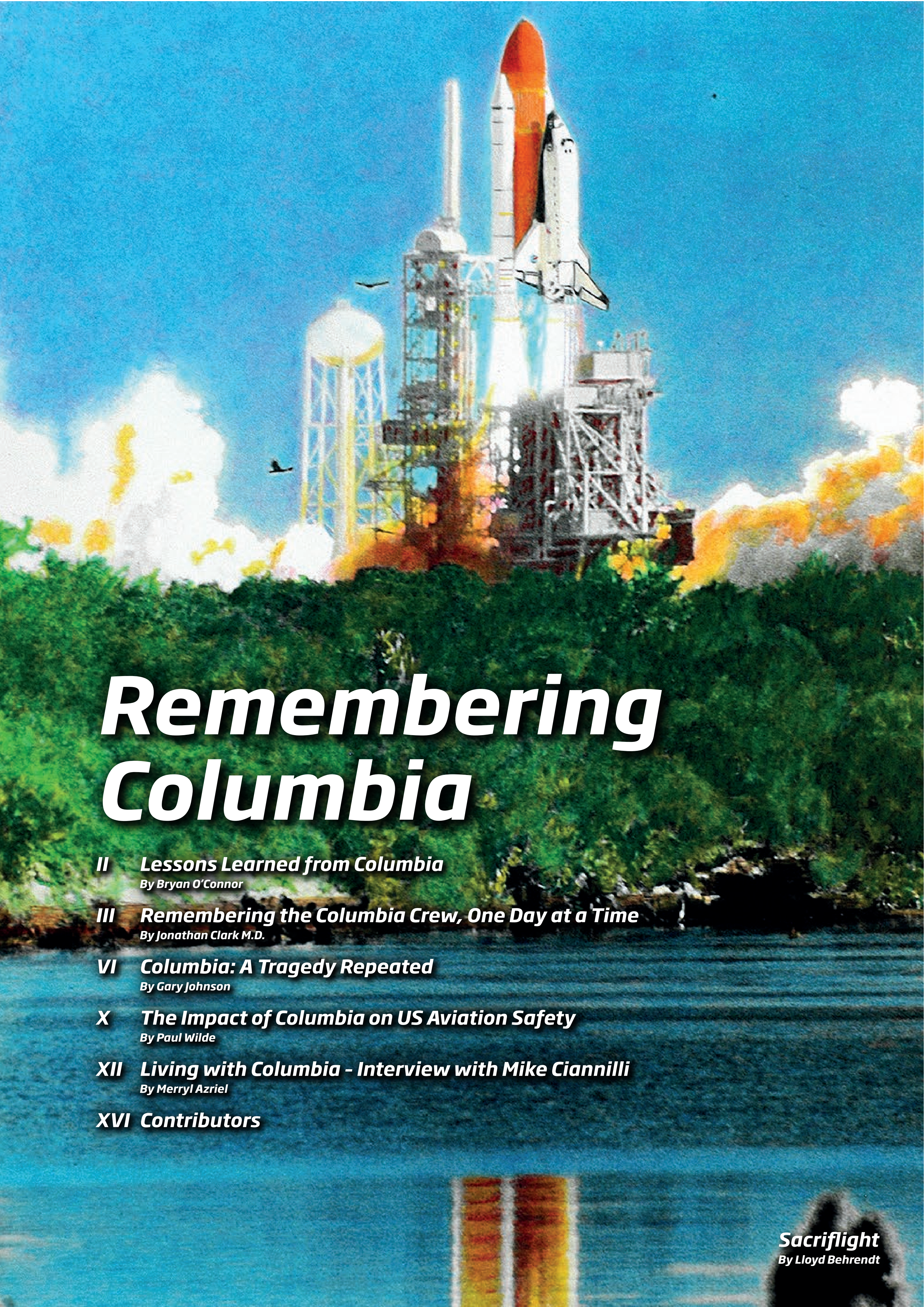


Remembering Columbia

Sacriflight
By Lloyd Behrendt

Lessons Learned from Columbia

By Bryan O'Connor

This photograph was taken aboard Columbia during STS-107; it was developed after the crew's death from film recovered in the wreckage.
From top left: David M. Brown, William C. McCool, and Michael P. Anderson.
From bottom left: Kalpana Chawla, Rick D. Husband, Laurel B. Clark, and Ilan Ramon.
Credits: NASA

It is with a cautionary note that I propose some of my personal lessons learned from the tragic loss of the crew of Space Shuttle Columbia. I have spent ten years comparing stories with others who were part of or close to the Shuttle program in the years leading up to the loss of Columbia and her crew... so I admit to being less than a reliable independent eye witness. That said, I will offer a few lessons that have driven me nearly every day since that sad Saturday in February 2003 in my jobs as a spaceflight safety advisor both in and out of NASA. They fit into three distinct but related categories: Flight Test, Complacency, and Checks and Balance.

Flight Test

Shortly after the last Shuttle flight, STS-135 in July, 2011, I shared a short elevator ride with one of the world's best test pilots, Maj. Gen. Joe Engle. I asked him, "Joe, could you tell me what you believe was the biggest lesson learned from the Space Shuttle Program?" Without pause, he answered: "***You don't know what you've got 'til you fly it!***"

When I hear people talk about flying a very short flight test program with the next human spaceflight system development, and then declaring it "operational," I cringe. The fact is that the Shuttle never was purely "operational." In retrospect, it was a 30-plus year flight test program during which NASA performed a variety of operational mission objectives. It would have been good for us to periodically remind ourselves and our stakeholders of that fact before, not just after the big accidents.

Complacency

"The greatest of faults is to be conscious of none."

Thomas Carlyle (1795 - 1881)

Success, or more honestly, the perception of success, fosters complacency. And we all know what comes of complacency. To be sure, through the 1990s the Shuttle program had experienced a long run of "successful" missions. We were bringing back the crews, we were accomplishing the mission objectives, and managing the cost and schedule relatively well considering the complexity of the program. Most importantly, we believed we were putting the right attention on the decreasing number of technical issues we experienced in flight. But when, after the accident, we donned the corrective lenses of the mishap analyst, it became clear that we had been fooling ourselves in some catastrophic ways. The hardware had been talking to us, and what we had believed at the time to be rational risk management looked in retrospect more like rationalization of inconvenient warnings. It was not a coincidence that we found ourselves under a great deal of pressure to meet impossible schedules and to cut costs even to the point of planning for privatization.

Checks and Balance

"Devil's Advocate (Roman Catholic Church): An official whose duty is to point out [to the Pope] defects in the evidence upon which a demand for beatification or canonization rests... [in order to] bring out the whole truth."

Webster's International English Dictionary, 2nd Edition

An enlightened high performing organization includes humility as a critical criterion for promoting its best and brightest to leadership positions. And to aid these humble leaders, it espouses some form of devil's advocacy as an important component of its high stakes decision-making. After the Columbia loss, NASA learned – or re-learned – that a competent, adequately-resourced technical authority and a respected safety advisor provide necessary checks and balance for the decision maker as he/she strives to "bring out the whole truth" of the inevitable technical challenges.

When all is said and done, NASA and the aerospace community learned much from the Columbia loss, but I believe most of the lessons fall into one or more of the three categories I've listed. They should be continuous considerations for any future human spaceflight endeavor.

Remembering the Columbia Crew, One Day at a Time

By Jonathan Clark M.D.

Dear Rick, Willie, Mike, KC, Dave, Laurel, and Ilan,

I can't believe it's been ten years since I last saw you guys. We really miss you a lot. A day doesn't go by without thinking of you all. At first it was mostly tears, but now it's about happier thoughts, all the good times we had. You would be amazed at how all of us pulled together after losing you all. It was hard on everyone, families and friends. We all changed forever, but I like to think that overall, it's been in a good way. I have to confess that I feel responsible for what happened to you all. I worked a shift in Mission Control for STS-107 the week before you were coming home and learned about the foam strike and the debate about what it might mean. I should have done something.

Laurel, after the accident our son Iain asked why you didn't bail out. He knew you had done a lot of parachute jumps and all the crew had the right equipment and had practiced it before. I told him that you were too high and going too fast and that it probably wouldn't work out. Then he said he was going to become a scientist and invent a time machine and go back and warn you all. I realized then that I had to focus the rest of my career making it safer for those following in your footsteps.

There was a big investigation by the Columbia Accident Investigation Board (CAIB) and they did a really great job finding out what happened and getting the Shuttle back to flying safer than it's ever been. NASA had wanted the section done by the Crew Survival Working Group to be removed from the CAIB report because they thought the Columbia families wouldn't like it. We all got together and discussed it and sent the CAIB a note, and here is part of what it said:

Jonathan Clark, NASA flight surgeon at the time of Columbia, his wife Laurel, STS-107 mission specialist, and their son Iain. Courtesy of Jonathan Clark

Laurel Blair Salton Clark
Mission Specialist

Laurel achieved an undergraduate degree in zoology before earning her doctorate of medicine. She joined the Navy as a submarine and diving medical officer, eventually becoming a Naval Flight Surgeon before serving with the Marines as Group Flight Surgeon. She became an astronaut candidate in 1996; STS-107 was her first spaceflight mission. The launch of Columbia took place just six weeks after Laurel's whole family survived a crash that destroyed their family plane. Laurel was never one to sidestep a challenge, as her husband related after her death: "One of Laurel's favorite quotes was: "A ship in harbor is safe – but that is not what ships are for."

William "Willie" Cameron McCool
Pilot

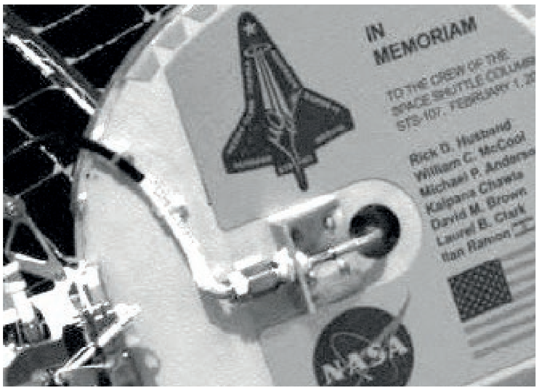
A Navy man before joining NASA, Willie attended the Naval Academy, accumulating degrees in applied science, computer science, and aeronautical engineering, even as he deployed as a Navy pilot, and later, test pilot. He was selected as an astronaut in 1996. Unlike many astronauts, Willie loved exercising in space. "I'll tell you, there's nothing better than listening to a good album and looking out the windows and watching the world go by while you pedal on the bike," he said while aboard Columbia. STS-107 was his only space mission.

David McDowell Brown
Mission Specialist

An athletic man, David was a four year collegiate varsity gymnast and circus acrobat, unicyclist, and stilt walker, before graduating with a degree in biology and achieving his doctorate in medicine. He joined the Navy as a flight surgeon. In 1988 he became the first flight surgeon in a decade to be selected for pilot training. David began astronaut training in 1996. STS-107 was his first and only mission. Before taking off, he told his girlfriend what to do if something went wrong: "I want you to find that person that made the mistake, and I want you to tell that person that I hold no animosity. I died doing what I loved."

Kalpana "KC" Chawla
Mission Specialist

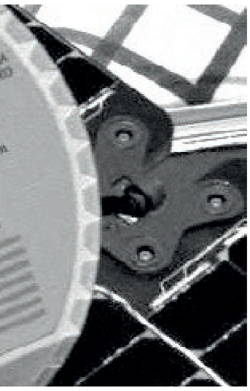
Born in Karnal, India, KC moved to the United States after undergraduate school, proceeding to obtain her doctorate in aeronautical engineering. She began her career at NASA Ames, researching computational fluid dynamics relating to aircraft air flows. She was selected as an astronaut candidate in 1995. Her first flight took place in 1996 aboard Columbia STS-87 as mission specialist and prime robotic arm operator. KC loved flying and was a licensed pilot and flight instructor of commercial land and sea planes and gliders. She was an inspiration to young girls in her birth country, where her achievements were much celebrated as the first Indian-born woman to fly in space.



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 fundamental 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.

In 2004 NASA created a follow on group to look at crew survival issues, which was called the Spacecraft Crew Survival Integrated Investigation Team, and I was a member. We looked at all the space mishaps including Columbia, and really came up with a better understanding of how to make it safer for human spaceflight. In 2008 we published our report "Columbia Crew Survival Investigation Report." I've also been involved with the International Association for the Advancement of Space Safety, which was created in 2004, and they are dedicated to making it safer to fly in space.

In 2009 I wrote an article "Crew Survival Lessons Learned from the Columbia Mishap" and kept thinking about what our son Iain had said, "Why didn't the crew bail out from the Shuttle?" Based on what we had learned from the Columbia mishap, the final breakup was below 140,000 feet (42,672m). In 2009 I joined a team that wanted to expand the stratospheric bailout envelope above 100,000 feet (30,480m), which



A memorial plaque mounted on the back of the high gain antenna on the Mars rover Spirit. Credits: NASA

was what the Shuttle Advanced Crew Escape Suit (ACES) was certified to. The mission was called Red Bull Stratos. It was an aggressive flight test program, with many aerospace experts and an international team.

We built a pressurized capsule, used a pressure suit based on the Shuttle ACES suit, and used large helium balloons to get to the stratosphere. We tested in the vertical wind tunnel, vacuum chamber, thermal-vacuum chamber, and made many test jumps before setting off to the stratosphere. We learned all we could from the manned stratospheric balloon flights conducted by the United States and Russia in the 1950s and 1960s that supported their impending manned space programs. We studied the US Navy Strato-Lab mission, which tested the Project Mercury pressure suit, the US Air Force Project Excelsior stratospheric parachute jumps, which showed that a jump from 102,800 feet (31,333m) was survivable, and the Russian high altitude balloon parachute program "Volga" which used a pressurized capsule modeled after the Vostok spacecraft. We developed new medical procedures to deal with the hazards of space, like exposure to vacuum.

After two unmanned flights to test the balloon systems, in 2012 we flew three manned flights into the stratosphere, and on 14 October 2012, 65 years to the day after Chuck Yeager broke the sound barrier in the X-1, we successfully accomplished the highest stratospheric freefall parachute jump from 128,100 feet (39,045m), achieving human supersonic flight without an aircraft at 837 miles per hour (374.3 meters/second), or Mach 1.27. Sonic booms were heard on the ground from a human breaking the sound barrier in freefall. We never gave up, despite the risk, to show that anything is possible if you believe it can be done.

Rick, Willie, Mike, KC, Dave, Laurel, and Ilan we miss you all so much, but it warms our hearts to know that your legacy will endure in making it safer for the next generation of space flyers. Our sorrow and grief will pass, and we will meet up with you on the path ahead.

Michael P. Anderson
Payload Commander

A physicist, Michael began his career as an Air Force Communication Electronics Officer. He rose to Director of Information System Maintenance before taking up pilot training and becoming an aircraft commander and instructor pilot. He was selected as an astronaut candidate in 1994. His first mission was STS-89, the eighth Shuttle-Mir docking mission. His second and final flight was aboard STS-107. Before his flight, Michael's minister asked him what would happen if the shuttle were to not make it back. "Don't worry about me," he responded, "I'm just going higher."

Rick Douglas Husband
Commander

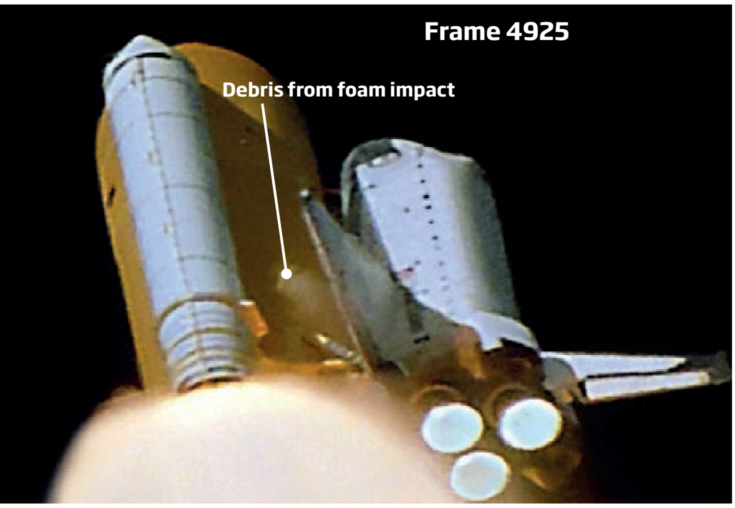
A mechanical engineer by education, Rick joined the Air Force and became a test pilot before being selected as an astronaut candidate in 1994. After completing his initial training, Rick served as Chief of Safety for the Astronaut Office. He first flew to space aboard Discovery STS-96 in May 1999 , the first Shuttle mission to dock with the International Space Station. His second space mission was STS-107. For Rick, being an astronaut was a lifelong dream, and he loved every minute of it.

Ilan Ramon
Payload Specialist

An Israeli-born citizen and son of Holocaust survivors, Ilan became a career fighter pilot in the Israeli Air Force, where he was known as the youngest pilot to participate in Operation Opera, the mission that destroyed the Iraqi nuclear reactor Osiraq. Ilan was selected as the first Israeli astronaut and began training with NASA in 1998. STS-107 was his only spaceflight. His diary was recovered from the wreckage of Columbia; on the last legible page of the journal, he wrote "I have become a man who lives and works in space."

Columbia: A Tragedy Repeated

By Gary Johnson



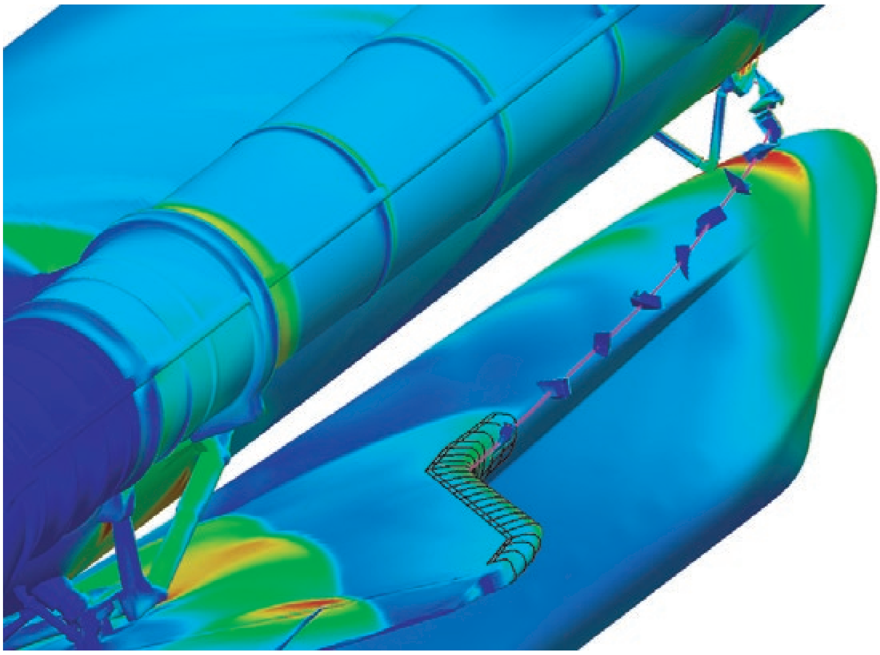
A color enhanced, de-blurred still frame of the foam strike, derived from video recording. Credits: NASA

The Space Shuttle Columbia STS-107 was launched on January 16, 2003 at 10:39 a.m. Eastern Standard Time. At 81.7 seconds after launch, when the Shuttle was at about 20,000m and traveling at Mach 2.46 (2,655km/h), a large piece of insulating foam came off the External Tank (ET) left bipod ramp area, close to where the orbiter attaches to the ET. The foam impacted under the leading edge of the left wing at 81.9 seconds. This incident was not seen by anyone on the ground or in the Kennedy Space Center (KSC) Firing Room or Johnson Space Center (JSC) Mission Control Center (MCC); there was no onboard indication to the crew. The impact was detected the next day during the detailed review of all launch camera photography that is conducted after every Shuttle launch. The analysis revealed that the debris was approximately 53-68cm long and 30-45cm wide, tumbling and moving at a relative velocity of 670-922km/h at the time of impact. Neither the crew nor MCC were aware that on flight day two an Air Force Command review of radar tracking data detected an object drifting away from the orbiter, that subsequent analysis suggested may have been related to the foam strike. On flight day eight, MCC emailed the crew that post-launch photo analysis showed External Tank foam had struck the orbiter's left wing during ascent. MCC stated there was "absolutely no concern for entry" because the phenomenon had been seen before. MCC also emailed a short video clip of the foam strike. Columbia continued its 16 day mission without further incident – until Entry Interface.

MCC stated there was "absolutely no concern for entry"

On-orbit Photo Request

On the second day of the mission, the Intercenter Photo Working Group Chair contacted the Shuttle Program Manager for Launch Integration at KSC to request imagery of



A trajectory analysis that used a computational fluid dynamics approach to determine the likely position and velocity histories of the foam. (Ref [1] p61) - Credits: NASA

Columbia's left wing on-orbit. The Program Manager agreed to explore the possibility – this was the first imagery request of the mission. A Debris Assessment Team (DAT) was formed with NASA and contractor engineers. DAT contractor engineers prompted a NASA Shuttle manager to make a second imagery request. The Department of Defense (DoD) Manned Space Flight Support Office began implementing the request, albeit with the assurance from MCC that this was merely information gathering, not a formal request for action. The first formal DAT meeting was held on January 21st, five days into the mission. Without additional on-orbit pictures, the DAT was restricted to using a mathematical modeling tool called Crater, that predicts the depth to which debris will penetrate a Thermal Protection System (TPS) tile. Crater was suitable for small debris impacts, on the order of 49cm^3 – versus 19,665cm^3, the estimated size of the bipod ramp foam. Crater was classified as a "conservative" tool based on its projections of ice projectile damage to RCC turning out to be more severe than that achieved experimentally. Because foam is less dense than ice, the DAT used a *qualitative* extrapolation of the test data and *engineering judgment* that a foam impact angle of up to 21° would not penetrate the RCC.

The assumptions and uncertainty incorporated in this analysis were never fully presented to the Mission Management Team (MMT). The DAT assigned the NASA Co-Chair to pursue a request for imagery of the vehicle on-orbit – constituting the third request for imagery – by going through the Engineering department rather than through Shuttle Program Managers. The imaging request was viewed by Shuttle Program Managers as a non-critical engineering desire rather than a critical operational need. Seven days into the mission, a NASA Headquarters Safety and Mission Assurance (S&MA) manager called a JSC S&MA manager for the Shuttle Safety Program and the Associate Administrator (AA) for S&MA, to discuss a potential DoD imaging request. The JSC manager for Shuttle Safety program said he was told this was an "in-family" event – meaning it was normal and nothing to worry about. The AA for S&MA stated that he would defer to Shuttle management in handling such a request. Despite two safety officials being contacted, safety personnel took no actions to obtain imagery. After discussion with other MMT members, the Shuttle Program Manager cancelled the DoD imagery request. The MMT had concluded this was not a safety-of-flight issue, apparently confusing the notion of foam posing an "acceptable risk" with foam not being a "safety-of-flight" issue. MMT members were making critical decisions about TPS damage tolerance based on little or no knowledge.

A frame from a tape recording taken by the crew 4 minutes before the breakup. Credits: NASA

Columbia reentered the atmosphere with a breach in the reinforced left wing leading edge

Sequence of Reentry Events

Columbia reentered the atmosphere with a breach in the Reinforced Carbon-Carbon (RCC) left wing leading edge near Panel 8. This breach allowed super-heated air, estimated to be about 2,760°C, to penetrate behind the TPS, destroying the insulation that protected the leading edge support structure and melting the aluminum wing spar. This resulted in thermal degradation of structural properties of the left wing. At Entry Interface (EI) plus 555 seconds, video from the ground shows pieces of material shedding from the orbiter, which continued to fly its pre-planned flight profile. Later, over the Dallas-Fort Worth, Texas area at about 60,960m, the increasing aerodynamic forces caused catastrophic damage to the left wing. At EI+613s, when the super-heated air had penetrated to the outside of the left wheel well, and destroyed the four hydraulic sensor electrical cables, controllers on the ground saw the first anomalies in telemetry data. At EI+727s, Mission Control noted an increase in left wheel well hydraulic line temperatures. At EI+790s, the two left main gear outboard tire pressure sensors began trending upward, then off-scale low. At EI+834s, a sharp change in the rolling tendency of the orbiter occurred along with additional shedding of debris. In an attempt to maintain attitude control, the orbiter responded with a sharp change in aileron trim, likely due to wing deformation. At EI+917s, the data

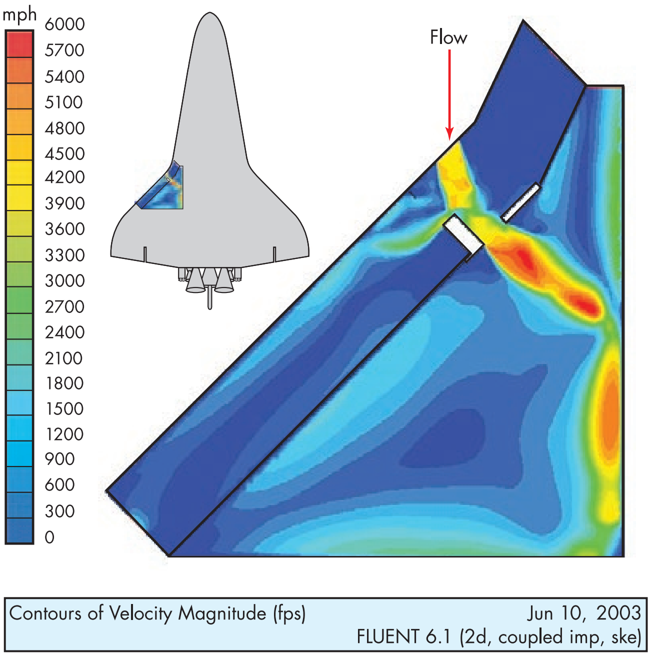
The shuttle flight control room in Houston's Mission Control Center at JSC right after flight controllers lost contact with the Space Shuttle Columbia. Credits: NASA

According to CAIB, destruction of the crew module took place over a period of 24 seconds, beginning at an altitude of approximately 42,672m and ending at 32,000m. Credits: NASA

showed a significant increase in positive roll and negative yaw, an indication of increased drag on and lift from the damaged left wing. The flight control system attempted to compensate for this increased left yaw at EI+921s by firing two aft right yaw Reaction Control System (RCS) jets continuously. By EI+927s, the third RCS yaw jet began firing continuously and at EI+928s the fourth and last right yaw RCS jet began firing continuously. It is probable that hydraulic pressure to the aero control surfaces was lost at EI+928s when hot plasma burned through all four hydraulic lines in the area of the left wheel well. This loss of control and beginning of orbiter pitch-up marks the transition from a controlled glide to an uncontrolled ballistic entry with orbiter aero-thermal breakup at EI+970s.

Failure of the crew module resulted from the thermal degradation of structural properties, which resulted in a rapid catastrophic structural breakdown rather than an instantaneous explosive failure. Separation of the crew module assembly from the rest of the orbiter likely occurred at the interface with the payload bay. The crew module, pressurized compartment, and outer forebody separated at EI+1004s. Debris assessment indicates that cabin depressurization probably occurred when the lower cabin structure impacted the forebody structure. Increasing aero-thermal loads resulted in the total destruction of the crew module and forebody by EI+1021s. From data and analysis it appears that the destruction of the crew module took place over a period of 24 seconds, beginning at an altitude of approximately 42,672m and ending at 32,000m. The death of the crew was due to blunt force trauma and hypoxia (Ref **[1]** pp 70-77; **[2]** pp 1-63, 72).

Death of the crew was due to blunt force trauma and hypoxia



Computational fluid dynamics analysis of the speed of the superheated air as it entered the breach in RCC panel 8 and travels through the wing leading edge spar. The darkest red color indicates speeds of over 6,400 km/h; temperatures likely exceeded 2,760 degrees Celsius (Ref [1] p69) - Credits: NASA

The Aftermath

NASA commissioned the Columbia Accident Investigation Board (CAIB) to "conduct a thorough review of both the technical and the organizational causes of the loss of the Space Shuttle Columbia and her crew on February 1, 2003." To capture lessons learned for future vehicle design, the Space Shuttle Program (SSP) commissioned the Spacecraft Crew Survival Integrated Investigation Team (SCSITT). "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," (Ref **[2]** p xix).

"The physical cause of the loss of Columbia and its crew was a breach in the Thermal Protection System on the leading edge of the left wing, caused by a piece of insulating foam," CAIB reported. CAIB found that the design of the orbiter left no possibility for a crew to survive given the resulting conditions. Once the breach occurred, the crew's fate was sealed.

But there were plenty of opportunities before the breach occurred to have prevented this tragedy. CAIB cited "the organizational causes of this accident," stretching back before the Shuttle program even began: "original compromises that were required to gain approval for the Shuttle, subsequent years of resource constraints, fluctuating priorities, schedule pressures, mischaracterization of the Shuttle as operational rather than developmental, and lack of an agreed national vision for human space flight." CAIB particularly called out a NASA culture that accepted mission success over engineering understanding, the stifling of differences of opinion, and evolution of an informal chain of command (Ref **[1]**, p 9).

The same organizational causes were cited with reference to the Challenger accident. "By the eve of the Columbia accident, institutional practices that were in effect at the time of the Challenger accident – such as inadequate concern over deviations from expected performance, a silent safety program, and schedule pressure – had returned to NASA," (Ref **[1]**, p 101). Sally Ride, who was on both the Rogers Commission Challenger ▶▶

investigation and the Columbia Accident Investigation Board, stated she was surprised at how similar the cause factors were for both accidents. The tile losses went directly against the Space Shuttle's original design requirements that precluded foam-shedding by the External Tank. Engineers stated that had they known in advance that the ET was going to produce the debris shower that occurred during Columbia's first launch in 1981, they would have had a difficult time clearing it for flight. As we now know, from 1981 until the accident there was ET foam shedding to various degrees on every flight (Ref **[1]** p 122). The CAIB noted that while there is a process for conducting hazard analysis when the system is first designed, and a process for re-evaluating them when a design is changed or a component is replaced, no process addressed the need to update a hazard analysis when anomalies occur.

The CAIB identified 14 In-Flight Anomalies (IFAs) that had significant TPS damage or major foam loss. "Space Shuttle Program personnel knew that monitoring of tile damage was inadequate and that clear trends could be more readily identified if monitoring was improved, but no such improvements were made," CAIB stated. The process for closing IFAs was not well documented and appeared to vary. Had the correct information been available, it may have led to a concern by NASA management and engineering about ascent debris damaging RCC (Ref **[1]**; **[3]**).

A view of Columbia taken at approximately 7:57 a.m. CST upon reentry as it passed by the Starfire Optical Range at Kirtland Air Force Base, New Mexico. Note debris coming from the left wing (bottom). Credits: SOR/NASA

There were plenty of opportunities to prevent this tragedy

Space Shuttle Return to Flight

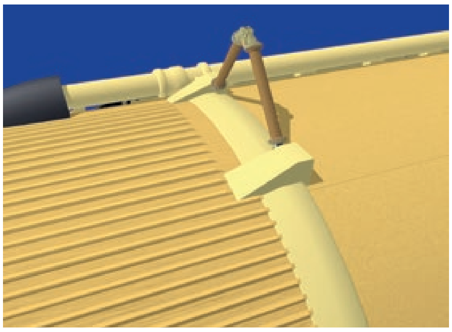
The Space Shuttle was grounded following the loss of Columbia and did not return to flight until July 26, 2005. In the intervening two and a half years, the ET TPS was redesigned and capabilities for detecting an impact were installed: video cameras on the solid rocket boosters and ET feedline, high speed cameras at the launch site, aircraft mounted cameras and radar, and an impact sensor mounted on the backside of the wing's RCC and nose cap. The crew of STS-114 was instructed to inspect their vehicle for damage and equipped with a limited repair kit to deal with the damage if they found it.

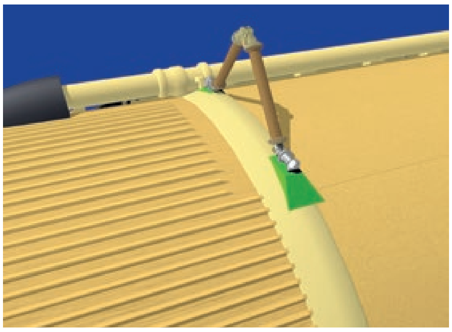
Meanwhile, NASA was working on its safety organization. The agency established the NASA Engineering Safety Center (NESC) at the Langley Research Center, charged with providing independent engineering safety assessments and testing, and funded by the Headquarters Office of Safety and Mission Assurance to assure independence (Ref **[5]**, p xxiv). A Chief Safety Officer for Space Shuttle was established, and S&MA began using analytical tools for risk characterization and trade studies. S&MA developed the capability to support real-time operations and for rapid team response to significant events or anomalies, as well as detailed Shuttle Probabilistic Risk Assessment models. S&MA and the SSP made a concerted effort to maintain and continually improve the risk-based decision making process. This effort was carried out through the end of the Space Shuttle Program and in that time avoided the decline and atrophy that occurred post-Challenger (Ref **[4]**).

References

[1] Columbia Accident Investigation Board, Report Volume 1, August 2003.
[2] NASA/SP-2008-565 "Columbia Crew Survival Investigation Report".
[3] NASA JSC Safety and Mission Assurance Qualification Training Program, Columbia Case Study Course No. BA-601, by Gary W. Johnson/SAIC, February 2008.
[4] JS-2011-025 "JSC Safety and Mission Assurance Space Shuttle Program Legacy Report", October 18, 2011.
[5] NASA's Implementation Plan for Space Shuttle Return to Flight and Beyond, Volume 1, Revision 1.1, November 20, 2003.

Left: the External Tank's bipod fittings covered by foam ramps, as flown on the Space Shuttle Columbia. Center and right: the redesigned fitting. Credits: Lockheed Martin/NASA Michoud





The Impact of Columbia on US Aviation Safety

By Paul D. Wilde, Ph.D., P.E

Columbia changed my personal and professional life dramatically. The morning of the accident a fellow Federal Aviation Administration (FAA) employee called me from the Cape; he said the orbiter was 30 minutes overdue and suggested I pack my bags. Within a week I was in Houston, meeting Admiral Gehman and the rest of the Columbia Accident Investigation Board (CAIB) members.

As the leader of the flight safety analysis team for the Office of Commercial Space Transportation, I was one of two FAA employees selected as an investigator on the Independent Analysis Team (IAT). The CAIB put so much value on independent analyses that we had an IAT inside the CAIB, which was itself an independent safety organization. Mostly I worked on the technical analysis of the accident performed by "Group 3" and directed various independent analyses funded by the CAIB, such as the foam impact analysis performed at the Southwest Research Institute (SwRI) and the public risk study. As an example of CAIB thoroughness, the SwRI analysis supplemented at least three other technically separate analyses performed by Boeing, NASA, and the Sandia National Laboratory. For six solid months, the CAIB worked seven days a week, starting with an all-hands staff meeting every morning except Sunday, at 0700.

Responsibility for Public Safety

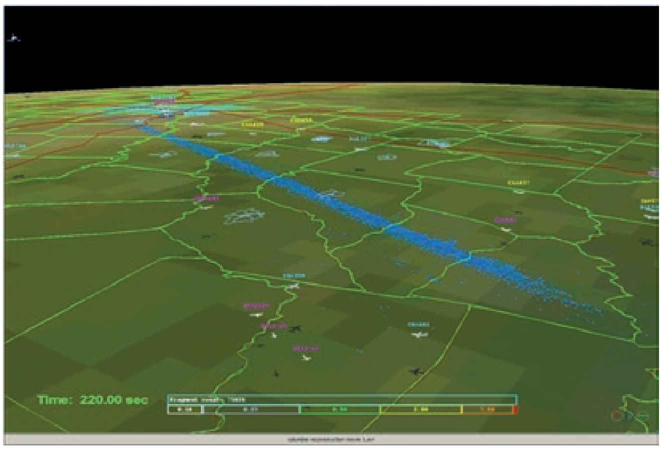
I was fully engaged in figuring out what happened to Columbia and why it happened when Bryan O'Connor called me into his office on his last day as an Ex-Officio Member of the Board. He recommended investigating the public safety implications of the accident, specifically to see if it was "a miracle" that no one was hurt on the ground. He wanted to know the public safety implications of the accident; this concern was highlighted when NASA Administrator Sean O'Keefe testified before the US Senate on May 14, 2003 that "stunningly, in as much as this was tragic and horrific through a loss of seven very important lives, it is amazing that there were no other collateral damage happened as a result of it. No one else was injured."

Mr. O'Connor's recommendation started me on a more challenging quest than I had realized. My first step was to speak with Steve Wallace, Director of the FAA's Office of Accident Investigation and a CAIB member, about the potential public safety implications, which he agreed were of interest. However, the CAIB was still entirely focused on the cause of the accident, so not much energy went into a public safety investigation until after NASA briefed the CAIB about the Probabilistic Risk Assessment (PRA) for the STS program, which was almost ready for publication just prior to the accident. Toward the end of that briefing, I asked about the potential applications of the PRA to public safety. The response was that NASA would not apply PRA insights to any public safety applications because the United States Air Force (USAF) and FAA were responsible for public safety during launch and reentry, respectively. As an FAA employee, it was clear to me that at least some people at NASA had the wrong impression about responsibility for public safety during reentry. After the PRA briefing, Steve Wallace agreed that the public safety issues demanded a thorough investigation. And they got one.

Danger Below Columbia

CAIB directed an independent study of the public risks posed by Columbia, which was performed by ACTA Inc. and documented in Volume II of the CAIB final report. The results demonstrated a 10-30% chance of one or more casualties on the ground given that the

O'Connor recommended investigating if it was "a miracle" that no one was hurt



Simulation of Columbia Breakup to Compute Probability of Impact on Aircraft. Credits: ACTA inc accident happened when and where it did. Thus, the absence of serious injuries to people on the ground due to the Columbia accident was the statistically expected outcome, not "a miracle" by risk analysis standards. However, the populous city of Houston would have been hit if that fateful reentry was delayed one orbit. The probability of casualty was much higher, 89-98%, if the same debris field fell on Houston, with two casualties expected.

CAIB published preliminary results on the conditional risks to aircraft: the expected number of plane impacts from Columbia was approximately 0.03 based on estimated air-traffic nearby. A subsequent FAA study used the actual commercial aircraft trajectory data at the time of the accident to compute between 0.003 and 0.1 expected collisions of Columbia debris with commercial aircraft [see AIAA 2005-6506].

The highest probability of impact to any individual aircraft was between 1 in 1,000 and 1 in 100, depending primarily on the uncertainty associated with how many small fragments survived to aircraft altitudes but were unrecovered. The consequences of an aircraft impact with Columbia debris was highly uncertain, but the fact that over half the recovered debris was under 0.5 kg and extremely low density materials suggested that many would have been benign even if they had impacted.

A Public Safety Policy

CAIB published a section on public safety (10.1) in Volume I that called out NASA for failing to follow public risk standards already in place at other flight institutions. "FAA and U.S. space launch ranges have safety standards designed to ensure that the general public is exposed to less than a one-in-a-million chance of serious injury from the operation of space launch vehicles and unmanned aircraft," reported CAIB. "NASA did not demonstrably follow public risk acceptability standards during past orbiter reentries." The findings concluded that NASA needed "a national policy for the protection of public safety during all operations involving space launch vehicles." Columbia became a part of this policy development, with the recovered debris from the orbiter used to facilitate realistic estimates of the risk to the public during orbiter reentry.

In 2005, NASA issued range safety policy NPR 8715.5 that included public risk acceptability criteria for all launches and reentries. This policy regarding collective public risk associated with Space Shuttle entries required an evaluation of entry trajectories from the ISS orbit inclination of 51.6 degrees and the collective public risk associated with each trajectory. This policy allowed the Space Shuttle Program to "continue to use Kennedy Space Center as its primary landing site, and establishes a public safety risk threshold to be used when considering alternate landing sites."

Columbia streaking over the Very Large Array radio telescope in Socorro, New Mexico. Credits: NASA

Houston would have been hit if reentry was delayed one orbit

Columbia's Aviation Legacy

The impact of the Columbia accident on aviation safety cannot be overstated. In the wake of the accident, multiple US agencies collaborated to develop consensus based aircraft protection standards and models to characterize aircraft vulnerability to launch and reentry debris. Columbia prompted NASA and the FAA to develop and implement a real-time mishap response system to alert aircraft and rapidly clear potentially threatened airspace during subsequent Shuttle reentries [see AIAA 2010-1349].

The FAA is currently expanding the real-time aircraft warning system, based on containment for debris that exceeds aircraft hazard thresholds, to more efficiently integrate launch and reentry vehicles into the US national airspace without compromising safety. The FAA continues to sponsor tests and analyses to produce more refined aircraft vulnerability models. These tests and analyses are part of the ongoing efforts to ensure no space vehicle debris collision will cause an aircraft accident the way the foam strike destroyed *Columbia*.

Physical Test to Simulate Foam Impact on Columbia's Wing Leading Edge. An air gun is used to launch a 757g foam piece into a Reinforced Carbon-Carbon test article at a speed of 234 m/s, with a 20 degree angle of incidence. Inset: the test article a fraction of a second after being impacted. Credits: Rick Stiles/ CAIB

Living with Columbia

Interview with Mike Ciannilli

By Merryl Azriel

Mike Ciannilli with his long-time charge, the orbiter Columbia. Courtesy: Mike Ciannilli

On February 1, 2003, Mike Ciannilli was a contractor for NASA. He worked as a test project engineer, responsible for the engineering systems coming together in the firing room. He was assigned to Space Shuttle Columbia, which seemed fitting somehow. Ciannilli had a long love affair with Columbia, dating from his middle school days, when he made a replica of the ship for his school science fair. At the time of the STS-107 mission, he was monitoring issues during processing flow in the turnaround between landing and launch and he manned the launch countdown. When he talks about listening to your vehicle, it's clear he still hears the rumbles and creaks of Columbia, a decade after she disintegrated before his and everyone's eyes.

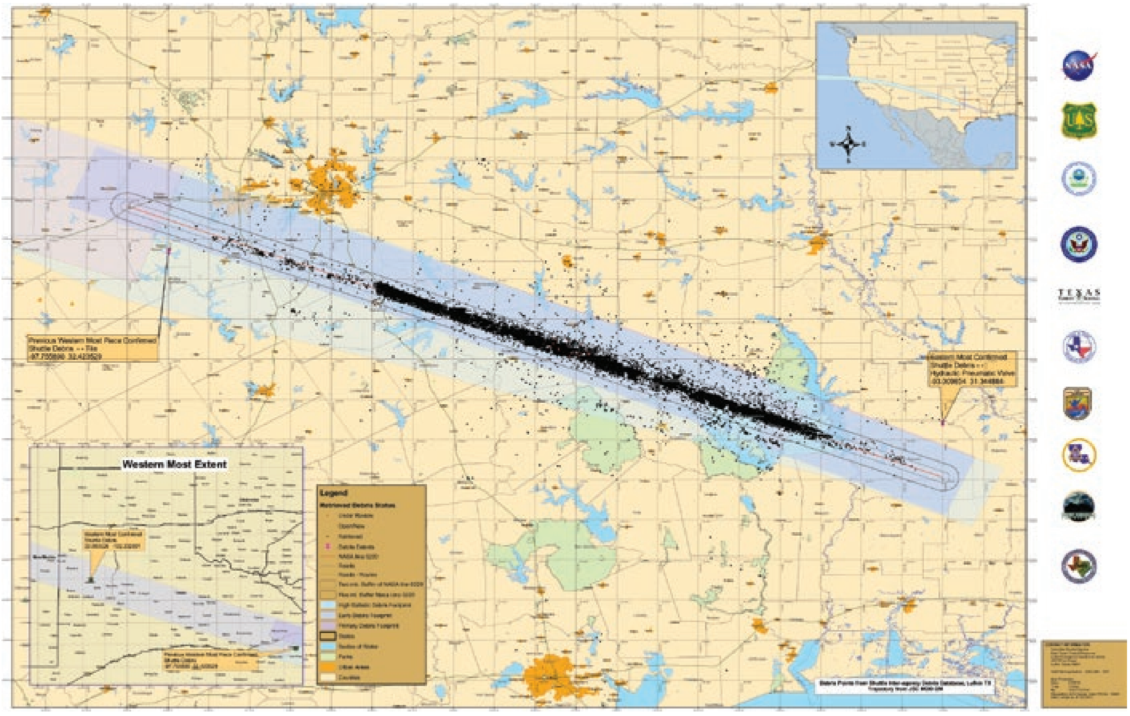
"Columbia was always personally very special to me"

The Search

Mid-February 2003 found Ciannilli in the middle of Texas, overflying Columbia's final flight path again and again. His job was to look out the helicopter doors, watching for signs of anything that might be a piece of the shuttle. When he spotted something promising, the copter would land while he attempted to identify the bit, bringing it aboard if it looked to be a likely match. "We'd do our initial identification, put it on board, and then launch up again. It was a lot of long days, flying every single day, for weeks on end."

He was far from alone on this search. "We had to pull off what in the end was the largest search in American history," Ciannilli says, describing the 420x16km stretch that comprised Columbia's flight path. If it wasn't for the "thousands of volunteers – the American Indian tribes, volunteer firefighters and policemen, and everyday people that came down," he says, with something of wonder still in his voice, the job would have been nearly impossible. Ciannilli's respect for those volunteers is palpable: "These folks came on buses from around the country, lived in tents in freezing rain conditions. They worked twelve hour plus days through very, very rough conditions and then their reward at night was to sleep in a small tent in freezing rain." Ciannilli describes how incredible it was to interact with these volunteers, who simply felt that this was something they owed to their country. "And these folks did it with a smile, you'd walk around they'd be thanking you for the experience."

Members of a US Forest Service team walk a Columbia recovery search grid. Credits: NASA



The debris field in East Texas spread over 5,179 km^2. The search covered 700,000 acres. Source: CAIB Report, p 45

When you wonder if space really matters to people, Ciannilli says, think of these volunteers. "When you see these folks come down and put their life on hold to help out the nation's space program, it becomes very real what space means to people."

"It was an extremely bittersweet emotional experience," says Ciannilli, "I never want to have to do it again, but you can't imagine not living through the experience because of the amazing people that you met and the amazing spirit of those people. They wanted to bring Columbia home."

After several weeks, Ciannilli became the Air Operations lead: "I was helping organize the flights at that point and trying to coordinate the scheduling." They did not finish the search until May 2003, nearly four months after the accident. By the time he got back to Cape Canaveral, the Columbia Accident Investigation Board was well on its way to producing what is now known as the CAIB Report. It is still one of the defining accident reports of modern spaceflight, what Ciannilli describes as "an awesome tool," one he recommends everyone, especially anyone involved in spaceflight, read and reread.

Curating the Remains

While Ciannilli, his colleagues, and volunteers were out hunting for pieces, a reconstruction team was hard at work at the shuttle landing facility, trying to figure out where those pieces fit. "They were reconstructing Columbia as best they could and they did a really amazing job of putting her back together," says Ciannilli. When the CAIB Report was delivered to US President Bush in August 2003, the remains of Columbia were turned over to NASA, who moved them from the shuttle hangar to the Vehicle Assembly Building.

"I never want to have to do it again, but you can't imagine not living through the experience"

Four years later, Ciannilli gained custody of Columbia when he was appointed Project Manager of the Columbia Research and Preservation Office. "It was and is humbling," he says. "Columbia was always personally very special to me."

Managing the office gives Ciannilli something of a pulpit from which to deliver the message of Columbia. He recently convinced NASA to require all new co-ops and employees at Kennedy Space Center to tour the Columbia Office "I'm a huge believer in know your history, remember your history, and understand your history. I think you really need to educate your folks on the reality of what happened."

He's also proud of the work the office is able to do in helping to continue research based on the shuttle. The office has an active loan program that allows researchers to borrow artifacts for study. "It's really interesting because they'll take a look at a piece and you can watch the wheels turning. They can see so much into it." The office also works with educational institutions: "A university or a high school can apply to have a piece of Columbia sent to them and they can use it in the classroom for an engineering forensics class or engineering analysis class. Hopefully it inspires the younger folks to study and have Columbia be the catalyst to help that conversation."

Listening to Your Vehicle

The discussion turns to the lessons learned from Columbia, and for a moment Ciannilli seems not to know where to start. "There's a bunch," he says, and proceeds to list some of the big ones: keep your models and tools up to date, understand your materials, guard against the off-nominal becoming normal, continually question and revalidate your design, and of course, institute a culture of open communication. But one thing that Ciannilli comes back to again and again is listening to your vehicle.

"People say that the vehicles become alive. They become personalities," explains Ciannilli. "I can tell you how Atlantis behaves and how Columbia starts up in the morning." These quirks, much like those you might be familiar with from your family automobile, can provide important clues to changes in spacecraft behavior – clues that may not be present in more formal types of data. "The vehicle's talking to you, the hardware's talking to you – listen to it," urges Ciannilli. "Things are happening and they often start as very small things. Understand what's happening." He specifically notes the issues shuttle managers faced relating to tile incidents. "Even the last few years, we didn't really understand carbon-carbon, its strengths and its weaknesses." Accepting tile incidents as normal without understanding the source of the incidents was a clear pre-Columbia failure.

Ciannilli gets animated when he describes what the shuttle program could have been like had the Columbia accident never occurred. "Our plan was to fly space shuttle to 2020 or 2025 even," he says, describing the extension program and the upgrades to cockpit, engines, instrumentation, computers, GPS, and "a whole host of systems," that were already underway at the beginning of 2003. Even after the accident, technically the shuttles were in excellent condition,

Mike Ciannilli in back of a helicopter during Columbia aerial search operations in Texas. Courtesy: Mike Ciannilli

"The vehicle's talking to you – listen to it"

possibly the best they'd ever been. "The incidents between flows were being significantly reduced, the crews were reporting on orbit the vehicles were performing better and better every flight," Ciannilli recalls. But political winds blew NASA down a different path.

"For 30 years we had a tremendous database." Ciannilli notes with pride. Unfortunately, that database moves to the shelf now, as new vehicles come in with quirks and personalities yet to be discovered. In some ways, new vehicles can advance safety systems, with enhanced opportunities for designing in safety factors that cannot be retrofitted to an existing vehicle. But in other ways, the loss of familiarity can be a stumbling block. "It's kind of like buying a new car," explains Ciannilli." You're gonna have new features and you don't know how it's going to perform."

"But," he says, "you can never keep flying the same vehicle forever."

Standing up to Say Something's Wrong

Ciannilli observed clear changes in NASA's communication culture following release of the CAIB report. "After the accident it definitely improved a lot and I think it got better as time went on after the accident - more improvements were put in place and the culture was established," he recounts. But, he says, that fear of standing up to say something is wrong will never go away entirely. "It's human nature," says Ciannilli. "If you're going to a flight readiness review, a launch readiness review, any kind of environment it's gonna be difficult at times for folks to come forward."

That's where Ciannilli hopes the memory of Columbia can help. "I say this at the end of every tour I give of the Columbia room: if you're ever sitting at a flight readiness review, or a launch readiness review, or anything and you have that feeling in your stomach, you feel there's something not right... If you ever need that courage, think back to this room. Think back to your time here with Columbia. And that might be the one little extra piece of encouragement that will help get you out of your seat."

Safety in Any Industry

Clearly, Ciannilli hopes that the lessons of Columbia and Challenger will be carried forward into the next generations of spacecraft development and developers. "The practices, what's good to do, the safety checks that are important what kind of redundancy is important and necessary, a lot of that is transferrable," says Ciannilli, despite the differences in design and approach. And, Ciannilli emphasizes, these lessons are not isolated to NASA or even commercial crew: "aircraft, cars, submarines, it's all the same in a lot of ways."

Ciannilli advises those developers to "keep looking for the risks that are out there, capture them in your processes, promote them in your training, instill them in your culture, and then keep revisiting them." And most importantly, he says, act on them. "It's like a parent, you know. You tell your kids certain things to do or not to do, but if you don't do them yourself in a very visible way it's not going to be taken seriously."

"I don't care if you're a technician turning a wrench or if you're the CEO," he admonishes. "Be the example of that culture and let others see how serious you are."

Keeping the Message Alive

"As time gets removed, as time goes on, memories kind of fade, like old family stories," says Ciannilli. "After a while the stories don't have quite the same effect."

In many ways, remembering Columbia – and Challenger before it – is very much a personal responsibility. Ciannilli talks about he and others from that time trying to transfer their experiences to new employees – employees who were in middle school or high school when the crew of STS-107 died. "They don't have the personal connection that we have that lived it." Ciannilli sees the Columbia room as a critical component in that communication. "They walk through the Columbia room and you can just see the impact it has. It becomes real for them, as close as it could be. And hopefully they take that into their career and it really means something in their future decision making processes."

Ciannilli is also clearly excited about the new research that results from studying Columbia's remains. "It's definitely pushing the bounds of knowledge for the upper atmosphere and the effects there." While researchers commonly publish their

Recovery volunteers camp in a warehouse in Texas after a day of searching for debris. Credits: NASA

findings, there is no formal mechanism to incorporate new materials and structural knowledge back into the next generation of space vehicles. "It's a treasure trove for the folks that do want to learn about it," says Ciannilli.

"We do our best to keep it going and the best way you really can do that is passing down from one generation of engineer to the next." So the Mercury engineers talk to Gemini and Apollo engineers who talk to the Space Shuttle engineers: "Tribal knowledge I call it." But Ciannilli acknowledges that keeping it going is a constant challenge. "There's a tremendous amount of experience that we don't have any more," both from NASA layoffs at the end of the shuttle program and the aging of engineers with those decades of experience. "You can't replace the thousands and thousands that aren't here anymore, but you try the best you can to get as much of the knowledge across that we learned and pass that on to the next folks."

"As time goes on, memories fade"

"The STS-107 mission was a mission of education and research," Ciannilli concludes. "I always say that what we do is, in their name, continue that mission, continue that research, and continue the education, so Columbia in a way still flies. And so do they, in spirit."

Mike Ciannilli has launched a website, Columbia.nasa.gov, as a one stop shop for everything Columbia, including a place to share your memories of Columbia with the community. He urges anyone who thinks they may have a piece of Columbia or Challenger to give him a call. "Having any of Columbia or Challenger is a felony, so they don't want to do that," says Ciannilli. "But if they do find something, we thank them so much and want them to contact us. We want to bring all of Challenger and Columbia home."

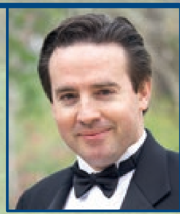
Reconstruction of Columbia debris in the hangar at Kennedy Space Center. Credits: NASA

Contributors

Credits: NASA

Bryan O'Connor

Bryan O'Connor was Shuttle pilot on STS-61B in 1985. After the loss of Challenger, he was given a number of safety and management assignments. In 1991, he commanded STS-40. In 1993 he became Director of the NASA Space Station Redesign team and, in 1994, Director of the Space Shuttle Program. In June 2002 he became NASA Associate Administrator, Office of Safety and Mission Assurance (OSMA). In 2004, following the Shuttle Columbia accident investigation conclusion, his title changed to NASA Chief, Safety and Mission Assurance and his functional responsibilities enlarged. Bryan O'Connor is recipient of the IAASS Jerome Lederer Space Safety Pioneer Award 2011.



Courtesy: P. Wilde

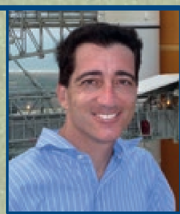
Paul Wilde

Dr. Paul Wilde is a founding fellow of the IAASS with 20 years experience in safety standards development, launch and reentry safety evaluations, explosive safety analysis, and operations safety. Currently a technical advisor for the Chief Engineer in the US Federal Aviation Administration's Office of Commercial Space Transportation, he preformed leading roles for multi-organization projects in high-profile situations, such as investigation of public safety issues and the foam impact tests for the Columbia Accident Investigation Board, flight safety evaluations for the maiden flights of the ATV, Atlas V, Delta IV, Falcon 9-Dragon, Spaceship 1, Titan IVB, and the development of US standards on launch and reentry risk management. He received the NASA Exceptional Achievement Medal and is a licensed professional engineer in Texas.

Credits: Red Bull Stratos

Jonathan Clark

Dr. Jonathan Clark is an Associate Professor of Neurology and Space Medicine at Baylor College of Medicine and teaches operational space medicine at BCM's Center for Space Medicine. He was a Member of the NASA Spacecraft Survival Integrated Investigation Team from 2004 to 2007 and Constellation EVA Systems Project Standing Review Board from 2007 to 2010. From 1997 to 2005 he worked at NASA as a Space Shuttle Crew Surgeon. He served 26 years active duty in the US Navy as a Naval Flight Officer, Flight Surgeon, and Military Freefall parachutist. Dr. Clark is Medical Director of the Red Bull Stratos Project. His professional interests focus on the neurological effects of extreme environments and crew survival in space.



Courtesy: M. Ciannilli

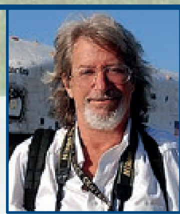
Michael Ciannilli

Mike Ciannilli is NASA Test Director, Project Manager of the Columbia Research and Preservation Office, and Project Manager of the Space Shuttle Challenger Office at Kennedy Space Center. He started his career as a systems engineer supporting the Fuel Cells Orbiter group, later moving on to serve as a test engineer for the orbiter Columbia, which was his position on February 1, 2003. Ciannilli took a hands-on role in recovering Columbia's debris and he's still the individual to call when someone uncovers a new debris candidate. Five years after the loss of STS-107, Ciannilli took over as curator of the Columbia room, where he continues to share the lessons of Columbia with anyone who will listen.

Courtesy: G. Johnson

Gary Johnson

Gary W. Johnson is an Aerospace Safety Consultant, currently working for J&P Technologies. He worked for NASA on the major manned programs from Apollo on since 1964. He served as Manager for the Sequential Subsystem for the Apollo CSM, Lunar Module, and Skylab CSM; member of ASTP Working Group 4; first Space Shuttle flight Orbit Flight Control Team Electrical, General Instrumentation, and Lighting (EGIL) flight controller; Mission Operations Directorate Systems Division Mechanical and Payload Systems Branch Chief and Guidance and Propulsion Systems Branch Chief; Deputy Director, SR&QA Office; NASA/Mir Program Joint Safety Assurance Working Group Co-Chairman; deputy director of Russian Projects SR&QA; and NASA Co-Chairman of the International Space Station Program Joint American Russian Safety Working Group.



Credits: Jim Siegel, Celebration News.

Lloyd Behrendt

Lloyd Behrendt is an artist and photojournalist who has collected more than 300 launches on film since Apollo 14. His work is based on black and white photographs transformed into original oil paintings. His book "Birds of Hope... A Primer for the Future" depicts the coexistence of Central Florida's man-made "space birds" with the natural, winged creatures living in the area, and shares the story of how rockets have saved their feathered neighbors. According to Behrendt, the decision to represent Columbia's fated launch was an attempt "to represent the accomplishments of the STS program and to memorialize the precious sacrifices of those lost over the years as we have explored the harsh and sometimes unforgiving environment of space."

Credits: Jtesla16/Wikimedia