items. Columbia items may be loaned to scientific, research, academic, and government entities with an approved justification for use. Scientific studies of the debris have benefited NASA's remaining Shuttle fleet operations and the design of future spacecraft.

Columbia Memorial Service at the KSC Shuttle Landing Facility, February 7, 2003. This is the site where Columbia was to land.

Memorials

In a tribute to both the crew and the vehicle that so many KSC employees loved and maintained over their careers, KSC conducted a memorial service at the Shuttle Landing Facility on February 7, 2003. There, with the powerful symbolism of the Shuttle's landing runway, the memorial allowed NASA employees to mourn collectively.

In honor of the recovery and reconstruction efforts and before its closing, employees and their families were invited by NASA to walk through the Columbia Reconstruction Hangar in July 2003 and personally witness the debris and the reconstruction efforts. Medical first aid and private counseling were available on site as needed. About 11,000 persons passed through the hangar during the 1-week period in a solemn demonstration of respect.

Lessons Learned

Immediately after the mishap, it became clear that communications were compromised because of the demands of multiple simultaneous inquires and a saturation of critical phone lines and cell phone service. As a result, NASA established dedicated lines of communication for use only by medical personnel and included communication priorities, with the flow of information limited to a need-to-know basis. Dedicated cell service in the aftermath of disaster is difficult to achieve, but cordless communication at KSC has since been instituted in an effort to provide increased mobility and privacy in the event of another contingency.

After the loss of signal from Columbia, those at KSC had limited situational awareness of the event, and their initial information about the event was sought only from NASA data feeds and communications. Awareness improved when commercial news services made available reports of the mishap that were streaming in from civilian witnesses in the field. Non-NASA information resources are now available on site for NASA personnel, even in the Launch Control Room and other restricted operational sites. These resources include regularly updated television news feeds, Internet, social media, and other channels of communication.

Though KSC carefully prepared and practiced emergency response plans, a real contingency event added layers of complexity and unanticipated stress that is difficult to recreate in training scenarios. Many parts of the response plan that are most often practiced, such as the mode, rescue, and medical evacuation procedures, did not apply to the Columbia scenario at hand. Therefore, several elements of the KSC EMS operating procedures, though they had been practiced, did not need to be executed. Instead, the emotional and mental health of the astronaut families and KSC visitors became the highest priority, yet only a few medical care providers (EAP personnel) were on site and prepared to support such psychological stress.

Extra personnel would have been reassigned from existing staff already on site, but this option was limited because of the reduced weekend staffing at the time of the scheduled landing. It was great good fortune that extra medical personnel were present on site preparing to support the busy post-landing experiment data collection process; these individuals immediately made themselves available for assistance where needed, and it was only with their efforts that it was possible to fully cover the level of medical support needed after the mishap.

In retrospect, it has become clear that multiple alternative contingency possibilities must be considered, with careful planning and incorporation of all potential scenarios into training and medical planning. Further, it is crucial to anticipate and plan for the need of more support than is generally available in normal scenarios. The KSC Medical Office has subsequently added both non-emergent medical care and the disposition of crewmembers with non-survivable injuries to all training and exercise scenarios. The Medical Office has also strengthened its on site and on-call personnel lists during off-hour and weekend mission support. As the provision of psychological counseling was of utmost importance, and was one of the most limited aspects of the contingency response due to a lack of available personnel, all KSC medical care personnel are now provided with CISD training. In addition, JSC Medical Operations now provides behavioral health specialists to accompany astronaut families for every NASA astronaut launch and landing.

Finally, although agreements, plans, and procedures regarding flight crew fatalities occurring at KSC were in place several years before the accident, after the accident further technical exchanges with the DOD Department of Mortuary Affairs and the DOD AFIP substantially improved KSC's preparations for responding to an astronaut fatality.

Recovery Support and Reconstruction Lessons Learned

The massive recovery effort after the Columbia accident quickly placed large amounts of personnel and assets into the field with limited planning for safety and health. Unfortunately, illnesses, injuries, and fatal accidents occurred during the recovery operations. In an ideal world, responders should never become victims, and support responses should always emphasize safety and health with careful planning and coordination. Adequate emergency medical services, occupational medicine, environmental health, medical screening, pre-deployment and in-field training, post-recovery debriefing, and return-to-work examination and counseling should be made available for all remote assignments or assignments with limited support and exceptional work demands. Routine post-recovery debriefings and return-to-work fitness examinations were not instituted for the Columbia search and recovery effort but might have benefited returning recovery workers. This should be considered for any future operation of this kind.

Infrastructure (policies, plans, and procedures) for safe operations in the reconstruction hangar did not exist before the accident and was created during the mishap response. Hangar personnel had significant concerns about biological exposures; this had an impact on initial reconstruction operations. KSC immediately put training and safety measures for potential exposure to blood-borne pathogens into place for all screening of biological items. This both reduced concerns and aided medical personnel in identifying biological material coming into and existing in the reconstruction hangar.

Conducting several separate assessments of the same biological item became cumbersome and inefficient; as a result, a team approach was used whenever potential biological material arrived at the reconstruction hangar. The team consisted of a KSC physician and representatives from the Astronaut Office, Vehicle Integration Test Team (VITT) Office, Payloads Office, and KSC Environmental Health Department. Representatives of the Astronaut Office and VITT Office determined whether any crew cabin or crew items were present, and the Payloads Office representative identified the payload items. The physician determined whether the material was biological, belonging to Shuttle components, and whether suspected human remains were present. The environmental health specialist assessed the potential for toxic exposure from the items. Many payload items were identified at this time, allowing recovery of useful science. For example, in one instance a payload experiment involving live worms was recovered intact. To improve the likelihood of receiving biological material sent from the field, NASA provided training for field personnel to recognize such items and KSC medical personnel pre-screened transmitted images of items sent from the field. Despite plans being in place, new issues would sometimes arise that required innovative solutions. It was realized that biomedical support needed to stay flexible, and be continually learning and adapting to provide the best support possible. Biomedical support was a process in continual evolution.

The recovery and reconstruction activities, like many accident investigations, had high visibility and were the object of great public interest, both within and outside of NASA. The potential existed that hangar operations could become distracted or interrupted by the pressures, influences, and sensitivities of political, media, or societal entities. Simple awareness training provided to hangar personnel concerning these potential influences could help future operations from being affected by any of these social influences.

Conclusions and Recommendations

The KSC medical response to the Space Shuttle Columbia accident was multifaceted and tested KSC's capabilities and readiness. In contrast to the commonly practiced contingency scenarios, the mishap did not take place at KSC, was not lifesaving in nature, and included mental health concerns and primary care support to astronaut families and site visitors that were not fully anticipated. The KSC biomedical support was needed for recovery, not rescue. Occupational medicine and environmental health support were more important in support of this event than providing emergency medical services. A need was identified to maintain safety and health in all operations that involve NASA employees whose work places them in harm's way. As the center with the largest NASA workforce exposed to work-related hazards, KSC will continue to make such factors a primary concern and responsibility.

KSC employees and their families, whether or not they were directly involved in the event, suffered emotionally from the loss of the crew and the vehicle. Although the needs were outside the scope of the practiced operations, the KSC medical community performed admirably by providing psychological resources for large numbers of people over a prolonged period of time during the grieving process.

Plans and infrastructure must be in place to provide biomedical support when it is needed, but it is equally important to remain flexible for necessary changes, continually learning and adapting to provide the best possible support. The lessons learned from this accident should never be forgotten; it is now our responsibility to apply these lessons to future space flight programs to honor and respect the crew and all those who have been touched by the loss of Columbia.

Crew Medical and Psychological Support Operations

Smith Johnston and Christopher Flynn

Collection of flowers, balloons, flags, signs, and other remembrance items placed at the Johnson Space Center sign at the main entrance.

Background

At the time of the initial Columbia STS-107 mission assignment in July of 2000, the Johnson Space Center (JSC) Medical Operations Branch consisted of 15 certified operational flight surgeons, qualified to act as primary care physicians to a mission-assigned crew and their family members. These physicians have two primary responsibilities. First, they maintain a doctor-patient relationship with each crewmember, providing medical guidance and expertise in both normal training and emergency situations. Second, the physicians act as medical representatives for Space Shuttle operations. This includes both recognizing and resolving medical concerns that may have an impact on the mission, and also acting as an advocate for their crewmembers throughout training and flight. As a result, many crews become quite close to their flight surgeons throughout the course of their training. For each Shuttle mission, a lead crew surgeon and a deputy crew surgeon were assigned about 9 months before launch to ensure that all the crewmembers were physically and mentally prepared for their mission responsibilities.

The behavioral health and performance group at the Johnson Space Center (JSC) worked closely with both the Astronaut Office and the Medical Operations Branch in 2003. This group included highly trained psychologists and psychiatrists who were well integrated with training and flight activities. Even during normal operations, psychological stress can affect a crew or their families. The behavioral health team offers crewmembers emotional preparation and support for handling their mission. The team also becomes a valuable asset for family members as they learn to cope with both the stress of the upcoming mission and the inevitable celebrity and attention that accompanies flight.

Medical Operations for the Columbia STS-107 Mission

The Columbia STS-107 mission was unique. It was dedicated to research, and crewmembers conducted multiple scientific experiments and used specialized onboard laboratories in the SPACEHAB located in the payload bay. From a crew surgeon's perspective, the mission was particularly challenging because crewmembers were assigned to it earlier than to most other missions. The extended time commitment and additional training to perform scientific experiments was integrated into the usual training and preparations for the mission. The crew flight surgeons acted as liaisons between the crew and the investigators who had proposed and designed the experiments, working closely with the mission scientists (John Charles and David Liskowsky) and the international scientific community to ensure that experiment and technical procedures were appropriately addressed in the crewmembers' training. Crew flight surgeons focused on safety issues related to the science and worked to ensure smooth communication between the mission control surgeon console, the investigators, and mission control directors. They facilitated the logistics and interfaced with the investigation teams in coordination of timeline planning.


The STS-107 crew poses in front of the entry into Space Shuttle Columbia during Terminal Countdown Demonstration Test activities on the pad. Kneeling in front are (left to right) Payload Specialist Ilan Ramon (the first Israeli astronaut), Pilot William "Willie" McCool and Mission Specialist David Brown. Standing in back are (left to right) Payload Commander Michael Anderson, Mission Specialist Kalpana Chawla, Commander Rick Husband and Mission Specialist Laurel Clark.

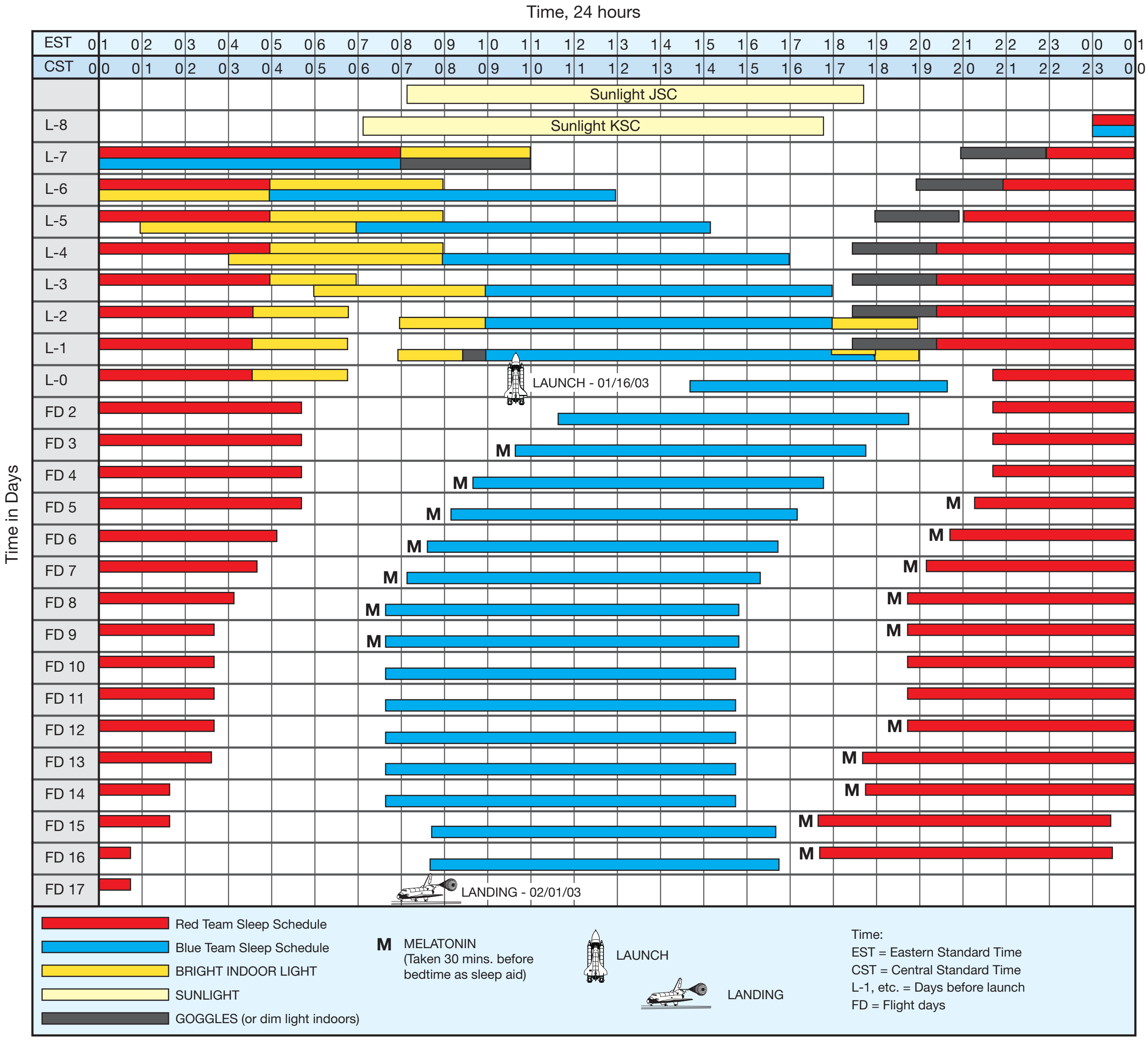
The STS-107 SPACEHAB Research Double Module was filled with scientific equipment and experiments. To fully prepare for the mission, the crew required intense preflight training and simulation time as well as multiple trips to the Kennedy Space Center (KSC) for familiarization with the module and unique

Shuttle payloads. Of particular interest, multiple life science experiments, with organisms from bacteria and mosses to nematodes to rodents, were part of the flight's science payload, requiring a sensitive and humane understanding of experiment procedures as well as extensive coordination with the scientists and veterinarians responsible for these payloads. The crewmembers served as subjects in human research experiments, which required collection of data before, during and after flight. Data collection sessions required practice for the investigators and participation by the crew flight surgeons. Landing-day operations for the scientific mission were equally complicated because of various experiment protocols that had to be followed. These details were extensively outlined and coordinated before the mission, and the crew and investigators participated in simulations involving facilities, equipment, and support personnel. Further, post-landing operations required crewmember participation at the KSC baseline data collection facility before they returned to their families. This added a psychological component to the challenges of the landing timeline.

Finally, because of the nature and amount of scientific experimentation, the crew was required to perform round-the-clock monitoring and activity during the mission. This necessitated extensive timeline development, circadian sleep-cycle planning, and the use of isolated sleep stations to ensure that the crewmembers could receive enough rest. To coordinate such an intense research schedule, the crew was split into two teams, Red and Blue, that would work opposing shifts to best utilize their time in orbit. The crew surgeon developed these sleep-shift plans and worked with the crew, the investigators, and mission operations teams to ensure optimization of the mission activities.

Left to right: Mission Specialist Laurel Blair Salton Clark, Commander Rick D. Husband, and Mission Specialist Kalpana 'KC' Chawla, all red team members, peer out at the world from the comfort of their sleep compartments on orbiter Columbia's middeck.

Example of STS-107 Circadian Adjustment Lighting Schedule



On the ground, 24-hour activities required increased support, in both personnel numbers and longer hours, from physicians and biomedical engineers. The work was dynamic and timelines changed daily, and all ground teams had to be fully qualified and capable to support the medical and scientific experiments on orbit. The entire ground support team worked diligently to develop many unique mission-specific flight rules that were needed for payload hazardous materials, SPACEHAB life-support requirements, and contingency responses unique to the altered payload configuration. Training specific to the medical support team included SPACEHAB payload instruction and multiple integrated simulations before launch. In particular, medical safety was important. Blood draws and training in performing blood draws were required for physiological experiments. Twenty-four-hour operations required that ground teams, as well as the crew, participate in sleep-shifting to ensure that the crew had constant support from mission control.

Team Cohesion

As discussed in previous chapters, the launch of STS-107 was significantly delayed because of Shuttle technical issues and pressures to complete the International Space Station. As a result, the crew, the scientists, the flight control team, all training personnel, and the crew surgeons had worked and trained together for nearly 3 years by the time of the launch. Commander Husband had set a tone of constant team cohesion and camaraderie, both during work and after. Crew spouses interacted daily, including setting up biking and camping trips, and crewmembers and their families shared holidays and other social gatherings with family, friends, and their Casualty Assistance Calls Officers (CACOs) and crew flight surgeons. Many of the crewmembers' children were of similar ages and became playmates and good friends. The multifaceted backgrounds and diverse cultures of the families seemed to complement each other, and the crewmembers and their families became extremely close as a result.

Casualty Assistance Calls Officer (CACO)

The CACOs are members of the NASA astronaut corps and are charged to render assistance needed to settle the personal affairs of a deceased astronaut or to support a seriously ill or seriously injured astronaut. Their duties include assisting the family and next of kin in making all necessary decisions to deal with a fatality. This includes making arrangements for handling the remains, making funeral arrangements, collecting death gratuities, filing for benefits and entitlements, and sorting out other day-to-day and personal affairs during the period immediately after the death.

The integration of the medical team into this social circle occurred naturally. The flight surgeons and physicians were often included in after-work activities

Crew during their preflight training at the National Outdoor Leadership School. First row, left to right: William McCool, Ilan Ramon, Laurel Clark, Kalpana Chawla; back row, left to right: David Brown, Richard Husband, Michael Anderson.

and social events. Some behavioral health and performance team members worked closely with the families to prepare them for the mission. Also, two members of the crew, David Brown and Laurel Clark, were former Navy flight surgeons themselves with significant medical training and experience, further deepening the bond between the crew and their flight surgeons. Clark's husband had also been a Navy flight surgeon and at the time of the mission was a certified NASA flight surgeon in the JSC Medical Operations Branch.

Mishap Response

At the time of the mishap, the crew flight surgeons were at KSC waiting with the crew families for the return of their loved ones. As the scope of the disaster was realized, the mood rapidly shifted from one of joy and anticipation to sudden and crushing devastation. Crew surgeons were notified of Columbia's destruction and were faced with the responsibility of sharing that information with the families. There was a mixture of emotions among the clinicians, including tremendous loss, dread, and guilt that NASA actions, or the lack thereof, may have contributed to the tragedy.

Even as they tried to process these emotions, the flight surgeons and the psychological team immediately began to assess available resources to care for the families and close friends, many of whom had been at KSC for the landing. Thankfully, a number of psychological specialists were also present who were already known to the families: two operational psychologists, two operational psychiatrists, and one child psychiatrist had already become trusted consultants. Still, providers were forced to try and balance their own grief with the need to help. They quickly developed a response strategy based on the concept that the families could not be abandoned at the worst time of grief. Though words seemed utterly inadequate to meet the horror of the losses, the hope was that the presence of the support team would provide some measure of comfort and sympathy to the families to help restore trust and reduce fear.

Providing Psychological Assistance

The providers knew that they would not be able to answer, technically or existentially, the inevitable question of "why." Technical details were slow to arrive, and as they did they often led to more questions, as it was simply impossible to comprehend the nature of the disaster from the confusing early details of the investigation. This amplified the grief and the stress of both the flight surgeons and the behavioral health providers, but at the same time their role became perfectly clear: they would need to find other ways to assist the families in their time of suffering. In finding other ways, the CACOs were instrumental as each had authority to request actions and information from NASA, allowing them to become powerful advisors for both the families and the medical team. Further, each had been chosen individually by the families, and as a result they became the most trusted advisors to the family members after the accident. They advised the behavioral health providers on scheduling visits to provide emotional support, ensuring that visits were only helpful and never disruptive. The CACOs and designated NASA flight surgeons were the liaisons between each family's needs and the organization's response; through them, the medical and psychological support teams could act as skilled assets available when the families most needed them.

As the families trusted the flight surgeons and psychologists enough to share their grief, the providers were determined to be patient, to listen, and to speak honestly—not in platitudes. Providers sought out indications of how each family member could be best helped through the grieving process. Coordination with additional community mental health providers was established so that families could transition from Agency-related care, if desired. Connections to other supportive relationships were encouraged, including to family members, friends, co-workers, and clergy. The support team looked for ways to ensure that there were always familiar faces nearby and that no family member would ever feel alone when they needed help.

The constant public and media interest added challenges to the grieving process. Providers learned not to allow the appearance of a family member "in public" to define how much support he or she might actually need "in private." Occasionally, the support team offered medications to ensure sleep and to reduce overwhelming anxiety. As time progressed, the children in the families expressed their own questions and fears, and the clinicians held group and individual meetings in response. The support team encouraged a family's verbal communication and physical contact (including hugging and holding by parents and trusted adults) as the most helpful soothers for children.

As expected, there were times when a family member's anger would lead that person to distance him- or herself from the medical or psychological providers for a time. Some families did not request or allow psychological support visits after the first few sessions. However, the overwhelming sentiment was that simply talking about the loss of the crew, with someone who truly understood that loss through "living the mission" with them, was uniquely helpful after the tragedy. For families who were suffering so greatly, providers were aware that they could only offer consistent efforts to build a solid connection of support that would be trustworthy, honest, and thoughtful.

The timeline of grief is personal, as each grieving individual searches for meaning to the loss in his or her life. It is a painful but necessary process, made even more challenging because it must occur during a very dark emotional time. It was the goal of the medical and psychological support team to act as guides and companions through this process, no matter how long it might take. Sadly, NASA had experienced this process previously, after the Challenger disaster, and that tragedy brought the wisdom to ensure that prolonged care was available for the families. The grief process for a high-profile death is unique, as it is staged first by an extreme reversal of fortune as families in a state of elation over an event such as a crew's homecoming suddenly are faced with disaster and horror. This extreme pendulum swing of emotion only adds to the anguish. Families are also regularly reminded of their loss as the world holds ceremonies and honors anniversaries for the fallen crew. With this in mind, the support team actively sought to be available to the families for continued familiar and trusted counsel during these times.

Lessons Learned

The medical and psychological support teams searched for insight from their mishap response. First and foremost, a recognition of the depth of the challenges facing the grieving family was necessary before providers could truly be helpful. Each member of the medical team was acutely aware that their association with NASA could cause them to be less than welcomed into a family's grieving process. It would have been a natural response for families to direct anger by affiliation and classify any NASA employee as one of the perpetrators of the disaster rather than someone offering help. However, all families graciously accepted the support of the medical team during the initial days of grieving.

The precoordination and integration of medical and psychological support assets before the mission were exceedingly valuable for the response to the disaster. It would have been terribly difficult for the families to accept help from personnel brought in only after the loss of the crew. The trust and friendship built over the years of association allowed the flight surgeons, behavioral health team members, and CACOs to empathize with the loss as well as truly understand how best to support the grieving families.

It became clear that the ability to keep the families isolated from the press was both necessary and relieving. Constant media presence is extremely disruptive to the grieving process, as those in the spotlight feel the need to suppress emotions and provide a "public face" to the cameras. At the same time, media presence can heighten negative emotional responses such as anger and blame. One of the most powerful lessons learned by support personnel was a recognition of the great extent of misinformation surrounding families and how much it influenced the families' grieving and the organization's responses. Families became frustrated by the wildly diverse mishap "facts" (of questionable reliability) that circulated constantly. The "latest" information was rarely the most accurate information about the catastrophe. This created an uncomfortable frustration between families, who were hungry for any information about the mishap, and NASA officials, who could

The Houston Astros honored the crew of Columbia on April 1, 2003, the opening day of the season, by having simultaneous first pitches thrown by family and friends of the Columbia crew.

offer updates only when information was absolutely confirmed. The most effective way to respond to these concerns was to establish daily, scheduled CACO and flight surgeon meetings with the Astronaut Office leadership. Early on, these meetings became the primary source of information for the families about the investigation, providing a source of confirmed and complete information that could be trusted by the family members.

The CACOs were instrumental in providing a direct line of communication to and from the families. They acted as a single point of contact, minimizing miscommunication, and further coordinated with the search and recovery teams to make sure the families would receive the best information and that all questions could be answered. One of the most difficult aspects of communication was to ensure the equivalent flow of information to all families. The CACOs provided a means to this end, preventing miscommunications that could otherwise have led to resentment and a breakdown of the relationship between the family and the support team.

It was extremely important that the families did not feel that those around them were hiding details, including mistakes. The more honest and open the support team was, the more the family could embrace the team as trusted advisors. Mistakes are inevitable, and providers took the intentional approach of admitting to all mistakes while actively working to solve the problem. The families expressed great appreciation for the honesty and integrity of the support team providers in the wake of the disaster.

Families should never be made to feel abandoned by those around them after a loss of this magnitude. The medical and psychological team recognized this and continued to provide emotional and psychological

Photo credit: Patricia Huffman—Smith Museum, Remembering Columbia

The Patricia Huffman Smith Museum, Remembering Columbia, opened in Hemphill, Texas, in February 2011. In addition to telling the story of Columbia, the museum highlights the efforts of local citizens during the recovery of Columbia and its crew.

Photo credit: Patricia Huffman—Smith Museum, Remembering Columbia

A monument on Sabine Street in Hemphill, Texas, honors the astronauts who perished in the Space Shuttle Columbia disaster.

support even years after the disaster. After such a public mishap, momentous occasions may reopen emotional wounds. Memorials, birthdays, anniversaries, and similar occasions might be recognized as difficult for the family for years to come. However, these events also offer them an opportunity to develop closure and confirm a sense of pride in the fact that their family members are being honored. Maintaining close relationships between the providers and the families has enabled the support process to continue throughout these emotional challenges.

The response to the disaster was not perfect. One of the challenges faced by the providers was the management of their own grief. In most cases, the support team compartmentalized their own emotions to focus instead on caring for the families. Requiring the support team, including the CACOs, crew flight surgeons, and even the psychological providers, to receive some degree of counseling themselves would have been helpful. As was done for the astronauts participating in field recovery efforts, establishing a requirement for psychological decompression visit(s) would have reduced feelings of inadequacy or embarrassment for those desiring help. Even those responsible for helping others grieve must recognize and accept the need to care for themselves.

The medical and psychological providers felt a deep sense of privilege in being allowed to respond to the needs of the families of the STS-107 crew. By describing our goals and methods here, it is our hope that the lessons we learned may someday lessen the pain felt by others experiencing such devastating loss. It is important that these lessons are not lost to history, but that instead we may learn from this tragedy and the sacrifices made by the STS-107 crew and their families.

Section 3 – The Investigation

Columbia Accident Investigation Board
Medical Operations and
Crew Survivability Working Group

The Columbia Crew Survival Investigation Report:
The Five Potentially Lethal Events and Crew Survivability

Columbia Accident Investigation Board Medical Operations and Crew Survivability Working Group

James P. Bagian

The Columbia Accident Investigation Board (CAIB) appointed advisors to the chair to assist in the focus and management of the investigations. These advisors included a chief flight surgeon (CFS) and medical consultant, James Bagian, MD, former astronaut and lead medical investigator for the Challenger accident that occurred in January 1986. This chapter tells the story of the CFS-led efforts to provide NASA with insight into crew recovery and identification as well as the events that led to the crew deaths. Included are descriptions of the efforts undertaken to ascertain the impact of different stages of the accident on the crew module, review of the pertinent engineering data and information about the crew equipment, and determination of what equipment or procedures might have kept the crew alive. These efforts concluded with the issuance of the CAIB Report Volume V, Appendix G.12 Crew Survivability Report.

Within hours of the STS-107 mishap, hundreds of personnel converged on East Texas and Louisiana to begin the process of gathering information to assist in the investigation of the mishap. NASA's Mishap Investigation Team (MIT) medical members and the Barksdale Air Force Base (AFB) medical staff set up a temporary space to receive crew remains that might be recovered. Individuals from the Johnson Space Center (JSC) Medical Operations Branch and the Astronaut Office arrived at Barksdale AFB the day of the accident, February 1. On February 2, Philip Stepaniak, MD, NASA flight surgeon and the medical lead for the MIT, met with the CFS to discuss aspects of the investigation related to recovery, initial identification and transfer of the crewmember remains to the Armed Forces Institute of Pathology at Dover AFB, Delaware for further forensic analysis and final disposition.

Challenges

As with any large accident investigation, organization and communication were challenges, and the Columbia accident investigation experienced many of these issues. Compared to the Challenger mishap investigation, the Columbia investigation went more smoothly with respect to providing the ability to recover evidence and to develop and implement a mature plan of action. Even so, many obstacles were encountered related to logistics, organizational responsibility and authority, chain of command, technical capability required to allow the investigation to proceed, and pressure to block the release of the final report regarding crew related information (CAIB Report, Volume V, Appendix G.12). Overcoming these obstacles required a number of actions in order for the CAIB to be successful in determining what had happened to the crew and in discerning and communicating the lessons that could be gleaned from the mishap that would support and improve future space flight-related activities.

As in many field operations, communication of the various parties with each other was often difficult. In addition, even when communication was possible, the ability to conduct secure communication, when required, was initially non-existent. As a result, it was necessary for key personnel involved with the recovery of human remains to have face-to-face communication with each other to promote the most efficient and effective recovery of these materials. Because the debris field was very large and the initial recovery operations difficult, access to various forms of transportation including helicopters was essential to facilitate communication, understanding, and direction of the operations.

Columbia Accident Investigation Board Background

For mishaps the National Aeronautics and Space Administration uses the agency contingency action plan (CAP) for space operations (SO), which states, “in the case of a high-visibility, mission-related SO mishap the NASA administrator may activate the independent ISS and Space Shuttle Mishap Interagency Investigation Boards (the Board). Board activation is anticipated for events involving serious injury, significant public interest, and other serious mishaps. For mishaps that involve loss of crew or loss of vehicle, a Commission will be formed.”

The Commission’s membership consists of the following:

Board Chair – Appointed by the NASA Administrator

Board Members

Commander, Naval Safety Center

Representative, USAF Materiel Command

USAF Chief of Safety

Department of Transportation Director, Aviation Safety Division

Federal Aviation Adminstration Office of Accident Investigation

Representative, USAF Space Command

NASA Field Center Director

The Board was supported by the following personnel:

Standing Board Support Personnel

Ex officio member: NASA Chief Safety and Mission Assurance Officer

Executive Secretary: NASA Chief Engineer

Contracts and Procurement Specialist to be designated by the Assistant Administrator for Institutions and Management

Additional Personnel Support

The Board may designate consultants, experts, or other government or nongovernment individuals to support the Board as necessary. The Department of Justice Litigation Team provided document control. In addition, the Board may substitute non-NASA personnel as Executive Secretary at the discretion of the Board chair. The Board appointed an aeromedical advisor to the chair, James P. Bagian, MD, astronaut retired, who acted as a medical consultant and chief flight surgeon.

The Board responsibilities are the following:

1. Conduct activities in accordance with the policies and procedures adopted by the Board.
2. Schedule Board activities, interim Board reports, and submission of the final Board report as the Board deems appropriate.
3. Determine the facts, as well as the actual or probable causes of the mishap in terms of dominant and contributing root causes and significant observations and recommend preventive and other appropriate actions to preclude recurrence of a similar mishap. The investigation will not be conducted or used to determine questions of culpability, legal liability, or disciplinary action.
4. Use the established NASA support structure of working groups, NASA field center support, and supporting facilities to conduct the investigation, as the Board deems appropriate. The Board may use non-NASA support as it deems appropriate.
5. Activate the working groups appropriate to the mishap.
6. Obtain and analyze whatever facts, evidence, and opinions it considers relevant by relying upon reports of studies, findings, recommendations, and other actions by NASA officials and contractors or by conducting inquiries, hearings, tests, and other actions the Board deems appropriate. In so doing, the Board may take testimony and receive statements from witnesses. All elements of NASA will cooperate fully with the Board and provide any records, data, and other administrative or technical support and services that may be requested.
7. Impound property, equipment, and records to the extent that the Board considers necessary.
8. Release mishap information and mishap investigation reports as the Board deems appropriate.
9. Develop recommendations for preventive and other appropriate actions. A finding may warrant one or more recommendations or it may stand alone.
10. Provide a final written report at such time and in such manner as the Board deems appropriate which upon its completion will be immediately released to the public.

Initial Operations of Crew Recovery

Starting almost immediately after the mishap on February 1, multiple individuals from the JSC Flight Medicine Clinic, as well as others who would later officially be part of the CAIB began to assure that human remains were collected and brought to the temporary morgue facilities at Barksdale AFB. Many of the pivotal individuals involved with the location and recovery of crew remains were from the astronaut office and had personal familiarity with the deceased crew.

With regard to human remains, the problem in the field was figuring out where to find the remains. Initially, NASA did not think that there would be any appreciable amount of remains that would have survived the mishap. By the afternoon of the accident the physical evidence that was immediately recovered demonstrated that this was absolutely not true. This necessitated steps being put in place to deal with locating and recovering crew remains. Close work between the CFS and the Search and Recovery Team in East Texas at Lufkin ultimately resulted in a more timely location of the crew remains than would otherwise have occurred. This was the result of the CFS having the ability to examine debris as it arrived at Barksdale AFB, having access and ability to examine and view recovery operations in the field, and integrating this information to help predict where additional crew remains might be located. These discussions and decisions were guided by actual physical findings on the ground, not the myriad of theories proffered by individuals in the field.

The CFS conducted the fact-finding and analytic activities primarily on February 3rd and 4th. The CFS reviewed the information regarding where the remains were recovered and correlated that with other debris and its location. This analysis generated an evidence-based plan that was aimed at locating the crew remains which had not yet been found. Due to the lack of secure and reliable communication links, the CFS flew to Lufkin to meet with Search and Recovery Operations Director (astronaut James Wetherbee, Captain USN), on February 4. This meeting led to a revision to the plan for locating the remaining crewmember remains.

The CFS created and supplied to the Search and Recovery Operations Director a coded way by which they could discuss ongoing operations and plans through the existing non-secure communication links while maintaining security. This code prevented revealing to searchers and the public where specific crew remains were found. The new plan resulted in a more methodical search based on concrete information rather than poorly founded conjectures given to the search and recovery team from well-meaning disparate personnel in the field. This resulted in the search for crew remains changing from a "hasty search" to a more rationally based systematic search. Thus, the Operations Director changed the search areas from the northwest to the southeast. Over succeeding days the Operations Director continued to communicate with the CFS the results of their search operations and these efforts led to the recovery of the remains of all crewmembers by February 12.

CAIB Operations

In the first few days after the mishap, the CAIB was in the process of getting organized, and many of the activities that were undertaken by CAIB members and others were based on individual initiative rather than a well-coordinated and planned response. Despite the potential challenges stemming from an ill-defined processes and command structure, operations went very well, being aided by those involved recognizing the need to clearly communicate needs and actions to the wide variety of entities involved.

On the evening of February 5, CAIB operations – including the CFS – relocated from Barksdale AFB to Houston to have access to facilities and personnel at JSC. The CAIB and associated staff set up their work in the Regency Park office complex that was just outside of the gates to JSC. This location allowed ready access to JSC technical experts and information that was needed to conduct the investigation.

On February 6, the CAIB chair was briefed by CFS about the extent of the crew remains that had been recovered and how their condition indicated that the crew were not immediately killed at the time of loss of signal, as many had incorrectly initially presumed to be the case. The CAIB chair understood that the nature and condition of the crew remains recovered indicated that the crew compartment of Columbia may have stayed intact for a significant time and that the crew was probably alive after the time of loss of signal. The condition of the remains also implied that valuable information might

The Columbia Accident Investigation Board
Left to right: first row, G. Scott Hubbard, James N. Hallock, PhD, Sally T. Ride, PhD, Admiral Harold W. Gehman, Jr, (retired), Steven B. Wallace, John M. Logsdon, PhD, Sheila E. Widnall, PhD. Back row: Roger E. Terault, Major General John L. Barry, Rear Admiral Stephen A. Turcotte, Brigadier General Duane W. Deal, Major General Kenneth W. Hess, Douglas D. Osheroff, PhD.

exist that could increase the likelihood of crew survival in future Space Shuttle operations and be applied to the design of future vehicles.

The original focus of the CAIB and JSC personnel was “why the wing came off.” NASA furnished the CAIB a single point of contact (POC) who was responsible for providing the technical information requested by the CAIB. Initially, the POC provided only information that he felt was directly related to “why the wing came off” regardless of whether the CAIB requested it or not. However, this narrow focus obstructed the CFS efforts to address crew survivability and the related engineering and processes so as to elucidate the physical/cognitive environment that impacted the crew and other information that would contribute to understanding lessons for the future. This meant that the CFS was denied access, by the NASA POC, to important information because it was deemed not directly related to the root cause of the accident. The CAIB chair had to repeatedly intervene to remind the NASA POC that his job was to get the information that was requested by the CAIB, not to determine whether it should be supplied. During this rocky period the CFS used informal channels to obtain the information needed to carry out his investigation. While this created a real obstacle in the beginning, it was eventually rectified through the continued efforts of the CAIB chair.

Early on, the CFS contacted Jeffrey Davis, MD, Director of the Space Life Sciences Directorate (SLSD) at JSC to discuss the CAIB’s plan related to the crew-related portion of the investigation and how it would be handled including the various ways the CAIB and NASA would be required to cooperate to facilitate the investigation. From this point forward, Davis and the CFS engaged in frequent communications to make sure the crew-related investigation moved forward in a timely manner. Davis’ active cooperation and collaboration was an essential element in the ultimate success of the CAIB efforts regarding crew survivability. On February 6, Davis also assigned a flight surgeon from the Medical Operations Branch, Rainer Effenhauser, MD, to be the liaison to the investigation group to facilitate the acquisition of any medical information required. The CFS also approached Frank Benz, Director of Engineering Directorate at JSC, who provided a similar liaison, Lauri Hansen, to facilitate support from the engineering personnel at JSC and other centers and entities concerning crew survivability.

Because of the sensitive nature of the crew-related investigation, this effort was handled in a discreet manner between the CFS, the CAIB chair, and certain other CAIB members during the formative stages of the investigation. Once the crew-related investigation clarified its findings, the results were shared by the CFS with all the CAIB members, and the findings and recommendations were included as part of the initial part of the official CAIB report released in August 2003.

Crew Survivability Working Group

Organization and Communication

The CAIB requested the formation of the Crew Survivability Working Group (CSWG), which was subsequently commissioned by JSC Center Director, General Jefferson Howell. The CSWG was operational by February 21. The group, chaired by the CFS, was comprised of personnel from SLSD, Engineering Directorate, Flight Crew Operations, Mission Operations, and the CAIB, including Donald White, Lt Col, USAF.

The CAIB chair tasked the CSWG with a limited charter: First, to determine the cause of death of the crew; second, to determine the "survival gap" (what equipment or procedures might have kept the crew alive); third, to pass the results to the CAIB. The CSWG investigation was managed solely by the group itself, which allowed it to be agile in making decisions.

The CSWG performed aerodynamic, thermal, and structural analysis on individual debris items and an intensive study of the crew helmets, suit hardware, and seats. In the process, team members made several trips to Kennedy Space Center to view debris that had been recovered including portions of the crew module, crew-worn equipment including helmets, and seat debris. The CSWG developed a timeline that was consistent with the official CAIB timeline to derive the sequence of crew survival events from the data.

It became evident that the expertise needed to make the most effective use of all the evidence that had been recovered was not entirely present within NASA. For that reason the CFS contacted the FBI laboratory facilities at Quantico, Virginia, and the Armed Forces Institute of Pathology (AFIP) at Rockville, Maryland, to provide additional forensic support. AFIP functions are now part of the Office of the Armed Forces Medical Examiner System. The inputs from these organizations helped to reinforce and complement the information that was available from more traditional sources. The AFIP had been involved with the Challenger investigation in 1986, and had an established relationship with the NASA Medical Operations Branch.

The CSWG kept the CAIB chair aware of major developments and decisions and was essentially autonomous. The CAIB chair deliberately set up the scope of authority in this decentralized manner to facilitate timely action and mission success.

Scope of the Analysis

The analysis of crew compartment debris was pivotal to understanding the environment that the crew module experienced and more importantly the environment to which the crew was subjected. The analysis from an engineering perspective yielded far more information than that gleaned from the crew remains alone. Information from the condition of items worn by crewmembers, such as helmets and suit hardware, as well as debris related to the crew compartment and the location on the ground where they were recovered, allowed a better understanding of where in the trajectory the crew module experienced a catastrophic structural failure and total dispersal. It also allowed the determination of crew positions at the time of crew module failure and the manner in which the crewmembers used their crew equipment. The analysis of this physical information was made possible through the expertise and superb support of the JSC Engineering Directorate, which was engaged in the CSWG activities from the outset and without whose efforts the ultimate findings and conclusions would not have been possible. All analyses were completed as data became available.

Prevent Bias

It is important to note that from the outset many theories were circulating as to what caused the mishap and what transpired with respect to the dispersal of the crew module and the cause of death of the crew. The CFS made a deliberate decision early on that the people working on the crew-related investigation would not engage officially or informally in discussing hypotheses relating to potential scenarios that would account for the loss of Columbia and the crew. This approach was taken to try to minimize as much as possible the impact of confirmation bias on the activities of the investigation. Confirmation bias is always a concern, as there is a decided tendency for individuals to give greater credence to pieces of information that support their theories and conjectures, and to explain away information that does not support their theories, often calling the non-supporting information "outliers."

By essentially banning the discussion or formulation of scenarios in the earlier parts of the investigation, the group placed their emphasis on collecting all relevant physical evidence and then figuring out how all of it fit together and generating hypotheses at that time. Using this method meant that any hypothesis about what happened to the crew had to incorporate all information and was formulated only after the physical data was collected and available. It also meant that the initial discussions about scenarios did not occur until more than 2 months after the mishap itself. Members of the CSWG believed then and in retrospect that this was vital to the success of the CSWG's activities.

Engineering Analysis

All of the engineering-related information and analysis was available by the end of the summer of 2003. The CSWG undertook a number of initiatives to uncover information that likely would have been otherwise ignored, such as proof that the crewmembers were in their normal shirt-sleeve environment (1 atmosphere of pressure and room temperature) from the time of loss of signal for at least another 32 seconds and then for at least another 15 seconds during which accelerations of the crew module were trivial, and that this benign environment probably continued until orbiter breakup. The CSWG evaluated four types of data—aerodynamic, orbiter, forensic hardware, and forensic medical. By June 24, 2003, the CSWG had enough data to prepare their initial report for the CAIB. These data demonstrated that the initial loss of the orbiter wing did not immediately cause death.

Human Forensic Analysis

After the crew remains were recovered in the field, they were transported to Dover AFB for final forensic analysis. Tissue samples were also sent to the FBI for additional analysis. The Office of the Armed Forces Medical Examiner is the department within the AFIP that was responsible for determining the cause and manner of death of the crew of Columbia. The AFIP had been a valuable partner during the Challenger investigation in 1986. While they possessed a wealth of experience that they ably, effectively and aggressively brought to bear during the recovery, identification and disposition of the Columbia crewmember's remains, their input was not timely and did not meet the expectations for a medical forensic report.

Eventually the AFIP provided medical evidence that showed death was caused by blunt trauma and hypobaria, which further demonstrated that the crew module failure and death of the crew occurred at a time substantially later than the loss of signal.

Release of the Findings from the CSWG

The CSWG reported their initial findings in the CAIB Report, Vol. 1, of August 2003 and planned to release a more in-depth final report several weeks later.

Ensuring that the full CSWG report would be released was considered to be extremely important to avoid repeating the experience regarding the handling of crew survival-related information during the Challenger mishap investigation. In the Challenger mishap, the crew survival investigation was controlled by NASA, and the details of the investigation into what happened to the crew were never allowed to be officially placed in any report and resulted in lessons learned being either lost or not widely communicated. The CFS, who had been an investigator for the Challenger mishap, discussed this concern with the CAIB chair at the outset of the CAIB activities and they agreed that no such outcome would take place with the CSWG findings.

During the initial stages of the CAIB investigation, the Director of JSC Flight Crew Operations Directorate (the Directorate where the astronauts are organizationally located) had strongly expressed concern about how the investigation into the fate of the crew could hurt the families and this had initially slowed the investigation process. In order to anticipate and mitigate these possible objections to release of the CSWG report, the CFS had directly furnished the families, through their POC – one of the crew spouses (Jonathan Clark, MD) – also at

Crew Survival Working Group Findings Published in CAIB Report, August 2003, page 77

STS-107 Crew Survivability

At the Board's request, NASA formed a Crew Survivability Working Group within two weeks of the accident to better understand the cause of crew death and the breakup of the crew module. This group made the following observations.

Medical and Life Sciences

The Working Group found no irregularities in its extensive review of all applicable medical records and crew health data. The Armed Forces Institute of Pathology and the Federal Bureau of Investigation conducted forensic analyses on the remains of the crew of *Columbia* after they were recovered. It was determined that the acceleration levels the crew module experienced prior to its catastrophic failure were not lethal. The death of the crew members was due to blunt trauma and hypoxia. The exact time of death – sometime after 9:00:19 a.m. Eastern Standard Time – cannot be determined because of the lack of direct physical or recorded evidence.

Failure of the Crew Module

The forensic evaluation of all recovered crew module/forward fuselage components did not show any evidence of over-pressurization or explosion. This conclusion is supported by both the lack of forensic evidence and a credible source for either sort of event.[11] The failure of the crew module resulted from the thermal degradation of structural properties, which resulted in a rapid catastrophic sequential structural breakdown rather than an instantaneous "explosive" failure.

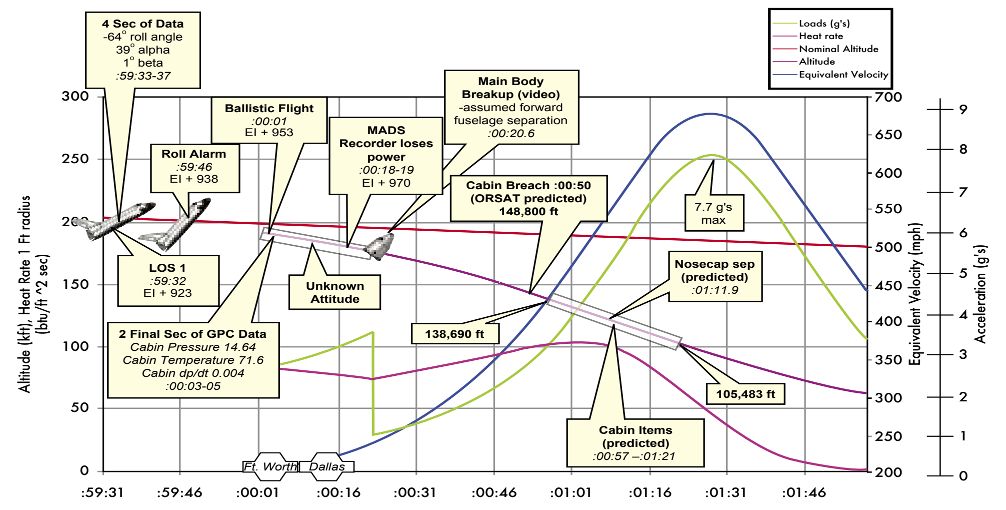
Separation of the crew module/forward fuselage assembly from the rest of the Orbiter likely occurred immediately in front of the payload bay (between Xo576 and Xo582 bulkheads). Subsequent breakup of the assembly was a result of ballistic heating and dynamic loading. Evaluations of fractures on both primary and secondary structure elements suggest that structural failures occurred at high temperatures and in some cases at high strain rates. An extensive trajectory reconstruction established the most likely breakup sequence, shown below.

The load and heat rate calculations are shown for the crew module along its reconstructed trajectory. The band superimposed on the trajectory (starting about 9:00:58 a.m. EST) represents the window where all the evaluated debris originated. It appears that the destruction of the crew module took place over a period of 24 seconds beginning at an altitude of approximately 140,000 feet and ending at 105,000 feet. These figures are consistent with the results of independent thermal re-entry and aerodynamic models. The debris footprint proved consistent with the results of these trajectory analyses and models. Approximately 40 to 50 percent, by weight, of the crew module was recovered.

The Working Group's results significantly add to the knowledge gained from the loss of *Challenger* in 1986. Such knowledge is critical to efforts to improve crew survivability when designing new vehicles and identifying feasible improvements to the existing Orbiters.

Crew Worn Equipment

Videos of the crew during re-entry that have been made public demonstrate that prescribed procedures for use of equipment such as full-pressure suits, gloves, and helmets were not strictly followed. This is confirmed by the Working Group's conclusions that three crew members were not wearing gloves, and one was not wearing a helmet. However, under these circumstances, this did not affect their chances of survival.



The CSWG provided this timeline, which shows where the module failure and decompression started. This timeline was slightly revised in future investigations and more details were published with the Columbia Crew Survival Investigation Report, 2008. The forensic evaluation of all recovered crew module and forward fuselage components did not show any evidence of over-pressure or explosion. This conclusion was supported by both the lack of forensic evidence and a credible source for either sort of event. The failure of the crew module resulted from the thermal degradation of structural properties, which resulted in a rapid, catastrophic sequential structural breakdown rather than an instantaneous "explosive" failure.

GPC – Orbiter's General Purpose Computer – critical for flight
ORSAT – Object Reentry Survival Analysis Tool – NASA computer code for predicting reentry survivability
LOS – Loss of Signal from Columbia
EI – Entry Interface – begins at 400K feet

that time a NASA flight surgeon, a draft version of the report so that the family members had an opportunity to understand what was in the report and why it was included. The families were also informed by the CFS that if they had concerns surrounding any facts that were included, the CFS would be glad to entertain their concerns but that the decision for inclusion would be the decision of the CFS and the CSWG. The families were comfortable with this arrangement and after reviewing the draft report responded that they did not want anything changed.

By the early fall of 2003, all the information was available to produce the final report of the CSWG. The day before the report was to be issued the Office of the NASA Administrator directed the CFS and CAIB that the report not be released due to their concerns for the families. This intention to block the release of the final report was strenuously opposed by the CFS who then informed Jon Clark of NASA's intention to block the release of the report and suggested that if Clark and the families wanted the report released that they write the CAIB Chair, Admiral Harold Gehman, to make the families' wishes clear, an action that they did take.

The CSWG report with the final findings and recommendations was ultimately published as intended in Volume V, Appendix G.12 of the CAIB Report in October 2003. This chain of events raises the question that had the CAIB not been established as an independent part of NASA's investigation that the CSWG final report may not have been released which would have prevented the Agency and the aerospace community from gaining the maximal amount of learning from the tragic loss of the Columbia and its crew.

-----Original Message-----
From: CLARK, JONATHAN B. (JSC-SD2) (NASA) <jonathan.b.clark@nasa.gov>
To: GEHMAN, HAROLD (JSC-MA) (NASA) <harold.gehman-1@nasa.gov>; BARRY, JOHN (JSC-MA) (NASA) <john.barry-1@nasa.gov>; WHITE, DON (JSC-MA) (NASA) <don.white-1@nasa.gov>; BAGIAN, JIM (JSC-MA) (NASA) <jim.bagian-1@nasa.gov>
CC: 'Jim Bagian (James.Bagian@med.va.gov)' <James.Bagian@med.va.gov>
Sent: Fri Oct 17 00:15:05 2003
Subject: CAIB Crew Survival Section

Gentlemen,
First of all let me offer my profoundest admiration for the tremendous work on the Columbia Accident Investigation. This has been a trying time for us all and the thoroughness of your efforts have been a great comfort to us. The STS 107 families will be sending the CAIB a statement concerning the report and have had much to deal with in the aftermath of the investigation.

I have had discussions with the Crew Survival Working Group concerning the 1 page section dealing with crew survival in the CAIB Report volume 1 (Page 77) to ensure that it would not be distressful to the Columbia spouses. The Columbia spouses met tonight and I discussed that a follow on section on crew survival would be coming out with more detail than Volume 1. The draft of this has been vetted of any crew specific issues and I believe that it is an accurate representation of the facts concerning crew issues in the final moments. In discussion with the Columbia spouses we were entirely unified in our desire to ensure that all the lessons learned from this mishap be applied to prevent this type of accident from happening again. We discussed the crew survival section and our desire is to ensure this information is made available to learn all we can from it. A fundemental aspect of every aerospace mishap investigation is the understanding of crew survivability issues and there is much still to learn about survival during upper atmospheric reentry. As sensitive as this issue is, it is essential that the facts related to crew survival be disseminated to ensure the next generation of spacecraft are afforded the maximum protection. This is particularly apparent with the upcoming Orbital Space Plane and future commercial spacecraft. Perhaps the greatest legacy of the Columbia crew will be these enduring lessons applied to future human space endeavors.

Jonathan B. Clark M.D., M.P.H.
Neurologist/ Flight Surgeon
Space Medicine Office

Lessons Learned & Recommendations

Relative to the Challenger mishap investigation, the Columbia investigation went much more smoothly. However, there were a number of lessons learned or reinforced from past experiences that should be considered when planning for similar activities in the future that are summarized below:

- The accident investigation board should be independent of NASA to mitigate inappropriate personal and political influence on the operation and to mitigate potential bias in the final findings and recommendations that the board is charged with producing.
- Team leads and principal investigators of the accident investigation board should not be current NASA employees. This requirement would mitigate real or apparent conflicts of interest; they could be former employees, as their specialized knowledge and experience could be invaluable to the success of the investigation. In any case, members with no previous NASA connection should balance the board's membership.
- Any human space flight mishap investigation team should include a group that performs the function that was provided by the CSWG. Because the fate of the crew will usually be subject to inordinate scrutiny, it is desirable to have a CSWG-like group operate as a semiautonomous unit within the overall mishap investigation team, in order to provide independence and a greater ability to maintain appropriate confidentiality and minimize interference with their activities.
- Both the Challenger and the Columbia activities to recover the crew remains involved participation by astronauts from the crew office at a very intimate level including the handling of crew remains. Although these individuals are very capable, bring many valuable assets to the table, and were responsible for much of the timeliness and effectiveness of the operations, it is probably ill-advised to have close associates of the deceased participate in the material recovery of the remains from the standpoint of their own future welfare. Although critical stress debriefings were offered to these individuals during the Columbia mishap operations, this is a secondary prevention mechanism; it is better to develop alternative methods to obviate the need to subject them to these stressors.
- Communication was often difficult among personnel who were planning or performing recovery operations. This was true of both open and secure communication capabilities. In planning for mishap response, adequate provision should be made for both open and secure communication.
- Every human space flight mishap investigation board should include an individual who has an aeromedical background. In addition, it is highly desirable for this individual to have technical knowledge of the aerospace platform being investigated and it is even better for the individual to have an engineering background as well. If one person with all of these characteristics cannot be appointed, then an additional person with an engineering and systems-based background should be teamed with the aeromedical specialist.
- NASA should identify appropriate internal and external resources to provide the various types of technical expertise needed to perform a thorough and credible investigation. Identification and assurance of the availability of the required experts before a mishap occurs would preclude the potential reduced efficiency, effectiveness, and timeliness that can occur if the board is forced to identify and locate experts after the incident has happened.
- The capacity and competency of the identified internal and external experts and organizations that would be relied upon to participate in a mishap investigation need to be periodically evaluated to ensure that they are still competent, able, and available to furnish the desired services. Failure to do this resulted in problems during the CAIB investigation when it was incorrectly assumed that the AFIP could perform critical pathological evaluations based on past experience with their performance during the Challenger mishap investigation. Unfortunately, it became apparent that in the intervening years, the AFIP had changed their emphasis away from aerospace mishap investigations.

Conclusions

The activities of the CAIB, and the CSWG in particular, ultimately produced a thorough report. This was accomplished through outstanding commitment and tireless effort by the CAIB, the CSWG, as well as a multitude of people both within and outside of NASA. While the ultimate product accomplished its intended goal it should not have been so difficult. Better prior planning would have made it possible for the investigation to have been completed in an even timelier manner and not have necessitated the reliance on individual initiative instead of a well-planned and implemented system to produce a thorough and timely report.

Finally, and most importantly, absolute independence of the CAIB and CSWG from NASA was of paramount importance to ensure that the release of information could not be readily blocked as occurred in the Challenger mishap investigation and was attempted in the case of the CAIB and CSWG. Had the CAIB not been independent of NASA, it is quite possible that a loss of critical information, as occurred in the Challenger investigation, would have occurred again.

"The right to search for the truth implies also a duty; one must not conceal any part of what one has recognized to be true."

Albert Einstein

The Columbia Crew Survival Investigation Report: *The Five Potentially Lethal Events and Crew Survivability*

Nigel J. Packham, David J. Pogue, and Pamela A. Melroy

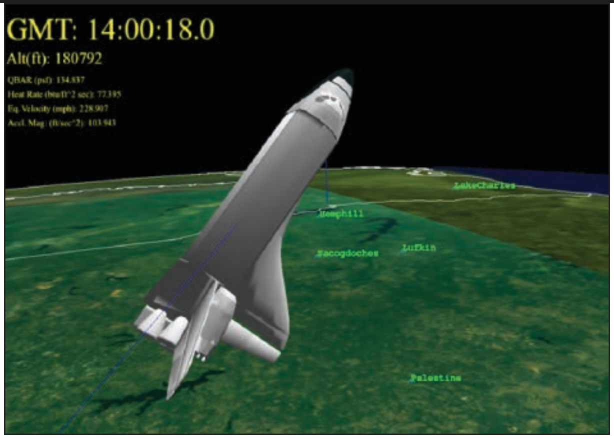
At the conclusion of their deliberations, the Columbia Accident Investigation Board (CAIB) made multiple recommendations to NASA for the improvement of systems and processes. However, they made no recommendations regarding improvements that could specifically address crew survival. In their report (which was published in August of 2003 and can be found at *http://caib.nasa.gov*), the CAIB did identify one observation (CAIB Report Observation 010.2-1) that reads

> *Future crewed-vehicle requirements should incorporate the knowledge gained from the* Challenger *and* Columbia *accidents in assessing the feasibility of vehicles that could ensure crew survival even if the vehicle is destroyed.*

The Space Shuttle Program recognized the importance of capturing the lessons learned from the loss of Columbia and its crew to benefit future human exploration, particularly future vehicle design. In October 2004, the Program commissioned the Spacecraft Crew Survival Integrated Investigation Team (SCSIIT). The SCSIIT was asked to perform a comprehensive analysis of the accident, focusing on factors and events affecting crew survival, and to develop recommendations for improving crew survival for all future human space flight vehicles. To do this, the SCSIIT investigated all elements of crew survival, including the design features, equipment, training, and procedures intended to protect the crew. The investigation relied on data in the form of vehicle telemetry (while Columbia was still intact and transmitting data), video (both from the general public and the news media), recovered debris, and medical findings, each supplemented with modeling and

Visual Representation of the Breakup Sequence

This simulation represents the Orbiter just before loss of control.



The Catastrophic Event (CE) was a period of time during which the orbiter vehicle was undergoing a major structural breakup. At this time, the accelerations on the forebody were estimated to be 3.5 Gs. The breakup sequence progressed over several seconds. Analysis of ground-based video of the event established the first detectable signs at GMT 14:00:18.

analyses when needed. The SCSIIT used these data to identify all events with lethal potential (even those that occurred after the crew was deceased) during reentry into Earth's atmosphere so that threats to crew survival could be described and methodically approached in future designs. In the course of the investigation, five events with lethal potential were identified.

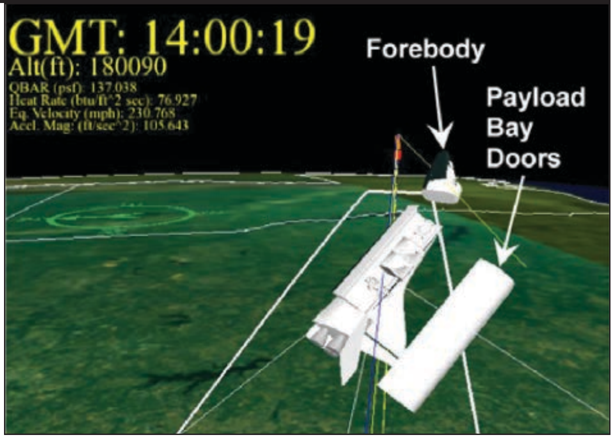
The analysis proved to be extremely difficult for many reasons. First, recovered debris items from adjacent locations inside the vehicle (the middeck floor, for example) showed highly variable degrees of thermal damage. Developing a failure scenario based on just one piece of debris could result in incorrect conclusions, so failure scenarios needed to be developed taking into account all recovered debris items. Second, it was difficult to model the reentry dynamics of the separated forebody because no aerodynamic models existed for that one section of the Space Shuttle orbiter (an aerodynamic model did exist for an intact orbiter). Third, a large set of well-understood data from civilian and military aircraft accidents exists, but data from spacecraft accidents at very high altitude and velocity/acceleration environments did not exist; this lack of data hampered the team. Finally, many members of the team knew the crew personally, so the investigation of the final moments of the crewmembers' lives was emotionally difficult and occasionally resulted in periods of "burnout" for some members of the team.

Definition of Greenwich Mean Time

Greenwich Mean Time (GMT), also known as Greenwich Meridian Time, is measured from the Greenwich meridian line at the Royal Observatory in Greenwich, England. It is the place from where all time zones are measured. Even though the term GMT is used frequently in documents, the actual time used in space flight is Coordinated Universal Time (UTC).

Some conclusions were purely factual, drawn from hard data recovered from telemetry, such as the exact timing of the forebody separation from the rest of the orbiter. Conclusions drawn from analytical techniques other than vehicle telemetry were associated with varying degrees of certainty. In general, the team defined its conclusions along a continuum of certainty, using

Based on engineering analysis, the CE is thought to have started with the compromise of the payload bay doors, exposing the payload bay longeron sill to entry heating. The skin splice between the midbody and the Xo 582 ring frame bulkhead area, aft of the starboard x-link, failed due to a combination of mechanical and thermal loads. The forebody rotated away from starboard to port, causing the port x-link to fail due to bending loads. As the forebody separated from the midbody, various power, data, and Environmental Control Life Support Systems lines failed and the crew module was free to move forward and strike the inside of the forward fuselage.



This simulation represents the orbiter just after the catastrophic event. The three main items in this view are the payload bay doors, the forebody, and the main portion of the orbiter. The left wing has already departed from the orbiter and is not visible in this view.

The Catastrophic Event is depicted in these three frames of video that cover 0.1 second. There is no change in the magnification/zoom factor. The third frame represents GMT 14:00:18.30

"possible," "likely," or "probable" to define increasing levels of confidence.

Once the team completed its investigation and deliberations, the findings, conclusions, and recommendations were documented in the "*Columbia* Crew Survival Investigation Report" (NASA/SP-2008-565, available at *http://history.nasa.gov/columbia/columbiacrewsurvival.pdf*). The report also includes the highly technical data that were used in the development of those findings, conclusions, and recommendations. The exhaustive data were included because of difficulties finding relevant technical data from the previous Challenger accident; the investigation team believed that it was important to include all data in one location for future investigators to easily reference.

NASA disseminated this report publicly in the hope that the world's spacefaring organizations (government-sponsored and commercial) could benefit from the findings and incorporate into their spacecraft designs to maximize crew survivability.

The report identified the five potentially lethal events that the crew experienced during the mishap. For each of the five events, the report addressed whether current technology existed that could have precluded the lethality of the event. ***It is important to note that the crew of Columbia was exposed to all five of the events, and that the Columbia accident was not survivable.***

The five events with lethal potential will now be discussed at a high level along with some key recommendations associated with each one and a brief discussion of how NASA's Multi-Purpose Crew Vehicle (MPCV) program is addressing the recommendations. For more details or a deeper technical understanding of the events surrounding the Columbia accident from the crew survival perspective, the reader is referred to the "*Columbia* Crew Survival Investigation Report."

The following were the five potentially lethal events:

1. The first event with lethal potential was depressurization of the crew module, which started at or shortly after the breakup of the orbiter vehicle.
2. The second event with lethal potential was the exposure of unconscious or deceased crewmembers to a dynamic rotating load environment with non-conformal helmets and a lack of upper-body restraint.
3. The third event with lethal potential was separation of crewmembers from the crew module and the seats, with associated forces, material interactions, and thermal consequences. This event is the least understood, because of limitations in current knowledge of mechanisms at this Mach number and altitude. Seat restraints played a role in the lethality of this event.
4. The fourth event with lethal potential was exposure to near vacuum, aerodynamic accelerations, and cold temperatures.
5. The final event with lethal potential was ground impact.

1. Cabin Depressurization

Description of the event

The Space Shuttle Columbia crew module was not recovered intact. In fact, the crew module debris footprint was more than 50 miles long, indicating that the crew module broke up at altitude. Obviously, a cabin breach occurred at some point during the orbiter crew module breakup sequence. The SCSIIT concluded that the Columbia crew module cabin pressure was nominal (14.7 pounds per square inch absolute) and the crew was capable of conscious actions up to the beginning of the orbiter breakup. The crew module depressurization began at or shortly after the orbiter breakup (when the vehicle was at about 180,000 ft altitude), and was caused by cabin breaches above and below the middeck floor.

Impact on the crew

Evidence indicates that the crew was aware of the vehicle loss of control (which began 41 seconds before the vehicle breakup) and was responding to failures of orbiter systems before the vehicle breakup. The pressure suit helmets that Space Shuttle crewmembers wore included a pressure visor that could be lowered quickly to protect crewmembers in the event of a cabin depressurization. However, analysis of recovered suit components indicates that none of the crewmembers lowered their helmet visors. The accelerations acting on the crewmembers during this time were not severe enough to preclude this action. Therefore, the depressurization rate was high enough to incapacitate the crewmembers within seconds so that they were unable to perform actions such as lowering their visors. Once the depressurization occurred, the crewmembers were rendered unconscious or deceased and were unaware of the subsequent events. Given the level of tissue damage observed in the remains, crewmembers could not have regained consciousness even if the cabin could have been repressurized. At this point survival was possible but would not have been likely, even with immediate and extensive medical intervention. Although respiration would have ceased after depressurization, circulatory functions can exist for a short period without respiration.

Survivability using today's technology

After the Space Shuttle Challenger accident in 1986, all Space Shuttle crewmembers wore pressure suits during ascent and reentry. The pressure suits and their attached emergency oxygen system could protect the crewmembers from a cabin depressurization. However, the pressure suits were added to the Space Shuttle after the vehicle was designed, and this retrofit resulted in some operational inefficiencies and incompatibilities. For example, the deorbit preparation period of Shuttle missions was so busy that crewmembers often did not have enough time to complete the deorbit preparation tasks (putting on their pressure suit, helmet, gloves, parachute, and other equipment, strapping into the seat, and so on) before the deorbit burn. Suit debris evidence indicates that three of the seven Columbia crewmembers did not finish putting on their suit gloves for reentry. One of these three crewmembers did not have the helmet donned at the time of the vehicle breakup.

Additionally, as mentioned above, none of the crewmembers lowered their helmet pressure visors, so none of the pressure suits provided protection against the

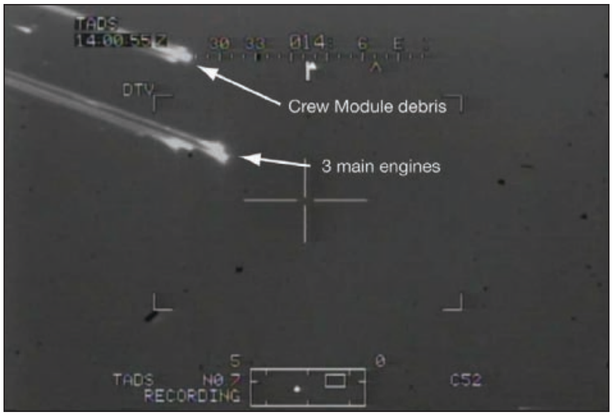
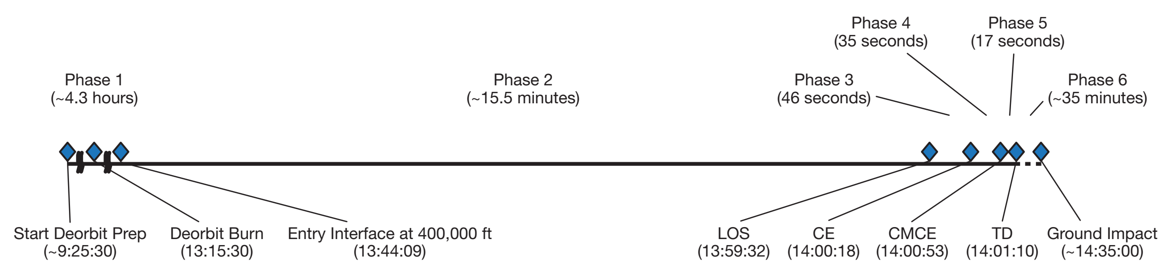


Image from Apache video showing the crew module debris and the orbiter's three main engines. Based on engineering analysis, the crew module catastrophic event is thought to have started with the failure of the forward fuselage. Once the forward fuselage began to break away, the exposed crew module rapidly failed due to the combined effects of the high G-loads, aerodynamic forces, and thermal loads. The flight deck maintained structural integrity longer than the middeck.

Image is from the Apache video. Dotted circle indicates area where the crew module debris was last visible. The three points in the lower right are the orbiter's three main engines. The forward fuselage and crew module fragmented into pieces quickly and became too small to detect by ground-based video. At approximately GMT 14:35:00, the crew remains and the majority of the crew module debris completed the free fall to the ground.

cabin depressurization. Had the suits been configured with the visors down and locked, gloves on, and emergency oxygen system activated, the depressurization event by itself probably would have been survivable.

Overall Timeline



This timeline represents the best fit to known and inferred data, but it is subject to some inherent uncertainty. It is divided into six phases, based on key events. Each phase of the timeline is addressed in sequence.

Phase 1 (GMT 09:15:30 to entry interface (GMT 13:44:09.): The deorbit preparation timeline begins 4 hours prior to the deorbit burn. After the burn, the orbiter descends in altitude until atmospheric drag effects become noticeable, roughly an altitude of 400,000 feet and approximately 4,300 nautical miles from the landing site, traveling in excess of Mach 24.

Phase 2 (GMT 13:44:09 to GMT 13:59:32): Loss of signal (LOS) is the loss of voice and real-time data transmissions from Columbia.

Phase 3 (GMT 13:59:32 to GMT 14:00:18): From LOS to the Catastrophic Event (CE). The CE is defined as the initiation of the orbiter breakup into the primary subcomponents of the forebody, midbody, and aftbody.

Phase 4 (GMT 14:00:18 to GMT 14:00:53): From the CE to the Crew Module Catastrophic Event (CMCE). The CMCE is defined as the initiation of the forebody breakup.

Phase 5 (GMT 14:00:53 to GMT 14:01:10): From the CMCE to Total Dispersal (TD). TD is defined as the time when the crew module was substantively broken down into subcomponents and was no longer visible on ground-based videos.

Phase 6 (GMT 14:01:10 to approximately GMT 14:35:00): Ground impact of the crew remains and the majority of the crew module debris.

Recommendations to future programs

The "*Columbia* Crew Survival Investigation Report" contains many recommendations related to pressure suits. The two key recommendations listed below are related to the cabin depressurization lethal event. The findings and conclusions related to these recommendations are described in detail in the "*Columbia* Crew Survival Investigation Report."

Recommendation L1-2[1]

"Future spacecraft and crew survival systems should be designed such that the equipment and procedures provided to protect the crew in emergency situations are compatible with nominal operations. Future spacecraft vehicles, equipment, and mission timelines should be designed such that a suited crewmember can perform all operations without compromising the configuration of the survival suit during critical phases of flight."

Recommendation L1-3/L5-1

"Future spacecraft crew survival systems should not rely on manual activation to protect the crew."

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[1] The recommendation numbers trace to the recommendations listed in the "*Columbia* Crew Survival Investigation Report."

How NASA's MPCV program is addressing the recommendations

The next vehicle NASA is developing for human space flight, the Multi-Purpose Crew Vehicle (MPCV), includes pressure suits in the design. The suits will be worn for ascent and reentry. They are included in the vehicle design from the beginning, and critical controls are designed to be compatible with a pressure-suited crew. Additionally, vehicle operations will address the incompatibilities described in Recommendation L1-2.

2. Exposure to a Dynamic Rotating Environment with Non-Conformal Helmets and a Lack of Upper-Body Restraint

Description of the event

The initial breakup of Space Shuttle Columbia resulted in an intact nose portion, or "forebody," of the vehicle separating from the rest of the major vehicle components. The forebody consisted of the forward fuselage (outer skin) structure and the crew module (pressure vessel) structure. This forebody was not aerodynamically stable. From the time of vehicle breakup until the crew module breakup, the forebody was rotating about all three axes at about 0.1 revolution per second (6 revolutions per minute, 36 degrees per second) with increasing rates and accelerations. The increasing atmospheric drag on the forebody and the rotational motion of the tumbling forebody resulted in the crew being exposed to oscillatory and increasing accelerations in all three axes.

Impact on the crew

Shortly after the vehicle breakup, the crewmembers lost consciousness as a result of the loss of cabin pressure. Debris evidence indicates that the seat inertial reel mechanisms on the crewmembers' shoulder harnesses did not lock and that the inertial reel straps were extended. Therefore, the unconscious or deceased crewmembers were exposed to the cyclical rotational motion while being restrained only at the lower body. The suit pressure helmets were not conformal. Consequently, lethal trauma occurred to the unconscious or deceased crewmembers because of the lack of upper-body support and restraint.

Survivability using today's technology

The Shuttle seat and helmet design and operational practices did not protect the crewmembers from this lethal event. Complete strap-in with inertial reels locked would have reduced the risk of injury or death; however, even in this configuration, the Shuttle seat and restraint system provided limited protection from dynamic acceleration events (specifically, it had no lateral restraints, no control of extremity motion, and no head and neck support). Better restraint designs that include head and neck support (that is, conformal helmets), extremity control, and spine support are achievable to reduce the risk of injury or death.

Crashes in automobile racing are common, and it is not unusual for crashes to expose the driver to dynamic rotating environments as the car tumbles. The racing community has evolved driver seats, seat restraints, helmets, and head-and-neck restraint devices that protect drivers during crashes. The technology exists to protect occupants of a spacecraft from a dynamic rotating environment such as was experienced by the Columbia crew during lethal event #2.

Recommendations to future programs

The three key SCSIIT recommendations listed below are related to the dynamic rotating environment lethal event. The findings and conclusions related to these recommendations are described in detail in the "*Columbia* Crew Survival Investigation Report."

Recommendation L2-4/L3-4
"Future spacecraft suits and seat restraints should use state-of-the-art technology in an integrated solution to minimize crew injury and maximize crew survival in off-nominal acceleration environments."

Recommendation L2-7
"Design suit helmets with head protection as a functional requirement, not just as a portion of the pressure garment. Suits should incorporate conformal helmets with head and neck restraint devices, similar to helmet/head restraint techniques used in professional automobile racing."

Recommendation L2-9
"The use of inertial reels in future restraint systems should be evaluated to ensure that they are capable of protecting the crew during nominal and off-nominal situations without active crew intervention."

How NASA's MPCV program is addressing the recommendations

The MPCV spacecraft seat design includes side bolsters and more robust seat restraints. Also, the seat does not use inertial reels.

3. Separation from the Crew Module and Seats with Associated Forces, Material Interactions, and Thermal Consequences

Description of the event

This lethal event occurred around the time of the crew module breakup. The breakup of the crew module and resultant exposure of the crew to reentry conditions was an extremely significant event but was difficult to characterize, as many related events occurred in a short period. During this lethal event, the crewmembers were separated from their seats and the crew module, and were exposed to the hostile reentry environment. The seat restraints played a role in the lethality of this event. All crewmembers were deceased before, or by the end of, this event.

Impact on the crew

The seat restraint system caused lethal-level injuries to the unconscious or deceased crewmembers when they separated from their seats. Upon separation from the seat and crew module, the crewmembers' bodies were exposed to aerodynamic forces, elevated temperatures, and the chemical environment associated with the disintegration of the vehicle structure. Analysis of the recovered suit debris indicated that the pressure suits completely failed and separated from the crewmembers' bodies. Suit failure was caused by mechanical loading (due to aerodynamic forces), and hastened by thermal exposure and possibly chemical effects from the atomic oxygen present in the upper atmosphere.

Survivability using today's technology

Although the seat restraints played a significant role in the lethal injuries, there is currently no full range of equipment to protect for this event. The event was not survivable by any means known to the investigative team, other than by ensuring the integrity of the crew module until the airspeed and altitude were within survival limits. This was not possible for the Space Shuttle design; however, future vehicle designs incorporating a principle of "graceful degradation" and crew module stabilization may be possible.

Recommendations to future programs

The two key SCSIIT recommendations listed below are related to the separation lethal event. The findings and conclusions related to these recommendations are described in detail in the "*Columbia* Crew Survival Investigation Report."

Recommendation L2-4/L3-4
"Future spacecraft suits and seat restraints should use state-of-the-art technology in an integrated solution to minimize crew injury and maximize crew survival in off-nominal acceleration environments."

Recommendation L3-5/L4-1
"Evaluate crew survival suits as an integrated system that includes boots, helmet, and other elements to determine the weak points, such as thermal, pressure, windblast, or chemical exposure. Once identified, alternatives should be explored to strengthen the weak areas. Materials with low resistance to chemicals, heat, and flames should not be used on equipment that is intended to protect the wearer from such hostile environments."

How NASA's MPCV program is addressing the recommendations

The MPCV spacecraft seat design includes side bolsters and more robust seat restraints. Suit design currently is in the preliminary stages. The suit is being designed to be compatible with the various environments to which it may be exposed.

4. Exposure to Near Vacuum, Aerodynamic Accelerations, and Cold Temperatures

Description of the event

This lethal event occurred as the crewmembers' bodies were in free-fall from about 140,000 ft, after being exposed to the hostile, chaotic environment discussed in lethal event #3 above.

Impact on the crew

At the altitude and speeds that the deceased crewmembers departed the crew module, the environmental risks included lack of oxygen, low atmospheric pressure, high thermal loads as a result of deceleration from high Mach numbers, shock wave interactions, aerodynamic accelerations, and exposure to cold temperatures.

Survivability using today's technology

The Shuttle pressure suit system was certified to operate at a maximum altitude of 100,000 ft, and certified to survive exposure to windblast associated with 560 knots equivalent air speed. The operating envelope of the orbiter was much greater than this. The actual maximum protection environment for the Shuttle suit system is not known, and the Shuttle suit was not evaluated for protection from high temperature exposures. The only protection that is achievable is to ensure the integrity of the crew module until the airspeed and altitude are within the suit capability, which was not precisely determined.

On October 14, 2012, the Red Bull Stratos high-altitude skydiving project had Austrian skydiver Felix Baumgartner fly a helium balloon to about 127,000 ft over New Mexico. Wearing a pressure suit similar to the Space Shuttle suits, Baumgartner jumped from the balloon's capsule, free-falling for more than 4 minutes before landing safely under parachute. Baumgartner reportedly reached a maximum speed greater than 840 mph or 1.25 times the speed of sound. The Stratos project demonstrated the possibility of surviving a high-altitude free fall.

Threat Matrix and Survival Gap

Table summarizes the events of lethal potential that the crew members of STS-107 faced, the possible threat mitigations at the time of the STS-107 accident, and the potential future, achievable threat mitigations.

Lethal Threats*	STS-107	Achievable
1. Depressurization	R	G
2. Off-nominal dynamic G environment	R	G
3. Thermal intrusion into crew cabin	R	Y
4. Exposure to high-speed/ high-altitude environment	R	Y
5. Ground impact	R	G

** As configured during STS-107 (visors open, some gloves off, inertial reels unlocked, etc)*

Red (R) = *Threat could not be mitigated.*

Yellow (Y) = *Threat can probably be mitigated with new designs, operational procedures and/or hardware.*

Green (G) = *Threat can be mitigated*

Recommendations to future programs

The key SCSIIT recommendation listed below is related to the lethal event of exposure to the high-altitude environment. The findings and conclusions related to this recommendation are described in detail in the "*Columbia* Crew Survival Investigation Report."

Recommendation L3-5/L4-1
"Evaluate crew survival suits as an integrated system that includes boots, helmet, and other elements to determine the weak points, such as thermal, pressure, windblast, or chemical exposure. Once identified, alternatives should be explored to strengthen the weak areas. Materials with low resistance to chemicals, heat, and flames should not be used on equipment that is intended to protect the wearer from such hostile environments."

How NASA's MPCV program is addressing the recommendation

Unlike the Space Shuttle, the MPCV does not include an in-flight bailout capability with an individual parachute for each crewmember. Free-falling from a high altitude after a vehicle breakup is not a survivable scenario for the MPCV.

5. Ground Impact

Description of the event

After a period of free fall, the crewmembers' bodies struck the ground.

Impact on the crew

The deceased crewmembers' bodies had lethal-level injuries caused by ground impact.

Survivability using today's technology

The Shuttle crew escape equipment included a parachute that protected against ground impact. However, the parachute system required manual action by a crewmember to initiate the parachute opening sequence. Military and sport parachuting solutions exist for opening parachutes independent of crew action.

Recommendations to future programs

The key SCSIIT recommendation listed below is related to the ground impact lethal event. The findings and conclusions related to this recommendation are described in detail in the "*Columbia* Crew Survival Investigation Report."

Recommendation L1-3/L5-1
"Future spacecraft crew survival systems should not rely on manual activation to protect the crew."

How NASA's MPCV program is addressing the recommendation

Unlike the Space Shuttle, the MPCV does not include an in-flight bailout capability with an individual parachute for each crewmember. Therefore, automatic opening of individual parachutes to protect against ground impact is not relevant to MPCV. However, the MPCV design incorporates crew seats mounted on stroking struts. In the event of a hard landing of the vehicle (due to a failure of one of the capsule's three parachutes), the struts will attenuate the loads so the crewmembers will not be exposed to excessive forces.

Conclusion

The Space Shuttle Program recognized the importance of capturing the lessons learned from the loss of Columbia and its crew to benefit future human exploration. The SCSIIT performed a comprehensive analysis of the accident, focusing on factors and events affecting crew survival. The SCSIIT report documents the five events that had lethal potential, and provides recommendations for improving survival of crews on future human space flight vehicles.

Section 4 – The Analysis

Aerospace Medical Forensic Analysis

Legal Analysis and Issues from Recovery and Investigation of the Columbia Accident

Aerospace Medical Forensic Analysis

Michael Barratt, Robert Banks, Philip C. Stepaniak, and Helen W. Lane


Photo credit: Gene Blevins/Los Angeles Daily News

Columbia streaking over the Owens Valley Radio Observatory in Big Pine, California
Columbia crossed the California coast west of Sacramento at 8:53:26 a.m. CST, traveling at Mach 23 and 231,600 feet. The leading edge of the orbiter's wing typically reached more than an estimated 2,800ºF. Crossing California toward Nevada, the orbiter appeared to observers on the ground as a bright spot of light moving rapidly across the sky. Signs of debris being shed were sighted at 8:53:46 a.m. CST, when the superheated air surrounding the orbiter suddenly brightened, causing a noticeable streak in the orbiter's luminescent trail.

Human space flight involves large energies and forces to overcome Earth's gravity, attain orbital velocity, and eventually return through the atmosphere, with flight hardware operating at extreme limits of performance in a poorly characterized environment. Although the level of risk to crew is understandably high, mishaps are rare events. When an accident does happen that involves human casualties, just as in the aviation world no investigation is complete without a forensic pathology analysis. That human tissue bears witness to physical events is well established and can be extremely useful in understanding the processes at work, the sequence of events, and causal mechanisms. These findings directly contribute to understanding and eventually closing gaps in survivability.

After 16 days in orbit, the crew of Columbia tragically died as the orbiter broke apart at an altitude of between 181,000 and 140,000 feet while traveling at approximately Mach 15. The Columbia accident comprises the only source of information on high-altitude hypersonic spacecraft breakup during reentry to Earth's atmosphere and on the resulting human exposure to these forces. An interpretation of the forensic findings in the context of the physical forces involved is crucial to a complete understanding of mishap events and crew protection factors that might be enhanced to optimize safety and survival. This chapter summarizes the human forensic findings of the Columbia accident, emphasizing those that truly contribute to our understanding. The primary aim is to ensure that the lessons learned and recommendations resulting from the Columbia mishap investigation are available to current and future spacecraft designers in the development of new vehicles and systems.

There is no evidence that the crew contributed to this accident.

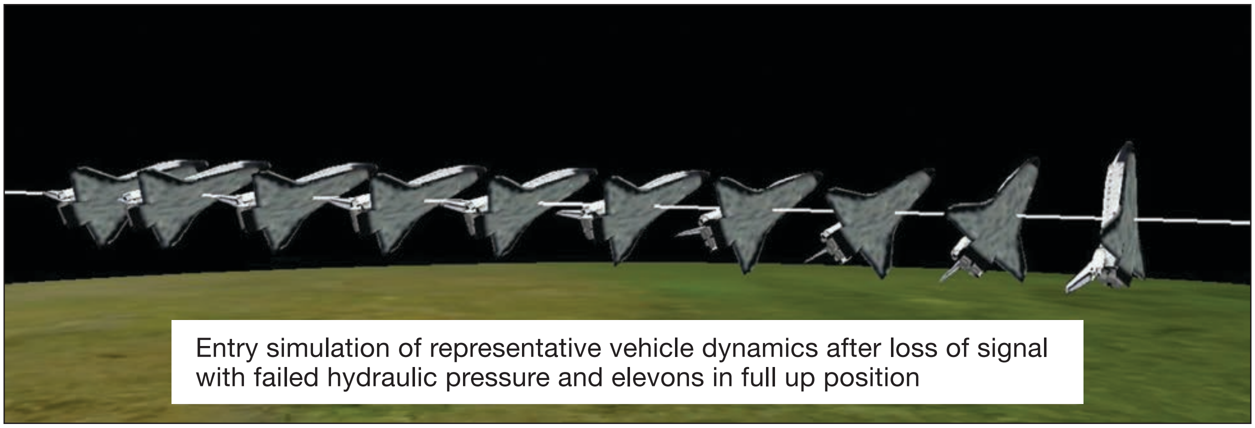
Aeromedical Forensic Analysis

Crew awareness and actions during reentry, loss of signal, and loss of vehicle control and before the catastrophic event

During reentry the flight deck crew of Columbia most probably was aware of a multisystem problem when tire pressure warnings and ambiguous gear deployment indications occurred, involving the left main landing gear. The flight deck crew could only monitor the problem and acknowledge communications from the Johnson Space Center Mission Control Center. The orbiter then lost ground communications at GMT 13:59:32. At the time of loss of signal, the flight deck crew was likely troubleshooting the caution-and-warning messages associated with the left tire pressure, left gear deployment, and flight-control system fault messages.

Jet firings from the orbital maneuvering system thrusters were increasing in frequency to maintain vehicle attitude as aerodynamic integrity became increasingly compromised. The orbiter then lost all hydraulic pressure for flight-control surface activation, which further resulted in a rapid override of the orbital maneuvering system jets; this, in combination with the damage to the left wing, resulted in an uncontrolled pitch-up and loss of vehicle control at GMT 13:59:37. The orbiter motion can be described as a highly oscillatory flat spin. The orbiter was pitching and rolling with a strong and consistent yaw component of the overall motion, but its “belly” was the structure predominantly oriented to the velocity vector. After hydraulic pressure was lost, the flight deck crew most certainly understood that a serious situation had developed. Evidence exists that the pilot tried to recover hydraulics by attempting an auxiliary power unit restart. This showed good system understanding and an appropriate cognitive and motor response to the emergency in the face of a hostile motion environment. Although G loads at this time were still relatively light, after 16 days of weightlessness it is expected that the effects of these loads would be magnified somewhat, producing spatial disorientation out of proportion to that of a normal ground or aviation population. The middeck crewmembers had no outside visual reference, and this motion environment potentially would have produced greater disorientation.

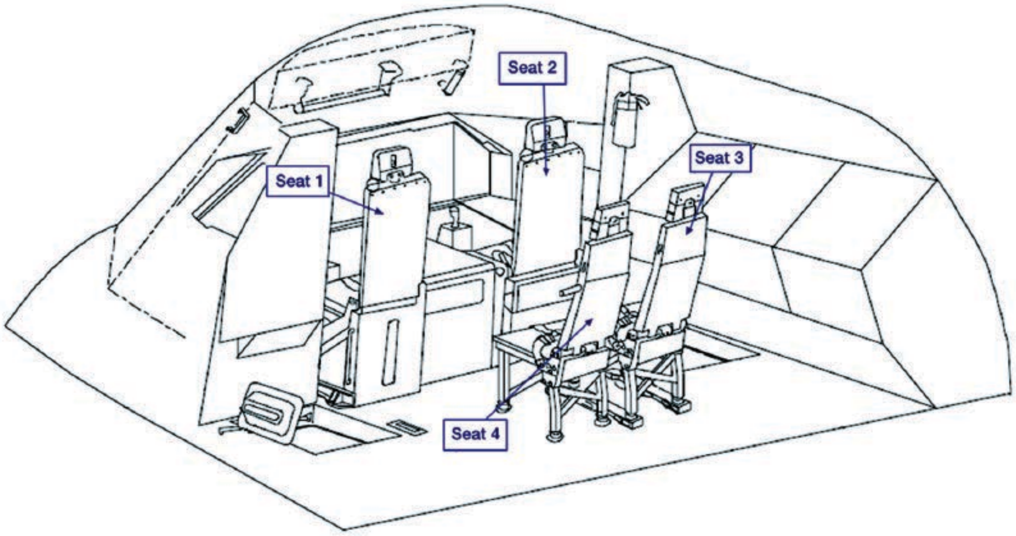
The G loads in the three axes continued and the left wing departed the vehicle. The loads were initially low and then peaked at 3.5 G at the time of the catastrophic event (CE), defined as separation of the forebody from the midbody of the orbiter. The time of the CE was approximately GMT 14:00:18, when the orbiter was at an altitude of between 181,000 and 140,000 feet, traveling at about Mach 15. The crew module remained intact initially after CE but depressurized rapidly. The crew module catastrophic event (CMCE) involved the complete breakup of the crew module after several seconds of high G loads, occurring at GMT 14:00:53. Bracing injuries, catastrophic depressurization with nearly immediate loss of consciousness and pulmonary barotrauma, and other mechanical injuries all occurred in sequence during the 35-second interval between CE and CMCE.



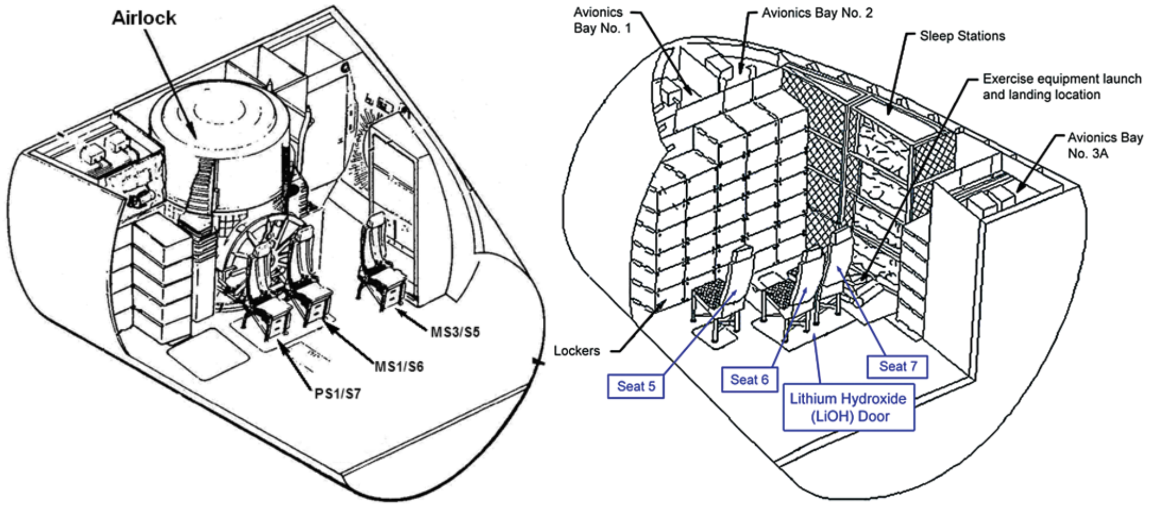
This graphic represents the sequence (1-second intervals) showing a simulation of orbiter loss of control pitch-up from GMT 13:59:37 to GMT 15:59:46. The Spacecraft Crew Survival Integration Investigation Team concluded that loss of control occurred as a result of the loss of hydraulics at GMT 13:59:37. The white line indicates vehicle trajectory relative to the ground.

Crew Configuration During Reentry

The orbiter had a habitable volume of 2,525 ft^3 and consisted of three levels: flight deck, middeck, and utility area. The flight deck, located on the top level, accommodated the commander (CDR), pilot (PLT), and two mission specialists (MS). The middeck, located directly below the flight deck, accommodated three additional crewmembers: two mission specialists and a payload specialist (PS). The crewmembers' preparation for reentry into the Earth's atmosphere included securing the crew compartment, setting up the seats, and donning their Advanced Crew Escape Suit (ACES), which included the suits, helmets, oxygen supply, gloves, and radios. For landing they connected their restraint system.



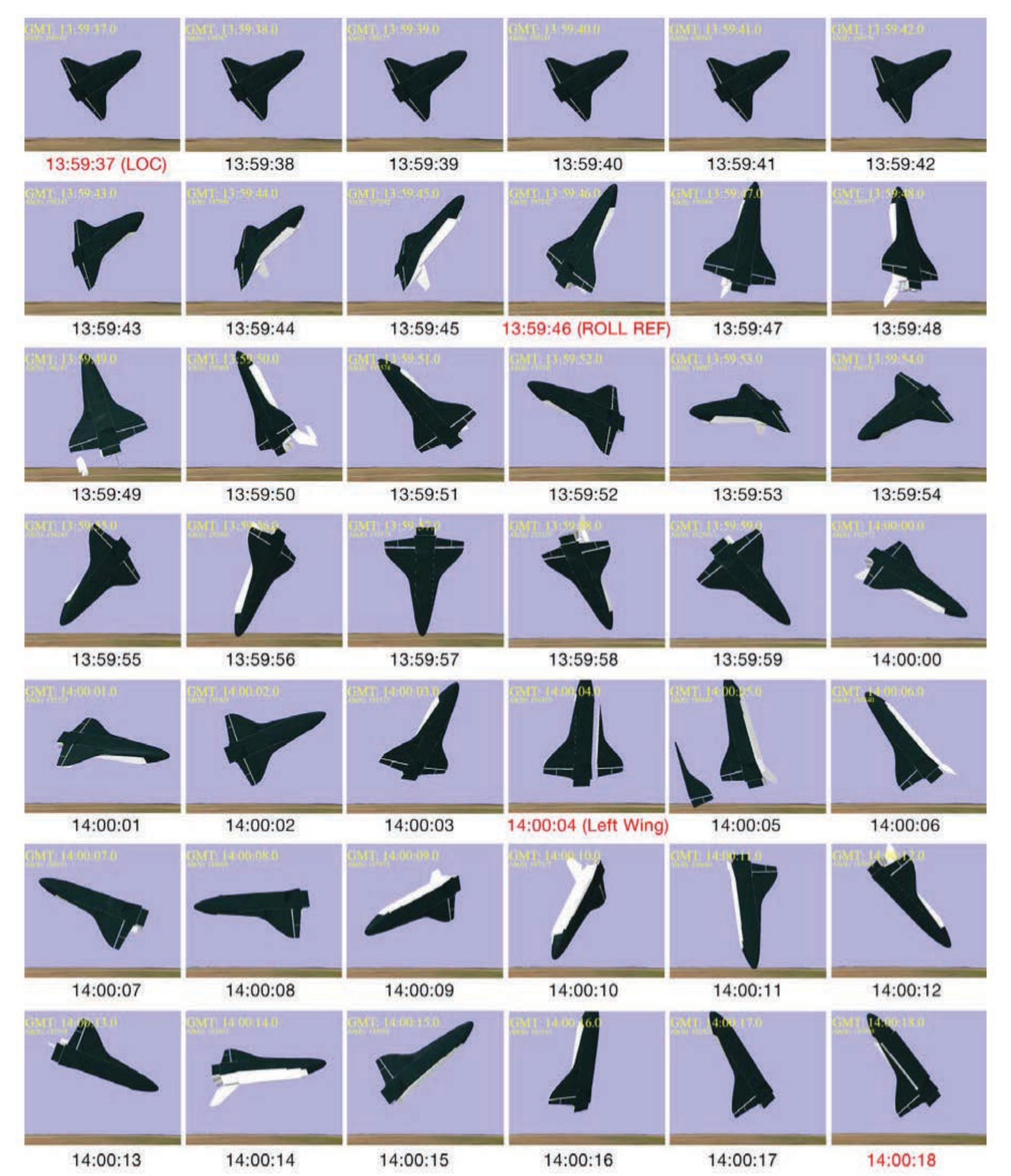
Flight deck seating



Middeck seating (views from aft to starboard and forward to port)

Orbiter Motion Entry Simulation and Representative Vehicle Dynamics After Loss of Control and Before the Catastrophic Event

This graphic illustrates a possible sequence of dynamic vehicle motions derived from best fit synthesis of ballistic data, imagery and debris analysis. The view is from a point in front of the orbiter's direction of travel, looking backward along the velocity vector. The snapshot for GMT 14:00:04 shows the left wing departing intact. In reality, the left wing did not come off all at one time but was shedding debris over a period of time.



The forensic medical findings of injuries incurred during and after the CE and the CMCE can be categorized as follows:

1. Mechanical injuries incurred during the CE
2. Depressurization injuries incurred after the CE
3. Mechanical injuries incurred after the CE and before the CMCE
4. Thermal injuries incurred after the CMCE and exposure to the atmospheric environment
5. Common injuries incurred during the CMCE and ground impact

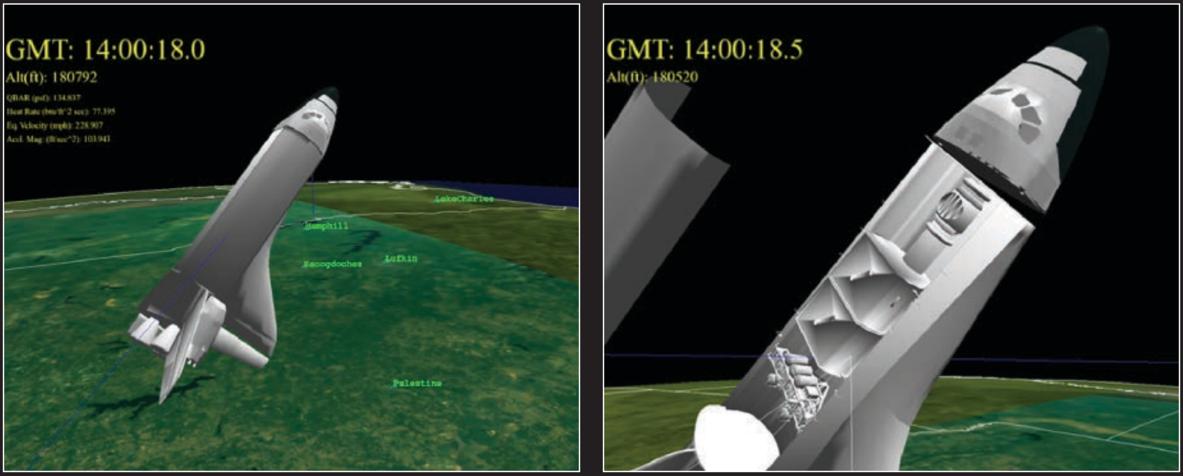
Mechanical injuries incurred during the catastrophic event

Very soon after loss of vehicle control, the left wing shed debris for a period of time and then departed the vehicle, followed by the CE, separation of the orbiter forebody from the midbody. Analysis of structural debris supports the hypothesis that an impact occurred between the forward fuselage (outer vehicle shell) and the crew module (internal pressure vessel) in the area of Volume E on the floor of the middeck. When the vehicle forebody separated, all resources from the midbody were lost, including electrical power from the fuel cells required for lighting, crew displays, radios, intercommunications, ventilation, and the main oxygen supply. At this time the entire crew may have realized that it was not a recoverable situation.

Probably at this time some crewmembers responded to the motion associated with the CE by bracing against structures, subsequently sustaining defensive-type injuries. Bracing indicates that crewmembers were capable of conscious and volitional action up to this point. Shoulder harness restraint was apparently ineffective because of the relatively low acceleration rates involved compared with the designed impact rates required to lock the inertia reels on the restraints.

Catastrophic Event

This graphic illustrates the catastrophic event (CE). The CE was a period during which the orbiter vehicle was undergoing a major structural breakup. At this time, the accelerations on the forebody were estimated to be 3.5 G. The breakup sequence progressed over several seconds. Analysis of ground-based video of the event established the first detectable signs at GMT 14:00:18. On the basis of engineering analysis, the CE is thought to have started with the compromise of the payload bay doors, exposing the payload bay longeron sill to entry heating. As shown in the illustration, the forebody rotated away, from its starboard side to its port side. As the forebody separated from the midbody, various power, data, and life-support systems failed and the crew module moved forward with the forward fuselage.

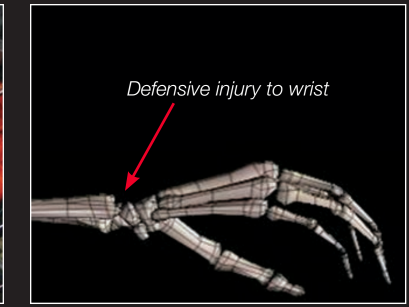


Bracing Injuries

Probably during the catastrophic event, the crewmembers responded to the motion by bracing themselves against structures, resulting in sustained defensive-type injuries. The photos show how the crew may have braced themselves. These injuries indicate that crewmembers were capable of conscious and volitional action up to this point. This bracing caused fractures as illustrated by the schematic showing a wrist fracture.

Demonstration of possible bracing position in the middeck.

Demonstration of possible bracing positon using legs, middeck.

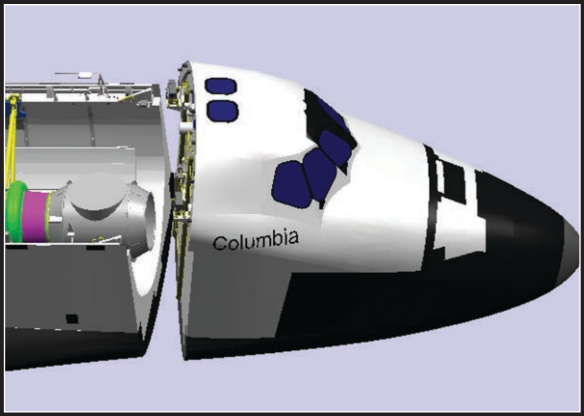


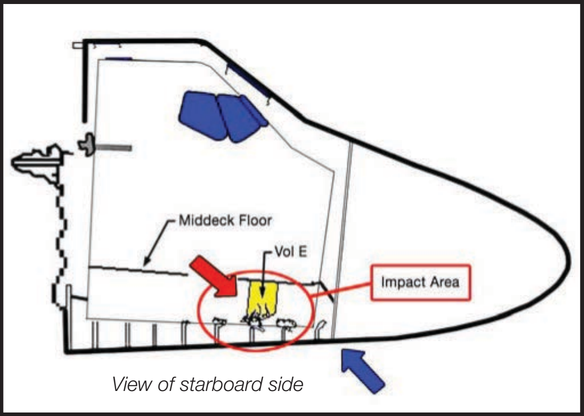
Schematic showing defensive injury to wrist.

Depressurization

The Spacecraft Crew Survival Integrated Investigation Team report concluded that failure of the starboard x-link attachment resulted in separation of the forward fuselage. This failure allowed the crew module to move within the forward fuselage, resulting in damage to the crew module pressure vessel in the area of Volume E (red circle).

The depressurization was due to relatively small cabin breaches above and below the middeck floor and was not a result of a major loss of cabin structural integrity. The crew compartment depressurization began at GMT 14:00:18. The depressurization rate was high enough to incapacitate the crewmembers within seconds. As the crew module lost structural integrity, it was fully depressurized by GMT 14:00:59, if not sooner.





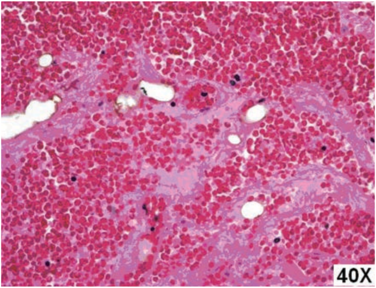
View of starboard side

Depressurization injuries incurred after the catastrophic event

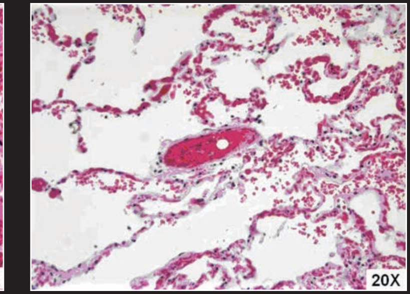
After the forebody separated from the midbody, rapid depressurization occurred at an altitude greater than 100,000 feet. This is well above the altitude at which ambient pressure is less than the vapor pressure of water at body temperature (Armstrong's line, 62,000–63,500 feet). This event would cause ear barotrauma with attendant severe pain and disorientation and rapid loss of consciousness due to hypoxia within 3 to 10 seconds. The transient differential between alveolar and ambient pressure led to massive pulmonary barotrauma with alveolar rupture and hemorrhage, and all respiratory

Tissues Showing Bubbling

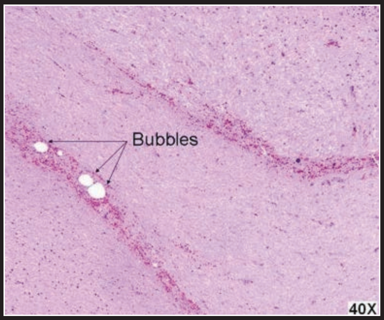
After the forebody separated from the midbody, complete depressurization occurred over a maximum of 41 seconds and probably over much less time, with resulting cessation of respiration, hypoxia, and rapid loss of consciousness. With pulmonary and vascular tissues exposed to near vacuum, the phenomenon of ebullism ensued, with bubbling or vacuolation occurring in multiple tissues throughout the body. Along with the pulmonary barotrauma seen, this rapid depressurization may have caused ear barotrauma with attendant severe pain and disorientation. The micrographs illustrate the bubbling observed in multiple tissues in crewmembers: lung, brain, spinal cord, and bone marrow. Formation of vapor bubbles in body fluids occurs when the ambient pressure falls below the vapor pressure of water at 98.6°F (47 mm Hg) or applicable body temperature.



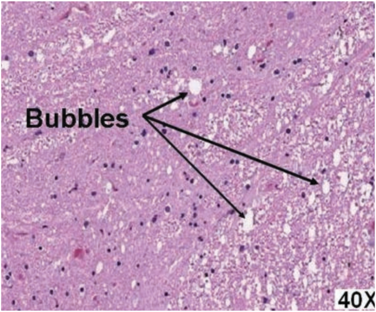
Intra-alveolar hemorrhage in lung.



Rupture of alveolar septa, the partitions dividing one alveolus from another.

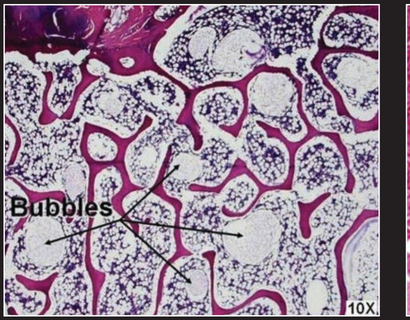


Bubbles in vasculature of the brain.

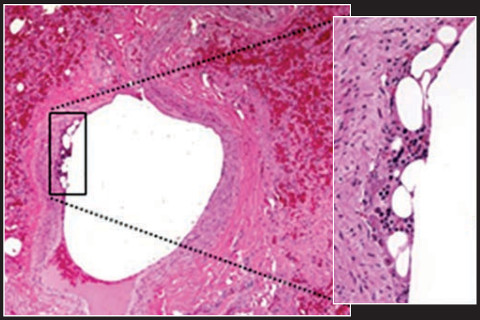


Bubbles in spinal cord.

Bubbles in lung tissue.



Bubbles in bone marrow.



Bone marrow embolus in pulmonary tissues.

exchange ceased. With pulmonary and vascular tissues exposed to near vacuum, the phenomenon of ebullism ensued, with bubbling or vacuolation occurring in multiple tissues throughout the body. One crewmember is known to have died from massive pulmonary barotrauma, as evidenced by lack of hemorrhage associated with subsequent tissue injuries, because of complete cessation of circulation.

Although all crewmembers were wearing pressure suits, none managed to pull their visors down to form a protective pressure seal, an action that normally takes only a few seconds. The investigation team concluded that the depressurization event was sufficiently rapid to promptly incapacitate all crewmembers and preclude this response.

Mechanical injuries incurred after the catastrophic event and before the crew module catastrophic event

After the CE and depressurization occurred, the motion and acceleration dynamics rapidly became increasingly hostile. During this time the unconscious crewmembers sustained mechanical trauma and associated hemorrhage into soft tissues, with the exception of the individual who succumbed to pulmonary barotrauma. Active hemorrhage into injured tissue implies active circulation; therefore this is an important temporal marker for events occurring antemortem.

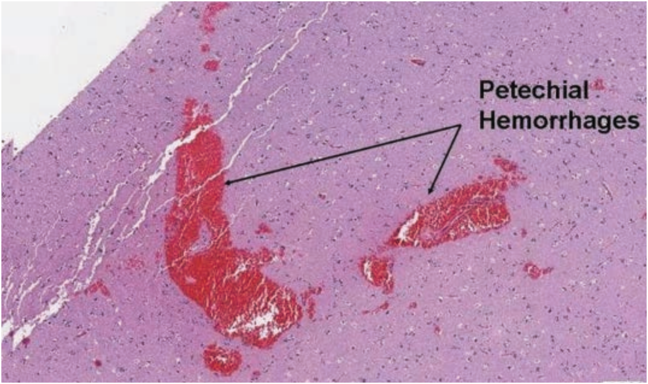
An unconscious individual with an unsupported head-neck complex is vulnerable to head flail injury. The anterior and posterior hemorrhages found in the neck strap muscles of most crewmembers indicated that anterior, posterior, and lateral flail of their heads did occur along with atlanto-occipital separation. The unsupported head in association with the weight of the helmet and the helmet neck-ring geometry provided a fulcrum that caused cervical spine fractures together with neck injuries such as fractures of the hyoid bone and thyroid cartilage.

Most crewmembers sustained head trauma from internal (head-to-helmet) and external (helmet-to-structure) impacts consistent with movement of the head within a non-conformal helmet. These injuries included soft-tissue scalp hematomas, depressed skull fractures, small hemorrhages into the subdural space, and petechial hemorrhages of the brain parenchyma. Also noted were subarachnoid hemorrhages of the spinal cord.

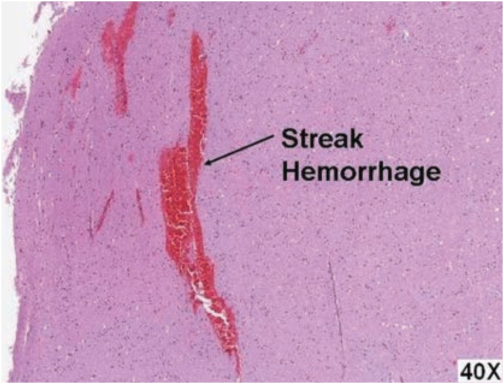
Correlations between the injuries sustained and the restraint system contribute to understanding of safety system function. With one exception, all

Tissues Showing Bleeding due to Mechanical Trauma

Between the catastrophic event and the crew module catastrophic event, the unconscious crewmembers (with the exception of one crewmember who succumbed to pulmonary barotrauma) sustained mechanical trauma and associated bleeding into soft tissues. Active hemorrhage into injured tissue implies active circulation, as seen in these slides of crewmember neck muscles. This is an important temporal marker for events that occurred antemortem.



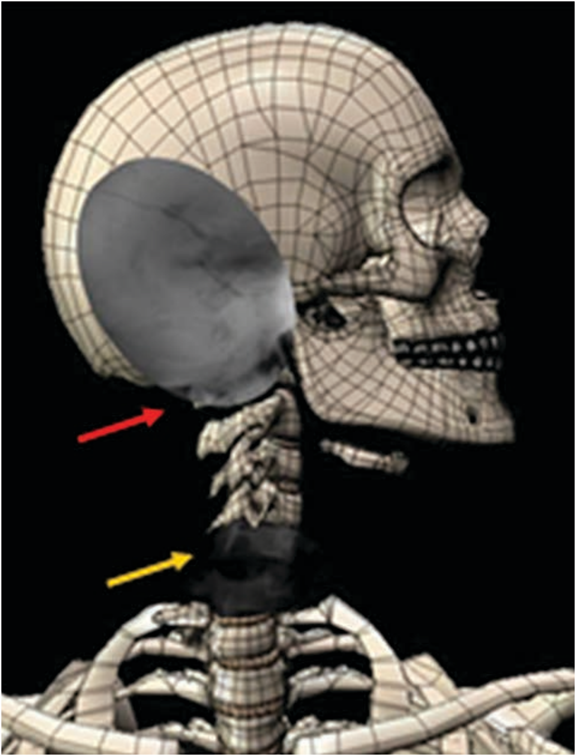
Petechial hemorrhages in neck muscle.



Streak hemorrhage in neck muscle.

Head and Neck Injuries

An unconscious individual with an unsupported head-neck complex is vulnerable to head flail injury. The unsupported head, in association with the weight of the helmet and the helmet neck-ring geometry, provided a fulcrum that caused cervical spine fractures together with neck injuries such as fracture of the hyoid bone and thyroid cartilage. The following illustrations show the effects of the helmet and the suit and harness on the cervical spine and the soft tissues of the head and neck complex. This illustration shows the atlanto-occipital dislocation (red arrows) and distraction fractures (yellow arrows) of the cervical spine.



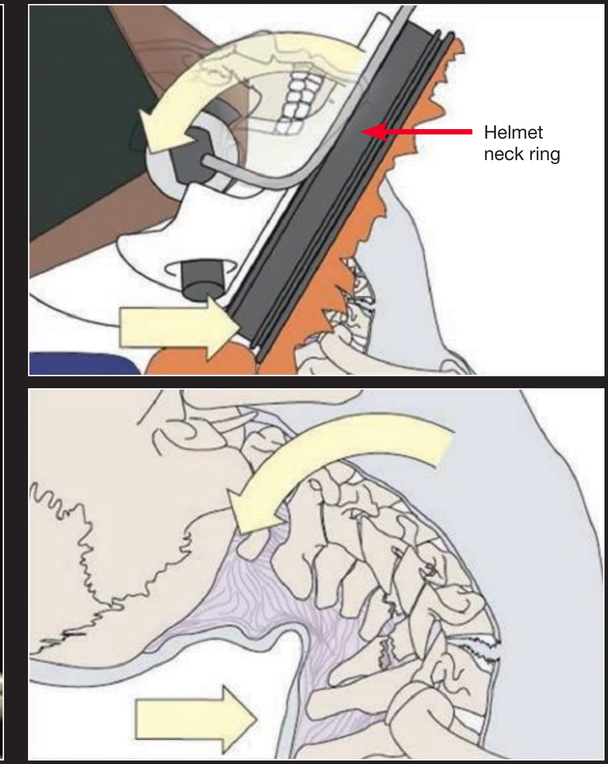
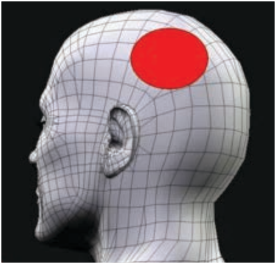
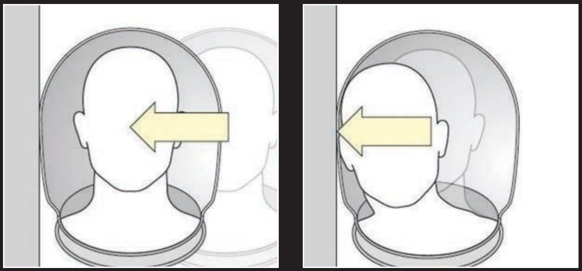


Illustration provided by Biodynamic Research Corporation – BRC

Head Injuries Caused by the Non-conformal Helmet

Soft-tissue injuries in the area shown by the red circle on the manikin were caused by impacts with the helmet, which was non-conformal. The Advanced Crew Escape Suit helmet shown is not from STS-107 but is identical to the STS-107 helmets.





Head strike within non-conformal helmet.

Illustration provided by Biodynamic Research Corporation – BRC crewmembers were restrained in their entry seats by a standard five-point harness system. (One crewmember was incompletely restrained, suggesting that donning restraints was in progress at the time of CE.) A lap belt secured the lower torso and a crotch strap prevented “submarining,” keeping the occupant from sliding forward and beneath the lap belt. Two shoulder harnesses attached to an inertial reel via the inertial reel strap that was designed to secure the upper torso. Engineering analysis of the STS-107 restraints indicated that the inertial reel straps did not lock and were extended during dynamic motion, leaving the upper torso unsupported and free to move. As stated above, this happened because the strap velocity was lower than the locking threshold velocity of the inertia reel system, which was designed for higher velocity transient acceleration associated with impact. With the upper body functionally unrestrained and the lap belts secured, the crewmembers sustained lower spinal and pelvic fractures; these injuries were also noted to have a hemorrhagic component in most crewmembers. The lumbar spine injuries (Chance fracture or transverse vertebral body fracture) resulted from the sudden forward and downward rotation of the torso over the lap belts. This injury pattern is similar to those experienced by victims of automobile accidents who were secured with only a lap belt in a forward impact.

Crew Restraints

Crewmembers were restrained in their seats by a five-point harness system (diagram on the left). A lap belt secures the lower torso and a crotch strap prevents “submarining,” keeping the occupant from sliding forward and beneath the lap belt. The photo of a technician shows how the two shoulder harnesses attach to the restraint buckle. The drawing of the seat with restraints shows that the two shoulder harnesses attach to the inertial reel by means of the inertial reel strap which was designed to secure the upper torso.

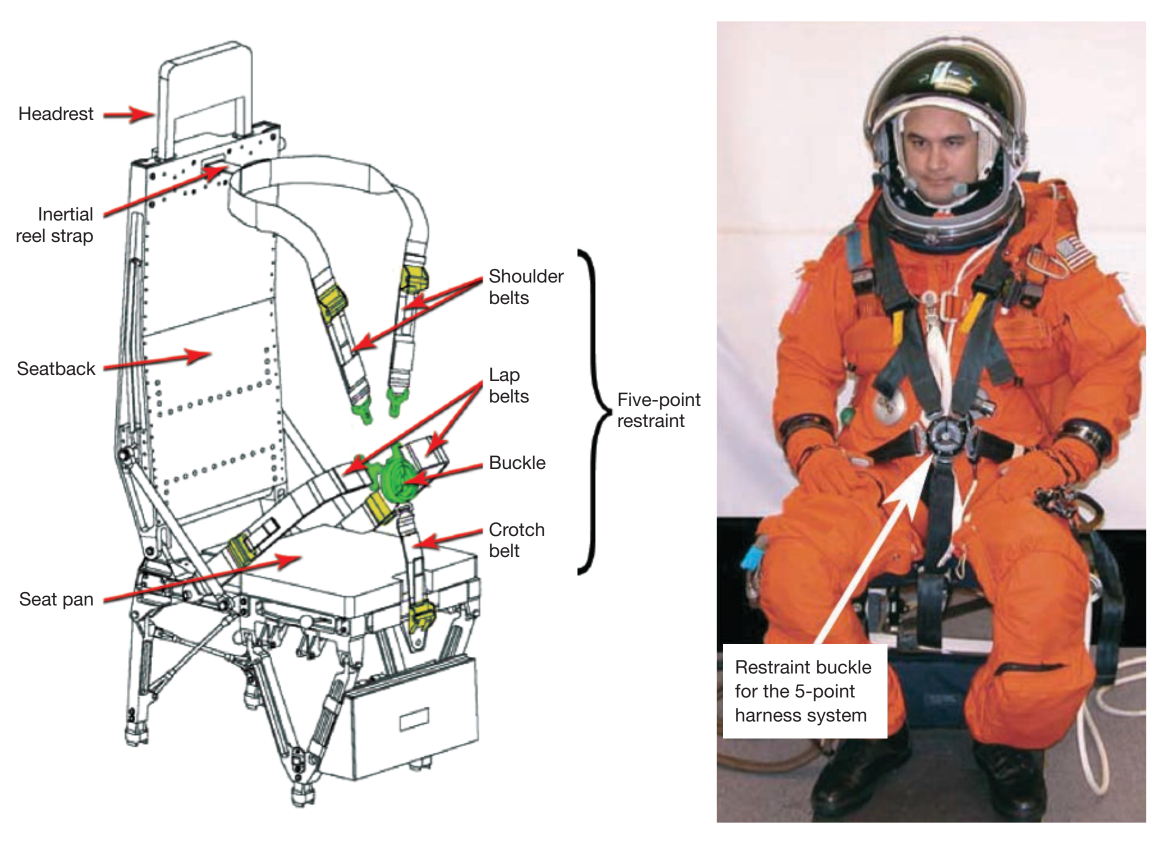


Illustration (left) and photograph (right) of five-point harness.

Chance-type Fracture

This is an illustration of the mechanism causing lumbar spine Chance-type fracture. With the upper body functionally unrestrained and the lap belts secured, the unconcious crewmembers' lumbar spine injuries occurred from the sudden forward and downward rotation of the torso over the lap belts.

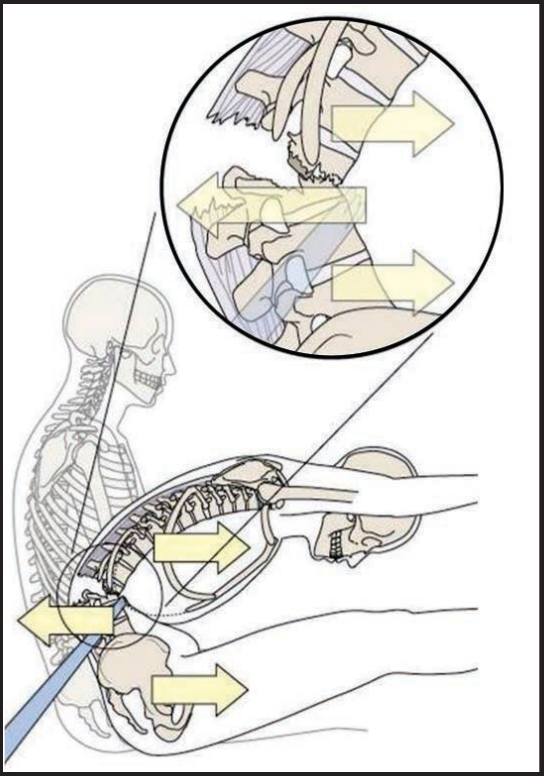


Illustration provided by Biodynamic Research Corporation – BRC

Flail Injuries

All crewmembers exhibited upper- and lower extremity fractures consistent with deceleration injury or aerodynamic flail. Using a model that analyzed the possible strike envelopes of the seated crewmembers, correlation was found between the possible injury locations and the actual sites found at autopsy. The static flail analysis predicted that most injuries would be located in the distal limbs and parietal skull, with some slight variations due to crewmember seat location. The shaded areas represent the common flail injury patterns found. The illustration is based on an analysis using a static strike envelope.

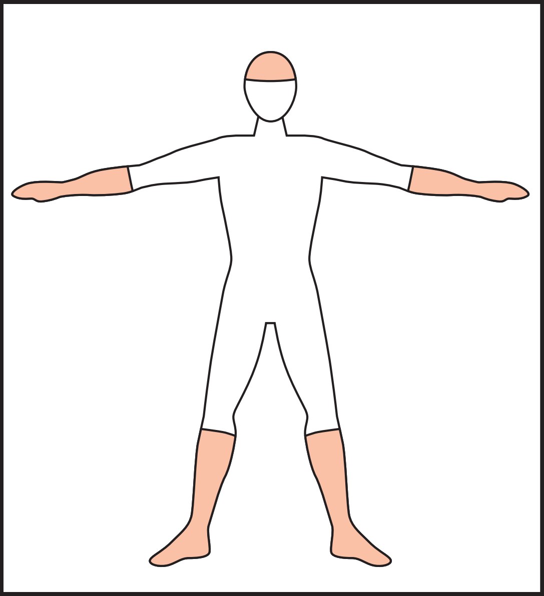


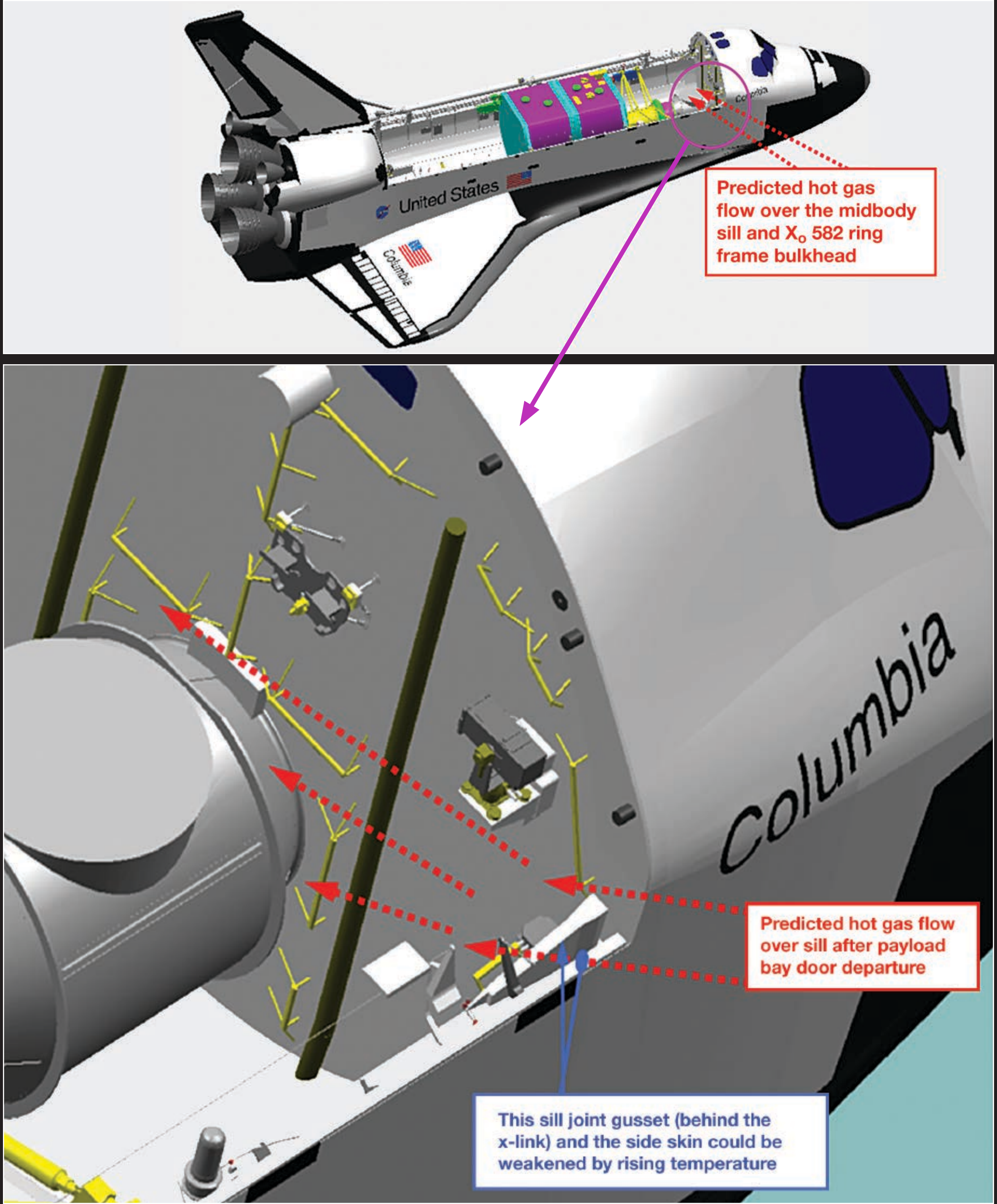
Illustration provided by Biodynamic Research Corporation – BRC

All crewmembers had exhibited upper and lower extremity fractures consistent with deceleration injury (G flail) before CMCE and aerodynamic flail after CMCE and exposure to windblast. Using a model that analyzed the possible strike envelopes of the seated crew, correlation was found between the possible injury locations and the actual sites. The static flail analysis predicted that most injuries would be located in the distal limbs and parietal skull, with some slight variations due to crewmember seat location.

Thermal injuries after the crew module catastrophic event and exposure to the atmospheric environment

Forensic evidence supported exposure of the deceased crewmembers to at least two separate thermal events. The first was a directional thermal event that occurred while the crewmembers were suited and restrained in their seats. This first thermal event is consistent with a breach of the crew module pressure vessel in the vicinity of the starboard x-link when the forebody separated from the midbody at the CE. A breach in

The Initial Stages of the Destruction of the Crew Module with the Separation of the Forward Fuselage from the Body of the Crew Module



Predicted hot gas flow over the midbody sill and X_o 582 ring frame bulkhead

Predicted hot gas flow over sill after payload bay door departure

This sill joint gusset (behind the x-link) and the side skin could be weakened by rising temperature

Position and condition of starboard x-link.

this location permitted thermal energy to enter the crew cabin after atmosphere evacuation had occurred. Analysis of thermal skin burn patterns suggested that the burns initially occurred within the crew cabin with crewmembers in their seats protected by relatively intact suits. As the thermal environment worsened, the suit material was weakened and failed, allowing second- and third-degree burns and thermal shadowing patterns consistent with thermal intrusion.

The second thermal event occurred during the interval from the start of crew module disintegration at GMT 14:00:53 through the total dispersal of the crew compartment structures at GMT 14:01:10. In this time interval the deceased crewmembers underwent additional mechanical trauma. As the remaining forward fuselage and crew module structures were disintegrating, exposure to windblast and possibly shock wave forces rapidly stripped the damaged Advanced Crew Escape Suits (ACES) from the deceased crewmembers. The denuded crewmember remains then passed through the surrounding hot gas and molten metal mist "cloud," incurring additional, universal second-degree flash burns and molten metal

Burns During the Thermal Events

These graphics illustrate the thermal skin burn patterns that occurred during the thermal events with the breakup of the crew module and its dispersal. The crewmembers had 2nd- and 3rd-degree burns and patterns of thermal shadowing with molten metal deposition. The thermal event was severe enough to cause portions of the ACES material to adhere to the skin of one crewmember.

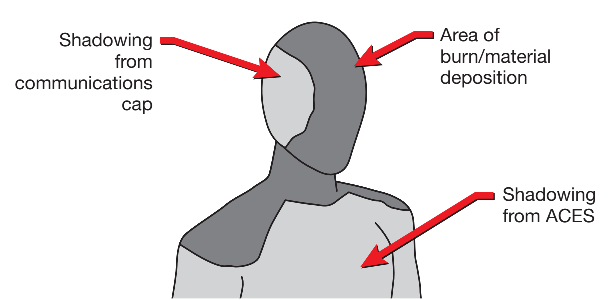
All crewmembers exhibited some degree of increased thermal injury/metal deposition on their heads and necks consistent with exposure while wearing an ACES with helmet visors open. Some shadowing from the communications cap was visible on some crewmembers. It is therefore concluded, from the burn/metal deposition patterns, that the initial burns occurred with the crewmembers in the cabin, in their seats, helmet visors up and covered by a relatively intact ACES that afforded them some thermal protection.

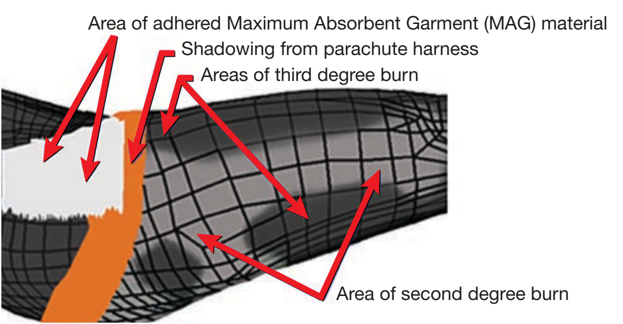
Burn and metal deposition patterns

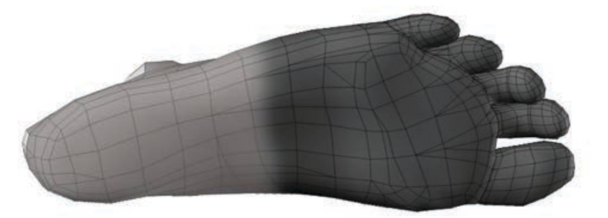
The shadowing is caused by some of the suit materials protecting the crewmembers from the thermal intrusion into the crew module.

Burns on the feet

The feet of several crewmembers exhibited thermal injuries in areas coinciding with the nylon panels of the boots vs. the leather portions. These injuries are consistent with initial failure of the nylon panels and boot soles. The feet of several of the crewmembers exhibited a greater degree of burn/material deposition on the forefoot consistent with failure of the boots at the mid-sole. All of these second-degree burns were associated with "molten metal mist" deposits.



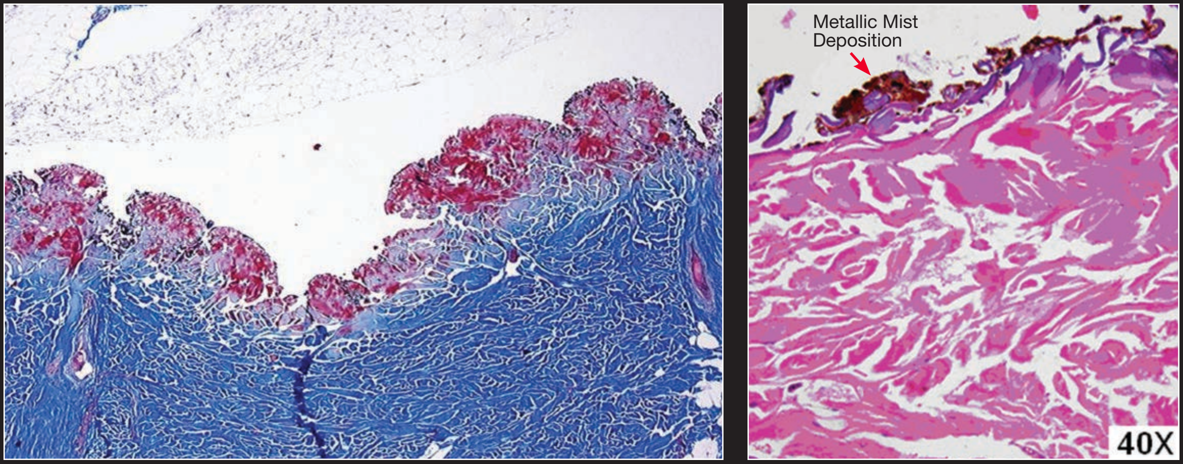




This illustrates the burn mapping of a deceased crewmember's foot.

Thermal Injuries

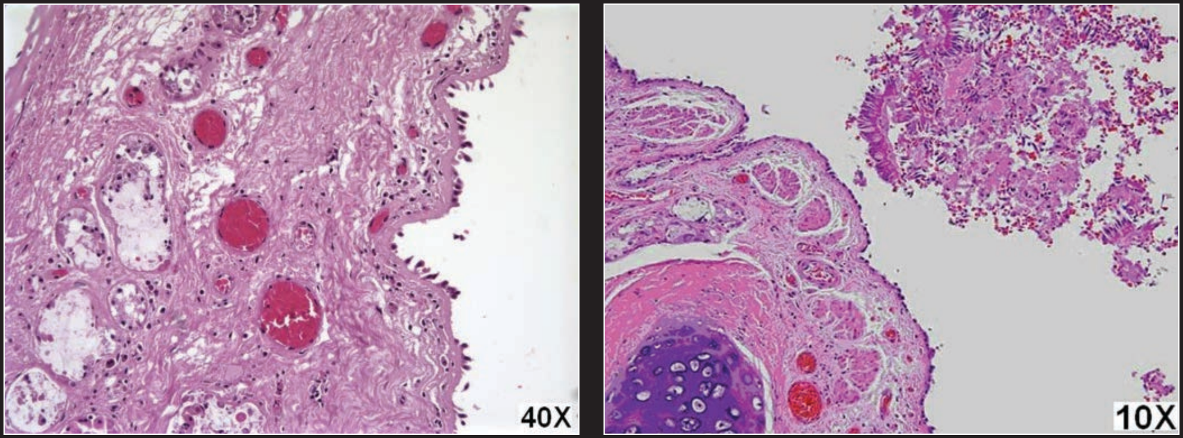
During the second thermal event, the crew module catastrophic event through total dispersal of the crew module, the unconscious crewmembers passed through a surrounding mist "cloud" of hot gas and molten metal, which caused additional 2nd-degree flash burns.



These slides show examples of the superficial skin burns incurred by crewmembers. The left-hand image (20X) is stained with a trichrome stain and demonstrates a superficially burned epidermis in red and the spared deeper reticular dermis in blue (characteristic of a flash burn). The right-hand image is a higher magnification (40X) hematoxylin-eosin stained skin section showing the metallic deposits over the burned surface.

No Evidence of Fire

No deposition of foreign material or evidence of thermal injury was present in any of the respiratory tracts available for review. Forensic analysis showed no significant levels of carbon monoxide or cyanide (combustion by-products) in body fluids. These facts indicate that there was no fire in the crew module before breathing cessation and crew death. These micrographs show a representative section of a crewmember's trachea with intact cilia, free of deposits and evidence of thermal injury.



deposition caused by conductive and irradiative transfer of thermal energy. The FBI material analysis laboratory, using scanning electron microscopy and energy-dispersive x-ray spectrometry, identified the following elements present in the skin deposits: aluminum, calcium (normal component of skin), copper, iron (normal component of skin), manganese (normal component of skin), nickel, phosphorus (normal component of skin), silicon, sulfur (normal component of skin), and titanium.

No deposition of foreign material or evidence of thermal injury was present in any of the respiratory tracts available for review in spite of the presence of superficial facial burning associated with the first thermal event while crewmembers were still suited and seated. Forensic analysis showed no significant levels of carbon monoxide or cyanide (combustion by-products) in body fluids. This is consistent with the complete cessation of respiration after depressurization, shortly after the CE and before the thermal intrusion.

After these two thermal events, the crew remains were exposed to the atmospheric environment at an altitude above 100,000 feet. The remains were subjected to additional thermal injuries during the hypersonic to subsonic deceleration. The findings indicated exposure to near vacuum, aerodynamic heating, highly reactive monatomic oxygen, and subfreezing ambient temperatures during the free-fall descent. As human exposure to these environmental extremes is not well documented, the contribution of these environmental conditions to the pathology findings remains uncertain.

Common injuries incurred during the crew module catastrophic event and ground impact

The common injuries that occurred during the CMCE period were consistent with the application of high dynamic loading, from complex deceleration forces, to the seated, partially restrained and unconscious crewmembers. Engineering and ballistic analyses of the CMCE supports the scenario that the middeck floor and everything attached to it separated from the crew module structure first. When this lower half of the crew module separated from the flight deck "pod," it is likely that a negative G_z load was imparted along the hinge line where the middeck floor was attached

Mechanical Injuries During the Destruction of the Crew Module

Mechanical injuries occurred during the destruction of the crew module. The high negative Gz translational and rotational decelerations at the time of module disintegration were thought to be the major cause of the most severe traumatic mechanical injuries sustained by the deceased crew. An example of these injuries is the basilar skull fracture depicted in this graphic. The fracture was probably caused by the neck ring on the Advanced Crew Escape Suit sticking the lower jaw as the neck ring departed the body due to windblast. All crewmembers but one exhibited these basilar skull fractures.

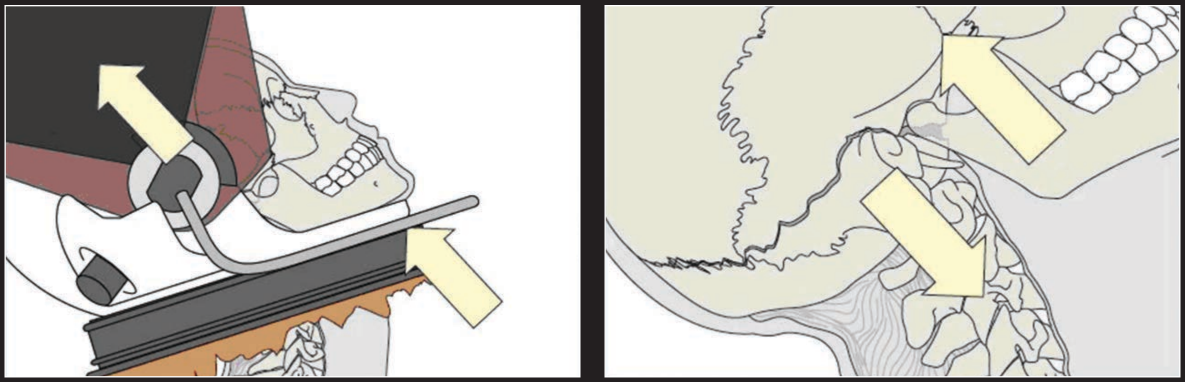


Illustration provided by Biodynamic Research Corporation – BRC

Illustration of the mechanism of basilar skull fracture.

Plot of Relative Range and Recovery Locations Based on the Ballistic Coefficients of the Principal Human Remains Found on the Ground

Relative distance between principal remains.
Plotted from West to East.

to the aft bulkhead. Because of this negative G_z loading, the middeck floor and the Environmental Control and Life Support System bay would have quickly disintegrated together with the middeck floor panels. On the basis of structural design analysis, thermal damage, and position in the debris field, the flight deck "pod" and aft bulkhead are thought to have remained intact for a slightly longer time. At the time of disintegration, the high negative G_z translational and rotational decelerations were thought to be the major cause of the most severe traumatic mechanical injuries sustained by the deceased crewmembers. These mechanical injuries included hemi-transection associated with multiple flexion-type distraction fractures of the spine and separation fractures of the pelvis. In addition to the major traumatic injuries involving the pelvis and spine, all but one crewmember exhibited basilar skull fractures, which are thought to have been caused by the neck ring on the ACES striking the lower jaw as the neck ring departed due to windblast; all exhibited comminuted fractures of facial bone(s); and all exhibited other multiple skeletal fractures, disarticulations, dislocations, and amputations. Although some of the flail injuries were sustained while the crewmembers were restrained in their seats, other flail injuries were inflicted during a period of deceleration from supersonic to subsonic velocity, during free-fall descent and ground impact. Some crewmembers' remains found later in the recovery process had evidence of insect and animal predation.

Gross examination of the recovered remains revealed that the occupants on the starboard side of the vehicle incurred a greater degree of mechanical trauma than those on the port side, suggesting that more energy was imparted to these individuals. This is consistent with the calculated ballistic coefficients of the remains and where the crewmembers were found on the ground during the recovery operations. The ballistic analysis could not be used to determine the sequence and the release times of the crewmembers.

Summary

In summary, the forensic analysis of the Columbia accident led to the following conclusions regarding lethal events and lessons learned:

1. The STS-107 crew died as a direct result of a rapid depressurization causing pulmonary barotrauma and ebullism, followed by blunt-force trauma.
2. An off-nominal dynamic G environment, combined with a lack of restraint of the upper body and nonconforming helmets, contributed significantly to lethal trauma.
3. A third traumatic event consisted of thermal intrusion into the crew cabin, causing extensive second- and third-degree burns on all crewmembers.
4. A fourth traumatic event occurred when the crewmembers separated from the crew module and were subjected to restraint injuries, transonic velocity changes, windblast, aerodynamic flail, exposure to near vacuum, aerodynamic heating, monatomic oxygen, and subfreezing temperatures during free fall.
5. The fifth traumatic event was ground impact.

Aerospace Medical Forensic Findings and Recommendations

Finding 1: Spacecraft accidents are rare; each event adds critical knowledge and understanding for future spacecraft designs and for improvement of operational procedures.

Recommendation 1: As was executed with the Columbia mishap, spacecraft accident investigation plans must include provisions for debris recovery and storage, data preservation, and security. The investigators must catalog, store, and preserve all debris and data so it will be available for future study.

Finding 2: Crewmembers exhibited injuries consistent with bracing, a conscious and volitional act. The loads associated with the CE, together with the lax shoulder harnesses and mass of the crew escape equipment, contributed to these injuries.

Recommendation 2: The design of the restraint system should be integrated with the design of suit and seat, so that crewmembers are not required to use their arms and legs to brace against nominal and off-nominal loads.

Finding 3a: The unprotected crewmembers (helmet visors open, some gloves off) were exposed to a depressurization event sufficient to cause severe barotrauma, hypoxic hypoxemia, ebullism, and death.

Finding 3b: The depressurization incapacitated the crew so rapidly that they were not able to configure their crew survival equipment (e.g., lower their helmet visors).

Finding 3c: When the ACES is properly deployed (visor down, gloves on, O_2 flowing), it is incompatible with the Shuttle hazard controls for preventing cabin fires, impedes operation of user interfaces, and interferes with crew communications.

Recommendation 3a: Future spacecraft and crew survival systems should be designed so that the equipment and procedures provided to protect the crew in emergency situations are compatible with nominal operations. Future spacecraft vehicles, equipment, and mission timelines should be designed so that a suited crewmember can perform all operations without compromising the configuration of the survival suit during critical phases of flight.

Recommendation 3b: A feature should be incorporated into the suit helmet/O_2 system that will automatically activate (lower the visor and turn on O_2) upon cabin depressurization. Operational and design changes must also be made so the integrity of the ACES is ensured and prolonged emergency "in suit" O_2 breathing is permitted without exceeding the O_2 cabin safety fire limits.

Recommendation 3c: None.

Finding 4: Ebullism or bubble formation was present in examined tissues (brain, spinal cord, lung, thyroid, myocardium, and bone marrow), indicating that the unprotected crew was exposed to a pressure altitude above 62,000 ft (Armstrong's line, the altitude that produces an atmospheric pressure so low [0.0618 atmosphere] that water boils at the normal temperature of the human body: 98.6°F [37°C]).

Recommendation 4: None.

Finding 5: Injuries of the lower lumbar spine, upper body extremity, and skull were consistent with crewmembers' torsos flailing forward and downward while anchored by their seat belts. This evidence indicates that those so injured had their seat belts in place, but their inertial reel straps were extended.

Recommendation 5: The use of inertial reels in future restraint systems should be redesigned to ensure that they are capable of protecting crewmembers during off-nominal situations (for example, seat belts should be wider, and extremity flail protection could be provided) without active crew intervention.

Finding 6: The crewmembers had lethal injuries due to the seat restraint system.

Recommendation 6: The design of the seat restraint systems should include considerations to preclude restraint-induced injuries during dynamic motion (e.g., NASCAR racing-type straps).

Finding 7: Most crewmembers had hemorrhage into the anterior and posterior strap muscles of the neck and fractures of cervical vertebrae. The unsupported head (nonconformal helmet) in association with the helmet neck ring acting as a fulcrum contributed to the neck flail injuries.

Recommendation 7: The suit-seat-restraint system should provide support for the head-neck complex (e.g., conformal helmets, head and neck restraint-type devices).

Finding 8: All crewmembers had evidence of global second-degree burns with deposition of metallic particles and pyrolysis products on skin surfaces.

Recommendation 8: Future crew cabin designs should protect the crew in the event of vehicle disintegration (e.g., crew encapsulation).

Finding 9: The crewmembers' body fluids had no significant levels of carbon monoxide or cyanide (combustion by-products), and they had intact ciliated columnar cells in their tracheas with no evidence of deposition or other thermal injury to the respiratory tracts. This indicates that there was no cabin fire before depressurization and that the crew had ceased breathing before any thermal intrusion into the crew module occurred.

Recommendation 9: None.

Conclusion

One of the legacies of the Columbia accident was the documentation of the catastrophic injuries of the crewmembers themselves. NASA, through the efforts of the Crew Survival Working Group, the Spacecraft Crew Survival Integrated Investigation Team, the Office of the Armed Forces Medical Examiner, the Armed Forces Institute of Pathology, the Federal Bureau of Investigation, and the Biodynamic Research Corporation, developed findings and recommendations about the effects of a high-altitude hypervelocity spacecraft accident on the crewmembers. These medical findings and recommendations provide the basis for improved systems design, engineering, and operations of human spacecraft to enable a crew to survive such a mishap in the future. We honor the Columbia crew for the significant aeromedical lessons learned from this mishap.

Integrated Summary Timeline of Crew-related Events

A high-level overview depicts the probable timeline of medically significant events, illustrating their temporal relationship with major environmental conditions. The illustration also emphasizes the short period of time over which these events occurred: about 35 seconds from the forward fuselage separation (catastrophic event or CE) to the crew module disintegration (crew module catastrophic event or CMCE). The cabin pressure profile presented is a reconstructed scenario based on debris analysis and ballistics. The rapid depressurization event started at GMT 14:00:18 with an uncertainty of up to +10 seconds.

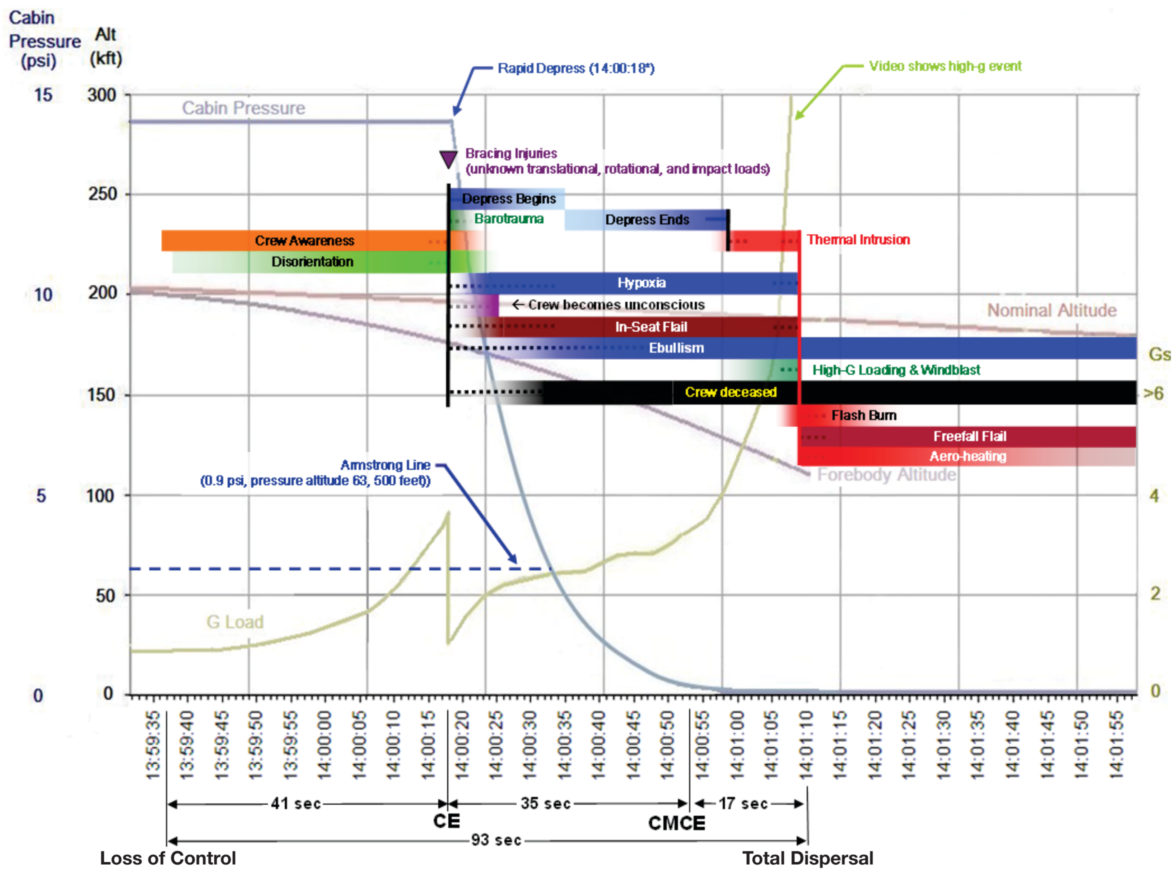


Illustration provided by Biodynamic Research Corporation – BRC

Legal Analysis and Issues from Recovery and Investigation of the Columbia Accident

Donna M. Shafer and Amy V. Xenofos

Immediate Response Phase

Despite the extraordinary focus and perseverance of the personnel at NASA, the Columbia accident was not the first time NASA has lost a Space Shuttle orbiter and its crew—Challenger was tragically lost 73 seconds after lift-off from the Kennedy Space Center in 1986. NASA learned and applied many lessons from the Challenger accident, including a need for an overall contingency plan to be in place as well as a plan for an independent assessment. As a result, today at NASA, activation of an investigation board is required for any event involving serious injury or loss of life, other serious mishaps, or significant public interest. The plan to activate an investigation board was accomplished through the implementation of NASA Policy Directive 8621.1, NASA Mishap and Close Call Reporting, Investigating, and Recordkeeping Policy.

After the Columbia accident, NASA immediately established recovery and investigation teams. At 10:30 a.m. on February 1, 2003, NASA Administrator Sean O'Keefe activated the International Space Station and Space Shuttle Mishap Investigation Board, naming retired naval Admiral Harold Gehman, Jr. as its chairman. The board renamed itself the Columbia Accident Investigation Board (CAIB). On the NASA side, we established the Space Shuttle Mishap Investigation Team (MIT) and the Columbia Task Force (CTF). The CTF served as the primary interface between the Agency and the CAIB. The MIT was responsible for gathering and preserving evidence to allow the CAIB to conduct its analysis and make a causal determination. By the evening of February 1, 2003, the MIT arrived at Barksdale Air Force Base and began organizing its efforts.

The Johnson Space Center Legal Office logo at the time of the Columbia Space Shuttle Accident.

This chapter will focus on some of the matters addressed by the NASA legal community. First we cover the primary legal framework within which the recovery and investigation efforts were completed. Then we cover the methods used in the collection and control of the enormous amount of data involved in the aftermath of the accident. Next, we will look separately at the recovery and investigation phases and the unique legal questions raised by each. Finally, we will discuss the claims associated with the search and recovery efforts, survivor privacy issues, balancing assessments, the Crew Survival Investigation Report, and some lessons learned.

Primary Legal Framework

This section will describe some of the more important laws and legal frameworks within which NASA conducted activities related to the Columbia mishap. This framework is by no means all-inclusive.

National Aeronautics and Space Act of 1958: The National Aeronautics and Space Act of 1958 (Space Act) created NASA to carry out US policy that "activities in space should be devoted to peaceful purposes for the benefit of all mankind." From a legal perspective, the Space Act encompasses almost any situation and is one of the most flexible pieces of organic legislation written for a federal agency.

Under the Space Act, NASA may enter into and perform such contracts, leases, cooperative agreements, or other transactions as may be necessary in the conduct of its work and on such terms as it may deem appropriate. This provision gave NASA the ability to enter into agreements with some of the more than 100 state and local agencies and individuals in Texas, Louisiana, New Mexico, Nevada, and Utah, who assisted NASA in the search for debris. The Space Act was also used in making initial preparations for conducting investigative tests in support of the CAIB.

Stafford Act and Emergency Assistance Act: Ultimately the Space Act did not play a significant role during the recovery efforts because the Federal Emergency Management Agency (FEMA) became involved. On February 1 and reiterated on February 6, 2003, President Bush issued a declaration, under the Stafford Act and Emergency Assistance Act, of emergency conditions in certain areas of the United States relating to the loss of the Space Shuttle Columbia. The Stafford Act was drafted to provide an orderly and continuing means of assistance by the federal government to state and local governments in carrying out their responsibilities to alleviate suffering and damage resulting from disasters. The basis for this presidential declaration included the fact that the Space Shuttle and the space program are federal property and federal programs. The memo issued by the White House authorized FEMA to coordinate and direct other federal agencies and to fund activities not otherwise authorized. FEMA was instructed to consult with the governor of any affected state before providing assistance. This is because FEMA Public Assistance grants are given only to states, and the state distributes money to qualified applicants.

Freedom of Information Act: The Freedom of Information Act (FOIA) was enacted in 1966 and generally provides that any person has the right to request access to federal agency records or information. Nine statutory exemptions authorize withholding of certain information, including information of a sensitive nature. FOIA exemptions found in 5 U.S.C. § 552(d) include (1) classified information, (2) internal personnel rules and policies, (3) information exempt under other laws, (4) confidential business information, (5) internal government communications, (6) personal privacy interests, (7) records or information compiled for law enforcement purposes, (8) records related to the regulation or supervision of financial institutions, and (9) geological information. For any exemption cited by an agency as a reason to withhold requested information, an administrative appeal process is described in NASA regulations available to the requestor. One of the lessons learned from the Challenger accident was that the Agency should release as much information as it is legally authorized to release without the need of a FOIA request. Even though the CAIB and the Agency learned this lesson and proactively released as much information as possible, without in any way disrupting or jeopardizing the integrity of the investigation, the number of requests specifically related to the accident still totaled nearly 500.

Other Acts that played a significant role include the Privacy Act of 1974 and, to a much lesser degree, the Arms Export Control Act (and its implementing regulations: the International Traffic in Arms Regulations [ITAR] and the Export Administration Regulations) and the Federal Advisory Committee Act.

Privacy Act: This Act is a companion to the FOIA. It allows individuals to seek access to agency records about themselves. The Act also restricts the disclosure of personally identifiable information by federal agencies. The essential feature of both the Privacy Act and FOIA is that they make agencies accountable for information disclosure policies and practices. If a record cannot be released, the requestor is entitled to be informed of the rationale for the denial and has a right to appeal the denial as well as challenge it in court.

Export Control: The existing NASA export control process was used to facilitate public releases of information by the CAIB. The Space Shuttle Program Office Export Control Representative reviewed all NASA data turned over to the CAIB and made a written recommendation concerning releasability of that information. It was important to sensitize individuals unfamiliar with NASA data to the fact that much of the Shuttle data is controlled by ITAR. As the cognizant Agency, NASA had the authority to approve such data for public release.

Guide to the Law

NASA's actions are governed by three levels of requirements: Federal Law, which defines what we *must do*; Federal Regulations, which define how we implement Federal Law; and Federal Policy, which defines how we will *exercise our discretion* under the Regulations. Below is a list of all the Federal laws and regulations discussed in the chapter, along with a citation, to aid readers interested in further research.

Federal Law

National Aeronautics and Space Act of 1958,
51 U.S.C. § 201

Robert T. Stafford Disaster Relief and Emergency Assistance Act, 42 U.S.C. §§ 5121-5206

Freedom of Information Act (FOIA), 5 U.S.C. § 552

Privacy Act of 1974, 5 U.S.C. § 552a, as amended

Arms Export Control Act (AECA),
22 U.S.C. §§ 2751-2799

Federal Advisory Committee Act (FACA),
5 U.S.C. apps. §§ 1-16, as amended

Federal Regulations

Availability of Agency Records to Members of the Public, 14 C.F.R. 1206

International Traffic in Arms Regulations (ITAR),
22 C.F.R. §§ 120-130

Export Administration Regulations (EAR),
15 C.F.R. §§ 730-774

Federal Advisory Committee Act (FACA): The purpose of the FACA is to ensure that advice rendered to the executive branch of the US government is both objective and accessible to the public. All of the formalities required by the Act for record keeping and publications were not compatible with the broadly defined, time-intensive Columbia accident investigation or with the effective oversight of more than 100 staff members and thousands of debris searchers. Because of a number of practical considerations, all CAIB members who were not already employees or officers of the United States were hired as full-time federal employees. However, (5 U.S.C. app. 3(2) provides that FACA does not apply to committees "comprised wholly of full-time officers or employees of the federal government.") Even though the Act was therefore not applicable to the CAIB's activities, the Board resolved to comply, to the maximum extent practicable, with its standards.

Collection and Control Methods

The recovery of human remains began immediately, and within only 10 days of the accident, February 10, 2003, NASA Human Remains for Columbia Recovery Guidelines had been drafted and concurred on by NASA, FBI, FEMA, the Office of the Armed Forces Medical Examiners, and Air Force Mortuary Affairs. The objectives of the guidelines were to optimize use of resources available in the main search area and to deliver suspected human remains as soon as practical for definitive forensic examination. The guidelines outlined operations for material in the main search area near Lufkin, Texas, material outside the main search area, and late-phase operations for suspected human remains. Formal human remains efforts terminated on February 13, 2003, with instructions to refer any suspected human remains located after that date to local law enforcement authorities, all of whom were instructed to contact USAF mortuary Affairs. NASA also provided points of contact within the Agency for questions concerning human remains, life support, or biohazards via the JSC Emergency Operations Center.

With any investigation quickly comes the compilation of data. The CAIB soon realized that the sheer volume of available data involved with the technically complex Space Shuttle could quite easily overwhelm them if it was not properly cataloged. As a result, the US Department of Justice was enlisted to assist with the collection and control of the data for the CAIB. The US Department of Justice Office of Litigation Support was brought in because of their vast experience in collecting and controlling evidence for the US attorneys conducting litigation on behalf of the US government. Configuration management between the CAIB and NASA was accomplished through the Columbia Task Force.

The CAIB Document Database contains over 35,000 records created or received by the CAIB during its investigation. Records include testing reports, interim recommendations, independent assessment team reports, presentations, photographic images, drawings, correspondence, and e-mail messages. These records are permanent government records that NASA transferred to the custody of the National Archives and Records Administration after the work of the CAIB was completed.

NASA maintained its own database, known as the CTF Document Database. The CTF Database contains about 45,000 records that the CAIB requested, reviewed, and used during its investigation. It is important in noting the sheer volume of information that there is minimal duplication between the CTF and the CAIB databases.

The CAIB created and controlled extensive witness testimonies in the formats of audio recordings, electronic transcripts, and interview notes. Consistent with longstanding practice in aircraft accident investigation, the CAIB granted confidentiality to individuals who were interviewed. The Archivist of the US, the chief official overseeing the operation of the National Archives and Records Administration, acceded to the CAIB's request to restrict access to the statements for a period of 50 years. These statements have been found privileged with respect to pretrial discovery. The US Supreme Court has also recognized the privilege as exempting such statements from disclosure under FOIA. Also included in these records are copies of the written statements made by the staff of NASA's Mission Control Center immediately after the accident.

Other records were divided into permanent and temporary records and were archived or deleted/destroyed according to the appropriate disposition for the record. Those records include interim and final report records, public affairs records, public comment records, CAIB World Wide Web content and Web management records, and e-mail and word-processing system copies. For more information, see the article "First Hand Account of Selected Legal Issues From the Recovery and Investigation of the Space Shuttle Columbia," *Journal of Space Law*, Volume 30, Number 1 (2004).

Right of Entry Agreements: NASA entered into an agreement with FEMA which included the stipulation that NASA would not remove debris from public and private property until the landowner signed an unconditional authorization termed a "Right of Entry Agreement." The agreement included notification that the agreement's execution did not obligate the government to clear the debris and contained a hold harmless agreement for claims arising from activities on the property.

Recovery Phase Legal Issues

As of May 5, 2003, ground, water, and air searches combined covered more than 2.28 million acres, and about 25,000 personnel took part in the Columbia recovery operations. The Texas operation was unique. Texas was the site of the majority of debris recovered and had by far the largest number of state and local agencies with which NASA coordinated. By one count, about 130 different agencies were involved. Debris reports came in daily from 28 other states and three foreign countries.

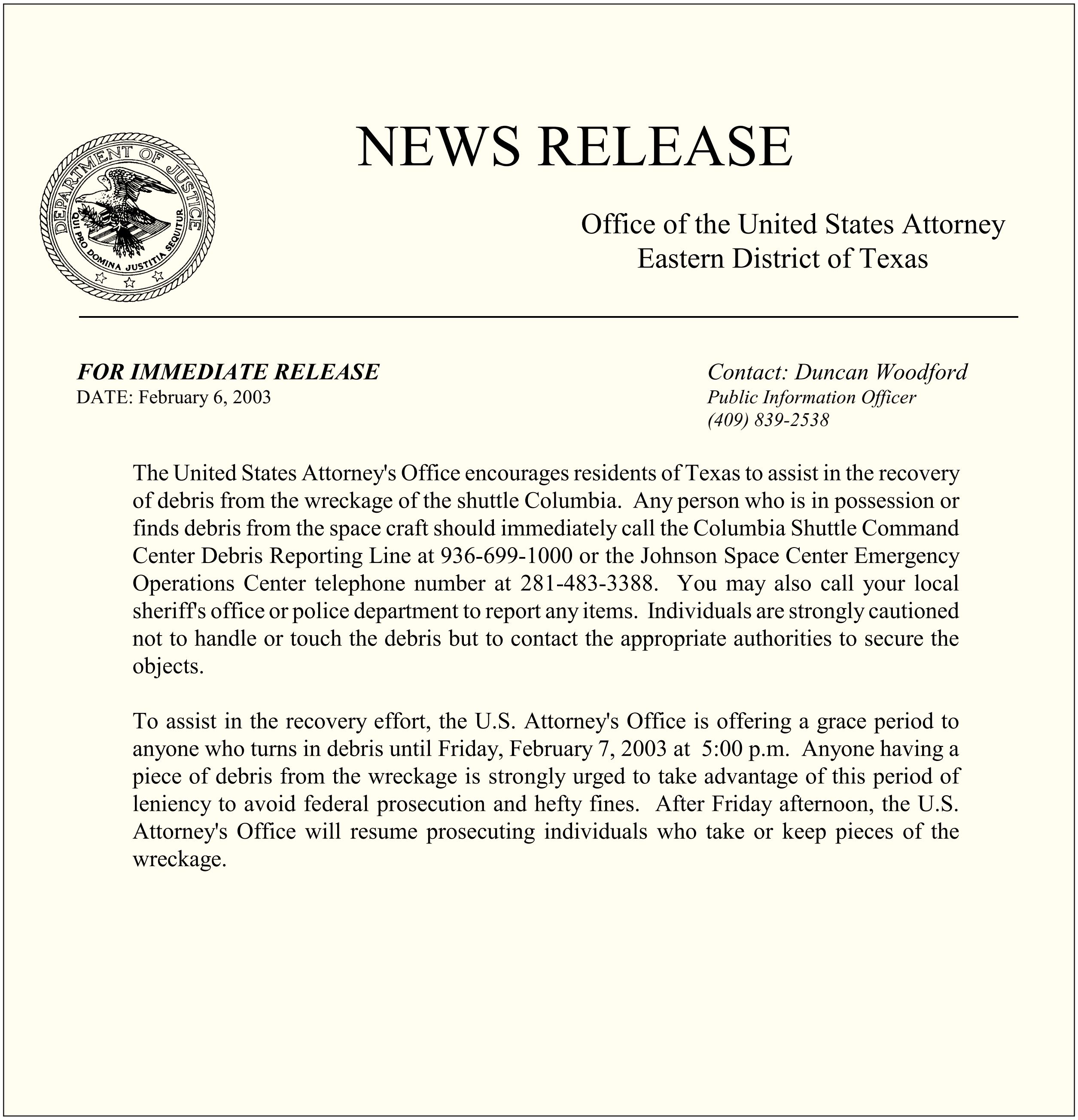
Reimbursable and Tort Claims

FEMA's public assistance program projected reimbursable payments in Texas and Louisiana to total about $10.5 million; however, the parameters of the program were such that many groups were not eligible for FEMA support. Because FEMA's funding efforts were not all-inclusive, NASA took the highly unusual step of soliciting claims. The many state agencies and individual entities assisting NASA were all happy to learn that NASA was being very proactive in our efforts to ensure that all entities providing assistance were being reimbursed by NASA. Generally, if NASA's search and recovery efforts led to unintended expenses, NASA reimbursed those costs under Space Act authority. For example, NASA paid Nacogdoches County $4,000 for expenses incurred in moving the Texas Spring Classic Horse Show to Navarro County. NASA paid Stephen F. Austin State University $15,000 for the mapping work they did, associated with human remains recovery. NASA paid Palestine Texas Regional Medical Center $6,000 for medical transportation and decontamination services. Carroway-Claybar Funeral Home was reimbursed for transportation of remains. In addition to claims from Texas and Louisiana, we paid claims from Utah and New Mexico. NASA reviewed about 70 requests for reimbursement from various entities and provided compensation totaling just over $1.2 million. NASA also provided about $90,000 resulting from153 property-damage claims.

For the processing of monetary claims against NASA under the Federal Tort Claims Act or under the Space Act, the claimant is required to submit a claims form which was furnished by NASA installations upon request. For example, a mounted patrol officer fell off of his horse and broke his leg and was required to seek reimbursement for medical expenses under the Federal Tort Claims Act.

Controlling Theft of Debris

In an attempt to curb the desire of any individual to retain any debris as a souvenir of an historic event, the US Attorneys for the Southern and Eastern Districts of Texas issued a 1-day moratorium from prosecution for anyone who had Shuttle debris and had not reported it or turned it in to authorities. The



DEPARTMENT OF JUSTICE

NEWS RELEASE

Office of the United States Attorney
Eastern District of Texas

FOR IMMEDIATE RELEASE
DATE: February 6, 2003

Contact: Duncan Woodford
Public Information Officer
(409) 839-2538

The United States Attorney's Office encourages residents of Texas to assist in the recovery of debris from the wreckage of the shuttle Columbia. Any person who is in possession or finds debris from the space craft should immediately call the Columbia Shuttle Command Center Debris Reporting Line at 936-699-1000 or the Johnson Space Center Emergency Operations Center telephone number at 281-483-3388. You may also call your local sheriff's office or police department to report any items. Individuals are strongly cautioned not to handle or touch the debris but to contact the appropriate authorities to secure the objects.

To assist in the recovery effort, the U.S. Attorney's Office is offering a grace period to anyone who turns in debris until Friday, February 7, 2003 at 5:00 p.m. Anyone having a piece of debris from the wreckage is strongly urged to take advantage of this period of leniency to avoid federal prosecution and hefty fines. After Friday afternoon, the U.S. Attorney's Office will resume prosecuting individuals who take or keep pieces of the wreckage.

moratorium was publicized in a press release (Press Release, US Department of Justice, US Attorney Eastern District of Texas, First Indictments in Shuttle Debris Recovery, Limited Prosecution Moratorium Announced, available at *http://www.usdoj.gov/usao/txs/releases/February2003/030205-columbiamoratorium.htm* (Feb. 5, 2003). During the moratorium quite a few individuals called about turning in property to NASA, including individuals who had debris from the Challenger accident.

Texas Death Investigation System

The Death Investigation System in the State of Texas, including the state's 254 counties, has a mixed system of coroners and medical examiners. The preparation of certificates of death includes the direction that the provider pronouncing death prepares a death certificate and sends it to proper authorities according to state and civil requirements. Although human remains from the Columbia accident were originally located in Texas, they were initially transported to Louisiana and then to Delaware. The death certificates were issued by the State of Texas, Angelina County, and executed by Philip Stepaniak, MD, with certification by the Armed Forces Medical Examiner, Craig Mallak, MD. The immediate cause of death was "blunt force and thermal injuries in association with exposure to extreme altitude" with an underlying cause of "Spacecraft Mishap."

Investigation Phase Legal Issues

Survivor Privacy Rights

As an agency, NASA flies high-performance and experimental vehicles in mission-oriented operations like the military services, but it is a more public organization with relatively high-profile operators. As a result, NASA policy for the release of sensitive information is necessarily a hybrid of the two approaches, with points at which decisions are to be made by and at the discretion of identified personnel. The aim of making NASA aircraft and spacecraft mishap information available is to educate the aerospace medical communities and to inform the design and development processes of new spacecraft by the lessons learned about crew safety and survivability.

The privacy of an individual and surviving relatives is a personal and fundamental right that must be respected and protected. Survivor privacy rights for families of government employees have been recognized by the United States government for more than 40 years. In the case of *Hale v. United States Dep't of Justice*, 973 F. 2d 894, 902 (10th Cir. 1992), the court ruled that there was "…no public interest in photographs of the deceased victim, let alone one that would outweigh the personal privacy interests of the victim's family" (Exemption 6(C), *cert. granted, vacated and remanded on other grounds*, 509 U.S. 918 (1993). In *KTVY-TV v. United States*, No. 87-1432-T, slip op. at 9 (W.D. Okla. May 4, 1989), the court ruled that "The privacy rights asserted—those of the survivors and family of the victims in not having photographs of the bodies of the victims and clinical descriptions of their wounds being divulged—are patent and compelling and within the protections of the Act." (Exemption 6(C), *aff'd per curiam*, 919 F. 2d 1465 (10th Cir. 1990)).

The recognition of survivor privacy rights is primarily found in case law and government policy and memoranda, and stems from a long common law tradition of acknowledging a family's control over the body and death images. After much litigation, spanning 1987–1991, in *New York Times v. NASA*, 782 F. Supp. 628, 631-32b (D.D.C. 1991), NASA's recording of the voices of the Challenger crew was found properly withheld under FOIA exemption 6 on the basis that "exposure to the voice of a beloved family member immediately prior to death is what would cause pain… a disruption of their peace of mind."

This recognition of rights protects survivors against the clearly unwarranted invasion of personal privacy. Concern about family is well ensconced into investigation activities and information release. NASA is also obligated to distribute information, including investigational findings, to stakeholders involved in human space flight, both government and commercial, particularly to those who are integrating safety and survivability elements into new designs. The overarching goal is to prevent further losses of crew or vehicle by incorporating observations and lessons learned into new designs as well as ongoing flight operations.

To best protect surviving families and also adequately inform communities involved in prevention, there must be a well-defined balance between privacy and the public need to know.

Balancing Assessment for Survivor Privacy Determination

To determine if information would be protected, a balancing assessment was made by considering the following factors:

- Does disclosure violate a viable privacy interest? Privacy encompasses the identifiable living individual's control of information concerning his/her person. This interest extends to surviving family member(s) primarily under case law.
- Is there a public interest in disclosure? Does it directly reveal operations or activities of the federal government?
- Does public interest qualify for balancing? (Only if an identified public interest sheds light on NASA's performance of statutory duties.)
- Balance personal privacy against qualifying public interest. This involves assessment and comparison of the relative magnitudes of the two interests.

A "public release" is any external release of data, including information given to the academic, engineering, and industrial communities involved in high-performance aircraft and spacecraft design, construction, and operation. The assessment to determine what information to release is informed by what the public needs to know. The basic guidelines of this assessment are as follows:

What the public needs to know about crewmembers:

- Fundamental causative factors
- Factors contributing to the mishap (eye toward prevention), structural and medical
- Circumstances of injury
- Mechanism of injury

What the public does not need to know:

- Photographs, video, or other imagery of human remains
- Audio of sensitive content
- Medical information or levels of detail not germane to the understanding of the event
- Information about family members or personal items not germane to the understanding of the event

At the conclusion of the investigation, which can be defined as the release date of the investigative committee's findings, NASA determined how best to use the sensitive information from the accident to improve medical care and vehicle performance and safety. A body of stakeholders consisting of representatives from the JSC Flight Crew Operations Directorate (astronaut management), Space Life Sciences Directorate (medical), Safety and Mission Assurance Directorate, and Office of Chief Counsel informally worked together to determine how to do the following:

- Provide for long-term curation of the medical and biomechanical data used and generated by the investigation.
- Ensure that this information is used for preparing and educating teams for timely and correct response to aircraft and spacecraft mishaps.
- Ensure that this information is fed into the design of new vehicles, if the information is deemed applicable to a particular aspect of design that would influence crew safety or survivability.
- Review and approve public release of information related to medical and human factors of a mishap including the following:

    Internal NASA reports

    Academic journal articles and other publications

    Academic meetings and symposia

    Presentation to industry

NASA routinely tries to maintain all medical data in non-attributable form. However, the small number of crewmembers involved, the unique circumstances of the mishap, and the large number of people involved in aircraft and spacecraft operations may cause circumstances to arise in which data are attributable to a specific individual.

NASA astronauts are public figures, but they do not surrender all rights to privacy by placing themselves in the public eye, though their expectations of privacy certainly may be diminished. Disclosure of sensitive personal information contained in an investigative report about a public figure is appropriate only where exceptional interests militate in favor of disclosure. Although one's status as a public figure might tip the balance in favor of disclosure, a public figure does not, by virtue of status, forfeit all rights of privacy. Redaction of all identifying information is possibly sufficient to protect privacy interests.

If the information at issue is particularly well known or is widely available within the public domain, there generally is no expectation of privacy. In *Nat'l W. Life Ins. Co. v. United States*, 512 F. Supp. at 461, the court noted that names and duty stations of most federal employees are routinely published and available through the Government Printing Office. Nor does an individual have any expectation of privacy with respect to information that the individual has made public. On the other hand, if the information in question was at some time or place available to the public, but now is "hard-to-obtain information," the individual to whom it pertains may have a privacy interest in maintaining its "practical obscurity." See *Dayton Newspapers, Inc.*, 257 F. Supp. 2d at 1010 (reasoning that although modern search engines might make even otherwise obscure personal information more widely available, that "does not mean that [individuals] have lost all traits of privacy" in that information); *Linn v. United States Dep't of Justice*, No. 92-1406, 1995 WL 417810, at 31 (D.D.C. June 6, 1995) (declaring that even if "some of the names at issue were at one time released to the general public, individuals are entitled to maintaining the 'practical obscurity' of personal information that is developed through the passage of time"). Public availability of information in question will disqualify it from privacy protection only where it fails the new "practical obscurity" standard.

Columbia Crew Survival Investigation Report

As in all mishap investigations, NASA was motivated both to understand the cause of the accident and to find ways to prevent future accidents. Although the Columbia accident was not survivable, the investigation looked into the survival aspects of the accident and published a report to recommend enhancements to equipment and operations, to improve survivability in future accidents. The most sensitive medical data from the accident were not publicly released; however, we needed to balance the protection of the privacy interests with the inclusion of sufficient data to support the report's conclusions. We minimized the disclosure of medical information and endeavored to ensure that no injury could be definitively tied to a specific crewmember.

One of the key recommendations from the *Columbia Crew Survival Investigation Report* is that medically sensitive and personal effects data should always be protected to preserve the privacy of the victims and their families. Additionally, issues surrounding public release of this type of sensitive information during a NASA accident investigation should be resolved and policies documented throughout the Agency to ensure that the recommendation is followed when future crew survival investigations are performed. The successful publication of the *Columbia Crew Survival Investigation Report* is in large part a result of the team's tireless dedication to ensuring close and careful coordination with the surviving family members.

Future Investigations

In 1986 after the loss of Challenger, a Presidential commission was established to investigate the accident. This body, named the Rogers Commission, was chaired by William P. Rogers. In contrast, after the Columbia accident, the ISS and SSP Mishap Interagency Investigation Board, an external board, was established by the NASA Administrator. The positions on this board, renamed the Columbia Accident Investigation Board, were filled with employees who occupied specific government positions.

To create more consistency, on December 30, 2005, Congress passed Public Law 109-155, the National Aeronautics and Space Administration Authorization Act of 1958 as amended. This law had two provisions, under which NASA now operates, that pertain to investigation of space flight mishaps.

One provision established a Human Space Flight Independent Investigation Commission, an independent

Presidential Commission to investigate loss of a Space Shuttle; loss of the International Space Station or its operational viability; loss of any other US space vehicle (owned or contracted); or loss of a crewmember or passenger in any of these types of space vehicle.

Under the new law, the Commission shall, to the extent possible:

- Investigate the incident
- Determine the cause
- Identify all contributing factors to the cause
- Make recommendations for corrective action
- Provide additional findings or recommendations deemed important whether or not they are related to the specific incident
- Prepare a report to Congress, the President, and the public

The other provision established recovery and disposition authority. Under this authority, the NASA Administrator may take control over human remains and order autopsies and other scientific or medical tests. Additionally, each crewmember shall provide his/her preferences regarding the treatment accorded to their remains and the Administrator shall, to the extent possible, respect those preferences.

This provision does not permit the Administrator to interfere with any federal investigation of a mishap or accident. A crewmember is defined as an astronaut or other person assigned to a NASA human space flight. A NASA human space flight vehicle is a space vehicle that is intended to transport one or more persons; is designed to operate in outer space; and is owned by NASA or a NASA contractor or cooperating party and operated as part of a NASA mission or joint mission with NASA.

Summary

Even though NASA understood the cause of the Challenger accident fairly early on, we were not proactive in getting information out to the public. After the Columbia accident, the lengthy investigation into the cause of the accident was conducted in an open and thorough manner, and records were released to the public as quickly as possible. Improvements that can be made include formalization of policies relating to the public release of sensitive information during a NASA accident investigation and documentation of these policies throughout the Agency, to ensure that future crew survival investigations are performed; documentation of authority for the payment of claims; documentation of methods for obtaining complete and accurate witness statements; and review of internal guidance on existing regulations and how those regulations may need to be altered with the emergence of commercial space flight.

Including attorneys as an integral part of the Columbia accident teams as they were formed enabled proactive legal advice to be given in the areas of FOIA and its exemptions, payment of reimbursable claims, and protection of survivor privacy rights. The work performed by the NASA legal team, though less visible to the public than that of recovery teams, made possible the expeditious recognition and resolution of legal issues that might otherwise have encumbered progress. One thing that was evident on February 1, 2003, was a strong commitment and dedication among the employees in the Agency to the mission and goals of space exploration.

Section 5 – The Future

Human Space Flight Incidents and Crew Survival Lessons Learned

The Future: Crew Survival Investigations

Human Space Flight Incidents and Crew Survival Lessons Learned

Jonathan B. Clark

This section describes human space flight incidents and historic lessons learned related to occupant protection and crew survivability in space exploration. Mishaps, incidents, and close calls often serve as a basis for making improvements in system designs, mission architecture, and operations.

Challenges

Crew survivability is the collective implementation of abort, escape, emergency egress, safe haven, emergency medical, and rescue capabilities throughout all phases of a mission. The survivability concept of operations includes the autonomy of systems, size of the crew, duration and type of life support measures, and systems protecting individual crewmembers. The challenges of developing a crew survival system include predicting its effect on vehicle design and performance, and such systems are limited in that they should not create added risks to the crew or significantly limit spacecraft capability, affordability, and sustainability. Survival and escape systems that jeopardize nominal operations may defeat overall mission success. The main challenges are to strengthen the ability to keep the crew alive and return them to Earth safely in response to an imminent catastrophic condition.

Major Historical Mishaps

Human space flight is extremely risky, and threats to crew health have happened in all mission phases including ground testing, launch pad aborts, ascent, orbit, reentry, landing, and post-landing. Fatalities related to space operations include 5 Russian fatalities: 1 during an altitude chamber oxygen (O_2) fire and 4 on reentry and landing (Soyuz 1 and Soyuz 11). The US has had 18 fatalities: 3 during ground testing (Apollo 1 crew cabin fire), 7 on ascent (Challenger accident), and 8 on reentry (7 in the Columbia accident and 1 during a high-altitude X-15 flight). Catastrophic loss of crewed launch vehicles has occurred on the pad (Soyuz 18A) and on ascent (Soyuz T10A); both of the Soyuz crews survived. Reentry anomalies have occurred frequently and are often due to vehicle configuration or faulty separation from modules. Landing and post-impact issues also occur, including hard-impact injuries and inability of rescue forces to reach a crew in a timely fashion. On-orbit space flight emergencies have included cabin pressure loss, fire, and toxic environment. Also, evacuations from space have occurred due to intractable headaches following combustion event (Salyut 5/1976), for fever and urinary infection (Salyut 7/1985), and for a cardiac irregularity (Mir/1987). Space flyers and ground controllers have made human errors to which near-catastrophes and effects on mission milestones were attributed in the following programs: Mercury, Gemini, Apollo, Space Shuttle, and Russian Mir.

Ground System and Vacuum Chamber Test Incidents

Accidents have also occurred during vacuum chamber tests, used to evaluate equipment at high altitude. During a chamber ground test in 1961, a Russian crewmember died when an alcohol wipe hit a hot plate and started a fire in the oxygen-rich chamber.

In 1966 a spacesuit technician experienced rapid decompression to 120,000 ft altitude equivalent, and recalled the saliva boiling off his tongue as he passed out. He regained consciousness once the chamber pressure increased to that of 14,000 ft altitude equivalent and suffered no neurological sequelae and was not hospitalized. In another case occurring in an industrial vacuum chamber in 1982, a technician was accidentally decompressed to greater than 74,000 ft, and remained above 63,000 ft for 1 to 3 minutes. He underwent hyperbaric recompression for 5 hours, and by 24 hours he was awake and alert. At a 1-year follow-up he was neurologically normal. The lessons from these vacuum chamber events are that exposure to near-vacuum for seconds is survivable with no medical care, and exposure to near-vacuum for a minute or two is survivable with aggressive medical care. A field treatment protocol for ebullism and vacuum exposure is now available.

On January 27, 1967, the three US Apollo 1 crewmembers died in a cabin fire when an electrical short circuit occurred during a test in a high-O_2

On January 27, 1967, a flash fire swept through the Apollo 1 Command Module during a launch rehearsal test. Astronauts Virgil “Gus” Grissom, Ed White, and Roger Chaffee perished in the fire.

atmosphere. An accident board listed findings, determinations, and recommendations. The conditions leading to the disaster were summarized as follows:

- Failed to identify the test as hazardous – 100-percent pure oxygen cabin atmosphere at 16.7 psi.
- Spacecraft inward opening hatch required at least 90 seconds for either internal or external removal and crew egress.
- Ground safety procedures were completely inadequate.
- Operational test procedures were subjected to last-minute changes.
- Communications were overall unsatisfactory.
- Control of combustible material standards established for nonmetallic materials were too low and the criteria for selection and approval of spacecraft material were inadequate.
- Engineering, workmanship, and quality control deficiencies created an unnecessarily hazardous condition.

The rapid spread of the fire caused an increase in cabin pressure and temperature and filled the cabin with toxic gases. The increased pressure prevented the rescue crew from being able to open the inwardly opening hatch. Rescuers were only able to open the hatch after the Command Module pressure shell ruptured and the pressure equalized. Death of the crew was from asphyxiation due to inhalation of toxic gases caused by fire. The fire melted the hoses that connected the crewmembers’ spacesuits to their life-support system. It was estimated that the crewmembers lost consciousness between 15 and 30 seconds after the first suit failed. A contributory cause of death was thermal burns. NASA implemented changes including limitations on oxygen levels, reduction in flammable materials, spacecraft designs to improve crew egress, and increased crew and personal emergency training.

Parachutes and Aviation High-Altitude Mishap Incidents

In preparation for sending humans to space, both the former Soviet Union (Russia) and the US military tested life support and survival systems with human test subjects using high-altitude balloon parachute jumps.

The US Air Force conducted high-altitude balloon studies on humans in programs such as Project Excelsior, which consisted of a series of high-altitude balloon flights and bailouts, with free fall and descent under canopy. These flights were fraught with difficulties, but many lessons were learned about survivability at high altitudes. In 1959, on the Excelsior I jump, Joe Kittinger became entangled with the drogue and went into a high-speed spin and lost consciousness. On the third flight in Project Excelsior in 1960, Kittinger, wearing the David Clark MC-3 partial pressure suit, parachuted in free

USAF Captain Joe Kittinger begins his historic free fall in August 1960.

fall with a small stabilizing drogue chute from an open gondola at 102,800 ft for 4 minutes, 36 seconds until the main parachute opened at 17,500 ft. His right glove lost partial pressure during the final ascent phase and his hand became swollen, causing extreme pain, but the hand had completely returned to normal by 3 hours after landing. The lesson learned was that a localized suit leak may result in focal tissue swelling from exposure to near vacuum and can completely recover in hours.

The Russian Volga stratospheric balloon parachute test program evaluated the pressure suit for the Vostok space program in a pressurized gondola in 1962. Evgeny Andreev exited at 83,524 ft and free-fell 80,360 ft, setting the record at that time for highest free fall without a drogue parachute, a record that stood for 50 years. In the same program, Pyotr Dolgov intentionally opened his parachute as he exited at 86,156 ft above the Earth, but as he exited, his helmet visor hit the capsule and cracked, and his suit depressurized. Because of the high altitude and prolonged descent, he was unable to survive the depressurization and was found dead on landing.

An American civilian high-altitude parachute test (Project Strato Jump) was conducted in 1966, with parachutist Nick Piantinata. While Piantinata was ascending through 57,600 ft, his visor inadvertently opened and the suit depressurized. Ground controllers recognized the emergency and cut the balloon from the gondola. Piantinata landed 25 minutes later. The rescue team was on the scene within 30 seconds, and found him unconscious; he died 4 months later in a hospital.

On Soyuz 1 in 1967, both the main and reserve parachutes failed, leading to the death of the crewman. On Apollo 15 in 1971, one of the three main chutes failed, resulting in a slightly harder splashdown landing than normal (32 feet per section (fps) vs. 28 fps), but the seat stroking (load-limiting) mechanisms did not reach activation threshold and no injuries occurred. Possible causes of the parachute failure were

- damage from the jettisoned forward heat shield, which was in close proximity to the spacecraft flight path;
- a broken riser/suspension line connector link, which was found on the recovered parachute;
- damage from firing of the propellant in the command module reaction control system and fuel dump from the same system.

The Soyuz 1 parachute failures in 1967 resulted in loss of the sole crewman aboard the spacecraft.

The Apollo 15 Command Module, with astronauts David R. Scott, commander; Alfred M. Worden, command module pilot; and James B. Irwin, lunar module pilot, aboard, nears a safe touchdown in the mid-Pacific Ocean to conclude a highly successful lunar landing mission. Although causing no harm to the crewmen, one of the three main parachutes failed to function properly. The splashdown occurred at 3:45:53 p.m. (CDT), August 7, 1971, some 330 miles north of Honolulu, Hawaii. The three astronauts were picked up by helicopter and flown to the prime recovery ship USS Okinawa, which was only 6 1/2 miles away.

The most probable cause of the anomaly was the burning of raw fuel (monomethyl hydrazine) being expelled during the latter portion of the depletion firing, and this resulted in exceeding the parachute riser and suspension-line temperature limits.

Red Bull Stratos was a privately funded manned stratosphere balloon flight test; its free-fall parachute jump program was completed in 2012. The test program included unmanned balloon and capsule tests, vertical wind tunnel and high troposphere tests of the drogue and main parachutes and the spacesuit, low-pressure chamber tests of the spacesuit, and integrated thermal and vacuum chamber tests of the capsule, spacesuit, and parachute and life support systems. These tests ultimately led to incremental stratosphere free-fall parachute jumps. A team was formed to develop and implement medical and physiological support for this program. Issues addressed included development of a protocol for oxygen prebreathe to reduce the risk of decompression sickness, briefing crewmembers on medical and physiological threats, medical and physiological monitoring for the thermal vacuum test phase and stratospheric flights, launch and recovery medical planning, and contingency planning. Contingency planning included the development of protocols against two serious known threats during a stratospheric bailout. The Red Bull team developed a protocol for treatment of ebullism in response to the potential threat of exposure to vacuum from a suit depressurization. Also the team addressed another serious threat, flat spin with negative acceleration in the vertical direction ($-G_z$).

Manned Balloon Flight (MBF) 1 occurred on March 15, 2012, with test parachutist Felix Baumgartner ascending to 71,581 ft in a 1.22-million cubic foot (MCF) balloon, from which height he free-fell 63,691 ft, reaching a maximum speed of 364.4 mph. For MBF 2 on July 25, 2012, Baumgartner ascended to 97,146 ft in a 5.3-MCF balloon from which he free-fell 84,357 ft, reaching 546 mph. For the last test, MBF3 on October 14, 2012, Baumgartner ascended to 127,852 ft in a 29-MCF balloon and free-fell 119,431 ft, reaching 843.6 mph (Mach 1.25). The parachutist was in free fall for 3 minutes 40 seconds on MBF1, 3 minutes 48 seconds on MBF2, and 4 minutes 20 seconds on MBF3. He was weightless (< 0.1g) until he reached terminal velocity, for 6 seconds on MBF1, 9 seconds on MBF2, and 25 seconds on MBF3. During the weightless phase the jumper had no aerodynamic control. A manually or automatically deployed drogue chute was available if the jumper became significantly unstable. A multiaxis, dynamically unstable spin occurred on MBF3, reaching a maximum of 60 rpm for 10 seconds, which was below the automatic drogue trigger set for 3.5 G for 6 seconds. Aerodynamic control was regained by the test parachutist, but the spin, which was multiaxis and approached $-2.5\ G_z$, approached human physical performance (but not injury) limits. The conclusion was that stratospheric free fall should include stabilization with a drogue parachute.

Aviation accidents have also tested human exposure to high altitudes. In 1966 an SR-71 Blackbird traveling at a speed of Mach 3.18 at 78,800 ft became unstable, broke up, and disintegrated in flight because of an engine unstart. The pilot and system operator were torn from the aircraft and both parachutes deployed automatically. The pilot suffered only minor injury, but the system operator in the back seat sustained a fatal neck injury. The pilot attributed his survival to the protection afforded by his inflated pressure suit from the intense buffeting and g forces during the supersonic transition. A second SR-71 breakup at a similar airspeed and altitude occurred in 1966 during a drone release. Both crewmembers survived the breakup and successfully ejected, although one died from drowning after landing.


Photo credit: Red Bull Stratos

On October 14, 2012, Red Bull Stratos team member Felix Baumgartner jumped from a helium balloon at 127,851 ft into the stratosphere over New Mexico, before free-falling in a pressure suit and then parachuting to Earth.

Acceleration Risks Associated with Ejection Seats

Ejection seats were used in the US Gemini capsule, the first 4 Space Shuttle missions, and the Russian Vostok capsule. All 6 of the cosmonauts on the Vostok series ejected before the capsule landed. Ejection seats were considered in a Shuttle escape study. The injury potential with ejection seats is related to ejection seat G forces, fouling with seat/cockpit structure, windblast, flail and wind drag deceleration, and parachute opening shock. Major injuries and fatalities, mainly from flail, rise sharply at ejection speeds over 600 knots airspeed. For the first four flights, the Orbital Flight Test phase, the Space Shuttle program used a modified SR-71 seat and pressure suit.

Challenger Accident and Lessons Learned

In 1986 the Shuttle flight 51L (Challenger mishap) broke up on ascent while traveling at Mach 1.92 at 48,000 ft, and the crew module lofted to 65,000 ft and then fell back to the ocean. The vehicle breakup forces were estimated to be 12 to 20 G and were short-term and survivable. The crew at this time wore standard Nomex® flight suits accompanied by a launch and entry helmet that interfaced with a personal egress air pack that provided breathing air. The external investigation body for this accident, called the Rogers Commission, recommended that a system be developed to ensure crew egress and escape: “The crew egress and escape (CEE) together with other elements of the egress/escape system, shall enhance the capability for all crewmembers to safely escape from a disabled orbiter on the pad, in subsonic flight, or on the ground. Controlled subsonic gliding flight conditions shall be required for in-flight use of the CEE. The CEE shall provide the necessary protective and survival equipment to sustain the crew

On January 28, 1986, the Space Shuttle Challenger broke apart on ascent while traveling at Mach 1.92 at 48,000 ft.

Portrait of the Space Shuttle Challenger crewmembers holding their launch and entry helmets and wearing their standard Nomex® flight suits. Back row, left to right: Ellison Onizuka, Christa McAuliffe, Gregory Jarvis, and Judith Resnik; front row: Michael Smith, Francis Scobee, and Ronald McNair.

at or below 100,000 ft altitude and to ensure the crew's safety after vehicle egress until such time as the danger is past and/or they are removed to a safe area."

NASA has considered various crew escape systems that provide coverage during ascent and reentry, including bailout, ejection seats, extraction rocket systems, encapsulated seats, modular separation, and hybrid combinations of these systems. However, implementing modifications after a vehicle has been designed could dramatically affect other operational parameters. The Space Shuttle Program performed several escape studies during its 30-plus years of existence. Initial design considerations in 1971 (the first shuttle flight was in 1981) determined that the only system that could provide protection for more than the two crewmembers on the experimental flights was the separable crew compartment, which would add substantial weight and developmental cost.

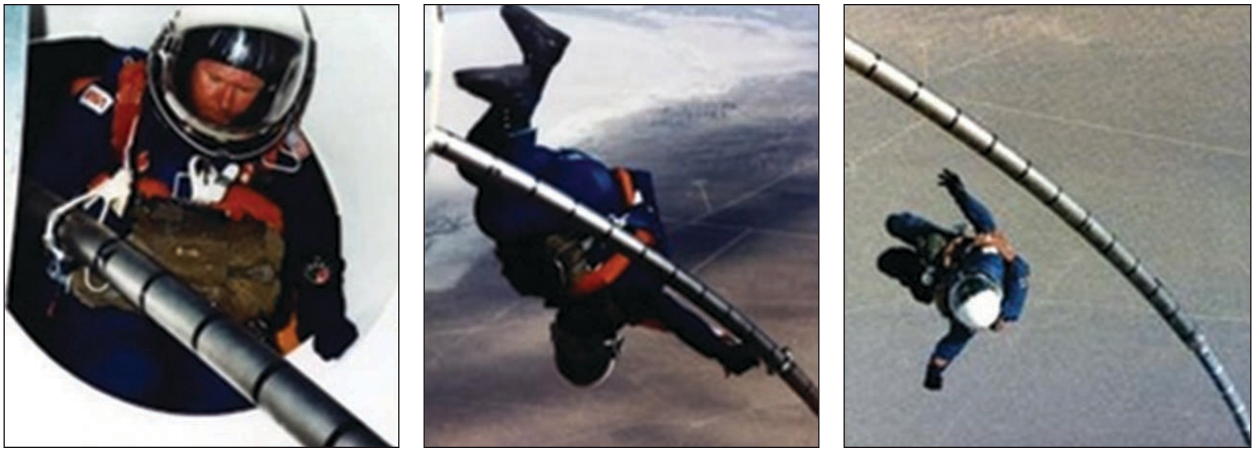
The National Space Transportation System Crew Egress and Escape Study, conducted after the Challenger accident in 1986, reviewed past studies to identify new and innovative concepts. Low-cost options provided less coverage, whereas more costly concepts would have had a severe impact on the performance capability of the Shuttle orbiters. In 1989 the Crew Escape Module Study assessed the impacts of retrofitting a crew escape module into the orbiters that would be equivalent to a "new" orbiter program. The Shuttle Evolution II Crew Escape Study, done in 1991, assessed the impacts of incorporating ejection seat and extraction seat concepts into the existing orbiters.

The ejection seat concept was the option having the lowest risk, and it provided for the escape of five or fewer crewmembers (the Space Shuttle routinely had six or seven crewmembers for complicated payloads). The high cost of incorporating additional escape capabilities, combined with the significant impact on vehicle capabilities, did not warrant the addition of escape seats or an escape pod.

However, after the Challenger accident, the program implemented a Crew Escape System (CES) suit and supporting equipment. The CES includes a pressure suit, personal parachute assembly, emergency oxygen system, survival kit, and flotation system. The original CES suit was a partial pressure suit (David Clark Company Model S1032) called the Launch Entry Suit. In 1994 the Advanced Crew Escape Suit Model S1035 full pressure suit began replacing the Launch Entry Suit. The Shuttle CES was certified to an atmospheric altitude environment up to 100,000 ft. Bailout scenarios were developed for the CES. A bailout below 30,000 ft required stable gliding flight below Mach 1. The plan was for the crew to jettison the Shuttle hatch below 30,000 ft, using the crew escape pole, which allowed them to clear the left wing on exit. Jettisoning the hatch and using the crew escape pole initiated the automatic parachute opening sequence that would deploy the parachute at 14,000 ft.

The scenario for a bailout at or above 30,000 ft was egress from a loss-of-control breakup from a detached crew module, the situation in the Challenger accident. As there was no wing to clear, the crew would jettison from the hatch without deploying the escape pole, and this action eliminated the automatic parachute-opening sequence. Hence each crewmember was required to manually deploy their parachute. If crewmembers became disabled or unconscious during the bailout or descent, they would not be able to manually deploy their parachute. Consequently, astronauts William

In 1994 the David Clark Company Model S1035 Advanced Crew Escape Suit began replacing the S1032 Launch Entry Suit.



Test of Space Shuttle bailout using the crew escape pole to allow crewmembers to clear the left wing.

Shepherd and Michael Foale reviewed the feasibility of using the Shuttle CES equipment for egress during a loss of control or breakup. They examined the forces leading to vehicle breakup, crew module dynamics following a breakup, crew module survivability, crew module stable attitudes, and time available to egress. The primary egress concern was when to leave the orbiter. Shepherd and Foale recommended crew egress procedures and techniques.

Vehicle egress should begin once the crew module was below 40,000 ft. Cues to egress should be G forces diminishing and suit depressurizing; use of this guideline would allow about 80–90 seconds to egress. The contingency egress during a loss of control following vehicle breakup was not a defined egress mode, but a bailout. Shepherd's and Foale's conclusion was that the crew module could withstand reentry heating for an ascent breakup occurring at 280,000 ft and below. The forces causing breakup of the Challenger were estimated to be <12–20 G and were short-duration and non-lethal. For vehicle breakup during ascent below 100,000 ft, drag would cause initial rapid deceleration. Then G forces on the crew module would be low while it was lofting, followed by a 1-G force while the module was nose down in free fall.

After a high-altitude breakup (>100,000 ft), no initial deceleration would occur. The module would travel in a low-G-force ballistic arc while lofting, then below 70,000 ft it would be subject to a deceleration of 3 G to 8.5 G from aerodynamic drag, then to 1 G while nose down in free fall below 50,000 ft.

Columbia Accident Lessons Learned

After the Columbia accident, NASA Associate Administrator Bill Readdy said "…. I do not anticipate that the next system will talk about 'crew escape' – but rather 'crew survival'…." The Columbia Accident Investigation Board (CAIB) asked NASA to form the Crew Survival Working Group (CSWG) to evaluate life-support concerns related to the disaster. The CSWG report was summarized in the original CAIB Report in August 2003. The CAIB, in Observation O 10.2-1, stated, "Future crewed-vehicle requirements should incorporate the knowledge gained from the Challenger and Columbia accidents in assessing the feasibility of vehicles that could ensure crew survival even if the vehicle is destroyed." Clearly, designing for crew survivability early is more effective than post-production modification. Escape systems must also consider human factors and the deconditioning effects of space flight.

NASA then appointed an independent team, called the Return to Flight Task Group, to assess NASA actions to implement the 15 CAIB return-to-flight recommendations. NASA met 12 of these recommendations before the STS-114 Shuttle mission in 2005. NASA could not completely comply with the three more challenging recommendations, but conducted further work to improve safety, as documented in the report *NASA's Implementation Plan for Space Shuttle Return to Flight and Beyond*.

NASA commissioned a more complete report, *Spacecraft Crew Survival Integrated Investigation Teams (SCSIIT)*, which was published in December 2008. This report confirmed that the crew of Columbia died as a result of an unprotected rapid decompression and blunt force trauma at an altitude of between 181,000 and 140,000 ft, resulting in severe hypoxia, pulmonary injury, and cardiovascular collapse. Post mortem, the crew was exposed to acceleration-induced in-seat flail, third-degree skin burns from thermal intrusion, aerodynamic flail at the time of crew module disintegration, lack of protection from high-altitude conditions (low pressure, monoatomic oxygen, subfreezing temperatures), and ground impact.

Crew Survival Enhancements after the Columbia Mishap

The SCSIIT report concluded that significant failures occurred in the crew restraint system. Specifically, inertial reels on the Shuttle seat belts were found to be unlocked during exposure of the crew to acceleration forces during the orbiter destruction. As a result of these findings, the Space Shuttle Program upgraded the inertial reels that lock with absolute load and differential acceleration in any direction. The specifications for crew escape equipment were changed to add a fail-safe parachute capability for crew bailout from a detached crew module, as well as adding an upgraded survival radio with Global Positioning System (GPS) location reporting. An improved portable O_2 system was added to enhance survivability in launch pad and landing emergencies. Shuttle training for loss of control was modified to emphasize transition between problem-solving (flying the vehicle) and survival (lock inertial reels, close visors, and activate personal O_2 system). Training in Shuttle unusual attitudes was incorporated (by using nose-down mockups) to develop egress paths in unusual attitudes.

Closing the Survival Gap for Columbia Crew

In the course of the Columbia mishap analysis, considerable discussion occurred about how close the crew was to a survivable state. Survival has occurred after free fall from stratospheric balloons at 102,800 and 127,852 ft and from aerodynamic aircraft breakups at Mach 3.18 and 78,800 ft. During the Columbia debris recovery, live worms were found in four of five experiment canisters, demonstrating that primitive animals can survive a relatively unprotected reentry into the Earth's atmosphere. However, given that a rescue was not feasible, the only other option that might have been possible for the Columbia crew was repair of the wing breach, payload jettison, pre-entry cold soak, and modified reentry profile.

The repair would have required complex, unproven extravehicular activity (EVA) procedures. Perhaps contingency water containers could have been placed into the hole in the wing leading edge and some other heat-and cold-resistant material could have been applied. This would have presented substantial difficulties, however. Another complex, unproven EVA procedure could have been performed to detach and jettison consumables and the Spacehab Research Module in the Shuttle payload bay, which could have reduced landing weight by over 30,000 pounds from a nominal 250,000-pound vehicle. Although these measures might have reduced wing dynamics and thermal loading, they could have adversely altered the delicate wing boundary layer and vehicle aerodynamics. Optimistically this could have provided more time for the crew module to reach a lower altitude and airspeed. The Columbia mishap analysis showed that the detached crew module probably did not attain a stable aerodynamic trim condition that would have been necessary for a bailout. Video footage of the Challenger breakup showed a relatively stable nose-down crew module, with trailing wires acting as an aerodynamic decelerator, making bailout in this scenario at least possible. The Challenger breakup was transonic/low supersonic and lofted to a point where airspeed would have been close to zero, while the Columbia mishap was hypersonic. Any trailing wires on Columbia would have likely been destroyed from thermal or shock waves. The vehicle state of Columbia at the time of the catastrophic event (initial breakup and cabin depressurization) was estimated on the basis of modeling to be altitude 181,000 ft, Mach 15, and the final crew module breakup was estimated to have occurred between 148,000 ft and 138,000 ft and Mach 10–12.

Survival Enhancements for the Crew Exploration Vehicle for Commercial Crew and Exploration

The lessons learned from the Columbia mishap have had a significant impact on both commercial and NASA crew vehicle designs, including vehicles, such as Orion, that leave low Earth orbit but return to Earth for a water landing. These vehicle designs must address the threats to human health, listed with proposed countermeasures, in the accompanying table.

NASA contracted for several studies to be done, using manikins and three cadavers for impact studies, to better understand occupant protection. These studies have led to major design changes in requirements for helmets, suits, and seat restraints. For example, pressure suits, restraints, and the seats themselves must be integrated into the vehicle. The restraint belt size and position were modified to improve limb mobility to maintain vehicle control under high acceleration. An autonomously activated GPS personal locator beacon was added to the NASA Launch Entry Suits, as was a survival kit for post-landing contingencies. To better understand the mishap environment, a requirement for a crashworthy data recorder for NASA capsules was established. The crew of the Orion space exploration vehicle will be recumbent, and thus some of these additional recommendations, such as inertia reels, will not be needed for that spacecraft.

A mockup of the Orion Multi-purpose Crew Vehicle at the Johnson Space Center shows NASA's next-generation spacecraft, designed to carry humans beyond low Earth orbit to the moon, asteroids, and Mars.

Human Health Threats and Countermeasures

Entry Phenomenon	Physical Characteristics	Altitude/Speed	Biological Effect	Countermeasure
Plasma	Ionized molecular O_2	> 130,000 ft	Chemical/thermal burn	Thermal protection system
Excessive acceleration gradients	Delta G (dG/dT) x, y, z linear/ angular planes	Below entry interface (<400,000 ft)	Organ/skeletal damage, body fragmentation	Crew compartment stability system, axial restraint system
Shock-shock interaction	Blast wave pressure	NA/supersonic speeds	Organ damage, body fragmentation	Aerodynamic design, crew compartment integrity
Dynamic heating	Temperature	> 150,000 ft	Thermal burn	Thermal protection system
Dynamic pressure	Q = measure of dynamic pressure		Organ/skeletal damage, body fragmentation	Crew protection system
Atmospheric pressure	Atmosphere absolute (ATA)	> 63,000 ft (<0.06 ATA)	Tissue water vaporized to gas resulting in ebullism	Pressure vessel, pressure suit, pressure breathing mask
Atmospheric pressure	Atmosphere absolute (ATA)	> 18,000 ft (<0.5 ATA)	Evolved tissue nitrogen resulting in decompression sickness	Pressure vessel, pressure suit, pressure breathing mask
Pressure differential	Delta pressure (dP)		Barotrauma in gas-filled spaces (lung, ear, gastrointestinal) resulting in arterial gas embolism	Pressure vessel, pressure suit
Oxygen partial pressure	ppO_2	> 10,000 ft	Hypoxia and asphyxiation	Pressure vessel, pressure suit, mask, supplemental oxygen
Intrusion of habitable space	Physical trauma	NA	Fatal or severe organ damage due to penetration	Crew compartment protective system
Terrain impact	Delta G (dG/dT) x, y, z linear planes	Surface	Injury due to rapid deceleration	Parachute, ballute, lifting body, airbag, braking rocket, automated and crew initiated

NA, not applicable

Conclusions and Recommendations

Crew survivability should be considered the primary mission success criterion and should be the main driver in vehicle design and mission architecture. Crew survivability should incorporate advanced technologies where feasible and should be simple, reliable, and attainable to address catastrophic failure modes. Lessons learned from related high-risk operations, as well as space mishaps, incidents, and close calls, can enhance crew survival by providing insight into failure modes, and improving procedures, design requirements, and occupant protection strategies.

Survival systems should be designed so that the equipment and procedures provided to protect the crew in emergency situations are compatible with nominal operations. A pressure-suited crewmember should be able to perform all operations without compromising the configuration of the survival suit during critical phases of flight. The design of personal protective equipment needs to adequately address anticipated catastrophic failure modes, and compliance with protective equipment and procedures is essential.

Our current knowledge of injury mechanisms at high Mach numbers and altitudes over 100,000 ft has significant limitations, and crew survivability could be enhanced by advanced technologies. Occupant protection and crew survivability studies should be conducted to fill these gaps. Although NASA has recognized the importance of capturing lessons learned, it has often been criticized for not following that principle. However, NASA learned important lessons about crew survival from the Columbia mishap, and these lessons hold great benefit for all future human space exploration.

"The only thing we learn from history is that we learn nothing from history."

Georg Wilhelm Friedrich Hegel (1770-1831)

The Future: Crew Survival Investigations

Karon Woods

> ***"Those who don't know history are destined to repeat it."***
>
> Edmund Burke (1729-1797)

One of the lessons learned from the loss of the Space Shuttle Columbia was that root-cause investigations do not dig deep enough to trace the individual crewmember experiences to determine the successes and failures of protective measures. Past mishap investigations focused on determining the root cause of the mishap and preventing recurrence. However, if the crewmembers were not identified in the causal chain of events, their experiences were not analyzed and lessons were lost.

Until NASA's Constellation Program[1] vehicle, crew survivability under emergency conditions was not assessed. By postulating the outcomes of system and operational failures that would result in potentially catastrophic conditions, and analyzing those chains of events, it was possible to identify credible crew responses under emergency conditions. In each scenario, the must-work functions and equipment are evaluated for their ability to prevent crew injury or death.

NASA documented a process for performing crew survival investigation by integrating an understanding of historical and potential spacecraft accidents with an understanding of mishap investigation practices. By understanding which emergency scenarios can happen, how they may manifest, and anticipating crew actions; we can predict potential mishap causes and outcomes. This process adds space flight-unique information to the aviation mishap knowledge base and creates common language between the medical and engineering team members.

The crew survival in-depth investigation process supplements the root-cause investigation. The crew survival investigation focus is different from that of the usual mishap investigation. Specifically, the crew survival investigation team investigates the performance of the crew, crew protective equipment, crew-vehicle interfaces, emergency and crew survival systems, training, and procedures that are intended to protect the crew.

Johnson Space Center Safety & Mission Assurance Directorate logo.

The outcomes of the crew survival investigation are the awareness of factors and events that affected crew survivability and recommendations for improving crew survival for future human space flight. This chapter provides an overview of investigation elements including data and information management; imagery; debris recovery and reconstruction; timelines; and assessments.

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[1] NASA Constellation Program goals included vehicles that could have rocket and crew module capability to leave low Earth orbit.

Space Flight Considerations

The starting point for spacecraft mishap investigation is the wealth of experience from aviation mishap investigations. Using aviation mishap investigation processes, analytical tools, and historical results, space flight specialists apply their understanding of the dynamic mission envelope and the hazards of space flight to the investigation. Some aspects of space flight that make crew survival investigation different from aviation mishap investigation are these:

- Large quantities of fuels, presence of oxidizer, cryogenic temperatures
- Severe vibroacoustic environment, high kinetic and potential energy, high acceleration loads, dynamic separation events, constrained flight trajectory
- Extreme aerodynamic heating, plume heating, thermal cycling (extreme heat and cold), entry heating and hot gas intrusion, reactivity of heated gases
- Consequences of depressurization, radiation, vacuum, plasma charging, atomic oxygen, collision with micrometeoroids or orbital debris
- Orbital mechanics, abort modes, plume impingement, shock-shock interaction, hypersonic environment, absence of aerodynamic effects
- Limited energy or capability for downrange correction; reliance on parachute, flotation, and uprighting systems
- Limited egress paths, sea conditions at landing, crew deconditioning, crew suits that limit mobility, limited visibility and visual cues
- Complex and constrained timeline, critical time sequencing, critical event timing

The crew survival investigation process lends itself to a full range of investigations, from the destruction of a spacecraft to a crewmember injury during a spacewalk to an electrocution while interacting with onboard hardware.

Team Member Selection

Crew survival investigation team member selection is determined by the mission phase of occurrence, the systems involved, and the likely cause of the mishap. In all cases, a crew survival specialist, with extensive mishap investigation and human factors training, leads the team. Typical team members are a medical doctor, a pathologist, a legal representative, and specialists in structures, environmental control and life support systems, flight performance, and crew equipment (crew survival and emergency equipment and crew suits). Depending on the scenario, communications, mission operations, or ground operations specialists, as well as other technical specialists, may supplement the investigation team.

Management of Data and Information

All information generated by the investigation and collected from other sources must be documented, organized, and uncompromised to be useful to teams performing current and future investigations. Because of the high volume of information collected and analyzed during a crew survival investigation, much of which may be sensitive, organization and information control are important features of the crew survival investigation plan. Medical forensics data are graphic and highly sensitive, so “need to know” criteria must be established before any information is distributed.

Data and information exist in many forms including presentations, spreadsheets, diagrams, user manuals, analysis reports, photographs, operating manuals, models and simulations, written notes, videos, and audio recordings. Improper cataloging practices make organizing or retrieving the information difficult. All items should be marked with a title, date, version, source or author’s name, and any other pertinent information. Information sources include mishap-site records (diagrams, maps, notes, and photographs), vehicle telemetry, analytical results, vehicle processing records, crew medical and training records, interviews, and debris and remains.

This information is used in analyses, tests, and reconstructions to identify the sequence of events that resulted in the mishap, to identify the cause(s) of crewmember injury or death, and to justify the recommendations. Once the investigation is complete, a crew survival investigation report captures the investigation results, recommendations, and investigation lessons learned. Not only is the information used in the current investigation, but it may identify trends or justify improvements in vehicle design, crew equipment, or operations to improve crew survival. A data retention plan should identify where, how, and for how long the investigation information will be kept.

Imagery

It is likely that other response teams will document the initial scene before the crew survival investigation team arrives, so it is important to collect copies of their photographs and video. Imagery documents the locations of crewmembers relative to the vehicle and to crew protective equipment, and captures evidence of crew actions. Videos and photographs help determine the breakup sequence, and videos reveal the conditions the crew experienced during the mishap. Regardless of the imagery medium, it is important to catalog and store all collected images for quick, reliable access. Because of the sensitive nature of some images, not all imagery may be accessible by all team members. For this reason, protocols should be established to manage release of crewmember photographs, videos, and advanced imagery.

Photographs

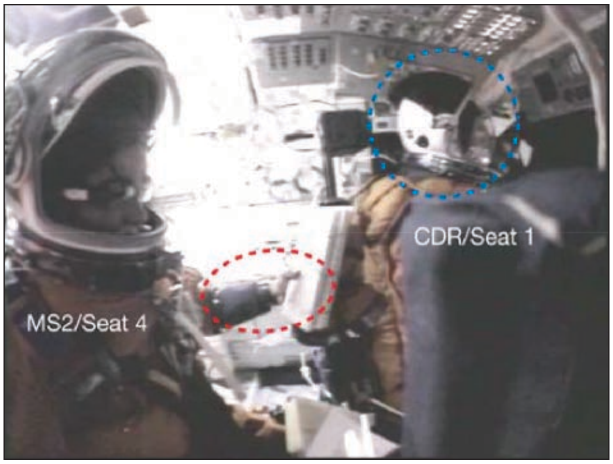
The adage that a picture is worth a thousand words holds true in mishap investigation as well. NASA routinely takes photographs throughout vehicle processing and the mission. During processing, closeout photographs capture the final (or “as-flown”) configuration of the vehicle, payloads, and equipment. Launch and ascent photographs document the performance of the launch vehicle. On-orbit photographs, transmitted throughout the mission, document the latest vehicle configurations and onboard conditions. Photographs also capture the operation and performance of the returning vehicle. A further benefit to a crew survival investigation is photographs of the interactions of crewmembers with each other and with the vehicle and equipment throughout the mission.

Photographs of a spacecraft mishap come from many sources (including amateur photographers and astronomers, the news media, and mission photographs) and in some circumstances capture the mishap as it unfolds. “As-found” photographs are taken of the mishap scene or where the debris is located, as applicable. Aerial photographs may capture such features as spatial relationships, vehicle components, ground fire damage, and fuel spills. Reconstruction photographs are taken of reassembled vehicle wreckage or only the portion of recovered wreckage that is of interest to the investigation. Images of the crew protective equipment and systems and the hardware closest to the crew help the team relate the vehicle and equipment condition to crew injuries.

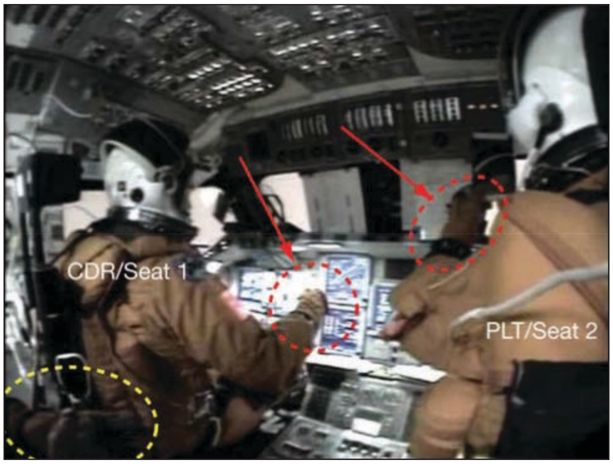
Similar to the vehicle “as-found” photographs, “as-found” crew photographs capture the human remains as they are discovered. These photographs are used to understand the relationship of the body or remains to the vehicle and the environment. “As-received” photographs are taken when the human remains are received at the facility for autopsy. The purpose of these photographs is to rule out confounding information, injuries induced during transport, or other noted changes in the remains. Autopsy photographs document the condition of the human remains to establish injury patterns and/or causes.

Videos

Videos are also important to an investigation. Onboard video provides insight into the status of the crew and of the crew protective measures, and the sights, sounds, and configuration of the vehicle. Depending on the type of mishap, the onboard video may provide critical information about the environmental conditions and timing of key events, capture crew communications and crew actions, record audible caution and warning alarms, or document damage to the vehicle. In addition to onboard video sources, ground-based or radar video can show deviations of the mission profile, capture a debris trail, reveal indications of leakages from vehicle systems, document events with their associated times, and document recontact of spacecraft elements or contact with foreign bodies or terrain.



STS-107 Columbia Commander/Seat 1 visor down and latched for suit pressure integrity check (blue dashed circle) and Mission Specialist 2/Seat 4 with helmet on and left glove off (red dashed circle). Upon completion of the pressure integrity check the visor is raised for reentry.



STS-107 Columbia Mission Specialist 2/Seat 4 donning left glove; Commander/Seat 1 and Pilot/Seat 2 with gloves ON and MATED.

Advanced Imaging

In addition to photography and videos, other imaging methods (including magnetic resonance imaging [MRI], radiology, computed tomography [CT], and electron microscopy) can document the current condition of the debris, body, and remains to further develop cause-and-effect relationships.

As a practice, imagery should be reviewed at the start of the investigation, then periodically reviewed as the analyses progress and scenarios develop. As with all other analyses, images can support or refute findings.

Debris Recovery and Reconstruction

Debris recovered from a spacecraft mishap provides tangible evidence that can be used to determine failure mechanisms, failure modes, fracture dynamics, and thermal exposure. It can also provide insight into crewmembers' injuries and the environmental conditions the crew experienced. The focus of the crew survival investigation is on the bodies and remains on the crew-vehicle interactions (the crew cabin, windows, vehicle systems, crew-worn equipment), and on crew emergency and survival equipment and systems. One relevant vehicle system is the environmental control and life support system; this system provides the atmospheric pressure, oxygen, humidity, and temperature, along with water for sanitation and potable water. The evidence collection techniques described in this section are applicable to both spacecraft debris and bodies or remains. For example, instead of collecting debris to reconstruct the spacecraft for analysis, the crew survival investigation team can collect remains to virtually reconstruct a crewmember. Of course, the timeliness and sensitivity when dealing with crew remains or injuries differ greatly from such considerations when dealing with spacecraft debris.

The amount and type of evidence generated during the mishap will vary, depending on the mishap and when it occurs during the mission. The amount of recovered debris depends on the size of the recovery effort, location of the debris (e.g., on board a vehicle, in rugged or remote terrain, in water), and when the mishap occurred in the mission profile.

Site Documentation and Debris Recovery Plan

The first step in a debris recovery plan is to observe the site and document the scene. The major components of the spacecraft and the flight path should be located as references to crew-relevant debris. Specifically, the relative locations of the crew and crew protective and survival equipment and systems should be diagrammed. When a crewmember is rescued or remains are recovered, their condition should be documented along with their relationship to their crew equipment, the vehicle, prominent terrain features, and areas of post-impact fire. These "as-found" records (e.g., descriptions, photographs, videos) provide clues for interpreting injury patterns and comparing conditions of crewmembers. Mechanisms at the scene that could explain the injuries and any protective equipment accessed by the crew should be documented. For a crew survival investigation, the highest priority is locating and retrieving the vehicle components that were closest to the crew during the mishap and at the mishap site, emergency or protective equipment and systems that were activated or should have been activated, and crew remains. It is also important to document what debris is missing or out of place given the circumstances of the mishap.

Crew survival investigation teams should consider indications of intrusion into the cabin, of seat restraint failures or separation of the seat from the vehicle, of ejection from the cabin, of impacts with interior surfaces or equipment, that the crew was not seated, and that crewmembers were executing procedures such as indications of deployed emergency hardware and switch or lever positions. They should look for indications that the crew survived the initial mishap but could not escape the ensuing conditions inside the vehicle (such as an obstruction or fire) or the hazards of the post-impact external environment.

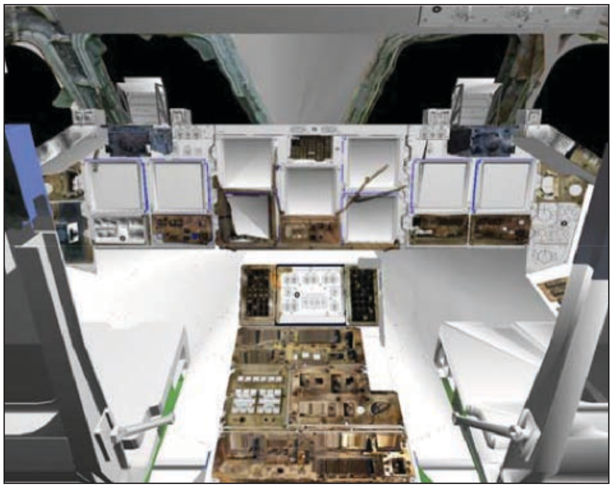
Many samples may be taken at the scene including medical samples, environmental samples (water, soil, foliage), and spacecraft samples (fuels, coolants, fire or toxic release products). For example, a pre- or postmishap toxic environment may be indicated by samples taken at the scene. Samples for crewmember-to-crewmember comparisons should be collected at a consistent sampling site.

It is important to distinguish damage related to recovery and transportation of evidence from damage related to the mishap. If the scene is not thoroughly documented before the crewmembers are removed, evidence on the crewmembers may be lost, further damage to the vehicle-related evidence may occur, or positions of controls or switches may be altered during removal of the crewmembers from the scene. At the collection location, by comparing the debris to photographs or video taken in the field, the crew survival investigation team can document any changes in the debris that are incurred during handling or transportation. After the recovered debris has been cataloged and stored, specific items of interest can be identified for reconstruction, testing, or analysis.

Debris Reconstruction

Reconstruction provides the team an opportunity to see how the debris pieces fit together and the final positions of parts such as switches, valves, and levers, to determine the sequence of events. Reconstruction of all or a portion of the vehicle involves assembling the vehicle in the as-flown configuration using physical or virtual recovered debris. Physical reconstruction is the reconstruction of the vehicle using recovered debris, usually on a constructed grid or frame. Virtual reconstruction is the electronic reconstruction of the recovered debris, creating an as-flown configuration using specialized software and debris photographs to simulate the debris. It can also be an interactive, three-dimensional simulation of the flight dynamics and failure sequence.

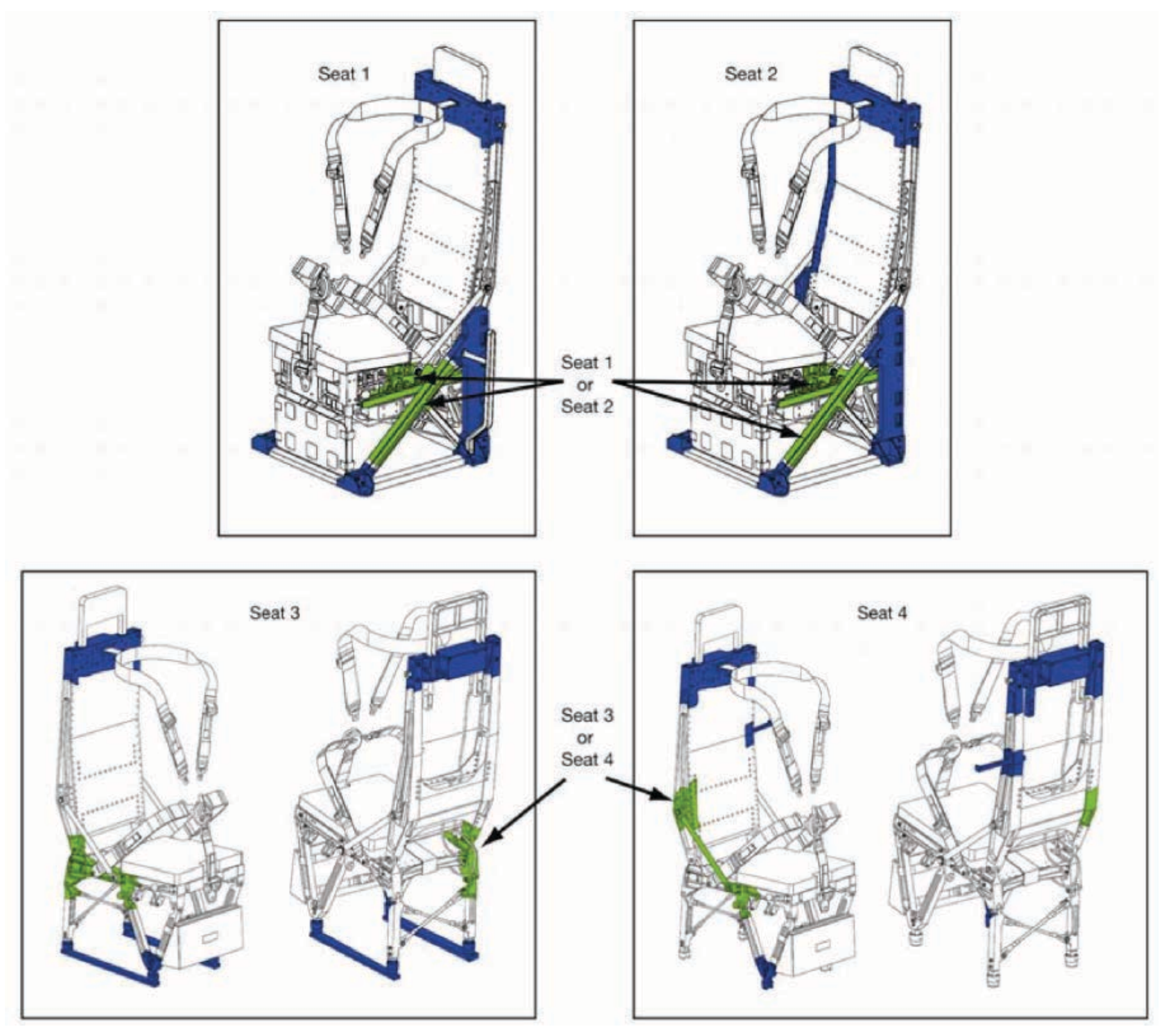
The focus of reconstruction is to observe the damage characteristics, or patterns, among the debris. The reconstructed wreckage may include only the portion of wreckage of interest to the crew survival investigation, such as the crew cabin, seats, and crew-protective emergency equipment and systems, which can assist the team in relating the hardware to the crew actions, conditions, and injuries. The recovered debris is tracked to a specific location on the vehicle, or in the



Virtual reconstruction of the recovered Columbia flight deck panels.

Identified Debris from the Flight Deck Seats from the Columbia Accident

More than 68 pieces of seat structure debris were recovered. The blue items in these figures represent pieces of seat structure that were positively identified to a seat location. The green items are those pieces that could be from one of two seats.



case of the crew equipment, to a specific crewmember. Part numbers and serial numbers provide definitive proof of the as-flown location. For debris without part numbers, comparing the material composition of the recovered debris to vehicle drawings may determine the origin of the debris.

Reconstruction also provides an opportunity to identify missing pieces of the vehicle and determine if additional debris recovery is necessary. It is unlikely that the team will recover the entire vehicle or match all debris to a definitive position on the reconstructed vehicle, so uncertainty is associated with reconstruction.

Analysis of the Evidence and Reconstruction Results

The purpose of analyzing physical evidence is to develop scenarios or sequences of what may have taken place that caused the crew to incur the observed injuries. From a crew survival investigation perspective, reconstruction provides insight into the performance of the crew cabin and the surrounding structure, crew-vehicle interactions, initial and subsequent system or structural failures, toxic releases, fire, and other circumstances. To begin with, secondary, debris-debris, and ground-impact damage should be identified and excluded from consideration. Then, the collected evidence should be analyzed for indications of failure progression and crew actions. Team members should note outliers, anything that does not follow logic. The relative locations of debris (what departed first or last, emergency equipment in proximity to each crewmember, and so on), equipment settings and configurations, and other relevant evidence should be considered.

In identifying the cause of the mishap, system or structural failures, the environment, crew actions, and anything else that might be relevant should be considered. Observations may include these categories:

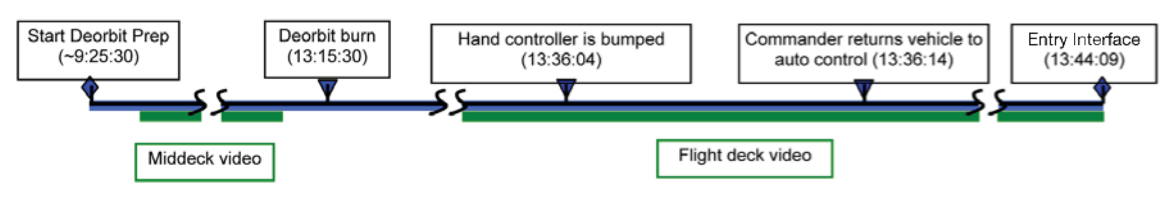
- Thermal (directional heating, random heating, thermal erosion or degradation, hot gas flow, shock-shock interaction, combustion/oxidation, melting, fire, freezing)
- Structural (fractures, breach, rupture, weakening, shadowing, warping, fragmentation, tearing)
- Materials (deterioration of paint or primer, sources and patterns of material deposits, deformation, degradation caused by exposure to the environments, flow redirection, properties)
- Loads (mechanical, structural overloading, impact)
- Chemical (residue deposit, discoloration, residual fuels, fluids or coolants)
- Configuration (switch, handle, control surface or gimbal, and valve positions; deviations of settings, positions, or locations from nominal; configuration of deployed equipment and crew restraints)
- Foreign material or debris
- Premishap system failures

This analysis may encompass a broad range of activities that include observing the physical evidence, conducting an engineering analysis of the debris, identifying the role of any system failures or crew actions, and determining the origin and progression of the failure(s).

Timelines

Timelines are one of the most effective tools used to build scenarios and to document the sequence of events. Timelines are graphical representations of the sequence of events based on collected information and analytical results. Developing scenarios and sequencing events is an iterative process as evidence and analytical results are integrated, eventually converging on a scenario supported by all of the available information. Using timelines, a team can visualize the progression of the events that led to crew injuries or death.

Deorbit Preparation to Entry Interface from the Columbia Timeline



This timeline illustrates key events from the beginning of deorbit preparation to entry interface. Green bars represent times when video data were available. The blue bar represents times when voice and telemetry transmissions were available (throughout this phase). Times shown are GMT.

When determining where the timeline starts, an event occurring before the mishap may be relevant. For instance, a change to a crew procedure for which the crew was not trained may be a significant event on a timeline. Typically, a good starting point is the start of the mission. In most cases, the timeline ends with the mishap. An example of an exception is one where the crew survives a parachute failure at landing, but succumbs to exposure because the emergency equipment was not available or suited for the environment.

The task of determining what is and is not relevant is different for each investigation. When constructing a crew survival investigation timeline, one should begin with events that have established confirmed times; those without uncertainty. These events are based on telemetry, video, air-to-ground communications, or some other source that provides a time stamp for events. Next, add events that occurred in conjunction with a specific mission event or crew action, but with associated uncertainty, such as a crewmember lowering their visor during entry preparations. Include events that would produce a crew action or reaction, system response, or known injury. If possible, verify individual crew-related milestones on the timelines with survivor interviews or substantiate with engineering or medical evidence. Assess all timelined events for significance as contributors to the survival or injury of the crewmembers.

A separate medical timeline allows the crew survival investigation team to capture relevant medical events and develop an injury event sequence. A separate timeline permits limited dissemination of sensitive information. When sequencing the events, associate the incidence of crewmember injuries with the timelines. Remember that fire precedes burns, impacts precede fractures, loss of pressure integrity precedes decompression sickness, and so on. When correlating injuries with an event on a timeline, account for all injuries experienced by the individual crewmembers. It is unlikely that all crewmembers experienced identical injuries, so consider constructing an individual medical timeline for each of the crewmembers, and then add the significant events to the crew survival investigation timeline. Before finalizing the crew survival and medical timelines, reconcile any conflicts and confirm the times of as many events as is practical.

Assessments

Crew Survival Investigation Assessments

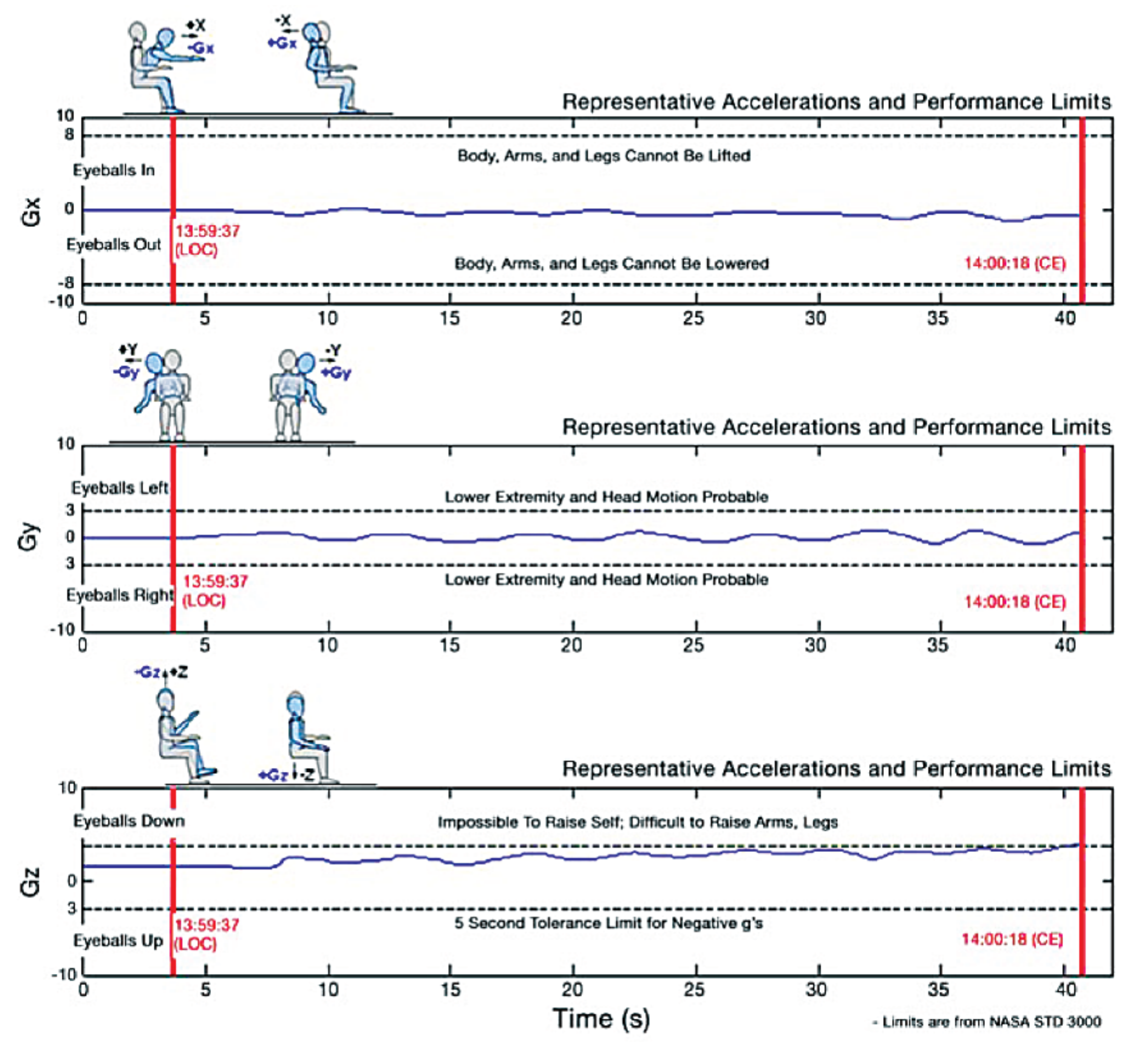
The material presented in this section is not all-inclusive, but provides general information and insight regarding the assessments and analyses that may be performed by a crew survival investigation to bound the crew experience during the mishap. The crew survival investigation assessments focus on (1) the failure of the vehicle, especially the portion of the vehicle closest to the crew at the time of the mishap; (2) the performance of equipment and systems designed to protect the crew; and (3) the medical forensics to identify each crewmember's experience during the mishap. Both objective (e.g., air-to-ground communications, vehicle forensics) and derived (e.g., ballistics analysis, thermal analysis) data are used. The assessment results are used to develop failure scenarios, place events in the proper sequence, confirm times, and support or refute findings. The crew experience is defined by mapping analytical results to specific seat locations and/or crewmembers, then correlating vehicle or system failures and crew actions with the injuries observed in the crew. These results are essential for identifying the successes and failures of the protective measures of the vehicle and crew equipment and systems, and improvements for future missions.

Spacecraft Assessments

Typical spacecraft-related analyses include, but are not limited to, aerodynamic and propulsive loading, ballistics, motion, thermal, aero-thermal, structural, environmental, and materials analysis; and evaluation of debris, vehicle systems performance, and vehicle telemetry. Depending on the type of mishap and the phase in which it occurs, the team may include evaluations of ground operations, mission operations, and communications. Knowledge of the relevant phase(s) of flight helps to determine the scope of the analyses and bounds the likely velocities, trajectories, altitude, environmental factors, and potential aerodynamic, propulsive, and thermal loads. The phase of flight in which destruction occurs (e.g., prelaunch, ascent, orbit, rendezvous, reentry into Earth's atmosphere, landing, or post-landing) may be obvious. However, the mishap may result from latent damage, failures, or events occurring in a previous mission phase, so the initial cause and timing of the mishap may be difficult to discern.

Human Performance Limits of the Columbia Crew

This graphic illustrates representative loads based on modeling in all three axes, including the effects of increasing rotational loads. Models showed that accelerations were initially low, and peaked between 2 G and 3.5 G by the time of the catastrophic event (separation of the forebody from the midbody). The dashed black lines (upper and lower) on the chart indicate human performance limits based on NASA-STD-3000.* The representative loads, which are based on modeling, were well within these human performance limits.



* NASA-STD-3000, Man-Systems Integration Standards, Volume I, Section 5, Revision B, 1995.

LOC – Loss of Control of Columbia
CE – Catastrophic Event

Analyses for Spacecraft Assessments

- Flight Dynamics
- Ballistics
- Motion
- Thermal
- Aero-Thermal
- Structural
- Materials
- Environmental

The results of analyses conducted on the vehicle can be used to calculate the resulting loads applied to the crew cabin and to the crew. The loads and forces acting on the vehicle can be mapped to the individual crewmembers. Through understanding of the mission phases, altitude, ballistic coefficient, and other factors, engineers can calculate loads and other relevant information vital to the crew survival investigation medical team. The medical team uses this information to determine the causes of the crew injuries and fatalities, and the sequence of the medical events.

In addition to conducting engineering analyses, a crew survival investigation team should review historical records to identify any potential contributors to the mishap. Begin with the subset of vehicle records applicable to the crew protective equipment and systems, environmental systems, and the crew-vehicle interface. These records include relevant design and manufacturing drawings, and the subject spacecraft and fleet manufacturing, assembly, and maintenance histories, including any problem reports and corrective actions, non-conformances, or design changes resulting from past issues. In addition, capture any crew and safety concerns with operational (human) factors, such as cabin layout; emergency hardware quantity, accessibility, and stowage locations; and situational awareness (annunciation, indications, visibility, auditory levels, and so on).

Flight Dynamics Analysis
The spacecraft is subjected to thrust, drag, gravitational, and lifting loads of varying magnitudes throughout the mission. Together, the aerodynamic and propulsive loads define the flight dynamics. Analyses of aerodynamic and propulsive loads provide insight into the vehicle's trajectory, motion, and loads, and provide the reference data necessary for other analyses such as thermal analysis. Also, the vehicle's trajectory provides information on the gross vehicle motion, velocities, and acceleration forces acting on the vehicle. An aerodynamics analysis is done to study the interaction of aerodynamic forces on an object. For mishaps that occur during flight through the atmosphere (as during launch, reentry to Earth's atmosphere, and landing), the analysis of aerodynamic stability data provides the relative motion of the vehicle. A propulsive loads analysis is used to study the loads imparted by the propulsive thrust of the engine, motor, and thruster propulsion systems. Other sources of loading events include collision of spacecraft elements, actuation of the pyrotechnic system, inputs to directional flight control, parachute deployment, landing, and braking. These vehicle motions and forces are translated into the motions and loads experienced by crewmembers.

Types of accelerations experienced by crewmembers include sustained, oscillatory, impulse, and instantaneous (impact) accelerations. Acceleration loads, whether positive or negative, can affect human performance, and can lead to loss of consciousness and/or physical injuries. The degree of injury is related to the magnitude, duration, and direction of the acceleration forces. The human body is more able to withstand accelerations in the fore-aft direction than in the up-down or side-to-side directions. Also, deconditioned crewmembers have a reduced tolerance for acceleration loads.

Ballistics Analysis
In cases of spacecraft breakup occurring during ascent or reentry to Earth's atmosphere, a ballistics analysis can provide the order in which the crew, equipment, and debris were shed during the mishap and determine debris trajectories. This analysis uses the ground location of the recovered debris (latitude and longitude) and the debris properties (size, shape, and mass) to characterize the breakup sequence. The ballistics analysis makes use of the ballistic trajectory, controlling forces, ballistic number, reference trajectory, and any cascading failures.

Motion Analysis
Motion analysis determines the gross movements of the spacecraft during the mishap. Data to support the motion analysis comes from telemetry, a flight data recorder, radar, and video. In the absence of any recorded data,

flight dynamics and ballistic analyses can provide information on the representative loads and motions experienced by the vehicle. Through understanding the motion of the vehicle, it is possible to combine these data with the flight dynamics and ballistic analysis to determine the loads the crew experienced through the evolving conditions. This information assists the medical team in evaluating the crew injuries and determining possible mechanisms of injury.

Thermal Analysis

Thermal analysis identifies the thermal loads imposed on the vehicle, the crew equipment, and crewmembers. The spacecraft and crew are subjected to an induced thermal environment managed by flight profiles, vehicle orientation, and onboard thermal systems. When induced heating exceeds the design limits of the spacecraft materials, material failure may lead to the destruction of the vehicle. This analysis considers the source of the thermal energy, the transfer mechanisms (e.g., conduction, convection, or radiation), thermal effects, the ambient thermal environment, and the duration of exposure. The temperatures resulting from the thermal loads can affect the properties of the materials (e.g., strength, toughness, chemical composition, and phase state). Thermal injuries to the crew can also provide information on the sequence of the thermal event relative to any other traumas and/or death, and on the intensity, duration, and directionality of the event and the state of any crew protective equipment and surrounding structures at the time of the thermal exposure.

If thermal systems fail to maintain a habitable environment, the crew may experience heat- and cold-related injuries, or conditions may affect their ability to function. Temperature-related injuries include hypothermia, frostbite, cryogenic burns (caused by contact with cryogenic materials), contact burns, heat stroke, heat exhaustion, and dehydration. The extent and severity of the injuries depend on the source and exposure time. Burns from radiant heat sources may show signs of shadowing, deposition, and/or adhered material and appear only on the side of the body exposed to the heat source. Sources of radiant heating are fire, materials heated to high temperatures, and exothermic chemical reactions. At high Mach numbers, shock-shock interactions result from an amplification of energy at the point where two shock waves intersect, and these interactions can result in laser-like damage to exposed tissue; cases exhibit areas of focal burning and cauterization injuries.

Aero-Thermal Analysis

Aero-thermal analysis is performed on the spacecraft to identify probable failure sequences for launch, launch abort, and reentry mishaps. When considerable heat is generated, the high temperatures can affect the properties of the spacecraft materials and contribute to structural failure. Such high temperatures can result in combustion and chemical reactions unique to space flight. The aero-thermal analysis considers atmospheric reentry conditions, maximum survivable altitude analysis, reentry heating thermal analysis, vehicle orientation, and ablation.

Structural Analysis

Structural analysis studies the behavior of the spacecraft structure under various loading conditions. Structural analysis performed in support of the crew survival investigation is focused on the crew cabin and the structure surrounding it for understanding of the crew-to-vehicle load paths and how this hardware is attached to the vehicle, and to determine when and how it failed. The many types of structural, or mechanical, failures include deflection, ductile fracture, brittle fracture, impact, creep, thermal loading, buckling, corrosion, stress corrosion, wear, and fatigue. Each type of failure produces unique indicators near the fracture surface. A crew survival investigation should consider vehicle design margins, vehicle stresses, environmental conditions, structural loads, translational loads from aerodynamic drag, propulsive loads, rotational loads from vehicle rotation, linear moments from motion in roll, pitch, and yaw, and loads caused by differences between internal cabin pressure and external static and dynamic pressures.

It is important to distinguish each of the indicators on the debris as either a cause of the initial failure, a consequence of a subsequent failure, or an impact.

Materials Analysis

The mishap may expose spacecraft materials to conditions beyond their design limits and cause the materials to fracture, degrade, melt, and deform. Materials analysis can determine the sequence of the failures by identifying the progression of changes in the properties of the materials (e.g., strength, hardness, toughness, chemical composition, phase state) and provide insight into the origin of any material deposits found on the vehicle structure or crew. Also, comparisons of the materials properties to the debris attributes may identify the origin of a piece of debris when other methods cannot.

Environmental Analysis
The environmental conditions affecting a spacecraft and crew are both natural and induced, and affect crew health and performance. Environmental factors may be direct causes for injury or death, or contributors that compromised the ability of the crew to function. When determining whether the environment contributed to the crew condition, a crew survival investigation should consider human factors and environmental hazards in microgravity, space, and terrestrial environments.

Inadvertent actions and crew errors can result from human factors such as overly complex procedures, insufficient lighting, unguarded switches, or excessive background noise, and contribute to a mishap. In a microgravity environment, translation corridors obstructed by stowage and unrestrained equipment can entangle the crew or the crew can be entrapped while moving or rotating equipment. Sharp corners and edges, pinch points, protrusions, and rough edges can snag clothing and impede crew actions or result in head trauma, lacerations, or broken bones.

In a space environment and in the spacecraft design, ionizing and nonionizing radiation and electric shock hazards can contribute to a mishap. Ionizing radiation from the natural environment, radioactive power and heat sources, and some equipment may produce short-term effects including nausea, vomiting, headache, diarrhea, burns, and cognitive impairment. Non-ionizing radiation sources, such as lasers, radiofrequency transmitters, or the sun viewed through unprotected windows, can result in eye irritation or damage, temporary blindness, increased body temperature, or burns. Electric shock can interfere with nerve control or result in burns, ventricular fibrillation, loss of consciousness, or death.

The environment at the landing site poses hazards to the crew including natural predators (e.g., fish, birds, mammals), lightning strikes, exposure, drowning, and entanglement. Although recovery forces and onboard emergency equipment may mitigate the hazards at the nominal landing site, recovery forces may be delayed or the emergency equipment may be inadequate or fail to function. Launch aborts and aborts from orbit may place the crew in an undesirable location without the necessary survival equipment. In some cases, well-meaning Samaritans may extract the crew from their spacecraft and cause or exacerbate injuries.

Crew Cabin Environment Assessments

The cabin environment analysis determines whether conditions within the crew cabin affected the crew's ability to respond under mishap conditions and/or caused injury. For example, a crew survival investigation should

- determine whether the vehicle structure invaded the space necessary for each crewmember;
- evaluate the performance of the restraint system that secured the crewmembers to their seats and ultimately to the vehicle;
- determine whether the energy-absorbing mechanisms in the design reduced the loads to within the tolerance limits for human survival;
- determine whether and when a crewmember was unable to perform a response action, became permanently compromised, or lost consciousness due to loss of a habitable environment, toxic material release, or fire;
- determine if postmishap conditions contributed to crew injuries by limiting egress, exposure to fire or toxic materials, or landing in a hostile environment or under hazardous conditions.

Conditions in the crew cabin can produce in-flight or postflight incapacitation, decrease visibility, hinder egress and rescue efforts, or contribute to crew injuries, all of which reduce survival chances.

Impact injuries
When investigating the cause of impact injuries, a crew survival investigation starts by assessing the cabin area in proximity to the crew for evidence of contact

with equipment or stowage. Impact injuries occur when a crewmember collides with an object or an object collides with a crewmember, such as when injuries result from forceful contact with equipment liberated during the mishap. Intrusion is also a type of impact injury. In this case, a deformation of the crew cabin reduces the available volume surrounding the crew and constricts respiratory function; this may be a momentary or permanent condition. Other consequences of impact are fracture, penetration, lacerations, contusion, blood loss, eye damage, and loss of consciousness due to head trauma or constriction.

Toxicological injuries

Toxicological injuries result from exposure to toxic substances (e.g., combustion products, fuels, coolants, airborne microbes, contaminated water, fire extinguishing gases) that damage tissues. Although spacecraft designers attempt to eliminate these substances from the crew environment, toxic substances can be introduced during a fire or enter the crew cabin on a contaminated spacesuit. Also, faulty environmental control and life support systems can fail to remove carbon dioxide, water can become contaminated, batteries can rupture, and solutions used to pretreat urine can leak out of their containers. Depending on the level of toxicity, exposure time, and concentration, exposure can result in burns, an inflammatory response, eye and mucosal irritation, visual disturbances, liver damage, gastrointestinal toxicity, central nervous system depression, and other effects. In microgravity, without forced airflow and the subsequent mixing of gaseous constituents, toxic accumulations of gases can lead to lung, eye, and skin damage; burns; unconsciousness; or death by poisoning or asphyxiation.

Thermal injuries

Thermal injuries result from failure to maintain a temperature-controlled environment or from thermal sources including radiation and combustion events. These injuries result from exposure to environmental temperatures and/or objects at temperatures that can harm the crew. The principal effect of a microgravity environment on heat transfer in the crew cabin is the loss of natural convection; that is, warmer air will not naturally rise. All convection under these conditions must be forced through the use of fans or blowers.

Pressure injuries

Pressure injuries result from excessive or insufficient atmospheric pressure conditions, barotraumas, and from exposure to high airflow. Changes in pressure generated by explosions, failed systems, cabin breach, leaks, failed overboard vents and valves, or ejection of the crew from a pressurized environment can cause incapacitation, injury, or death. An overpressure condition (e.g, explosion) that exceeds the pressure relief capability of the cabin can damage the ears, lungs, sinus cavities, circulatory system (pressure waves transmitted through blood), and teeth. Injuries to the lungs and ears due to overpressurization are similar to those observed from a rapid depressurization. Without sufficient venting, an overpressure condition may result from the unmitigated introduction of gases from failed environmental control and life support systems, or a cabin fire may increase pressure. Long-term exposure to elevated pressures can result in oxygen toxicity and increase the amount of nitrogen saturation. Ultimately, overpressurization of the crew cabin may result in a cabin breach.

Depressurization occurs when the crew cabin is breached by structural failure, penetration, inadvertent hatch opening, a cabin leak (hatch, seal, or window), or failed overboard vent or valve. At pressure altitudes above 10,000 feet, as the pressure altitude increases, the oxygen partial pressure in the arterial blood decreases, which affects eyesight and cognitive abilities. The amount and pressure of oxygen delivered to the tissues is determined by arterial oxygen saturation, by the total oxygen-carrying capacity of the blood, and by the rate of oxygen delivery to the tissues. When the body is deprived of sufficient oxygen, hypoxia occurs. The four types of hypoxia are hypoxemic hypoxia, anemic hypoxia, stagnant hypoxia, and histotoxic hypoxia.

In general, at pressure altitudes above 18,000 feet, decompression sickness occurs during depressurization when dissolved gases come out of solution and create bubbles inside the body. Symptoms include joint pain, rashes, paralysis, and death. Barotraumas are damage to the body’s tissues caused by the pressure differences between internal air cavities (e.g., sinus cavities, ears, dental fillings, lungs, and digestive tract) and the surrounding tissue when the body moves to or from higher pressures. Barotrauma effects include pain, tearing or rupture of tissue, retarded breathing, disorientation, unconsciousness, and shock.

Arterial gas embolism occurs when the depressurization rate overpressurizes the lungs, forcing gas into the arterial circulation, which disperses it throughout the body. The onset of arterial gas embolism is usually sudden, dramatic, and life-threatening. At higher altitudes, even while a person is breathing pure oxygen, the arterial oxygen partial pressure falls to a level that cannot support consciousness. Above 62,000 feet, the ambient pressure is low enough that the water in the body begins to boil at normal body temperature and ebullism occurs. Symptoms include bubbles forming in the blood, eyes, and mouth; tissue swelling and hemorrhaging; impaired breathing and circulation; and death.

Acceleration injuries

During atmospheric flight phases, breaches of the cabin or ejection of the crew from the vehicle expose the crew to the aerodynamic effects of high-velocity airflows, or windblast, and acceleration loads. The effects of windblast vary with the density of the air and are proportional to the surface area exposed to the flow. The atmosphere can exert significant loads on exposed crewmembers even at high altitudes. During ejection, the body can be subjected to substantial loads from various sources (e.g., maneuvering loads, escape system-induced loads, windblast) and may experience torsional and shearing forces that produce internal tears. The compressive loads acting on the body can result in vertebral fractures and compress the chest and abdomen. Injuries can be produced by windblast, including petechial and subconjunctival hemorrhage, and flail. Flail injuries occur when inadequacy of body restraints for the vehicle's dynamic environment causes differential acceleration between the extremities and the torso, terminating at the range of motion limit or contact with surrounding structure. The effects of a load on the crew are determined by its direction, onset, magnitude, frequency, and duration. This information may be available from video, radar, modeling, and engineering analysis. Aircraft pilot ejection data are relevant for many conditions experienced by a spacecraft crewmember ejected from the crew cabin during atmospheric flight.

Crew Equipment Assessment

Crew equipment assessments focus on the utilization and performance of the individual crewmember seats, on crew protection and crew survival emergency equipment and systems, and on the analysis of each crew-vehicle interface. Data sources are audio and video recordings and the results of debris analysis. The as-found location of an equipment item can indicate when it was released from the vehicle. Because of their proximity to the crew, the condition and as-found locations of the seats, items worn by crewmembers, crew emergency and crew survival equipment and systems indicate the conditions experienced by the individual crewmembers during the mishap. Members of the crew survival investigation team should visually examine crew equipment for witness marks, thermal effects, materials effects, potential loads, hardware failures, and debris-debris impacts resulting from the mishap. The postmishap configuration of the equipment and systems, such as switch positions, provides insight into possible crew actions (e.g., activation of emergency breathing supplies, raft deployment, and activation of nitrogen purge). Analysis of the crew equipment and systems indicates whether individual crewmembers used or attempted to use the equipment and/or systems, how accessible the equipment was, and how well it performed. This analysis also provides insight into crew awareness of a hazardous condition and which hazardous conditions the crew experienced.

Analysis of the crew seat-vehicle interface derives the loading events experienced by the crew. The investigation of recovered seat debris provides insight into injuries resulting from loss of restraint. Injuries resulting from restraint failures include bracing and flail injuries, transections, fractures, disarticulations, dislocations, and amputations. Bracing injuries, usually noted on the lower legs and feet or lower arms and hands, are a result of inadequate upper-body restraint against the vehicle motion (e.g., tumbling, spinning). Bracing is a deliberate act by a conscious crewmember to counter loads imposed on them or to respond to ineffective or failed restraints. Flail produces fractures, dislocations, or total disarticulations. Transecting (or shearing) fractures of the vertebral column result when extremely high loads imposed on the crewmember react against the restraint in such a way that the restraint transects the body. Fractures, disarticulations, and dislocations may be caused by overloading of the seat structure or the loss of restraint. Fractures of the extremities are consistent with deceleration injury or aerodynamic flail. Amputations may result from impact, flail, or exposure to high pressures or inertial forces. They may not occur at a joint but may be coincident with a restraint.

Crew-worn or crew-donned equipment may cause injuries at the crew-equipment interface. Injuries can result when the weight of equipment under inertial loads is imposed on a crewmember by crew-worn or crew-donned protective equipment. The types of injuries include head and neck injury and mass augmentation injuries. Head injuries may result from the failure of helmets or head/neck devices to support the head and neck. Equipment worn or donned by a crewmember augments the crewmember's mass properties (such as center of gravity and moment of inertia), and this augmentation may exacerbate the loads imposed on the crewmember and result in injuries such as a neck injury to a crewmember wearing a portable breathing apparatus during an acceleration event.

Medical Forensics Assessment

Medical forensic assessments are sensitive in nature and encompass medical factors, types of injuries, autopsy, crew involvement, and mechanisms of crew injury and crew death. These assessments also include evaluation of the crew's awareness of and responses to timeline events, including any that were potentially lethal to the crew. Through review of medical and training records, autopsies, survivor examinations and interviews, and examination and analysis of data and physical evidence, the crew survival investigation team systematically creates and substantiates the mishap scenario for each crewmember. This assessment considers each crewmember's awareness, response, and involvement from the start to the end of the mishap, the mechanisms and sequence of injuries and/or death, and any conditions limiting the crewmember's awareness or response, including human physiological limits under mishap conditions. The team considers the mishap conditions, injury patterns, and other potentially lethal conditions relative to each of the crewmembers, and determines why some crewmembers sustained injuries and others did not, and why some crewmembers survived, or survived longer, while others did not. Detailed documentation of all injuries and medical conditions is important when assessing the safety of the spacecraft design and the effectiveness of the protective equipment.

The Crew Condition

The investigative team should develop the medical sequence of events by first differentiating between premishap, mishap, and postmishap contributors to the condition of the crew. It is possible that an event that occurred before the mishap may be relevant. So review preflight psychological evaluations and medical records for evidence of preexisting conditions, injuries, or diseases of crewmembers, their psychological state (e.g., stress, family events, sleep, significant emotional events), and each crewmember's performance during training and on previous missions, if applicable. Consider any conditions that might make a crewmember more sensitive to mission conditions, such as reduced sensory or motor capacities. Identify any injuries or illnesses the crewmember incurred before the flight that are relevant to the crewmember's circumstances. Determine the role, if any, that preflight conditions played in the mishap or in contributing to the crewmember's injuries or death.

For conditions occurring during the mission, assess the crewmember's workload, interactions, performance, and human factors issues immediately before and throughout the mission. Identify the roles and responsibilities of each of the crewmembers as well as any indications of their performance throughout the mission. Changes to mission timelines (e.g., sleep schedules, reprioritization of tasks, added activities such as extravehicular activities, isolation of the crew, and mission termination, extension, or delays) and off-nominal or contingency operations or system failures can affect the crew. The duration of the flight may also be a factor because of the short- and long-term effects of microgravity on body functions and capabilities; consider the consequences of bone loss and morphology changes, immune system suppression, intracranial and eye pressure changes, and psychological alterations. Also, injuries may have occurred during the mission that impair crew performance during the mishap.

Payload specialist Ilan Ramon (left), astronauts Laurel B. Clark, mission specialist, and Michael P. Anderson, payload commander, participate in mission training in one of the high fidelity trainers/mockups in the Space Vehicle Mockup Facility at the Johnson Space Center (JSC). The three, attired in training versions of the full-pressure launch and entry suit, are seated on the middeck for an emergency egress training session. Ramon represents the Israeli Space Agency.

Next, assess all of the areas mentioned earlier, including human factors and psychological, physiological, and environmental conditions, but only the findings specific to the time of the mishap event. For instance, if a crewmember was incapacitated by motion sickness, this may have affected their actions. Evaluate the crewmember's exposure to potential environmental conditions resulting from the mishap, in light of their injuries. Mishaps occurring in a microgravity environment make the analysis of fluid splatter patterns more challenging because the fluid may have floated free or pooled on a surface, then been transferred when conditions changed. In microgravity, blood and other fluids can cross-contaminate crewmembers. DNA analysis and blood serology may be needed to trace blood to the source crewmember. After a mishap, the contributors to the crew condition are exposure (which could lead to decomposition or artifacts), environment (e.g., weather, temperature, humidity, season), and predation (causing, for example, alteration of evidence due to insects, mammals and plant life), or sometimes dispersal of remains. Environmental conditions influence the effects of delayed recovery. Evidence can be lost and artificial evidence introduced if a significant amount of time passes before remains are recovered. Awareness of postmishap contributing factors allows the team to rule out any postmishap injuries.

Medical Examinations and Autopsies

The medical examinations of the crewmembers should follow a systematic and well-organized plan. The objectives of the pathology inquiry are the diagnosis of preexisting disease or injury conditions, documentation of all injuries and analysis of the injury pathogenesis, and cataloging all observations, to substantiate the mishap cause and sequence. During the medical examination of a survivor or autopsy of human remains, record all injuries and document all evidence that can be used to identify potential sources of injury and to sequence the injuries. Many methods are available, such as thorough descriptions, photographs, diagrams, sketches, X-rays, MRI, and CT, to reveal various aspects of the injuries. Full-body radiographs with special emphasis on the head, neck, and extremities are useful in the clarification of injury mechanisms, particularly when the radiographs are correlated with photographs and diagrams. Describe and interpret all observed injuries in sufficient detail to identify possible causes in the context of the mishap, the time and/or sequence of injury, and the nature of the injurious event, and to differentiate mishap injuries from postmishap injuries. The pathologist performing the postmortem exam should be familiar with the spacecraft, the mission phase of the mishap, the environmental factors that were present from the time of the mishap until the time of the autopsy, and any handling errors.

When you are interpreting medical evidence, relationships are important. These include the locations and conditions of the crew equipment relative to the crewmembers or remains, of the crew relative to hardware, and of injured crewmembers and their injuries relative to other crewmembers. It is ideal if all of the crew-worn or crew-protective equipment on the crewmember is documented before it is removed, or if it is left in place until the time of the autopsy. Assess whether any equipment limited the crewmember's ability to respond (e.g., by impairing vision) or shows evidence of an impact that was translated to the crewmember. When analyzing the location of crewmembers relative to that of hardware, consider the events that resulted in the final configuration and identify supporting evidence found during the medical examination or autopsy. An example of an important relationship would be a fire extinguisher or breathing mask located next to a crewmember exhibiting evidence of smoke inhalation. Patterns of injuries may define events and injury mechanisms. Document each crewmember's injury patterns, and then compare them to the injury patterns of the other crewmembers. A suggested technique is mapping the injuries onto virtual crewmembers. The virtual crew can be placed into a virtual model of the spacecraft to aid in visualizing injury patterns relative to potential sources.

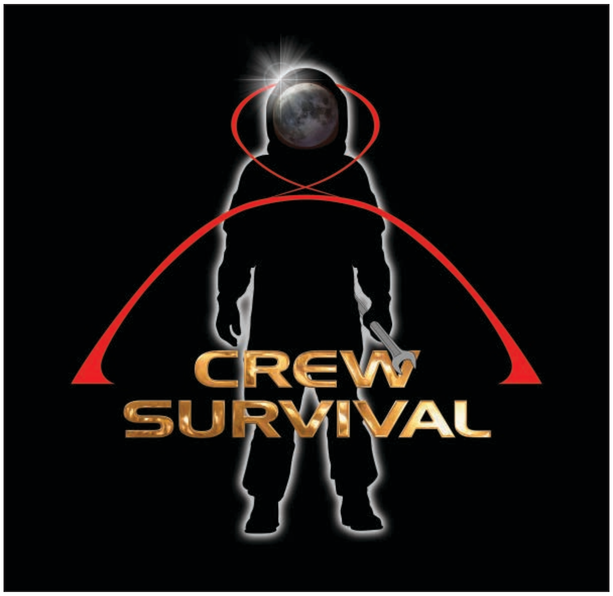
Mechanisms of Injuries

Typical causes of crew injury are categorized as impact, loads, pressure, toxicological, thermal, and those from other environmental causes. This is not a comprehensive list, and a mishap may not involve all of these mechanisms of crew injury. To determine the mechanisms of crew injury, identify the crew's injury patterns, reconstruct the mishap scenario, and correlate the injuries to a cause. This is an iterative process between examining the vehicle for evidence of interaction with the crew and mapping any interaction to a crew response or injury, and examining the crewmembers and correlating the source of an injury with the physical evidence on the vehicle or with analytical results. During this iterative process, eliminate postmishap injuries from consideration. The medical interpretations must be consistent with the circumstances of the mishap and findings from other lines of the investigation.

Mechanisms of Survival

The goal of the crew survival investigation is to identify ways to eliminate the mechanisms of injury and death and enhance crew survival. The injury potential must be reduced to a level that would not impede life-critical actions. Life-critical actions are actions the crew must take to protect themselves from serious harm or death (e.g., being able to release their harness and exit a sinking capsule). Once the mechanisms of injury and death are identified, the team can identify ways to prevent or mitigate them. Items that may be needed for crew survival include these:

- Energy-attenuation systems to maintain loads within a tolerable range
- A life-compatible environment (i.e., pressure, breathable atmosphere, temperature, and humidity that are compatible with life)
- Adequate post-event factors such as escape paths, removal of fire or toxic event byproducts, secondary flotation methods, and availability of portable breathing apparatus



The Crew Survivability logo.

- Structural integrity of the crew cabin sufficient to preclude intrusion
- Adequate head and body restraint
- Clear translation paths and control of stowage
- Elimination of contact surfaces or rigid structures in close proximity to a seated crew
- Elimination of hazards in the crew cabin such as sharp edges, surfaces exceeding touch temperatures, or pinch points
- Protective measures that effectively mitigate the hazards without inhibiting mobility or the senses

Ultimately, the purpose of the crew survival investigation is to identify the successes and failures of the crew protective equipment and systems in order to make recommendations for future spacecraft. This is accomplished by identifying the sequence of events; the attempted, unsuccessful, and successful crew actions; the performance of the crew protective equipment and systems; and the resulting outcome for each crewmember. If equipment or systems failed to provide a habitable environment for the crew for the duration of the mishap, the crew survival investigation team must understand why they failed. To answer this question, they must determine whether the failure occurred within certified capabilities or if the conditions exceeded the design specifications. If the conditions exceeded the design specifications, they should attempt to determine the amount by which the design specifications were exceeded so that they can recommend changes to improve survival in a future spacecraft mishap.

Crew Survival Investigation — Process of Discovery

The crew survival investigation is an iterative process of discovery. By examining the hardware and cross-matching the crew injuries to the hardware, the crew survival investigation team substantiates the mishap scenario. Once the mishap scenario is understood, the crew survival investigation team can recommend changes to spacecraft design, equipment, or operations to improve crew survivability. These are the lessons learned that improve the safety of human space flight.

Section 6 – Appendix

Abbreviations and Acronyms

Selected Readings

Recognition and Acknowledgments

Contributors’ Biographies

Index

Abbreviations and Acronyms

ACES	advanced crew escape suit
AFB	Air Force Base
AFIP	Armed Forces Institute of Pathology
AFMES	Armed Forces Medical Examiner System
AsMA	Aerospace Medicine Association
ATA	atmosphere absolute
BRC	Biodynamic Research Corporation
CACO	casualty assistance calls officer
CAIB	Columbia Accident Investigation Board
CAP	contingency action plan
CAPCOM	capsule communicator
CDR	commander
CE	Catastrophic Event
CEE	crew egress and escape
CES	crew escape system
CFS	chief flight surgeon
CISD	critical incident stress debriefing
CMCE	Crew Module Catastrophic Event
CMG	Contingency Medical Group
CSI	crew survival investigation
CSWG	Crew Survival Working Group
CT	computed tomography
CTF	Columbia Task Force
DDMS	Department of Defense Manned Space Flight Program Support Office
DNA	deoxyribonucleic acid
DOD	Department of Defense
EAP	employee assistance program
ECLSS	environmental control and life support system
EI	entry interface
EMS	emergency medical services
EPA	Environmental Protection Agency
ERT	Evidence Response Team
ET	external tank
EVA	extravehicular activity
FACA	Federal Advisory Committee Act
FBI	Federal Bureau of Investigation
FEMA	Federal Emergency Management Agency
FOIA	Freedom of Information Act
G	acceleration acting on objects or crewmembers, in units of the Earth's gravitational acceleration
g	acceleration due to gravity (1g = Earth gravity)
GMT	Greenwich Mean Time
GPC	general purpose computer
GPS	global positioning system
ISS	International Space Station
ITAR	International Traffic in Arms Regulations
JSC	Johnson Space Center
KSC	Kennedy Space Center
LOC	loss of control
LOS	loss of signal
MBF	manned balloon flight
MCC	Mission Control Center
MCF	million cubic feet
MEIDEX	Mediterranean-Israeli Dust Experiment
MILA	Merritt Island Launch Annex
MIT	Mishap Investigation Team
MMACS	maintenance, mechanics, and crew systems
MMT	Mission Management Team
MPCV	Multi-Purpose Crew Vehicle
MRI	magnetic resonance imaging
MS	mission specialist
NTSB	National Transportation Safety Board
OAFME	Office of the Armed Forces Medical Examiner
ORSAT	object reentry survival analysis tool
PLT	pilot
PLBD	payload bay doors
POC	point of contact
PPE	personal protective equipment
PS	payload specialist
SCSIIT	Spacecraft Crew Survival Integrated Investigation Team
SLF	shuttle landing facility
SLSD	Space Life Sciences Directorate
SO	space operations
STS	Space Transportation System
TAEM	terminal area energy management
TD	total dispersal
TPS	Thermal Protection System
UTC	Coordinated Universal Time
VITT	Vehicle Integration Test Team

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There are many others whose names are not listed here who also contributed to the Columbia crewmember search, recovery, and investigation efforts. To all who helped—your willingness to contribute to this honorable effort with a higher purpose will always be inspiring and humbling. Out of tragedy came greatness.

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Dr. Charles earned his BS in Biophysics at The Ohio State University and his Doctorate in Physiology and Biophysics at the University of Kentucky. He has been at the Johnson Space Center since 1983, where he investigated the cardiovascular effects of space flight on Space Shuttle astronauts and on crewmembers of the Russian space station *Mir*. He was Mission Scientist for the NASA research on American astronauts on *Mir*, on John Glenn's Space Shuttle flight STS-95 and on STS-107, Columbia's last mission in January 2003. He co-chaired the 18th "Humans in Space Symposium" of the International Academy of Astronautics in Houston, Texas, in 2011. Dr. Charles is now the chief of the International Science Office of NASA's Human Research Program and leads space life sciences planning for the joint US/Russian one-year mission on ISS. He is a Fellow of the Aerospace Medical Association and a Full Member of the International Academy of Astronautics, has published over 60 scientific articles, and has received several professional awards.

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Dr. Gilmore has been a flight surgeon with NASA since 2002 and has been a crew surgeon for multiple Space Shuttle and International Space Station missions. He is also assigned to support the medical operations contingency group providing contingency planning, training, and mission support. Dr. Gilmore studied Chemistry at Grinnell College prior to attending Wake Forest Bowman Gray School of Medicine. He completed clinical residencies in Emergency Medicine and Aerospace Medicine at Wright State University and the University of Texas Medical Branch respectively. Dr. Gilmore is board certified by the American Board of Emergency Medicine (ABEM).

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Loss of Signal, presents the aeromedical lessons learned from the Columbia accident that will result in enhanced crew safety and survival on human space flight missions. As we embark on the development of new spacefaring vehicles through both government and commercial efforts, the NASA Johnson Space Center Human Health and Performance Directorate is continuing to make this information available to a wider audience engaged in the design and development of future space vehicles. Loss of Signal summarizes and consolidates the aeromedical impacts of the Columbia mishap process—the response, recovery, identification, investigative studies, medical and legal forensic analysis, and future preparation that are needed to respond to spacecraft mishaps. The goal of this book is to provide an account of the aeromedical aspects of the Columbia accident and the investigation that followed, and to encourage aerospace medical specialists to continue to capture information, learn from it, and improve procedures and spacecraft designs for the safety of future crews.

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