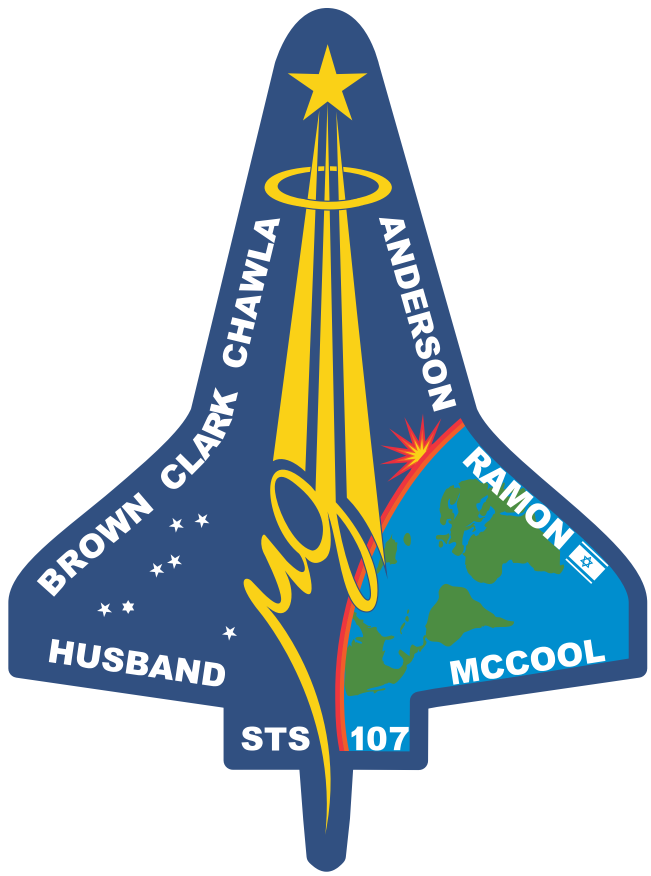
National Aeronautics and Space Administration

# *Columbia* Crew Survival Investigation Report

NASA/SP-2008-565



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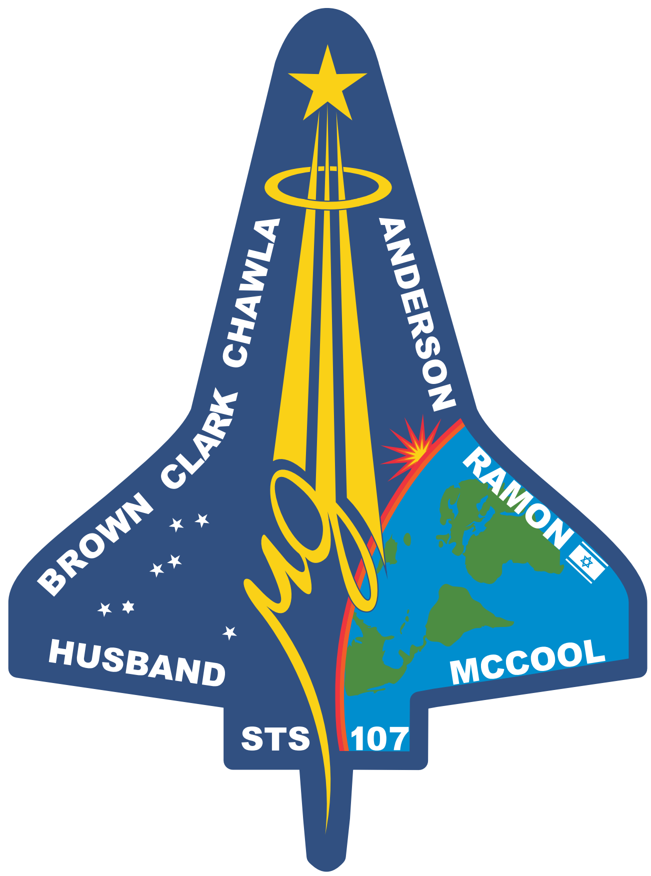

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# Acronyms and Abbreviations

| | |
|---|---|
| A/G | air-to-ground |
| A/G1 | air-to-ground 1 |
| A/N PRC | Army/Navy personal radio communications |
| AC | alternating current |
| AC3 | alternating current Bus 3 |
| ACES | advanced crew escape suit |
| AFIP | Air Force Institute of Pathology |
| AOD | automatic opening device |
| AOS | acquisition of signal |
| APU | auxiliary power unit |
| ASCAN | astronaut candidate |
| | |
| BFS | backup flight software |
| BIP | bio-instrument pass-through |
| BLIMP-K | Boundary Layer Integral Matrix Procedure-Kinetic |
| BN | ballistic number |
| BRC | Biodynamic Research Corporation |
| Btu | British thermal unit |
| Btu/lbm | Btu per pound of mass |
| | |
| c.g. | center of gravity |
| CAIB | *Columbia* Accident Investigation Board |
| CAPCOM | capsule communicator |
| CCA | communications carrier assembly |
| $C_D$ | coefficient of drag |
| CDR | Commander |
| CE | Catastrophic Event |
| CEE | crew escape equipment |
| CEL | Concept Exploration Laboratory |
| CES | Crew Escape System |
| CFD | computational fluid dynamics |
| CH4 | Channel 4 |
| CM | crew module |
| CMCE | Crew Module Catastrophic Event |
| $CO_2$ | carbon dioxide |
| COMM | communications |
| CRD | *Columbia* Reconstruction Database |
| CRP | *Columbia* Research and Preservation |
| CRT | cathode ray tube |
| CSS | control stick steering |
| CSWG | Crew Survival Working Group |
| CTB | cargo transfer bag |
| CWE | crew worn equipment |
| | |
| D/O PREP | deorbit preparation |
| DAP | digital autopilot |
| DD.ddddd | degrees and decimal degrees |
| DD MM.mmm | degrees, minutes, and decimal minutes |
| DD MM SS.sss | degrees, minutes, seconds, and decimal seconds |
| DNA | deoxyribonucleic acid |
| DoD | Department of Defense |

| | |
|---|---|
| DP/dt | pressure change rate |
| DSC | dual suit controller |
| ECLSS | Environmental Control and Life Support System |
| EI | entry interface |
| EOS | Emergency Oxygen System |
| ET | external tank |
| EVA | extravehicular activity |
| FAA | Federal Aviation Administration |
| FBI | Federal Bureau of Investigation |
| FCS | Flight Control System |
| FF | forward fuselage |
| FOV | field of view |
| fps | feet per second |
| FREESTAR | Fast Reaction Experiments Enabling Science, Technology, Applications, and Research |
| FSP | Fault Summary Page |
| GMT | Greenwich Mean Time |
| GPC | general purpose computer |
| GPS | Global Positioning System |
| hh:mm:ss | hours:minutes:seconds |
| ICU | individual cooling unit |
| ISAG | Image Science and Analysis Group |
| ISS | International Space Station |
| JSC | Johnson Space Center |
| KEAS | knots equivalent air speed |
| KSC | Kennedy Space Center |
| LCAT | Large Core Arc Tunnel |
| LCG | liquid cooling garment |
| LED | light emitting diode |
| LIB | left inboard |
| LiOH | lithium hydroxide |
| LOB | left outboard |
| LOC | loss of control |
| LOS | loss of signal |
| LPU | life preserver unit |
| LRWG | Late Re-entry Working Group |
| MADS | Module Auxiliary Data System |
| MAGR | Miniaturized Airborne Global Receiver |
| MAP | middeck access panel |
| MAR | middeck accommodation rack |
| MCC | Mission Control Center |
| µm | micron |
| MMACS | Mechanical, Maintenance, Arm, and Crew Systems |
| MPS | Main Propulsion System |
| MS | Mission Specialist |
| MSID | measurement and stimulus indication |
| $N_2$ | nitrogen |
| NBC | National Broadcasting Corporation |
| NET | no earlier than |
| NLT | no later than |
| NO | nitric oxide |
| NTSB | National Transportation Safety Board |

| | |
|---|---|
| $O_2$ | oxygen |
| OEX | orbiter experiment |
| OMS | Orbital Maneuvering System |
| ORSAT | Object Reentry Survival Analysis Tool |
| OSL | off-scale low |
| PASS | Primary Avionics Software System |
| PGSC | payload general support computer |
| PLBD | payload bay door |
| PLT | Pilot |
| PPA | personal parachute assembly |
| $ppCO_2$ | partial pressure of carbon dioxide |
| $ppO_2$ | partial pressure of oxygen |
| PS | Payload Specialist |
| psf | pounds per square foot |
| psi | pounds per square inch |
| psia | pounds per square inch absolute |
| psid | pounds per square inch differential |
| QD | quick disconnect |
| RCC | reinforced carbon-carbon |
| RCS | Reaction Control System |
| RGPC | reconstructed general purpose computer |
| RHC | rotational hand controller |
| RPTA | rudder pedal transducer assembly |
| SARSAT | search and rescue satellite-aided tracking |
| SCSIIT | Spacecraft Crew Survival Integrated Investigation Team |
| SEAWARS | Seawater Activated Release System |
| SES | Shuttle Engineering Simulator |
| SFRM | space flight resource management |
| SINDA | Systems Improved Numerical Differencing Analyzer |
| SMPTE | Society of Motion Picture and Television Engineers |
| SMS | shuttle mission simulator |
| SORT | Simulation and Optimization of Rocket Trajectories |
| SSME | space shuttle main engine |
| SUPA | shuttle urine pretreat assembly |
| 3-D | three-dimensional |
| TAA | tunnel adapter assembly |
| TCDT | terminal countdown demonstration test |
| TD | Total Dispersal |
| | thickness dimension |
| TDRS-W | Telemetry, Tracking, and Data Relay Satellite-West |
| TELCU | thermal electric liquid cooling unit |
| TET | tape elapsed time |
| TIG | time of ignition |
| TIM | Technical Interchange Meeting |
| $TiO_2$ | titanium oxide |
| TPS | Thermal Protection System |
| TSUB-A | Telonics Satellite Uplink Beacon-A |
| TUC | time of useful consciousness |
| WCS | Waste Collection System |
| WSB | water spray boiler |

# Executive Summary

## Background

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. The accident investigation that followed determined that a large piece of insulating foam from *Columbia*'s external tank (ET) had come off during ascent and struck the leading edge of the left wing, causing critical damage. The damage was undetected during the mission. The CAIB's findings and recommendations were published in 2003 and are available on the web at http://caib.nasa.gov/. NASA responded to the CAIB findings and recommendations with the Space Shuttle Return to Flight Implementation Plan.[1] Significant enhancements were made to NASA's organizational structure, technical rigor, and understanding of the flight environment. The ET was redesigned to reduce foam shedding and eliminate critical debris. In 2005, NASA succeeded in returning the space shuttle to flight. In 2010, the space shuttle will complete its mission of assembling the International Space Station and will be retired to make way for the next generation of human space flight vehicles: the Constellation Program.

The Space Shuttle Program recognized the importance of capturing the lessons learned from the loss of *Columbia* and her crew to benefit future human exploration, particularly future vehicle design. 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. This report documents the SCSIIT findings, conclusions, and recommendations.

## Results

One of the more difficult problems facing the SCSIIT was how to characterize events that occurred in an operating regime that was far outside the collective experience of aircraft accident investigation and without significant applicable test data. The investigation relied on data in the form of video, recovered debris, and medical findings, each supplemented with modeling and 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 entry 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.

1. **Depressurization of the crew module at or shortly after orbiter breakup.**
   The pressure suit used by space shuttle crews on ascent and entry was not a part of the initial design of the orbiter. It was introduced in response to the *Challenger* accident. While it protects the crew from many contingency scenarios, there are several areas where integration difficulties diminish the capability of the suit to protect the crew. The *Columbia* depressurization event occurred so rapidly that the crew members were incapacitated within seconds, before they could configure the suit for full protection from loss of cabin pressure. Although circulatory systems functioned for a brief time, the effects of the depressurization were severe enough that the crew could not have regained consciousness. This event was lethal to the crew.

[1]NASA's Implementation Plan for Space Shuttle Return to Flight and Beyond, 10th Edition, June 3, 2005.

### *Key Recommendations*

Space shuttle crew training should include greater emphasis on the transition between problem-solving and survival operations.

Future spacecraft must fully integrate suit operations into the design of the vehicle and provide features that will protect the crew without hindering normal operations.

**2. Exposure of unconscious or deceased crew members to a dynamic rotating load environment with a lack of upper body restraint and nonconformal helmets.**
When the orbiter lost control, the resultant motion was not lethal but did require crew members to brace against the motion. The forebody, which is made up of the crew module and forward fuselage, separated at orbiter breakup. The forebody continued to rotate. After the crew lost consciousness due to the loss of cabin pressure, the seat inertial reel mechanisms on the crews' shoulder harnesses did not lock. As a result, the unconscious or deceased crew was exposed to cyclical rotational motion while restrained only at the lower body. Crew helmets do not conform to the head. Consequently, lethal trauma occurred to the unconscious or deceased crew due to the lack of upper body support and restraint.

### *Key Recommendations*

Crew procedures must be re-evaluated in light of the findings regarding the motion of the intact orbiter and the forebody after separation.

Future spacecraft should be evaluated for loss of control motion and dynamics for adequate integration into development, design, and crew training.

Future spacecraft seats and suits should be integrated to ensure proper restraint of the crew in off-nominal situations while not affecting operational performance. Future crewed spacecraft vehicle design should account for vehicle loss of control to maximize the probability of crew survival.

**3. Separation of the crew from the crew module and the seat with associated forces, material interactions, and thermal consequences.**
The breakup of the crew module and the crew's subsequent exposure to hypersonic entry conditions was not survivable by any currently existing capability. It was an extremely significant event, but it was very difficult to characterize because many events appeared to happen in a short period of time. The actual maximum survivable altitude for the crew module following a breakup of the orbiter is too complex to compute because it depends on the altitude and velocity at release as well as rotational dynamics that are understood only in a general way. The lethal-type consequences of exposure to entry conditions included traumatic injury due to seat restraints, high loads associated with deceleration due to a change in ballistic number, aerodynamic loads, and thermal events. Crew circulatory functions ceased shortly before or during this event. The ascent and entry suit had no performance requirements for occupant protection from thermal events. The only known complete protection from this event would be to prevent its occurrence.

### *Key Recommendation*

Future vehicle design should incorporate an analysis for loss of control/breakup to optimize for the most graceful degradation of vehicle systems and structure to enhance chances for crew survival. Operational procedures can then integrate the most likely scenarios into survival strategies.

**4. Exposure to near vacuum, aerodynamic accelerations, and cold temperatures.**
The ascent and entry suit system is certified to a maximum altitude of 100,000 feet and velocity of 560 knots equivalent air speed. It is uncertain whether it can protect a crew member at higher altitudes and air speeds.

### *Key Recommendation*

Crew survival suits should be evaluated as an integrated system to determine the various weak points (thermal, pressure, windblast, chemical exposure, etc.). Once identified, alternatives should be explored to strengthen the weak areas.

5. **Ground impact.**
The ascent and entry suit system provides protection from ground impact with a parachute system. The current parachute system requires manual action by a crew member to activate the opening sequence.

### *Key Recommendation*

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

## Improving Crew Survival Investigations

The SCSIIT also identified recommendations regarding crew survival investigations. These include that:

- Crew survival investigations should be given high priority for all future spacecraft mishaps. Medically sensitive data should always be protected to preserve the privacy of the victims and their families. Because there is a limited database of information, each accident provides crucial understanding of the environment and expanding the envelope for survival.
- Data management proved to be critical to the investigation in many areas, such as equipment identification marking, debris recovery ground coordinates, database documentation, and tracking versions of reports, briefings, and analyses. Preservation of debris and data that may be of value in future investigations should be standardized and continued.

The SCSIIT investigation was performed with the belief that a comprehensive, respectful investigation could provide knowledge that would improve the safety of future space flight crews and explorers. By learning these lessons and ensuring that we continue the journey begun by the crews of Apollo 1, *Challenger*, and *Columbia*, we help to give meaning to their sacrifice and the sacrifice of their families. It is for them, and for the future generations of explorers, that we strive to be better and go farther.

# Introduction

Human space flight is still in its infancy; spacecraft navigate narrow tracks of carefully computed ascent and entry trajectories with little allowable deviation. Until recently, it remained the province of a few governments. As private industry and more countries join in this great enterprise, we must share findings that may help protect those who venture into space. In the history of NASA, this approach has resulted in many improvements in crew survival. After the Apollo 1 fire, sweeping changes were made to spacecraft design and to the way crew rescue equipment was positioned and available at the launch pad. After the *Challenger* accident, a jettisonable hatch, personal oxygen systems, parachutes, rafts, and pressure suits were added to ascent and entry operations of the space shuttle.

As we move toward a time when human space flight will be commonplace, there is an obligation to make this inherently risky endeavor as safe as feasible. Design features, equipment, training, and procedures all play a role in improving crew safety and survival in contingencies. In aviation, continual improvement in oxygen systems, pressure suits, parachutes, ejection seats, and other equipment and systems has been made. It is a core value in the aviation world to evaluate these systems in every accident and pool the data to understand how design improvements may improve the chances that a crew will survive in a future accident.

The *Columbia* accident was not survivable. After the *Columbia* Accident Investigation Board (CAIB) investigation regarding the cause of the accident was completed, further consideration produced the question of whether there were lessons to be learned about how to improve crew survival in the future.

This investigation was performed with the belief that a comprehensive, respectful investigation could provide knowledge that can protect future crews in the worldwide community of human space flight. Additionally, in the course of the investigation, several areas of research were identified that could improve our understanding of both nominal space flight and future spacecraft accidents.

This report is the first comprehensive, publicly available accident investigation report addressing crew survival for a human spacecraft mishap, and it provides key information for future crew survival investigations. The results of this investigation are intended to add meaning to the sacrifice of the crew's lives by making space flight safer for all future generations.

## *The* Columbia *Accident Investigation Board Report*

The CAIB completed its investigation into the *Columbia* mishap and published Volume I of its report in August 2003. Five supporting volumes were subsequently completed and published. The CAIB Report provides a thorough study of the accident and its causes. Since the crew had no role in causing the accident, the CAIB Report contained limited discussion of crew-related events. Although the CAIB Report included no formal recommendations concerning crew survival, it did contain the following relevant observation:[2]

> Observation 10.2-1 *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*.

[2] *Columbia* Accident Investigation Board Report, Volume I, Section 10.2, Crew Escape and Survival, August 2003.

Additionally, Appendix G12, Crew Survivability, page 355, Volume V, October 2003 added:

> *To enhance the likelihood of crew survivability, NASA must evaluate the feasibility of improvements to protect the crew cabin in existing orbiters.*
>
> *NASA should investigate techniques that will prevent the structural failure of the CM* [crew module] *due to thermal degradation of structural properties and determine their feasibility for application.*
>
> *Future crewed vehicles should incorporate the knowledge gained from the 51-L* [Challenger] *and STS-107 mishaps in assessing the feasibility of designing vehicles that will provide for crew survival even in the face of a mishap that results in the loss of vehicle.*
>
> *Crew procedures and techniques for use of CWE [crew worn equipment] should be standardized and complied with by all crewmembers.*

To address post-*Columbia* Return to Flight actions, the Space Shuttle Program approved the formation of a multidisciplinary Spacecraft Crew Survival Integrated Investigation Team (SCSIIT) in July 2004. The team's primary objective was to combine engineering and medical analyses to determine what happened to the crew module and the *Columbia* crew to enhance crew safety and survival for future human space flights. This effort built upon and extended the activities of the Crew Survival Working Group (CSWG), which was formed at the time of the CAIB investigation.

In many regards this investigation presented several challenges. First, space flight is a relatively new and rare experience and there have been only a few fatal mishaps. Consequently, there is no integrated or widely available body of information regarding the analysis of spacecraft accidents for crew survival. The environment of atmospheric entry is also unique when compared to aviation. The SCSIIT had to break new ground in conducting the investigation of a singular event in such a complex environment. The team had to modify existing models and tools, normally used for specific nominal situations in a predictive manner, to understand the mishap environment. Many of the technical tools and concepts used will be of great assistance to a future spacecraft accident investigator. With the proliferation of commercial and international human space flight activities, it is crucial that all participants begin to develop a more comprehensive process and database of information regarding spacecraft accident investigation.

Because of the nature of the *Columbia* accident, there are many unknowns associated with it. The SCSIIT attempted to address these unknowns through calculated judgment and some speculation. In the end, there were varying degrees of certainty and confidence. The word "probable" refers to events that the team was very confident occurred. "Likely" refers to events that the team is somewhat confident occurred, although supporting evidence may be less definite. When an event is described as "possible," it generally reflects a lack of data to confirm or refute the scenario but is still considered valuable to mention. The reconstruction of this accident relied on a wide array of data. This report reflects the final consensus reached by the investigators.

## Summary of Conclusions and Recommendations

### Lethal events

The SCSIIT framed its analysis by attempting to identify all of the potentially lethal events that occurred during the mishap, including those that occurred after the crew was deceased. This allowed the team to identify specific threats to crew survival at different phases of entry and address those threats in recommendations for future vehicles. In the course of the investigation, the SCSIIT identified five events with lethal potential. These events are summarized below, along with the findings and recommendations that accompany each one. Each event is discussed in detail in the body of the report.

1. **The first event with lethal potential was depressurization of the crew module, which started at or shortly after orbiter breakup.**
The majority of the SCSIIT findings related to the first lethal event were connected to the operational incompatibilities of the advanced crew escape suit (ACES) with the orbiter. The launch and entry suit was added in response to the *Challenger* accident, rather than as a part of the original vehicle design. The ACES was the successor to that suit. The suit protects the crew in many scenarios; however, there are several areas where integration difficulties diminish the capability of the suit to protect the crew. Integration issues include: the crew cannot keep their visors down throughout entry because doing so results in high oxygen concentrations in the cabin; gloves can inhibit the performance of nominal tasks; and the cabin stow/deorbit preparation timeframe is so busy that sometimes crew members do not have enough time to complete suit-related steps prior to atmospheric entry.

As *Columbia* entered the atmosphere, one crew member was not yet wearing the ACES helmet and three crew members were not wearing gloves. Per nominal procedures, the crew wearing helmets had visors up. There was a period of about 40 seconds after the orbiter loss of control (LOC) but prior to depressurization when the crew was conscious and capable of action. Part of this short timeframe was undoubtedly employed in recognizing that a problem existed, as the indications of LOC developed gradually. The crew members could have closed their visors in this timeframe but did not. The SCSIIT attributed this to the training regimen, which separates vehicle systems training from emergency egress training and does not emphasize the *transition* between problem resolution and a survival situation. Once the cabin depressurization began, the rate of depressurization incapacitated the crew so quickly that even those crew members who had fully donned the ACES did not have time to lower their visors. Although circulatory systems functioned for a brief time, the crew could not have regained consciousness upon descent to lower altitudes due to the effects of the depressurization.

### *Key Recommendations*

- Crew survival systems and procedures should be incorporated early into future spacecraft designs to ensure that they are compatible with nominal operations and that sufficient time exists to ensure all safety-critical equipment can be configured prior to entry interface.
- The training program should be evaluated to determine how to best incorporate the transition from problem-solving to survival.
- Future spacecraft crew survival systems should not rely solely on manual activation to protect the crew.

2. **The second event with lethal potential was unconscious or deceased crew members exposed to a dynamic rotating load environment with nonconformal helmets and a lack of upper body restraint.**
The orbiter lost control, probably when the hydraulic systems failed due to hot gas intrusion in the left wing. The resulting motion was not lethal but did require bracing by the crew. The forebody (crew module and forward fuselage) eventually separated and the crew module lost pressure at orbiter breakup. When it separated, the forebody began a multi-axis rotation at approximately 0.1 revolution/second. Loads due to deceleration significantly decreased at the moment of breakup due to the change in ballistic number, but began to climb as the forebody continued to decelerate.

After the crew module depressurized and the crew lost consciousness, the seat inertial reel mechanisms failed to lock despite the off-nominal motion. The reels were not defective; they were simply not designed to lock under the conditions the forebody experienced. The upper harness straps failed at some point prior to the forebody breakup, causing the straps to recoil back into the inertial reel mechanism. Because the reel mechanisms did not lock, the unconscious or deceased crew members were exposed to cyclical rotational motion while their upper bodies were inadequately restrained. Helmets that did not conform to the head and the lack of upper body restraint resulted in injuries and lethal trauma.

Current emergency egress procedures for a vehicle LOC or breakup assume that the crew module will eventually stop rotating and will stabilize in a specific attitude. Aerodynamic analysis completed during this investigation shows that this is extremely unlikely. Further, the procedures are based on ascent conditions only.

### *Key Recommendations*

- 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. Inertial reels should be evaluated for appropriateness of design for off-nominal scenarios.
- Helmets should provide head and neck protection in off-nominal dynamic load conditions. The current space shuttle inertial reels should be manually locked at the first sign of an off-nominal situation.
- A team of crew escape instructors, flight directors, and astronauts should be assembled to assess orbiter procedures in the context of ascent, deorbit, and entry contingencies.
- Future spacecraft should be evaluated while still in the design phase for dynamics and entry thermal and aerodynamic loads during a vehicle LOC for adequate integration into development, design, and crew training.
- Future crewed spacecraft vehicle design should account for vehicle LOC contingencies to maximize the probability of crew survival.

**3. The third event with lethal potential was separation from the crew module and the seats with associated forces, material interactions, and thermal consequences. This event is the least understood due to limitations in current knowledge of mechanisms at this Mach number and altitude. Seat restraints played a role in the lethality of this event.**

The breakup of the crew module and resultant exposure of the crew to entry conditions was an extremely significant event but was very difficult to characterize since many related events occurred in a short period of time. The consequences of exposure to entry conditions included traumatic injury related to seat restraints, high loads associated with deceleration due to a change in ballistic number, aerodynamic loads, and thermal events. All crew were deceased before, or by the end of, this event. The ACES has no performance requirements for occupant protection from thermal events and may not provide adequate protection even for egress scenarios involving heat and flames. There is no known complete protection from the breakup event except to prevent its occurrence.

The actual maximum survivable altitude for the crew module following a breakup of the orbiter is too complex to compute because it depends on the altitude and velocity at release as well as rotational dynamics, which are understood only in a general way.

### *Key Recommendations*

- Future vehicle design should incorporate analysis for LOC/breakup to optimize for the most graceful degradation to vehicle systems and structure to enhance chances for crew survival. Operational procedures can then integrate the most likely scenarios into survival strategies.
- Future spacecraft suits, seats, 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.
- Crew survival systems should be evaluated as an integrated system that includes boots, helmet, seat restraints, etc. to determine the various weak points (thermal, pressure, windblast, chemical exposure, etc.). 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.

4. **The fourth event with lethal potential was exposure to near vacuum, aerodynamic accelerations, and cold temperatures.**
   The ACES system is certified to operate at a maximum altitude of 100,000 feet, and certified to survive exposure to a maximum velocity of 560 knots equivalent air speed. The operating envelope of the orbiter is much greater than this. The actual maximum protection environment for the ACES is not known.

   The recommendation to strengthen the weak areas of the suit system will increase the probability of survival through this type of event as well.

5. **The final event with lethal potential was ground impact.**
   The ACES system provides protection from ground impact with a parachute system. The current parachute system requires manual action by a crew member to activate the opening sequence.

   The earlier recommendation that future survival systems should not rely on manual activation will address this lethal event as well.

## Crew survival accident investigation

Although this investigation was a follow-up to the actual mishap investigation, there were many findings, conclusions, and recommendations that apply to spacecraft accident investigations in general and crew survival investigations in particular. The recommendations address both NASA processes and investigation processes in general.

This crew survival investigation was difficult to do because of both the technical complexity and the sensitivity of the topic. Other Return to Flight activities took priority over the crew survival follow-up investigation, leading to resource issues for the SCSIIT.

### *Key Recommendations*

- In the event of a future fatal spacecraft mishap, NASA should place a high priority on the performance of crew survival investigations.
- Medically sensitive and personal effects data should always be protected to preserve the privacy of the victims and their families. 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 future crew survival investigations are performed.
- Stress debriefings and other counseling services should be available to those experiencing ongoing stress as a result of participating in the debris recovery and investigation.
- Data management proved to be critical to the investigation in many areas. Specifically, location of and access to debris recovery ground coordinates, database documentation, and configuration management of versions of reports, briefings, and analyses were all important. Many elements were highly successful, but improvements could be made. Global Positioning System coordinates for recovered items should be standardized.[3] Configuration control for documents was not initiated as early as it could have been. Additionally, *Challenger* supporting data were generally not cataloged by references to crew survival or the crew module. It was extremely difficult to find relevant data. *Challenger* debris is unpreserved and inaccessible for analysis. Report generation should start early in the investigation process to help provide consistency and documentation. Preservation of debris and data that may be of value in future investigations should be continued using the approach of the *Columbia* Research and Preservation Team. Accident investigation teams should develop standard templates across all areas of data management for the types of investigations performed for *Columbia*.

[3]STS-107 *Columbia* Reconstruction Report, NSTS-60501, June 30, 2003, p. 142.

- Configuration management documentation of seat and suit components had a significant impact on the investigation – positive when done well and negative when inadequate. Serialization and quality marking requirements and policies for space flight hardware should be developed to the lowest component level practical to aid in accident investigation.
- There were many findings relative to ground-based video of the entry and mishap. The video was a vital source of data for understanding the accident, especially after telemetry was no longer available. Video was used to timeline key events and to help understand the motion and trajectory of the objects of interest. One video that proved important had been mis-categorized initially, when the timeline of the accident was not yet understood, and was not used until very late in the investigation. After a mishap timeline has been established, videos should be re-reviewed to ensure relevant data are being used.

### Other

Thermal analysis of some titanium components showed that entry heating alone was insufficient to cause the damage seen. Shock wave interactions can account for the damage to some extent, but arc jet testing showed that titanium combustion may also have played a role. In many other cases, evaluation of material performance in the low-pressure, high-temperature environment did not exist. Studies should be performed to further characterize the material behavior of titanium in entry environments to better understand optimal space applications of this material.

## Summary

In summary, many findings, conclusions, and recommendations have resulted from this investigation that will be valuable both to spacecraft designers and accident investigators. This report provides the reader an expert level of knowledge regarding the sequence of events that contributed to the loss of *Columbia*'s crew on February 1, 2003 and what can be learned to improve the safety of human space flight for all future crews. It is the team's expectation that readers will approach the report with the respect and integrity that the subject and the crew of *Columbia* deserve.

# Report Format

The *Executive Summary* highlights the intention of the investigation and key results.

*Introduction* explains the purpose and scope of the report and summarizes key results.

*Conclusions and Recommendations* contains a brief summary of all conclusions and recommendations.

Chapter 1 Integrated Story provides the sequence of events of the mishap that related to the crew.

*1.1 Integrated Investigation Results* brings together into one integrated story the results from the various aspects of the investigation.

*1.2 Master Timeline* provides a reference timeline of key events including vehicle configuration and status, crew activities, and changing circumstances.

Chapters 2 and 3 provide detailed insight into the examination, analysis, and understanding of evidence and results. Findings, conclusions, and recommendations are embedded in these chapters. The different sections address the accident from the individual subject matter perspective. By intent, these sections contain highly interrelated data and information that are shared or duplicated. This repetition provides mutually supportive information from the different aspects of the investigation. It is expected that future technical readers may only have interest in a few of these sections, so repetition was accepted for completeness so that each section could stand on its own. To aid future investigations, this report contains substantially more technical data and information than is normally contained in an aviation mishap report.

Chapter 2 Vehicle Failure Assessment describes the vehicle analyses. These were used to understand what happened to the orbiter and the crew module structures.

*2.1 Motion and Thermal Analyses* describes the analyses performed to understand the motion of the vehicle and crew module and the resultant loads acting upon the crew and structure. Thermal analyses rely heavily on trajectory assessments and, therefore, are also covered in this section.

*2.2 Orbiter Breakup Sequence* describes the analyses performed to understand the sequence in which the orbiter breakup occurred.

*2.3 Crew Cabin Pressure Environment Analysis* describes the integrated analyses used to understand the cabin pressure conditions of the crew module during the mishap.

*2.4 Forebody Breakup Sequence* describes the analyses performed to understand the sequence of the breakup of the forebody (crew module and forward fuselage) of the orbiter.

Chapter 3 Occupant Protection addresses crew and crew equipment special assessments.

*3.1 Crew Seats* and *3.2 Crew Worn Equipment* address the function and performance of the equipment intended to protect the crew in the experienced motion, load, and thermal environment.

*3.3 Crew Training* addresses procedures and preparations associated with examined events and activities.

*3.4 Crew Analysis* encompasses the awareness the crew had of events, crew actions in response to the events, and the events of lethal potential to which the crew was exposed.

*Chapter 4 Investigative Methods and Processes* explains the structure and makeup of the team, the approach taken to conduct the investigation, a description of the tools used, and the collection and management of data and information.

*Future Work* addresses suggestions for forward work.

*Appendix A* contains a tutorial on ballistic trajectories, providing more conceptual insight into a critical topic discussed extensively in the report.

# Conclusions and Recommendations

**The first event with lethal potential was depressurization of the crew module, which started at or shortly after orbiter breakup.**

***Conclusion L1-1.*** After loss of control at GMT[4] 13:59:37 and prior to orbiter breakup at GMT 14:00:18, the *Columbia* cabin pressure was nominal and the crew was capable of conscious actions. (p. 2-89, p. 3-82)

***Conclusion L1-2.*** 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. (p. 2-93)

***Conclusion L1-3.*** The crew was exposed to a pressure altitude above 63,500 feet, indicating that the cabin depressurization event occurred above this altitude. (p. 2-91, p. 3-83)

***Conclusion L1-4.*** The crew was not exposed to a cabin fire or thermal injury prior to depressurization, cessation of breathing, and loss of consciousness. (p. 3-89)

***Conclusion L1-5.*** The depressurization incapacitated the crew members so rapidly that they were not able to lower their helmet visors. (p. 2-90, p. 3-84)

***Recommendation L1-1.*** Incorporate objectives in the astronaut training program that emphasize understanding the transition from recoverable systems problems to impending survival situations. (p. 3-66)

***Recommendation L1-2.*** 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 crew member can perform all operations without compromising the configuration of the survival suit during critical phases of flight. (p. 3-38, p. 3-86)

***Recommendation L1-3/L5-1.*** Future spacecraft crew survival systems should not rely on manual activation to protect the crew. (p. 3-20, p. 3-44, p. 3-84)

***Recommendation L1-4.*** Future suit design should incorporate the ability for crew members to communicate visors-down without relying on spacecraft power. (p. 3-82)

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**The second event with lethal potential was unconscious or deceased crew members exposed to a dynamic rotating load environment with nonconformal helmets and a lack of upper body restraint.**

***Conclusion L2-1.*** Between orbiter breakup and the forebody[5] breakup, the free-flying forebody was rotating about all three axes at approximately 0.1 rev/sec and did not trim into a specific attitude. (p. 2-23)

[4]Greenwich Mean Time.
[5]The orbiter forebody consists of the crew module, forward fuselage, forward Reaction Control System, nose cap, and nose landing gear.

***Conclusion L2-2.*** The seat inertial reels did not lock. (p. 3-20)

***Conclusion L2-3.*** Lethal injuries resulted from inadequate upper body restraint and protection during rotational motion. (p. 3-20, p. 3-87)

***Recommendation L2-1.*** Assemble a team of crew escape instructors, flight directors, and astronauts to assess orbiter procedures in the context of ascent, deorbit, and entry contingencies. Revise the procedures with consideration to time constraints and the interplay among the thermal environment, expected crew module dynamics, and crew and crew equipment capabilities. (p. 3-67)

***Recommendation L2-2.*** Prior to operational deployment of future crewed spacecraft, determine the vehicle dynamics, entry thermal and aerodynamic loads, and crew survival envelopes during a vehicle loss of control so that they may be adequately integrated into training programs. (p. 2-10, p. 2-29, p. 3-67)

***Recommendation L2-3.*** Future crewed spacecraft vehicle design should account for vehicle loss of control contingencies to maximize the probability of crew survival. (p. 3-67)

***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. (p. 3-20, p. 3-53, p. 3-87, p. 3-88)

***Recommendation L2-5.*** Incorporate features into the pass-through slots on the seats such that the slot will not damage the strap. (p. 3-24)

***Recommendation L2-6.*** Perform dynamic testing of straps and testing of straps at elevated temperatures to determine load-carrying capabilities under these conditions. Perform testing of strap materials in high-temperature/low-oxygen/low-pressure environments to determine materials properties under these conditions. (p. 3-27)

***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. (p. 3-53, p. 3-87)

***Recommendation L2-8.*** The current shuttle inertial reels should be manually locked at the first sign of an off-nominal situation. (p. 3-21, p. 3-88)

***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. (p. 3-88)

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**The third event with lethal potential was separation from the crew module and the seats with associated forces, material interactions, and thermal consequences. This event is the least understood due to limitations in current knowledge of mechanisms at this Mach number and altitude. Seat restraints played a role in the lethality of this event.**

***Conclusion L3-1.*** Complete loss of hydraulic pressure to the aerosurfaces resulting from the breach in the left wing was the probable proximal cause for the vehicle loss of control. (p. 2-6)

***Conclusion L3-2.*** The breakup of both *Challenger* and *Columbia* resulted in most of the $X_o$ 582[6] ring frame bulkhead remaining with the crew module or forebody. (p. 2-84)

[6] $X_o$ 582 refers to the location of the bulkhead in the orbiter coordinate frame. This bulkhead is immediately aft of the crew module.

***Conclusion L3-3.*** The actual maximum survivable altitude for a breakup of the space shuttle is not known. (p. 2-29)

***Conclusion L3-4.*** The seat restraint system caused lethal-level injuries to the unconscious or deceased crew members when they separated from the seat. (p. 3-88)

***Recommendation L3-1.*** Future vehicles should incorporate a design analysis for breakup to help guide design toward the most graceful degradation of the integrated vehicle systems and structure to maximize crew survival. (p. 2-87, p. 2-139, p. 3-88)

***Recommendation L3-2.*** Future vehicles should be designed with a separation of critical functions to the maximum extent possible and robust protection for individual functional components when separation is not practical. (p. 2-6)

***Recommendation L3-3.*** Future spacecraft design should incorporate crashworthy, locatable data recorders for accident/incident flight reconstruction. (p. 2-36)

***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. (p. 3-53)

***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. (p. 3-46, p. 3-63)

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**The fourth event with lethal potential was exposure to near vacuum, aerodynamic accelerations, and cold temperatures.**

***Conclusion L4-1.*** Although the advanced crew escape suit (ACES) system is certified to operate at a maximum altitude of 100,000 feet and to survive exposure to a maximum velocity of 560 knots equivalent air speed, the actual maximum protection environment for the ACES is not known. (p. 3-46)

See **Recommendation L3-5/L4-1** above, which also addresses this event.

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**The final event with lethal potential was ground impact.**

***Conclusion L5-1.*** The current parachute system requires manual action by a crew member to activate the opening sequence. (p. 3-44)

See **Recommendation L1-3/L5-1** above, which also addresses this event.

## Crew Survival Investigations for Spacecraft Accidents

***Recommendation A1.*** In the event of a future fatal human space flight mishap, NASA should place high priority on the crew survival aspects of the mishap both during the investigation as well as in its follow-up actions using dedicated individuals who are appropriately qualified in this specialized work. (p. 4-5, p. 4-9)

***Recommendation A2.*** Medically sensitive and personal debris and data should always be available to designated investigators but protected from release to preserve the privacy of the victims and their families. (p. 4-11)

***Recommendation A3.*** Resolve issues and document policies surrounding public release of sensitive information relative to the crew during a NASA accident investigation to ensure that all levels of the agency understand how future crew survival investigations should be performed. (p. 4-11)

***Recommendation A4.*** Due to the complexity of the operating environment, in addition to traditional accident investigation techniques, spacecraft accident investigators must evaluate multiple sources of information including ballistics, video analysis, aerodynamic trajectories, and thermal and material analyses. (p. 4-9)

***Recommendation A5.*** Develop equipment failure investigation marking (“fingerprinting”) requirements and policies for space flight programs. Equipment fingerprinting requires three aspects to be effective: component serialization, marking, and tracking to the lowest assembly level practical. (p. 3-35, p. 3-63)

***Recommendation A6.*** Standard templates for accident investigation data (document, presentation, data spreadsheet, etc.) should be used. All reports, presentations, spreadsheets, and other documents should include the following data on every page: title, date the file was created, date the file was updated, version (if applicable), person creating the file, and person editing the file (if different from author). (p. 4-10)

***Recommendation A7.*** To aid in configuration control and ensure data are properly documented, report generation must begin early in the investigation process. (p. 4-10)

***Conclusion A8-1.*** Spacecraft accidents are rare, and each event adds critical knowledge and understanding to the database of experience. (p. 3-84, p. 4-11)

***Recommendation A8.*** As was executed with *Columbia*, spacecraft accident investigation plans must include provisions for debris and data preservation and security. All debris and data should be cataloged, stored, and preserved so they will be available for future investigations or studies. (p. 3-85, p. 4-11)

***Recommendation A9.*** Post-traumatic stress debriefings and other counseling services should be available to those experiencing ongoing stress as a result of participating in the debris recovery and investigation. Designated personnel should follow up on a regular basis to ensure that individual needs are being met. (p. 4-12)

***Recommendation A10.*** Global Positioning System receivers used for recording the latitude/longitude of recovered debris must all be calibrated the same way (i.e., using the same reference system), and the latitude/longitude data should be recorded in a standardized format.[7] (p. 4-25)

***Recommendation A11.*** All video segments within a compilation should be categorized and summarized. All videos should be re-reviewed once the investigation has progressed to the point that a timeline has been established to verify that all relevant video data are being used. (p. 2-49, p. 4-23)

[7]STS-107 *Columbia* Reconstruction Report, NSTS-60501, June 30, 2003, p. 142.

## ADDITIONAL CONCLUSIONS AND RECOMMENDATIONS

***Conclusion A13-1.*** Titanium may oxidize and combust in entry heating conditions dependent on enthalpy, pressure, and geometry. (p. 2-45)

***Conclusion A13-2.*** The heating from a Type IV shock-shock[8] impingement and titanium combustion (in some combination) likely resulted in the damage seen by the forward payload bay door rollers and the x-links.[9] (p. 2-45)

***Recommendation A13.*** Studies should be performed to further characterize the material behavior of titanium in entry environments to better understand optimal space applications of this material. (p. 2-46)

[8]This refers to a specific type of intersecting hypersonic shock waves and is discussed in Section 2.1.
[9]The x-links are fittings that attach the crew module to the forward fuselage of the orbiter (see Section 2.1).

# Chapter 1 – Integrated Story

# 1.1 Integrated Investigation Results

## 1.1.1 Events with lethal potential

There were five events identified with lethal potential to the crew.

**The first event with lethal potential was depressurization of the crew module, which started at or shortly after orbiter breakup.**

**The second event with lethal potential was unconscious or deceased crew members exposed to a dynamic rotating load environment with nonconformal helmets and a lack of upper body restraint.**

**The third event with lethal potential was separation from the crew module and the seats with associated forces, material interactions, and thermal consequences. This event is the least understood due to limitations in current knowledge of mechanisms at this Mach number and altitude. Seat restraints played a role in the lethality of this event.**

**The fourth event with lethal potential was exposure to near vacuum, aerodynamic accelerations, and cold temperatures.**

**The final event with lethal potential was ground impact.**

## 1.1.2 Integrated summary of events

This section provides an integrated summary of key events during the *Columbia* mishap as they relate to the crew and orbiter forebody (figures 1.1-1 and 1.1-2).[1] Figures 1.1-3 and 1.1-4 show depictions of the flight deck and middeck seats.

[1]The orbiter forebody consists of the crew module, forward fuselage, forward Reaction Control System (RCS), nose cap, and nose landing gear.

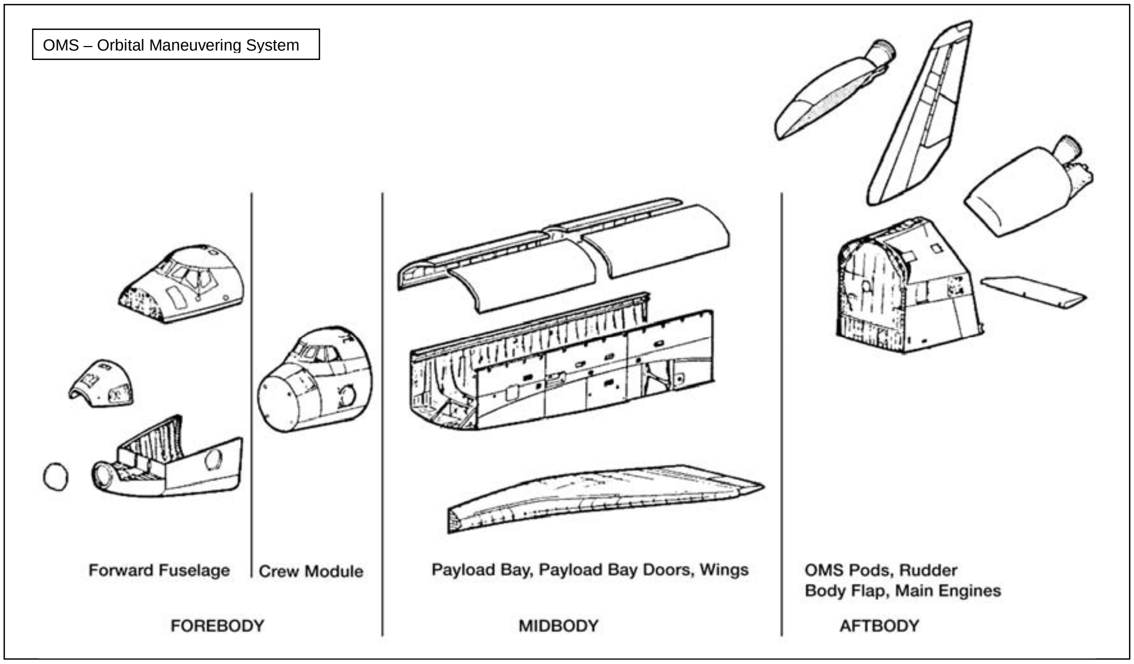


**Figure 1.1-1.** ***Depiction of the orbiter forebody, midbody, and aftbody elements*.**

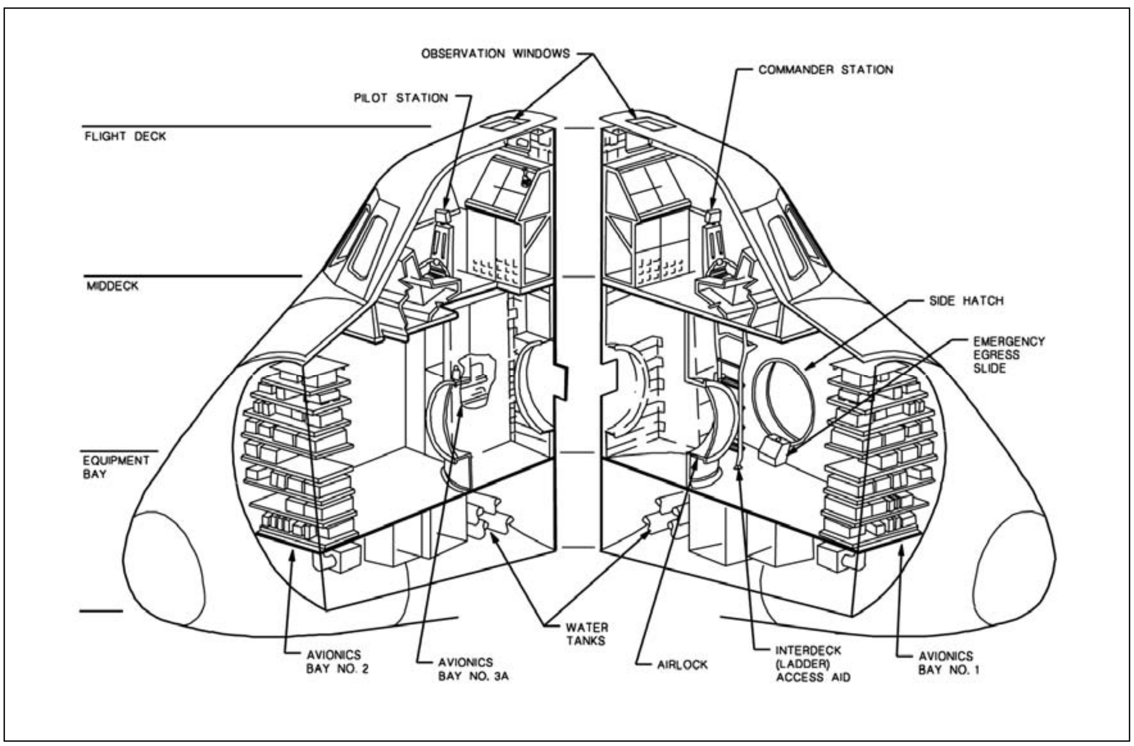


**Figure 1.1-2.** ***Depiction of the crew module flight deck and middeck within the forebody*. [Adapted from the Shuttle Operations Data Book]**

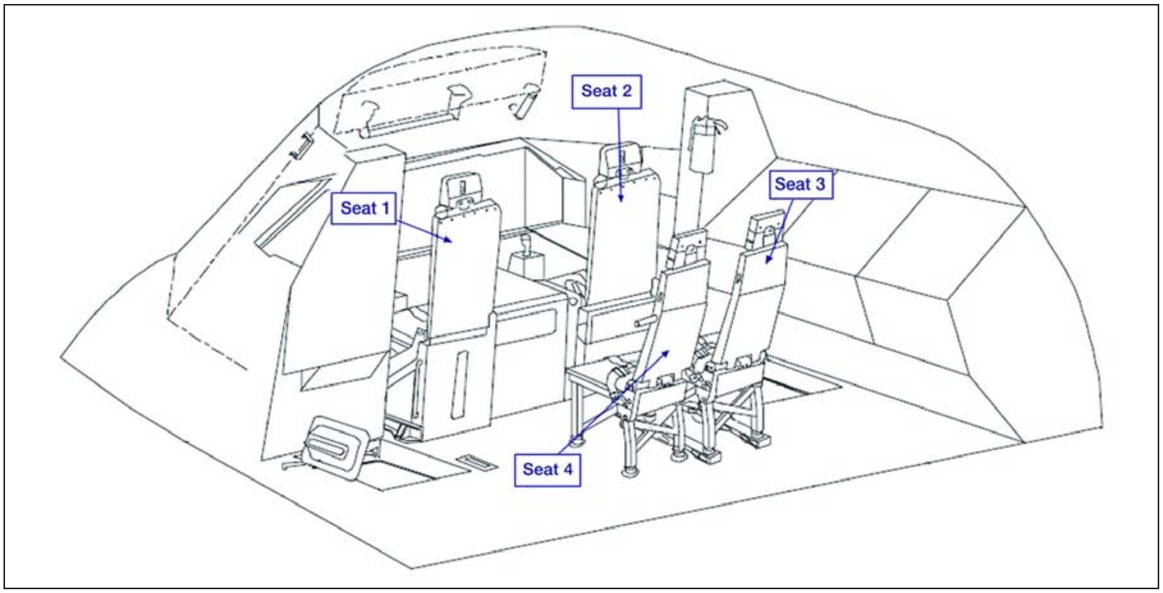


**Figure 1.1-3.** ***Depiction of the flight deck seats*.**

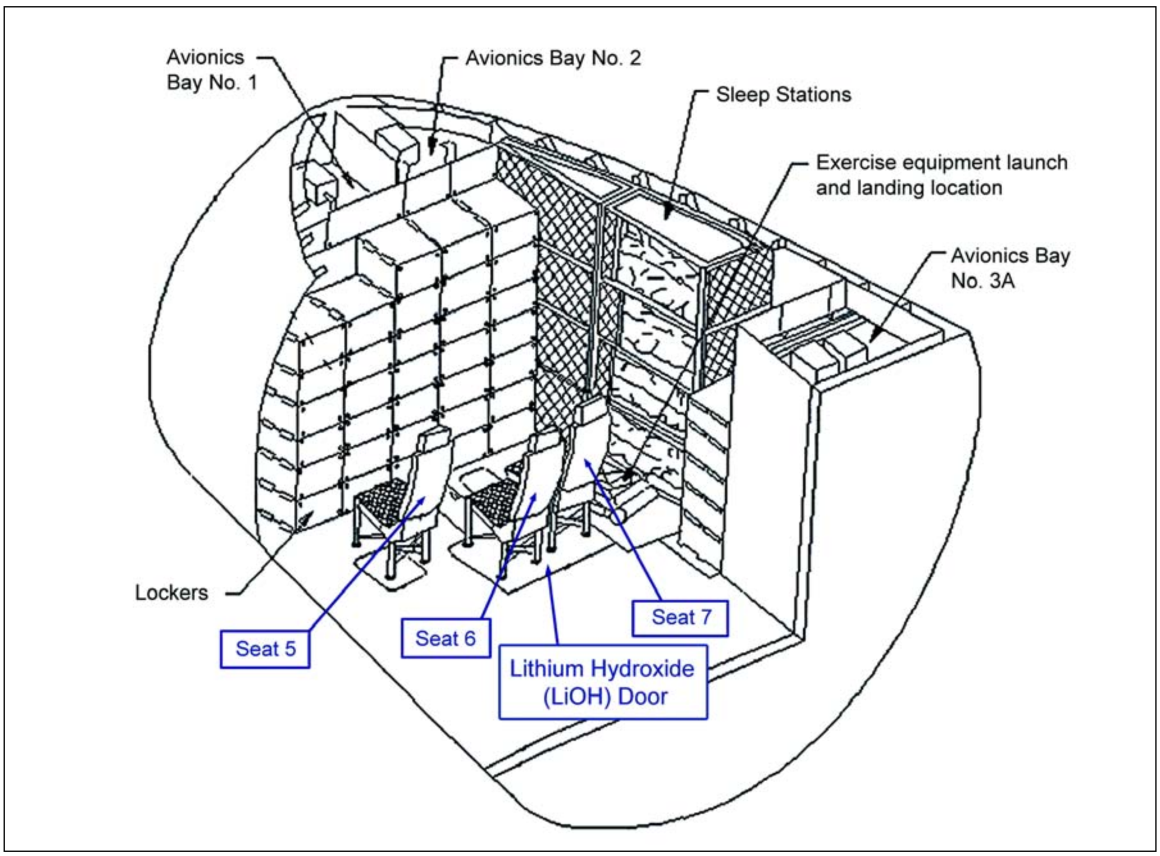


**Figure 1.1-4.** ***Depiction of the middeck seats*. [Adapted from the Shuttle Crew Operations Manual]**

This timeline begins at Greenwich Mean Time (GMT) 09:15:30 (entry interface (EI)–16119 seconds) and ends at GMT 14:35:00 (EI+3051) (by which time most debris items had impacted the ground). This timeline overlaps with the latter portion of the timeline of the *Columbia* Accident Investigation Board (CAIB) Report.[2] The cause of the mishap will not be discussed because it was fully covered in the CAIB Report.

This timeline is divided into six phases, based on key events. Each phase of the timeline is addressed in sequence.

- Phase 1 [GMT 09:15:30 (EI–16119) to GMT 13:44:09 (EI)]: From the beginning of the deorbit preparation portion of the mission to EI. 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 at EI. EI is defined as the time the orbiter descends through an altitude of 400,000 feet. At EI, *Columbia* was approximately 4,300 nautical miles from the landing site, traveling in excess of Mach 24.
- Phase 2 [GMT 13:44:09 (EI) to GMT 13:59:32 (EI+923)]: From EI to loss of signal (LOS). LOS is the loss of voice and real-time data transmissions from *Columbia*.
- Phase 3 [GMT 13:59:32 (EI+923) to GMT 14:00:18 (EI+969)]: 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,[3] and aftbody.[4] The CAIB timeline ends with the CE.
- Phase 4 [GMT 14:00:18 (EI+969) to GMT 14:00:53 (EI+1004)]: 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 (EI+1004) to GMT 14:01:10 (EI+1021)]: 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 (EI+1021) to approximately GMT 14:35:00 (EI+3051)]: From the TD to ground impact of the crew remains and the majority of the crew module debris.

Figure 1.1-5 shows the overall graphical timeline. This timeline represents the best fit to known and inferred data, but it is subject to some inherent uncertainty.

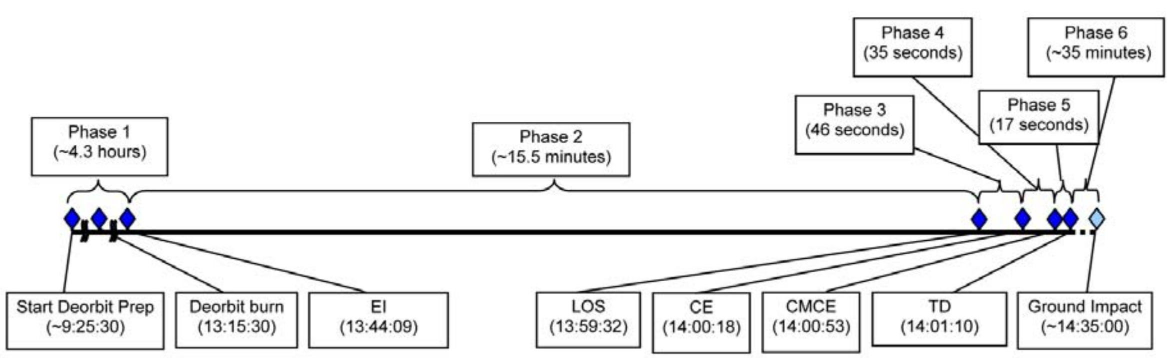


**Figure 1.1-5. *Overall timeline.***

[2]*Columbia* Accident Investigation Board Report, Volume I, August 2003, pp. 40-41.
[3]The midbody consists of the payload bay and wings.
[4]The aftbody consists of the aft fuselage structure and internal components, the main engines, the left and right OMS pods (including the aft RCS), and the vertical tail.

The early portion of the timeline was developed from objective data such as on-board and downlinked vehicle instrumentation data, on-board video data recovered from the debris, and air-to-ground crew communications. As the timeline progresses into the later phases, the analysis increasingly relied on derived data such as results from ballistic analyses, thermal analyses, ground-based video, and recovered debris. All available data sets were integrated for this analysis.

The environmental conditions experienced by the crew are the focus for each phase. The conditions of interest are atmospheric pressure, thermal situation, and acceleration.[5] The data and methods used to understand the environment are described individually for each phase, and known and inferred events are integrated with the environmental information into a time-based sequence.

#### 1.1.2.1 *Phase 1: Deorbit preparation to entry interface*
**[GMT 09:15:30 (EI–16119) to GMT 13:44:09 (EI)]**
**4 hours, 28 minutes, 39 seconds in duration**

This section discusses events affecting the crew from the deorbit preparation timeframe (4 hours prior to the deorbit burn) until EI, about 4 hours and 20 minutes in total. Figure 1.1-6 shows a timeline of this phase. All times are in GMT.

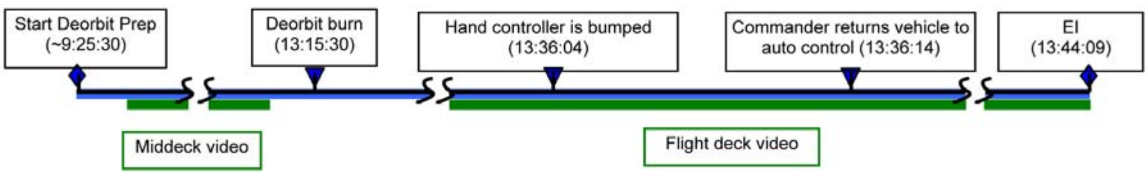


**Figure 1.1-6. *Phase 1 timeline with key events*. Green bars represent times when video data are available. Blue bar represents when voice and telemetry transmissions are available (throughout this phase).**

The principal sources of data for this phase are orbiter transmissions and recovered on-board video of middeck and flight deck activities. Transmissions include vehicle general purpose computer (GPC)-generated telemetry and audio transmissions made by the crew. The recovered middeck video shows the crew involved in deorbit preparation checklist activities about 2 hours prior to EI from approximately GMT 11:40:00 (EI–7449) to GMT 12:10:00 (EI–5649). The recovered flight deck video shows the flight deck crew seated and preparing for entry. This video was time-synchronized with audio transmissions and crew keystrokes recorded on the ground. The time duration of the video spanned across EI, showing activities from GMT 13:35:34 (EI–515) to GMT 13:48:45 (EI+276).

The crew performed cabin stow activities the day prior to entry and on the morning of entry day. Items were stowed and secured to prevent articles from coming loose in the cabin during entry. Objects aboard the orbiter are stowed in lockers, or are bagged and strapped down in the airlock and in the SPACEHAB module. The only "loose" items on the middeck or flight deck are clips, kneeboards, checklists, timers, writing instruments, drink bags used for fluid loading, and some crew escape equipment (CEE) prior to donning.[6] Any items that are not worn are restrained with VELCRO® or tethers.

The recovered middeck and flight deck videos show that all seats in the crew module were installed and the escape pole was in the process of being installed (figure 1.1-7). Recovered debris analysis shows that the pole installation was completed.

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[5]Discussions of acceleration will use the Aerospace Medical Association convention. References to the standard gravitational acceleration of the Earth will use the lowercase "g." References to acceleration acting on objects and crew members in multiples of the Earth's gravitational acceleration will use the uppercase "G."
[6]CEE consists of things such as the g-suit, advanced crew escape suit (ACES), parachute, etc. See Section 3.2 Crew Worn Equipment for details.

The cabin stow and deorbit preparation portion of a shuttle mission is a busy period; according to many experienced crew members, shuttle crews often struggle to complete all actions in the time allotted, giving priority to time-critical orbiter systems activities. It is an accepted operational practice for a crew to reorder the tasks as necessary. The middeck video, which ended approximately an hour before the deorbit burn, indicates that the *Columbia* crew members were using their discretion to order their tasks. As a result, the middeck video cannot be precisely time-synchronized using either the published checklist or the crew-specific plan.

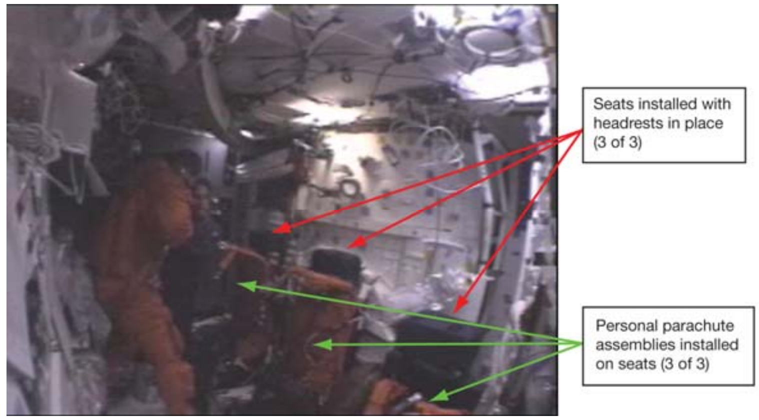


**Figure 1.1-7.** ***This early image from the recovered middeck video shows progress of the crew in deorbit preparation tasks.***

At 45 minutes prior to time of ignition (TIG)–45 minutes), the Commander (CDR) and Pilot (PLT) began working tasks in the entry checklist. By TIG–30 minutes, the rest of the crew should have completed items in the deorbit preparation checklist and transitioned to the entry checklist.

Deorbit burn occurred at GMT 13:15:30 (EI–1719/TIG+0). The burn was nominal, and *Columbia* began entry into the Earth's atmosphere. Per the checklist, a few tasks remain to be completed after the burn, including stowing the last laptop computer, which requires a crew member to be out of the seat. Crew equipment configuration items on the entry checklist (all crew members seated and strapped in, helmets and gloves donned, and suit pressure checked) were not entirely completed prior to EI. At least one crew member was not wearing the helmet and several were not wearing gloves.

The flight deck video shows that conditions on the flight deck were nominal during the entire time of the video recording. The video shows the flight deck crew finishing most checklist tasks close to the planned times. However, one flight deck crew member did not yet have gloves in place in time for the ACES pressure check. One event of note occurred at GMT 13:36:04 (EI–485/TIG+1234) when the CDR bumped the rotational hand controller (RHC) accidentally. Movement of the RHC out of the centered position caused the digital autopilot (DAP) to "downmode" from the "Auto" mode to "Inertial" mode. When this occurred, a "DAP DOWNMODE RHC" caution and warning message was displayed, the INRTL button on the C3 panel was illuminated, and a tone, which can be heard in the recovered flight deck video, was annunciated. An immediate reactivation of the autopilot was performed by the CDR. The capsule communicator (CAPCOM) in the Mission Control Center (MCC) then requested the CDR to enter "another Item 27," which is a command to fully recover the vehicle attitude from the bumped RHC.

Bumping of the RHC is a relatively common occurrence by either the PLT or the CDR because the ACES is bulky and the area near the controls is confined. Such RHC bumps with prompt recovery represent a very low hazard to the crew. The original design specifications of the orbiters were for a shirtsleeve environment (i.e., no special clothing needed to be worn). Although pressure suits have been worn during launch and entry since the *Challenger* accident, no modifications were made to displays and controls to accommodate the ACES.

### 1.1.2.2 *Phase 2: Entry interface to loss of signal*
**[GMT 13:44:09 (EI) to GMT 13:59:32 (EI+923)]**
**15 minutes, 23 seconds in duration**

This section discusses events affecting the crew from EI (GMT 13:44:09) to LOS (the last audio and real-time telemetry transmission received from *Columbia*) at GMT 13:59:32 (EI+923).[7] This section discusses *Columbia*'s entry and the minimal indications available to *Columbia*'s crew and the MCC that *Columbia*'s structure was compromised. Ground-based video of the orbiter's flight is first available in this phase. This phase was approximately 15 minutes long. Figure 1.1-8 shows the timeline and key events for Phase 2.

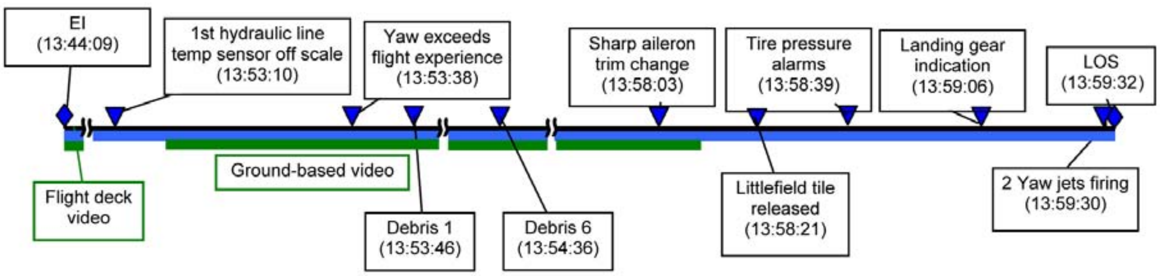


**Figure 1.1-8. *Phase 2 timeline with key events*. Green bars represent times when video data are available. Blue bar represents when the Modular Auxiliary Data System/orbiter experiment (MADS/OEX) recorder data, and voice and telemetry transmissions are available (throughout this phase).**

The sources of information that provided data for the investigation of Phase 2 are: orbiter transmissions; the MADS/OEX recorder; recovered flight deck video; ground-based video; and recovered debris. The MADS/OEX recorder was an on-board data collection recording system located in the crew module. Recorded data parameters consisted of structural temperature, strain, and accelerations from sensors located throughout the orbiter and concentrated in the left wing. This system was unique to *Columbia*. The MADS/OEX system did not display data to the crew or transmit telemetry to the MCC. Consequently, no MADS/OEX data were available in real time. The MADS/OEX recorder was recovered intact in the debris field and the data were recovered. The recovered flight deck video, beginning in Phase 1 at GMT 13:35:34 (EI–515), contains data through GMT 13:48:45 (EI+276), 4 minutes into this phase. Ground-based imagery recorded the entry of *Columbia* from the coast of California to the final breakup over Texas, with a gap in coverage from eastern New Mexico to western Texas.

Crew cabin pressure and the thermal environment inside the cockpit were nominal throughout this phase. At EI, atmospheric drag on the orbiter began to gradually increase. The initial roll and subsequent roll reversals caused accelerations of up to 0.8 G during entry. During this period of a shuttle mission, crew members typically experience heaviness, dizziness, and sometimes stomach awareness or mild nausea. Based upon telemetry, accelerations were nominal despite the damage-induced aerodynamic changes to the orbiter. The orbiter was shedding debris during at least part of this phase, although changes in mass properties were small and no detectable load spikes were noted by the MCC, reported by the crew, or found in post-mishap analysis data. No anomalous orbiter systems conditions were displayed to the crew until the end of this phase.

At EI, the vehicle also began to experience the thermal effects of the Earth's atmosphere. Shock waves due to the vehicle's hypersonic velocities and the frictional effect of the atmosphere began to heat the orbiter's surface. Temperatures on the surface of the orbiter during entry vary by location, with the nose and leading edge of the wings experiencing temperatures greater than 2,800°F (1,538°C). The Thermal Protection

[7]Although LOS is defined here as the loss of audio and real-time data transmissions, some instrument-based telemetry was received shortly into Phase 3; this will be discussed in the next section.

System (TPS) of the orbiter consists of reinforced carbon-carbon (RCC) panels, tile, and thermal blankets, and is designed to protect the orbiter's structure from this nominal entry heating.

The CAIB concluded that the breach in the TPS on the leading edge of the left wing allowed hot gas to penetrate the wing and to work its way aft and inboard, toward the midbody fuselage and left main landing gear wheel well (figure 1.1-9). CAIB analysis showed that this eventually caused significant internal damage to *Columbia*'s left wing, changing the wing's aerodynamic properties. There were no indications to the crew of this ongoing damage. Throughout phase 2, the orbiter Flight Control System (FCS) corrected for the damage-induced yaw and roll moments, and control of the orbiter was maintained.[8]

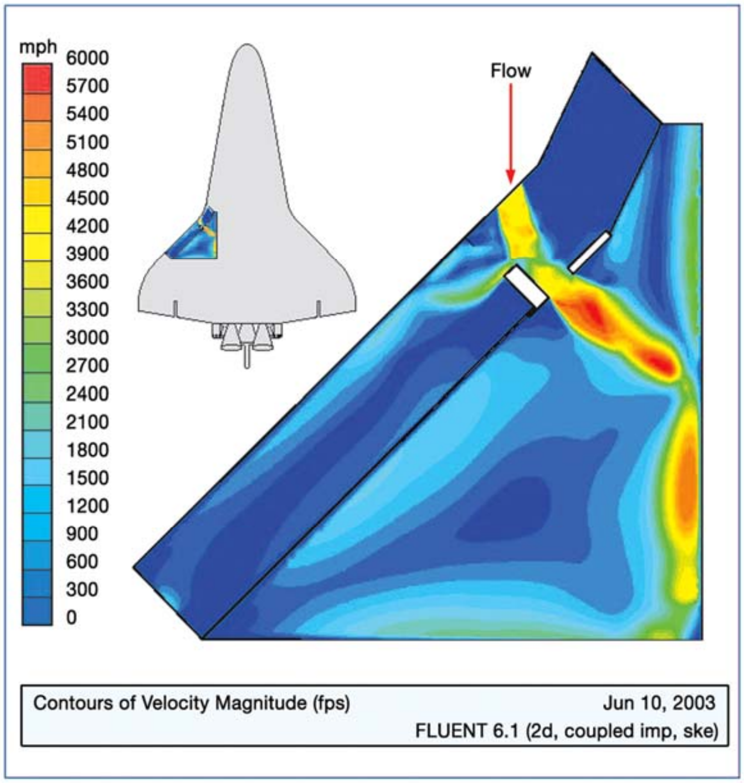


**Figure 1.1-9.** ***The effects of wing Thermal Protection System damage as reported by the* Columbia *Accident Investigation Board.***

The recovered flight deck video shows the CDR requesting a suit pressure integrity check from the other crew members. Suit pressurization checks for the CDR, PLT, and Mission Specialist (MS) 4 were observed in the video and validated with telemetry of the oxygen ($O_2$) system. After the ACES pressure checks, the crew members turned off the flow of $O_2$ to the ACES and opened their visors. The $O_2$ must be turned off because the suit vents $O_2$-enriched air into the cabin with the visor down and $O_2$ flowing. Venting $O_2$-enriched air eventually creates an increased concentration of $O_2$, leading to an increased fire hazard. To prevent carbon dioxide buildup inside the helmet, visors are returned to the open position. Open visors have the added benefit of improved crew comfort and communication. Telemetry data were consistent with one or two more suit pressure integrity checks occurring after the end of the flight deck video. It could not be determined which crew member(s) performed these checks. The video, which ended at GMT 13:48:45 (EI+276), shows the four flight deck crew members suited, seated, and strapped in with helmets donned. All except one had fully donned and connected gloves. The recovered flight deck video indicates that the crew was not aware of any problems.

At GMT 13:49:32 (EI+323), a nominal roll to the right was completed for energy management. At GMT 13:50:53 (EI+404), *Columbia* started the expected 10-minute window of nominal peak heating.[9]

At GMT 13:51:46 (EI+457), the inertial sideslip (yaw) angle began a negative trend (yaw to the left), although the angle remained within previous flight experience for almost 2 minutes (figure 1.1-10). At GMT 13:52:05 (EI+476), the yaw moment changed due to increased drag from the damaged left wing; the orbiter's FCS commanded the aileron trim to compensate (figure 1.1-11). Neither the yaw moment change nor the aileron trim change was obvious to either the MCC or the crew as an off-nominal condition, although post-accident analysis concluded that this was the first indication of the orbiter's response to the

[8]*Columbia* Accident Investigation Board Report, Volume I, August 2003, p. 78.
[9]*Columbia* Accident Investigation Board Report, Volume I, August 2003, p. 38.

changing aerodynamic properties brought about by the left wing damage. Otherr post-mishap analysis determined that damage inside the wing began no later than GMT 13:52:17 (EI+488).[10]

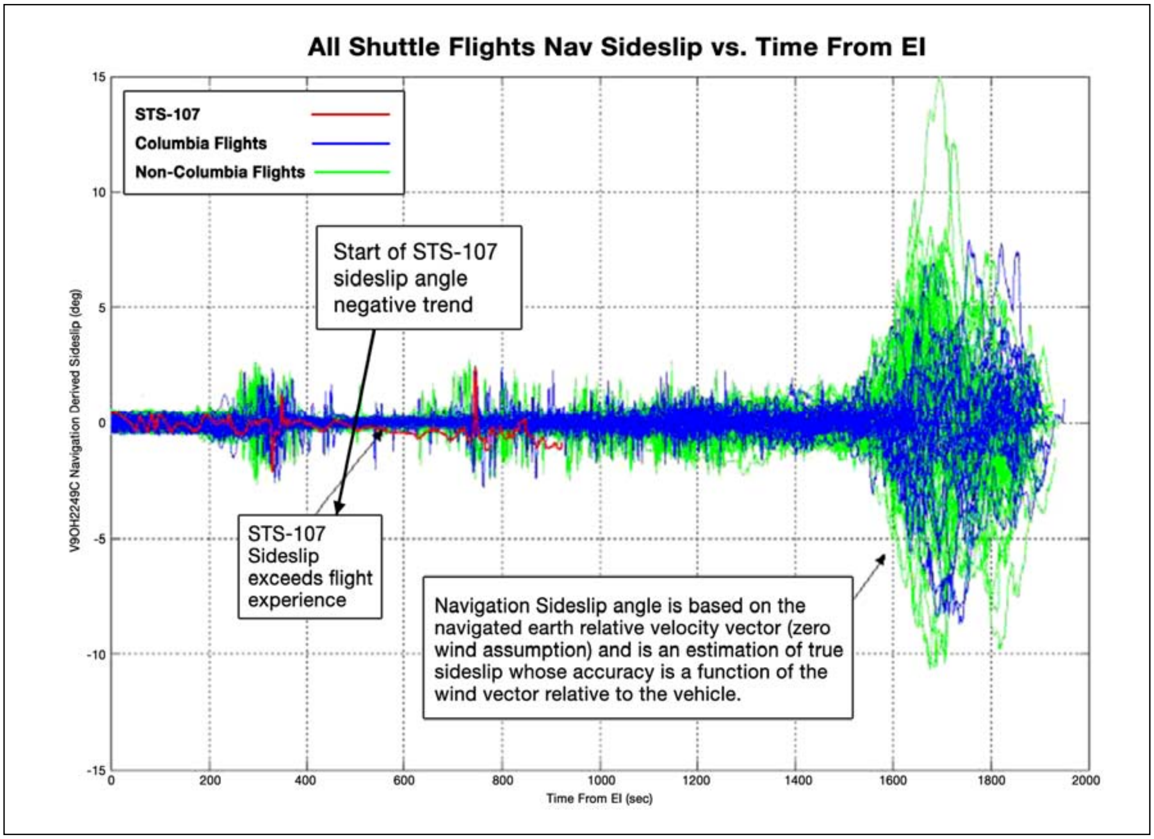


**Figure 1.1-10.** ***Negative trend starts at GMT 13:51:46 (EI+457) and exceeds flight experience at GMT 13:53:38 (EI+569).***[11]

[10]*Columbia* Accident Investigation Board Report, Volume I, August 2003, pp. 68 and 71.
[11]Integrated Entry Environment Team Final Report, May 30, 2003, Figure 6.6-2, p. 30; taken verbatim from document.

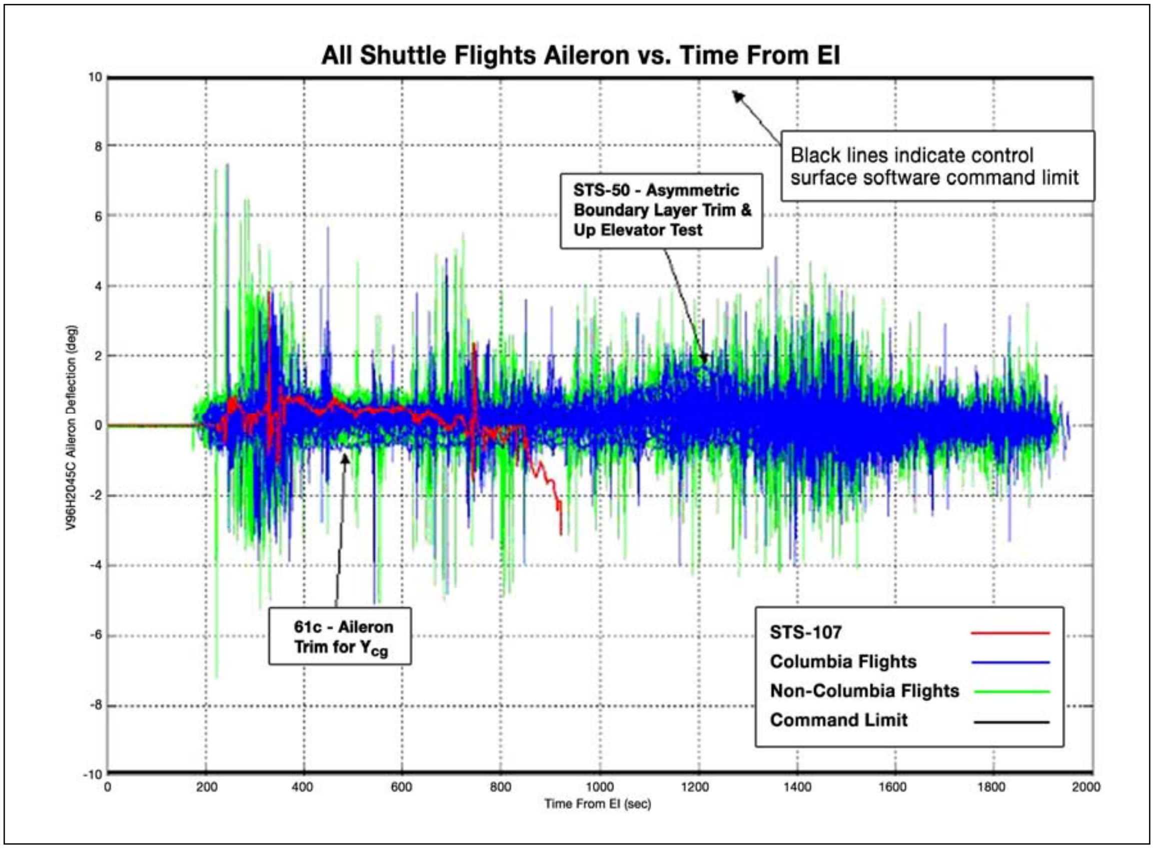


**Figure 1.1-11.** ***The sharp divergence from previous flight experience starts at approximately GMT 13:58:19 (EI+850).***[12]

The left main landing gear brake line in the inboard sidewall of the wheel well began to show an off-nominal temperature rise rate at GMT 13:52:17 (EI+488).

MCC personnel became aware of an off-nominal flight condition when four hydraulic return line temperature sensors in the left wing went off-scale low from GMT 13:53:10 (EI+541)[13] to GMT 13:53:36 (EI+567). A sensor suddenly going off-scale usually indicates a failure of the sensor or the wiring. Loss of an individual sensor for various reasons has occurred in previous missions. However, the simultaneous failure of multiple sensors from separate redundant systems was an event outside previous flight experience. These temperature data were not available to the crew and the crew was not notified of these indications. The loss of sensors generated concern in the MCC, and investigation by the flight control team began immediately.

Ground-based video coverage of *Columbia* was acquired by videographers unassociated with NASA at GMT 13:53:15 (EI+546).[14] Figure 1.1-12 is the first ground-based image of *Columbia* acquired. The bright spot circled is the "orbiter envelope" and is the nominally produced hot gas and plasma that surround the orbiter during entry. The actual shape of the orbiter (and most debris) cannot be seen in any non-telescopic-based video; only the surrounding hot gas/plasma envelope is visible.

[12]Integrated Entry Environment Team Final Report, May 30, 2003, Figure 6.6-1, p. 30; taken verbatim from document.
[13]*Columbia* Accident Investigation Board Report, Volume I, August 2003, description of these sensor failures.
[14]All video frames of the orbiter prior to GMT 13:59:32 (EI+923) were processed by the STS-107 Image Analysis Team. Details of video processing can be found in the *Columbia* Accident Investigation Board Report, Volume III, Appendix E.2, STS-107 Image Analysis Team Final Report, October 2003. All videos are assumed to have an approximately 1-second error.

*Columbia* crossed the California coastline at GMT 13:53:26 (EI+557).

At GMT 13:53:38 (EI+569), the sideslip angle (left yaw) exceeded all previous flight experience (figure 1.1-10).

The first known debris shedding event on entry was identified as Debris 1 and most likely originated from the left wing. Debris 1 becomes visible on ground-based video at GMT 13:53:46 (EI+577). Later ballistic analysis estimated a release time of GMT 13:53:44.8 (EI+575).[15] Luminosity measurements and calculated rates of deceleration were used to determine that the mass was < 8 lbs.[16] Figure 1.1-13 shows the orbiter and the debris.


**Figure 1.1-12. *This is the first frame of ground-based video. Columbia* is circled. Time 1 (TM1) shows the Greenwich Mean Time. The Pacific Standard Time displayed on the lower portion of the image is inexact.**

The Mechanical, Maintenance, Arm, and Crew Systems (MMACS) officer in the MCC notified the Flight Director of the off-scale low hydraulic line temperature sensors at GMT 13:54:24 (EI+615).

The brightest debris shedding event that occurred in this phase, Debris 6, is first visible on video at GMT 13:54:36 (EI+627) (figure 1.1-14). Ballistic estimates determined that the actual release time was 4 seconds earlier. Luminosity measurements and calculated rates of deceleration were used to determine that the mass was probably a few hundred pounds.[17] There were no data from sensors, instrumental indications, or apparent crew recognition of this debris loss.

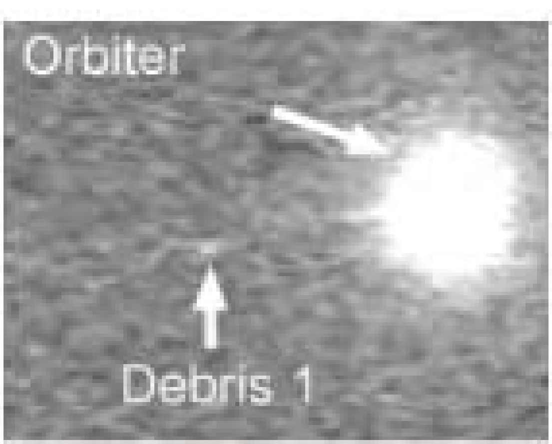


**Figure 1.1-13. *Video capture of the first observed incident of debris being shed*. The orbiter is traveling from left to right in this image.**

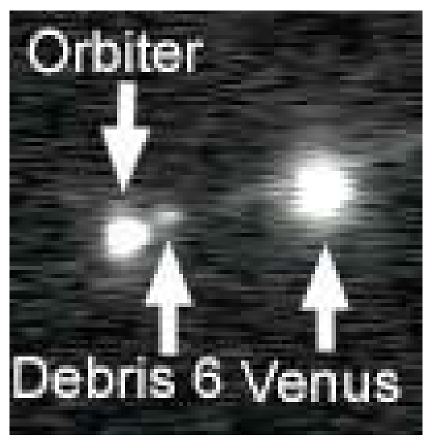


**Figure 1.1-14. *The brightest debris event known to have occurred prior to loss of signal*. The orbiter is traveling from right to left.**

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[15] All ballistic analysis release times have a ±5-second uncertainty.
[16] *Columbia* Accident Investigation Board Report, Volume III, Appendix E.2, STS-107 Image Analysis Team Final Report, October 2003, p. 110.
[17] *Columbia* Accident Investigation Board Report, Volume III, Appendix E.2, STS-107 Image Analysis Team Final Report, October 2003, p. 110.

At approximately GMT 13:54:30 (EI+621), cabin $O_2$ partial pressure and cabin pressure telemetry indicated signatures consistent with additional ACES pressurization events, indicating that the crew was continuing suit activities.

The first planned roll reversal was initiated from right wing low to left wing low at GMT 13:56:30 (EI+741).

At approximately GMT 13:58:03 (EI+834), the aileron trim begins to diverge sharply from the expected values to counteract the increasing adverse moments due to the left wing damage (figure 1.1-15).

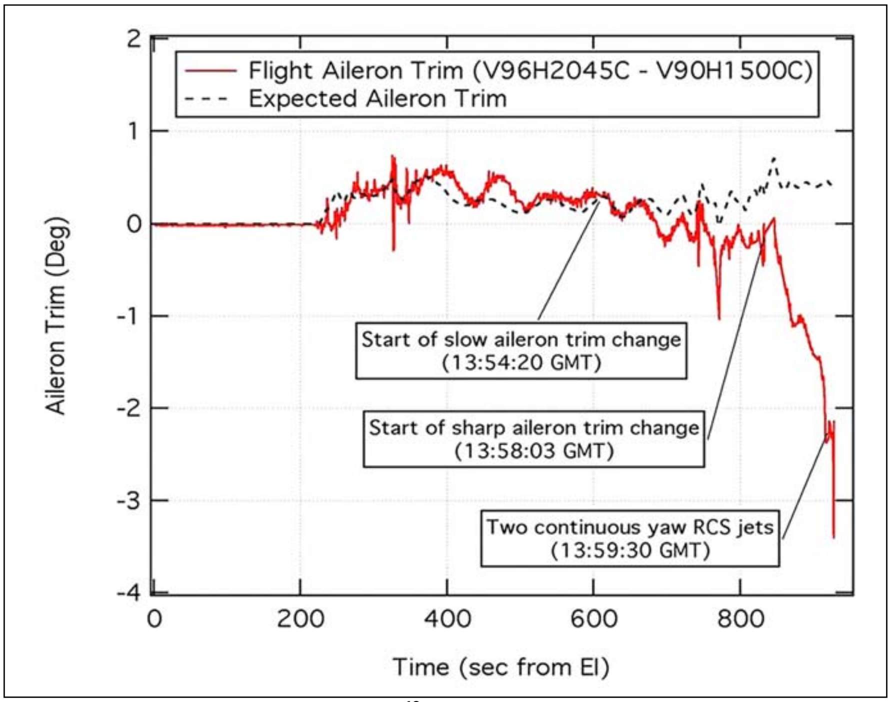


**Figure 1.1-15. *Aileron trim discrepancy*.**[18]

Western ground-based video coverage ends at GMT 13:58:12 (EI+843).

Ballistic analysis indicates that the westernmost piece of recovered *Columbia* debris was released at GMT 13:58:21 (EI+852). This debris, a tile from the left wing upper surface located just inboard of RCC panels 8 and 9, was found in Littlefield, Texas[19] (figure 1.1-16).

**Figure 1.1-16. *The Littlefield tile*. [Picture from the *Columbia* Reconstruction Database, debris item no. 14768]**

[18]Integrated Entry Environment Team Final Report, May 30, 2003, Figure 6.3-4, p. 20.
[19]STS-107 *Columbia* Reconstruction Report, NSTS-60501, June 2003, pp. 21 and 121.

*Columbia*'s crew received the first indication of a problem at GMT 13:58:39 (EI+870) when the first of four fault messages was annunciated on the on-board Backup Flight Software monitor. These messages were accompanied by an audible tone. The fault messages indicated a loss of pressure on the left main landing gear tires. These indications also were presented to the flight control team in the MCC. The CDR and PLT called up the fault page for these messages and reviewed the information. The failure the crew saw would be familiar, although slightly different from what they saw in training. One of the failure scenarios the crew practiced during training was a circuit breaker trip that resulted in one-half of the tire pressure sensors being disabled. A circuit breaker trip would disable some sensors for all of the tires (left main gear, right main gear, and nose gear), but the failure signature during the accident involved all the tire pressure sensors on the left main gear only. At GMT 13:58:48 (EI+879), the crew began a call to the MCC but the call was broken and not repeated. Brief interruptions of communications often occur due to the tracking and data relay satellite antenna pointing angles changing relative to the orbiter's transceivers. This specific dropout of communication was not unexpected.

At GMT 13:59:06 (EI+897), 10 seconds after the fourth of four tire pressure fault messages, telemetry indicated the "LEFT MAIN GEAR DOWN" lock sensor transferred to "ON." Other sensors indicated that the landing gear door was still closed and the landing gear was locked in the up (stowed) position. These mixed signals caused the left landing gear position indicator to display a "barber pole" (figure 1.1-17), which indicates an indeterminate landing gear position. Post-accident analysis of the data and recovered debris indicates that the left landing gear was locked in the "up" position and the landing gear door was closed. The signal indicating that the gear was down was a false signal that was likely triggered by damage to the sensor system (sensor, wiring harness, etc.). Based on training experience, the crew was probably attempting to diagnose the situation given that it involved the same landing gear as the tire pressure messages and indicated a potential landing gear deployment problem.

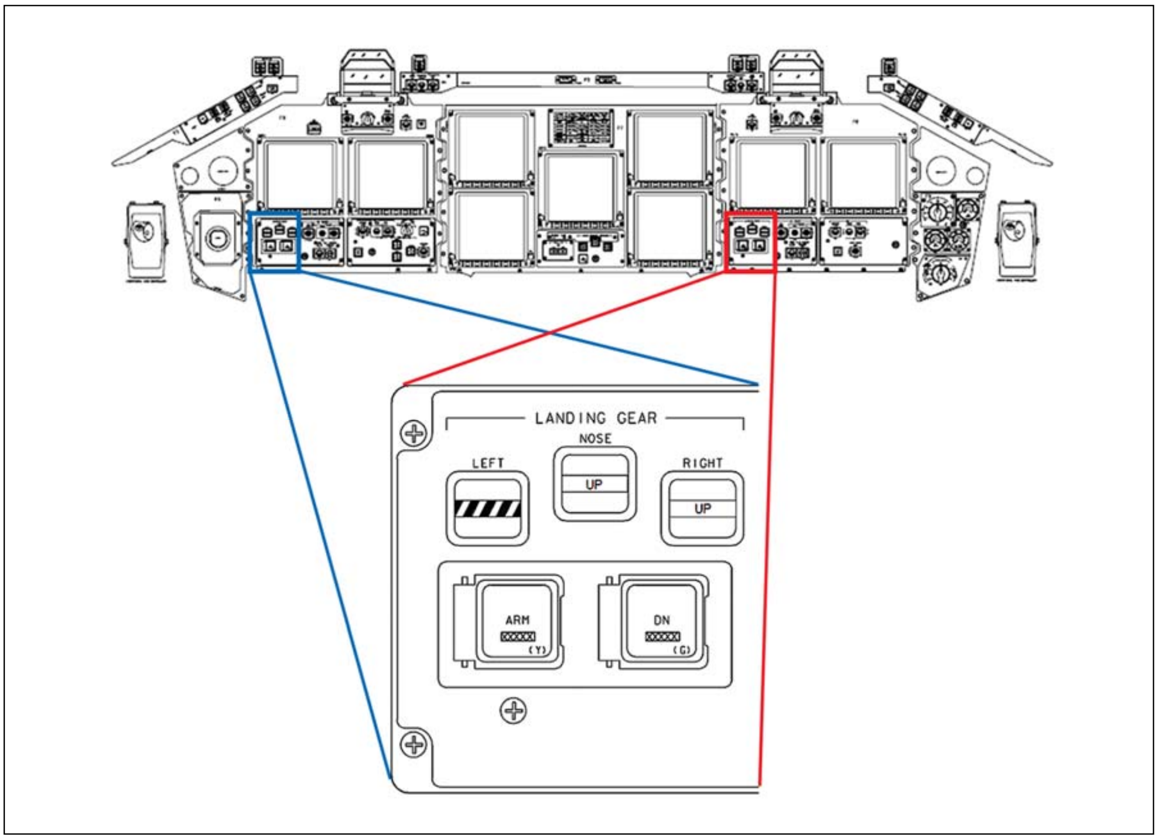


**Figure 1.1-17. *Landing gear indicator panel, identical on both sides of the flight deck forward display panels*. Left indicator showing "barber pole" (indeterminate position). [Adapted from the Space Shuttle Systems Handbook]**

At GMT 13:59:29 (EI+920), the orbiter yaw and roll rates exceeded the ability of the aileron trim to compensate for the changing drag of the deformed left wing. One second later, the R2R and R3R RCS jets[20] activated. Typically, RCS jets pulse throughout entry, adjusting the orbiter's flight path as needed. RCS jets had been pulsing nominally until this time when R2R and R3R began firing continuously as the orbiter attempted to counteract the increased left wing drag and resulting yaw moment. A small light on a panel in front of the CDR would have become illuminated continuously (figure 1.1-18). Experience shows that this jet fire light is not easily noticed.

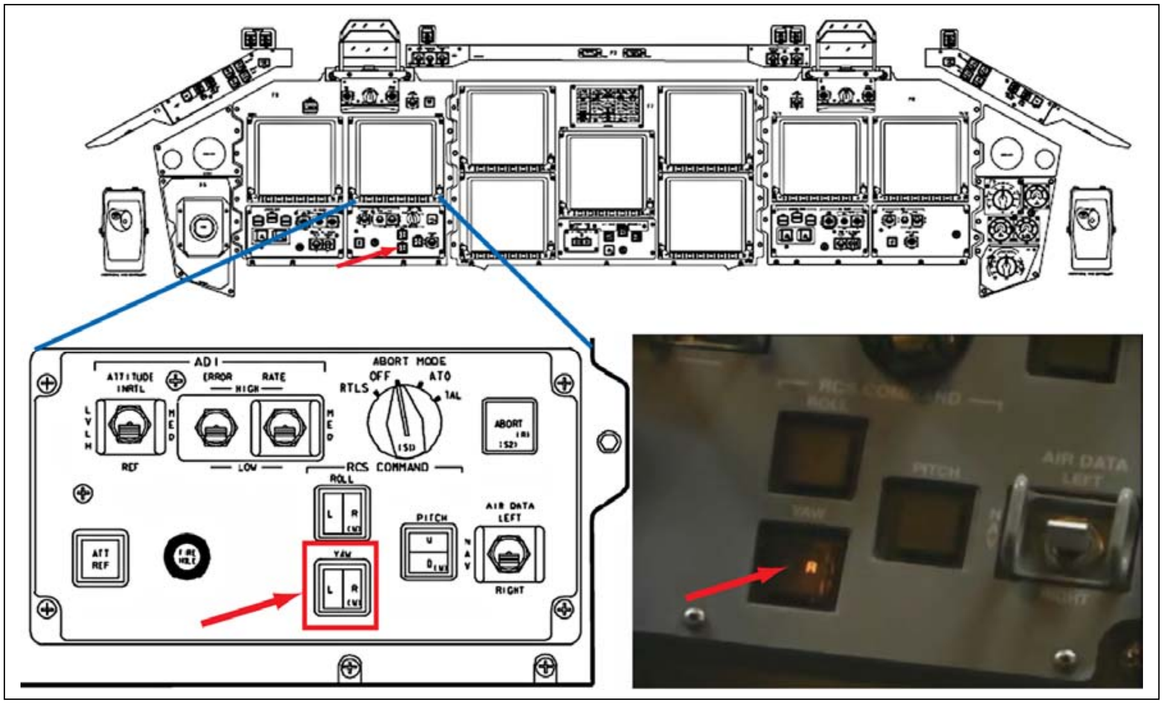


**Figure 1.1-18.** ***Reaction Control System thruster status display*. [Pictures (top and bottom left) adapted from the Space Shuttle Systems Handbook; picture (bottom right) from the Shuttle Engineering Simulator]**

At GMT 13:59:32 (EI+923), the crew acknowledged a call from the MCC but the crew's response was interrupted in mid-sentence ("Roger, uh …"[21]). This was the final call heard from *Columbia*. This is also the time of LOS, when all audio and real-time data to the MCC from *Columbia* was lost. A short dropout (seconds) was expected at this time based on pre-mission analysis as the orbiter switched from one communication satellite to another. The CAPCOM replied to the partial transmission to let the crew know that the flight controllers saw the tire pressure fault messages and that the MCC did not understand the last transmission.[22] The MCC personnel recognized that there were problems occurring with *Columbia*, but the telemetry signatures were such that these personnel were unable to complete analysis of the wide-ranging (and seemingly unrelated) problems before contact was lost.

There were no indications to the crew and the MCC that the loss of audio communications and real-time data was more than a brief condition. To all on-board appearances, *Columbia* only had a potential issue with landing gear deployment; a non-trivial event, but the crew had time to troubleshoot the problem. Changing drag on the left wing was just beginning to develop into a potentially recognizable problem.

[20]Right-firing RCS jets on the right OMS pod.
[21]*Columbia* Accident Investigation Board Report, Volume I, August 2003, p. 43.
[22]The CAPCOM continued to attempt to contact the crew on different radio frequencies to re-establish voice communications.

Based on seat debris and medical findings, at the end of this phase one middeck crew member had not fully ingressed the seat yet, although the action may have been in progress. This crew member was responsible for completing post-deorbit burn tasks and was assigned to be the last to ingress the seat.

### 1.1.2.3 *Phase 3: Loss of signal to Catastrophic Event* [GMT 13:59:32 (EI+923) to GMT 14:00:18 (EI+969)] 46 seconds in duration

This section discusses key events that affected the crew from LOS at GMT 13:59:32 (EI+923) to the CE, which began at 14:00:18 (EI+969) (figure 1.1-19). During this period of time at about GMT 13:59:37 (EI+928), loss of control (LOC) of *Columbia* occurred. LOC marks the beginning of the transition from controlled flight to an uncontrolled ballistic entry. This phase is 46 seconds long.

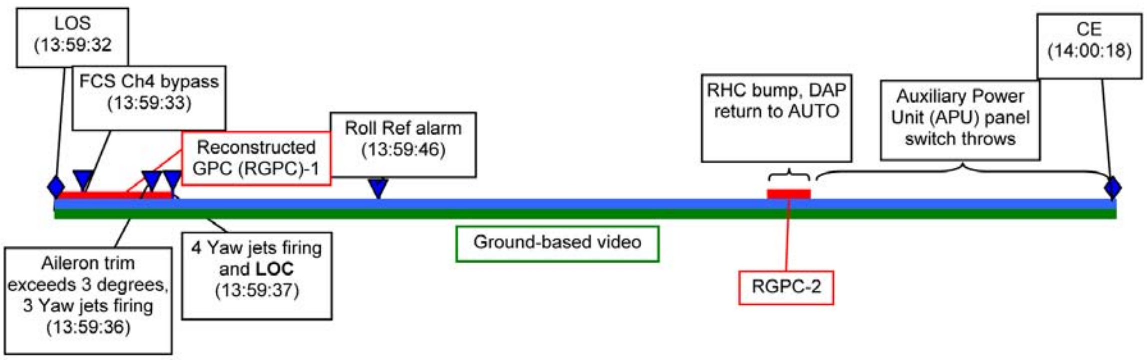


**Figure 1.1-19. *Phase 3 timeline with key events.* Real-time voice and telemetry transmissions were not available in this phase or subsequent phases. The green bar represents time when video data are available; the blue bar represents when the Modular Auxiliary Data System/orbiter experiment recorder data are available (both available throughout this phase). Red bars represent times when reconstructed general purpose computer data were available.**

Available instrumentation data (recorded and recovered) become scarce in Phase 3 (and nonexistent in subsequent phases). The sources of data used to reconstruct conditions in Phase 3 are: reconstructed telemetry; MADS/OEX recorder; ground-based videos; recovered debris; and aerodynamic and ballistics analyses. Reconstructed general purpose computer (RGPC) data were data that were recorded at the telemetry receiving ground station at White Sands, New Mexico, but not transmitted to the MCC in real time due to quality filtering. After the accident, the data were retrieved and manually reconstructed.[23] The RGPC data include real-time parameter data (such as pressures, temperatures, and switch positions), time-stamped alert messages, and non-time-stamped alert messages. Ground-based video was re-established starting at approximately GMT 13:59:32.5 (EI+923), at about LOS. For the first 16 seconds of this phase, a single video supplies coverage. Additional video coverage begins at GMT 13:59:48 (EI+939). Recovered *Columbia* debris was used for reconstruction via visual inspection, material sampling, and ballistic analysis. This led to conclusions regarding thermal events and material loads. Ballistic analysis was performed on select debris items to help understand the events and their sequence.

At GMT 13:59:33 (EI+924), data from RGPC-1 showed the primary software system annunciated that FCS Channel 4 had been automatically bypassed out of the control loop. This bypass occurred because of a failed wire bundle and resulted in a Master Alarm. The Master Alarm was annunciated visually and aurally. While there is no crew action associated with this frequently trained FCS fault message other than to perform a message reset, the crew may have called up a display to analyze the failure. Crews are trained to troubleshoot systems errors, and this crew would have been evaluating this new message along with the previous tire pressure and landing gear down-lock indications to assess whether there was a common

[23]*Columbia* Accident Investigation Board Report, Volume II, Appendix D.9, Data Review and Timeline Reconstruction Report, October 2003.

system fault that could account for all of these messages. It is unknown whether the increasing aileron trim and thruster firings were noticed by the flight deck crew members.

At GMT 13:59:36 (EI+927), the third RCS yaw jet, R4R, began firing continuously and aileron trim exceeded 3 degrees. There is no alarm associated with a deviating trim condition, and the crew is not expected to monitor the trim during this period of entry. At GMT 13:59:37 (EI+928), the fourth and last RCS yaw jet, R1R, began firing continuously.

To summarize, in the minute prior to LOC, the crew received several indications of various vehicle systems problems:

1. 58 seconds prior: the first of four tire pressure alert messages was displayed.
2. 31 seconds prior: left main landing gear indicator transitioned to an indeterminate state (no annunciated alarm).
3. 7 seconds prior: pulsing RCS yaw light became constant as two RCS jets began firing continuously (no annunciated alarm).
4. 4 seconds prior: FCS channel bypass message and Master Alarm.
5. 0.6 second prior: aileron trim exceeded 3 degrees (no annunciated alarm).

Ground-based video data show a brightening event at GMT 13:59:37 (EI+928).

RGPC-1 ends[24] at GMT 13:59:37.4 (EI+928) with an approximately 25-second gap in data until RGPC-2 data begins at GMT 14:00:02.660 (EI+953). RGPC-2 data include messages generated during the 25-second gap; some of the messages do not have time tags, and some message time tags are corrupted.

Vehicle LOC probably occurred at GMT 13:59:37 (EI+928).[25] The CAIB Report concluded that "During re-entry this breach in the TPS allowed superheated air to penetrate through the leading edge insulation and progressively melt the aluminum structure of the left wing, resulting in a weakening of the structure until increasing aerodynamic forces caused loss of control, failure of the wing, and breakup of the orbiter."[26] An in-depth review of the data by the Integrated Entry Environment team provided further insight into the probable sequence of events. The RGPC-2 data showed that a "ROLL REF" alarm was recorded at GMT 13:59:46 (EI+937), only 9 seconds after the end of RGPC-1. A ROLL REF alarm generally indicates that the drag of the orbiter has exceeded the entry drag profile. The Integrated Entry Environment team concluded that the most credible scenario that could cause this message within 9 seconds would be from a pitch deviation rather than a roll deviation (which would be expected with increasing drag on the wing).[27] A complete loss of hydraulics would cause the elevons and body flap to move to a floating position, resulting in an uncontrolled pitch-up. RGPC-2 data (approximately 25 seconds later) showed that the hydraulics systems failed, but no time signature was available to confirm when the loss occurred. Video data supported this time for LOC. The Spacecraft Crew Survival Integration Investigation Team (SCSIIT) concluded that the LOC occurred as a result of the loss of hydraulics at GMT 13:59:37 (EI+928). The loss of hydraulics likely occurred when all three redundant hydraulic systems lost pressure due to breaches in the hydraulic lines from thermal damage in the left wing. A visual simulation of the pitch-up associated with this type of LOC is shown in figure 1.1-20.

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[24] Although data were received after GMT 13:59:37 (EI+928), none could be reconstructed until RGPC-2. See *Columbia* Accident Investigation Board Report, Volume II, Appendix D.19, Qualification and Interpretation of Sensor Data from STS-107, October 2003.
[25] This LOC time (GMT 13:59:37 (EI+928)) occurs 42 seconds earlier than that concluded in the *Columbia* Accident Investigation Board Report, Volume I, August 2003, p. 73.
[26] *Columbia* Accident Investigation Board Report, Volume I, Executive Summary, August 2003, p. 9.
[27] EG-DIV-08-32- Integrated Entry Team Report, Appendix G - Post-LOS Analysis.

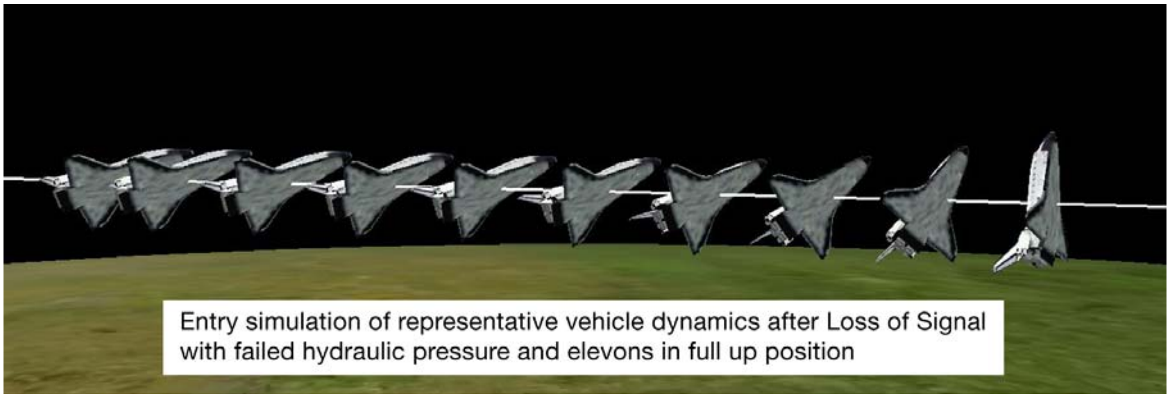



**Figure 1.1-20.** ***Sequence (1-second intervals) showing a simulation of orbiter loss of control pitch-up from GMT 13:59:37 (EI+928) to GMT 13:59:46 (EI+937)*. White line indicates vehicle trajectory relative to the ground.**

The LOC event marked the beginning of the transition from a controlled gliding trajectory into an uncontrolled ballistic trajectory. Once attitude control was lost, orbiter heating, lift, and drag were dictated predominantly by ballistic number.[28] The out-of-control orbiter configuration had significantly more drag than the nominal entry configuration, and the trajectory became steeper. Changes in the flight profile are recognizable in the ground-based video as changes in the orbiter's trail and in the brightness of the visual signal ("brightening events").

Video imagery shows a dynamically changing orbiter trail after GMT 13:59:37 (EI+928) with a braided or corkscrew appearance, implying motion of the orbiter. However, the specific attitude of the orbiter cannot be derived from ground-based imagery. Brightening events, objects separating, "puffs," and splitting of the trail are all seen in the video during this timeframe. Ballistic analysis of debris could not positively correlate a specific orbiter source to shedding events seen in the video. However, it is known that the left wing and the left OMS pod were being compromised.[29] Figure 1.1-21 shows video frames from GMT 13:59:35.5 (EI+925) through GMT 13:59:43.5 (EI+934) and displays some of these dynamic changes, although they are much more clearly seen in the video.

[28]Ballistic number is affected by the coefficient of drag of an object (which changes with its velocity), its weight, and the area presented to the velocity vector. A low ballistic number indicates high drag. The initial trajectory of an object with a low ballistic number is steeper than the trajectory of an object with a high ballistic number. See Section 2.1.
[29]*Columbia* Accident Investigation Board Report, Volume I, August 2003, p. 68.

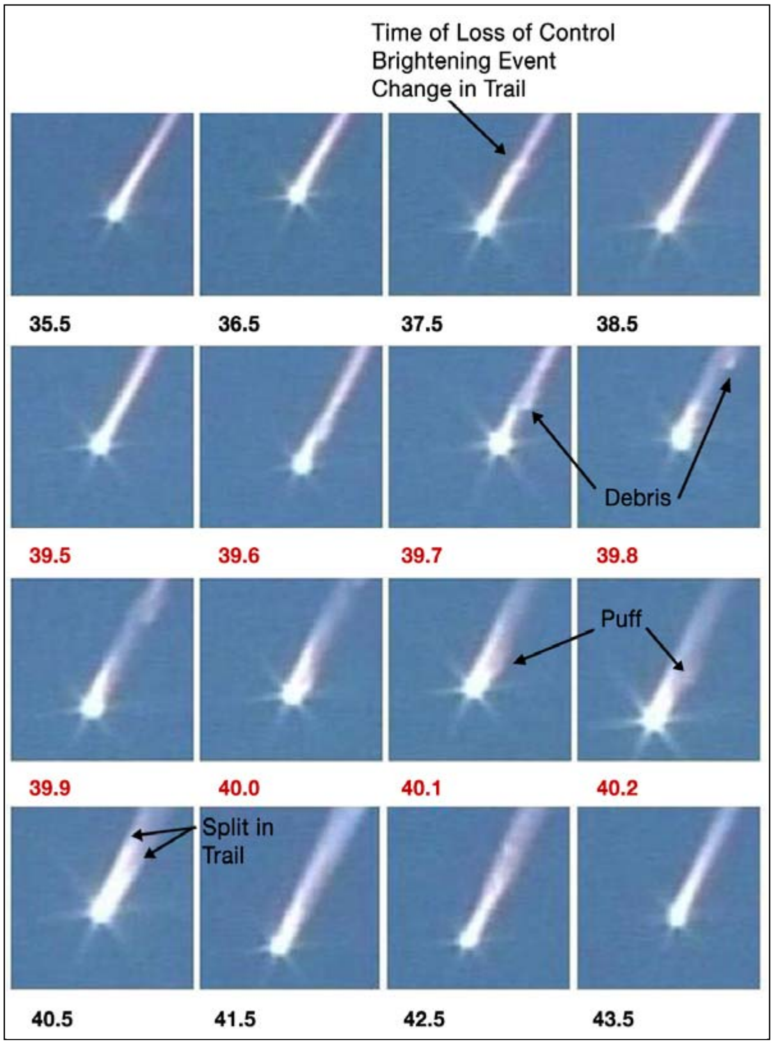



**Figure 1.1-21.** ***Video frame captures from ground-based video, beginning at GMT 13:59:35.5 (EI+926) and ending at GMT 13:59:43.5 (EI+937).*** **The numbers below each frame indicate the seconds after GMT 13:59:00. The frames in the first and last rows are 1 second apart. The frames in the second and third rows are 0.1 second apart.**

For the crew, the first strong indications of the LOC would be lighting and horizon changes seen through the windows and changes on the vehicle attitude displays. Additionally, the forces experienced by the crew changed significantly and began to differ from the nominal, expected accelerations. The accelerations were translational (due to aerodynamic drag) and angular (due to rotation of the orbiter). The translational acceleration due to drag was dominant, and the direction was changing as the orbiter attitude changed relative to the velocity vector (along the direction of flight).

Results of a shuttle LOC simulation show that the motion of the orbiter in this timeframe is best described as a highly oscillatory slow (30 to 40 degrees per second) flat spin, with the orbiter’s belly generally facing into the velocity vector. It is important to note that the velocity vector was still nearly parallel to the ground as the vehicle was moving along its trajectory in excess of Mach 15. The crew experienced a swaying motion to the left and right (Y-axis) combined with a pull forward (X-axis) away from the seatback. The Z-axis accelerations pushed the crew members down into their seats. These motions might induce nausea, dizziness, and disorientation in crew members, but they were not incapacitating. The total acceleration experienced by the crew increased from approximately 0.8 G at LOC to slightly more than 3 G by the CE (figure 1.1-22).

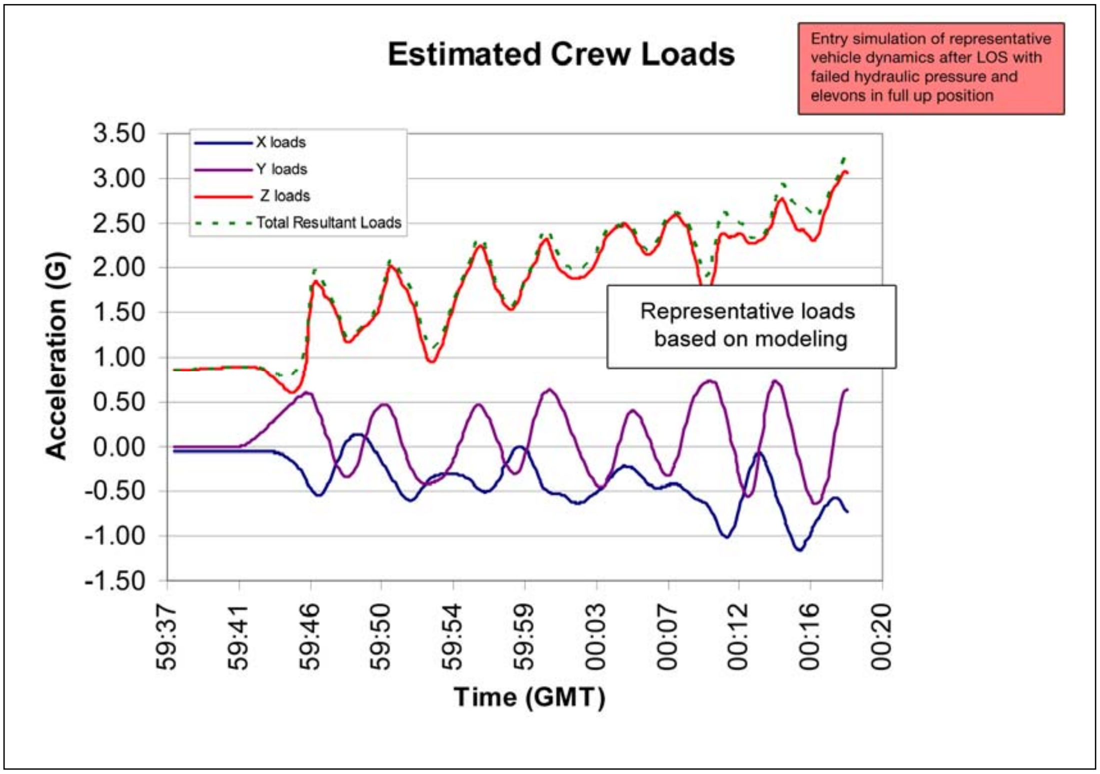



**Figure 1.1-22.** ***Resultant acceleration (G) vs. time prior to Catastrophic Event in the*** **crew** ***coordinate frame from the aerodynamic simulation model.***

The onset of this highly oscillatory flat spin likely resulted in the need for crew members to brace as they attempted to diagnose and correct the orbiter systems. As mentioned in the previous phase discussion, one middeck crew member had not completed seat ingress and strap-in at the beginning of this phase. Seat debris and medical analyses indicate that this crew member was not fully restrained before loss of consciousness. Only the shoulder and crotch straps appear to have been connected. The normal sequence for strap-in is to attach the lap belts to the crotch strap first, followed by the shoulder straps. Analysis of the seven recovered helmets indicated that this same crew member was the only one not wearing a helmet. Additionally, this crew member was tasked with post-deorbit burn duties. This suggests that this crew member was preparing to become seated and restrained when the LOC dynamics began. During a dynamic flight condition, the lap belts hanging down between the closely space seats would be difficult to grasp due to the motion of the orbiter, which may be why only the shoulder straps were connected.

At GMT 13:59:46 (EI+937), ground-based video indicates that a bright piece of debris was released followed by a second piece 2 seconds later. This second piece of debris[30] separated from the orbiter's trail and decelerated slowly, remaining visible for more than 37 seconds before dispersing into significantly fainter pieces. Ballistic analyses of ground debris indicate that pieces of the left OMS pod were being shed starting at about GMT 13:59:49 (EI+940).

RGPC-2 data show a message reset sometime between GMT 13:59:37.4 (EI+928) and GMT 14:00:05 (EI+956). This action is a nominal crew response to a fault message and requires a crew member to manually acknowledge the message by keyboard entry on the center panel. RGPC-2 data indicate that the RHC was moved beyond neutral sometime between GMT 14:00:01.7 (EI+952) and GMT 14:00:03.6 (EI+954), triggering a "DAP DOWNMODE RHC" message at GMT 14:00:03.637 (EI+954). This message, which is identical to the DAP DOWNMODE message that occurred at GMT 13:36:04 (EI-485) in the first phase,

[30]Identified as Debris D in the CAIB timeline.

was likely due to an RHC bump due to the oscillatory motion of the orbiter. At GMT 14:00:03.678 (EI+954), the orbiter autopilot was returned to the AUTO mode. Returning the DAP to AUTO requires either the CDR or the PLT to press a button located on the glare shield. These actions indicate that the CDR or the PLT was still mentally and physically capable of processing display information and executing commands, and that the orbiter dynamics were still within human performance limitations.

RGPC-2 data show normal crew module temperature and pressure through the end of the period of reconstructed data [GMT 14:00:04.826 (EI+956)].

The RGPC-2 data show normal Freon flow through the radiators on the inside of the payload bay doors (PLBDs). This indicates that the radiators and PLBDs also retained structural integrity up to this point. Based on structural analysis, it is likely that the PLBDs were compromised prior to CE, after the end of RGPC-2 data. Loss of the PLBDs reduced the structural strength of the orbiter midbody and allowed hot gas to impinge upon the sills in the payload bay.

The RGPC-2 data also indicate that while all three auxiliary power units (APUs)[31] were running, all three hydraulic systems had zero pressure and zero quantities in the reservoirs. With the loss of hydraulic pressures and the vehicle LOC, the crew likely assumed a generic problem with the APUs. A crew module panel was recovered with switch configurations indicating an attempt by the PLT to recover the hydraulic systems and hydraulic pressure by performing steps to initiate a restart of two of the three APUs. Switches for the same two of the three system hydraulic circulation pumps were also in the “On” position. While turning on the hydraulic circulation pump is not on the emergency checklist, it nonetheless can provide some limited hydraulic pressure and shows good systems knowledge by the crew members as they worked to attempt to restore orbiter control. These switch positions were not reflected in RPGC-2 data and, therefore, must have occurred after GMT 14:00:05 (EI+956).

Although the orbiter continued to shed debris, ground-based video from GMT 14:00:09 (EI+960) to GMT 14:00:18 (EI+969) shows a thin, relatively consistent trail, suggesting that the conditions remained steady for a short period of time (~9 seconds). Aerodynamic modeling indicates that this was a time of growing stresses on the orbiter and increasing Gs on the crew.

#### 1.1.2.4 *Phase 4: Catastrophic Event to Crew Module Catastrophic Event* [GMT 14:00:18 (EI+969) to GMT 14:00:53 (EI+1004)] 35 seconds in duration

This section discusses events affecting the crew from the CE at GMT 14:00:18 (EI+969) to the CMCE at GMT 14:00:53 (EI+1004) (figure 1.1-23). Separation of the forebody from the midbody and aftbody occurred at or just after CE. This phase lasted 35 seconds.

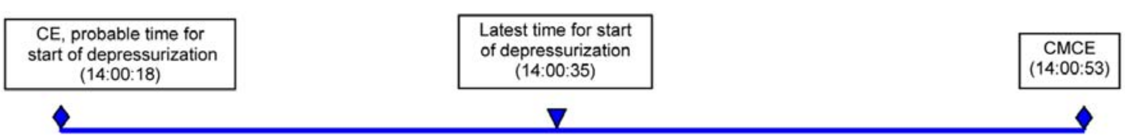



**Figure 1.1-23. *Phase 4 timeline with key events*.**

No telemetry or orbiter systems data are available during this phase. An on-board Global Positioning System (GPS) data recorder stopped at GMT 14:00:18.7 (EI+969) and the MADS/OEX recorder tape spool stopped at GMT 14:00:19 (EI+970) when the forebody lost power.[32] The sources of data that are available for reconstruction of events include ground-based video, recovered debris, medical findings, and modeling.

[31]The APUs drive the hydraulic pumps.
[32]The fuel cells, which provide all orbiter electrical power, are located in the midbody. Separation of the midbody from the forebody resulted in a total loss of power in the forebody.

Analysis of ground-based video identified specific events such as debris shedding and luminosity changes. A major luminosity event and orbiter trail characteristic change occurred at GMT 14:00:18.3 (EI+969) and is identified as the initiation of a major structural breakup called the CE. The aftbody and the forebody were identifiable as separate objects by GMT 14:00:25 (EI+976). Triangulating the video data provided relative motion, which was analyzed for an estimate of the deceleration and rotation rates of the forebody.

*Columbia* debris analysis consisted of five different methods: cluster analysis (plots of the ground location of recovered debris sorted by origination point on the orbiter), visual observations of debris, material analyses of melted deposits on select debris, and ballistic and thermal analysis of select debris. See Chapter 2.

Modeling was performed for various properties of the forebody. Aero thermal modeling provided estimated heat exposure. Aerodynamic modeling was used to evaluate the possible stable modes of the forebody. Aerodynamic modeling also provided estimates of G-loads, which increased as the forebody decelerated. The effects of the changing G-loads on both the forebody and the crew were analyzed. A combined environmental and structural analysis was performed to understand the effects of depressurization due to a single hole (or multiple holes equivalent to the same cross-sectional area) and the subsequent delta-pressure effects on the crew module structure.

At GMT 14:00:18 (EI+969), video showed that a significant event (the CE) occurred to the orbiter (figure 1.1-24). The GPS Miniaturized Airborne Global Receiver (MAGR) experiment, which was located in the middeck and powered by a fuel cell in the payload bay, experienced a loss of power at the CE. Less than 1 second later, the MADS/OEX recorder, which was also located in the crew module and similarly powered from the payload bay, also experienced a total power loss. The conclusion was that the forward and midbody orbiter segments separated at the CE. The CE is actually the start of a period of several seconds in which the orbiter underwent a major structural breakup. At GMT 14:00:25 (EI+976), there were visual indications that the orbiter was in multiple pieces. Ballistics analysis and structural debris analysis supports this period as the breakup event.


**Figure 1.1-24. *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 14:00:18.3 (EI+969).**

The CAIB Report, based on data provided by the Crew Survival Working Group (CSWG), concluded that "Separation of the crew module/forward fuselage assembly from the rest of the orbiter likely occurred immediately in front of the payload bay (between $X_o$ 576[33] and $X_o$ 582 ring frame bulkheads)."[34] However, the SCSIIT's subsequent in-depth review of the debris field showed that significant portions of the $X_o$ 582 ring frame bulkhead were found intermingled with the crew module debris field. Structural analysis led to the conclusion that the forebody separated from the midbody aft of the $X_o$ 582 ring frame bulkhead. An aerodynamic simulation indicates that the structural operating load limits for the orbiter were not exceeded, indicating thermal degradation likely played a role in the failure.

The simulation also indicates that the crew module attachment fittings' (the x-links, y-links, and z-link) load limits were not exceeded. Although the exact sequence is not known, structural debris analysis suggests that the initial failure occurred immediately aft of the starboard x-link, where it attached to the payload bay

[33]The $X_o$ terminology refers to the X position in inches in the orbiter coordinate frame, where the X-axis runs the length of the orbiter from fore to aft. See Section 2.1 for a visual graphic of the orbiter coordinate frame.
[34]*Columbia* Accident Investigation Board Report, Volume 1, August, 2003, p. 77.

sill, and was likely from a combination of thermal degradation and structural loads. The forebody probably separated from the midbody from starboard to port. Based on structural evidence and the debris field, the crew module remained with the forward fuselage indicating that the links attaching the two structures remained intact. The remaining orbiter structure separated into aft and midbody/right wing segments. See Chapter 2. Figure 1.1-25 shows the recovered x-links.

**Figure 1.1-25.** ***Port x-link, debris item no. 1678*** **(top)*****, and starboard x-link, debris item no. 1765*** **(bottom)*****, from the*** **Columbia** ***Reconstruction Database*****.**

The resulting jerk acting on the crew module attach fittings as the forebody separated from midbody structure caused motion of the crew module within the forward fuselage shell. The crew module pressure vessel impacted the forward fuselage, which apparently resulted in damage to the crew module pressure vessel, internal crew module structure, and forward fuselage structure. Debris evidence shows that internal damage occurred to some volumes and lockers on the middeck in close proximity to the pressure vessel shell. At least one crew module pressure vessel breach occurred in the lower equipment bay or middeck area (figure 1.1-26), probably at or near the time of the CE, but definitely not later than GMT 14:00:35 (EI+986) ±5 sec. This time is based on the ballistic analysis of a recovered mission patch confirmed to have come from inside the crew module from one of the volumes (Volume E) that suffered damage.

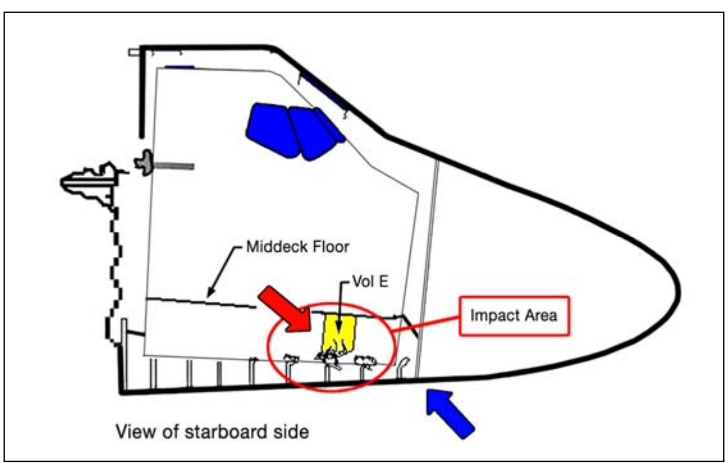



**Figure 1.1-26.** ***Scenario showing how the crew module pressure vessel could impact the forward fuselage, and the middeck Volume E could impact the crew module pressure vessel, with resultant damage.***

The start of crew cabin depressurization can be narrowed to a range of 17 seconds, from between GMT 14:00:18 (EI+969) to GMT 14:00:35 (EI+986) ±5 sec (see Section 2.3). Crew module debris items recovered west of the main crew module debris field were 8 in. in diameter or smaller, were not comprised of crew module primary structure, and originated from areas above and below the middeck floor. This indicates that the crew module depressurization was due to multiple breaches (above and below the floor), and that these breaches were initially small. Another crew module breach possibly occurred at the starboard x-link area, but no significant flight deck debris is seen west of the CMCE-related debris, suggesting that this breach occurred later rather than earlier in the timeline.

When the forebody separated from the midbody, the crew members experienced three dramatic changes in their environment:

1. all power was lost,
2. the motion and acceleration environment changed; and
3. crew cabin depressurization began within 0 to 17 seconds.

With the loss of power, all of the lights and displays went dark (although each astronaut already had individual chem-lights activated). The intercom system was no longer functional and the orbiter $O_2$ system was no longer available for use, although individual, crew worn Emergency Oxygen System (EOS) bottles were still available.

As the forebody broke free from the rest of the orbiter, its ballistic number underwent a sharp change from an average ballistic number of 41.7 pounds per square foot (psf) (out of control intact orbiter) to 122 psf (free-flying forebody). The aerodynamic drag of the forebody instantaneously decreased, resulting in a reduction in the translational deceleration from approximately 3.5 G to about 1 G (figure 1.1-27).

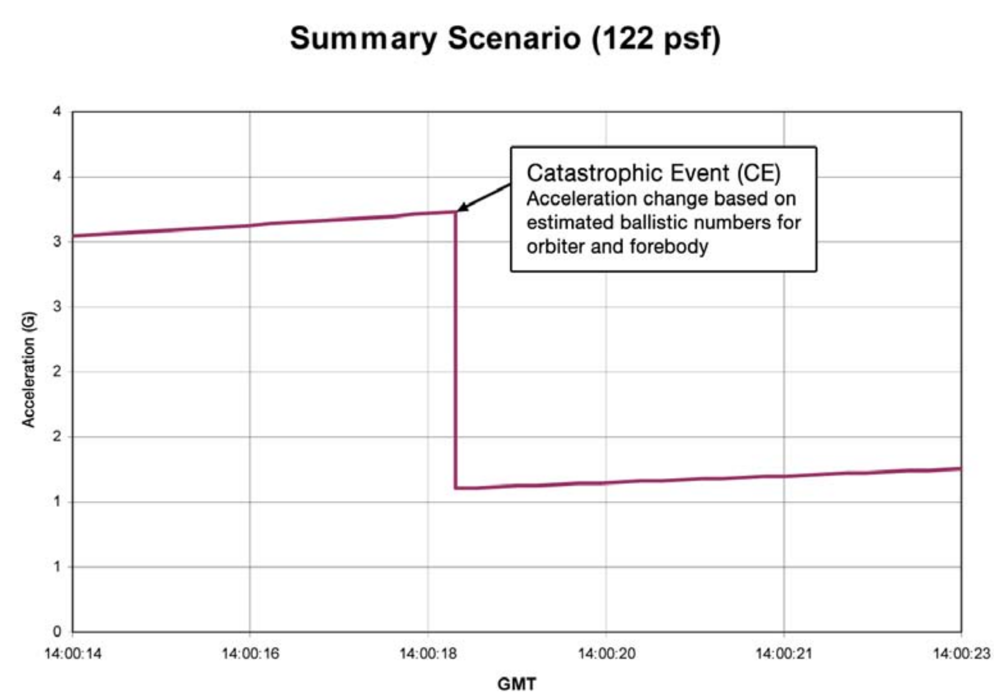



**Figure 1.1-27.** ***Estimated change in total G experienced by the forebody due to a change in ballistic number from the orbiter breakup.***

The asymmetrical starboard to port separation of the forebody from the midbody would have induced rotation in the forebody, introducing new angular accelerations. The angular accelerations acting on the forebody at this time are impossible to accurately characterize due to inadequate data, but they likely changed significantly due to the abrupt change in the center of axis of rotation when the center of gravity (c.g.) changed from $X_o$ 1075.5 to $X_o$ 470.8 (figure 1.1-28).

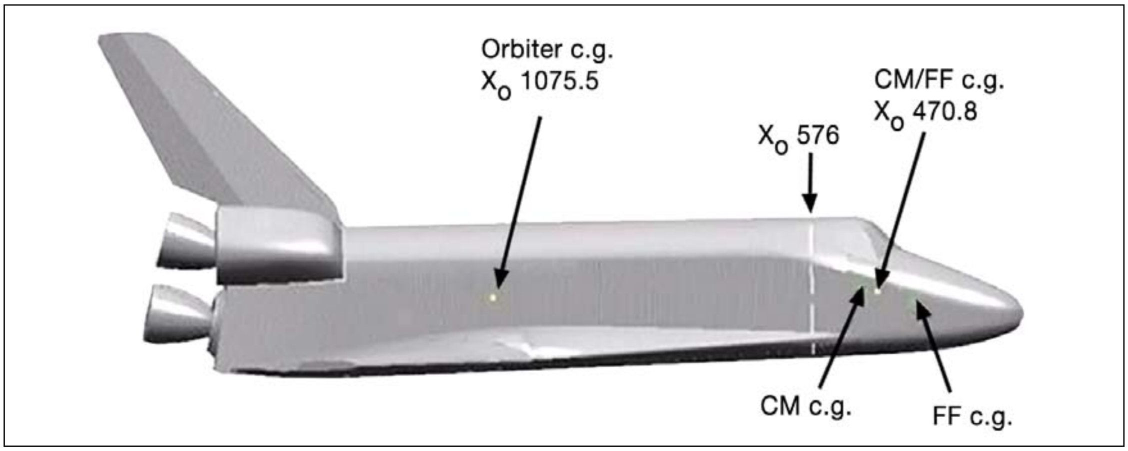



**Figure 1.1-28.** ***X-axis center-of-gravity locations for the intact orbiter, the crew module, the forward fuselage, and the forebody (crew module plus forward fuselage).*** **The $X_o$ 576 is the aft bulkhead of the crew module.**

Also, as the forebody broke from the vehicle, the crew module moved within the forward fuselage shell resulting in transient rates of change (described earlier). Although it is probable that momentary sharp changes in acceleration caused high instantaneous G-loads, medical evidence indicates that the crew cabin pressure and load environment at the CE were still within human limitations for survival.

Effects of cabin depressurization on the crew would depend on the rate of depressurization. Existing CEE is capable of protecting the crew from rapid decompression via pressure suit, helmet, and either the orbiter $O_2$ or an individual EOS for a limited time. However, recovered crew equipment shows crew visors were in the nominal (up) position rather than emergency configuration (down and locked). Inspection of the wrist and glove rings showed that the glove wrist rings were not attached to the suit for two crew members on the middeck and one crew member on the flight deck, and one crew member had not yet donned the helmet. The change (from the crew's vantage point) from a nominal entry profile to the LOC and subsequent separation of the forebody from the orbiter all occurred in approximately 40 seconds. Experience shows that this is not sufficient time to don gloves and helmets.

Histological (tissue) examination of all crew member remains showed the effects of depressurization. Neither the effects of CE nor the accelerations immediately post-CE would preclude the crew members who were wearing helmets from closing and locking their visors at the first indication of a cabin depressurization. This action can be accomplished in seconds. This strongly suggests that the depressurization rate was rapid enough to be nearly immediately incapacitating. The exact rate of cabin depressurization could not be determined, but based on video evidence complete loss of pressure was reached no later than (NLT) GMT 14:00:59 (EI+1010), and was likely much earlier. The medical findings show that the crew could not have regained consciousness after this event. Additionally, respiration ceased after the depressurization, but circulatory functions could still have existed for a short period of time for at least some crew members.

**The first event with lethal potential was depressurization of the crew module, which started at or shortly after orbiter breakup.** Existing crew equipment protects for this type of lethal event, but inadequate time existed to configure the equipment for the environment encountered.

After the CE, the forebody was exposed to a high thermal environment as it decelerated and descended into an increasingly dense atmosphere. TPS tile and blankets on the forward fuselage protected the crew module, but the aft bulkhead was unprotected. However, debris field analysis indicates that the aft bulkhead remained intact until crew module breakup. The volume between the forward fuselage and the crew module had openings to the environment, which could result in the entry of heated gas. Crew module breaches could allow the entry of this gas into the crew module after the dynamic pressure outside the crew module exceeded atmospheric pressure inside the crew module. A few molten globules of metal were found on recovered seat harness straps, indicating the presence of heated metal inside the crew module while the unconscious or deceased crew members were still restrained in their seats. Although the timing of the deposition cannot be determined precisely, it may have been very close to the crew module breakup. There is no evidence to suggest that the overall crew module internal structure temperature was severe, but local hot spots may have existed near breaches.

The orbiter had substantial rates of rotation in all axes of rotation when RGPC-2 data ended at GMT 14:00:04 (EI+955). The orbiter breakup at the CE imparted motion to the forebody, and the forebody began rotating after it broke free from the vehicle. Aerodynamic modeling indicates that the free-flying forebody would not achieve a stable attitude. Videos of the forebody show brightening and dimming, implying rotational motion. Triangulation analysis of the forebody in video showed a slow wobble motion in all three axes, also supporting rotation or tumbling. Thermal damage seen on external portions of the forebody indicates intermittent exposure to heat. Based on the wobble motion, rotation rates gradually increased with an estimated initial average rate of 0.1 revolution per second (36 degrees per second) around a changing body axis (see Section 2.1). This rate is not extreme, and even peak rates toward the end of this phase result in angular accelerations of less than 2 G. Translational deceleration due to aerodynamic drag also increased, up to approximately 3 G at the CMCE. The loss and redistribution of mass as forward fuselage structure failed and separated would affect the rotation rate. Modeling suggests that the rate could continue to build, up to 0.5 revolution per second, although this was not verified with video data. The crew members seated farthest from the crew module c.g. experienced the highest angular accelerations due to the greater distance (moment arm) from the center of rotation. This acceleration was in addition to the translational accelerations and, depending on the attitude of the rotating forebody, the accelerations experienced by the crew members could vary from about –1 G to +5 G.

Under rapidly changing accelerations, the design intention is that inertial reels on the seat restraint shoulder harnesses will lock, and remain locked, until manually disengaged by the crew member. To lock, the inertial reel mechanism used on orbiter seats requires 1.78 G to 2 G of strap acceleration, in a direction orthogonal to the mechanism (straight out of the seatback). The abrupt dynamics associated with the CE would be expected to have locked the inertial reel. In the subsequent multi-axial rotating environment experienced during this phase, it is expected that the unconscious or deceased crew periodically would arrive at a posture allowing harness retraction. The harness would then remain retracted if the inertial reels had locked. However, seat analysis shows that several of the shoulder harness restraints failed with the inertial reel straps partly or fully extended, and other inertial reel straps were extended at some point during this phase (see Section 3.1). Either the acceleration on the straps was insufficient to lock the harness, the loading was not orthogonal (preventing harness retraction), ACES equipment blocked the strap retraction slot, or some combination of all three effects occurred. The net effect was that the crew members had no upper body restraint and were restrained solely by their lap belts.

The combination of the lack of upper body restraint and a helmet that, by design, does not internally conform to the head while exposed to cyclical motion resulted in lethal mechanical injuries for some of the unconscious or deceased crew members. The circulatory system of most of the unconscious or deceased crew was still functioning at the time of these lethal injuries. If the harnesses had been locked or the crew had been conscious and able to brace, the injuries likely would not have been lethal.

**The second event with lethal potential was unconscious or deceased crew members exposed to a dynamic rotating load environment with nonconformal helmets and a lack of upper body restraint.**

Existing seat and helmet design did not protect the crew from this lethal event.

Crew module structure temperature increased during this phase, resulting in a corresponding reduction in structural strength. The increase in loads due to the increasing deceleration and increasing rotational rate and thermal degradation resulted in eventual structural failure.

In summary, in the 35 seconds from the CE to the CMCE, the forebody detached, the crew module breached and depressurized, and the forebody experienced increased heating and began to structurally degrade.

Figure 1.1-29 shows an overall summary of accelerations, heat rates, and trajectory. *Information for post-CMCE (GMT 14:00:53 (EI+1004) and beyond) is predicted data for an* ***intact crew module*** *and* ***is not representative*** *of actual trajectory, accelerations, and thermal environment for the crew or for individual components of the crew module.*

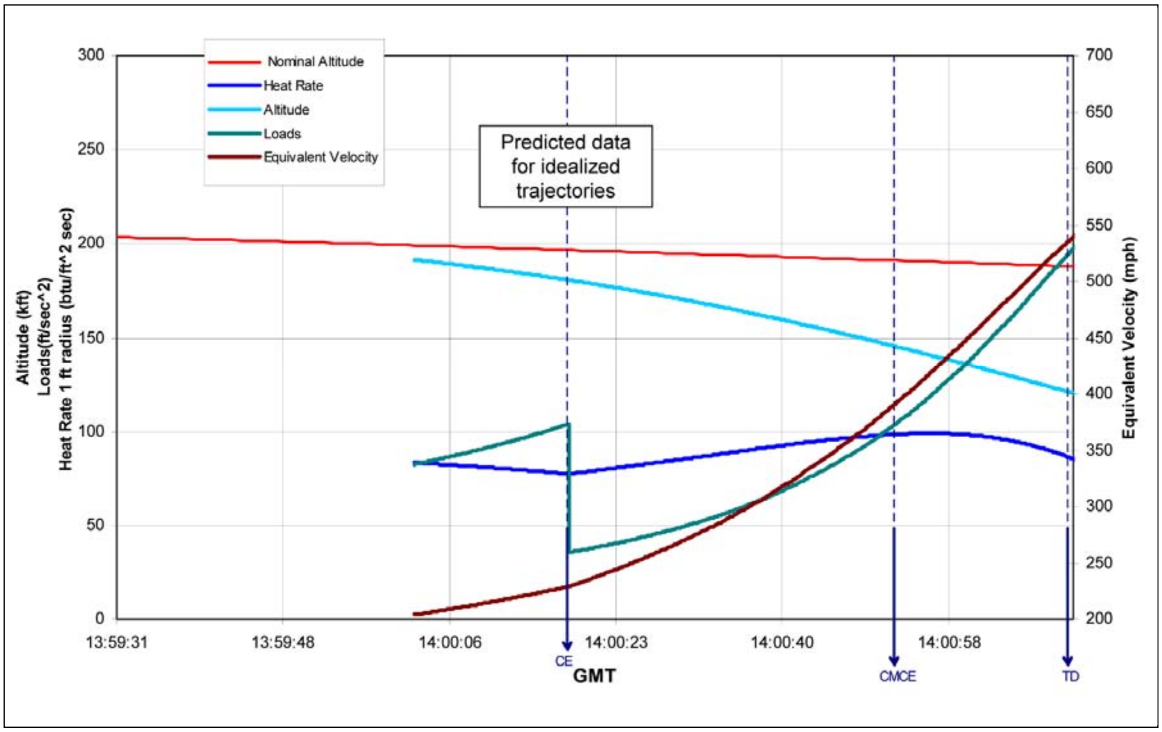



**Figure 1.1-29.** ***Predicted acceleration and thermal data for an idealized trajectory of the intact orbiter with a ballistic number of 42 pounds per square foot, and post-Catastrophic Event free-flying forebody with a ballistic number of 122 pounds per square foot.***

### 1.1.2.5 *Phase 5: Crew Module Catastrophic Event to Total Dispersal*
**[GMT 14:00:53 (EI+1004) to GMT 14:01:10 (EI+1021)]**
**17 seconds in duration**

This section discusses events affecting the crew from the CMCE at GMT 14:00:53 (EI+1004) to TD at GMT 14:01:10 (EI+1021). This phase lasted 17 seconds.

Three sources of data were available for analysis of Phase 5: video, debris, and medical findings.

Video data show that a significant forebody brightening event began at GMT 14:00:53 (EI+1004). By GMT 14:01:10 (EI+1021), the forward fuselage, crew module, and trailing debris clearly originating from the forebody are no longer visible in the video. In all videos, the last of this debris disappears from sight while in the middle of the field of view (FOV) rather than leaving the FOV, indicating either speed and/or size decreased such that its brightness, which was created by frictional heating from drag, was below the sensitivity of the video camera.

Debris analysis consisted of five techniques: cluster analysis, visual observations, materials analyses, ballistics, and thermal modeling predictions (see Section 2.4). Materials analysis was performed on select items to evaluate thermal exposure (see Sections 2.1 and 3.2). Materials evaluations were performed on the seats, some crew equipment, and some forebody structure. Additionally, some thermal modeling was done to estimate peak thermal temperatures after separation for various items. The model results were then compared to the actual debris appearance.

Based on video and ballistic evidence, at GMT 14:00:53 (EI+1004) a significant breakup event began. This event is designated as the CMCE.

The CMCE started with the separation of the forward fuselage from the crew module, exposing the entire crew module to the thermal effects of entry. The main forebody debris field included all recovered crew module pressure vessel structure, almost 90 percent of recovered forward fuselage structure, and around 90 percent of the crew module contents. This indicates that the failures of the forward fuselage and crew module were closely associated. Ballistic analysis confirmed this assessment.

The video recorded from an Apache helicopter operating in the area of Ft. Hood, Texas shows a significant event of two objects with similar luminosity and ballistic number separating simultaneously from the forebody (figure 1.1-30). The remaining central object maintained integrity for several more seconds in the video. Shortly after these items peeled away, the remaining object began to lose large pieces of structure.

The conclusion was drawn that these two objects were most likely the upper and lower forward fuselage sections, leaving the crew module (the central object) intact but no longer protected. Within seconds, the crew module began to lose structural integrity as well.

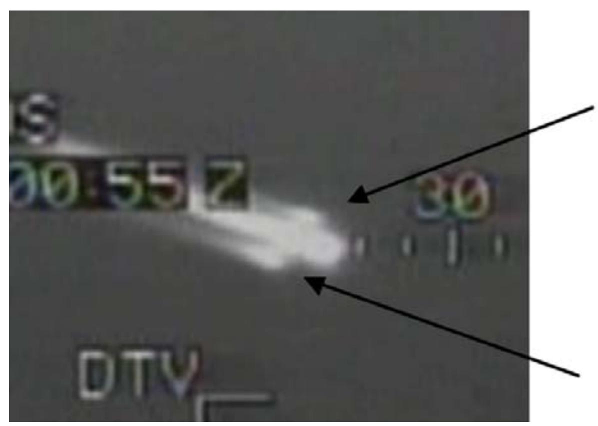



**Figure 1.1-30.** ***Video frame from the Apache video at GMT 14:00:55 (EI+1006) showing two similar luminosity objects separating from the forebody.***

Forward fuselage debris shows localized thermal damage and very little evidence of debris-debris interaction. Large portions of structure were recovered intact. Material deposition on the interior of the forward fuselage debris was not significant. Reconstruction of the forward fuselage debris supports a structural failure from starboard-to-port and forward-to-aft.

The crew module breakup was rapid (<15 seconds). The range of ballistic numbers of the debris items resulted in quickly diverging individual trajectories such that very little debris-debris interaction occurred. Cluster analysis of the debris field shows that the crew module forward $X_{cm}$[35] 200 bulkhead debris is farther west than the crew module aft $X_o$ 576 bulkhead debris. This indicates that the failure of the forward bulkhead happened prior to the failure of the aft bulkhead. The middeck floor debris field begins at the same longitude as the forward bulkhead, suggesting that the failures were nearly simultaneous. Debris evidence from the crew module structure suggests a starboard-to-port breakup of the middeck area, which probably included the forward bulkhead. Cluster analysis and evidence of significant heating of the flight deck floor and the flight deck seats indicates that the flight deck was intact for a short period of time (probably less than 5 seconds) after separation from the middeck. Cluster analysis indicates that the airlock stayed with the flight deck, possibly connected by the aft bulkhead.

[35]The $X_{cm}$ terminology refers to the X position in inches in the crew module coordinate frame, where the X-axis runs the length of the crew module from fore to aft. The crew module coordinate frame axes are coincident with the orbiter frame axes, but with a different X-axis origin.

There is no evidence of an explosion or a fire. Analysis of thermal vectors on numerous debris items showed multiple independent heat vectors across the structure. For example, many recovered middeck floor panels were nearly pristine with paint still visible, while floor panels from immediately adjacent locations had melted materials deposited on them and other signs of high thermal exposure (figure 1.1-31). After breakup, individual items experienced their own trajectories and heat exposure. This heat exposure can vary enormously with ballistic number and other effects such as shadowing from other debris items and orientation of the item into the heat vector. The lack of consistent directional heating vectors on crew module debris suggests heating was due to individual item trajectories and random exposure during breakup rather than a major breach resulting in directional heating.

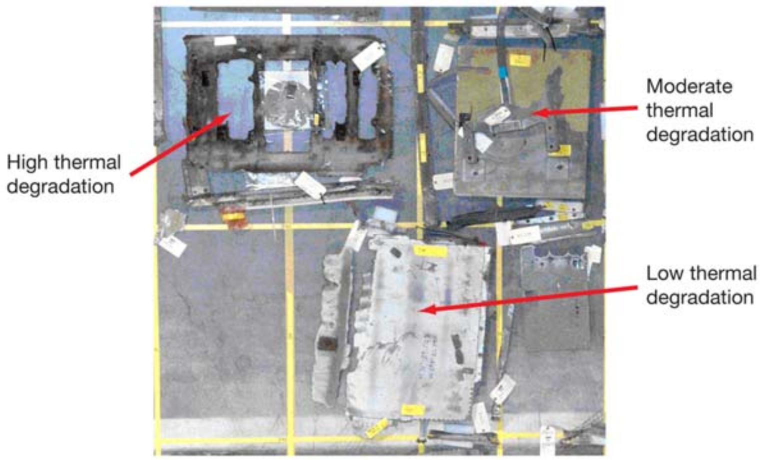



**Figure 1.1-31.** ***Middeck floor debris in original relative orientation showing varying thermal exposure.***

The exact time and sequence that the crew and seats separated from the crew module is unknown. A comprehensive evaluation of ballistic analysis of debris, crew member remains, and crew worn equipment indicates that the middeck crew remains were separated from the crew module prior to the flight deck crew remains, supporting the conclusion that the flight deck stayed intact a few seconds longer than the middeck.

The dynamic pressure environment exposure caused the mechanical failure of the crew suits (common to high-speed accidents, but somewhat unexpected given the aerodynamic pressure of only 450 to 550 psf). The suit is designed to maintain structural integrity when exposed to a windblast that is up to 560 knots equivalent air speed (KEAS) (806 psf). This assumes that the helmet visor is down. The helmet visors being in the up position is the most likely explanation for the hastened disruption of the suits. Although suit disruption was primarily due to aerodynamic (mechanical) loads, the thermal environment and atomic oxygen in the atmosphere may have been a contributing factor.

**The third event with lethal potential was separation from the crew module and the seats with associated forces, material interactions, and thermal consequences. This event is the least understood due to limitations in current knowledge of mechanisms at this Mach number and altitude. Seat restraints played a role in the lethality of this event.** Although the seat restraints played a significant role in the lethal-level mechanical injuries, there is currently no full range of equipment to protect for this event. This event was not survivable by any means currently known to the investigative team. All circulatory functions had ceased by the end of this phase.

Whether an item separated from the crew module or the crew module lost significant mass, an instantaneous change in ballistic number occurred and resulted in varying deceleration and thermal profiles. The accelerations varied from over 30 G for a short duration (less than 5 seconds) to over 10 G for up to 20 seconds. The range of ballistic numbers of debris generated a range of thermal conditions. Objects with higher ballistic numbers take longer to decelerate, and experience longer periods of heating and lower G-spikes (see Section 2.1). Video shows a large deceleration of the crew module relative to the main engines at GMT 14:01:08 (EI+1019). The visual object actually represents a cloud of multiple objects that experienced deceleration at varying rates. Several seconds elapsed before objects of varying ballistic numbers separated visually from each other, creating the impression of a solid object in the video for a few seconds. This is consistent with a gradually expanding breakup caused by items having a wide range of ballistic numbers and deceleration trajectories, resulting in a widely spread debris cloud.

TD was complete by GMT 14:01:10 (EI+1021).

#### 1.1.2.6 *Phase 6: Total Dispersal to ground impact* [GMT 14:01:10 (EI+1021) to approximately 14:35:00 (EI+3051)] approximately 34 minutes in duration

This section discusses events from TD (GMT 14:01:10 (EI+1021)) to the ground impact of debris. Heavy items impacted the ground much sooner than lighter objects but traveled much farther from the point of separation. It was calculated that a small fragment of cloth with a ballistic number of .5 psf would impact the ground around 33 minutes after separation. Based on this calculation, all crew module debris was likely on the ground (including very lightweight objects) by GMT 14:35:00 (EI+3051).

Three sources of data were available for Phase 6: video, debris analysis, and medical findings.

Very limited video data were available as the crew module rapidly disappeared from the FOV as it dispersed into smaller and smaller debris. The smaller size and loss of heating as the debris decelerated reduced the ability to detect items in the video. Debris analysis consisted of four techniques: visual observations, ballistics analysis, cluster analysis, and materials analysis (see Chapter 4).

The forebody breakup event occurred between 145,000 feet and 105,000 feet at an ambient pressure of approximately 0.03 pound per square inch (psi). After the deceleration peak, the overall deceleration would stabilize to 1 G at terminal velocity. At ground level, the ambient absolute pressure condition was approximately 14.7 psi and the temperature was 59°F (15°C).

**The fourth event with lethal potential was exposure to near vacuum, aerodynamic accelerations, and cold temperatures.** Current crew survival equipment is not certified to protect the crew above 100,000 feet, although it may potentially be capable of protecting the crew.

At the altitude the deceased crew departed from the crew module, the environmental risks include lack of $O_2$, low air pressure, high thermal exposure as a result of deceleration from high Mach numbers, and exposure to cold temperatures. Existing shuttle CEE is certified to protect a crew member exposed to an atmospheric/altitude environment up to 100,000 feet. Anecdotal evidence from the survival of the pilot of an SR-71 mishap[36] suggests that an intact, pressurized suit similar to the ACES can also protect a crew member at least up to speeds of Mach 3.

Shuttle crew members carry a personal $O_2$ supply that provides $O_2$ independent of the orbiter supply. This system can provide enough $O_2$ for a crew member to reach the ground from altitudes much greater than 100,000 feet, so it is not the limiting factor in the system.

The ground impact without parachute protection generated a very large instantaneous G event.

**The final event with lethal potential was ground impact.** Existing shuttle CEE protects for ground impact with a parachute. However, the crew must manually initiate the parachute opening sequence, or the parachute must be used in conjunction with the crew escape pole of the shuttle to initiate the parachute automatic opening sequence.

[36]Department of the Air Force, SR-71 Aircraft Mishap Report, January 25, 1966.

# 1.2 Master Timeline

The SCSIIT Master Timeline was developed as a tool to aid the SCSIIT with the investigation of what happened to the crew of STS-107. The SCSIIT Master Timeline began with the tailoring of the CAIB Master Timeline, Revision 15 to highlight crew-related events. Additional events were added from various sources, including:

- recorded telemetry
- RGPC data
- MADS/OEX recorder data
- MAGR data
- recovered on-board videos
- ground-based videos
- air-to-ground audio
- forensic analysis of medical findings
- engineering forensic analysis of vehicle and CEE debris
- ballistic analysis of vehicle and CEE debris

The timeline is divided into six phases:

- Phase 1: From the deorbit preparation checklist timeline initiation to EI. The deorbit preparation checklist timeline begins 4 hours prior to the deorbit burn. EI is defined as the time at which an altitude of 400,000 feet was reached. [GMT 09:15:30 (EI–16119 seconds) – GMT 13:44:09 (EI)]

- Phase 2: From EI to LOS. LOS is the time of the loss of voice and real-time data from *Columbia*. [GMT 13:44:09 (EI) – GMT 13:59:32 (EI+923)]

- Phase 3: From LOS to the CE. The CE is defined as the initiation of the orbiter breakup into the primary subcomponents of the forebody, midbody and aftbody. The CAIB timeline ends with the CE. [GMT 13:59:32 (EI+923) – GMT 14:00:18 (EI+969)]

- Phase 4: From the CE to the CMCE. The CMCE is defined as the initiation of the forebody breakup. [GMT 14:00:18 (EI+969) – GMT 14:00:53 (EI+1004)]

- Phase 5: From the CMCE to TD. TD is defined as the time at which the crew module was broken down into its subcomponents. [GMT 14:00:53 (EI+1004) – GMT 14:01:10 (EI+1021)]

- Phase 6: From the TD to ground impact of the crew and the bulk of the crew module debris. [GMT 14:01:10 (EI+1021) – approximately GMT 14:35:00 (EI+3051)]

All events are presented in GMT. In addition, events prior to the TIG of the deorbit burn also include the time prior to TIG. After TIG, the events include the time from TIG and the time to EI. After EI is reached, all events are presented in just GMT and EI.

Five symbols are used in the timeline to aid the reader in scanning for events of a certain category. The symbols are:

– indicates a crew-related event.

– indicates an event that is based/observed on video footage.

– indicates a vehicle-related event.

– indicates a vehicle-related event that occurred at the time of the separation of the forebody (crew module and forward fuselage) from the midbody.

– indicates a vehicle-related event that occurred after the separation of the forebody from the midbody.

The timeline does not include every event. For a comprehensive listing of events, the reader should consult sources such as:

- *Columbia* Accident Investigation Board Master Timeline, Revision 15
- *Columbia* Accident Investigation Board Report, Volume II, Appendix D.19, Qualification and Interpretation of Sensor Data from STS-107
- OEX Data Evaluation of End of Mission Data for STS-107, Vehicle Data Mapping Team, presentation, 8-22-2003, Rev B
- STS-107 Investigation Action Response: OVE-204 Crew Inputs After Loss of COMM (Voice); CAIB-MRT-00099, 3-10-2003

## 1.2.1 Phase 1: Deorbit preparation to entry interface
### GMT 09:15:30 (EI–16119) through GMT 13:44:09 (EI)

| TIME | EVENT |
|---|---|
| 09:15:30 (TIG[1]–04:00:00[1]) | **Deorbit Preparation.** The crew begins working items on the deorbit preparation (D/O PREP) checklist at TIG–4 hours per pre-mission planning. |
| 11:11:18 (TIG–02:04:12) | **OPS 301.** The crew, per nominal procedures, manually enters the OPS 301 command to initiate the Pre-Deorbit Coast Major Mode software. This is the first entry-phase software sequence in preparation for entry. [*Telemetry, Tracking, and Data Relay Satellite-West (TDRS-W) data*] |
| ~11:40:00 (TIG–01:35:30) | **Recovered Middeck Video Begins.** Approximately 30 minutes of video (without audio) were recovered from a camera in the middeck. On the video, the crew is shown working through D/O PREP checklist items. Times are approximate due to the lack of audio and visual cues to synchronize activities seen on the video with GMT (figure 1.2-1). |

[1]TIG is time of ignition and refers to the start time of the deorbit burn. TIG–hh:mm:ss is the time before the burn begins in hours (hh), minutes (mm), and seconds (ss). TIG+hh:mm:ss is the time after the burn begins.

**TIME** **EVENT**


**Figure 1.2-1.** ***Start of the recovered middeck video.***

The following was observed at the start of the video (figure 1.2-2):

- All middeck seats (seat 5, seat 6, and seat 7) are installed on the middeck floor.
- Personal parachute assemblies for MS3/Seat 5, MS1/Seat 6, and Payload Specialist 1 (PS1)/Seat 7 are positioned on seatbacks.
- MS3/Seat 5 has already donned the ACES (excluding gloves and helmet) and parachute harness.
- MS1/Seat 6 and PS1/Seat 7 have yet to don the ACESs.
- The escape pole is still stowed on the middeck ceiling (on-orbit location).

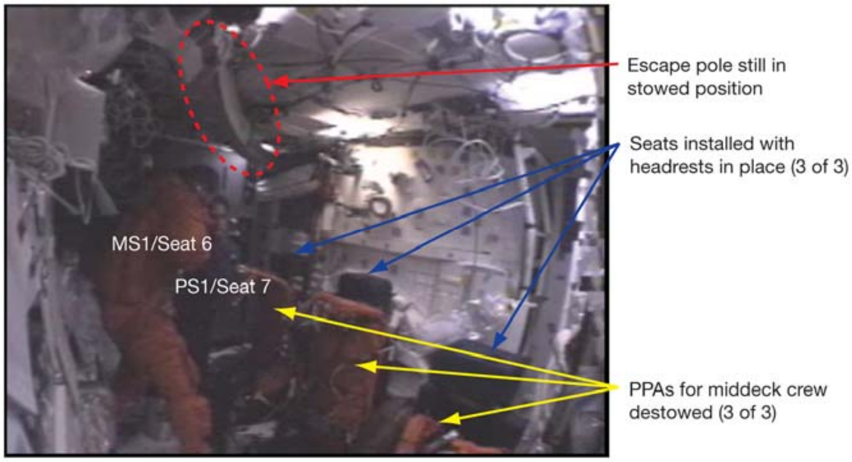



**Figure 1.2-2.** ***Middeck configuration during duration of the recovered video.***

| TIME | EVENT |
| --- | --- |
| ~11:48:56 (TIG–01:26:34) | CDR/Seat 1 dons ACES (excluding gloves and helmet) and parachute harness and goes to flight deck. |
| | MS3/Seat 5 and PS1/Seat 7 are observed fluid-loading in preparation for return to 1 G. |
| | MS1/Seat 6 dons ACES (excluding gloves and helmet) and parachute harness. |
| | PS1/Seat 7 and MS1/Seat 6 pass helmets in helmet bags to flight deck crew members. |
| 12:10:00 (TIG–01:05:30) | **Recovered Middeck Video Ends.** The video ends with PS1/Seat 7, MS3/Seat 5, and MS1/Seat 6 beginning to remove the escape pole from the ceiling to install it. The D/O PREP checklist calls for the pole to be installed as one of many activities in the Entry Cabin Configuration block, which starts at TIG–03:50:00. NOTE: Evaluation of the debris reveals that the pole was installed in the launch/entry position, so the crew completed the installation (figure 1.2-3). |


**Figure 1.2-3. *End of the recovered middeck video*. [Mission Specialist 3/Seat 5 in foreground]**

| TIME | EVENT |
|---|---|
| 12:53:04 (TIG–00:22:26) | **OPS 302.** Per nominal procedures, the crew manually enters the OPS 302 command to initiate the *Deorbit Execute* Major Mode software. [*Telemetry, TDRS-W data*] |
| 13:10:00 (TIG–00:05:00) | The MCC gives the "GO" for deorbit burn.[2] |
| 13:10:30 (TIG–00:05:00) | **TIG–5**. TIG refers to the time of the planned ignition of the OMS engines (referred to as the deorbit burn) to reduce the orbiter's velocity enough to result in entry into the atmosphere. This is a benchmark time to make sure the crew starts the APU in time for the deorbit burn and is also the time at which the last MS is to be seated. [*Based on TIG event in Master Timeline, Rev. 15 Baseline*] |
| 13:10:39 (TIG–00:04:51) | **APU 2 Start – Low Press.** Three APUs provide pressure to the orbiter hydraulic systems (engine gimbals, elevons, and body flap). Only one APU is used to support the deorbit burn. [*Master Timeline, Rev. 15 Baseline*] |
| 13:15:30 (TIG–00:00:00) | **TIG: Deorbit Burn Begins.** This is the beginning of the deorbit burn using the OMS engines. [*Master Timeline, Rev. 15 Baseline*] |
| 13:18:08 (EI–1561) | **Deorbit Burn Ends.** This is the end of the deorbit burn. [*Master Timeline, Rev. 15 Baseline*] |
| 13:20:21 (EI–1428) | **OPS 303.** Per nominal procedures, the crew manually enters the OPS 303 command to initiate the *Pre-entry Monitor* Major Mode software. |
| 13:26:09 (EI–1080) | **Forward RCS Dump Start.** This is a nominal operation to deplete the forward RCS fuel and oxidizer tanks in preparation for entry. [*Master Timeline, Rev. 15 Baseline*] |
| 13:27:12 (EI–1017) | **Forward RCS Dump Complete.** [*Master Timeline, Rev. 15 Baseline*] |
| 13:31:25 (EI–764) | **APU 1 Start.** APU 1 is started per the deorbit procedures. [*Master Timeline, Rev. 15 Baseline*] |
| 13:31:29 (EI–760) | **APU 3 Start.** APU 3 is started per the deorbit procedures. [*Master Timeline, Rev. 15 Baseline*] |
| 13:31:57 (EI–732) | APU 1 is performing nominally. [*Master Timeline, Rev. 15 Baseline*] |

[2]*Columbia* Accident Investigation Board Report, Volume I, August 2003, p. 38.

| TIME | EVENT |
|---|---|
| 13:31:59 (EI–730) | APU 2 is performing nominally. [*Master Timeline, Rev. 15 Baseline*] |
| 13:32:01 (EI–728) | APU 3 is performing nominally. [*Master Timeline, Rev. 15 Baseline*] |
| 13:32:11 (EI–718) | PLT/Seat 2: "Houston, here comes SSME HYD repress." This is part of the procedure to use the hydraulic system to move the space shuttle main engines (SSMEs) to the desired position for entry and landing. [*SCSIIT air-to-ground 1 (A/G1) Tape Elapsed Time (TET)*[3] *02:20:26*] |
| 13:32:18 (EI–711) | CAPCOM: "And we're ready, Willie. No deltas." This message informs the crew that there were no changes to the planned procedure. [*SCSIIT A/G1 TET 02:20:33*] |
| 13:32:22 (EI–707) | PLT/Seat 2: "Copy, no deltas." [*SCSIIT A/G1 TET 02:20:37*] |
| 13:35:16 (EI–533) | CAPCOM: "And *Columbia*, Houston. The HYD fluid thermal conditioning will not be required today. We'll meet you on the cards." [*SCSIIT A/G1 TET 02:23:31*] |
| 13:35:26 (EI–523) | CDR/Seat 1: "And we copy, Houston. HYD fluid thermal conditioning not required, and we copy going to the cards." [*SCSIIT A/G1 TET 02:23:41*] |
| 13:35:32 (EI–517) | CAPCOM: "And, Rick, don't want to lead you astray, and don't forget about the stuff on page 3-44." [*SCSIIT A/G1 TET 02:23:47*] Page 3-44 is part of the entry checklist; it contains the steps for enabling the RHCs by turning on the flight controller power and activating the entry video camera system. The last step has the crew go to the Entry Maneuvers cue card. |
| 13:35:34 (EI–515) | **Recovered Flight Deck Video Begins.** The first audio on the tape is of the CAPCOM completing the sentence recorded on the A/G audio at approximately GMT 13:35:32 (EI-517): "…and don't forget about the stuff on page 3-44." [*SCSIIT A/G1 TET 02:23:51*] The PLT/Seat 2 is shown adjusting g-suit setting (figure 1.2-4). |

[3]TET is the tape elapsed time from the start of the audio recording file.

| TIME | EVENT |
|---|---|

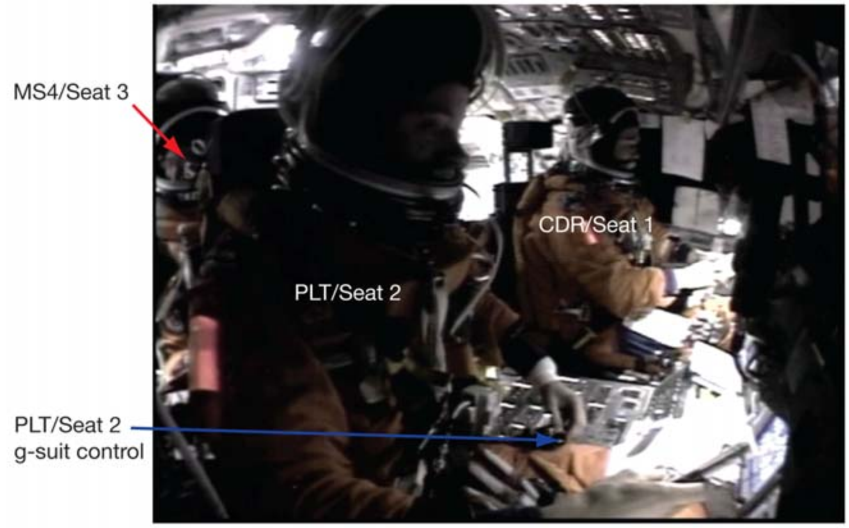



**Figure 1.2-4.** ***Pilot/Seat 2 adjusting g-suit setting*.**

All visible crew members (CDR/Seat 1, PLT/Seat 2, and MS4/Seat 3) are fully suited except for gloves and are strapped in. All helmet visors are OPEN per nominal procedure.

CDR/Seat 1: "Right, we're checking that. We've got the flight controller power on. We're working through the rest of it as well. Thanks." [*SCSIIT A/G1 TET 02:23:57*]

CAPCOM: "Sounds good."

13:36:02 (EI–487) MS4/Seat 3 is shown starting to don gloves (figure 1.2-5).


**Figure 1.2-5.** ***Mission Specialist 4/Seat 3 donning glove*.**
**[Glove is within dotted circle]**

| TIME | EVENT |
|---|---|
| 13:36:04 (EI–485) | Between GMT 13:36:04 (EI-485) and GMT 13:36:06 (EI-483), the CDR/Seat 1 is performing entry preparation actions that lead to the RHC being bumped (figure 1.2-6). |

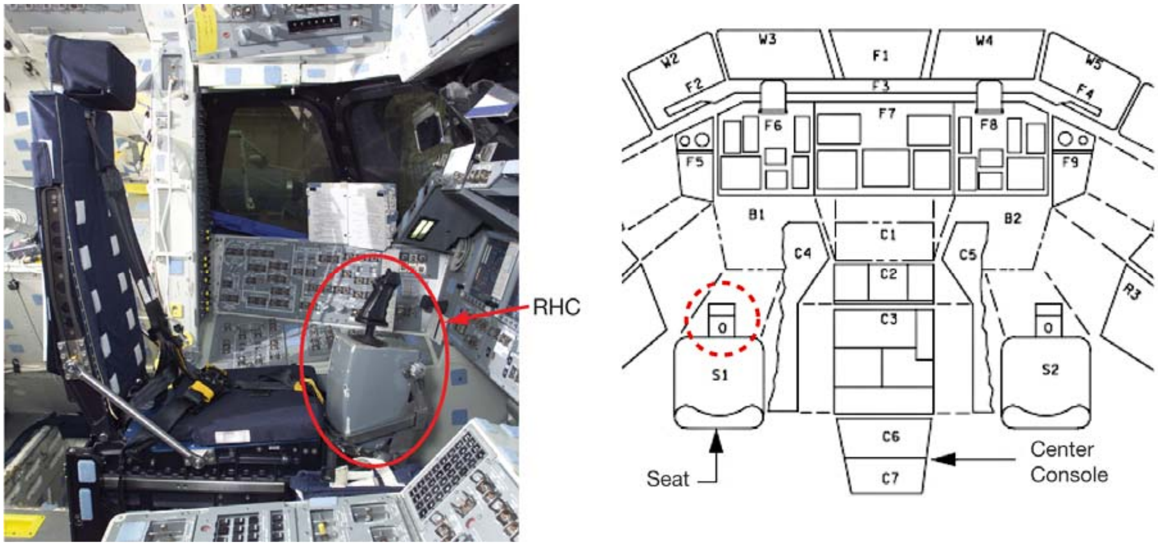



**Figure 1.2-6. *Location of Commander's seat and rotational hand controller*. [Left picture from the Shuttle Training Simulator looking from starboard to port; right picture adapted from the Space Shuttle Systems Handbook looking from aft to forward]**

| | |
|---|---|
| 13:36:07 (EI–482) | **DAP DNMODE RHC.** Primary Avionics Software System (PASS) DAP DOWNMODE RHC (time from telemetry analysis). The message indicates that the RHC movement in the previous event was sufficient to mode the DAP out of AUTO into Inertial mode. When this occurs, a "DAP DOWNMODE RHC" caution and warning message is displayed, the INRTL button on the C3 panel is illuminated (see arrow in figure 1.2-7), and a tone, which can be heard in the recovered video tape, is annunciated (figure 1.2-7). |

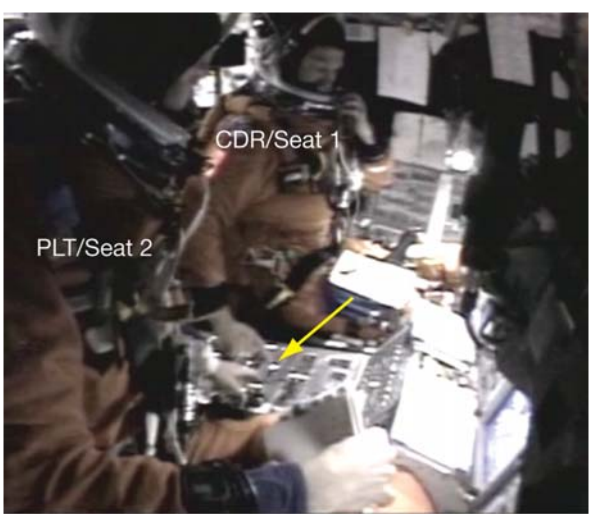



**Figure 1.2-7. *Digital autopilot button on the C3 panel is illuminated*.**

| **TIME** | **EVENT** |
|---|---|
| 13:36:14 (EI–475) | CDR/Seat 1 responds to the DAP DOWNMODE RHC message by pressing the illuminated AUTO button on the C3 panel to restore the DAP to AUTO (figures 1.2-8 and 1.2-9). |

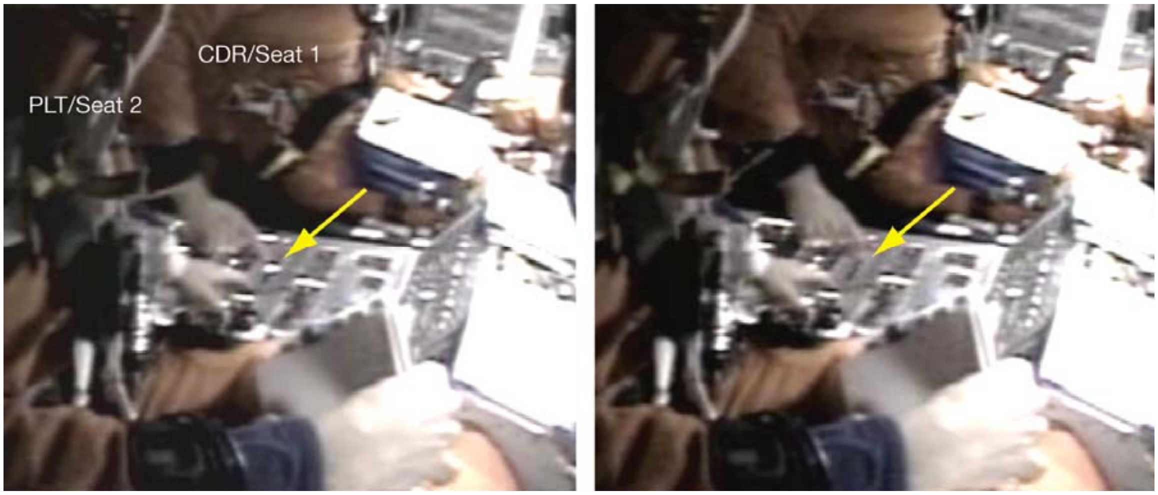



**Figure 1.2-8.** ***Digital autopilot is no longer in AUTO, INRTL light is ON*** **(left figure)*****; Commander/Seat 1 restores digital autopilot to AUTO, INRTL light is OFF*** **(right figure).**

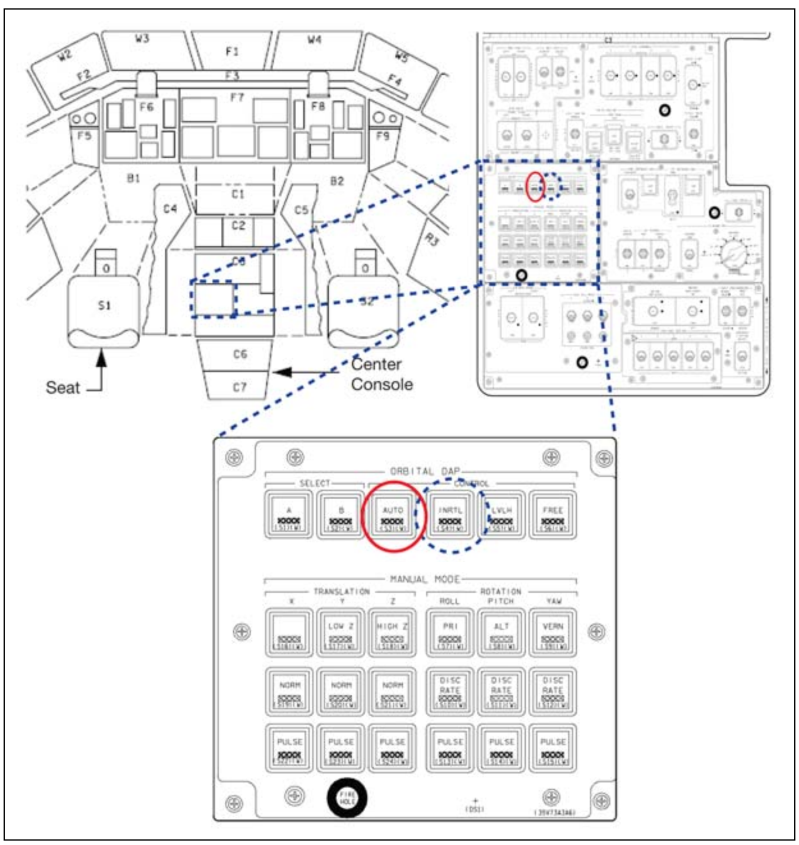



**Figure 1.2-9.** ***Location of the "INRTL" button*** **(blue circle)** ***that illuminated when the digital autopilot moded out of AUTO, and the "AUTO" button*** **(red circle)** ***that the Commander pressed to restore the digital autopilot to AUTO*****. [Adapted from the Space Shuttle Systems Handbook]**

| TIME | EVENT |
| --- | --- |
| 13:37:31 (EI–398) | CAPCOM: "*Columbia*, Houston for Rick. We'll take another ITEM 27 please." This is required to resume the maneuver (to the EI–5-minute attitude) that was interrupted by the bumped RHC. The CDR/Seat 1 acknowledges the request. [*A/G recording and recovered flight deck video*] |
| 13:37:39 (EI–390) | ITEM 27. CDR/Seat 1 manually inputs the ITEM 27 command using the keypad on the C2 panel. This fully recovers the vehicle from the bumped RHC. [*From video and telemetry*] (figures 1.2-10 and 1.2-11) |

**Figure 1.2-10.** ***Commander/Seat 1 inputting an ITEM 27.***

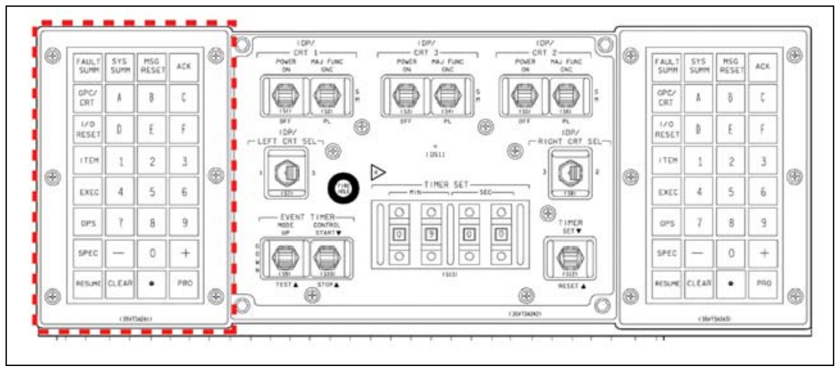



**Figure 1.2-11.** ***Entry keypad*** **(red dashes)** ***on the C2 panel*****. [Adapted from the Space Shuttle Systems Handbook]**

| TIME | EVENT |
| --- | --- |
| 13:37:44 (EI–385) | CDR/Seat 1: "And thanks for that, Houston. We gave you an ITEM 27. We bumped the stick earlier." |
| | CAPCOM: "Not a problem, Rick." |
| 13:38:50 (EI–319) | CDR/Seat 1 enters the OPS 304 command into the queue. OPS 304 is the *Entry* Major Mode software. |
| 13:38:56 (EI–313) | CDR/Seat 1: "And, Houston, we'll get the 304 at 5 minutes." |
| 13:39:04 (EI–305) | CAPCOM: "Rick, we're ready for OPS 304." |
| 13:39:09 (EI–300) | **OPS 304.** The CDR/Seat 1 executes OPS 304. [*Flight deck video, Telemetry, TDRS-W data – cathode ray tube (CRT) 1, Master Timeline, Rev. 15*] |
| 13:40:12 (EI–237) | PLT/Seat 2 gloves are observed ON and MATED (figure 1.2-12). |

| TIME | EVENT |
|---|---|


**Figure 1.2-12.** ***Pilot/Seat 2 observed with gloves ON and MATED.***

## 1.2.2 Phase 2: Entry interface to loss of signal
### [GMT 13:44:09 (EI) through GMT 13:59:32 (EI+923)]

13:44:09 (EI) — **EI.** This is the point where the orbiter is considered to be first encountering the atmosphere. (GPS derived) [*Master Timeline, Rev. 15 Baseline*]

Alt = 400,000 feet [per definition of EI]
Mach = 24.57 (*Master Timeline, Rev. 15 Baseline*]
Qbar = ~0.01 psf [modeling]

13:44:15 (EI+006) — CDR/Seat 1 states, "Just past EI."

13:44:58 (EI+049) — CDR/Seat 1 request for everyone to check suit pressure integrity.

13:45:13 (EI+064) — CDR/Seat 1 observed with helmet visor down and latched in preparation for the suit pressure check and the communication check. MS2/Seat 4 visor observed OPEN and both gloves OFF (figure 1.2-13).

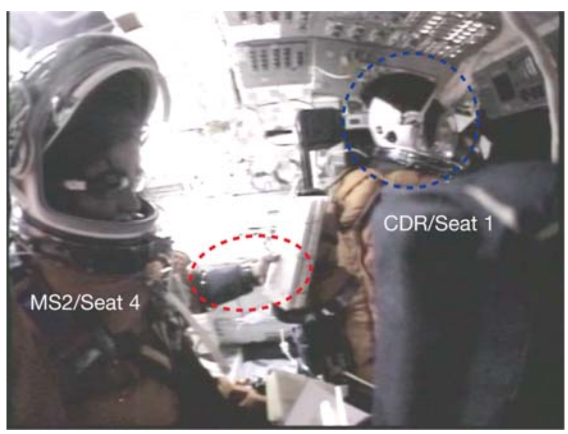



**Figure 1.2-13.** ***Commander/Seat 1 visor down and latched*** **(blue dashed circle)** ***and Mission Specialist 2/Seat 4 with helmet on and left glove off*** **(red dashed circle).**

| TIME | | EVENT |
|---|---|---|
| 13:45:24 (EI+075) | | **Suit Pressure/Communications (COMM) Check.** CDR/Seat 1, PLT/Seat 2, and MS4/Seat 3 complete COMM check. Visors are DOWN and locked during this check. Analysis of the $O_2$ supply pressure telemetry identified the $O_2$ supply pressure drop from the CDR/Seat 1, PLT/Seat 2, and MS4/Seat 3 suit pressure check. |
| | | During the suit pressure integrity check, the CDR/Seat 1, PLT/Seat 2, and/or MS4/Seat 3 microphone activated the intercom system. Breathing is heard for about 20 seconds. CDR/Seat 1 comments, “It’s noisy in there, isn’t it?” |
| 13:45:50 (EI+101) | | MS4/Seat 3 states going visor UP after suit pressure check. |
| 13:46:18 (EI+129) | | PLT/Seat 2 is observed with visor OPEN. |
| 13:46:48 (EI+159) | | Mach = 24.66 [*Master Timeline, Rev. 15 Baseline*]<br>Qbar = 0.5 psf [*Master Timeline, Rev. 15 Baseline*] |
| 13:47:13 (EI+184) | | **Accelerometer Bit Flip.** PLT/Seat 2 states that he observed a bit-flip on the accelerometer, indicating that the entry deceleration loads are starting to build as expected and were finally large enough to be registered by the vehicle accelerometers. |
| 13:47:20 (EI+191) | | CDR/Seat 1 states to crew, “We’re at a hundredth of a G.” |
| 13:47:38 (EI+209) | | CDR/Seat 1 and PLT/Seat 2 are observed with gloves still ON and MATED (red circles in figure below), visors OPEN. MS2/Seat 4 is observed starting to don gloves (yellow circle in figure) and is also observed with left glove ON but NOT MATED and right glove OFF (figure 1.2-14). |

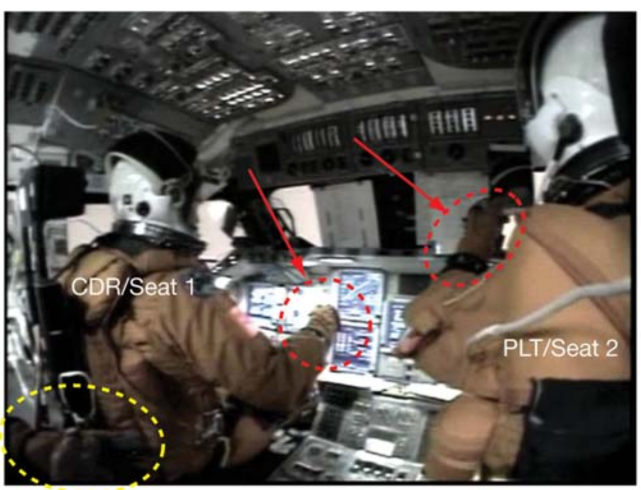



**Figure 1.2-14.** ***Mission Specialist 2/Seat 4 donning left glove; Commander/Seat 1 and Pilot/Seat 2 with gloves ON and MATED.***

| Time | Event |
|---|---|
| 13:47:51 (EI+222) | MS4/Seat 3 with right glove still ON and MATED (figure 1.2-15). |

**Figure 1.2-15.** ***Mission Specialist 4/Seat 3 right glove still ON and MATED*.**

| Time | Event |
|---|---|
| 13:47:52 (EI+223) | Mach = 24.66 [*Master Timeline, Rev. 15 Baseline*]<br>Qbar = 2.0 psf [*Master Timeline, Rev. 15 Baseline*] |
| | **Elevon and Body Flap Active**. When the Qbar increases to 2 psf, the elevons and body flap aerodynamic control surfaces become effective for controlling the vehicle and are added as active effectors to the vehicle control logic. |
| 13:48:45 (EI+276) | **End of Recovered Flight Deck Video.** This is the last frame with a discernable image (figure 1.2-16). |

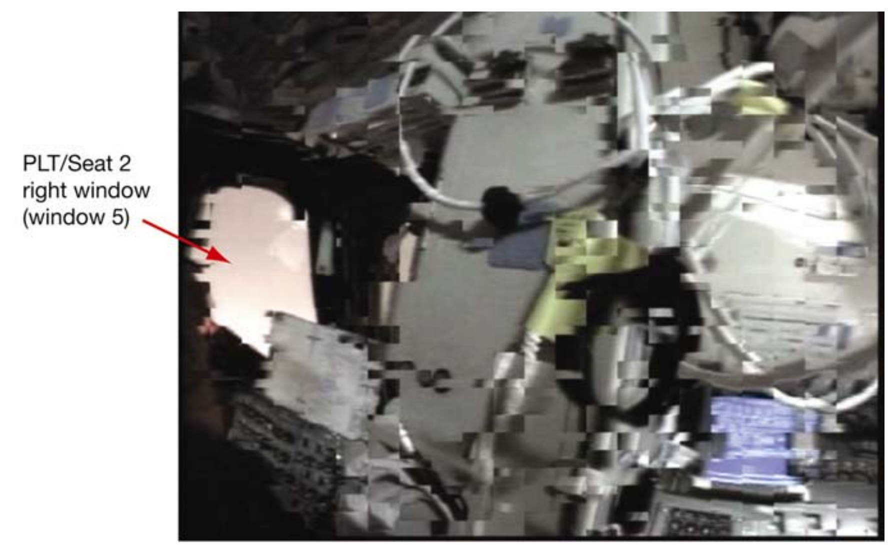



**Figure 1.2-16.** ***Last discernable image from recovered flight deck video*. [Window 5 and the right side of the crew module visible]**

| TIME | EVENT |
|---|---|
| 13:49:16 (EI+307) | Mach = 24.57 [*Master Timeline, Rev. 15 Baseline*]<br>Qbar = ~10.0 psf [*Master Timeline, Rev. 15 Baseline*] |
| | **Roll Jets Deactivated.** When the Qbar increases to 10 psf, the roll jets are removed from the control logic. [*Master Timeline, Rev. 15 Baseline*] |
| 13:49:32 (EI+323) | **Start of First Planned Roll to the Right for Energy Management.** [*Master Timeline, Rev. 15 Baseline*] (figure 1.2-17). |

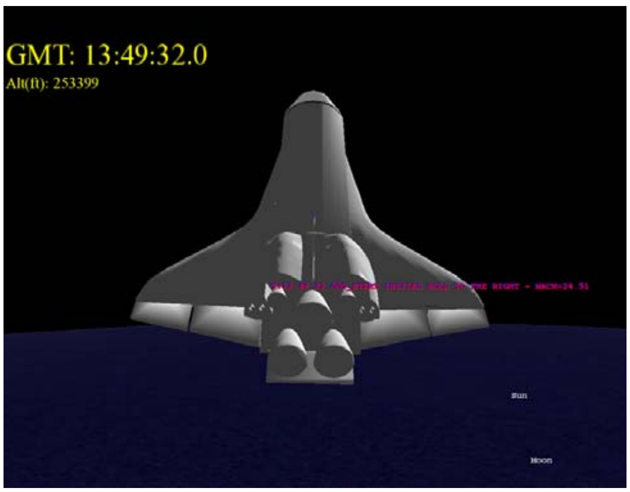



**Figure 1.2-17.** ***Attitude of*** **Columbia** ***at the start of the first planned roll.***

| | |
|---|---|
| | Mach = 24.51 [*Master Timeline, Rev. 15 Baseline*]<br>Qbar = ~15 psf [modeling] |
| 13:50:00 | **Completion of First Planned Roll to the Right for Energy Management.** [*Master Timeline, Rev. 15 Baseline*] (figure 1.2-18). |

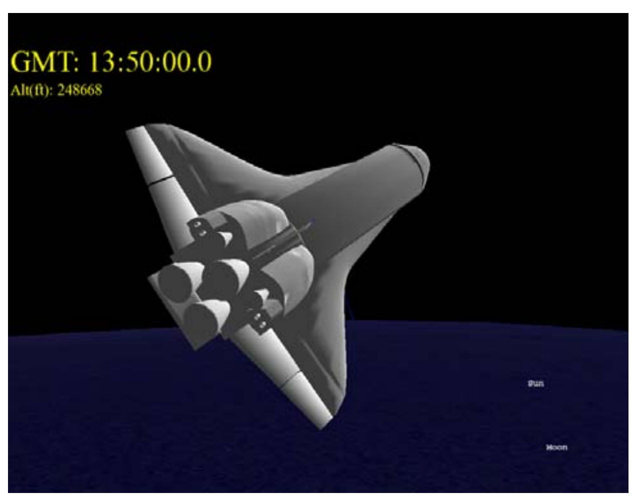



**Figure 1.2-18.** ***Attitude of*** **Columbia** ***at the end of the first planned roll.***

| TIME | EVENT |
|---|---|
| 13:50:30 (EI+381) | First indication of entry heating. A thermal sensor measurement and stimulus indication (MSID) V09T1702A in the aft fuselage center bottom bond line registers a normal rise in temperature due to entry heating. [*Master Timeline, Rev. 15 Baseline*] |
| 13:50:53 (EI+404) | Start of peak heating. [*Master Timeline, Rev. 15 Baseline*] |
| | Alt = 243,048 feet [*Master Timeline, Rev. 15 Baseline*]<br>Mach = 24.12 [*Master Timeline, Rev. 15 Baseline*]<br>Qbar = ~22 psf [modeling] |
| 13:51:19 -13:52:49 | Nominal yaw jet firings were occurring during this time (GMT 13:51:19 (EI+430) to GMT 13:52:49 (EI+520)). When the yaw jet(s) fires, an indicator on the F6 panel will illuminate while the jet(s) is on (see arrows on figure 1.2-19). [*Master Timeline, Rev. 15 Baseline*] |

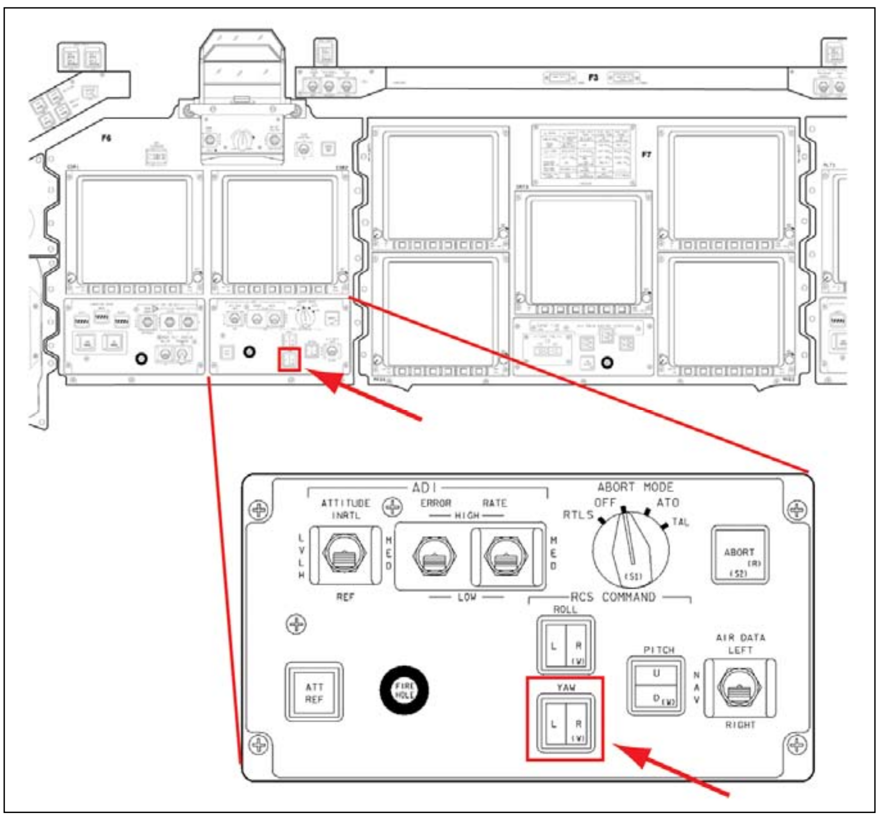



**Figure 1.2-19.** ***Location of the yaw jet indicator light*. [Adapted from the Space Shuttle Systems Handbook]**

| TIME | EVENT |
|---|---|
| 13:51:46 (EI+457) | Inertial sideslip angle (beta) goes negative (yaw to port/left) and stays negative until the LOS from *Columbia* at GMT 13:59:32 (EI+923) (figure 1.2-20). [*Master Timeline, Rev. 15 Baseline*] |

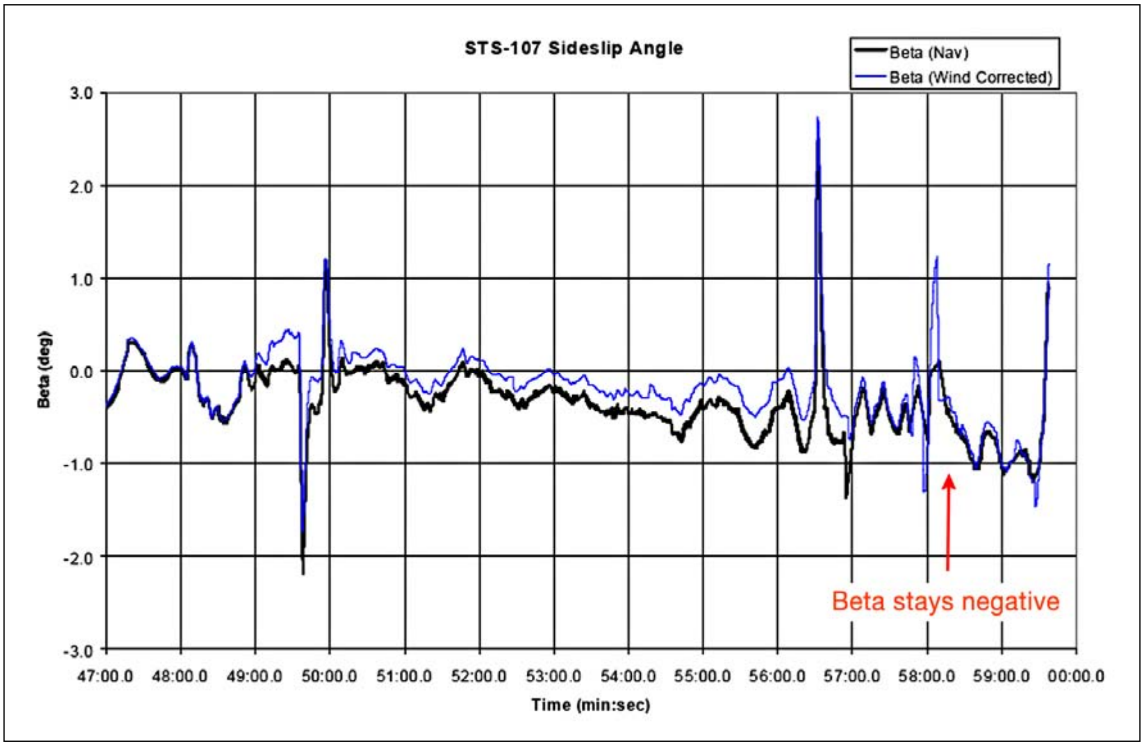



**Figure 1.2-20. *STS-107 sideslip angle vs. time.***[4]

| | |
|---|---|
| 13:52:05 (EI+476) | **Yaw-Moment Changed.** Post-accident analysis determined that this was the first clear indication of off-nominal aerodynamics. This information was not available/visible to the crew or controllers in real time. [*Master Timeline, Rev. 15 Baseline*] |
| 13:52:17 (EI+488) | Left main landing gear brake line temperature sensor (MSID V58T1703A), which was located on the inboard sidewall of the wheel well, starts to indicate an off-nominal temperature rise rate. This is the first indication of off-nominal system readings in the left wing. The information is not visible to the crew. [*Master Timeline, Rev. 15 Baseline*] |
| | **Damage to Left Wing Begins – NLT Time.** Post-accident analysis determined that damage inside the left wing began NLT this time.[5] |

[4]Integrated Entry Environment Team Final Report, May 30, 2003, Figure I-21, p. I-12.
[5]*Columbia* Accident Investigation Board Report, Volume I, August 2003, pp. 68 and 71.

| TIME | | EVENT |
|---|---|---|
| | | Approximately 300 miles west of the California coast (figure 1.2-21)<br>Alt = 236,791 feet [*Master Timeline, Rev. 15 Baseline*]<br>Mach = 23.58 [*Master Timeline, Rev. 15 Baseline*]<br>Qbar = ~27 psf [modeling] |

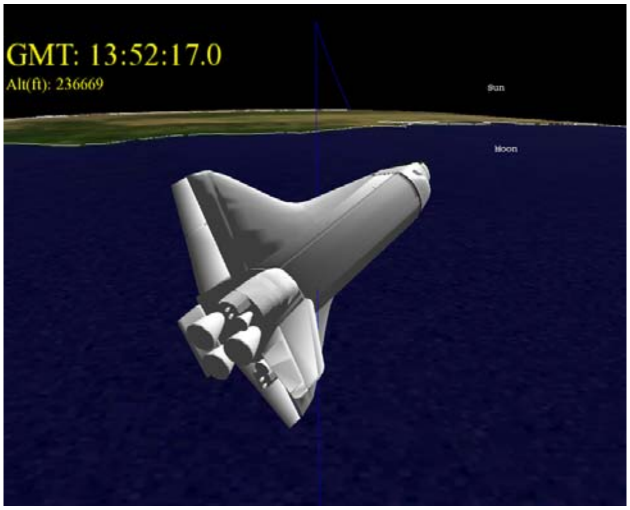



**Figure 1.2-21. Columbia *approaching the California coastline*.**

| | | |
|---|---|---|
| 13:53:00 (EI+531) | | Qbar = ~29 psf |
| 13:53:01 (EI+532) | | Off-nominal rolling moment. Post-accident analysis identifies the first clear indication of off-nominal rolling moment. Start of steady growth in roll moment. [*Master Timeline, Rev. 15 Baseline*] |
| 13:53:10 (EI+541) | | **First Indication in MCC of Off-nominal Readings.** Four hydraulic return line temperature sensors in the left wing went off-scale low (OSL) between GMT 13:53:10 (EI+541) and GMT 13:53:36 (EI+557). OSL refers to a reading that is below the lower display limit. When several sensors go OSL it usually indicates a suite of sensors has failed. These sensor failures were described in the CAIB Report. This information was not available to the crew. |
| 13:53:15 (EI+546) ±2 sec | | At GMT 13:53:15 (EI+546) ±2 sec, ground-based video coverage of *Columbia* is acquired by videographers who are unassociated with NASA (figure 1.2-22). |

**TIME** **EVENT**


**Figure 1.2-22.** ***This is the first frame of ground-based video. Columbia*** **is circled. Time 1 (TM1) shows the Greenwich Mean Time. The Pacific Standard Time displayed on the lower portion of the image is inexact.**

13:53:26 (EI+557)

*Columbia* crosses the California coastline west of Sacramento. [*Master Timeline, Rev. 15 Baseline*] (figure 1.2-23).


**Figure 1.2-23. Columbia *crossing the California coastline*.**

Alt = 231,600 feet [*Master Timeline, Rev. 15 Baseline*]
Mach = 23.0 [*Master Timeline, Rev. 15 Baseline*]
Qbar = ~30 psf [modeling]

13:53:38 (EI+569)

Sideslip angle exceeded all previous flight experience.[6]

13:53:46 (EI+577) ±2 sec

**First Observed Incident of Debris Being Shed**. This is most likely a piece of the left wing. Debris 1 is seen just aft of the orbiter envelope 1 second after a trail anomaly that consisted of a noticeably luminescent section of the plasma trail. There were no reported entry observations while *Columbia* was over the Pacific Ocean prior to GMT 13:53:15 (EI+546), so it is

[6]Integrated Entry Environment Team Final Report, May 30, 2003, p. 15.

| TIME | EVENT |
|---|---|
| | not possible to know whether debris was being shed before this time. Image of Debris 1 is 0.6 second after first visual detection of it. Analysis indicates that the mass of the debris was probably less than 8 lbs. Neither the crew nor MCC personnel were aware of the shedding events (blue arrow shows direction of flight) (figure 1.2-24). |

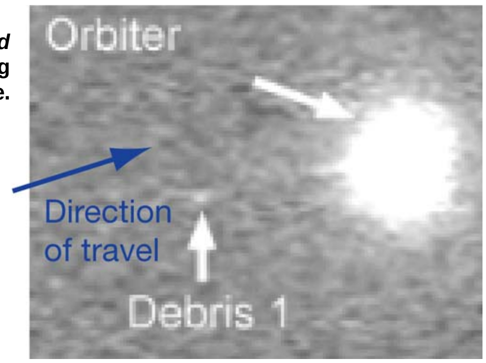



**Figure 1.2-24.** ***Video capture of the first observed incident of debris being shed*****. The orbiter is traveling from left to right in this image.**

| | |
|---|---|
| 13:54:20 (EI+611) ±10 sec | The beginning of the slow elevon trim change starts at GMT 13:54:20 (EI+611) ±10 sec. While there is a display that shows the aileron trim movement (figure 1.2-25), the initial change was so small that it would not be detectable by the crew. [*Master Timeline, Rev. 15 Baseline*] |

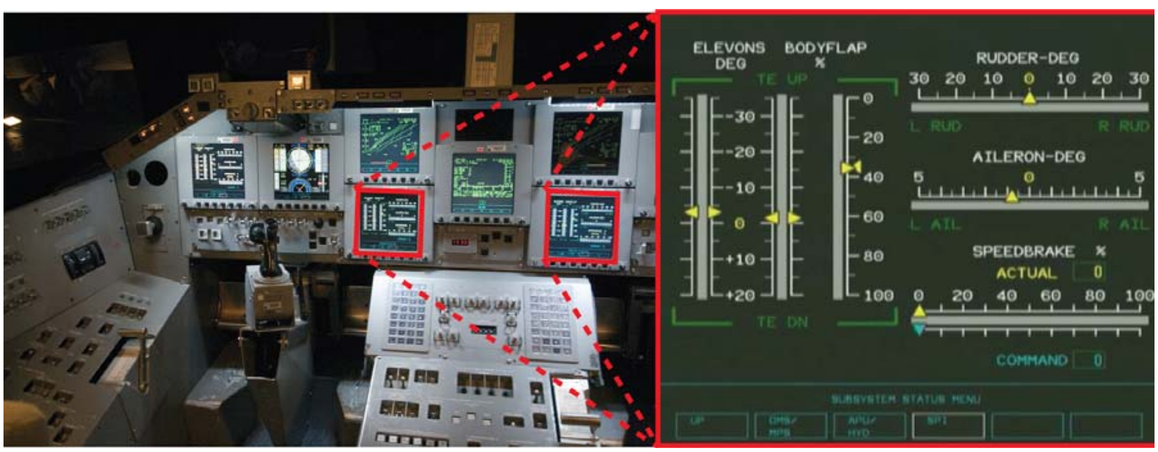



**Figure 1.2-25.** ***Elevon trim display*****. [Picture of the cockpit and display from the Shuttle Engineering Simulator]**

| | |
|---|---|
| 13:54:24 (EI+615) | **MCC Team Made Aware of Off-nominal Readings.** The MMACS flight controller makes a call over the MCC voice loops that the four hydraulic return line temperature sensors in the left wing went OSL at GMT 13:53:10 (EI+541). |
| 13:54:25 (EI+616) | *Columbia* crosses the California-Nevada border. [*Master Timeline, Rev. 15 Baseline*] (figure 1.2-26). |

| **TIME** | | **EVENT** |
|---|---|---|


**Figure 1.2-26. Columbia *crossing the California-Nevada border*.**

| | | |
|---|---|---|
| | ♁ | Alt = 227,400 feet [*Master Timeline, Rev. 15 Baseline*]<br>Mach = 22.5 [*Master Timeline, Rev. 15 Baseline*]<br>Qbar = ~34 psf [modeling] |
| 13:54:30 (EI+621) | ♁ | Indication of a second suit pressure check by three to five crew members (figure 1.2-27). |

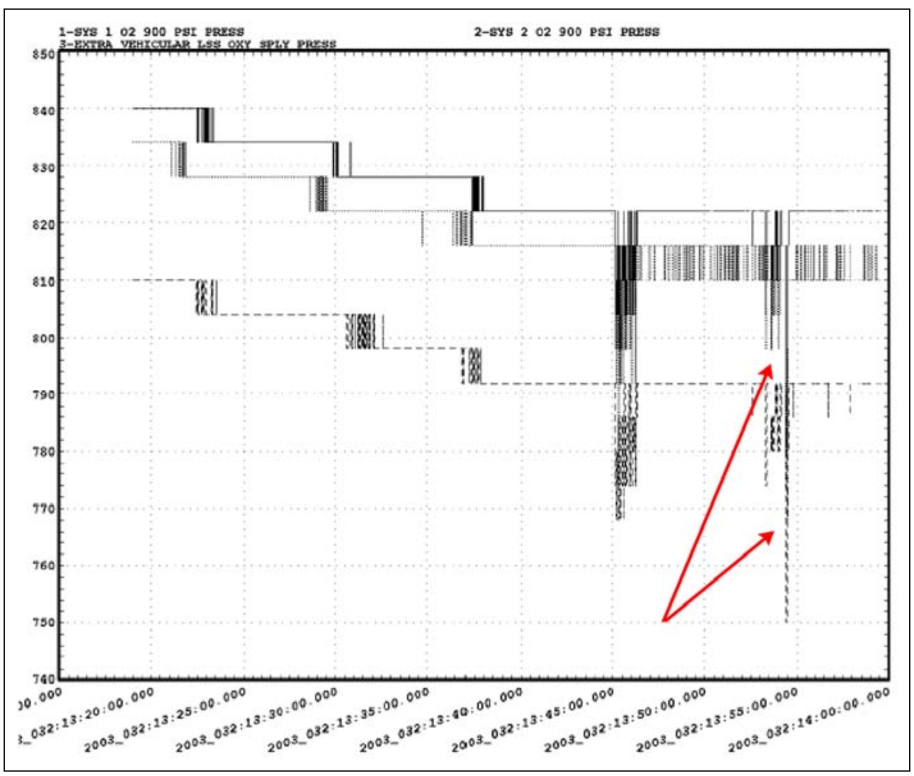
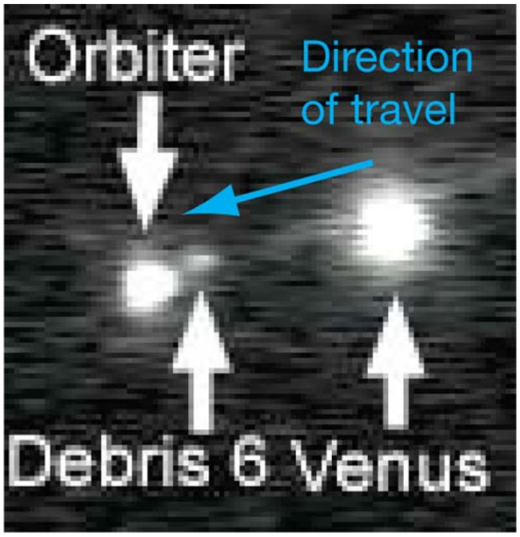



**Figure 1.2-27. *Plot of main oxygen supply pressure showing second series of suit pressure checks* (red arrows).**

| TIME | | EVENT |
|---|---|---|
| 13:54:32 (EI+623) | | Debris 6 released. The brightest debris-shedding event occurring in this phase, Debris 6, is first visible on video at GMT 13:54:36 (EI+627) (figure 1.2-28). Ballistic estimates determined that the actual release time was 4 seconds earlier. Luminosity measurements and calculated rates of deceleration were used to determine that the mass was probably a few hundred pounds.[7] There were no data from sensors, instrumental indications, or apparent crew recognition of this debris loss. |

**Figure 1.2-28.** ***The brightest debris event known to have occurred prior to loss of signal*. The orbiter is traveling from right to left.**




| | | |
|---|---|---|
| 13:54:33 (EI+624) | | At GMT 13:54:33.52 (EI+624.52), RCS yaw jet R3R fired followed by RCS yaw jet R2R at GMT 13:54:33.54 (EI+624.54). It is unknown whether the jet firings were in response to the debris-shedding event. [*Master Timeline, Rev. 15 Baseline*] |
| 13:54:36 (EI+627) | | Debris 6 first visible on ground-based video. |
| 13:55:21 (EI+672) | | Atmospheric drag on the orbiter was producing the nominal deceleration load on the crew of approximately 0.3 G. |
| 13:56:02 (EI+713) | | Aft RCS pitch jets deactivated when Qbar reached 40 psf. At 40 psf, the elevons and body flap have sufficient control authority to control the pitch of the orbiter. |
| 13:56:30 (EI+741) | | **First Roll Reversal Initiated.** *Columbia* initiated a roll from right wing low to left wing low (figure 1.2-29). |

[7]*Columbia* Accident Investigation Board Report, Volume III, Appendix E.2, STS-107 Image Analysis Team Final Report, October 2003.

| TIME | | EVENT |
|---|---|---|

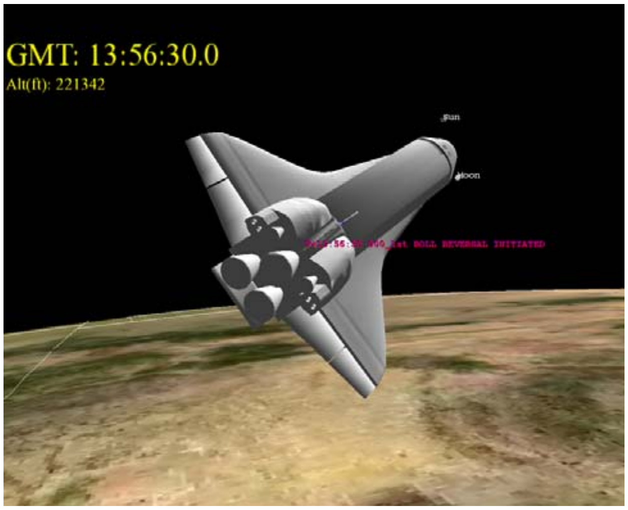



**Figure 1.2-29.** ***Attitude at the start of the roll reversal*.**

| | | |
|---|---|---|
| 13:56:55 (EI+766) | | **First Roll Reversal Completed.** Left wing low (figure 1.2-30). |

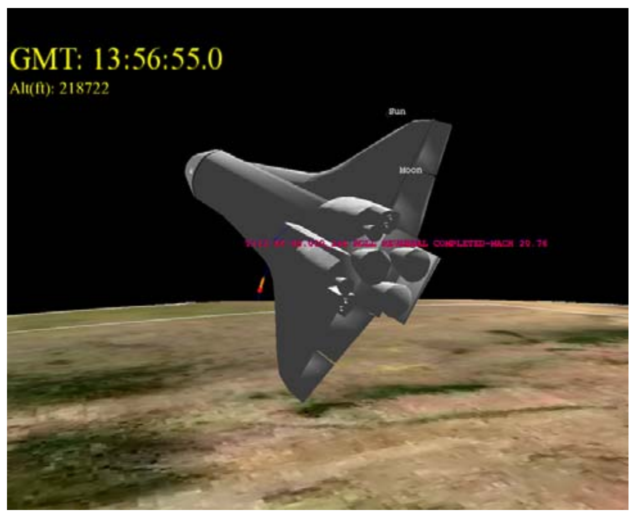



**Figure 1.2-30.** ***Attitude at the completion of the roll reversal*.**

| | | |
|---|---|---|
| | | Alt = 218,817 feet [*Master Timeline, Rev. 15 Baseline*]<br>Mach = 20.76 [*Master Timeline, Rev. 15 Baseline*]<br>Qbar = ~43 psf [modeling] |
| 13:57:14 (EI+785) ±1 sec | | **Starfire Image.** An image of the shuttle was taken while it was over the Starfire Optical Range located at the Kirtland Air Force Base, New Mexico. The photograph has been enhanced, and a wireframe representation of the orbiter has been overlaid. The bright areas behind the shuttle could be traced to orbiter sources and, thus, were generally considered to be nominal, as was the asymmetry that was seen in the bright gas around the nose area. The bulges that were seen |

| TIME | EVENT |
|---|---|
| | (as marked) at the left wing could not be explained by a nominal condition (figure 1.2-31). |

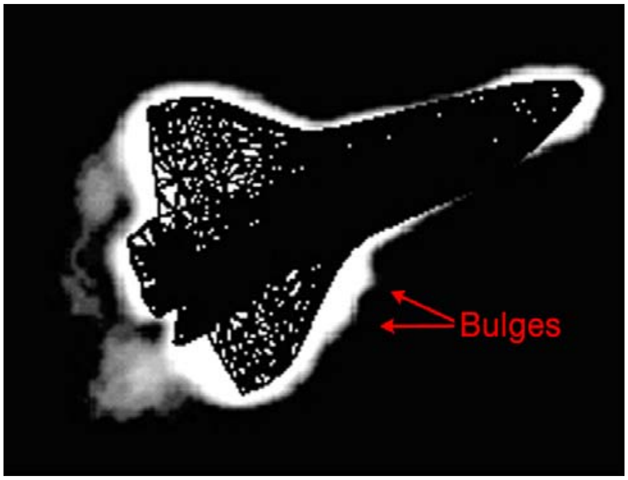



**Figure 1.2-31.** ***Infrared photograph of the shuttle during entry*.**[8]

| TIME | EVENT |
|---|---|
| 13:57:54 (EI+825) ±1 sec | Flare 1 is an asymmetrical brightening of the orbiter shape at GMT 13:57:54.7 (EI+825) ±1 sec. This brightening was detected in images taken by a charge coupled device camera on a telescope, so its image is well magnified. Another brightening event was detected 6 seconds later (see GMT 13:58:00 (EI+831)). The two small images are the raw images from the data. The left image is interpreted to be the orbiter in a nominal condition. The image on the right is 0.4 second later. The larger image has been rotated to its correct viewing orientation and enhanced; a wireframe model of the orbiter at approximately the correct scale and orientation has been overlaid (figure 1.2-32). |

[8]*Columbia* Accident Investigation Board Report, Volume V, Appendix G.7, Starfire Team Final Report, June 3, 2003, Figure 3, p. 360.

| TIME | EVENT |
|---|---|

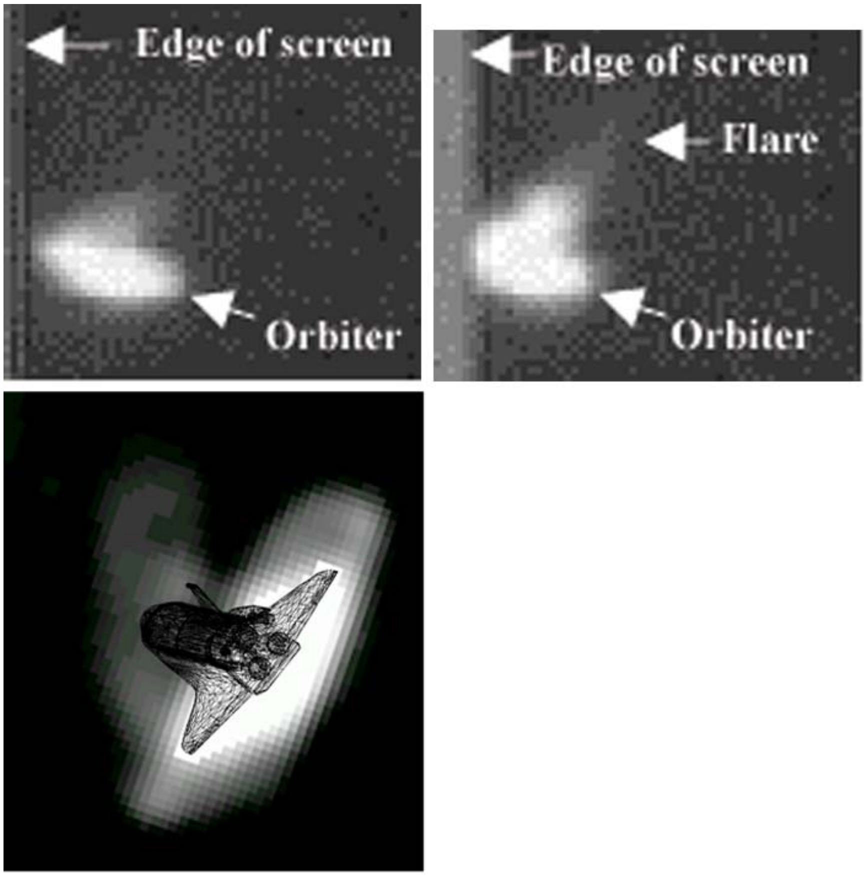



**Figure 1.2-32.** ***Enhanced video captures showing the first observed flare in the trail.***[9]

| TIME | EVENT |
|---|---|
| 13:58:00 (EI+831) ±1 sec | Flare 2 is an asymmetrical brightening of the orbiter shape at GMT 13:58:00.5 (EI+831.5) ±1 sec (figure 1.2-33). |

[9]*Columbia* Accident Investigation Board Report, Volume V, Appendix G.7, Starfire Team Final Report, June 3, 2003, Figure 6, p. 361 and Figure 6A, p. 362.

**TIME** **EVENT**

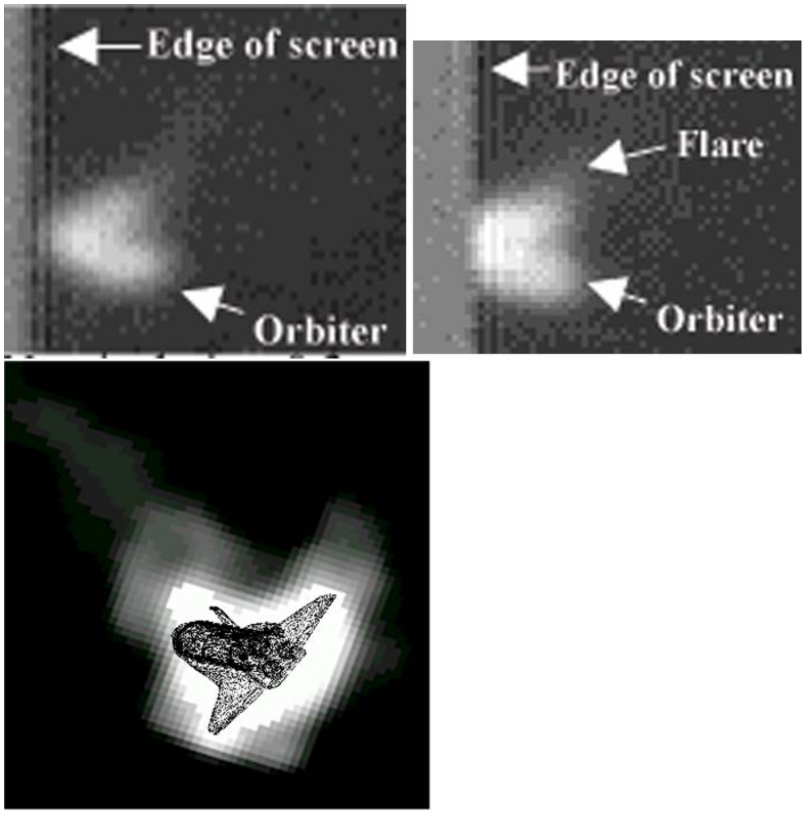



**Figure 1.2-33.** ***Enhanced video captures showing the second observed flare in the trail*****.**

Mach = 19.8 [modeling]
Qbar = ~53 psf [modeling]

13:58:03 (EI+834)

**Start of "Sharp" Elevon Trim Increase.** The FCS is now compensating for increasingly asymmetric aerodynamic loading and is commanding the elevon trim at a much higher than nominal rate. Time is uncertain (±10 sec) (figure 1.2-34). [*Master Timeline Rev. 15*]

| TIME | EVENT |
|---|---|

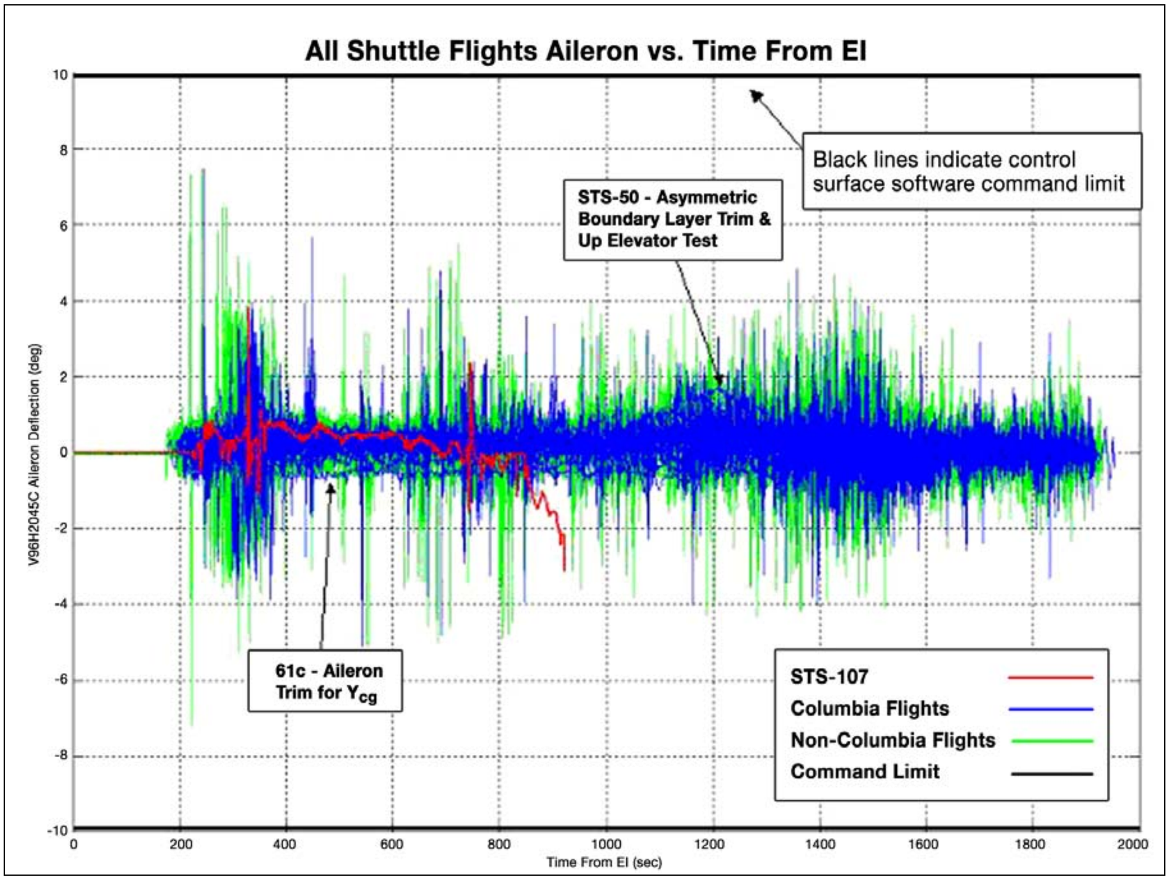



**Figure 1.2-34.** ***The sharp divergence from previous flight experience starts at approximately GMT 13:58:19 (EI+850).***[10]

| | | |
|---|---|---|
| | | Alt = 212,007 feet [*Master Timeline, Rev. 15 Baseline*]<br>Mach = 19.77 [*Master Timeline, Rev. 15 Baseline*]<br>Qbar = ~54 psf [modeling] |
| 13:58:12 (EI+843) | | End of ground-based video coverage for western portion of entry. |
| 13:58:21(EI+852) ±5 sec | | **Littlefield Tile Released**. This piece of tile was recovered in Littlefield, Texas; it is the westernmost piece of recovered debris (figure 1.2-35). |

[10] Integrated Entry Environment Team Final Report, May 30, 2003, Figure 6.6-1, p. 30.

**TIME** **EVENT**

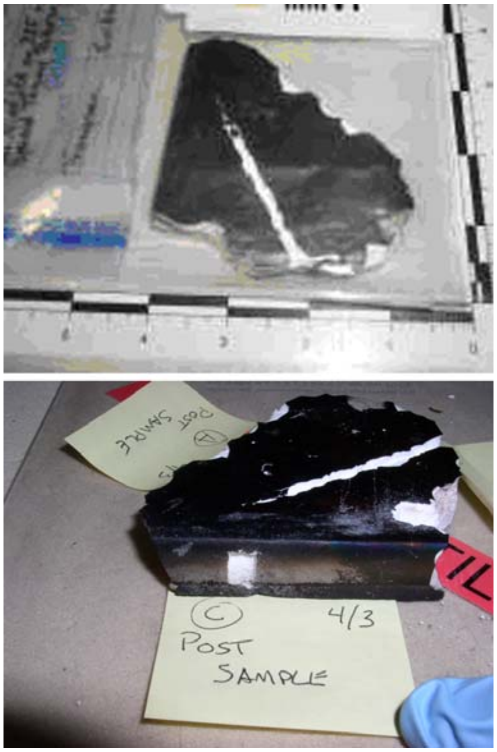



**Figure 1.2-35. *The Littlefield tile*. [Picture from the *Columbia* Reconstruction Database, debris item no. 14768]**

13:58:39 (EI+870)

TIRE PRESS LOB. This message, indicating a left outboard (LOB) tire pressure fault, was recorded by the backup flight software (BFS) in the downlink stack and had a time of GMT 13:58:39.94 (EI+870.94). The fault message was annunciated on the crew displays and with an audio tone. [*TDRS-W data; Master Timeline, Rev. 15 Baseline*]

13:58:40 (EI+871)

Main landing gear left inboard (LIB) tire pressure reading went OSL. Downlink telemetry from the GPC recorded that the BFS was indicating a tire pressure fault message. The fault message was annunciated on the crew displays and with an audio tone. [*TDRS-W data; Master Timeline, Rev. 15 Baseline*]

13:58:41 (EI+872)

TIRE PRESS LIB. This message, indicating an LIB tire pressure fault, was recorded by the BFS in the downlink stack and had a time of GMT 13:58:41.84 (EI+872.84). The fault message was annunciated on the crew displays and with an audio tone. [*TDRS-W data; Master Timeline, Rev. 15 Baseline*]

| TIME | EVENT |
|---|---|
| 3:58:48 (EI+879) | A partial voice transmission from *Columbia* is received over the A/G: "And, uh, Hou…" The vehicle and crew were still performing nominally.[11] |
| | CRT3: FAULT SUMM. The crew called up the fault summary display to look at the messages. [*TDRS-W data*] |
| 13:58:49 (EI+880) | BFS FSM: SM0 TIRE PRESS LIB. This message, indicating an LIB tire pressure fault, was recorded by the BFS in the downlink stack and had a time of GMT 13:58:49.54 (EI+880.54). The fault message was annunciated on the crew displays and with an audio tone. [*Master Timeline, Rev. 15 Baseline*] |
| 13:58:56 (EI+887) | BFS FSM: SM0 TIRE PRESS LOB. This message, indicating an LOB tire pressure fault, was recorded by the BFS in the downlink stack and had a time of GMT 13:58:56.26 (EI+887.26). The fault message was annunciated on the crew displays and with an audio tone. [*Master Timeline, Rev. 15 Baseline*] |
| 13:59:06 (EI+897) | Telemetry records the LEFT MAIN GEAR DOWN-lock sensor transferred to ON. This indicated that the left main landing gear was down and locked in the deployed position. Other sensors indicated that the landing gear door was still closed and the landing gear was locked in the stowed position. The mixed signals would result in the landing gear position indicator for the left gear displaying a "barber pole," which would indicate an indeterminate gear position. Analysis of the data and recovered debris indicates that the landing gear was locked in the stowed position and the landing gear door was closed. The signal, indicating that the gear was down, was a false signal that was likely triggered by damage to the sensor system (sensor, wiring harness, etc.) (figure 1.2-36). |

[11]*Columbia* Accident Investigation Board Report, Volume I, August 2003, p. 42.

| TIME | EVENT |
|---|---|

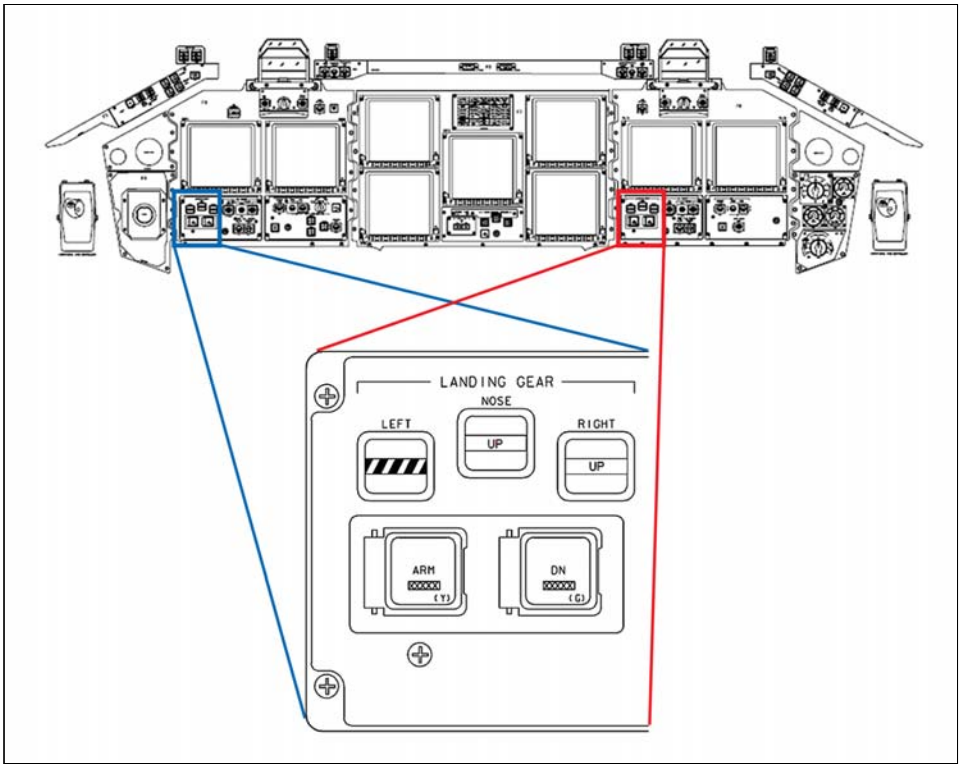



**Figure 1.2-36.** ***Landing gear indicator panel, identical on both sides of the flight deck forward display panels*****. Left indicator showing "barber pole" (indeterminate position). [Adapted from the Space Shuttle Systems Handbook]**

13:59:24 (EI+915)

The MCC calls *Columbia* regarding the tire pressure fault message, "And, *Columbia*, Houston, we see your tire pressure message and we did not copy your last call."[12] [*STS-107 A/G recording*]

13:59:29 (EI+920)

Aerodynamic control authority is exceeded. Damage to the left wing exceeds the elevon control surface ability to compensate. The aileron trim deflection derived from flight data shows that the aileron trim rate did reach the 4.2 deg/sec rate limit. This indicates that the amount of lateral control (aileron and yaw RCS jets) that was required to trim the vehicle was constantly increasing and by LOS+5 seconds was quickly approaching the limits of the FCS.[13]

Change in vehicle attitude from GMT 13:57:08 (EI+779) to GMT 13:59:29 (EI+920).

13:59:30 (EI+921)

**RCS Yaw JETS FIRING. RCS Yaw Jets (R2R and R3R) Begin Firing Continuously.** Aft right RCS yaw jets R2R and R3R started firing at GMT 13:59:30.66 (EI+921.66) and GMT 13:59:30.68 (EI+921.68), respectively, to correct an

[12]*Columbia* Accident Investigation Board Report, Volume I, August 2003, p. 43.
[13]Integrated Entry Environment Team Final Report, May 30, 2003, p. 20.

| TIME | EVENT |
|---|---|

increasing yaw to the left, and were still firing when all data were lost at GMT 13:59:37.4 (EI+928.4).

The only indication the crew would have that the jets were firing is from status lights on the F6 panel underneath the CDR2 display and the fuel quantity display on the overhead panel decrementing (figure 1.2-37).

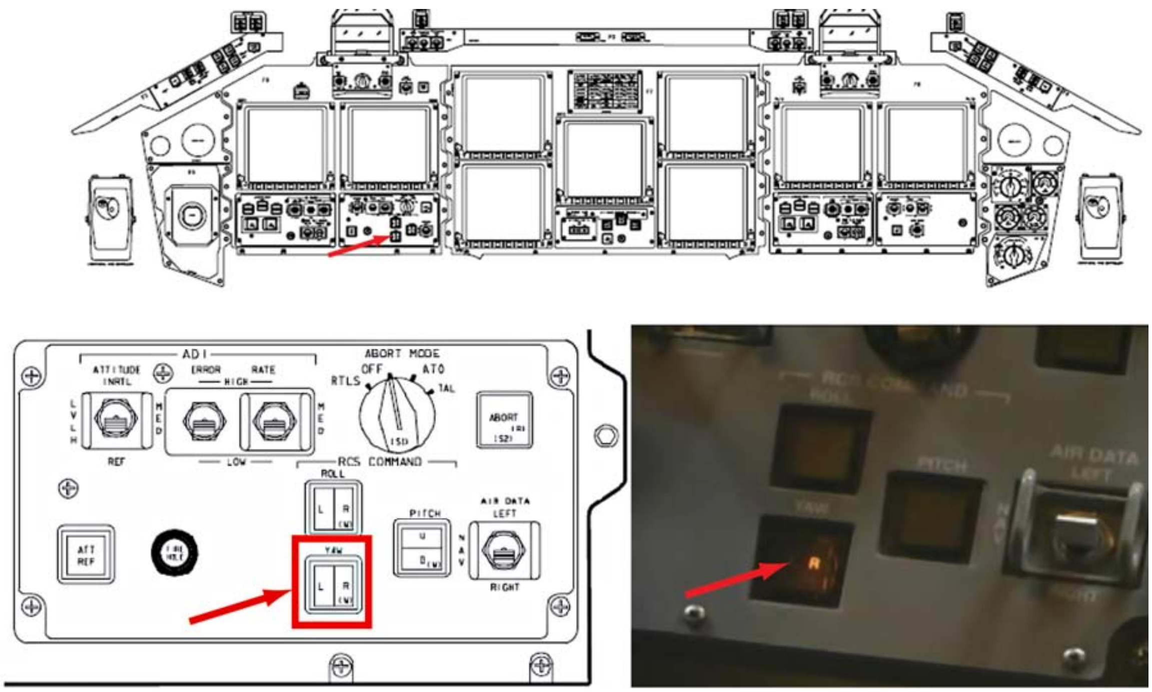



**Figure 1.2-37. *Reaction Control System thruster status display*. [Pictures [top and bottom left) adapted from the Space Shuttle Systems Handbook; picture (bottom right) from the Shuttle Engineering Simulator]**

13:59:31 (EI+922)

Fault Summary Page (FSP) Message Downlink Stack (last five messages) (figure 1.2-39):

| | | | | |
|---|---|---|---|---|
| FSP1: SM0 | TIRE PRESS | L | OB | 32/13:58:56.26 |
| FSP2: SM0 | TIRE PRESS | L | IB | 32/13:58:49.54 |
| FSP3: SM0 | TIRE PRESS | L | IB | 32/13:58:41.48 |
| FSP4: SM0 | TIRE PRESS | L | OB | 32/13:58:39.94 |
| FSP5: MPS[14] | PNEU | | REG | 32/13:58:04.42 |

Last observed elevon deflections (figure 1.2-38):[15]

[14]MPS = Main Propulsion System.
[15]Integrated Entry Environment Team Final Report, May 30, 2003, p. 15.

| **TIME** | **EVENT** |
|---|---|
| | Left: –8.11 deg (deflected up)<br>Right: –1.15 deg (deflected up) |

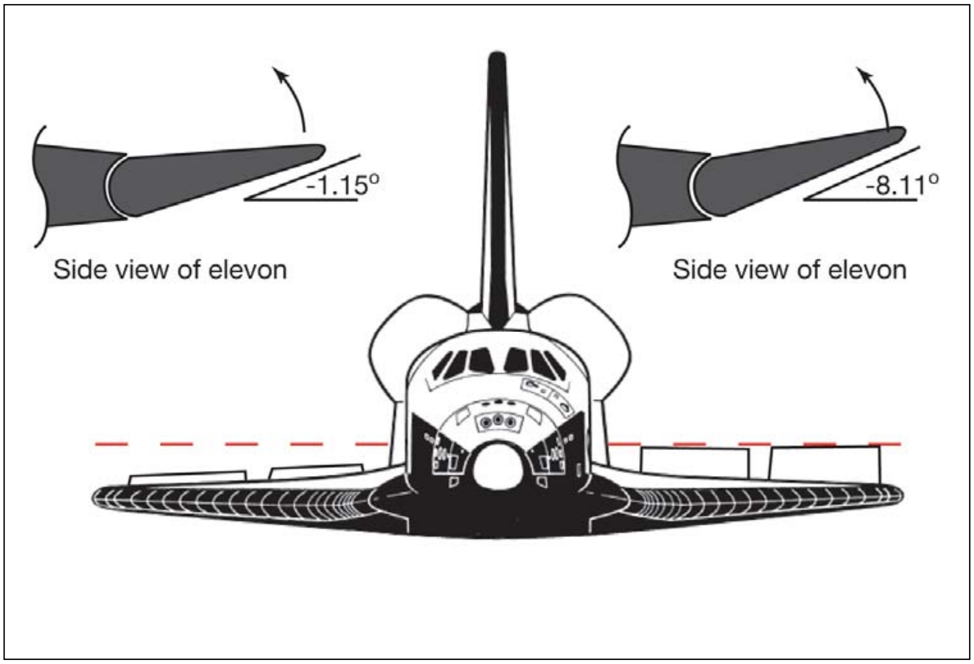



**Figure 1.2-38.** ***Illustration of the last observed elevon deflections*****.**

- At GMT 13:59:31.4 (EI+922.4) the FCS Channel 4 aerosurface position measurements start trending towards their null values, indicating a failure of the sensor due to a wiring short. This is the first indication of the eventual bypass of FCS Channel 4. [*Master Timeline, Rev. 15 Baseline*]

- At GMT 13:59:31.478 (EI+922.478) all of the FCS Channel 4 bypass valves close (i.e., bypassed condition). This is a leading indicator of an aeroservo actuator failure. [*Master Timeline, Rev. 15 Baseline*]

## 1.2.3 Phase 3: Loss of signal to Catastrophic Event [GMT 13:59:32 (EI+923) – GMT 14:00:18 (EI+969)]

13:59:32 (EI+923)

- Near Dallas, Texas
  Alt = ~200,700 feet [*Master Timeline, Rev. 15 Baseline*]
  Mach = ~18.1 [*Master Timeline, Rev. 15 Baseline*]
  Qbar = ~70 psf [modeling]