the crew's safety after vehicle egress. The crew worn equipment consists of the ACES and g-suit, a PPA, a parachute harness, and survival gear. The equipment provides the crew with altitude and atmospheric contamination protection during normal launch/entry operations and emergency conditions.

3.2.1.1 *Advanced crew escape suit*

The ACES is a full-pressure suit that is capable of applying static pressure over the entire body. A positive-pressure regulator delivers orbiter- or EOS-supplied 100% O_2 to the helmet at a pressure that is slightly above suit pressure. Breathing 100% O_2 results in O_2-enriched air being exhaled into the cabin. Over time, this increases the O_2 concentration in the cabin, amplifying the potential for fire. Therefore, the amount of time that crew members have their visors down and are breathing 100% O_2 is limited operationally to reduce this hazard.

Finding. Breathing 100% O_2 results in O_2-enriched air being exhaled into the shuttle cabin. Over time, this increases the O_2 concentration in the cabin, amplifying the potential for fire. Therefore, the amount of time that crew members have their visors down and are breathing 100% O_2 is limited operationally to reduce this hazard (see **Recommendation L1-2**).

The outer covering of the ACES is flame-resistant orange Nomex. Just beneath the outer layer of the Nomex fabric is a woven, open-link net restraint layer made of Nomex cord that provides structural support for the suit. Under the restraint layers is a pressure bladder made of nylon laminated to GORE-TEX® to wick body moisture away when unpressurized, while holding pressure when inflated. The ACES incorporates a rear entry pressure-sealing zipper for suit donning and doffing, a neck ring (figure 3.2-2) for helmet attachment, and wrist rings for glove attachment (figure 3.2-3).

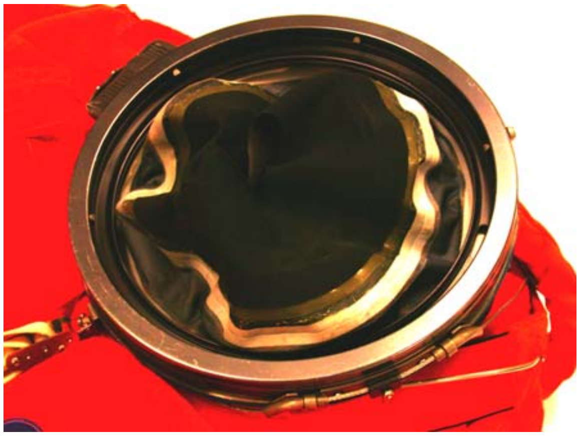

Figure 3.2-2. ***Example of neck ring*.**

Figure 3.2-3. ***Example of wrist ring*.**

The helmet (figure 3.2-4) attaches to the ACES neck ring. The neck ring has a latch (figure 3.2-5) that secures the helmet to the suit. Sliding the latch halves together moves six "latch dogs" to secure the helmet on the neck ring. Sliding them apart retracts the dogs, allowing removal of the helmet from the neck ring. Two independently rotating visors on the front of the helmet provide a dark sunshield and a clear pressure visor. The pressure visor is closed and locked by pulling the visor and the bailer bar down into the locked position. To open the pressure visor, a latch on the bailer bar lock must be pushed down and two buttons on either side of the lock must be pressed. This allows the bailer bar to unlock, after which the visor can be opened. O_2 is delivered to the helmet interior by a spray bar.[3] The shell of the helmet is made of fiberglass with a coating of reflective tape. The pressure visor is a laminate made of polycarbonate and polymethylmethacrylate.

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[3] The spray bar is a tube with numerous small holes in it that direct O_2 towards the crew member's face.

The helmet must be attached to the neck ring and the pressure visor must be closed and locked to pressurize the suit.

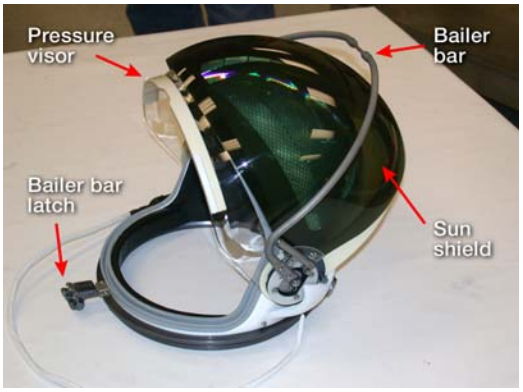

Figure 3.2-4. ***Example of helmet*.**

(a) Open.

(b) Closed.

Figure 3.2-5. ***Example of neck ring latch*.**

The helmet provides an interface between the communication carrier assembly (CCA) and the orbiter communications system. The CCA, or "comm cap," contains microphones and earphones. The communications cable passes through the lower left side of the helmet and connects to a headset interface unit, which in turn connects to the orbiter communications system.

Detachable gloves (figure 3.2-6) attach to the ACES sleeve via mating rings and must be worn for the ACES to provide full protection. The rings provide an airtight seal and allow the gloves to swivel for improved mobility. The gloves have adjustable straps around the palm to prevent "ballooning" during suit pressurization and to allow for flexion at the palms.

Figure 3.2-6. ***Example of gloves*.**

The ACES is worn in conjunction with Rocky 911 commercial off-the-shelf boots (worn over the pressure bladder) that have rubber soles and leather and nylon upper sections (figure 3.2-7).

Figure 3.2-7. ***Example of boots*.**

Crew members wear a g-suit (figure 3.2-8) under the ACES during shuttle entry and landing. The g-suit bladders surround the abdomen, thighs, and calves and apply pressure to the crew member's lower abdomen and legs. The g-suit is used to counteract the effects of orthostatic intolerance upon return to 1-G conditions after exposure to microgravity. The g-suit is made from Nomex and nylon and has lacing to achieve a proper fit. It is pressurized with suit O_2. Pressure is controlled manually by the crew member. The g-suit connects to the ACES O_2 manifold via a quick disconnect (QD) hose.

Various garments are worn under the ACES and the g-suit for crew comfort. These garments include a liquid cooling garment (LCG), thermal underwear, wool socks, and a diaper. The LCG (figure 3.2-9) consists of thermal underwear shirt and pants with tubes sewn into the fabric on the inside. A cooling unit (thermal electric liquid cooling unit (TELCU) or individual cooling unit (ICU)) cools and pumps water through the LCG's network of tubing to cool the crew member. The water supply and return lines are fed through a plug located on the right thigh area of the ACES.

Figure 3.2-8. ***Example of g-suit*.**

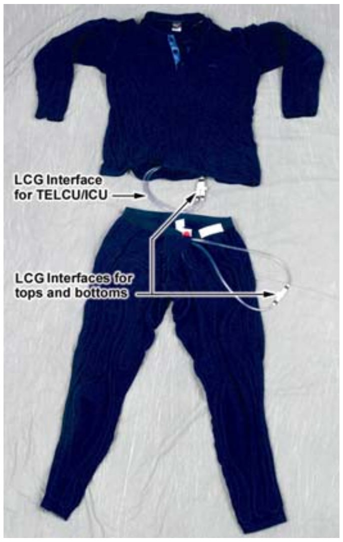

Figure 3.2-9. ***Example of liquid cooling garment*.**

One AN/PRC-112 radio (figure 3.2-10) is flown per crew member and is located in a survival gear pouch inside a pocket on the right shin area of the ACES. The PRC-112 radio is constructed of an outer aluminum casing, plastic external switches, a plastic external battery pack, and various internal electronic components.

Figure 3.2-10. ***Example of Army/Navy personal radio communications-112 radio*.**

3.2.1.2 *Parachute harness*

The parachute harness (figure 3.2-11) is a system of interwoven nylon webbing straps that provides an interface between the PPA and the crew member. The straps provide body support for crew members during bailout, emergency egress, and water rescue operations. Integrated into the harness are a carabineer, an EOS, an emergency water pack, and a life preserver unit (LPU).

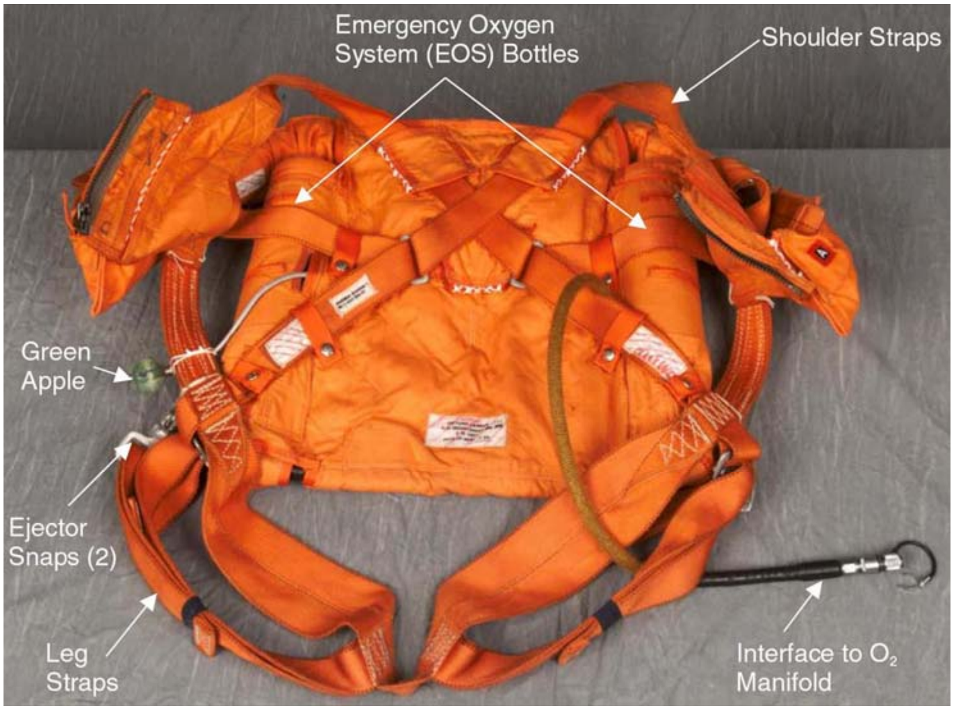

Figure 3.2-11. ***Example of parachute harness*.**

The EOS (figure 3.2-12), which is located within the parachute harness, consists of two bottles that are pressurized with O_2 at 3,000 pounds per square inch (psi). Each bottle has a pressure regulator that reduces the pressure down to 70 psi. A common manifold delivers the 70-psi O_2 from both bottles to the O_2 hose that connects to the ACES O_2 manifold via a QD. The system, activated by pulling the “green apple” activation knob on the right side of the harness, provides 381 liters of O_2.

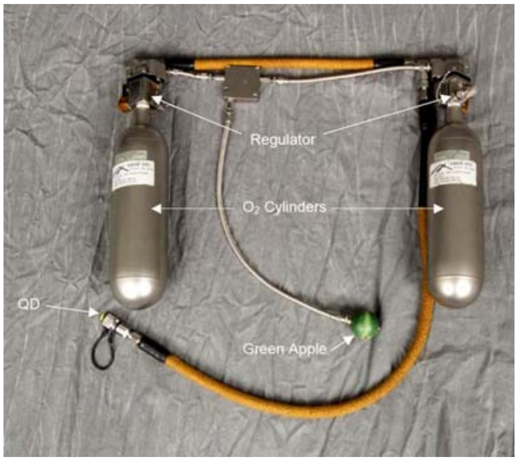

Figure 3.2-12. ***Example of Emergency Oxygen System*.**

3.2.1.3 *Personal parachute assembly*

All crew members wear a PPA (figure 3.2-13). It is secured to the crew member’s parachute harness at four locations. The parachute risers are connected to two attachment points on the harness which are called Frost fittings, and the metal triangular rings are secured to the ejector snaps on the harness. Two SEAWARS, one on each parachute riser, are part of the fittings on the PPA risers that interface to the harness. These two SEAWARS are designed to automatically release the risers from the harness upon immersion in saltwater. The SEAWARS consist of an outer aluminum casing, plastic external components, various internal electronic components, and a small pyrotechnic device.

Figure 3.2-13. ***Example of personal parachute assembly*.**

The outer covering of the parachute pack is made of Nomex. The parachute pack has three compartments: an upper compartment that contains a pilot chute and drogue chute, a middle compartment that contains the main parachute and the automatic opening device (AOD), and a lower compartment that contains a one-person life raft. The right riser houses the D-ring bridle, which connects to a lanyard hook on the escape pole for use during in-flight bailout. The D-ring bridle and lanyard hook initiate the parachute opening sequence. The left riser has a manual rip cord, which can be used to initiate the parachute opening sequence. Both methods require some crew action (either attaching the D-ring to the escape pole lanyard or pulling the rip cord) to initiate the parachute sequence.

> ***Conclusion L5-1.*** The current parachute system requires manual action by a crew member to activate the opening sequence.
>
> ***Recommendation L1-3/L5-1.*** Future spacecraft crew survival systems should not rely on manual activation to protect the crew.

The main parachute is a circular canopy made from nylon with Kevlar reinforcement.

The life raft is rubber and is inflated by two carbon dioxide (CO_2) bottles. A TSUB-A SARSAT beacon (figure 3.2-14) is secured to the life raft and activates automatically upon main parachute deployment. The SARSAT beacon consists of an outer aluminum casing, plastic external switches, and various internal electronic components.

Figure 3.2-14. ***Example of search and rescue satellite-aided tracking beacon.***

3.2.2 Crew worn equipment configuration

Recovered videotape from *Columbia* revealed information related to the configuration of the crew worn survival equipment, including the helmets and the ACESs. The recovered middeck video shows the seat 5 crew member suited (except for the helmet and gloves) and the seat 1 and seat 6 crew members donning their suits. The middeck video, which does not include views of other flight deck crew members donning their suits, ends prior to the seat 7 crew member donning the ACES.

Recovered flight deck video shows the flight deck crew members suited with helmets and gloves on (except one crew member, who had not completed donning gloves by the end of the video). This video also shows the helmet and helmet neck rings in close proximity to the crew members' chins. Because the helmets appeared to be restrained, investigators concluded that the crew members had the proper tension on the neck ring tie-down straps.

Although all crew members were wearing the main portion of the suit at the time of the accident, at some point the suits completely failed and separated. The SCSIIT investigated similar cases to understand the mechanism of suit failure.

3.2.3 Aircraft in-flight breakup case studies

The following civil aviation accidents provide examples of cases of passenger clothing being shed (body denuding) during in-flight breakups:

- Air India Flight 182 was flying at 31,000 feet over the Atlantic Ocean on June 23, 1985 when a terrorist bomb exploded in the baggage compartment. The Boeing 747 aircraft broke up in flight, and at least 21 of the 131 recovered bodies were denuded.
- Iran Air Flight 655 was mistakenly shot down by a U.S. Navy ship on July 3, 1988 while flying over the Persian Gulf. After missiles hit it, the Airbus A300 aircraft broke up in flight at an altitude of 13,500 feet. The denuded bodies of the passengers were recovered from the Persian Gulf waters.

- Pan Am Flight 103 was blown up by a terrorist bomb over Lockerbie, Scotland on December 21, 1988. The bomb went off when the Boeing 747 aircraft was at roughly 31,000 feet and 313 knots airspeed; numerous passengers who had separated from the aircraft prior to ground impact were denuded.
- COPA Flight 201 broke up over the jungle in Panama on June 6, 1992. The Boeing 737 aircraft broke up at approximately 13,000 feet while in a high-speed dive (the pilots entered the dive because of a faulty attitude indication that was due to a wiring problem). Many of the passengers' bodies were denuded.

These aviation accidents involved lower altitudes and slower speeds than those associated with the *Columbia* accident. However, a military accident more similar to the *Columbia* accident occurred on January 25, 1966 involving an SR-71 test flight.[4] The pilot lost control of the aircraft, and the SR-71 broke up while flying at approximately Mach 3 at over 75,000 feet (~400 knots equivalent airspeed (KEAS)). The pilot survived, but the reconnaissance systems officer was killed. Points of similarity to the *Columbia* accident include:

- The SR-71 accident occurred at high speed and relatively high altitude.
- The SR-71 aircraft breakup dynamics resulted in a fatality.
- The SR-71 aircraft breakup dynamics included crew member separation from the vehicle.
- The seat restraint straps failed.
- The SR-71 pressure suit is very similar to the shuttle ACES in design and construction.
- The dynamic pressure at the *Columbia* CMCE was roughly 405 pounds per square foot (psf) and the dynamic pressure at SR-71 aircraft breakup was roughly 398 psf, a difference of less than 2%.

However, there are also notable differences between the two accidents. These include:

- The SR-71 pilot's suit pressurized automatically (as designed) when the cockpit depressurized due to the aircraft breakup. The pilot attributed his survival to the pressurized suit, which protected him from the low-pressure/low-O_2 environment as well as the aerodynamic forces (windblast) that he experienced when he separated from the aircraft. As discussed in the sections below, the *Columbia* suits did not pressurize because the crew members did not lower visors or activate the suit O_2 system. Additionally, three crew members did not complete donning gloves, which is required for the suit to pressurize.
- While the *Columbia* crew members were exposed to a similar dynamic pressure environment as the SR-71 crew members, the thermal environment of the *Columbia* accident was much more severe than that experienced during the SR-71 breakup.
- Because of the altitude differences, the chemical environment (higher concentration of more reactive monatomic oxygen) of the *Columbia* accident differs from that of the SR-71 breakup.
- The *Columbia* suits did not remain intact, whereas the SR-71 pressure suits did remain intact.

Aerodynamic analysis indicates that the equivalent airspeed of the CM at the CMCE (GMT 14:00:53) was roughly 400 KEAS, and that it increased to 560 KEAS by the time of Total Dispersal (TD) (GMT 14:01:10). The ACES is designed to maintain structural integrity and pressure response capability when exposed to at least a 560-KEAS windblast. Since the suit is certified by NASA to meet this requirement based on its similarity to the pressure suit used by the U.S. Air Force, it was not subjected to windblast tests for certification. By contrast, the U.S. Air Force suit was tested in a certification program in 1990 during which it was exposed to a 600-KEAS windblast (the suit was worn by a manikin that was restrained in an ejection seat with the helmet visor down and locked). During the first test (suit not pressurized), the helmet sun shield separated from the helmet and a life preserver unit inflation tube separated from the life preserver unit. During the second test (the suit was pressurized to 2.99 psi), both shin pockets (survival gear storage pockets) were forced open. No other relevant anomalies were observed.

In the U.S. Air Force windblast test configuration, the helmet visors were lowered, which is notably different from the position of the *Columbia* visors. Debris evidence indicates that the *Columbia* helmet

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[4] *Aviation Week & Space Technology*, August 8, 2005, pp. 60–62.

visors were up. With the helmet visor up, the helmet cavity presents a high drag configuration that could contribute to a mechanical failure of the suit/helmet interface, leading to suit disruption.

Standard materials testing data exist for the suit materials (GORE-TEX®, Nomex, nylon, etc.). However, the data are for tests conducted at "normal" environmental conditions (sea-level atmospheric temperature, pressure, and composition). Little laboratory test data exist on the performance of the materials in extreme environments. The lack of laboratory data presents an information gap regarding how the materials properties of the ACES are affected by exposure to the thermal and chemical environments at the altitudes and speeds experienced by *Columbia.* Although the more severe thermal and chemical environment of the *Columbia* accident may have weakened the suit materials, hastening suit disruption, the extent to which the thermal/chemical environment contributed to suit disruption cannot be determined from the debris and because the environment's affects on suit materials is not understood.

> ***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.
>
> ***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.

3.2.4 Recovered debris

Although only a small percentage of ACES fabric was recovered, many hard suit components were recovered (Table 3.2-1). There was no obvious pattern to explain why the hard components that were associated with some crew members were recovered while those associated with other crew members were not recovered. Figures 3.2-15 through 3.2-21 show the major crew worn equipment components that were recovered and ascribed to specific crew members.

Table 3.2-1. ***Recovered Crew Worn Components***

Advanced Crew Escape Suit	
Helmets – seven flown	All seven helmets recovered and identified to crew members.
Suit-side helmet neck rings – seven flown	Six recovered. Seat 6 not recovered; seat 4 recovered separately from helmet; all others recovered attached to helmets.
Glove disconnect rings – 14 flown (seven right and seven left)	Nine recovered (five right and four left). • Seat 2 right side (attached to suit-side ring) • Seat 3 left side (attached to suit-side ring) • Seat 4 right side (not attached to suit-side ring) • Seat 4 left side (not attached to suit-side ring) • Seat 5 right side (attached to suit-side ring) • Seat 5 left side (attached to suit-side ring) • Seat 6 left side (not attached to suit-side ring) • Seat 6 right side (not attached to suit-side ring) • Seat 7 right side (not attached to suit-side ring)
Suit-side glove disconnect rings – 14 flown (seven right and seven left)	Seven recovered (three right and four left). • Seat 2 right side (attached to glove ring) • Seat 3 left side (attached to glove ring) • Seat 4 left side (not attached to glove ring) • Seat 5 right side (attached to glove ring) • Seat 5 left side (attached to glove ring) • Seat 6 right side (not attached to glove ring) • Seat 7 left side (not attached to glove ring)

Table 3.2-1. ***Recovered Crew Worn Components*** **(Continued)**

Advanced Crew Escape Suit	
A/N PRC-112 radios – seven flown	Four recovered. • Seat 1 • Seat 2 • Seat 4 • Seat 7
Boots – 14 flown (seven right and seven left)	Fifty-three items identified as ACES boot fragments recovered. Eight sole fragments identified from six different boots. Four matches of the sole fragments made, resulting in a total of one complete left sole, three complete right soles, a left heel fragment, and a left toe fragment.
Suit fabric	Approximately 30 fragments of suit material recovered (only one-third is cover layer material); none could be ascribed to a specific crew member.
Miscellaneous ACES components: DSC, suit breathing regulator, suit pressure relief valve, bio-instrumentation pass-through (BIP) plug (one spare BIP plug flown; it was not recovered), O_2 manifold and g-suit controller, suit vent inlet and elbow fitting, etc. – seven each flown	Four DSCs recovered. • Seat 1 • Seat 2 • Seat 3 • Seat 4 One suit breathing regulator (seat 1) recovered. Three suit pressure relief valves recovered. • Seat 3 • Seat 4 • Seat 7 Three BIP plugs recovered. • Seat 4 • Seat 6 • Seat 7 Four O_2 manifold/g-suit controllers recovered. • Seat 4 • Seat 5 (with entire EOS O_2 hose and ~34 in. of suit O_2 hose attached) • Seat 6 • Seat 7 (g-suit controller portion missing) One O_2 hose quick disconnect (seat 5) recovered. One suit vent inlet with elbow fitting (seat 6) recovered.
Parachute Harness	
EOS bottles – 14 flown (two per crew member)	Ten whole bottles and three bottle fragments (not ascribed to a specific crew member) recovered. • Seat 1 • Seat 3 • Seat 4 (two) • Seat 5 • Seat 6 (two) • Seat 7 • Two whole bottles not ascribed to a specific crew member • Three bottle fragments not ascribed to a specific crew member.
FLU-8 (life preserver unit inflation devices) – 14 flown (two per crew member)	Seven recovered. • Seat 1 • Seat 2 • Seat 3 (two) • Seat 4 • Seat 5 • Seat 6

Table 3.2-1. ***Recovered Crew Worn Components*** **(Continued)**

Parachute Pack	
SEAWARS – 14 flown (seven left, seven right)	Six recovered: four left and two right (none had parachute riser strap attached, all mated to the Frost fittings and had ~12 in. of parachute harness strap attached). • Seat 1 left • Seat 2 right • Seat 4 right • Seat 5 left • Seat 6 left • Seat 7 left
AODs – seven flown	Two recovered. • Seat 4 • Seat 7
SARSAT beacons – seven flown	Six recovered. • Seat 1 • Seat 3 • Seat 4 • Seat 5 • Seat 6 • Seat 7
Fabric	More than 180 fragments of parachute canopy, parachute cord, parachute pack, and parachute harness strap material recovered; none could be ascribed to a specific crew member.

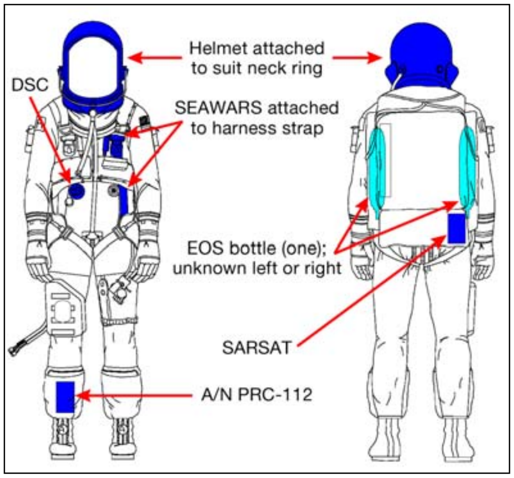

Figure 3.2-15. ***Seat 1 recovered crew worn equipment.***

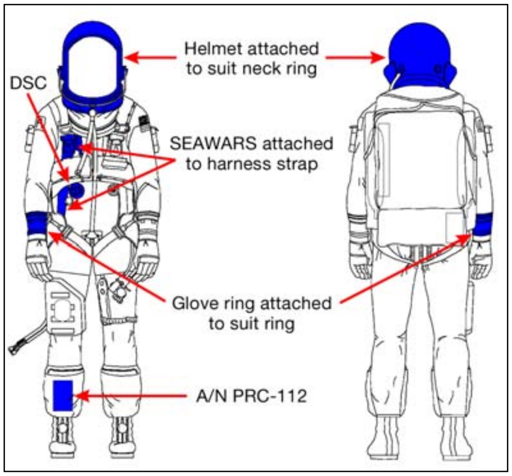

Figure 3.2-16. ***Seat 2 recovered crew worn equipment.***

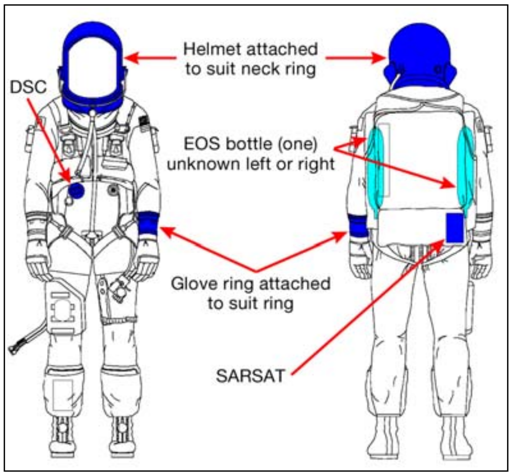

Figure 3.2-17. ***Seat 3 recovered crew worn equipment*.**

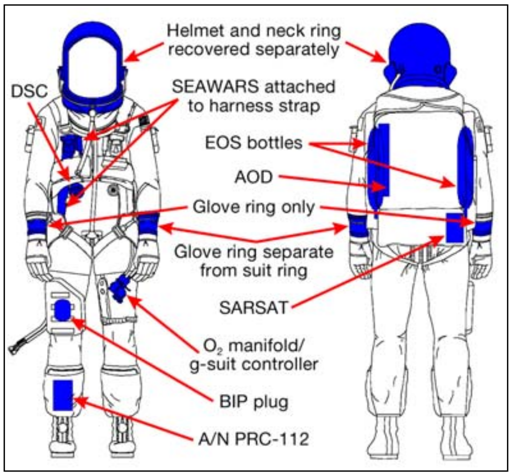

Figure 3.2-18. ***Seat 4 recovered crew worn equipment*.**

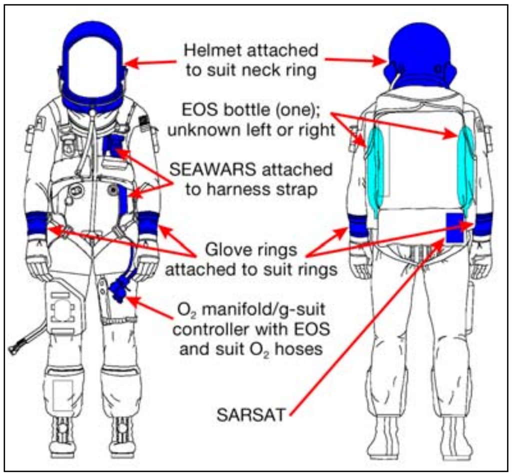

Figure 3.2-19. ***Seat 5 recovered crew worn equipment*.**

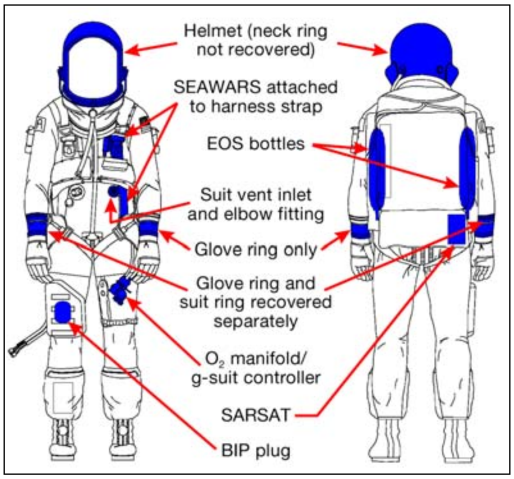

Figure 3.2-20. ***Seat 6 recovered crew worn equipment*.**

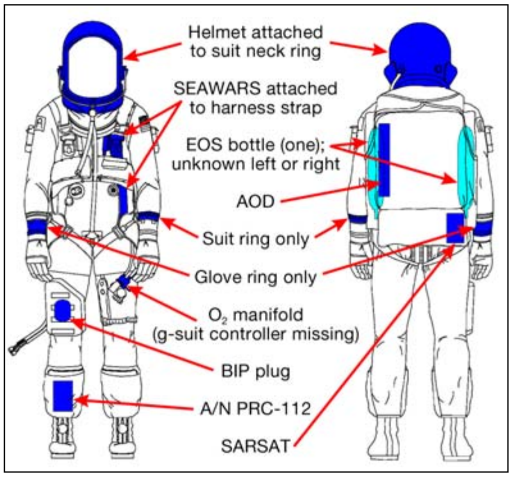

Figure 3.2-21. ***Seat 7 recovered crew worn equipment.***

Most of the suit components and subcomponents include serial numbers that are recorded and tracked to a specific crew member. This documentation aided greatly in the process of ascribing debris items to specific crew members. Thus, a very high percentage of recovered crew worn equipment was identified to specific crew members, aiding the post-accident analysis.

3.2.5 Helmets

Undamaged helmets and neck rings are shown in figure 3.2-4 and figure 3.2-2, respectively.

3.2.5.1 *General condition*

All seven helmets and six of the seven neck rings were recovered. Five of the seven helmets were recovered with the neck ring attached. One neck ring was recovered separate from the helmet. Inspection revealed that this neck ring had been mechanically removed from the helmet due to fracture of the latch mechanism. Detailed inspection of all helmets and helmet-to-neck-ring interfaces indicates that all crew members except one had their helmets on and latched at the time of the CMCE.[5] Helmet separation from the suit occurred between the suit-side neck ring and the suit fabric interface.

Finding. One crew member did not have the helmet donned at the time of the CMCE. Three of the seven crew members did not complete glove donning for entry. The deorbit preparation period of shuttle missions is so busy that crew members frequently do not have enough time to complete the deorbit preparation tasks (suit donning, seat ingress, strap-in, etc.) prior to the deorbit burn (see **Recommendation L1-2**).

The condition of each helmet shows effects from mechanical loading and thermal exposure. Effects from thermal exposure were generally consistent across all helmets, except for the helmet that was not donned at the time of the CMCE. This helmet had more pressure visor material remaining. The effects from mechanical loading were generally consistent across all seven helmets. The magnitude and distribution of mechanical damage was not severe, except for damage caused by ground impact.

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[5] According to experienced astronauts, shuttle crews often struggle to complete all actions in the time allotted, giving priority to time-critical orbiter systems activities and reordering the tasks as necessary. Deorbit preparation activities frequently extend into the time after the deorbit burn and entry interface. Per the STS-107 crew's deorbit preparations plan, the crew member whose helmet was not donned was the last crew member scheduled to ingress the seat and don the helmet.

3.2.5.2 *Thermal condition*

Thermal effects were apparent throughout all helmet surfaces. Significant variations in thermal conditions were noted from helmet to helmet (both interior and exterior helmet surfaces). The reflective tape was missing from all of the helmets, and fiberglass delaminations of various sizes and depths were observed. Some white paint remained, except in the areas removed via fiberglass delamination. Residual paint on the exterior helmet surfaces shows signs of damage (pitting) that are consistent with impacts with many small debris items. Figure 3.2-22 shows examples of delaminations and pitting damage.

Figure 3.2-22. ***Delamination and pitting damage*.**

Small amounts of residual melted suit material were discovered, all of which were confined to the helmet/neck ring area. Melted suit bladder materials (nylon and Teflon) were observed on both sides of the helmet/neck ring interface on all helmets (except on the one helmet for which the suit-side neck ring was not recovered). Nomex material was absent from the internal and external helmet surfaces. Inspection of the suit bladder clamp interface on the neck ring yielded only nylon and Teflon (no Nomex) materials. This indicates that the Nomex material failed mechanically before the thermal decomposition temperature of 932°F (500°C) was reached. Helmet separation from the suit occurred primarily due to mechanical (aerodynamic) forces; the helmets were not "melted off" the suit. Mechanical (aerodynamic) disruption of the suit occurred prior to completion of the heating period. Melted suit material was deposited onto the helmet and neck ring areas after mechanical separation of the neck ring (small fragments of suit material were still clamped into the neck ring upon mechanical separation).

On three of the seven helmets, the upper visor reinforcement bar was recovered with some pressure visor material still attached; no sun shield material remained on any of the helmets. The upper and lower visor bars along with visor materials on each of the other four helmets were not recovered. The visor is constructed of a laminate of polycarbonate and polymethylmethacrylate. These materials do not have a true melting point but instead have a glass transition temperature.[6] The glass transition temperature for polymethylmethacrylate is approximately 230°F (110°C). The glass transition temperature for polycarbonate is approximately 300°F (149°C). Thermal gravimetric analysis testing was conducted to determine the temperature at which thermal decomposition (pyrolysis) in air begins. The thermal decomposition temperatures for polymethylmethacrylate, fiberglass epoxy resin, and polycarbonate are 572°F (300°C), 735°F (391°C), and 752°F (400°C), respectively. These temperatures are for pyrolysis in air. Tests conducted in nitrogen (N_2) yielded thermal decomposition temperatures roughly 55°F (13°C) to 90°F (32°C) higher. It is unknown

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[6] The temperature above which the mechanical properties of a material are reduced significantly and the material will flow.

whether these temperatures would be higher or lower in a low-pressure, monatomic oxygen (highly reactive) environment.

On all three helmets that have remaining pressure visor material, the polymethylmethacrylate flowed and pyrolyzed and the polycarbonate flowed in some places but did not pyrolyze (figure 3.2-23). Therefore, helmet visor materials experienced at least 300°F (149°C), which is the glass transition temperature of polycarbonate, to over 572°F (300°C), the pyrolysis temperature of polymethylmethacrylate, but certainly less than 752°F (400°C), which is the pyrolysis temperature of polycarbonate. Although there were small localized areas of fiberglass pyrolysis, in no case was there global pyrolysis of the helmet fiberglass material, indicating that the helmets did not experience temperatures globally above 735°F (391°C).

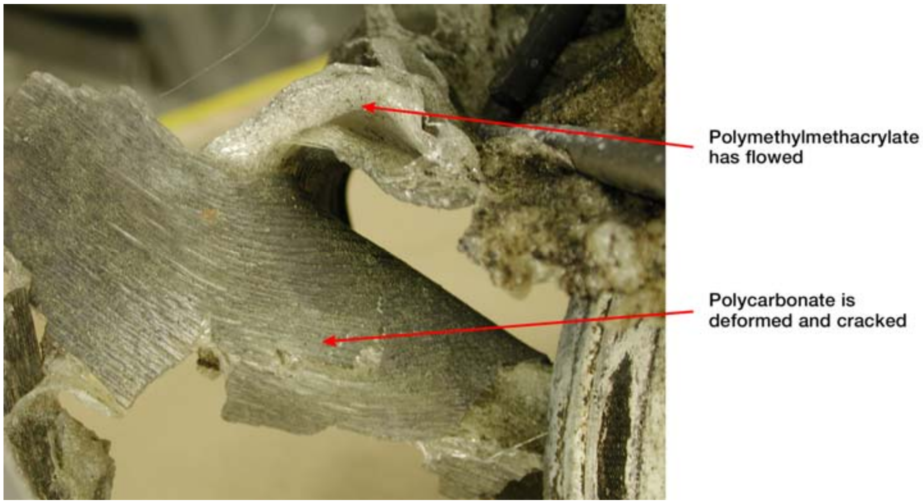

Figure 3.2-23. ***Helmet pressure visor thermal effects*****.**

The Object Reentry Survival Analysis Tool (ORSAT) was used to predict thermal damage for helmets released at various times in the trajectory. The helmet was modeled as an 11-in.-diameter sphere weighing 6.3 lbs., with an initial temperature of 80°F (27°C). The analysis concluded that free-flying helmets released around GMT 14:01:03 would have received heating sufficient to cause damage similar to that seen on the visors of the three recovered helmets. Ballistics analysis provided helmet release times consistent within 10 seconds of the ORSAT-predicted time, confirming the approximate time of helmet separation from the CM. No significant inconsistencies were noted among ballistics analysis, ORSAT analysis, materials testing, and debris observations.

Despite the flow of the visor material, this material is notably absent from the helmet visor seal around the face opening, indicating that the visors were not in contact with the visor seal when heating occurred and were not down and locked.

Finding. Inspection of all seven recovered helmets confirmed that none of the crew members lowered and locked their visors (see **Recommendation L1-3/L5-1**).

3.2.5.3 *Mechanical condition*

In all cases, the helmet structure remained intact. The helmets experienced a range of localized mechanical damage (fractures), but did not experience massive structural damage from external impacts prior to ground impact. External helmet impacts were insignificant in size and random in distribution. Detailed inspections differentiated the sources of internal impacts.

Finding. The current ACES helmets are nonconformal and do not provide adequate head protection or neck restraint for dynamic loading situations.

> ***Recommendation L2-4/L3-4.*** Future spacecraft suits and seat restraints should use state-of-the-art technology in an integrated solution to minimize crew injury and maximize crew survival in off-nominal acceleration environments.
>
> ***Recommendation L2-7.*** Design suit helmets with head protection as a functional requirement, not just as a portion of the pressure garment. Suits should incorporate conformal helmets with head and neck restraint devices, similar to helmet/head restraint techniques used in professional automobile racing.

The hold-down cables on each neck ring were severed at the attach points to the cable guide tubes due to mechanical overload (figure 3.2-24). Most cable guide tubes experienced significant plastic deformation. The guide tubes display evidence of external contaminants (i.e., melted metal and suit material) and thermal effects on top of the fractures and localized deformation. This indicates that mechanical loading preceded exposure to the thermal environment. Rotation of the helmet relative to the normal forward position was observed on all neck rings varying from 90 to 180 degrees. Major cable guide tube deformation and helmet rotation indicates that a significant loading event occurred where helmets were removed via a mechanical (nonthermal) mechanism.

Figure 3.2-24. ***Hold-down cable guide tube.***

One of the seven helmets was recovered with the bailer bar still attached. All other helmets had the bailer bar mechanically removed, although the bailer bar cam mechanism remained in place on the starboard and portside helmet interfaces.

The bailer bar latch mechanisms on five of the seven helmets remained attached to the helmets in good condition (figure 3.2-24). This would not be expected if the crew members had lowered and locked their visors. Mechanical separation of the bailer bar would be accompanied by fracture of the latch assembly if the visor was down and the bailer bar was locked. The other two helmets experienced latch mechanism separation due to failure of the fasteners that attach the latch mechanism to the helmet before subsequent deposition of melted suit materials. This suggests that latch separation was followed by suit melting. Neither of the two helmets shows evidence of the indentation or deformation that would be associated with forces expected if the bailer bar ripped the latch from the neck ring. Combined with the absence of melted visor material on the visor seal, this confirmed the conclusion that none of the crew members lowered and locked visors.

3.2.6 Glove disconnects

Undamaged glove disconnects are shown in figure 3.2-25.

Figure 3.2-25. ***Examples of intact suit-side* (left) *and glove-side* (right) *glove disconnects*.**

Twelve glove disconnect debris items were recovered, corresponding to six of the seven *Columbia* crew members (no glove disconnect rings were recovered for seat 1). Although evidence of exposure to entry heating was noted on all disconnect rings, the level of heating varied from item to item, with differences between the left and right sides of items from the same crew member. Inspection of recovered disconnect rings indicates that three crew members did not have their gloves mated to their suits for entry. Inspection indicates that three crew members had gloves mated to their suits. The recovered flight deck entry video supports these conclusions. The video also indicates that the crew member in seat 1 also had gloves mated to the suit.

Finding. One crew member did not have the helmet donned at the time of the CMCE. Three of the seven crew members did not complete glove donning for entry. The deorbit preparation period of shuttle missions is so busy that crew members frequently do not have enough time to complete the deorbit preparation tasks (suit donning, seat ingress, strap-in, etc.) prior to the deorbit burn (see **Recommendation L1-2**).

Melted aluminum deposits and/or tiny craters were observed on most of the glove and suit rings. Melted suit material (figure 3.2-26) was discovered on all recovered disconnect rings. Close inspection of the suit bladder clamp interface on the suit-side disconnect rings revealed mainly nylon and Teflon materials. In all cases, minimal amounts of Nomex remained clamped to the interface. Overall, the amount of residual melted suit material seems to correlate with the general magnitude of heating; that is, higher-magnitude heating resulted in the pyrolysis of residual suit material. As with the helmets, deposition of melted suit material on the glove disconnect areas occurred after mechanical separation. Small fragments of suit material were still clamped in the disconnect after mechanical separation. The failure modes at the disconnect ring (the ring-to-suit material interface) were similar to those observed in the suit-side helmet disconnect rings (see Section 3.2.5).

Figure 3.2-26. ***Recovered suit-side*** **(upper left)*****, glove-side*** **(upper right)*****, and mated*** **(bottom)** ***glove disconnects*****.**

3.2.7 Dual suit controllers

An undamaged DSC is shown in figure 3.2-27.

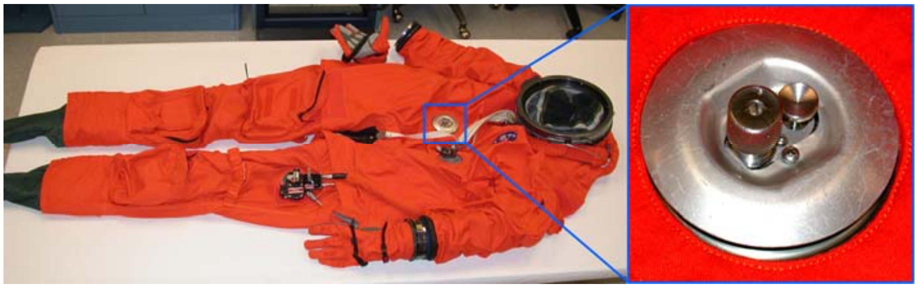

Figure 3.2-27. ***Example of an intact dual suit controller*****.**

Four DSCs were recovered, all from flight deck crew members and all presenting similar appearances. One DSC (figure 3.2-28) was disassembled and inspected to determine the thermal environment exposure. The suit material edges were ragged with some localized melting around the edges, indicating that there was a mechanical disruption of the suit followed by thermal exposure to the suit fabric that was still attached to the DSC body. The DSC body back surface (i.e., the surface inside the suit) had many craters and one penetration (~0.5 in. × 0.25 in.). This indicates a rapid disruption of the suit, releasing the DSC while it was still in close proximity to the CM debris cloud. Some melting of the suit material to the DSC body caused the suit flange to adhere to the DSC body. All internal soft goods (O-rings, seals, diaphragms) were intact and showed no signs of mechanical or thermal damage. Both of the aneroids[7] were still hermetically sealed with the sealing solder intact. The suit cover-layer Velcro was melted to the suit restraint-layer Velcro in some

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[7] Small, sealed metal bellows, sensitive to air pressure, that are part of the suit pressurization control mechanism.

areas. Although melting of the torn fabric edges and the Velcro® indicates thermal exposure, the complete lack of thermal damage to any of the internal soft goods suggests that the thermal exposure was limited in intensity and/or duration.

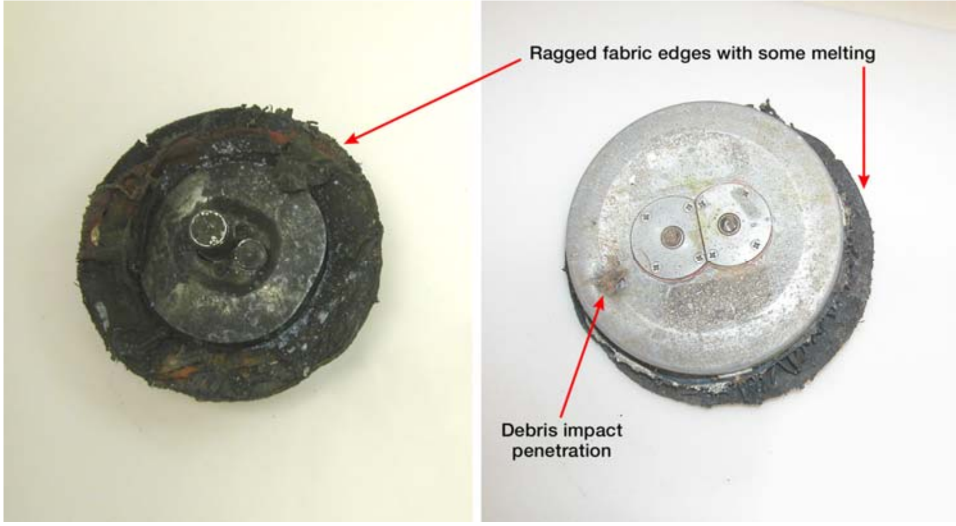

Figure 3.2-28. ***Recovered dual suit controller front*** **(left)** ***and back*** **(right).**

3.2.8 Boots

Undamaged boots are shown in figure 3.2-7.

A total of 53 possible boot fragments were recovered, including eight sole fragments from six boots and fragments of leather uppers and inserts. All fragments exhibited mechanical and thermal damage. No identifiable pieces of the shoe laces or nylon sections of the boots were recovered.

The condition of each recovered boot sole shows effects from mechanical loading and thermal exposure. Mechanical loading resulted in the removal of the boot leather uppers from five of the six recovered soles and fracture of four of the six recovered boot soles. Forensic evidence indicates that the boots were worn by the crew members during thermal exposure and that the boots failed mechanically prior to the conclusion of thermal exposure. Evidence indicates that the soles of these boots failed, with either the toe section or the complete sole being removed first followed by the remainder of the boot. The nylon lower sections of some of the boots appear to have been thermally penetrated prior to mechanical removal of the leather upper. Effects from thermal exposure were generally consistent across all soles. Edges, including the fracture edges, exhibited thermal erosion.

In an attempt to match the observed thermal damage, boot soles of flight-like boots were heated in an oven to identify the range of thermal effects with varying thermal exposure. The test samples were exposed to 750°F (399°C), 1,000°F (538°C), or 1,250°F (677°C) at normal atmospheric pressure conditions (~14.7 psi, ~20% O_2) for 15, 30, 45, or 60 seconds. The materials showed no significant changes in appearance until they combusted. This initially puzzled the team until it became clear that the presence of O_2 was affecting the results. The tests were repeated using new samples that were heated in an N_2 purge (<3% O_2). Results of the revised test protocol appeared to be similar to the recovered boot sole fragments. The test samples that most closely matched the recovered debris items were those that were exposed to 1,000°F (538°C) for 30 to 45 seconds or 1,250°F (677°C) for 15 to 30 seconds. However, no credible scenario could be envisioned in which the *Columbia* boots would be exposed to these temperatures for the length of time indicated by the tests, so the test results could not be correlated directly to the debris observations. Because the test conditions (~14.7 psi, 97% to 99% N_2, 1% to 3% O_2) did not sufficiently approximate the entry environment conditions (low ambient pressure, monatomic O_2, and possibly high dynamic pressure), they are a potential source of error in this analysis.

3.2.9 Emergency Oxygen System

An intact EOS is shown in figure 3.2-12.

Ten whole EOS bottle/reducers were recovered (eight were ascribed to specific crew members), each with no O_2 remaining. All 10 of the recovered EOS bottle/reducers have similar appearances, with some variance in the amounts of material deposition. Additionally, three fragments of bottles were also recovered (figure 3.2-29).

Figure 3.2-29. ***Recovered whole Emergency Oxygen System bottle/reducers*** **(left and center)** ***and a bottle fragment*** **(right).**

No nylon material from the parachute harness adhered to the bottle/regulator assemblies. Minor evidence of elevated temperatures, directional burn marks, and discrete external impacts are visible. As with most of the *Columbia* hardware, corrosion that occurred while the debris was on the ground is also evident. X ray revealed that all of the EOSs were activated. However, the crew members were trained not to activate them unless their visors were down. Therefore, activation of the EOS (achieved by applying tension to the activation cables) probably occurred as the bottles separated from the harnesses rather than by crew action.

The overall appearance of the 10 recovered whole EOS bottle/reducers suggests that each EOS bottle/reducer assembly experienced similar thermal and mechanical environments. Each EOS assembly was mechanically extracted from the harness as temperatures were rising; then for a short duration and nearly simultaneously, they experienced ballistic heating and some metal pellet-like impacts. This indicates a rapid disruption of the parachute harness, releasing the EOS while it was still in close proximity to the CM debris cloud.

The EOS bottle fragments exhibited irregular edges along the fracture surfaces, some outward bent edges, evidence of heating on the inner surfaces, and some deposited/flowed black material along a fracture surface.

Heating on the inner surfaces indicates that the bottle failure occurred before the end of entry heating. Neither the cause of the bottle failures nor the status of the bottles at the time of failure (pressurized or unpressurized) could be determined.

3.2.10 Seawater Activated Release System

Six SEAWARS were recovered. None had automatically ignited, and all had both of the Frost fitting male and female halves still mated. All SEAWARS had similar appearances (figure 3.2-30), consisting of the SEAWARS assembly still attached to approximately 12 in. of nylon parachute harness strap. None had any parachute riser material attached.

Figure 3.2-30. ***Seawater Activated Release System with Frost fittings (male/female) still mated, with a segment of harness strap attached*** **(two different SEAWARS are shown).**

Each SEAWARS/strap item shows evidence of directional melting, burning, and mechanical loading. The surviving length of parachute harness strap is consistent with a harness strap failure at the waist. While the terminating ends show evidence of melting on the top layer of fabric, these ends appear to have failed primarily due to mechanical overload, not melting. Some surface melting occurred along the length of the straps, with distinct directionality away from the SEAWARS towards the broken end of the strap, corresponding to a head-to-foot direction when the harness is on a crew member. These directional heating/melting features are present on both sides of the straps, with little difference between the front and the back of the straps. Because both sides of the straps show signs of heating, the heating and melting must have occurred after the straps had separated from the crew member. Localized heating on the metallic SEAWARS Frost fitting buckle suggests intense, short-duration heat exposure. Each SEAWARS and strap was mechanically extracted from the harness webbing before experiencing this short-duration heating. Directionality suggests that each piece of riser trimmed with the SEAWARS into the airflow (figure 3.2-31).

Figure 3.2-31. ***Directional melting on Seawater Activated Release System/parachute harness strap*.**

3.2.11 Telonics Satellite Uplink Beacon-A search and rescue satellite-aided tracking beacon

An undamaged TSUB-A SARSAT beacon is shown in figure 3.2-14.

One TSUB-A SARSAT beacon is flown per crew member; it is located in the survival raft packed in the PPA. Six SARSAT beacons were recovered; none of them were activated during the accident. All six recovered SARSAT beacons show similar thermal and mechanical damage (figure 3.2-32).

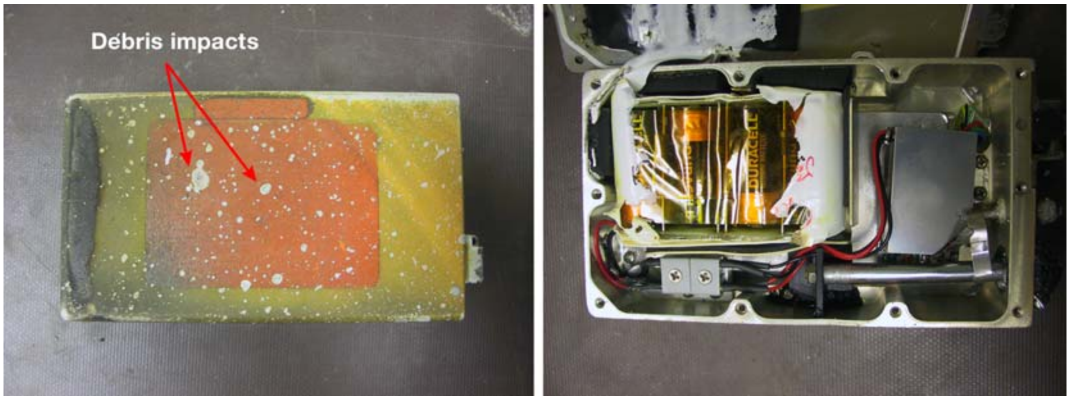

Figure 3.2-32. ***External*** **(left)** ***and internal*** **(right)** ***views of a recovered search and rescue satellite-aided tracking beacon*****.**

No material from the raft or the PPA was adhered to the outer aluminum casing. Various amounts of paint remained, displaying evidence of impacts with small, hot metal pellets. Corrosion was also present. All external plastic was melted. Internal inspection of the beacons revealed minor solder re-flow, with most of the components mechanically and electrically intact. Two SARSAT beacons were tested and, when externally powered, functioned properly. For each of the six SARSAT beacons, the processing module was extracted and interfaced with ground support equipment to read the beacon’s unique identifier, thereby allowing all six beacons to be ascribed to individual crew members. Each SARSAT beacon was mechanically extracted from the PPA as temperatures were rising; then for a short duration and nearly simultaneously, it experienced high heating and a hot metal pellet-like shower. This indicates a rapid disruption of the parachute packs and release of the SARSAT beacons while they were still in close proximity to the CM debris cloud.

3.2.12 Army/Navy personal radio communications-112 radio

An undamaged A/N PRC-112 radio is shown in figure 3.2-10.

Four A/N PRC-112 radios were recovered, all of which looked similar (figure 3.2-33). No Nomex material from either the suit pocket or the survival gear pouch was adhered to the outer aluminum casing. Various amounts of paint showed evidence of impact with small, hot metallic pellets. Corrosion was also present. All external plastic was melted or missing. Internal inspection of the radios revealed evidence of moderate heating, with the center-most components experiencing only minor solder re-flow. For each of the four radios that were recovered, the control module was extracted and interfaced with ground support equipment to read the unique identifier of the radio. Thus, all four radios were ascribed to a specific crew member. Overall appearance suggests that each A/N PRC-112 radio experienced similar thermal and mechanical environments. Each radio was mechanically extracted from the ACES pocket and the survival gear pouch as temperatures were rising and, for a short duration and nearly simultaneously, each of the radios experienced high heating and a hot metal pellet-like shower. This indicates a rapid disruption of the suit survival gear pockets, releasing the radios while they were still in close proximity to the CM debris cloud.

Figure 3.2-33. ***External*** **(left)** ***and internal*** **(right)** ***views of a recovered Army/Navy personal radio communications-112 radio*****.**

3.2.13 Ground plot analysis

To help understand the breakup sequence of the CM, the recovery locations of pieces of crew equipment were analyzed to determine the order in which the crew members separated from the CM. The human body's complex geometry is difficult to model for precise ballistic analysis and can result in significant variations in trajectory. As a result, the recovery locations of the crew remains is unreliable data for determining the order in which the crew members separated from the CM. Therefore, recovery locations of the crew remains were not included in this analysis.

Items selected for analysis (helmets, SARSAT beacons, and A/N PRC-112 radios) were chosen due to the small variations in the conditions of like items (i.e., all helmets were recovered in the same general condition) and their "regular" shapes (the helmets are roughly spherical, and the SARSAT beacons and A/N PRC-112 radios are rectangular prisms), which have known aerodynamic properties and result in predictable free-flying trajectories.[8] Thus, all like items had similar flight characteristics in the fall to the ground, and can be used to determine the relative order of crew member separation from the CM. It was assumed that the items separated from each crew member in the same manner and roughly the same amount of time after each crew member separated from the CM.

As discussed above, all seven helmets were recovered and ascribed to crew members.[9] The helmets impacted the ground from west to east in the order of seat 7, seat 6, seat 5, seat 4, seat 2, seat 3, and seat 1 (figure 3.2-34).

Six SARSAT beacons were recovered (all except seat 2) and ascribed to crew members. The SARSAT beacons impacted the ground from west to east in the order of seat 6, seat 7, seat 5, seat 4, seat 1, and seat 3 (figure 3.2-34).

Four A/N PRC-112 radios were recovered and identified to crew members (seat 1, seat 2, seat 4, and seat 7). The longitude data for the seat 4 radio is highly suspect, however. These data indicate that it was recovered more than 50 miles east of all other seat 4 crew equipment debris. It is assumed that the original data point was recorded incorrectly and is off by 1 degree, so a "corrected" data point was used in the analysis. The A/N PRC-112 radios impacted the ground from west to east in the order of seat 4, seat 7, seat 1, and seat 2 (figure 3.2-34).

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[8] Other crew equipment items were not selected for detailed ground plot analysis (EOS bottles, SEAWARS, etc.) due to their irregular shapes, which would result in lower confidence in the flight characteristics being similar.

[9] One of the middeck crew members did not have the helmet attached to the suit at the time of the breakup. It is possible that the helmet was released from the CM at a different time than it would have been if it had been attached to the suit.

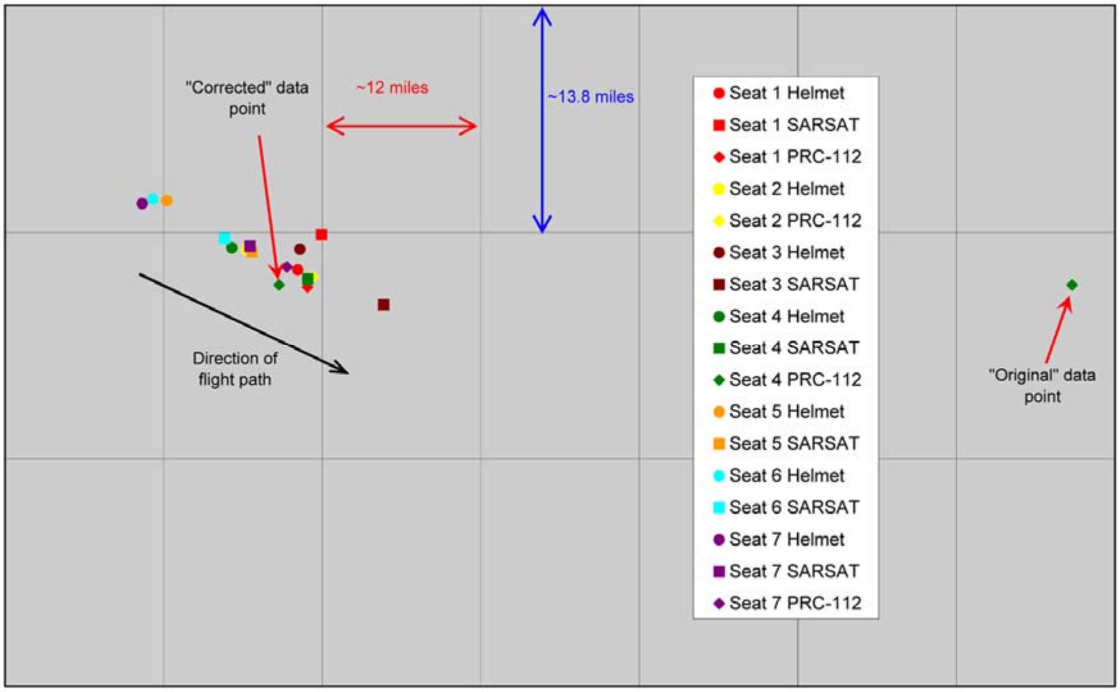

Figure 3.2-34. ***Relative location of helmets, search and rescue satellite-aided tracking beacons, and Army/Navy personal radio communications-112 radios*****.**

The investigation team concluded that the middeck crew members separated from the CM before the flight deck crew members. Orders within the middeck/flight deck groups cannot be determined conclusively, but it appears that seat 6 and seat 7 equipment items were first out of the middeck and seat 4 equipment was first out of the flight deck. All CEE associated with specific crew members was plotted by crew member. Analysis looking at the relative centers of the areas of recovered items for each crew member supports this conclusion. Figure 3.2-35 shows the locations of the recovered items for each crew member. The upper plot shows items for the flight deck crew members; the lower plot show items for the middeck crew members. Both plots are the same scale and represent the same geographic area.

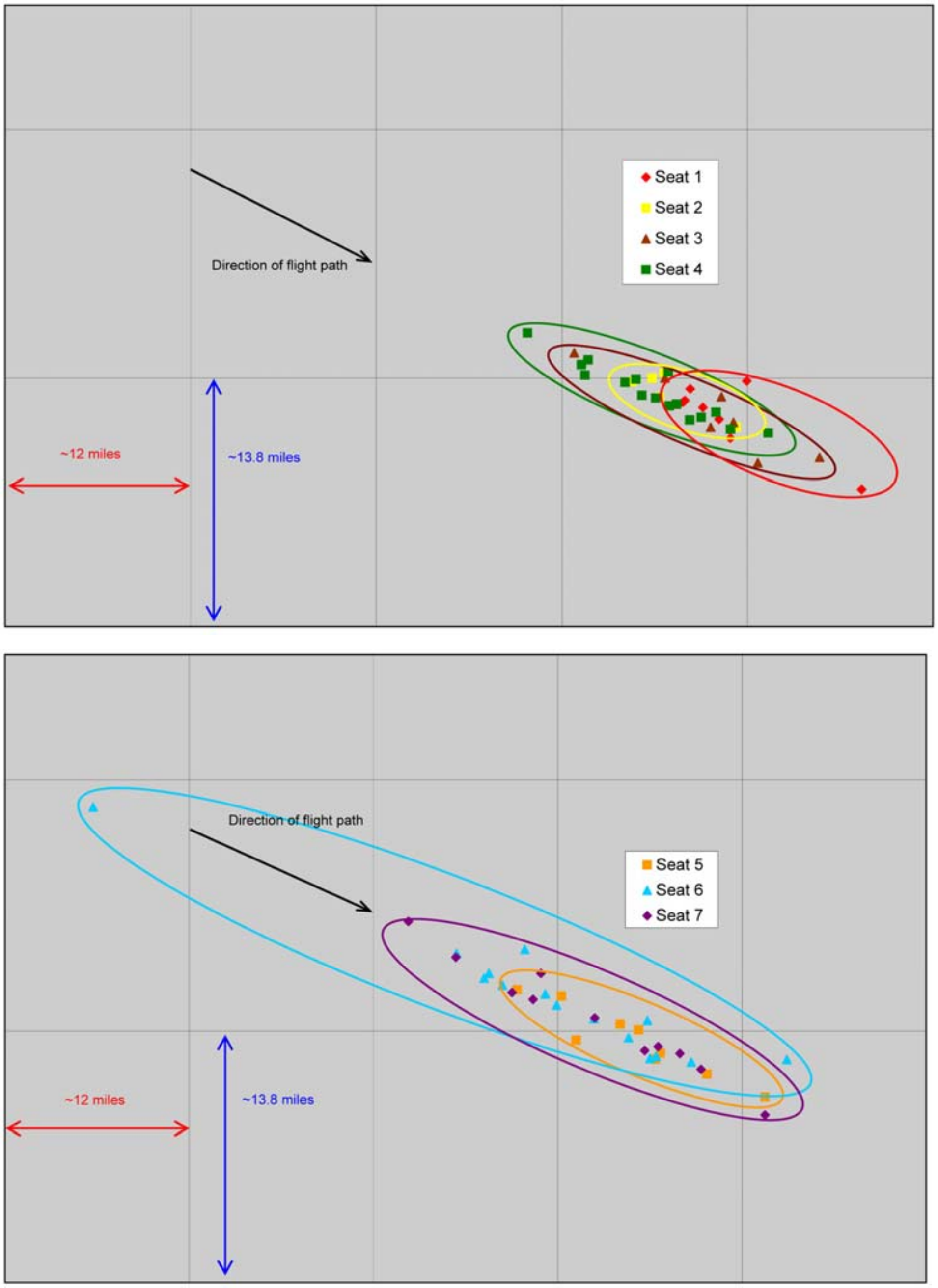

Figure 3.2-35. ***Relative locations of all crew escape equipment*** **– flight deck crew members (top) and middeck crew members (bottom).**

3.2.14 Lessons learned

3.2.14.1 *Equipment serialization and marking*

One of the most useful tools in investigating an aviation accident is physically or virtually reconstructing the vehicle from the recovered debris. Being able to identify the original location within the vehicle of debris items is of utmost importance in achieving an accurate reconstruction. Identifying the origins of debris items is made possible by serializing individual piece parts and subassemblies, and keeping accurate records of the piece part/subassembly serial numbers at the assembly and, ultimately, the vehicle levels.

This is especially useful when there are multiple units of identical or similar components, such as crew equipment, seats, engines, or structural members.

The hard components of the ACES, parachute harness, and parachute pack are serialized and tracked to the top-level assembly. Records are kept regarding which crew member is using which suit, harness, and parachute pack. Because of this meticulous recordkeeping, the recovered helmets, glove rings, SEAWARS, DSCs, ACES pressure relief valves, BIP plugs, O_2 manifolds, EOS bottles, and AODs were identified to a specific crew member. In most cases, the serial numbers are etched or physically stamped on the components, aiding identification. For the SEAWARS, the SARSAT emergency beacons, and the A/N PRC-112 survival radios, the identification labels were damaged or destroyed by entry heating. Identification was possible by disassembling the units and inspecting subcomponent serial number labels (in the case of the SEAWARS), or by reading the programmed unique transponder information in the beacon and radio electronics.

Finding. Most of the suit components and subcomponents include serial numbers that are recorded and tracked to a specific crew member. This configuration management documentation aided greatly in the process of ascribing the debris items to specific crew members.

> ***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.

3.2.14.2 *Suit requirements and design*

The crew escape suits (the ACESs) were designed to enable survival of crew members during egress and escape from the shuttle in emergency situations. There were specific requirements for the suit to protect crew members from contaminated atmosphere and smoke. As with other materials used in the shuttle, the suit materials were required to be nonflammable or self-extinguishing. However, the suit assembly did not have functional requirements to protect the crew members from environments involving elevated temperatures or fire, as might be present during an emergency egress due to a fire at the launch pad.

As part of the certification testing of the U.S. Air Force suit, suits were subjected to flame pit tests in which suited manikins were placed in a jet fuel fire for 3 seconds and then removed. The suits performed well, with no structural failures and no expected burns to the occupant (based on temperature sensors on the manikin). The ACES is similar to the U.S. Air Force suit, so it may be expected that the ACES would perform well in similar tests. However, the ACES ensemble has some design and materials differences from the U.S. Air Force suit. One notable difference is the use of nylon on the ACES parachute harness straps and the boots. The use of nylon presents a potential weakness in the suit if the suit is used in an environment entailing elevated temperatures or fire.

Finding. The ACES had no performance requirements for occupant protection from elevated temperatures or fire. The ensemble includes nylon on the parachute harness straps and the boots. The ACES may not provide adequate protection to crew members in emergency egress scenarios involving exposure to heat and flames.

> ***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.

3.3 Crew Training

Crew training, while not a factor in causing the *Columbia* accident, is nonetheless an important element of this report. This section will provide an overview of generic astronaut training and examine *Columbia*-specific crew training. Finally, this section will provide an in-depth analysis and discussion of the impact of training on the actions taken by the STS-107 crew as events unfolded during vehicle entry.

The following is a summary of findings, conclusions, and recommendations for this section.

Finding. The current training regimen separates vehicle systems training from emergency egress training. Emergency egress training sessions exercise the procedures and techniques for egressing the shuttle CM without emphasizing the systems failures that caused the emergency condition. The egress training events are performed on different days from the systems training events, with little discussion of the transition between systems malfunctions and the decision to egress the vehicle. Crew members become conditioned to focus on problem resolution rather than crew survival; the training does not adequately prepare the crew to recognize impending survival situations. It is possible that the STS-107 crew members did not close and lock their visors during the vehicle LOC dynamics (before cabin depressurization) because they were more focused on solving vehicle control problems rather than on their own survival.

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

Finding. Emergency egress training for a vehicle LOC/breakup is based on extrapolated data and basic assumptions from the *Challenger* accident for aerodynamic modeling and CM dynamics. The vehicle LOC emergency egress procedures taught to shuttle crews do not address a vehicle LOC occurring during entry.

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

3.3.1 Overview

NASA’s astronaut training program is designed to provide the systems familiarization and flight skills that are required for astronauts to operate the shuttle and carry out mission tasks effectively and efficiently. The training is structured in a building-block format, beginning with workbooks and briefings and progressing to lessons that use sophisticated trainers and simulators.

Individuals selected as astronaut candidates (ASCANs) undergo a training and evaluation period, which lasts over 1 year. This training introduces ASCANs to generic shuttle systems and flight operations, and it prepares them for more in-depth follow-on training as assigned crew members. The curriculum includes training on the Data Processing System; the Guidance, Navigation, and Control System; vehicle control and propulsion systems; the Communications and Tracking System; crew habitability; and shuttle crew escape (emergency egress) equipment and procedures. Additionally, ASCANs are given International Space Station (ISS) systems training. Upon completion of the ASCAN training, the student possesses a functional knowledge of the shuttle systems, ISS systems, and flight operations procedures.

After the initial training period, ASCANs receive advanced training that may lead to assignment to a shuttle flight crew. While awaiting flight assignment, ASCANs maintain proficiency in shuttle systems and flight operations through recurring proficiency lessons in the shuttle mission simulator (SMS). They may also elect to take single system trainer refresher lessons in various orbiter systems. In addition, ASCANs receive mission-specific courses such as Payload Deployment and Retrieval System, Mobile Servicing System, rendezvous and proximity operations, and extravehicular activity (spacewalk).

Upon assignment to a specific flight, crew members progress to flight-similar operations (ascent, orbit, and deorbit/entry) lessons and begin the appropriate mission-specific courses. Assigned crew training also includes flight-specific shuttle mockup training sessions on crew habitability and crew escape. Ascent/entry flight operations training prepares orbiter crew members for crew ingress, orbital insertion, deorbit burn, and landing.

Manual flying techniques are covered in several lessons. All CDRs and PLTs become proficient in manual skills for nominal[1] ascents, aborts, and entries. Crew coordination (space flight resource management (SFRM)) objectives are included to enhance team effectiveness and to ensure mission safety and success.

All training courses lead to integrated simulations. The integrated simulations build the team coordination between the crew and the flight control teams in the Mission Control Center (MCC) that is necessary to ensure a successful mission.

The training regimen encourages systems knowledge and problem resolution through appropriate analysis of displays and use of checklists. While the regimen incorporates scenarios that involve multiple systems failures, in general it is considered nonproductive to train scenarios from which there is no recovery and so those cases are not simulated. No simulation cases are intentionally scripted to result in explosive cabin depressurization or vehicle LOC. Unrecoverable conditions are not intentionally presented to the crew during training. There have been isolated cases in which simulations have ended in a vehicle LOC, but those instances are usually a result of an unrealistic number of simulated systems failures occurring at the same time, seemingly unrelated simulated failures interacting in unforeseen ways, failures being entered into the simulation computer system in the wrong order, crew or flight control team error or miscommunication, or an unexpected failure of the simulation computer.

Training is segregated based on the topic, the activity, and the limitations of each training facility. Sessions for systems failures, which may eventually result in the need to perform an emergency egress of the vehicle, are conducted in a facility that adequately simulates the software and hardware responses of the orbiter and provides an accurate representation of the flight deck interior only. In contrast, emergency egress procedure training is conducted in a volumetrically correct mockup of the entire CM that lacks the capacity for simulating systems malfunctions. The purpose of the emergency egress training sessions is to exercise the procedures and techniques for egressing the shuttle CM without emphasizing the systems failures that “caused” the emergency egress. The training events are performed at different times on different days with little discussion of the transition between a systems malfunction and the decision to egress the vehicle.

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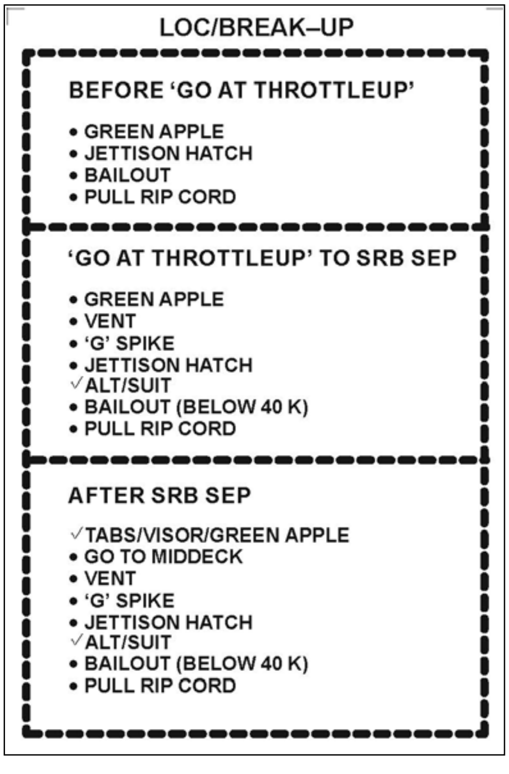
[1] Within acceptable boundaries.

Finding. The current training regimen separates vehicle systems training from emergency egress training. Emergency egress training sessions exercise the procedures and techniques for egressing the shuttle CM without emphasizing the systems failures that caused the emergency condition. The egress training events are performed on different days from the systems training events, with little discussion of the transition between systems malfunctions and the decision to egress the vehicle. Crew members become conditioned to focus on problem resolution rather than crew survival; the training does not adequately prepare the crew to recognize impending survival situations. It is possible that the STS-107 crew members did not close and lock their visors during the vehicle LOC dynamics (before cabin depressurization) because they were more focused on solving the vehicle control problems rather than on their own survival.

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

The emergency egress training program includes classroom sessions on shuttle CM egress procedures in the event of an LOC and vehicle breakup. This training is given to new astronauts as part of the ASCAN training program, and is given to flight-assigned shuttle crews in flight-assigned training just prior to launch in the escape systems refresher class. The training discusses procedures (figure 3.3-1) that are based on extrapolated data from the *Challenger* accident. The analysis of the *Challenger* data used basic assumptions for the vehicle/CM attitudes and dynamics.[2] However, this analysis had not been updated using the more sophisticated techniques available since the *Challenger* accident. Aerodynamic modeling performed for the current investigation provided estimates of CM dynamics following vehicle breakup. These dynamics differed from the assumptions that were made in the Shepherd-Foale Report, and have significant bearing on the LOC/breakup egress procedures. Additionally, the emergency egress procedures and training cover the case of a vehicle breakup during ascent,[3] which has a relatively benign thermal environment when compared to the entry trajectories. The *Columbia* accident brought to the forefront the higher aerodynamic and heat stresses that adversely affect the shuttle CM survival (and, therefore, crew survival) found in the entry environment.



LOC/BREAK–UP

BEFORE 'GO AT THROTTLEUP'

- GREEN APPLE
- JETTISON HATCH
- BAILOUT
- PULL RIP CORD

'GO AT THROTTLEUP' TO SRB SEP

- GREEN APPLE
- VENT
- 'G' SPIKE
- JETTISON HATCH
- ✓ALT/SUIT
- BAILOUT (BELOW 40 K)
- PULL RIP CORD

AFTER SRB SEP

- ✓TABS/VISOR/GREEN APPLE
- GO TO MIDDECK
- VENT
- 'G' SPIKE
- JETTISON HATCH
- ✓ALT/SUIT
- BAILOUT (BELOW 40 K)
- PULL RIP CORD

Figure 3.3-1. ***Loss of control/breakup cue card as flown on STS-107.***

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[2] Crew Bailout Procedure for LOC/Breakup Report, B. Shepherd and M. Foale, September 25, 1989.

[3] Prior to STS-107, NASA had not experienced a vehicle breakup during entry.

Finding. Emergency egress training for a vehicle LOC/breakup is based on extrapolated data and basic assumptions from the *Challenger* accident for aerodynamic modeling and CM dynamics. The vehicle LOC emergency egress procedures taught to shuttle crews do not address a vehicle LOC occurring during entry.

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

3.3.2 *Columbia* crew training

All STS-107 crew members completed the applicable ASCAN, core systems refresher, and ascent/entry flight operations training programs. The crew also completed all prescribed flight-specific training programs, including ascent and entry proficiency simulator training sessions, crew habitability, and crew escape/crew survival training as well as the prescribed ascent and entry integrated simulations prior to the launch delay in June 2002. An additional five ascent integrated simulations and three entry integrated simulations were completed prior to the January 2003 launch. The prescribed post-insertion and deorbit preparation simulations were also completed.

Launch delays, which were caused by main engine flowliner issues, resulted in the need to repeat some training. The entire crew repeated the water survival lessons (classroom and in-water sessions) in November 2002. The terminal countdown demonstration test (TCDT) was postponed several months. The crew had already completed the prelaunch ingress/egress mockup training session in June 2002, just prior to the postponement. Once the TCDT date was finalized, the CDR opted to retake the prelaunch ingress/egress lesson in November 2002. The escape systems refresher lesson was given in June 2002 but was also repeated in December 2002 at the CDR’s request. The crew also performed additional ascent and entry proficiency training sessions in the simulator following the launch delay in June 2002.

Throughout their training, the STS-107 crew members displayed expert orbiter systems knowledge, correct and thorough procedure execution, and excellent SFRM techniques. The crew was very rigorous in verbalizing and verifying procedural steps and routinely took time to brief SFRM topics before each simulation. The launch delays kept the crew in training together for more than 2 years, resulting in a well-trained and finely tuned team. For example, during a simulation run, the *Columbia* crew exercised crew coordination skills by performing the entire run without verbal communication. The crew worked through the systems failures and malfunctions by knowing the systems, procedures, and each other’s duties, while using nonverbal communication when appropriate.

3.3.3 Analysis and discussion

Following the loss of *Columbia*, the STS-107 training records were reviewed and the crew instructors were questioned with respect to failure scenarios that would result in the crew members closing visors. This research established that the crew had experienced numerous simulation scenarios in training with procedures requiring lowered visors (e.g., smoke/fire, cabin leaks, broken window panes, contingency aborts, systems failures resulting in an in-flight bailout, etc.). In line with the standard training regimen, very few simulations were performed with the crews wearing the ACES. When performing simulations unsuited, the STS-107 crew would verbalize the suit-specific steps of the procedures.

The CDR, Mission Specialist 2 (MS2), and MS3 were veterans of previous space flights. The CDR, PLT, MS1, MS3, and Payload Specialist 1 (PS1) were all professional military pilots, and the MS2 and MS4 were experienced civilian pilots. All members of the *Columbia* crew were highly trained and outstandingly competent. The training regimen that they underwent emphasized systems knowledge and problem resolution through appropriate analysis of displays and the use of checklists. As was previously stated, unrecoverable conditions are not presented to a shuttle crew during training. It is likely that the STS-107 crew members did not close and lock their visors before cabin depressurization because they were focused on solving the problems that had been presented to them rather than on their own survival. Upon cabin depressurization, a survival situation would be immediately apparent from a physiological perspective. The fact that they still did not close and lock their visors indicates that they were rapidly incapacitated and unable to do so.

3.3.4 Training effectiveness case study

Analysis of switch positions on recovered control panels can reveal crew actions. This analysis can provide insight into the crew members' thought processes and motives, which reveals their knowledge of vehicle systems.

Following the 1986 loss of *Challenger*, a review of the recovered equipment showed that the crew took a few actions after the breakup and prior to losing consciousness.[4] During the *Columbia* CM reconstruction, the switch panels were examined to determine whether any switches were out of the expected positions. Of the recovered flight deck panels (highlighted green in figure 3.3-2), an estimated 10% to15% of the switches were found out of position with respect to the expected positions for the entry timeframe.

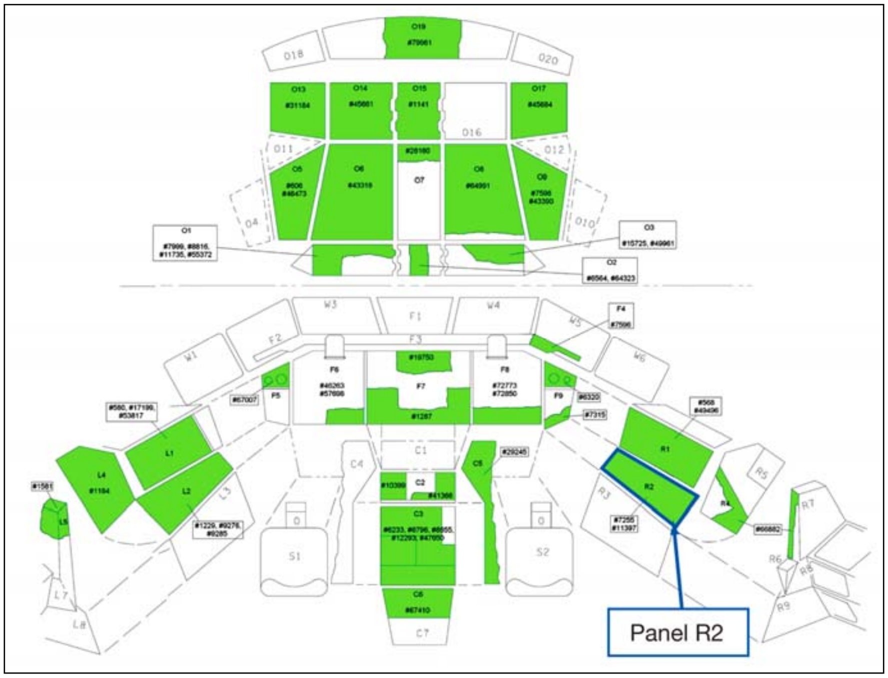

Figure 3.3-2. Columbia *recovered flight deck forward panels* (highlighted in green).

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[4] Report from Dr. Joe Kerwin to Rear Adm Truly, http://history.nasa.gov/kerwin.html, July 28, 1986.

No further analysis was performed at that time as it was not possible to know whether the switch positions were due to crew action, the mishap, or handling during debris recovery. However, the R2 panel, to the immediate right of the PLT on the flight deck (figure 3.3-2), warranted further investigation. This panel contains the primary controls for the auxiliary power units (APUs). The APUs drive the hydraulic pumps that provide hydraulic pressure to the flight control surface actuators. During entry, these surfaces become increasingly important to vehicle control, and loss of hydraulic pressure can have catastrophic results. Reconstructed general purpose computer (RGPC)-2 data revealed that the hydraulic systems failed prior to GMT 14:00:03 while the crew was conscious and capable of taking action.

When recovered, the R2 panel was folded back in on itself (figure 3.3-3), protecting the innermost switches from manipulation during recovery operations. The switch positions were considered to be unaltered by external factors, making the switches valuable in determining crew actions.

The panel was pried open during the investigation and switch positions were reviewed. In figure 3.3-4, all out-of-position switches are outlined with a pink box and noted with a pink dot.

Figure 3.3-3. ***Recovered R2 panel from*** **Columbia.**

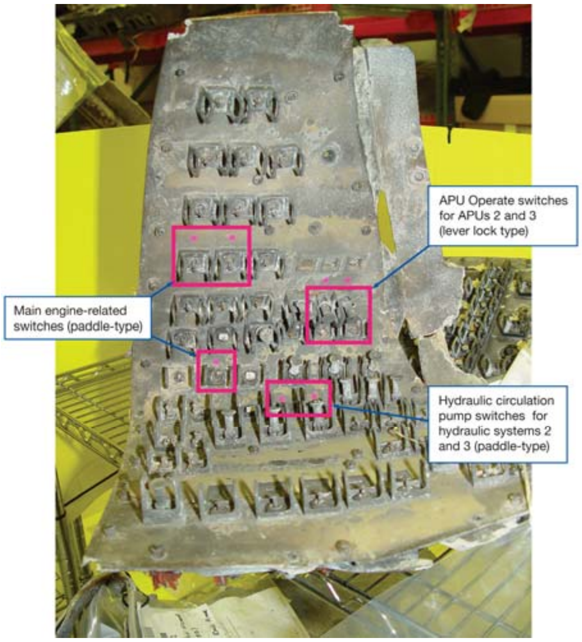

Figure 3.3-4. ***Recovered R2 panel from*** **Columbia** ***(after it was unfolded). Pink dots are above the out-of-configuration switches*****.**

The APU 2 and APU 3 Operate switches (“lever lock” switches that require two independent actions to change the switch position) were found in the “injector cool” position as opposed to the nominal “start/run” position. These switches are used when starting and stopping the APU. The “injector cool” position is used to cool down the APU after a shutdown prior to restarting it.

The remaining out-of-position switches are paddle-type switches that require just a push to move out of position. The switches on the left side of the panel are main engine-related switches that are not used during entry.[5] The two paddle-type switches in the lower center of the panel are the circulation pump switches for hydraulic systems 2 and 3. These were found in the "on" position as opposed to the normal "off" position. The circulation pump is used for thermal conditioning of the hydraulic fluid while the orbiter is on orbit. The pump also is used to keep the hydraulic reservoir pressurized. This pump is not powerful enough to deploy the landing gear, but it can provide some hydraulic pressure if activated. The pump is neither used nominally on entry nor is it used in off-nominal procedures.

At the end of RGPC-2 (GMT 14:00:05), all three APUs were operating but the hydraulic systems pressures and quantities were zero, presumably due to a loss of hydraulic fluid from damage to the left wing. While the crew members could not know the reason for the low hydraulic pressure, they would know from training that a loss of hydraulic pressure would result in a vehicle LOC such as they were experiencing.

In response to a hydraulic system failure, the procedures require shutting down the APUs by placing the APU Operate switches in the "off" position, then moving the APU Operate switches into the "injector cool" position to cool down the APUs before attempting a restart of the APUs. RGPC-2 data indicate that the APU Operate and hydraulic circulation pump switches were in their nominal, expected positions.[6] Therefore, these switches changed position after GMT 14:00:05, 13 seconds prior to the Catastrophic Event (CE).

Because the R2 panel was recovered folded in half and the APU Operate switches were not accessible, it is concluded that these switch positions were not altered during recovery operations. While the possibility exists for the lever lock switches to move due to random debris-debris interaction, the requirement for specific physical actions to enable switch movement makes it much more probable that the PLT deliberately moved the switches in an effort to regain hydraulic pressure and control of the vehicle. The paddle switches for the circulation pumps would be more subject to movement due to debris contact. However, the switches that were out of position (for hydraulic systems 2 and 3) correspond to the same APUs (APUs 2 and 3), lending credence to the theory that the actions were deliberate.

The catastrophic events that led to the loss of *Columbia* are not simulated in training or covered by existing systems procedures. The crew's attempt to recover at least two APUs by selecting the "injector cool" position and, in the interim, providing some hydraulic pressure to the flight control surfaces through the use of the circulation pump demonstrates remarkable aplomb. Their effort to regain hydraulic pressure to recover vehicle control shows excellent knowledge of the orbiter systems and problem-resolution techniques. This also indicates that deliberate crew actions (such as manipulating specific switches) were possible for some period of time after GMT 14:00:05, indicating that the CM was still pressurized and the dynamics of the out-of-control vehicle were not incapacitating.

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[5] These were paddle-type switches, so the positions could have been changed by any of the various methods described above. They are not relevant to entry systems, so no analysis was necessary.

[6] E-mail: from Jeff Kling, STS-107 Ascent/Entry Mechanical Maintenance and Crew Systems Officer, to Pam Melroy, November 8, 2005.

3.4 Crew Analysis

This section contains the analyses and results regarding what happened to the STS-107 crew. It encompasses the awareness that the crew had of events, crew actions in response to those events, and the events of lethal potential to which the crew was exposed. This analysis is meant to aid current and future spacecraft designers in developing vehicles and systems that incorporate the lessons learned from this accident.

The analysis is based on two types of data: objective data (e.g., medical forensic findings, on-board and downlinked vehicle instrumentation data, recovered on-board video data, and air-to-ground crew communications) and derived data (e.g., ballistics, thermal analysis, aerodynamic analyses, shock wave interactions, motion modeling, thermal injury mapping, and material testing). Although this section describes the best "data fit," it is subject to some inherent uncertainty due to the lack of data, both actual and experimental, on human exposure to conditions that are similar to the atmospheric entry environment.

Evidence indicates that the crew was aware of the LOC and was taking actions that were consistent with an attempt to recover hydraulic pressure. Once the depressurization event occurred, the crew was rendered unconscious or deceased and was unaware of the subsequent physical and thermal events. There is no evidence of crew error contributing to this accident.

[REDACTED.] Cause of death of the crew was unprotected exposure to high altitude and blunt trauma.

The first section discusses crew awareness. Next, medical findings are described by injury categories. A chronological sequence of the events with lethal potential is presented followed by a summary.

The following is a summary of the findings, conclusions, and recommendations from this section:

[REDACTED.]

> ***Conclusion L1-1.*** After loss of control at GMT 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.
>
> ***Recommendation L1-4.*** Future suit design should incorporate the ability for crew members to communicate visors-down without relying on spacecraft power.

Finding. Tissue samples revealed evidence of ebullism.[1]

> ***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.

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[1] Ebullism is defined as the formation of bubbles in bodily fluids under reduced environmental pressure.

Finding. The depressurization event occurred prior to the loss of circulatory function.

Finding. No conclusion could be drawn as to the rate of cabin depressurization based on medical evidence.

> ***Conclusion A8-1.*** Spacecraft accidents are rare, and each event adds critical knowledge and understanding to the database of experience.
>
> ***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.

Finding. None of the six crew members wearing helmets closed their visors.

> ***Conclusion L1-5.*** The depressurization incapacitated the crew members so rapidly that they were not able to lower their helmet visors.
>
> ***Recommendation L1-3/L5-1.*** Future spacecraft crew survival systems should not rely on manual activation to protect the crew.

Finding. One crew member appears to have been restrained only by the shoulder harness and crotch strap.

> ***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.

Finding. Injuries were consistent with the crews' upper bodies not being securely held to the seatbacks and with evidence indicating that the inertial reel straps were extended at the time of failure.

Finding. Injuries were consistent with the crews' upper bodies not being supported during the time of dynamic motion.

> ***Conclusion L2-3.*** Lethal injuries resulted from inadequate upper body restraint and protection during rotational motion.
>
> ***Recommendation L2-7.*** Design suit helmets with head protection as a functional requirement, not just as a portion of the pressure garment. Suits should incorporate conformal helmets with head and neck restraint devices, similar to helmet/head restraint techniques used in professional automobile racing.
>
> ***Recommendation L2-8.*** The current shuttle inertial reels should be manually locked at the first sign of an off-nominal situation.
>
> ***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.

Finding. Crew members experienced traumatic injuries in areas corresponding to the seat restraint system.

> ***Conclusion L3-4.*** The seat restraint system caused lethal-level injuries to the unconscious or deceased crew members when they separated from the seat.
>
> ***Recommendation L2-4/L3-4.*** Future spacecraft suits and seat restraints should use state-of-the-art technology in an integrated solution to minimize crew injury and maximize crew survival in off-nominal acceleration environments.
>
> ***Recommendation L3-1.*** 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.

Finding. No significant levels of carbon monoxide or cyanide (combustion by-products) were identified in any of the body fluids.

Finding. There was no evidence of thermal injury to the respiratory tracts.

> ***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.

[REDACTED.]

3.4.1 Crew awareness

3.4.1.1 *Preflight*

The crew members of STS-107 were placed in protective quarantine at the Johnson Space Center astronaut crew quarters on January 9, 2003 where their health was monitored by the assigned crew surgeons; no health issues were observed.

3.4.1.2 *Launch*

As reported in the CAIB Report, at 81.9 seconds mission elapsed time, post-launch video showed a piece of insulating foam striking the left wing of the orbiter. The remainder of the ascent phase went without incident; and the crew, which was unaware of the debris impact at this time, proceeded with the mission as planned.

3.4.1.3 *Orbital operations*

The *Columbia* orbiter performed satisfactorily on orbit and the crew worked well as a team, accomplishing all scientific goals. On Flight Day 8, the crew was notified via email about the foam strike, but was told it was “not even worth mentioning other than wanting to make sure that [the crew is] not surprised by it in a question from a reporter.” The capsule communicator (CAPCOM)[2] also relayed that there was “no concern for [reinforced carbon-carbon] or tile damage” and that there was “absolutely no concern for entry”. A video clip of the strike was included with the e-mail.[3] No changes in the mission profile were thought necessary or recommended by the shuttle Mission Management Team, and the entry was flown as originally planned.

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[2] The main individual with whom astronauts on a flight communicate with on the ground at the MCC in Houston.

[3] *Columbia* Accident Investigation Board Report, Volume I, August 2003, p. 36.

3.4.1.4 *Deorbit preparations*

The crew started the planned deorbit activities on Flight Day 16 (February 1, 2003). Per pre-mission planning, the crew began working items on the De-orbit Preparation checklist at GMT 09:15:30. At GMT 11:11:18, the flight deck crew entered a computer command (OPS 301) to initiate the *Pre-deorbit Coast* sequence. The Commander, Pilot, Mission Specialist 2, and Mission Specialist 4 seats were located on the flight deck. The Mission Specialist 1, Mission Specialist 3, and Payload Specialist 1 seats were located on the middeck. Figures 3.4-1 and 3.4-2 show the seating arrangements in the CM.

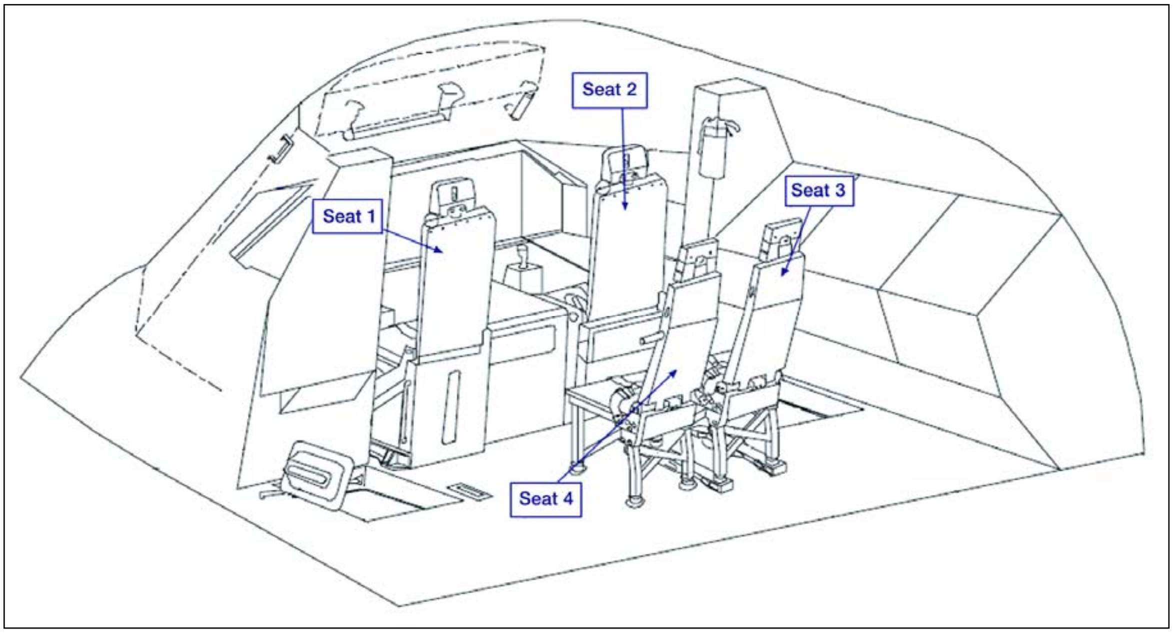

Figure 3.4-1. ***Depiction of the flight deck seats*.**

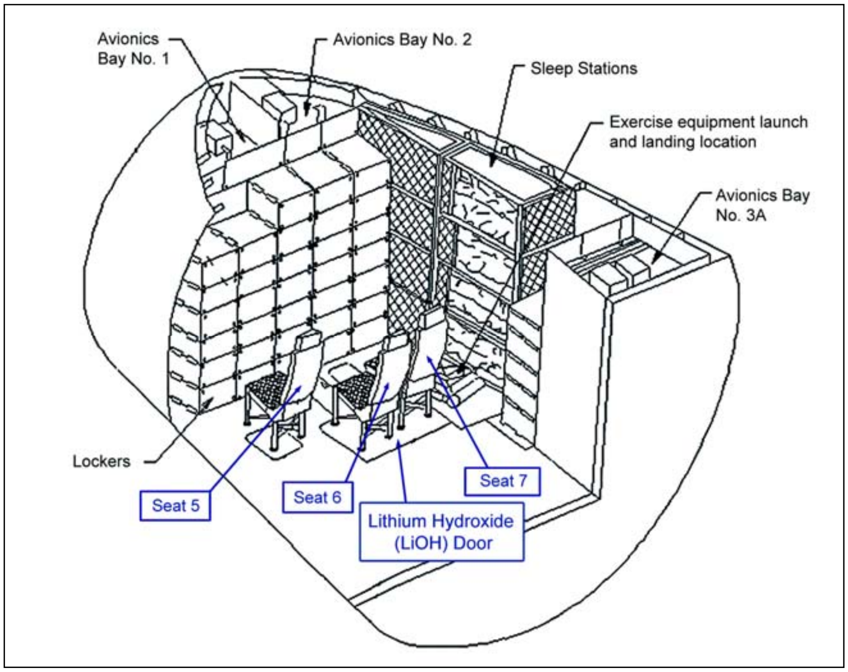

Figure 3.4-2. ***Depiction of the middeck seats*. [Adapted from the Shuttle Crew Operations Manual]**

Recovered middeck video, documenting events from approximately GMT 11:40:00 to GMT 12:10:00, shows the middeck crew members donning their ACESs and preparing the middeck for return. Figure 3.4-3 is a video frame-capture from the beginning of the tape showing the crew members in various states of landing preparation.

At GMT 12:10:10, the video ends with the middeck crew starting the escape pole installation procedure. Two of three crew members seen in the video were wearing their ACESs, but their gloves and helmets were not mated (typically not performed until after the crew member is strapped in their seat) and one crew member had not yet donned the ACES.

3.4.1.5 *Entry*

The initial phase of entry went without incident. A recovered flight deck video (figure 3.4-4), which runs from approximately GMT 13:35:34 to GMT 13:48:45, provides insight into the crew events taking place on the flight deck.

Figure 3.4-3. ***Video frame-capture from the recovered middeck video*.**

Figure 3.4-4. ***Video frame-capture from the recovered flight deck video*.**

The video shows that, at GMT 13:36:04, the CDR bumped the RHC accidentally (figure 3.4-5). Movement of the RHC out of the centered position caused the digital autopilot (DAP) to “downmode” from “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 CAPCOM in the MCC then requested the CDR to enter “another Item 27,” which is a command to fully recover the vehicle attitude from the bumped RHC. The CDR complied, and is heard on the recovered videotape commenting that he had forgotten that he needed to perform an Item 27 after a stick bump but had noticed the guidance needles “weren’t really down where they needed to be.” This indicates that the CDR was scanning the displays, noticing that the guidance needles were not centered after the stick bump, and was properly processing the information.

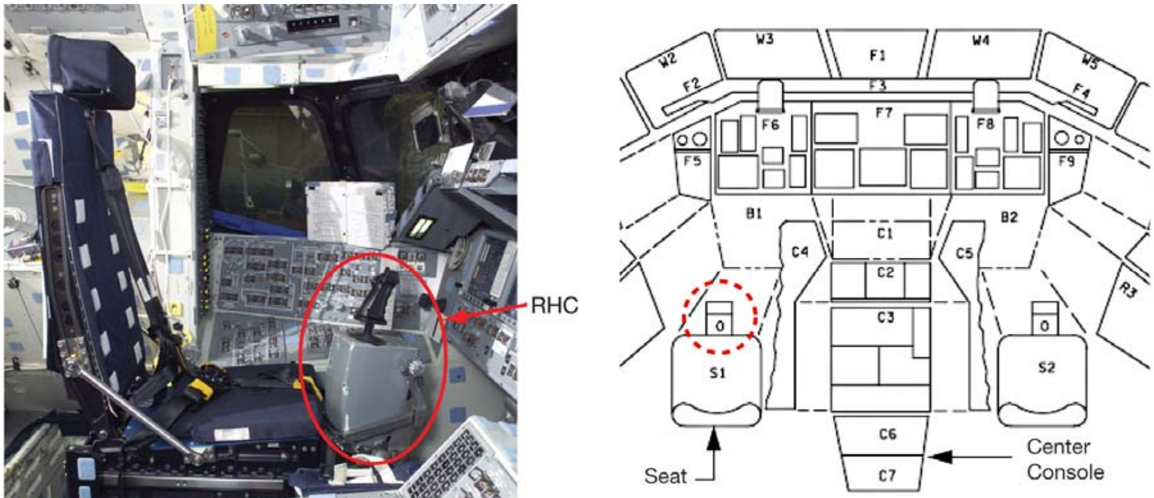

Figure 3.4-5. ***Location of the Commander's seat and the rotational hand controller*. [Left picture from a shuttle training mockup in the JSC Space Vehicle Mockup Facility, looking from starboard to port; right picture adapted from the Space Shuttle Systems Handbook, looking from aft to forward]**

At GMT 13:39:09, the CDR executed the OPS 304 command to load the computer software that was used to execute entry. The CDR and PLT both verified that the OPS 304 command was properly executed.

The CDR is next seen finishing a drink bag, as part of his required fluid-loading protocol,[4] and floating it back to a crew member for disposal. When the CDR went to pass the last drink bag to the crew member for disposal, that crew member requested that the CDR wait so that the crew member could finish donning the ACES gloves before the gravity levels increased. The video shows that the crew member had partially donned the gloves but did not mate the connecting rings to the ACES. Investigators, therefore, concluded that dealing with the disposal of the water bags and other loose items plus performing flight engineer duties (e.g., assisting the CDR and PLT with checklist items and throwing switches) caused the delay in configuring the ACES.

Recorded telemetry indicates that entry interface (EI) occurred at GMT 13:44:09. Upon observing the time cue for EI on the displays, the CDR states, "Just past EI." The crew then remarks on the flashes of plasma that are visible through the windows (these flashes are a normal part of entry). Shortly afterwards, the CDR requests that everyone perform suit integrity and communications checks. At GMT 13:45:24, three of the four flight deck crew members are observed performing successful communications and suit pressure integrity checks. One of the flight deck crew members could not participate in the suit pressure integrity check since that crew member's gloves were not completely donned at this time.[5] After completion of the check, a crew member asked the CDR whether the crew members were to keep their visors down after the test. The CDR replied, "No."

It should be noted that due to a limitation of the orbiter-suit system, the normal configuration for entry is with the visors up. If the crew keeps the visors down and the O_2 flowing for entry, the O_2 that is being vented from the ACES would increase the cabin O_2 concentration to a level that would violate the hazard controls for fire prevention. In addition, flown astronauts and crew trainers who were interviewed concerning this indicate that the visors also restrict the crews' field of vision and can interfere with nonverbal communication. With the visors down, inter-crew verbal communication is dependent on orbiter main power; there is no battery backup. A loss of power requires either verbal communications with the visor open or nonverbal communications, which can be hindered by having the visor down.

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[4] Fluid loading is one of the medical countermeasures that is used to mitigate orthostatic intolerance due to the fluid shift and blood plasma level changes that are experienced during space flight and the return to a gravity environment.
[5] The gloves must be mated to the suit for the ACES to pressurize.

By the end of the recovered video at GMT 13:48:45, plasma is visible through the windows (this is normal for this phase of entry) and three of the four flight deck crew members are observed with their ACES suits and helmets on, visors open, and gloves mated and are seated with restraint harnesses on. One crew member was suited with helmet on, visor open, left glove on but not mated, and right glove off and was seated with restraint harness on. There was no indication that the crew was aware of any problems with the orbiter.

Analysis of the telemetry from the O_2 supply system at GMT 13:54:30 shows a signature that is consistent with a second suit pressure check and/or g-suit pressurization by three to five crew members. Since no video or audio was recovered from this timeframe, it is unknown which crew members performed this check. It is possible that the flight deck crew member who was not ready for the first suit and communications check participated in this one.

Between GMT 13:58:39 and GMT 13:58:56, four left tire pressure fault messages were recorded by the Backup Flight Software. These messages were annunciated on the crew displays and accompanied by an audio 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. One of the failure scenarios that 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 of the tire pressure sensors on the left main gear only. So the indications that the crew saw would be familiar, although different from what they saw in training. At GMT 13:58:48, the crew began a call to the MCC but that 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 expected.

At GMT 13:59:06, 10 seconds after the fourth of four tire pressure fault messages, telemetry indicated that 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 3.4-6), 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.

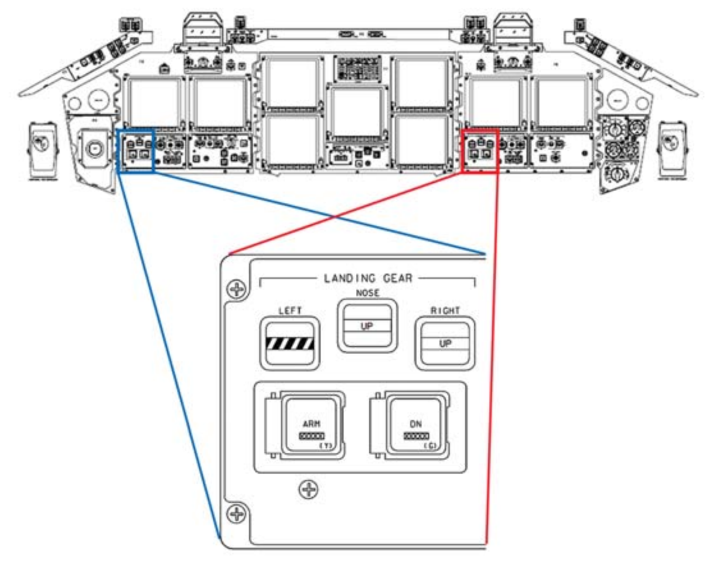

Figure 3.4-6. ***Landing gear indicator panel, identical on both sides of the flight deck forward display panels.*** **Left indicator showing "barber pole" (indeterminate position). [Adapted from the Space Shuttle Systems Handbook]**

Twenty-six seconds after the left main gear "talk-back" displayed the barber pole, the last audio transmission from the crew, "Roger, uh …," was received (GMT 13:59:32). The CAPCOM replied to the partial transmission to let the crew know that the flight controllers saw the tire pressure fault messages and did not "copy" the last transmission.

Analysis of RGPC data indicated that the Primary Avionics Software System recorded a fault message that was associated with the removal of Flight Control System (FCS) Channel 4 (CH4) from the control loop at GMT 13:59:33. This message would result in the annunciation of a Master Alarm. While there is no crew action associated with this frequently trained FCS fault message other than to perform a message reset, the crew likely 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 system fault that could account for all of these messages.

3.4.1.6 *Loss of control*

Based on engineering analysis and modeling (see Section 2.1), hydraulic pressure, which is required to move the flight control surfaces, was lost at approximately GMT 13:59:37. At that time, the Master Alarm would have sounded for the loss of hydraulics and the crew would have become aware of a serious problem. It is probable that the loss of hydraulic pressure as a result of the damage to the left wing resulted in an uncontrolled pitch-up and loss of vehicle control. A visual simulation of the pitch-up associated with this LOC scenario is shown in figure 3.4-7.[6] The flight deck crew would have been the first to be aware of this owing to the changing light levels, the view of the horizon through the windows, and the information on the flight displays. Space-adapted crews are reported to be very sensitive to motions and G-loads. As the orbiter motion dynamics began to increase, all of the crew members likely would have sensed this motion and been aware of the off-nominal[7] situation. At GMT 13:59:46, a "Roll Ref" alarm message was annunciated, indicating that the orbiter had exceeded the limits of the entry drag profile. In conjunction with the hydraulics messages and the unusual motion of the orbiter, the "Roll Ref" message would have reinforced the fact that a serious problem had developed.

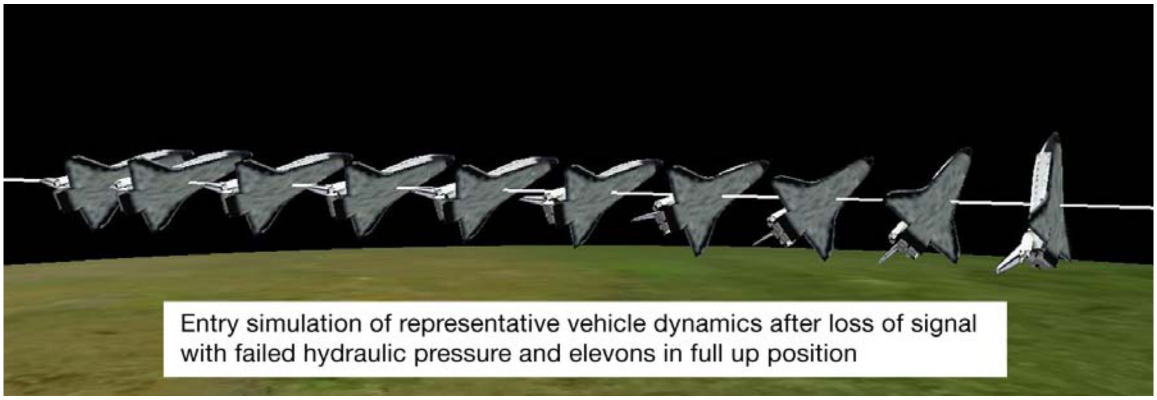

Figure 3.4-7. ***Sequence (1-second intervals) showing a simulation of orbiter loss of control pitch-up from GMT 13:59:37 to GMT 13:59:46*****. White line indicates vehicle trajectory relative to the ground.**

Based on the orbiter LOC entry simulation, the representative motion showed that the predominant orientation of the orbiter remained "belly-into-the-wind" with large excursions in pitch, roll, and yaw. This

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[6] Vehicle dynamics are based on aerodynamic modeling using orbiter aerodynamic models and accelerometer data.
[7] Outside of acceptable limits.

motion can be characterized[8] as a slow (30 to 40 degrees per second), highly oscillatory spin. Analysis of the accelerations describes the overall motion of the crew as a swaying to the left and the right ($\pm Y_{Crew}$ axis, eyeballs right and left[9]) combined with a pull (deceleration) forward ($+X_{Crew}/-G_x$, eyeballs out) against the seat harness straps. Z-axis accelerations pushed the crew (vertically) down into the seat ($-Z_{Crew}/+G_Z$ axis, eyeballs down). Figure 3.4-8 shows a depiction of the sign convention and the resulting motion for accelerations.

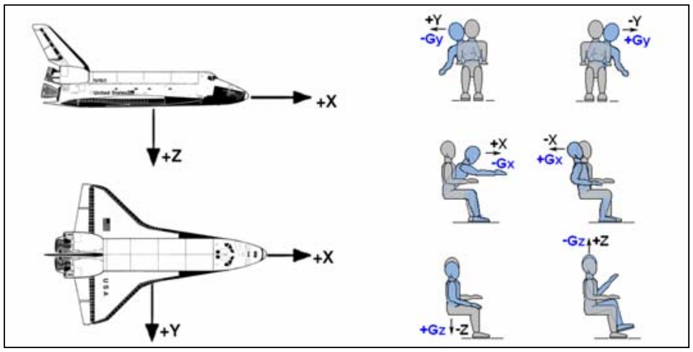

Figure 3.4-8. ***Depiction of the orbiter and crew member axes conventions.*** **(Note: Z axis sign convention for crew is opposite from orbiter.)**

Figure 3.4-9 shows representative loads based on modeling in all three axes, including the effects of increasing rotational loads. Models showed that accelerations were initially low, and peaked between 2 G and 3.5 G by the time of the CE (separation of the forebody from the midbody). The dashed black lines (upper and lower) on the chart indicate human performance limits based on NASA-STD-3000.[10] The representative loads, which are based on modeling, were well within these human performance limits.

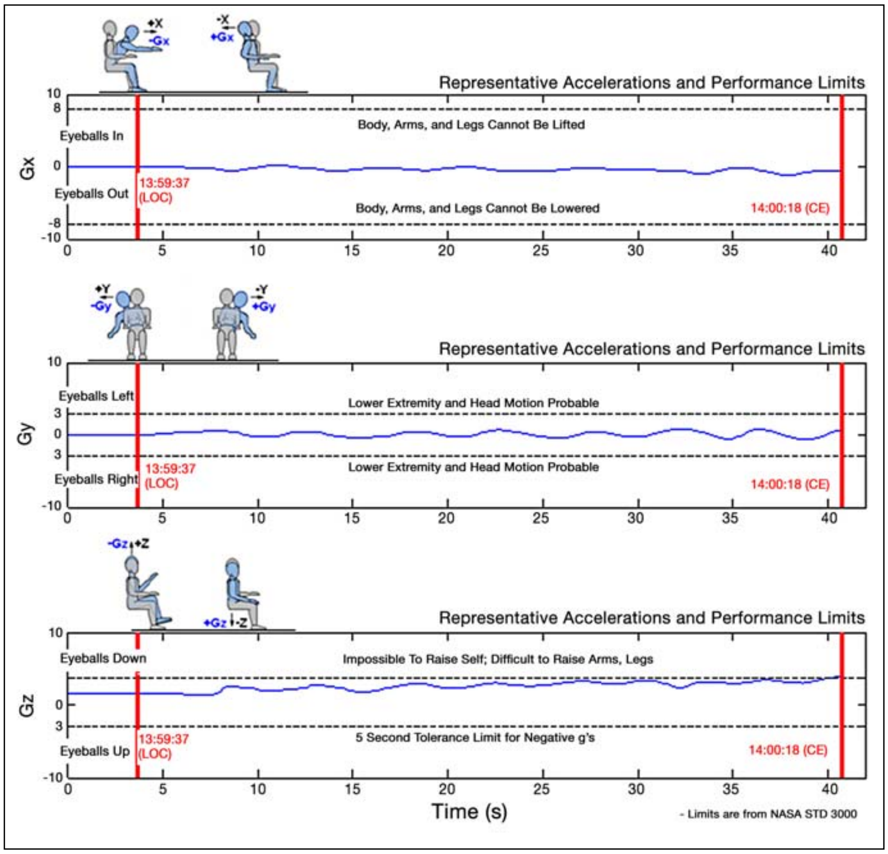

Figure 3.4-9. ***Representative accelerations from modeled motion analysis from loss of control to the Catastrophic Event*** **(see Section 2.1). Black dashed lines show human performance limits.**

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[8] See descriptors in Flight Test Demonstration Requirements for Departure Resistance and Post-Departure Characteristics of Piloted Airplanes, Air Force MIL-F-83691B, Change 1, May, 31, 1996.

[9] In the crew axis convention, the physiological reaction is in the opposite direction of the acceleration vector; i.e., an acceleration in the $+X_{Crew}$ direction pushes crew members into their seat (i.e., forces the crew in the –X direction, resulting in a +Gx reaction, also known as "eyeballs in").

[10] NASA-STD-3000, *Man-Systems Integration Standards*, Volume I, Section 5, Revision B, 1995.

Post-flight analysis of crew equipment revealed that none of the six recovered seat restraint inertial reel mechanisms locked prior to failure. This resulted in the upper bodies of the crew members being unrestrained. Loads of these magnitudes and rates would not be expected to produce crew injuries or prevent the crew from performing most actions. However, these loads, augmented by the loose harness configuration and mass of the crew worn equipment, would require the crew members to brace themselves.

As the LOC scenario progressed, the dynamic motion environment would be expected to increase the susceptibility to motion sickness and disorientation, particularly in those who had no visual reference (i.e., those on the middeck) or who were novice space flyers.

Based on seat debris and medical analyses, one crew member was not fully restrained before loss of consciousness. Only the shoulder and crotch straps of this crew member 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 indicates 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 attempting to become seated and restrained when the LOC dynamics began. Given the motion of the orbiter, the lap belts hanging down between the closely spaced seats would have been difficult to locate and grasp.

RGPC data indicate that between GMT 14:00:02 and GMT 14:00:04, the vehicle was experiencing a right yaw rate of at least 21 deg/sec, which was the sensor limit, and a right roll rate of 7 deg/sec, followed by a left roll rate of 23 deg/sec that was associated with a nose-down pitch rate of 5 deg/sec (because of possible inertial measuring unit saturation, these values may be inaccurate). All available data indicate that the crew cabin environment (temperature, atmosphere) and systems (APUs, fuel cells, lighting, etc.) were still generally nominal; however, the hydraulic pressures and quantities were indicating zero.

RGPC data show that a message reset was performed by the CDR or PLT sometime between GMT 13:59:37.4 and GMT 14:00:05. This action is a normal 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 and GMT 14:00:03.6, triggering a “DAP DOWNMODE RHC” message at GMT 14:00:03.637. This message was likely due to a crew member bumping the RHC out of the null position due to the oscillatory motion of the orbiter. At GMT 14:00:03.678, the orbiter autopilot was returned to the AUTO mode. Returning the DAP to AUTO mode requires either the CDR or the PLT to press one or two buttons that were 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.

Recovered debris revealed that the APU Operate switches on flight deck panel R2 were in positions that were consistent with an attempted restart of two of the three APUs[11] (figures 3.4-10 and 3.4-11). The hydraulic circulation pump paddle switches for the two hydraulic systems corresponding to the two APUs were also turned on. While turning on the hydraulic circulation pump is not in any crew emergency checklist, the pump can provide some hydraulic pressure, and this action shows good systems knowledge by the crew members as they responded to the limited information presented to them and worked to restore orbiter control. The APU Operate switches are “lever-lock” switches that require three actions to change the position. They must be (1) pulled outwards to disengage the switch lever from the lock, (2) moved to the desired position, and (3) released (figure 3.4-12). The switches are spring-loaded to hold them in the detents. The RGPC data indicate that all of these switches were in the nominal configuration up to GMT 14:00:04.826. These findings strongly suggest that despite the very dynamic vehicle motion, the PLT was still capable of taking appropriate actions to attempt a recovery of the hydraulic pressure by performing an APU restart at some time after GMT 14:00:04.826. Based on the panel R2 switch throws and the lack of visors being lowered, it is probable that the crew never realized that the vehicle LOC situation was unrecoverable and had become a survival situation.

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[11] APUs supply the hydraulic pressure to the flight control surfaces.

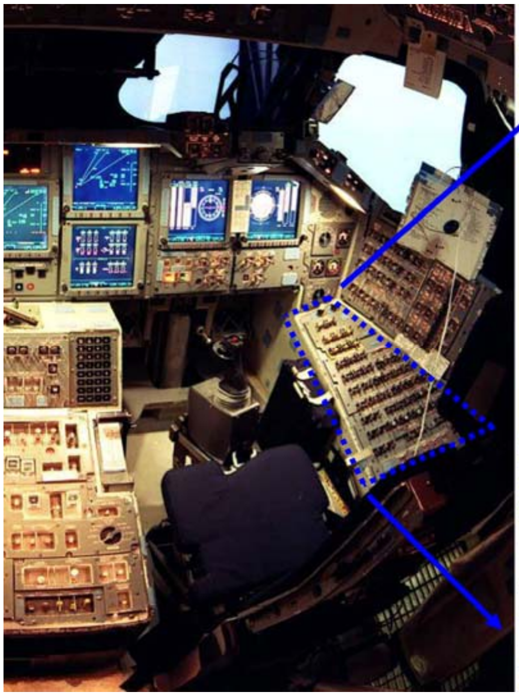


Figure 3.4-10. ***Location of the R2 panel*****.** **[Picture from the Shuttle Training Simulator]**

Figure 3.4-11. ***Recovered R2 panel from*** **Columbia** ***(after it was unfolded)*****. Pink dots are above the out-of-configuration switches.**

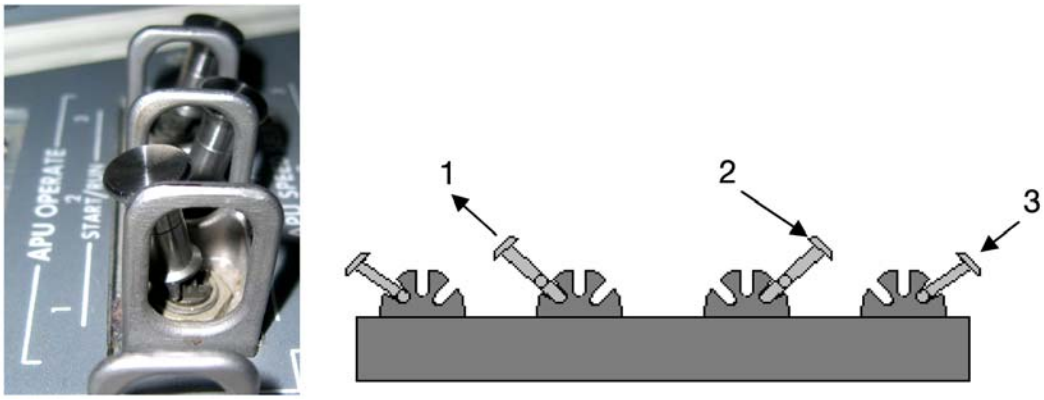


Figure 3.4-12. ***Operation of the lever-lock controller switches*** **(side view).**

Analysis of several sources of information indicates that the forebody separated from the midbody at or shortly after GMT 14:00:18. It is unknown what accelerations occurred during separation of the orbiter forebody from the midbody; however, ballistic analysis estimates that the translational G that was experienced by the orbiter forebody at the CE decreased from approximately 3.5 G to 1 G. It is also likely that there were additional translational and rotational loads acting on the crew at this time. Analysis of structural debris supports that multiple small impacts occurred between the forward fuselage (FF) and the CM, including in the area of middeck Volume E (figures 3.4-13a and 3.3-13b).

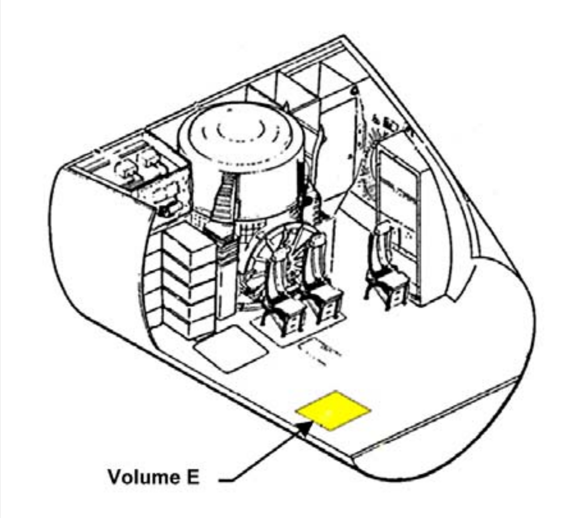
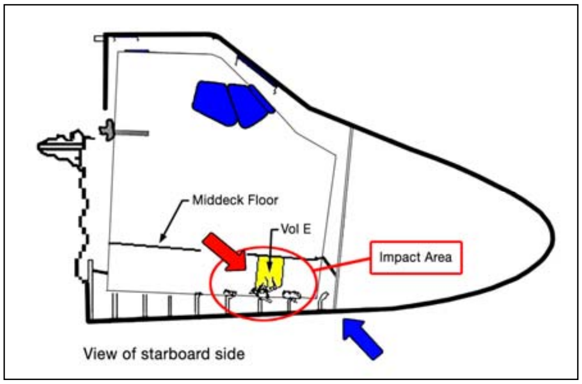


Figure 3.4-13a. ***View of middeck floor and Volume E, looking aft*.**

Figure 3.4-13b. ***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*.**



[REDACTED.]

[REDACTED. Figures 3.4-14a through 3.4-13d.]

[REDACTED.]

> ***Conclusion L1-1.*** After loss of control at GMT 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.

When the vehicle forebody separated from the rest of the vehicle, all resources from the midbody were lost, including power from the fuel cells. This resulted in the loss of all powered lighting, crew displays, radio, intercom, ventilation, and main O_2 supply. The flight deck would still have had light entering the cabin from the windows as well as from the activated chemical light sticks on each arm of the ACES and positioned throughout the cabin. The middeck would have been in total darkness except for some light filtering through the two inter-deck openings and from the activated chemical light sticks. This would indicate a survival situation.

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

It was concluded that the crew was incapacitated and incapable of action at or shortly after the CE. As a survival situation, one of the first crew actions that would be expected after the CE would be for the crew to manually lower their visors and turn on their EOS. As detailed in Section 3.2, none of the crew members wearing helmets closed their visors. The accelerations derived from the representative motion modeling (figure 3.4-10) would not have prevented this action. Since they did not, it was concluded that the crew members were incapacitated due to other factors. This will be discussed in the following section.

This concludes the discussion of crew awareness. Injury classifications are discussed next.

3.4.2 Injury classifications

3.4.2.1 *Exposure to high altitude*

[REDACTED.] Given the level of tissue damage, the crew could not have regained consciousness even with re-pressurization. Survival was possible, but not likely, even with immediate and extensive medical intervention at this point. Although respiration would cease after depressurization, circulatory functions can exist for a short period of time.

[REDACTED.]

Finding. Tissue samples revealed evidence of ebullism.

> ***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.

[REDACTED.]

Finding. The depressurization event occurred prior to the loss of circulatory function.

There is very limited data on human exposure to space-equivalent vacuum. **[REDACTED.]** Although the *Soyuz 11* cabin depressurization was relatively slow (reportedly taking more than 3.5 minutes to depressurize to 0 psi), it was stated that the depressurization was fatal to the crew in roughly 30 seconds.[12] Because the exact scenario cannot be positively identified, no conclusions with respect to the rate or timing of cabin depressurization can be made from the medical findings. **[REDACTED.]**

Depressurization events in aviation have led to extensive studies on “time of useful consciousness (TUC).” TUC is generally based on the remaining amount of O_2 in the tissues that is permitting brain functions to continue. Various factors affect the TUC (i.e., exertion, depressurization rate, pre-exposure O_2 partial pressure, G-loads, adrenaline loading, etc.). Since the shuttle cabin uses air, the pre-exposure O_2 partial pressure was only 21% O_2 (the normal for sea-level). Based on debris and structural evidence, the most likely time for the initiation of cabin depressurization was at orbiter breakup (CE) at GMT 14:00:18. Based on video evidence, the depressurization was complete no later than GMT 14:00:59 (figure 3.4-15), and likely much earlier (see Section 2.3). This corresponded to an altitude range of 181,000 feet to approximately 140,000 feet. Traditional aviation TUC would correlate a rapid depressurization at these altitudes to a TUC of 12 seconds.[13] This would have been enough time for the crew to close their visors and initiate O_2 flow, and yet they did not (see Section 3.2).

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[12] “A History of the Apollo-Soyuz Project, Midterm Review.” http://history.nasa.gov/SP-4209/ch8-2.htm.

[13] *Joint Aerospace Physiology, Air Education and Training Command/Bureau of Medicine and Surgery*, February 1998.

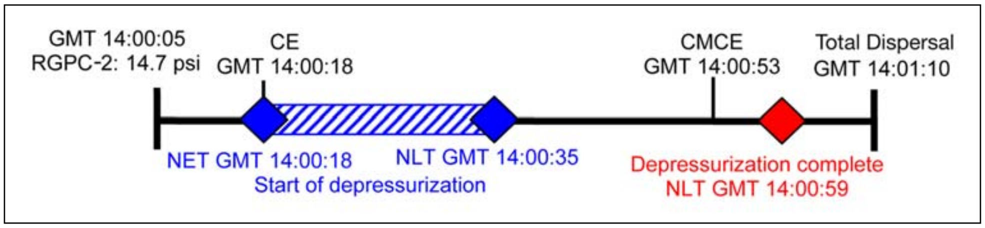

Figure 3.4-15. ***Cabin depressurization timeline*.**

However, additional research discussed in *Joint Aerospace Physiology, Air Education and Training Command/Bureau of Medicine and Surgery* shows that the physiological response to hypoxia during a rapid depressurization event at this extreme altitude (181,000 feet) would have reduced the conventional TUC interval by 50% (i.e., 12 seconds would have been reduced to 6 seconds). In addition to the depressurization effects, the physical exertion against the G-forces that the crew experienced at this time would further reduce the available metabolic O_2 reserves[14] and increase the CO_2 partial pressure. Also, NASA research data indicate that de-conditioned crews have a reduced tolerance to G-loads.[15] Further, anecdotal reports from accidental exposure to vacuum confirm much shorter periods of awareness as reported by survivors.[16]

The 51-L *Challenger* accident investigation showed that the *Challenger* CM remained intact and the crew was able to take some immediate actions after vehicle breakup, although the accelerations experienced were much higher as a result of the aerodynamic loads (estimated at 16 G to 21 G[17]). The *Challenger* crew became incapacitated quickly and could not complete activation of all breathing air systems, leading to the conclusion that an incapacitating cabin depressurization occurred.[18] By comparison, the *Columbia* crew experienced lower loads (~3.5 G) at the CE. The fact that none of the crew members lowered their visors[19] strongly suggests that the crew was incapacitated after the CE by a rapid depressurization.

From this time forward, the crew members would have been unconscious, totally unaware of events, and unable to brace against the loads. With the configuration of the ACES (i.e., visors up and three crew members without gloves donned), the depressurization was an event of lethal potential. Had the ACES been configured with the visors down and locked, gloves on, and EOS activated, the depressurization event by itself probably would have been survivable.

Finding. No conclusion could be drawn as to the rate of cabin depressurization based on medical evidence.

Finding. None of the six crew members wearing helmets closed their visors.

> ***Conclusion L1-5.*** The depressurization incapacitated the crew members so rapidly that they were not able to lower their helmet visors.
>
> ***Recommendation L1-3/L5-1.*** Future spacecraft crew survival systems should not rely on manual activation to protect the crew.
>
> ***Conclusion A8-1.*** Spacecraft accidents are rare, and each event adds critical knowledge and understanding to the database of experience.

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[14] Naval Aviation Survival Training Program, G-Tolerance Brief: *G-Tolerance Improvement Program*, 2004.

[15] K. V. Kumar and W. T. Norfleet, "Issues on Human Acceleration Tolerance After Long-Duration Space Flights," NASA Technical Memorandum 104753, October 1992.

[16] Description of Altitude Chamber Mishap, *Roundup*, Volume 6, No. 6, Jan. 6, 1967.

[17] JSC-22175, STS-51L, JSC Visual Data Analysis Sub-Team Report, Appendix D9, June 1986.

[18] Report from Dr. Joe Kerwin to Rear Adm. Truly, http://history.nasa.gov/kerwin.html, July 28, 1986.

[19] See Section 3.2 Crew Worn Equipment.

> ***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.

3.4.2.2 *Mechanical injuries*

Mechanical injuries were isolated to the period of time at which they most likely occurred, based on engineering analyses of motions and accelerations.

Pre-Catastrophic Event
[REDACTED.]

Catastrophic Event to Crew Module Catastrophic Event
A very dynamic motion environment existed after the CE (GMT 14:00:18); this environment became more intense as the CMCE (the breakup of the forebody) approached at GMT 14:00:53. Figure 3.4-16 shows representative loads on the unconscious or deceased crew members based on aerodynamic modeling of the forebody dynamics post-CE. The black dashed lines showing human performance limits[20] are for conscious crew members. Based on the conclusion that the rapid depressurization occurred at or close to the time of the orbiter forebody separation, the crew was unconscious or deceased and unable to brace against these loads.

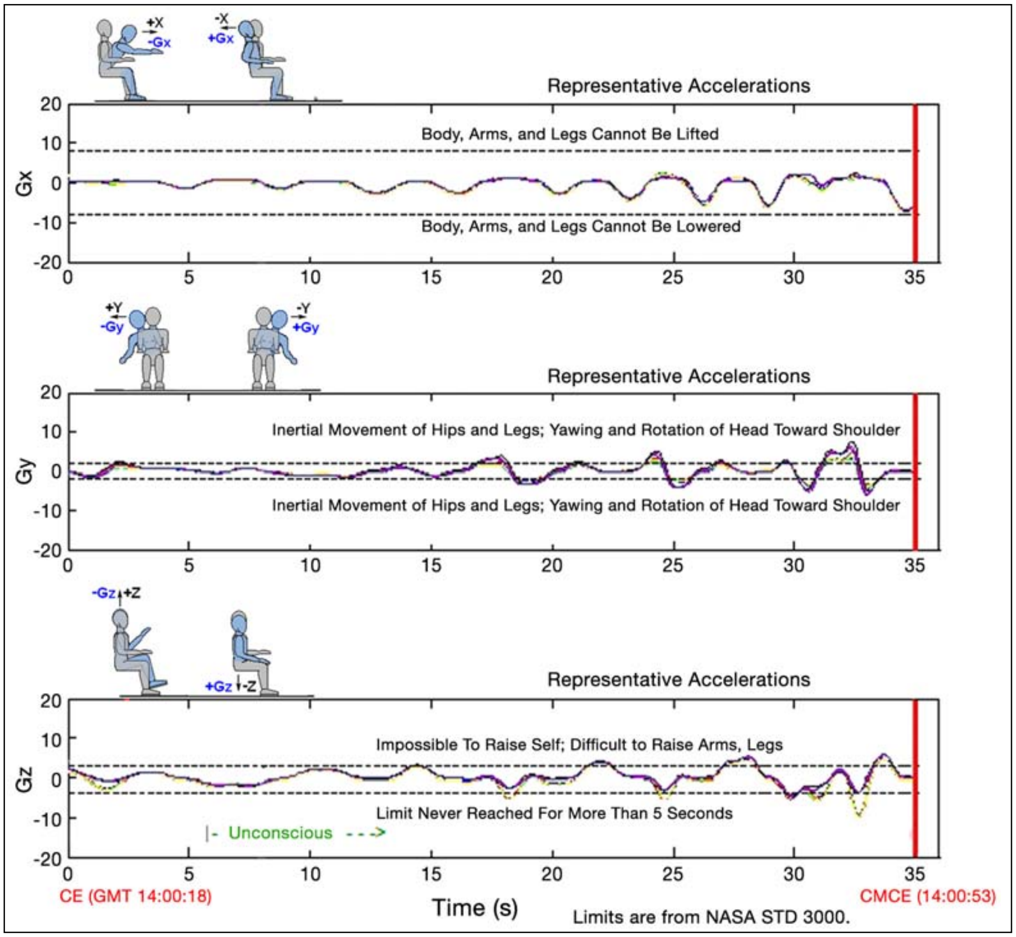

Figure 3.4-16. *Representative acceleration profiles from the orbiter breakup (Catastrophic Event) to the orbiter forebody breakup (Crew Module Catastrophic Event) based on aerodynamic modeling*. Black dashed lines show human performance limits.

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[20] NASA-STD-3000, *Man-Systems Integration Standards*, Volume I, Section 5, Revision B, 1995.

For the first 15 to 20 seconds, the modeled loads would not cause serious injuries to a conscious crew member who was capable of active bracing. An unconscious or deceased crew member would have been more susceptible to injury.

The crew is normally restrained in the seats by a five-point harness system (figure 3.4-17). A lap belt secures the lower torso. A crotch strap prevents “submarining.”[21] Two shoulder harnesses, which attach to an inertial reel via the inertial reel strap, secure the upper torso.

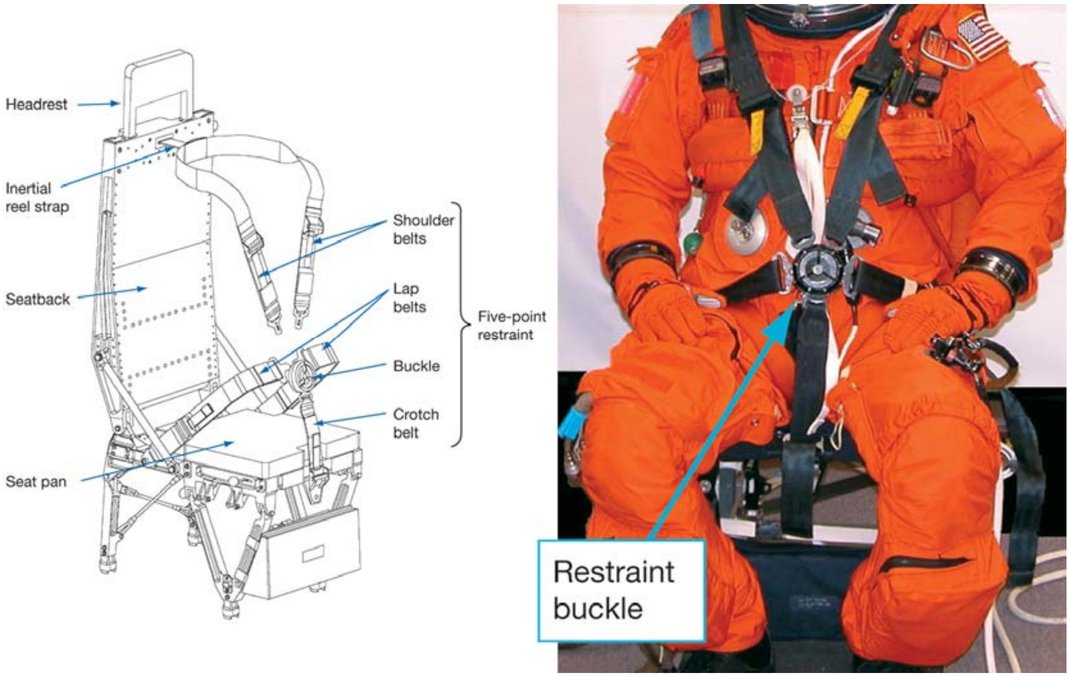

Figure 3.4-17. ***Detail of the five-point harness*.**

Engineering analysis of the STS-107 restraints indicates that most of the inertial reel straps were extended and did not lock or retract prior to failure of the straps. The inertial reels are normally unlocked to allow the crew to access displays and controls with a full range of motion. With the inertial reels unlocked, the crew members’ upper bodies were left unrestrained during the forebody dynamics. **[REDACTED.]**

Finding. One crew member appears to have been restrained only by the shoulder harness and crotch strap.

> ***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.

[REDACTED.]

Figure 3.4-18 provides a demonstration of an integrated seat/suit/crew member in entry configuration.

[REDACTED.] Figure 3.4-19 shows an interior view of an intact, pristine ACES helmet demonstrating exposed hardware. **[REDACTED.]**

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[21] “Submarining” is when the occupant slides forward and beneath the lap belt.

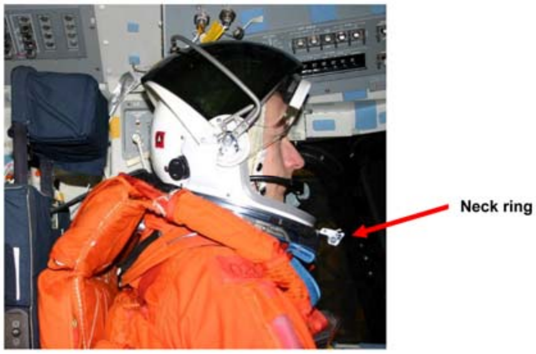

Figure 3.4-18. ***Demonstration of an integrated seat/suit/crew member in entry configuration*.**

Figure 3.4-19. ***Example of an intact, pristine advanced crew escape suit nonconformal helmet (not an STS-107 helmet)*.**

[REDACTED. Figure 3.4-20.]

Finding. Injuries were consistent with the crew's upper bodies not being securely held to the seatbacks and with the evidence indicating that the inertial reel straps were extended at the time of failure.

Finding. Injuries were consistent with the crew's upper bodies not being supported during the time of dynamic motion.

> ***Conclusion L2-3*.** Lethal injuries resulted from inadequate upper body restraint and protection during rotational motion.
>
> ***Recommendation L2-4/L3-4*.** Future spacecraft suits and seat restraints should use state-of-the-art technology in an integrated solution to minimize crew injury and maximize crew survival in off-nominal acceleration environments.
>
> ***Recommendation L2-7*.** Design suit helmets with head protection as a functional requirement, not just as a portion of the pressure garment. Suits should incorporate conformal helmets with head and neck restraint devices, similar to helmet/head restraint techniques used in professional automobile racing.

Recommendation L2-8. The current shuttle inertial reels should be manually locked at the first sign of an off-nominal situation.

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.

Crew Module Catastrophic Event

[REDACTED.] Engineering and ballistic analyses of the orbiter forebody failure indicate that the middeck separated prior to the flight deck. Crew members on the middeck separated along with the middeck accommodations rack, middeck lockers, sub-floor components, and Modular Auxiliary Data System/orbiter experiment data recorder – a scenario that is supported by debris plots (see Section 2.2). Based on structural design analysis, thermal damage, and position in the debris field, the flight deck "pod" and the CM aft bulkhead stayed intact for a longer time. The location of the recovered flight crew equipment, which is plotted in figure 3.4-21, supports the middeck departing prior to the flight deck.

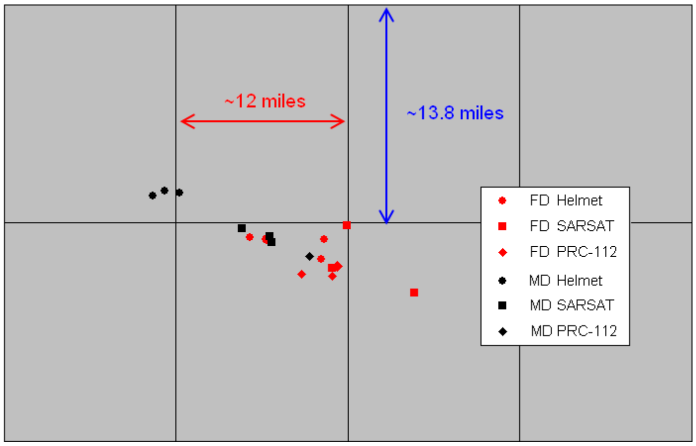

Figure 3.4-21. ***Ground location of the recovered flight crew equipment.***

[REDACTED.]

[REDACTED. Figure 3.4-22.]

[REDACTED.]

Finding. Crew members experienced traumatic injuries in areas corresponding to the seat restraint system.

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

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

Recommendation L3-1. 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.

3.4.2.3 *Thermal exposure*

[REDACTED.]

Finding. No significant levels of carbon monoxide or cyanide (combustion by-products) were identified in any of the body fluids.

Finding. There was no evidence of thermal injury to the respiratory tracts.

> ***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.

[REDACTED.]

[REDACTED. Figure 3.4-23.]

[REDACTED.]

The ambient absolute pressure condition at separation was approximately 0.03 psi.

3.4.3 Identified events with lethal potential

1. **The first event with lethal potential was depressurization of the CM, which started at or shortly after orbiter breakup.** Existing crew equipment protects for this type of lethal event, but operational practices and hardware limitations were such that the ACESs were not in a protective configuration. The current shuttle ACES relies on the crew to lower and lock the visor; therefore, complete protection from a depressurization event depends on a permissive environment. Design solutions that do not require crew action are achievable.

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.** Current shuttle seat and helmet design and operational practices did not protect the crew members from this lethal event. Complete strap-in with inertial reels locked would reduce the risk of injury/death; however, even in this configuration, the current seat-suit restraint system provides limited protection from dynamic G events (i.e., no lateral restraints, no control of extremity motion, and no head-neck support). Better restraint designs that include head-neck support (i.e., conformal helmets), extremity control, and spine support are achievable to reduce the risk of injury/death.

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.** Although the seat restraints (e.g., narrow width) played a significant role in the lethal mechanical injuries, there is currently no full range of equipment to protect for this event. The event was not survivable by any means currently known to the investigative team, with the exception of ensuring the integrity of the CM until the airspeed and altitude are within survival limits. This is not possible for the current space shuttle design; however, future vehicle designs incorporating a principle of “graceful degradation” and CM stabilization are possible.

4. **The fourth event with lethal potential was exposure to near vacuum, aerodynamic accelerations, and cold temperatures.** Although current crew survival equipment may be capable of protecting the crew, it is not certified to protect the crew above 100,000 feet. At the altitude and speeds at which the unconscious or deceased crew members departed from the CM, the environmental risks include lack of O_2, low atmospheric pressure, high thermal loads as a result of deceleration from high Mach numbers, shock wave interactions, aerodynamic accelerations, and exposure to cold temperatures. Existing shuttle

CEE is certified to protect up to 100,000 feet and 600 KEAS; however, the ACES is not designed to provide protection from high-temperature exposures. Anecdotal evidence from the survival of the pilot of an SR-71 mishap [*Aviation Week & Space Technology*, August 8, 2005, pp. 60–62] suggests that an intact, pressurized suit similar to the ACES can protect a crew member at an altitude of 78,000 feet and speeds of at least Mach 3 (~400 KEAS). More research is needed to close the survival gap. The only protection that is achievable is to ensure the integrity of the CM until the airspeed and altitude are within suit capability, which is currently not precisely determined.

5. **The final event with lethal potential was ground impact.** Existing shuttle CEE protects for ground impact with a parachute. However, the crew member 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. Military and sport parachuting solutions exist for opening parachutes independent of crew action.

3.4.4 Synopsis of crew analysis

The crew was unaware of an impending survival situation prior to the LOC. At the time of LOC, the flight deck crew was probably troubleshooting the caution-and-warning messages that were associated with the FCS fault, left main landing gear talk-back, and tire pressure messages. One of the middeck crew members was likely attempting to become seated and restrained under the dynamic LOC conditions. Until the fore-body separated from the orbiter vehicle, the crew was conscious and had not suffered serious injuries. Cause of death was unprotected exposure to high-altitude conditions and blunt trauma.

[REDACTED.]

Chapter 4 – Investigative Methods and Processes

4 Investigative Methods and Processes

This chapter discusses the methods and processes that were used during the Spacecraft Crew Survival Integrated Investigation team (SCSIIT) investigation. The SCSIIT activity was a continuation of the Crew Survival Working Group (CSWG), which was formed during the *Columbia* Accident Investigation Board (CAIB) investigation. The SCSIIT structure, personnel, and investigative process and lessons learned from that process are presented. The remainder of the chapter documents the methods, processes, and tools used by the SCSIIT for various analyses.

The following is a summary of the findings, conclusions, and recommendations for this section. Some recommendations are targeted at improving future NASA spacecraft crew survival accident investigation processes. Some are general suggestions for other organizations that may be tasked with such investigations in the future. In some cases, certain findings and conclusions reflect existing NASA policies and practices that were considered particularly effective and are included for emphasis for future investigators.

Finding. NASA priorities put emphasis on Return to Flight recommendations, long-term recommendations, and observations, in that order. As a result, the SCSIIT effort suffered from low priority relative to other program recovery efforts. Team members had to divide their time between the investigation work and the work for their home organization. This led to delays in completing the SCSIIT work and, in some cases, significant decrease in availability or complete loss of members of the SCSIIT.

Finding. Formally trained NASA-designated accident investigation personnel were not available for inclusion on the SCSIIT due to the intensity of safety and mission assurance work related to Return to Flight activities. SCSIIT members were selected primarily based on their technical knowledge and experience as well as availability. Many SCSIIT members did not have formal accident investigation training. The team preparation training sessions did not include the lengthy accident investigation training that is normally provided to NASA-designated investigators.

> ***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.
>
> ***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.

Finding. It was not uncommon to find several versions of documents supporting CAIB and CSWG work.

> ***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).

Finding. Concerns about public release of sensitive information relative to the crew creates obstacles to the performance of crew survival investigations.

> ***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.
>
> ***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.

Finding. The unique nature of the event, closeness of investigators to the accident victims, lack of previous exposure to the results of such tragedies, and need to keep information confidential created stress on some members of the investigation team. Counseling was provided, but the follow-up could be improved.

> ***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.
>
> ***Recommendation A7.*** To aid in configuration control and ensure data are properly documented, report generation must begin early in the investigation process.

Finding. CAIB/CSWG data were not cataloged. *Challenger* supporting data were mostly uncataloged and unorganized, limiting their usefulness for investigations. *Challenger* debris is unpreserved and inaccessible for analysis.

> ***Conclusion A8-1.*** Spacecraft accidents are rare, and each event adds critical knowledge and understanding to the database of experience.
>
> ***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.

Finding. Brightening events were easier to correlate between videos than debris-shedding events.

Finding. Sun angle illumination impacted the visibility of debris in video recordings.

Finding. Not all videos segments within compilations were individually categorized. Not all videos were re-reviewed once a better understanding of events had been gained.

> ***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.

Finding. The lack of a single, standard data format for latitude/longitude data and the potential ambiguity associated with the need to convert data of different formats resulted in possible data errors.

> ***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.

4.1 Background

Crew Survival Working Group

The CSWG was formed to support the CAIB on February 21, 2003 by authorization of the Johnson Space Center (JSC) Director. The CSWG was co-chaired by directors of the Space Life Sciences Directorate and the Engineering Directorate. Membership included personnel from Space Life Sciences, Engineering, Mission Operations, and Flight Crew Operations. Dr. James Bagian, a former astronaut and crew survival investigator for the *Challenger* accident, was the flight surgeon advising the CAIB. Dr. Bagian, together with Lt. Col. Don White of the Air Force Safety Center (an expert in crew equipment investigations), were the primary liaisons to the CAIB for the CSWG.

The CSWG was tasked with a limited charter: first, to determine the cause of death of the crew, second, to determine the “survival gap” (what equipment or procedures might have kept the crew alive), and, third, to pass the results to the CAIB. The CSWG performed aerodynamic, thermal, and structural analyses on individual debris items and an intensive study of the crew helmets and seats. In the process, team members made several trips to Kennedy Space Center (KSC) to view the crew module (CM) and helmet and seat debris. The CSWG developed a timeline that is consistent with the official CAIB timeline to derive the sequence of crew survival events based on the data.

Following recovery in the field, the crew remains were transported to the Air Force Institute of Pathology (AFIP) at Dover Air Force Base, Maryland for forensic and deoxyribonucleic acid (DNA) identification analysis. The Office of the Armed Forces Medical Examiner is the department within the AFIP that was responsible for determining the cause and manner of death for the crew of *Columbia*. The AFIP issued a report to the CSWG on the findings of the autopsies in May 2003, near the end of the CAIB investigation. Tissue samples were sent to the Federal Bureau of Investigation (FBI) for additional medical forensic analysis. Due to the timing of the AFIP report to the CSWG, little medical information was available to be discussed at the CSWG team level, and only a preliminary effort to integrate the medical findings with the engineering findings was possible. The need to fully integrate these findings was recognized by the CSWG team at the time.

Four types of data – aerodynamics, orbiter, forensic hardware, and forensic medical – were collected by the CSWG. These data were submitted to Dr. Bagian and Lt. Col. White on June 24, 2003 to assist them in preparation of the CAIB Report. The CAIB Report, Volume I, which was published in August 2003, contained a short discussion concerning crew survival.[1] Somewhat more detail was released in Volume V, which was published in October 2003.[2]

Unlike the other elements of the CAIB investigation, there was no NASA process for the administrative and financial framework of the CSWG investigation. As a result, when the CAIB investigation concluded, there were no resources available to continue the CSWG work although it was clear more work remained. The CAIB did not make any formal recommendations (only observations) regarding crew survival. Due to the priority of the Return to Flight program, CSWG activities were discontinued in October 2003. No report was published by the CSWG. Efforts were made to locate new funding and to identify an organization that would manage the continuation of the investigation and publish a report.

The SCSIIT was formed in October 2004 to resume the work of the CSWG and perform a multidisciplinary analysis of the *Columbia* fatal mishap that focused on the crew, crew equipment, and CM. The specific products include: the establishment of a comprehensive, computer-searchable body of information, the virtual reconstruction of the mishap, and a comprehensive report that provides valuable understanding and information for the design of crewed space vehicles and crew safety equipment.

To learn how improvements to crew survival could be made in the future, the following questions needed to be answered:

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[1] *Columbia* Accident Investigation Board Report, Volume I, Section 10.2, Crew Escape and Survival, August 2003.
[2] *Columbia* Accident Investigation Board Report, Volume V, Appendix G.12, Crew Survivability Report, October 2003.

- What events occurred that had lethal potential for the crew, even after the crew became deceased?
- How did the CM lose structural integrity?
- How did the crew equipment perform in the pressure, thermal, and acceleration environments that were experienced by the crew?
- What operational insight did the crew members have into the events that occurred, and was their training appropriate and adequate for the circumstances encountered?

4.2 Spacecraft Crew Survival Integrated Investigation Team Structure and Personnel

Because the SCSIIT investigation was mainly concerned with crew survival, the team had a "crew-centric" focus. Shuttle crew members are surrounded by layers of protection, with the crew equipment being the closest layer, the CM being the next layer, and the vehicle being the outermost layer (figure 4-1).

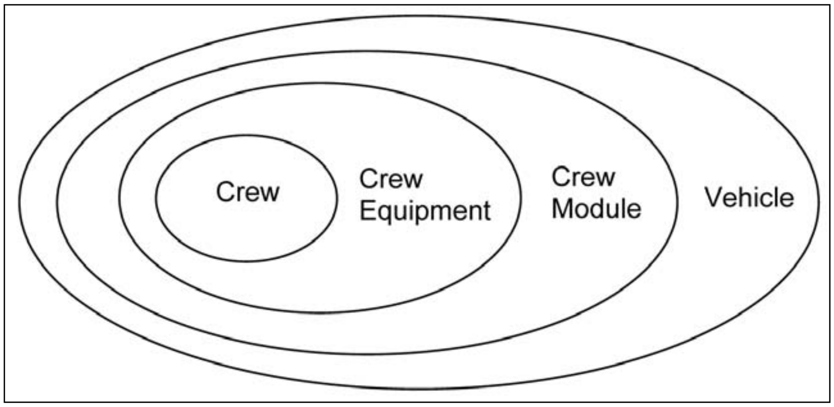

Figure 4-1. ***Concentric layers of protection for space shuttle crew members*.**

After it was decided that the crew and the three "layers" would be used as functional areas of focus for the SCSIIT investigation, four teams were formed. These teams were highly interdependent in the development and sharing of information.

1. The Vehicle Team was responsible for determining the dynamics of the vehicle from loss of control (LOC) until the vehicle breakup to ascertain the dynamics that the crew members experienced. This team determined the vehicle breakup sequence and the motion of the intact orbiter and the free-flying forebody, and performed all ballistics analysis on debris. Additionally, this team performed most of the thermal analyses.

2. The Crew Module Team was responsible for determining the CM environments (acceleration, thermal, and pressure) until CM breakup to ascertain the environments that the crew members experienced. This team also determined the CM breakup sequence.[3]

3. The Crew Equipment Team was responsible for determining the performance of the crew equipment (crew worn equipment, seats, etc.) to ascertain how the equipment enhanced or worsened the crew survival probabilities. Results of analysis on crew equipment were used by the Crew Module and Crew Teams to aid their analyses.

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[3] Prior to the completion of the investigation, the Crew Module Team lead had to return to his "home" organization. The Crew Module Team was essentially dissolved and its responsibilities were spread to the other three sub-teams.

4. The Crew Team was responsible for analyzing crew awareness during the mishap and the causes of deaths of the crew members, and identifying the threats to crew survival. Analysis of crew injuries was used by the vehicle and crew equipment teams to aid in developing their conclusions.

The SCSIIT management structure is shown in figure 4-2.

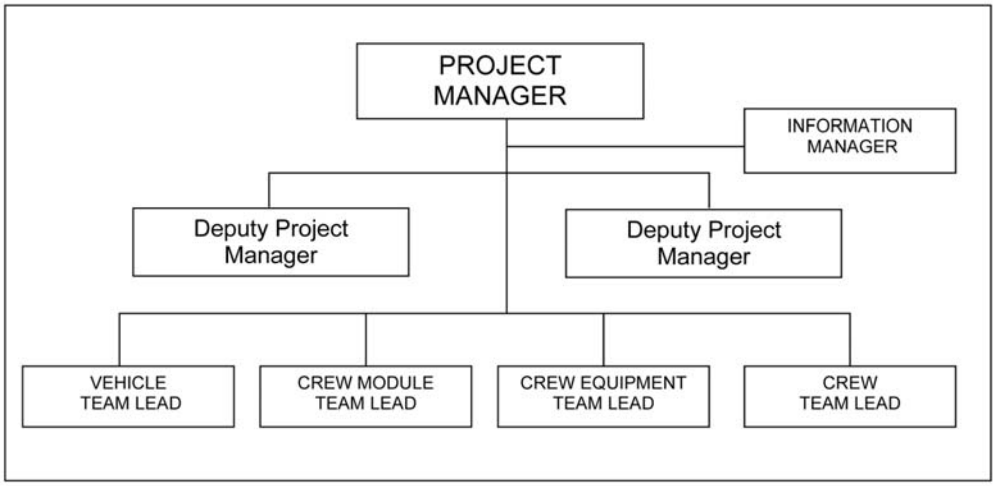

Figure 4-2. ***Management and leadership structure*****.**

4.2.1 Team membership

Potential SCSIIT members were identified based on previous association with the CAIB and CSWG and experience in the disciplines that were necessary to conduct this investigation. Selection was made considering an individual's area of knowledge, experience, interest, and availability. The team members were expected to divide their time between the SCSIIT project tasks and their "home" organization's tasks. At times, the home organization's work had deadlines requiring work to be prioritized over SCSIIT work. This led to delays in completing the SCSIIT work and, in some cases, significant decrease in availability or complete loss of members of the SCSIIT. It is recommended that personnel on future investigation teams be temporarily "released" from their "home" organizations to be free to work full time for the investigation organization.

Finding. NASA priorities put emphasis on Return to Flight recommendations, long-term recommendations, and observations, in that order. As a result, the SCSIIT effort suffered from low priority relative to other program recovery efforts. Team members had to divide their time between the investigation work and the work for their home organization. This led to delays in completing the SCSIIT work and, in some cases, significant decrease in availability or complete loss of members of the SCSIIT.

> ***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.

SCSIIT members were assigned to lead each of the four teams. The team lead was responsible for coordinating the analyses performed by that team and documenting the results. SCSIIT members were generally assigned to one team but often supported other teams when their expertise was called for. Although represented in figure 4-2 as a hierarchical team, the SCSIIT functioned as a highly integrated group with multiple interactions among the teams. This functional organization and the interactions among teams are shown in figure 4-3.

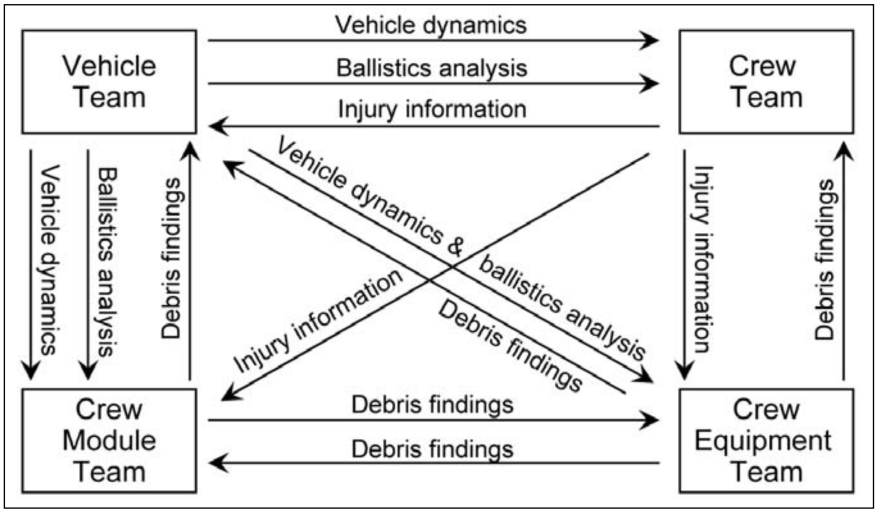

Figure 4-3. ***Functional organization of the Spacecraft Crew Survival Integration Investigation Team*****.**

The principal SCSIIT members and their respective home organizations, backgrounds, and responsibilities are listed in Table 4-1.

Table 4-1. ***Principal Spacecraft Crew Survival Integration Investigation Team Members***
(*Denotes SCSIIT members who were on the CSWG)

SCSIIT Member[4]	Organization	Background	Responsibilities
Dr. Gregory Hite	Shuttle and Exploration Division, Safety and Mission Assurance Directorate (retired 12/07)	Crew Survival	Project Manager
Dr. Nigel Packham	Safety and Mission Assurance Directorate	Safety and Life Sciences	Project Manager
Col. (ret) Pam Melroy, United States Air Force (USAF)*	Astronaut Office, Flight Crew Operations Directorate	Test Pilot, Shuttle Pilot Astronaut	Deputy Project Manager
Dr. Craig Fischer*	Space Life Sciences Directorate (retired 12/06)	Flight Surgeon and Pathology	Deputy Project Manager/ Crew Team Lead
Chrystal L. Hoelscher, Science Applications International Corporation (SAIC)	Shuttle and Exploration Division, Safety and Mission Assurance Directorate	Information/Knowledge Management and Database Administration	Information Management
Ellen Braden	Aeroscience and Flight Mechanics Division, Engineering Directorate	Aerodynamics and Flight Mechanics	Vehicle Team Lead
Mark Adams, United Space Alliance (USA)	Vehicle Integration Test Office, Flight Crew Operations Directorate	Shuttle Vehicle Integration Test Office	Crew Module Team Lead
David J. Pogue	EVA[5], Robotics and Crew Systems Operations Division, Mission Operations Directorate	Crew Systems and Crew Escape Equipment Operations Instructor and Flight Controller	Crew Equipment Team Lead
Eric Flagg, SAIC	Shuttle and Exploration Division, Safety and Mission Assurance Directorate	Military Pilot	Safety and Mission Assurance

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[4] With the exception of Duke Tran from Boeing/Palmdale, California, all personnel were based at JSC in Texas.
[5] EVA = extravehicular activity.

Table 4-1. ***Principal Spacecraft Crew Survival Integration Investigation Team Members*** **(Continued)**
(*Denotes SCSIIT members who were on the CSWG)

SCSIIT Member[6]	Organization	Background	Responsibilities
Joe Hamilton	Habitability and Environmental Factors Division, Space Life Sciences Directorate	Military Pilot	Virtual Reconstruction / Concept Evaluation Laboratory (CEL)
Kandy Jarvis*, Lockheed Martin Space Operations/Mission Services (LMSO/LMMS)	Human Exploration Science Office, Astromaterials Research and Exploration Science Directorate	Orbital Debris and Planetary Astronomy	Video and Debris Analysis
Dennis Pate, SAIC	Shuttle and Exploration Division, Safety and Mission Assurance Directorate	Human Factors	Timeline and Crew Awareness
Duke Tran, Boeing	Boeing/Palmdale	Senior Orbiter Structures Designer	Orbiter Structural Analysis

The SCSIIT team principals called on other individuals for analysis and information. These individuals are listed in Table 4-2.

Table 4-2. ***Individuals Supporting the Principal Spacecraft Crew Survival Integration Investigation Team***
(*Denotes SCSIIT members who were on the CSWG)

Name[7]	Organization
Ketan Chhipwadia*	Crew and Thermal Systems Division, Engineering Directorate
Katie Boyles Lee Bryant* Peter Cuthbert	Aeroscience and Flight Mechanics Division, Engineering Directorate
Lynda R. Estes Jeremy Jacobs* Kenneth Wong* Leslie Schaschl Brian Mayeaux	Structural Engineering Division, Engineering Directorate
Curtis Stephenson	Crew and Thermal Systems Division, Engineering Directorate
William Sarles, SAIC Paul Wilson, SAIC	Shuttle and Exploration Division, Safety and Mission Assurance Directorate
Robert Behrendsen, Barrios Technology (BAR) J. Lynn Coldiron, USA Adam Flagan, USA	EVA, Robotics, and Crew Systems Operations Division, Mission Operations Directorate
Laurie J. Bergman, Tietronix Software, Inc. Richard D. Delgado Jose Dobarco-Otero, Jacobs Technology (ESCG) William Rochelle,*[8] ESCG Ries Smith, ESCG	Space Life Sciences Directorate
Sudhakar Rajulu Kurt G. Clowers, Muniz Engineering (MEI) Sarah Margerum, LMSO Richard Morency	Habitability and Environmental Factors Division, Space Life Sciences Directorate

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[6] With the exception of Duke Tran from Boeing/Palmdale, California, all personnel were based at JSC in Texas.
[7] With the exception of where noted, all personnel were based at JSC.
[8] Tragically, Mr. Rochelle passed away before this report was published.

Table 4-2. ***Individuals Supporting the Principal Spacecraft Crew Survival Integration Investigation Team*** **(Continued)**
(*Denotes SCSIIT members who were on the CSWG)

Name[9]	Organization
Rita Alaniz, MEI Rodney DeSoto, LMSO Chris Keller, BAR Mark Langford, LMSO Terry Mayes, USA Jeremy Reyna, Wyle Laboratories Chris Slovacek, LMSO Matt Soltis	Habitability and Environmental Factors Division/Concept Exploration Laboratory (CEL), Space Life Sciences Directorate
Danny Olivas	Astronaut Office, Flight Crew Operations Directorate (materials analysis)
Sharon Hecht, Tesseda (TES) Perry Jackson, TES Cindy Bush, TES	Information and Applications Systems Division, Information Resources Directorate
Stacey Nakamura	Safety and Mission Assurance Directorate
James Comer, USA Amy Mangiacapra, USA	*Columbia* Research and Preservation (CRP) Office, KSC
Steve McDanels M. Clara Wright	Failure Analysis and Materials Evaluation Branch, Materials Science Division, Engineering Directorate, KSC
Rick Russell	Orbiter Sustaining Engineering Office, KSC
Roy Christoffersen, SAIC	Astromaterials Research Office, Astromaterials Research and Exploration Science Directorate
Darren Cone	White Sands Test Facility
David Bretz*, LMSO Tracy Thumm*, LMSO Kathleen McBride*, LMSO Kim Willis*, LMSO	Human Exploration Science Office, Astromaterials Research and Exploration Science Directorate
Donna Shafer	Office of the Chief Counsel

Additionally, expert personnel who were external to NASA provided assistance to the SCSIIT. These persons are listed in Table 4-3.

Table 4-3. ***Experts External to NASA***

Name	Organization
Dr. Robert Banks	Biodynamic Resource Corporation (BRC)
Dr. Jon Clark	National Space Biomedical Research Institute
Dr. Richard Harding	Biodynamic Research Corporation
Dr. Gregory Kovacs	Stanford University
Dr. Robert McMeekin	Previous Federal Air Surgeon
Dr. Thomas McNish	Biodynamic Resource Corporation
Dr. Charles Ruehle	Federal Aviation Administration (FAA)
Dr. Glenn Sandberg	Armed Forces Institute of Pathology
Dr. Charles Stahl	Former Chairman of the Department of Forensic Sciences at the Armed Forces Institute of Pathology
Dr. Harry Smith	Biodynamic Research Corporation

It should be noted that extensive training on accident investigation processes and procedures was not provided to the team. Many of the team members had no previous accident investigation training. Because the SCSIIT members supported the investigation on a part-time basis, taking a lengthy course in accident investigation processes and procedures was not feasible. NASA has only a small group of formally trained accident investigators across the many field centers. These investigators also have other safety duties. None

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[9] With the exception of where noted, all personnel were based at JSC.

were available to participate in the SCSIIT investigation due to higher priority activities occurring at the time, including Return to Flight preparation.

The SCSIIT leadership felt it was preferable for NASA space flight technical experts to learn accident investigation techniques rather than to have accident investigation experts become technical experts on the space shuttle. Therefore, personnel were selected for the SCSIIT based on experience with the CAIB and CSWG and/or who were technical experts in the disciplines that were necessary to conduct the investigation. Many SCSIIT team members did not have formal accident investigation training; advice from experienced investigators was sought at various times. Accident investigation experience would have been helpful to focus the team's efforts, especially early in the investigation.

Finding. Formally trained NASA-designated accident investigation personnel were not available for inclusion on the SCSIIT due to the intensity of safety and mission assurance work related to Return to Flight activities. SCSIIT members were selected primarily based on their technical knowledge and experience as well as availability. Many SCSIIT members did not have formal accident investigation training. The team preparation training sessions did not include the lengthy accident investigation training that is normally provided to NASA-designated investigators.

> ***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.

4.3 Investigative Process

The team traveled to KSC to perform first-hand inspection of the *Columbia* debris. Additionally, the results of previously performed analyses were reviewed. Additional analyses were then conducted (ballistics, materials, structural, aerodynamic, etc.).[10] Individually and in small groups, the team members assessed the results and formed conclusions. These conclusions were presented at Technical Interchange Meetings (TIMs) to the entire SCSIIT to compare and integrate results and findings. The team held four TIMs (March/April 2005, June 2005, August 2005, and March 2006). This was an iterative process, with each TIM resulting in more trips, analyses, and scenario revisions. In the process, integrated products were generated, with the most important being the timeline of key events. When possible, "no earlier than" and "no later than" times were identified for key events, and sequences were built.

In many regards, this investigation presented several challenges. Space flight is a relatively new and rare experience, and, fortunately, there have been only a few fatal mishaps. Consequently, there is no integrated or widely available body of information for how to analyze spacecraft accidents for crew survival. The physics of atmospheric entry and the environment in which a human spacecraft mishap occurs are unique when compared to aviation. The SCSIIT had to break new ground in how to conduct the investigation of a singular event in such a complex environment. The team had to determine how to modify existing models and tools, which are normally used for specific nominal situations in a predictive manner, to understand the mishap environment. Multiple tools and analyses were evaluated to provide multiple sources of information to develop scenarios.

> ***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.

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[10] Debris analysis and other analysis methods and tools are described in Section 4.5.

The SCSIIT collected a large amount of data from the CAIB and CSWG activities. Also, a large volume of new data was generated during the investigation. The SCSIIT Information Manager was tasked with organizing and tracking the information in a SCSIIT Project database.

The initial SCSIIT activities included review of data produced by the CSWG in support of the CAIB. It was discovered that the existing data had not been centrally cataloged or organized, making access to specific items difficult. The data that were available were dispersed among several groups, as shown in Table 4-4.

Table 4-4. ***Data Types and Data Sources***

Data Type	Data Source
Medical: X rays, autopsy reports, photographs, tissue samples	Armed Forces Institute of Pathology Biodynamic Research Corporation (BRC) Space Life Sciences Directorate, JSC
Debris: Seats, suits, CM, forward fuselage (FF), windows	*Columbia* Research and Preservation Team, KSC
Technical: Ballistics, thermal, structure, and materials analyses	Engineering Directorate, JSC
Video: Recovered On-board Video, Ground Based Video	Image Science and Analysis Group (ISAG) *Columbia* Video Archives Group Concept Exploration Laboratory
Operational: Vehicle Telemetry Data	Missions Operations Directorate

Because no final report was generated by the CSWG, it was not uncommon for several versions of specific analyses or presentations to exist as scenarios were iterated. Most of the files did not include the author, date, or version of the document, making it difficult to determine the final conclusions for the subject document. Additionally, without contact information, the team members were not always able to contact the original authors of these documents to discuss the contents or obtain additional information that may have aided the investigation. Report generation must begin very early in the investigation process, using a systematic approach with established procedures. At some point in the investigation, a transition from fact-finding must give way to documenting the findings, conclusions, and recommendations.

Finding. It was not uncommon to find several versions of documents supporting CAIB and CSWG work.

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

During the SCSIIT investigation, it was discovered that *Challenger* information was cataloged with keywords and descriptions that were more oriented toward the overall mishap investigation. This may be a result of the fact that the Rogers Commission did not specifically investigate crew survival. Additionally, the data were cataloged prior to current storage techniques and re-cataloged later by different personnel well after the accident investigation was complete. It was difficult to retrieve specific documents and analyses related to the CM and to crew survival. In many cases, *Challenger* information was obtained from individuals who were involved in the original investigation. Moreover, the *Challenger* debris items are unpreserved and inaccessible for analysis as they are stored in an abandoned underground missile silo with no access or climate control provisions. The lack of debris for comparison and methods of data preservation made the *Challenger* data essentially unavailable for this investigation. It is recommended that accident investigation plans 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.

Finding. CAIB/CSWG data were not cataloged. *Challenger* supporting data were mostly uncataloged and unorganized, limiting their usefulness for investigations. *Challenger* debris is unpreserved and inaccessible for analysis.

> ***Conclusion A8-1.*** Spacecraft accidents are rare, and each event adds critical knowledge and understanding to the database of experience.
>
> ***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.

4.3.1 Public release of information

For comparison and potential application to the SCSIIT investigation, the team researched how other government agencies conduct aircraft accident investigations. SCSIIT looked at processes that are used by the National Transportation Safety Board (NTSB), FAA, U.S. Air Force, and U. S. Navy to get an overview of the agencies' crew survival investigation processes. While the investigation process used by the SCSIIT was similar to those processes used in other agencies, there were some significant differences due to the uniqueness of the spacecraft operating environment. The most notable differences regarded public release of information and the use of personnel from the affected organization for the investigation.

The NTSB and FAA must conduct their affairs publicly, while Department of Defense (DoD) investigations are considered internal matters, and documents are released at the discretion of the DoD. At NASA, the public release of sensitive information is not specifically addressed in existing accident investigation plans. As a result, there was hesitation to investigate information that was relative to what happened to the crew out of the concern that the information would result in public release, and subsequent inappropriate speculation that would be painful to both the employees and the families. A more preferable situation would be to have a pre-determined plan for what crew-related information is appropriate to release to the public, and when the information should be released.

Finding. Concerns about public release of sensitive information relative to the crew creates obstacles to the performance of crew survival investigations.

Future spacecraft accidents may result in injuries and/or fatalities. To preserve the privacy of the *Columbia* crew members and their families, access to medically sensitive data, including the crew's personal items, was provided only to those personnel who had a need to know. This practice remains in place today and must remain in place in the future for *Columbia*-related information as well as for any future aerospace incident involving human casualties. This practice will preserve the privacy of the victims and their families. Almost as important, it will ensure that future investigations can be conducted without the concern of inappropriate release of sensitive information.

> ***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.
>
> ***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.

4.3.2 Using members of affected organizations in the investigation

In commercial or military aviation accidents, members of the organization that is affected by the accident generally are not members of the investigation teams. For example, pilots in a specific squadron would not be members of a team investigating an accident involving one of their squadron-mates. Because space flight operations are highly specialized and there are no other "external" organizations with sufficient relevant experience, it is impractical to follow this investigative practice for NASA crewed spacecraft accidents. Initially, the CSWG did not include current astronauts or crew escape operations training personnel. Astronauts were added to the CSWG and provided operational experience to the group. Crew escape operations and training joined the team during the follow-on SCSIIT portion of the investigation.

A potential downside to using accident investigation personnel who are close to the victims of the accident is the psychological impacts of the investigation on the investigators. A crew survival investigation is an emotionally charged process, causing considerable stress in the people involved in the investigation. The psychological welfare of personnel who are involved in debris recovery must be protected as part of the accident investigation process. In the aftermath of the *Columbia* accident, there were no consistent post-event stress debriefings to assist with post-traumatic stress disorder syndrome in recovery and mishap investigation personnel until later investigation phases.

Finding. The unique nature of the event, closeness of investigators to the accident victims, lack of previous exposure to the results of such tragedies, and need to keep information confidential created stress on some members of the investigation team. Counseling was provided, but the follow-up could be improved.

> ***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.

4.4 Medical Process Issues

When the *Columbia* accident first occurred, the highest priority task was rescuing the crew members. When it became apparent that they had not survived, the task transitioned to recovering the crew remains. The FBI was the agency that was in charge of recovering the crew member human remains. The Bureau was assisted by members of the Environmental Protection Agency, local and state law enforcement agencies, local coroners, and members of the NASA Astronaut Office. As searchers and citizens reported possible remains, teams were dispatched to document and recover the remains. In many cases, forensic experts in the field were able to make preliminary determinations of whether the remains were human or otherwise. Initially, trained recovery personnel were used to identify human remains in the field until all principal remains were recovered. Subsequently, recovery personnel were directed to collect all remains regardless of whether or not they could positively be identified as human or other. In most cases photographs of the remains were taken in the field prior to collection to document the "as-found" condition for use during the autopsies. The quality of the photographs and the information recorded varied greatly from site to site. In some instances where human remains may have been found near spacecraft hardware, there were no established procedures for documenting these important physical relationships.

After recovery, the remains were transported first to a local morgue facility. Intake photographs were taken to document the "as-received" condition of the remains for use during the autopsies. A forensic pathologist performed a review of the remains and was able to separate out many nonhuman remains that had been collected. The human remains were then prepared and transported to Barksdale Air Force Base, and then on to the AFIP at Dover Air Force Base.

The AFIP was the government agency that was tasked with positively identifying the remains, performing the autopsies, and preparing the remains for burial. Identification of the remains relied primarily on DNA testing and dental records.

NASA expected the AFIP service to include a complete cause of death analysis in similar fashion to what the Air Accident Investigation Team had historically done and had been done for the crew of STS-51L (*Challenger*). The AFIP performed very well in the receipt of human remains, gross examination, and definitive identification, and in providing death certificates and mortuary science support. However, the gross autopsy reports were incomplete and did not contain the level of detail necessary for a thorough accident investigation. X rays that were taken were of poor quality, and no interpretation of the X rays was transmitted to NASA. The microscopic examinations included in the final autopsy reports lacked many of the specific details that were required for the investigation. Although the AFIP continues to participate in routine aircraft accident investigations, in this instance it did not have the necessary resources to integrate all of the forensic findings into a comprehensive accident investigation report due to operational commitments. Subsequently, NASA has addressed these issues with process changes.

4.5 Analysis Methods, Processes, and Tools

Various methods, processes, and tools were used by the SCSIIT sub-teams to conduct their analyses. The following sections describe these methods, processes, and tools.

4.5.1 *Columbia* debris repository

Vehicle debris is one of the most useful sources of evidence in an accident. The debris can be used to determine failure modes, fracture dynamics, and thermal exposure, helping to develop vehicle breakup sequences. The debris also can be used to support physical and virtual vehicle reconstruction. *Columbia* debris is currently stored on the 16th floor of the Vehicle Assembly Building at KSC. The CRP Office is tasked with managing the debris and the database and providing access to the debris for research purposes. The investigation would not have been possible without the careful work done by the Reconstruction Team, particularly in the area of CM reconstruction. SCSIIT members made several trips to KSC to analyze the debris.

4.5.2 Physical reconstruction

Visual and microscopic inspection of individual debris items provided details of the thermal damage to components, the directionality of melted material deposits, and the characteristics of fracture surfaces. Evidence of mechanical damage or thermal exposure on fracture edges was used to help determine the timing of the breakup. For example, significant melting of fracture surfaces would indicate that the fracture occurred first, followed by thermal exposure. In addition to the study of individual debris items, multiple debris items were studied together as reconstructions of portions of the orbiter.[11] Reconstructions were performed for the flight deck and middeck floors, CM forward (X_{cm} 200) and aft (X_o 576) bulkheads, X_o 582 ring frame bulkhead, the airlock and tunnel adapter structure, CM avionics bays, crew seats, forward Reaction Control System pod components, and selected portions of the forward fuselage. These reconstructions were useful for helping to determine breakup sequences and mechanical and thermal damage patterns across large areas.

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[11] Physical and time constraints prohibited a full reconstruction of *Columbia*.

4.5.3 Virtual reconstruction

Using modeling, simulation, and visualization tools, members of the Concept Exploration Laboratory (CEL) at JSC integrated data from multiple disciplines to create an interactive, dynamic, 3-dimensional simulation of the orbiter. This simulation included a virtual reconstruction of the CM interior using photographs of recovered debris items. The simulation also provided a dynamic visualization of the vehicle dynamics and breakup sequence, thereby creating a virtual reconstruction not only of the vehicle but also of the accident events timeline. The CEL team also developed unique capabilities and analysis techniques to support the investigation.

Trajectory and vehicle dynamics data for the intact orbiter were entered into the simulation, as were trajectories for selected debris items. Coordinates of the recovery location for debris items were loaded into the CEL simulation, and the debris items were grouped according to their origin on the vehicle (i.e., left wing, tail structure, FF, etc.).

The simulation was used to visualize the predicted vehicle dynamics and breakup sequence. Telemetry data were used where available to represent the flight path and vehicle orientation. The reference trajectory was used to represent translation. The aerodynamic simulation of the vehicle attitude (see Section 2.1) was used between LOC and the Catastrophic Event (CE). The aerodynamic simulation of the forebody was used to represent the orientation after the CE. Figure 4-4 shows frames from the dynamic visual simulation. The image on the left represents the orbiter just before the LOC, and is viewed from a point above, behind (west), and to the left (north) of the flight path. The image on the right represents the orbiter just after the CE, and is viewed from above and behind (west) of the flight path. The three main items in this view are the payload bay doors, the forebody, and the main portion of the orbiter. The left wing has already departed from the orbiter and is not visible in this view.

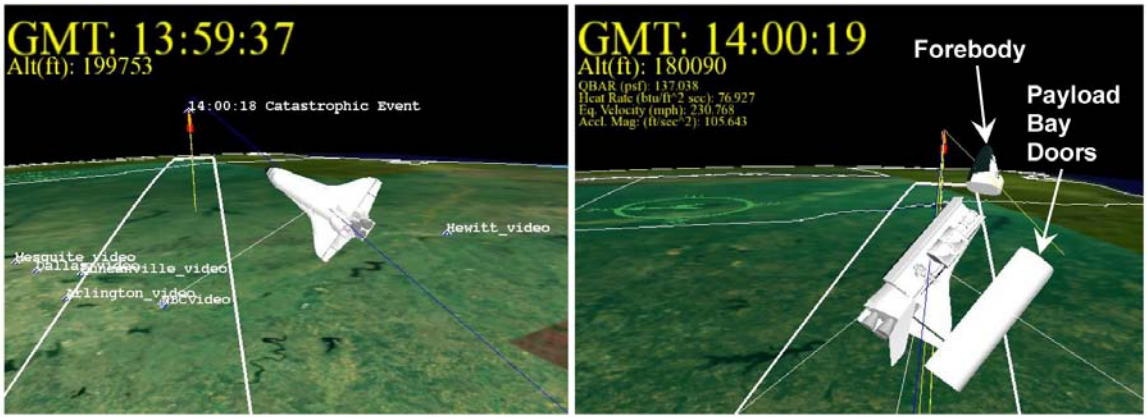

Figure 4-4. ***Visual representation of the breakup sequence, looking east*****.**

Figure 4-5 shows the trajectories of the intact orbiter (the blue line in the upper portion of the image) and multiple debris items (different color lines) as viewed from a point in space looking down toward the Earth in a westerly direction. State borders are shown in white, and selected cities are labeled in green. The white rectangle represents the main debris search area. Almost all of Texas is visible, with east Texas shown in the center of the image. Western Louisiana is at the bottom of the image.

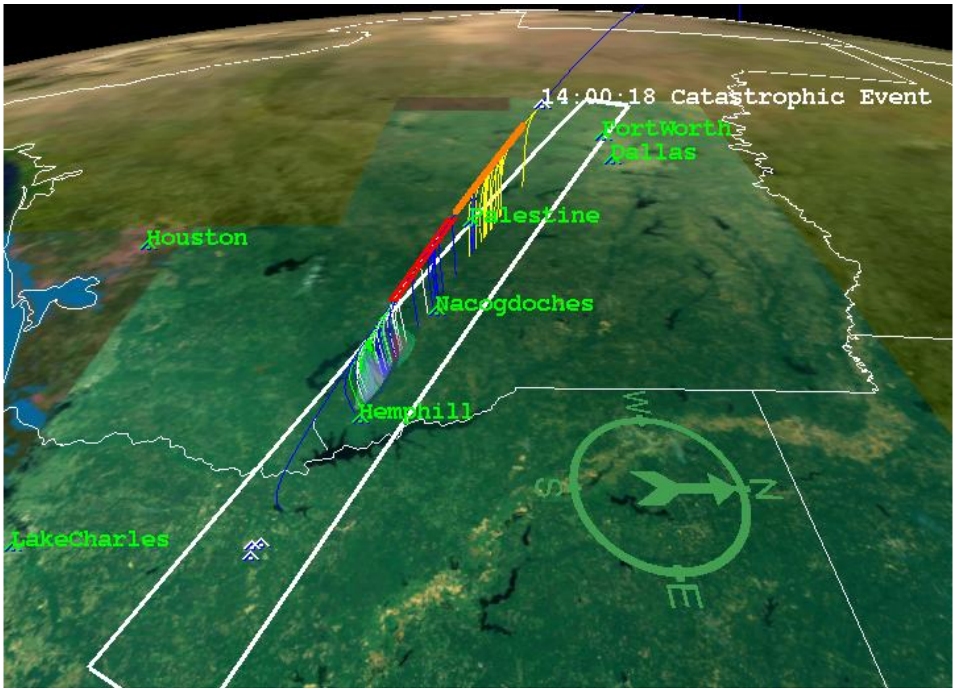

Figure 4-5. ***Orbiter and debris trajectories, looking down at Texas in a westerly direction*****.**

The simulation could be viewed from any vantage point, such as zooming in on the CM debris spread or any of the sites from which ground-based video was recorded. Figure 4-6 shows the trajectory and CM debris groupings as viewed from a point north of the trajectory, looking south-southwest. Debris item groupings are shown as triangles and are labeled (“Airlock”, Middeck floor”, etc.).

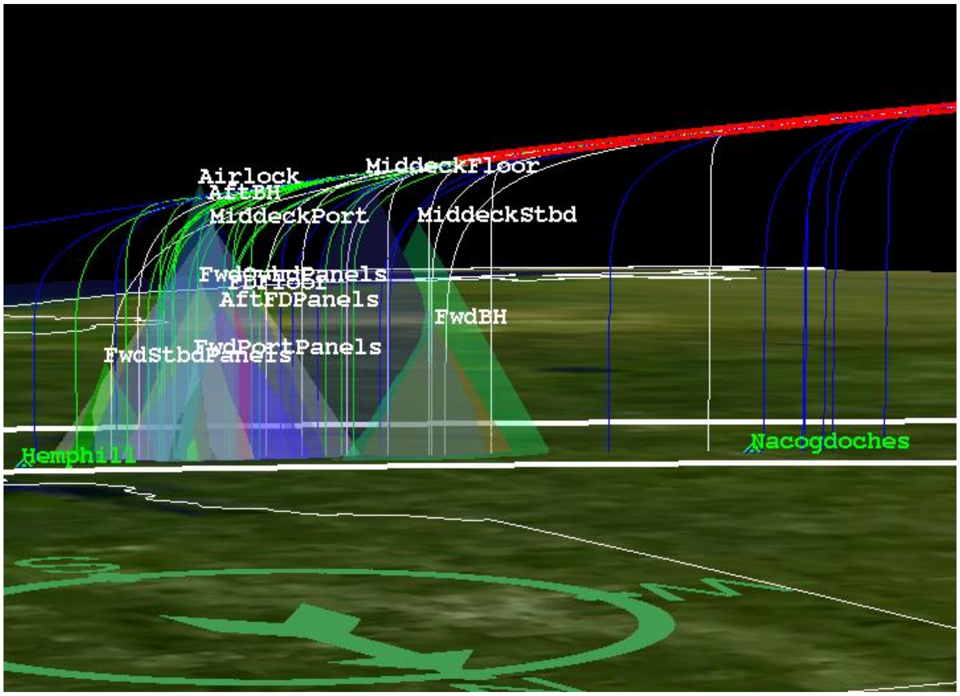

Figure 4-6. ***Crew module debris groups, looking south-southwest.***[12]

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[12] “FwdBH” = Forward Bulkhead; “AftFDPanels” = Aft Flight Deck Panels.

Portions of the TIMs were conducted in the CEL where the SCSIIT could interact with a dynamic simulation of the LOC and breakup events while simultaneously reviewing video from the various ground sites that recorded the events. This was an invaluable asset in developing and refining breakup sequences.

The CEL developed a virtual reconstruction of the cockpit by mapping photographs of selected debris items to a computer model of the crew cabin. This virtual reconstruction was used in a variety of ways to augment direct examination of the debris. Figure 4-7 shows examples of this virtual reconstruction. The image on the left shows the aft flight deck and overhead windows (looking aft) with photographs of recovered panels and window frames included. The image on the right shows several starboard side middeck floor panels and the starboard-most crew seat (the blue item in the upper right corner). This image is from a vantage point looking port and slightly aft.

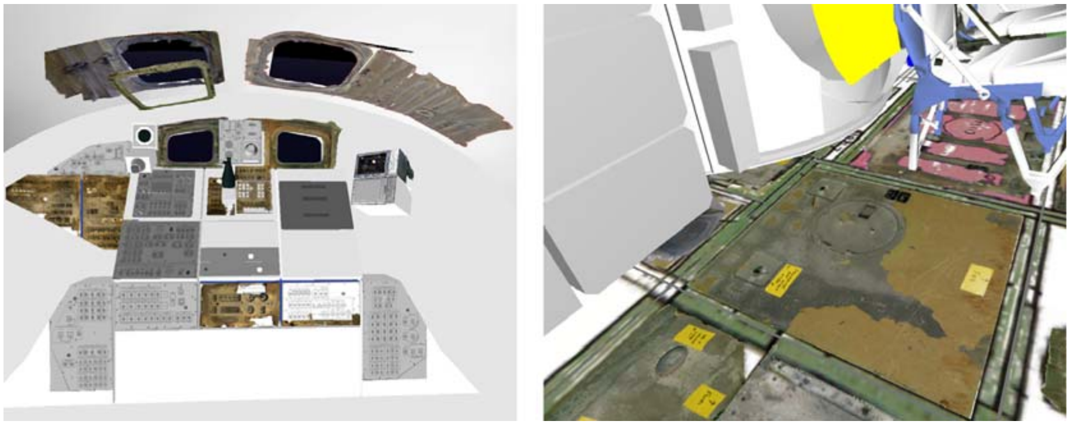

Figure 4-7. ***Virtual reconstruction of the aft flight deck*** **(left image)** ***and middeck floor*** **(right image).**

4.5.4 Motion analysis tools

The vehicle team was tasked with determining the behavior of the vehicle from LOC of the orbiter until forebody breakup. Analyses that were conducted include trajectory analysis, ballistics analysis, thermal analysis, forebody aerodynamic stability analysis, and CM survivability analysis. In addition to performing analysis on the vehicle and forebody, the Vehicle Team performed ballistics and thermal analyses on various items for the other SCSIIT sub-teams.

4.5.4.1 *Trajectory and attitude analyses*

Global Reference Atmospheric Model

The Global Reference Atmospheric Model was used to generate a representative flight day atmosphere, which is the U.S. Standard Atmosphere 1976 model. This model is a steady-state (year-round) model of the Earth's atmosphere at latitude 45N during moderate solar activity.

Intact Orbiter Simulation

The entry simulation[13] was developed to model the dynamics of the intact orbiter between loss of signal (LOS) at Greenwich Mean Time (GMT) 13:59:31 to the CE at GMT 14:00:18. This simulation provided the resulting modeled accelerations on the vehicle structure and crew during this timeframe. The simulation used the preflight predicted vehicle mass properties; downlinked general purpose computer (GPC) data including position, velocity, attitude, and any alarm/warning related data; and the Modular Auxiliary Data System/orbiter experiment recorder sensor data. The final 2-second period of reconstructed GPC data (RGPC-2) were used in an attempt to synchronize the simulation with the actual flight data. Full details about assumptions and models are described in EG-DIV-08-32, IEE Report, Appendix G – Post-LOS Analysis. The simulation used available data; therefore, there is a moderately high level of confidence in the representation of the motion and resulting accelerations.

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[13] EG-DIV-08-32, Integrated Entry Team Report, Appendix G – Post-LOS Analysis.

Reference Trajectory

The reference trajectory is the path of the intact orbiter and forebody given assumptions about their aerodynamics properties and ballistic numbers. The trajectory provides a continuous trajectory from LOS to the Crew Module Catastrophic Event (CMCE) to main engine ground impact. The trajectory was used as a common reference for the thermal and debris ballistic analyses. The reference trajectory was generated using Simulation and Optimization of Rocket Trajectories (SORT). The reference trajectory is divided into four phases: the “Nominal Orbiter,” with an average ballistic number of 108 pounds per square foot (psf); the “High-drag Orbiter,” with an average ballistic number of 41.7 psf (lift generation occurs); the “No-lift Orbiter,” with an average ballistic number of 41.7 psf (a 72-degree angle of attack assumed); and the “Forebody” vehicle, with an average ballistic number of 150 psf.

Simulation and Optimization of Rocket Trajectories

The SORT software program is a general-purpose, 3-degrees-of-freedom, computer-based simulation of the flight dynamics of aerospace vehicles. It was used to estimate the time of an object’s release from the various configurations that the orbiter experienced during the accident. The aerodynamic forces experienced on the reference trajectories and the heating and atmospheric conditions were also generated. This program was selected because it was previously used to design the shuttle ascent trajectory and because of user familiarity.

The aerodynamic coefficients, mass, area, and ground recovery location of the debris item were entered into SORT. SORT then calculated release times of the debris item from the reference orbiter trajectory until the location where the object was found matched the calculated ground location. The calculated release time had a ±5-second error bar due to unknowns in the reference trajectory.

Shuttle Engineering Simulator

In 2003, the Shuttle Engineering Simulator (SES) provided an engineering simulation flight reconstruction of the STS-107 entry. This simulation was based on flight data that had been recorded during the descent. The ascent/entry SES was supplied with a set of data files describing the atmospheric conditions during the descent. The original task was to model the changes to vehicle aerodynamics due to the left wing damage. The results of this work are documented in the guidance, navigation, and control portion of the CAIB Report. The visual simulation was also used as part of the “crew awareness” task that was assigned to the Crew Team. Additionally, video of the three primary SES cockpit displays covering the time from GMT 13:58:19 to GMT 13:59:39 (2 seconds after the LOC) were included in the CEL visual products.

Forebody Trim Analysis

The forebody configuration was idealized in that the mass properties were held constant from the CE to the CMCE and the aerodynamic geometry was symmetric. The configuration, which was an intact FF containing the CM, ended cleanly at the X_o 576 bulkhead. At the time, the team did not yet know that parts of the X_o 582 ring frame bulkhead stayed attached to the forebody. The forebody configuration is shown in figure 4-8.

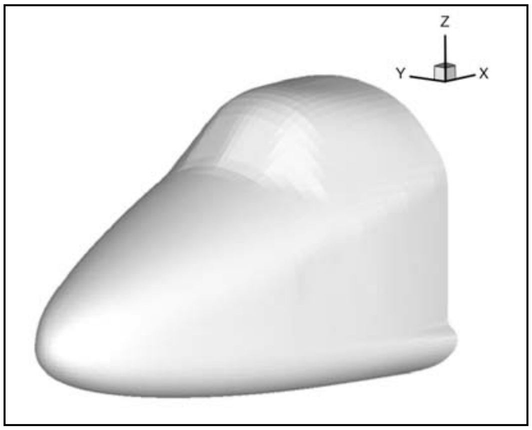

Figure 4-8. ***Forward fuselage/crew module (forebody) configuration.***

The aerodynamic coefficients and surface pressure distributions for the forebody traveling at hypersonic speeds were predicted using Snewt, an implementation of the Newtonian engineering method. The aerodynamic properties were generated at orientations through a 0-degree to 180-degree sweeps in α (angle of attack) and β (sideslip angle). The aerodynamic moments were plotted in a contour analysis to evaluate stability and were used as inputs to the 6-degree-of-freedom kinematic motion simulation.

A sensitivity study was conducted to examine the effect of the forebody's damping moments on the motion. Because no damping moment data were available for the forebody configuration, Apollo capsule damping moments were used as the closest approximation. At the high Mach numbers that were relevant to the *Columbia* flight conditions, the effect of damping moments is low. It was found that the damping moments had little effect on the motion. As a result, subsequent analyses set the damping moments to zero.

The pitch stability of the forebody was examined by plotting the pitching moment coefficient vs. the angle of attack with the sideslip angle held at 0 degree. The roll and yaw stability was examined by plotting the rolling and yawing moment coefficients vs. the sideslip angle with the angle of attack being held constant at the pitch stable angle. This study showed that with any lateral center of gravity other than zero, neither the forebody nor the CM would achieve a stable trim attitude.

These aerodynamic data were then used as inputs to an MSC Visual Nastran simulation. The simulation, which began at approximately the CE, determined the forebody motion to approximately the CMCE. The inputs to the simulation include forebody geometry and mass properties, aerodynamic coefficients, and initial vehicle state conditions. The outputs include the motion parameters, (position, velocity, and acceleration), attitude, attitude rate, and G-loads at the seat locations. Animations of several cases (forebody, CM, initial rates, etc.) were also generated to give a better understanding of possible forebody motion. Unlike the intact orbiter analysis, no data were available for the modeled motion. Therefore, fewer conclusions can be drawn from these data. However, all analyses showed a failure to achieve a trim attitude, and video data supported this conclusion.

Snewt

Snewt is the name of a program that uses the modified Newtonian method to compute a surface pressure distribution and various aerodynamic coefficients. The program uses numerous inputs (reference area, reference length, moment reference center location, Mach number, angle of attack (α), sideslip angle (β), and the ratio of specific heat) and the vehicle outer mold line shape to compute the following coefficients (figure 4-9):

CA = axial force (force component in the body "x" direction)
CY = side force (force component in the body "y" direction)
CN = normal force (force component in the body "z" direction)
Cl = rolling moment (about the "X" body axis)
Cm = pitching moment (about the "Y" body axis)
Cn = yawing moment (about the "Z" body axis)
D = drag (force in the opposite direction of the velocity vector)
Cs = wind side force (force in the wind "y" direction)
L = lift (force in the vertical direction perpendicular to the velocity vector)

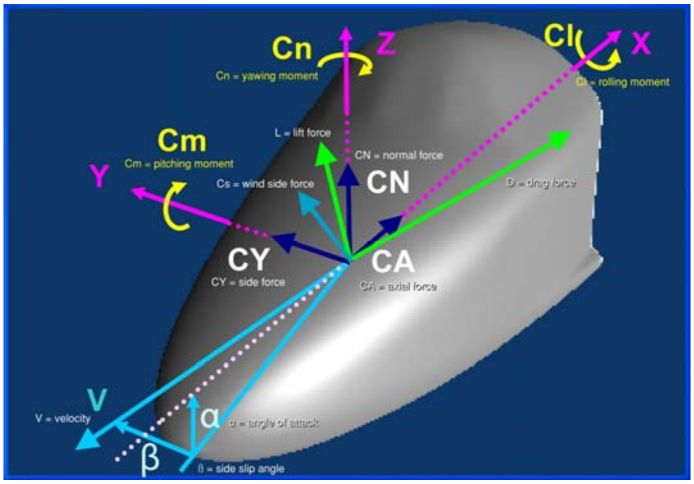

Figure 4-9. ***Coefficients that were used to define the vehicle outer mode line shape*.**

The modified Newtonian method is considered a simple model that has several limitations restricting its accuracy. One of the most significant limitations is that the Mach number should be greater than approximately M=5. This was appropriate for the conditions in this accident. Another significant limitation of the method is that regions of a vehicle behind multiple shock waves will not be treated correctly. An example is the portion of a wing that lies inside the bow shock.

MSC Visual Nastran Motion Working Model

The MSC Visual Nastran Motion Working Model is a conceptual design software tool that analyzes mechanical systems. It was used by the SCSIIT to simulate the motion of the forebody (both translational and rotational motion) after the CE to gain understanding into what type of accelerations and forces the forebody and crew may have experienced. This tool was chosen because many of the equations that were needed for the analysis were already embedded in the source code, thus reducing the time needed to set up, initialize, and verify the outcome. Events or additional equations could be integrated into the simulation using the built-in formula language or linking to MATLAB or Excel routines.

Objects can be imported from computer-aided drafting drawings or created within MSC Visual Nastran. An object's mass properties and initial conditions – such as position, velocity, and rotation rates – can be specified. Simulation properties can be measured and displayed in digital or graphical formats and saved to Excel files for further analysis. The MSC Visual Nastran Working Model also provides audio visual interface files of the vehicle's motion, acceleration at different locations on the vehicle, and vehicle rotational rates that can be used for additional evaluation and analysis.

4.5.4.2 *Ballistic analysis*

Ballistic analysis of the debris determined the estimated release time of individual debris items from the orbiter using the reference trajectory and the debris item's recovery location (latitude/longitude), calculated ballistic number and aerodynamic drag coefficients.

Snewt was used to calculate the average ballistic number and aerodynamic drag coefficients. To make these calculations, Snewt requires an object's mass and geometry. If these data were not available from the KSC debris database, the debris item would be measured.

SORT was used to estimate the release time of the debris piece given the reference trajectory, the average ballistic number and aerodynamic drag coefficients from Snewt, and the location of the recovered debris piece. These calculations assume that the recovered debris piece has the same mass and geometry on the ground as it had when it left the orbiter. SORT calculated the release times of the debris item from the reference trajectory until the calculated ground location matched the location where the object was found.

4.5.4.3 *Thermal analysis*

Debris thermal analysis was conducted to determine the entry heating environment for specific debris items. This analysis used the estimated release time and state of the item, the average ballistic number, and the aerodynamic drag coefficients.

Object Reentry Survival Analysis Tool

The Object Reentry Survival Analysis Tool (ORSAT) uses a 3-degrees-of-freedom trajectory model, Detra-Kemp-Riddell aero heating equations, and a 1-dimensional, finite-difference thermal conduction model to predict thermal damage to items experiencing the entry environment. ORSAT was used to predict the temperatures that specific debris items would experience after release from the orbiter. These predicted temperatures were then compared to the observed thermal damage to determine whether entry heating was responsible for the observed thermal damage. In several cases (described in Section 2.1), the observed heat damage on the recovered debris items could not be explained adequately by entry heating alone. Literature searches revealed the phenomena of shock wave impingement and shock wave interference leading to increased heating rates.[14] These phenomena and their effects on spacecraft during the hypersonic flight regime are not well understood. Due to limited resources, the team was not able to advance the understanding of these phenomena.

SINDA/FLUINT

The Systems Improved Numerical Differencing Analyzer (SINDA)/FLUINT is a general-purpose numerical thermal/fluid solver. It was used to compare heat rates for some of the thermal analyses (see

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[14] NASA TM X-1669 "Flight Experience with Shock Impingement and Interference Heating on the X-15-2 Research Airplane", October 1968.

Section 2.1), and is maintained by C&R Technologies (www.crtech.com). The user creates a thermal model that is represented by a nodal network of capacitors and conductors, applying the relevant initial and boundary conditions. The tool solves the thermal network and returns the desired parameters (i.e., temperature, heat flow) for the desired times in the simulation.

BLIMP-K

The Boundary Layer Integral Matrix Procedure-Kinetic (BLIMP-K) code is a FORTRAN-based code that was developed during the Apollo Program by Aerotherm for NASA for use in aeroheating analyses. The SCSIIT used it to compare to ORSAT and SINDA during some thermal evaluations (see Section 2.1). This kinetic version of BLIMP allows for a finite-rate, thermo-chemical model to be used in the analysis. The BLIMP-K model, which is described in the latest User's Guide,[15] incorporates temperature-dependent catalytic models and uses a maximum of 15 nodes across the boundary layer. Subsequent modifications allow the catalytic model to be updated at each station along the streamline, as well as allowing the ability to model up to 2,500 streamline stations. Macros and scripts have been used to speed up the pre-processing of the BLIMP-K input files for large parametric studies.

Computational Fluid Dynamics Thermal Analysis of Payload Bay Door Rollers

A computational fluid dynamics (CFD) thermal analysis of the payload bay door rollers was performed by the JSC Applied Aerosciences & CFD Branch. Various Mach numbers, from M = 7.5 to M = 15, were used to determine the flow field environment and temperature at the face of a roller for an orientation with the front of the roller facing directly into the direction of travel. Figure 4-10 shows the predicted heating rate and temperature distribution along the payload bay door roller at M = 10.5. The notations q_{cw} refers to "cold wall" and q_{hw} refers to "hot wall." In this figure, the CFD solution assumes a steady-state solution, meaning that given enough time, the flow will develop into the calculated results. This is a reasonable assumption for high-speed entry because the flow field will form very quickly. The wall temperature is calculated by assuming radiation equilibrium. This means that the amount of heat that is being absorbed by convective heating is the same amount of heat that is being expelled through re-radiation. Also seen in the upper right of figure 4-10 are two photographs of payload bay door rollers. The photograph for OV-105 shows an intact roller, and the photograph for OV-102 (*Columbia*) clearly shows the erosion of the exposed titanium surface on the front face of the roller.

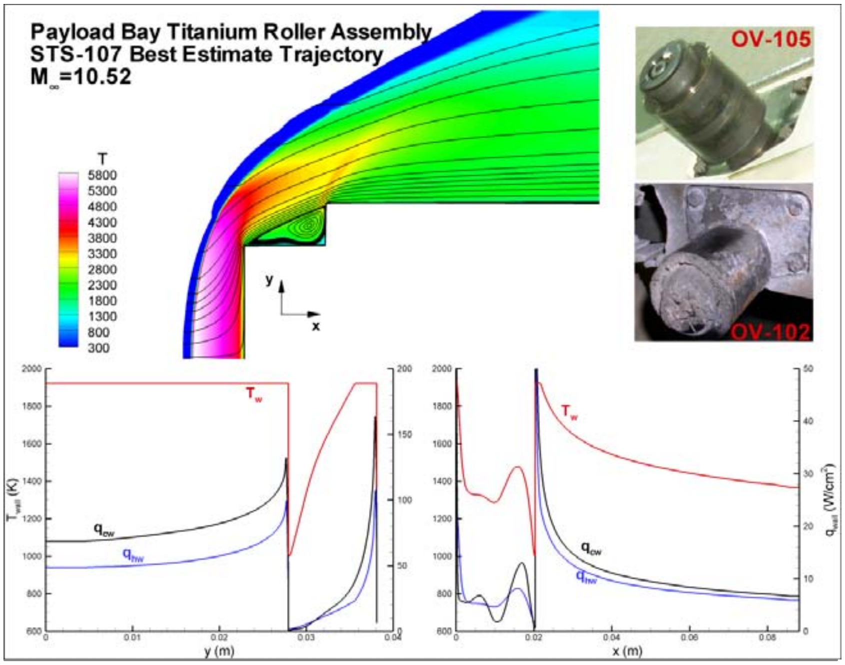

Figure 4-10. ***Computational fluid dynamics analysis of heating at the tip of the payload bay door roller for orthogonal geometry into the direction of travel at M = 10.5.***

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[15] Murray, A. L., "Further Enhancements of the BLIMP Computer Code and User's Guide," AFWAL-TR-88-3010, June 30, 1988.

Radiation equilibrium is a reasonable assumption when used for analyzing the Thermal Protection System (TPS) that was designed to have a very low thermal conductivity; e.g., high-temperature reusable surface insulation tiles or reinforced carbon-carbon panels. However, for metals that will conduct the temperature inward, there is a time factor that needs to be accounted for and a temperature distribution through the object. Thus, the CFD analysis is very good at producing accurate heating rates, and the temperature calculation can give a reasonable upper bound.

Arc jet testing

It was proposed that the erosion of both the x-links and the payload bay door rollers appeared to have some element of material selectivity. Combustion was proposed as an explanation for why some materials eroded and other materials did not and also to explain how oxide formation, which requires extremely high temperatures, occurred.

A selection of enthalpy-pressure test points was chosen based on the predicted trajectory and ballistic number of *Columbia* and the free-flying forebody. A series of tests was conducted at the Boeing St. Louis Large Core Arc Tunnel plasma arc facility. The complete results of the arc-jet testing can be found in Olivas, J. D., Mayeaux, B. M., Melroy, P. A., and Cone, D. M., "Study of Ti Alloy Combustion Susceptibility in Simulated Entry Environments," *AIAA Journal,* 2008 (submitted for publication).

4.5.5 Video analysis

4.5.5.1 *Ground-based video analysis*

The CAIB Report contains information that is related to video analysis performed during that investigation.[16] The process followed in performing video analyses is highlighted below.

When the ISAG received a video, that video was "screened." The video was watched from beginning to end, identified as an ascent or descent video, briefly summarized, entered into the ISAG database, and cross-referenced to any photographic stills or other versions of the same video.

Following the initial screening, a "detail screening" was performed on videos, noting key timing events. Key timing events may include the start and end of the data tape, the first and last appearance of the orbiter, and any visual event that was significant enough to be potentially useful in time-synchronizing with other videos. The first appearance of an object is referred to in the ISAG database as the acquisition of signal (AOS), and the last appearance of an object is referred to as the LOS.

Events appearing in multiple videos could not only time-synchronize the videos but could also provide confirmation of the nature of those events (for example, whether it was a brightness change or a debris-shedding event). Visual events that may be noted in the videos include object-brightening events, changes in the trails of the objects seen, color changes in objects and/or trails, separation and/or breakup of objects, and first and last appearance of additional objects. Generally, brightening events were easier to correlate between videos than debris-shedding events.

Finding. Brightening events were easier to correlate between videos than debris-shedding events.

The AOS of an object is usually well identified. An object can have multiple AOSs and LOSs if it passes in and out of the field of view (FOV) due to tracking of the camera or changes in the magnification factor of the video. Visual separation of objects is impacted by the zoom factor of the video, the resolution of the recording device, focus, image stability, the amount of saturation of the pixels of the recording device due to the brightness of the objects in the FOV, and the viewing geometry of the viewer in relation to the

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[16] *Columbia* Accident Investigation Board Report, Volume III, Appendix E.4 *Columbia* Early Sighting Assessment Team Final Report, June 13, 2003, details a combination of video, photograph, radar, and ground debris information and details data submission handling. *Columbia* Accident Investigation Board Report, Volume III, Appendix E.2, STS-107 Image Analysis Team Final Report, details the investigation of the imagery of the STS-107 entry (as well as imagery of the launch and suspect foam strike).

objects and the sun. The time of visual separation of objects in an FOV will always be later than the actual time of physical separation, with delays ranging from a few video frames (1 frame ≈ 1/30 second) to several seconds.

The LOS time for an object generally indicates that the object left the FOV rather than indicating the loss of a detectable visual signal. Typically, the videographers zoomed the FOV to concentrate on the largest or brightest object that was visible (typically the orbiter or the aftbody/engines). If an object left the FOV, it can be inferred that the object probably had a lower ballistic number (higher drag) than the object that the videographer was tracking. On rare occasions, LOS equated to an inability to track the object due to multiple pieces seen and/or a scintillating (flashing) visual signal. There were also cases when the visual signal dropped below the sensitivity of the camera or the object disintegrated. The cause of the LOS was rarely noted in the database.

The video key events times were used to develop event sequences for the CAIB. After the CAIB event sequence timeline was completed, a Late Re-entry Working Group (LRWG) was formed in support of the CSWG. The LRWG's primary tasks were to determine when the CM separated from the rest of the vehicle and when it broke up, any visible event that could relate to loss of cabin atmosphere, and any large deceleration event (i.e., an abrupt slowing of the CM). The LRWG results fed into some CSWG results and fed extensively into the SCSIIT work. A few videos provided good views of the breakup of the aftbody, but these were not studied in great detail since they were not relevant to the SCSIIT.

The SCSIIT used the time-synchronizing of the ISAG and the LRWG when possible. The "Apache" video source has an accurate GMT time since it is based upon the Global Positioning System (GPS). All other videos from the eastern timeline were synchronized from Apache video, if possible, and a few videos had adequate timing information to allow cross-checks of GMT. The times for video events have estimated errors ranging from ±0.3 second up to ±2 seconds, although generally they were less. Errors that were associated with video event times are impacted by the magnification of the FOV, resolution, and viewing geometry. For example, an image with a high magnification for the camera FOV will see the start of the CE sooner than an image from an FOV that was not zoomed. Resolution may delay timing for similar reasons. Viewing geometry can prevent an event from being seen until later, if it is seen at all. A combination of error sources can lead to an accuracy of ±1 second for defined events within a single video or between videos, although the actual error may be better or worse by up to an additional 1 second.

Although all 51 videos depicting the orbiter over Texas were examined and contributed to understanding the events, five videos were found to be key for the LRWG's investigation (see Table 4-5).

Table 4-5. ***Videos That Were Used***

Reference EOC No.	City in TX	Name	Latitude	Longitude
EOC2-4-0024	Arlington	Arlington	32.7	–97.1
EOC2-4-0209-B	Hewitt	Hewitt	31.4	–97.2
EOC2-4-0221-4	Mesquite	WFAA4/Mesquite	32.8	–96.6
EOC2-4-0221-3	Fairpark	WFAA3	32.8	–96.7
MIT-DVCAM	Fort Hood	Apache	31.2	–97.6
EOC2-4-0077	Burleson	NBC*	32.5	–97.3

*NBC = National Broadcasting Corporation

Late in the SCSIIT investigation, a previously unanalyzed video was discovered. Some videos received from television affiliates were compilations of video that had been collected by television camera operators and those that were submitted by the public. These compilations were not noted as "ascent" or "descent" videos if they were a mix of videos from both phases of the mission. Additionally, the original review of videos focused on identifying pre-CE videos, and this video was misclassified as recording events after the CE. It had been reviewed within the first 5 days of the video investigation related to the CAIB, when the importance of the video evidence was not fully realized. Because the video compilation did not have a "descent" annotation, both the LRWG and the SCSIIT were unaware of its existence. Additionally, because no team had initially identified it as a critical video, the original was not requested in a timely fashion. A copy of part of the original video from the television station was obtained (in addition to a copy of the full video in the ISAG archives), but the original video no longer exists. The copy provides adequate resolution for data interpretation. This video, which is designated "NBC" (EOC2-4-0076-B), added several seconds of good-quality imagery to the eastern timeline.

Finding. Not all videos segments within compilations were individually categorized. Not all videos were re-reviewed once a better understanding of events had been gained.

> ***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.

It was originally assumed that the sun would have little impact on the brightness of the debris pieces. If a piece of debris was generating a trail, it was expected that the debris was self-illuminating due to the thermal effects of entry heating. Objects that were tumbling were not expected to vary in brightness solely due to the sun. However, review and comparison of videos showed that the sun did contribute to the variations in illumination of objects, even those generating trails. Illumination by the sun impacted the visibility of all debris.

Finding. Sun angle illumination impacted the visibility of debris in video recordings.

In establishing the sequence of events as seen from video and photographic imagery, there are brightening events and debris-shedding events. The appearance of these events was impacted by illumination angle, viewing angle, viewing geometry, and timestamp accuracy. Additionally, the accuracy of the timeline and related data was dependent on information from the videographers. A standard information sheet was used that helped to ensure that most, if not all, key information was available.

4.5.5.2 *Forebody triangulation*

The CEL created a custom application to evaluate the relative motion between the forebody and the aft portion of the vehicle. The application used ground-based videos that were recorded from multiple locations and triangulation to determine the relative distance between the forebody and the aftbody. The original intent of the analysis was to identify the initial conditions of forebody separation (forebody rotation rates, separation rates, etc.). The time between the CE (GMT 14:00:18) and the first point where the forebody was visible in two videos (~GMT 14:00:30) made it difficult to draw conclusions about the forebody separation conditions. However, as described in Section 2.1.5, this triangulation analysis yielded information regarding the forebody motion after the CE. The analysis led to the conclusion that the forebody was rotating in all three axes at approximately 0.1 rev/sec.

4.5.6 Debris mapping/plots

Debris field analysis was conducted to investigate where components of the orbiter impacted the ground compared to where the debris items originated from on the orbiter. This analysis involved plotting the recovery locations of debris items, identifying debris groups based on their location on the orbiter (i.e., left wing, payload bay, FF, etc.), and comparing the relative positions of the groups. The debris groups were referred to as "clusters." Cluster analysis is a technique that uses the assumption that when a large number of debris items from the same structural zone (e.g., tail, wings, payload bay, CM) are considered, different clusters will have a similar range of ballistic numbers. With a similar range of ballistic numbers, the centroids of the clusters can be evaluated *relative* to each other to approximate sequencing of key events.

Ballistic analysis for selected debris items within the various clusters provided calculated release times, and the release times were used to develop ballistics-generated breakup sequences. These sequences yielded similar sequences to the cluster analysis-generated sequences, providing confidence in the breakup sequences that are described throughout this report.

Latitude and longitude errors

Performing these analyses required accurate latitude and longitude data in a format that was usable by the plotting application. The majority of the items in the KSC debris database include latitude and longitude data of the recovery location. In some cases, no latitude/longitude information exists because debris were recovered and submitted by local residents. In other cases, the latitude/longitude data may have been recorded in the field but not imported into the KSC debris database. The data that do exist in the KSC debris database were assumed to be accurate unless there were obvious factors that indicated otherwise, such as the resultant plot indicating that an object was recovered beyond the reasonable bounds of the debris field.

Much of the data that are in the KSC debris database are recorded in degrees and decimal degrees (DD.ddddd), for example: 31.31063° N, 93.87701° W. However, the database contained several other formats, including 31.21.26.3; 31 21′ 26.3″; 31 21 26.3; 31 21.263; and 31.21.263.

The first three formats were assumed to indicate degrees, minutes, seconds, and decimal seconds (DD MM SS.sss), unless information indicated otherwise. The last two formats were assumed to indicate degrees, minutes, and decimal minutes (DD MM.mmm), unless information indicated otherwise.

To be usable by the plotting application, the data were converted into the degrees and decimal degrees format (DD.ddddd). In many cases, there were indications that the data would not need to be converted, despite the placement of decimal points or spaces. If the “minutes” or “seconds” numbers were greater than 59 in either the latitude or longitude, the data were assumed to represent degrees and decimal degrees, regardless of the placement of extra decimal points. For example, although “31.87.70.1” appears to be in the DD.MM.SS.s format, it cannot be because 87 minutes and 70.1 seconds are not valid coordinates. Therefore, this latitude, and its corresponding longitude, would be used as 31.87701° (DD.ddddd) without converting the numbers. In the absence of conflicting cues, the latitude/longitude data would be converted according to the assumptions described above.

The lack of a single, standard data format for latitude/longitude data and the potential ambiguity that is associated with the need to convert data of different formats resulted in possible data errors. One possible error type is due to the numbers being entered in the DD.ddddd format when they actually represent another format. This results in a *lack of conversion*. For example, 31° 23′ 41.410″ was entered in the database as 31.2341410°. The format implies that no conversion to DD.ddddd is necessary, but the original numbers actually were in the DD MM SS.sss format and should have been entered in that format (making the need for conversion obvious). Another error type is due to the numbers being entered in a format other than the DD.ddddd format when they actually represent the DD.ddddd numbers. This results in an *unnecessary conversion* being performed on the numbers. For example, 31.31063° was entered into the database as 31.31.06.3 and erroneously converted to 31.51842°.

Finding. The lack of a single, standard data format for latitude/longitude data and the potential ambiguity that is associated with the need to convert data of different formats resulted in possible data errors.

Figure 4-11 shows a plot for a pair of number strings (31 39439 and 94 53462) that is interpreted for three different latitude/longitude formats. Point A shows the numbers interpreted as the DD.ddddd format (31.39439° N, 94.53462° W). Point B shows the numbers as a DD MM SS.sss format (31° 39′ 43.9″ N, 94° 53′ 46.2″ W). Point C shows the numbers as a DD MM.mmm format (31° 39.439′ N, 94° 53.462′ W).

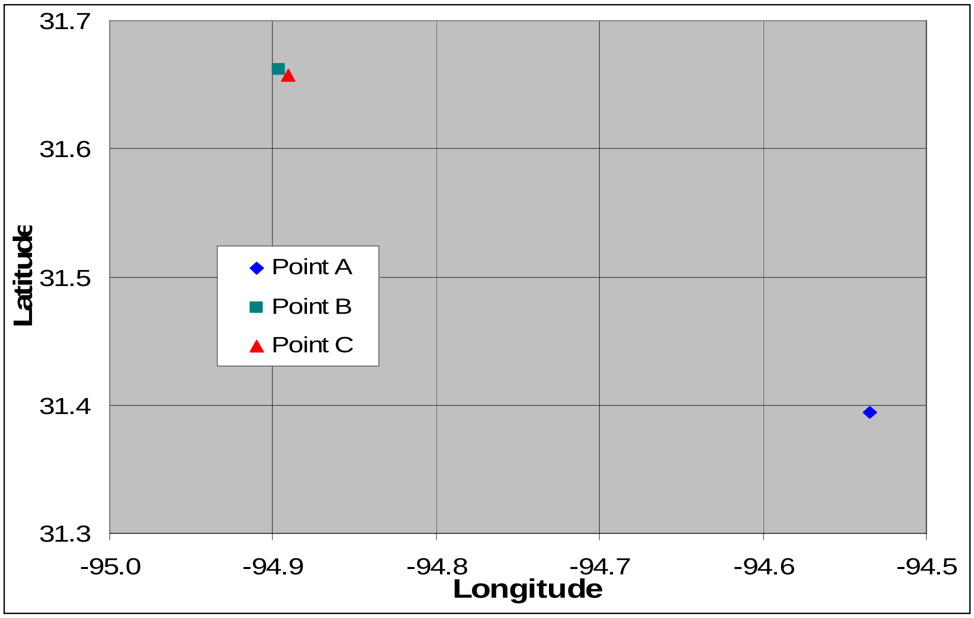

Figure 4-11. ***Plot for a pair of number strings that was interpreted for three different latitude/longitude formats*.**

In this example, Point A is approximately 28 miles from Points B and C; while Points B and C are less than six-tenths of a mile apart. This example demonstrates the magnitude of error that can occur if the wrong data format is assumed and a necessary conversion does not occur (or an *un*necessary conversion is performed).

To avert these errors and increase the confidence in the debris-plot-related analyses results, all forebody debris of critical importance that had suspect latitude and longitude data were researched to confirm or correct the latitude and longitude data recorded in the KSC debris database (or to provide missing data). Correcting the data involved researching the original field data sheets and the field photographs taken with GPS receivers in view, and, in some cases, using the field descriptions of the area (“100 feet north of county road X, one-quarter of a mile east of the intersection of county road X and county road Y”) and GPS/mapping software to establish corrected latitude and longitude data. This was a labor-intensive task, but the need for accurate debris recovery locations warranted the effort. Accurate debris recovery locations resulted in a higher degree of confidence in the debris plotting analyses and the ballistics-related analyses.

> ***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.[17]

4.5.7 Structural analysis

The recovered components of the CM and FF were studied in depth to provide information relating to failure mechanisms and timing. Areas of primary interest were the identified debris from the primary load bearing structures, windows, and hatches.

Figures were taken from drawings in the Orbiter Structures CATIA library, Version 4, which was developed by Boeing Engineer Daren Cokin.

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

OV-102 structural loads were taken from the following series of volumes:

- SSD96D0095, Volume 5, Book 1, OV-102 Structural Analysis for Performance Enhancement, Crew Module-Shell Structure, October 1997.
- STS 89-0537, Volume 5, Book 1, OV-102 Structural Analysis for 6.0 Loads, Crew Module-Shell Structure, Addendum A, October 1995.
- STS 89-0537, Volume 4, Book 1, OV-102 Structural Analysis for 6.0 Loads, Forward Fuselage Upper/RCS, Addendum A, October 1995.
- STS 89-0537, Volume 3, Book 1, OV-102 Structural Analysis for 6.0 Loads, Forward Fuselage Lower, Addendum A, October 1995.
- STS 89-0537, Volume 15, Book 1, OV-102 Structural Analysis for 6.0 Loads, Mid Fuselage, December 1992.

Estimated loads from aerodynamic simulations were compared to the structural load limits from the volumes cited above. The results from video analysis, debris field analysis, and debris inspection/analysis were used to determine the sequence of breakup. Engineering judgment and knowledge of the CM structure were used to assess the breakup.

4.5.7.1 *Structural capability*

When the orbiter was designed, structural analysis was performed to ensure that the CM and/or vehicle would maintain integrity under nominal conditions and a few defined off-nominal cases such as a crash landing. However, little work was done at that time to characterize failure modes in an effort to understand what might happen in a catastrophic situation. During this investigation, analysis was performed to determine the structural capabilities of the orbiter and the CM, and to predict failure modes and failure locations assuming certain load cases derived from the accident scenario.

The primary tools that were used to perform the assessments were structural certification documents, NASTRAN finite element structural analysis software code (using detailed finite element models of local structure), and a medium-fidelity, global-finite element model of the orbiter. With these tools, investigations were completed to assess the vehicle’s flight recorder loads, CM skin stress, CM attachment linkages and fittings forces, window thermal shock, window frame distortion, crew seat structural failures, and CM floor loading.

The objective of these assessments was to gain additional insight into CM structural performance and CM structural failures consistent with the accident debris. Load comparisons, conventional structural analysis approaches based on known conditions, and parametric analyses were the primary approaches that were used.

Conventional structural analyses were performed when primary inputs permitting this type of analysis were known, or when reasonable assumptions could be made regarding structural configuration, structure temperature, and loading. These analyses were performed using the flight data accelerations prior to LOS, while the vehicle was essentially intact.

Parametric assessments were required when less information was available. Since structural certification documents are based on nominal design conditions, the parametric assessments provided information about the structural response outside the design envelope. Exposure of the orbiter vehicle structure to high heating and changes in structural configuration required a parametric approach because, in many cases, the effects of heating shifted structural failure modes and failure locations away from areas that were documented as minimum capability zones in the certification reports. Parametric analyses were used to predict trends for structural failure with increasing temperature, stress contours for combined levels of pressure and inertial loading, and failure propagation as load paths changed.

4.5.7.2 *Crew seats*

In an attempt to determine individual crew load profiles, the team set out to identify seat debris items to specific seat locations. Configuration management records (tracking the serial numbers for seat components to the top-level seat assembly's serial number) were not accurately maintained, so identifying the locations of components by any surviving piece-part serial number was futile. The exceptions to this were components that were associated with the inertial reels, and all six recovered upper seatbacks were identified to specific seat locations.

Some seat debris items were identified to seat locations based on being attached to identifiable floor panels. One item was identified due to its unique application to one seat location. Most other seat components were identified to seat locations based on matching them to identified pieces (upper seatback components or pieces that were attached to floor panels). This process of matching pieces was very time-consuming and laborious. Eventually, slightly less than half of the recovered seat structure debris items were positively identified to specific seat locations. Had the individual seat components been permanently marked with serial numbers and those serial numbers tracked to the assembled seats using rigorous configuration management and control, reconstruction and identification would have been much easier and a higher percentage of pieces could have been identified to specific seats.

Seat structure debris items were studied to determine seat failure modes with the intent of determining the forces (and, therefore, CM dynamics) and the thermal profile. The analyses included gross and microscopic inspection of fracture surfaces, scanning electron microscopy of selected sectioned items, energy dispersive X-ray spectroscopy, and comparison to structural analysis of the seat design. These analyses provided information on the temperatures that were experienced by the seat components. Additionally, the identified failure modes revealed the loading conditions, directions, and dynamics.

Inertial reel mechanisms and straps were examined to obtain information on the seat restraint loading history (and, therefore, loads on the crew members), the thermal history, CM breach timeline, and crew separation timeline. Analyses included gross and microscopic inspection of the inertial reel mechanisms, straps, inertial reel housings, and upper seatbacks. Emphasis was placed on looking for evidence of loads (deformation or witness marks on the inertial reel components, failure modes and locations of the straps, deformation of inertial reel mounting hardware), and material deposits (metal deposits on the straps, melted strap material deposits on the inertial reel housings and seats).

4.5.8 Materials analysis

Materials analyses were performed by the JSC Materials and Processing Office, the JSC Astromaterials Research Office, the KSC Failure Analysis and Materials Evaluation Branch, and the White Sands Test Facility to characterize the deposition (char) on the window panes. Additionally, Langley Research Center performed materials testing on the seat fragments.

Analyses included performing microscopy of debris items to determine fracture dynamics and mechanisms, determining the compositions of materials deposited on the debris, testing materials to determine materials properties, and heating pristine materials samples in an attempt to match debris observations.

The following techniques were used for materials analysis:

- Optical microscopy including polarized light.
- Electron microscopy including scanning electron microscopy, transmission electron microscopy, and scanning tunneling electron microscopy.
- Energy dispersive X-ray spectroscopy.
- X-ray fluorescence spectroscopy.
- Fourier transform infrared spectroscopy.
- Focused ion beam milling.
- Selected area electron diffraction.

- X-ray diffraction.
- Backscattered Kikuchi diffraction pattern.
- Differential scanning calorimetry.
- Thermal gravimetric analysis.

4.5.8.1 *Crew seats*

Analyses were performed on the material deposited on the seat components to yield information relating to the CM breakup sequence and the thermal profile. These analyses included determining deposition patterns (portions of the seats containing deposits and directionality of the depositions) and analysis of the deposited material combined with investigation of vehicle materials to determine possible sources of the deposits.

Microscopy (optical and electron) and spectroscopy techniques were performed on the seat structures to determine failure mechanisms and thermal exposure.

4.5.8.2 *Boots materials thermal testing*

Thermal testing was performed on suit boot soles in an attempt to match the observed thermal damage. Boot soles of flight-like boots were heated in an oven to identify the range of thermal effects with varying thermal exposure. The test samples were exposed to 750°F (399°C), 1,000°F (538°C), or 1,250°F (677°C) at normal atmospheric pressure conditions (~14.7 pounds per square inch (psi), ~20% oxygen (O_2)) for 15, 30, 45, or 60 seconds. The materials showed no significant change in appearance until they combusted. This puzzled the team initially until it became clear that the presence of O_2 was affecting the results. The tests were repeated using new samples that were heated in a nitrogen (N_2) purge (<3% O_2). The samples were then compared to the recovered boot sole fragments. The results of the revised test protocol appeared similar to the recovered boot soles. The test samples that most closely matched the recovered debris items were those that were exposed to 1,000°F (538°C) for 30 to 45 seconds or 1,250°F (677°C) for 15 to 30 seconds. However, there is no credible scenario in which the *Columbia* boots would be exposed to these temperatures for the length of time indicated by the tests, so the test results could not be correlated directly to the debris observations. Because the test conditions (~14.7 psi, 97% to 99% N_2, 1% to 3% O_2) did not accurately approximate the entry environment conditions (low ambient pressure, monatomic oxygen, and possibly high dynamic pressure), they are a potential source of error in this analysis.

4.5.8.3 *Helmets*

Thermal gravimetric analysis was performed on helmet materials to determine the temperatures at which thermal decomposition (pyrolysis) begins. Determining these temperatures allowed the team to determine the thermal exposure of the helmets, which was used to predict helmet release times using ORSAT.

4.5.9 Medical processes

The SCSIIT Crew Team performed an extensive examination of all available medical evidence, performed additional studies including motion, thermal, and ballistic analyses, and correlated all of this information with the results of the other SCSIIT teams to develop a detailed crew event timeline sequence, cause(s) of death, threat matrix, and survival gap. NASA used an independent consulting firm specializing in injury analysis (BRC, San Antonio, Texas) to independently identify the threats with lethal potential that were faced by the STS-107 crew members and any mitigations that were in place at the time of the accident vs. those that are possible (i.e., the survival gap).

4.5.9.1 *Crew event timeline*

The crew event timeline development began with a review of the recorded air-to-ground (A/G) audio to identify any relevant information, such as timing of crew actions and the state of crew event awareness. The recovered videos, showing middeck and flight deck activities, were also reviewed and correlated with the A/G audio and recorded telemetry.

Forensic temporal markers were used to determine the sequence of observed injuries. The medical forensic evidence was then correlated with the audio and video evidence, recorded telemetry, and analysis of the recovered flight crew equipment. These correlations helped establish the configuration of the crew escape equipment at the time of the accident. All of this information was then used to develop the detailed crew event timeline.

4.5.9.2 *Cause of death determination*

The cause of death, blunt force trauma and hypoxia[18], was originally determined at the time of the autopsies, which were conducted by the AFIP.[19] During the CAIB investigation, a team that included members of the AFIP and FBI ensured definitive identification of the bodies, performed autopsies on the crew, provided photographic and X-ray documentation of the human remains, collected tissue specimens, provided sub-specialty interpretation of the microscopic slides, and performed toxicological analyses and spectral analysis of skin deposits. The data generated by the initial examining team were used by the SCSIIT as a starting point for determining what the crew experienced, the temporal sequence of events, and how these events related to the cause of death.

The standard AFIP autopsy protocol that was followed for determining the cause of death was subsequently found to be inadequate to address some of the unique aspects of a hypersonic, high-altitude-entry accident and did not include the collection of unique evidence that would have helped to better understand the sequence of events that the crew experienced and the unique injuries that were incurred from exposure to such extreme events and conditions. Although somewhat limited, the information that was derived from the autopsy reports was invaluable and was used to develop a matrix of the injuries inflicted on each crew member. This basic injury matrix was then expanded, based on additional studies and data reviews conducted by the SCSIIT Crew Team, and integrated with information derived from X rays, photographs, and additional reviews of the histology material. The expanded injury matrix was then used to identify any common injury patterns among the crew members. This also facilitated the identification of injury patterns based on crew location (i.e., flight deck vs. middeck, starboard vs. port).

All of the X rays and autopsy photographs were reviewed. A subset of the X rays and photographs, which was identified as having potentially useful information, was digitally enhanced and re-examined. This effort identified additional information that was not previously noted.

All of the histology slides were also re-examined to aid in confirming the cause of death and determine the temporal sequencing of injuries.

The Anthropometry Biomechanics Facility in the Habitability and Environmental Factors Division of the JSC Space Life Science Directorate was used to conduct medical analysis. A Vitus 3-dimensional scanner[20] was used to scan a SCSIIT member for use as a baseline in the suited and unsuited (i.e., minimally clothed) configuration. The anthropometry of the subject was recorded and compared to the STS-107 crew anthropometry data. The baseline subject's legs, torso, arm lengths, and shoulder and hip breadths were scaled using a percentage of the baseline subject's lengths to the STS-107 crew member's lengths to match each crew member's unique anthropometry, thus providing an anthropometrically correct model for each STS-107 crew member. The end results were scaled 3-dimensional (3-D) models representing the crew members. A simple 3-D skeleton model was also scaled to match the anthropometric measurements of each crew member. Each model was converted into a 3-D mesh and imported into a modeling tool called 3DStudioMax. Using the modeling software, the scaled suited mesh was attached to an underlying scaled skeleton that allowed all the linked scans to move in concert. After the individual crew member models were developed, they were incorporated into a 3-D computer model of the *Columbia* cockpit (developed by the CEL). Autopsy reports, dermatopathology data, and a review of the field intake and autopsy photographs were used.

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[18] *Columbia* Accident Investigation Board Report, Volume I, August 2003, p. 77.

[19] The AFIP is the U.S. government agency that is authorized to conduct autopsies on astronauts flying on U.S. spacecraft who die in the line of duty.

[20] Vitus is a 3-dimensional scanner that records a digitized image of the body using a laser to capture a surface image of an object. This surface image, which is a volumetric representation of the subject, can then be saved digitally and used to take anthropometric data.

The resulting models were then reviewed by the Crew Team. Patterns were analyzed to determine sequencing and potential injury sources.

All of this information was then integrated with the results of other SCSIIT sub-teams to form an integrated medical scenario and generate augmented autopsy reports that included all updated information and a final determination of the injury sequence leading up to death.

4.5.10 Other methods and processes

4.5.10.1 *Hygiene/drink package depressurization testing*

Intact hygiene bottles and empty (used) drink bags were recovered in the *Columbia* debris field. The fact that these items were not ruptured may indicate a depressurization rate that the CM experienced. Therefore, rapid depressurization tests were conducted in an attempt to determine the maximum depressurization rate that these packages can sustain without rupturing, determining an upper bound for the *Columbia* cabin depressurization rate.

Each trial consisted of testing shuttle-type shampoo bottles and drink bags. Testing was conducted at approximately 14.5 psi/second, approximately 18 psi/second, and approximately 31.5 psi/second. No packages ruptured at any of these rates. Because none of the shampoo bottles or drink bags ruptured during the depressurization tests indicates that the items are capable of withstanding depressurization rates greater than approximately 31.5 psi/second (which would represent an instantaneous, explosive depressurization of the CM – a scenario that is not supported by debris evidence). Therefore, no conclusions could be made regarding the rate of depressurization of the *Columbia* CM based on these tests.

4.5.10.2 *Advanced crew escape suits and crew worn equipment*

The recovered components of the crew worn equipment (advanced crew escape suit (ACES)), survival gear, parachute harness, and parachute pack) were studied in depth to provide information relating to crew injuries, CM breakup sequence, crew separation sequence, and suit disruption mechanism and timing.

Almost all of the approximately 75 recovered non-fabric components were identified to specific crew members. This identification was possible because most of the suit components and subcomponents were marked with serial numbers, and the serial numbers were recorded and tracked to the suit assembly, which was tracked to a specific crew member. In many cases, the serial numbers were stamped or etched on the hardware items and, therefore, survived the entry environment. In some cases, damage to the exterior of the component precluded reading the serial number, so other means were used to identify the hardware items. For the search and rescue satellite aided tracking beacons and the Army/Navy personal radio communications (A/N PRC) 112 radios, the processing modules were extracted and interfaced with ground support equipment to “read” the unique identifier codes of the specific unit. For the Sea Water Activated Release System (SEAWARS), the devices were disassembled and unique markings on the electronics packages were discovered. The vendor was contacted and the team was able to trace the unique markings to specific serial numbers for the SEAWARS units.

The ability to ascribe recovered crew worn items to specific crew members was critical to being able to draw conclusions based on the crew worn equipment.

4.5.10.3 *Helmets*

Visual inspection was performed on the helmets to qualify the helmet structural damage. Several nondestructive evaluation techniques were used in an attempt to determine the extent of thermal and mechanical damage beyond what the visual inspections revealed, with an emphasis on sub-surface damage. Computer tomography scans, real-time X-ray, thermographic (pulse flash and through transmission), and ultrasound testing were used to determine the structural condition of the fiberglass shell. These techniques validated damage sites that were seen in visual inspections and revealed some additional damage areas, but did not produce significant additional findings.

4.5.11 Cabin depressurization modeling

The Killer Press Model is a Microsoft Excel spreadsheet that was developed and used by NASA flight controllers to calculate pressure equalization times for two or three volumes connected in series. The user inputs the starting volume, pressure, and temperature of the air in the volumes in question and parameters for the venting path between the volumes. In all cases, the model assumes a circular vent path between volumes. The model outputs pressure with respect to time for the volumes. The cabin depressurization curves in Section 2.3 were generated using version 2.06 of Killer Press. These plots show the differential pressures between three volumes: the flight deck and middeck volume of the CM; the lower equipment bay of the CM; and the ambient atmosphere.

The following parameters were used as inputs: flight deck/middeck volume = 2,163 feet^3, pressure = 14.7 psi, temperature = 70°F (21°C); lower equipment bay volume = 337 feet^3, pressure = 14.7 psi, temperature = 70°F (21°C); vent path between lower equipment bay and middeck is ~50 in^2 (8-in.-diameter hole); ambient atmosphere volume = 1×10^{20} feet^3, pressure = 0.022 psi, and temperature = –67°F (–55°C).

Future Work

Future Work

Chapters 2, 3, and 4 outline the details of the analyses and assessments that were performed to understand the events with lethal potential that occurred. Many findings, conclusions, and recommendations were documented. However, it is also important to discuss the work that was not performed.

The Spacecraft Crew Survival Integrated Investigation Team (SCSIIT) was intentionally established as a small team. This allowed the team to maintain subject confidentiality, which was very important prior to publication of the report. However, the small size of the team, the resources that were available given Return to Flight and other very important programs, and the fact that most of the team members also had to continue their “regular” job assignments resulted in limitations to the investigation. Some items of interest were not accomplished due to lack of resources and schedule. A selection of future projects that may be of interest to complete in the future is listed below.

Although the list of testing and analyses below did not have significant influence on the SCSIIT conclusions and recommendations, the team believes that the data gained from these test and analyses will increase the knowledge base of the accident dynamics, spacecraft hardware, and materials commonly used in space vehicles.

> *Spacecraft Accident Investigation Database*. To develop a database for future investigators that will be cross-referenced across all spacecraft accidents to collect information in a single location.
>
> *Suit Destruction Testing*. To determine the forces that are required to disrupt the suit (remove helmet shell from helmet neck ring, remove suit-side neck ring from the suit, remove wrist rings from the suit), and to perform an analysis to determine the aerodynamic loads/windblast (Qbar or knots equivalent air speed (KEAS)) that is required to attain the above-mentioned forces with the end goal of determining the suit’s actual windblast capability. This evaluation should be done for visor down and visor up configurations.
>
> *Materials Analysis/Testing*. To positively determine the sources of the materials that were found deposited on various debris items. Also, testing should be done on suit materials (Nomex, GORE-TEX®, nylon), seat straps, and boot materials in a low ambient pressure (near vacuum), high heat, and atomic oxygen environment to simulate the environment at the Crew Module Catastrophic Event (CMCE) to understand how nonmetallic materials react in the thermal and chemical environments of spacecraft entry.
>
> *Static and Dynamic Testing on Seat Restraints*. To determine the forces that are required to fail the inertial reel strap with the strap fully extended and the strap partially retracted, and the forces that are required to fail the straps when at elevated temperature (200°F (93°C), 400°F (204°C), 600°F (316°C)).
>
> *Helmet Destruction Testing*. To determine the impact forces that are required to cause physical damage to the helmet.

Emergency Oxygen System (EOS) Bottle Testing. Investigate using microscopic analysis, materials analysis, etc. to determine the failure mode of the EOS bottle fragments and analyze the fracture surfaces to see whether the bottles were pressurized when they were fragmented.

Window Glass Analysis. To evaluate which window glass fragments collected in the field are from *Columbia* and which are non-orbiter.

Shock Wave Analysis. To better understand the effects of shock waves on aerodynamic heating in the hypersonic flight regime.

Titanium Combustion Analysis. To fully characterize the behavioral properties of titanium in an entry environment, including those that can lead to combustion.

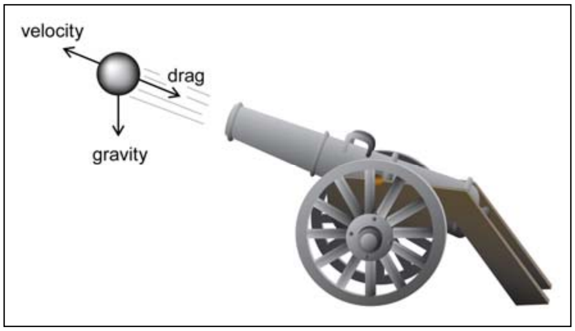
Challenger *Analysis*. Complete an analysis on the *Challenger* debris to compare and contrast with the *Columbia* findings.

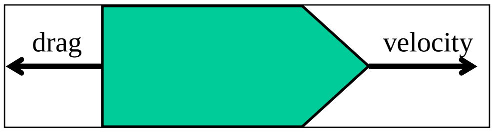
Appendix – Ballistic Tutorial

Appendix – Ballistic Tutorial

This is intended to give a reader a general understanding of ballistic number and ballistic trajectories. The objective is to give an intuitive understanding of the concepts rather than a rigorous derivation.

When the trajectory of an object is described as being ballistic, that means that the object has no control over its trajectory. As an example, think about a cannonball fired out of a cannon. Once the cannonball leaves the barrel of the cannon, the forces determining its trajectory are its own momentum (mass multiplied by velocity), gravity, drag, and winds.





Drag is the force that slows an object down as it travels through the atmosphere, and it is always opposite the velocity vector.

Drag is a function of thickness of the atmosphere, the velocity, reference area, and the coefficient of drag, C_D. The equation for the drag acceleration is

$$Drag\ \ acceleration = -\frac{1}{2} C_D \frac{Area}{Mass} \rho v^2$$

where C_D = coefficient of drag
Area = reference area
ρ = atmospheric density (thickness)
v = velocity

The minus sign indicates that drag acts opposite to the direction of travel. The coefficient of drag, C_D, is a function of the shape, orientation, and velocity of an object.

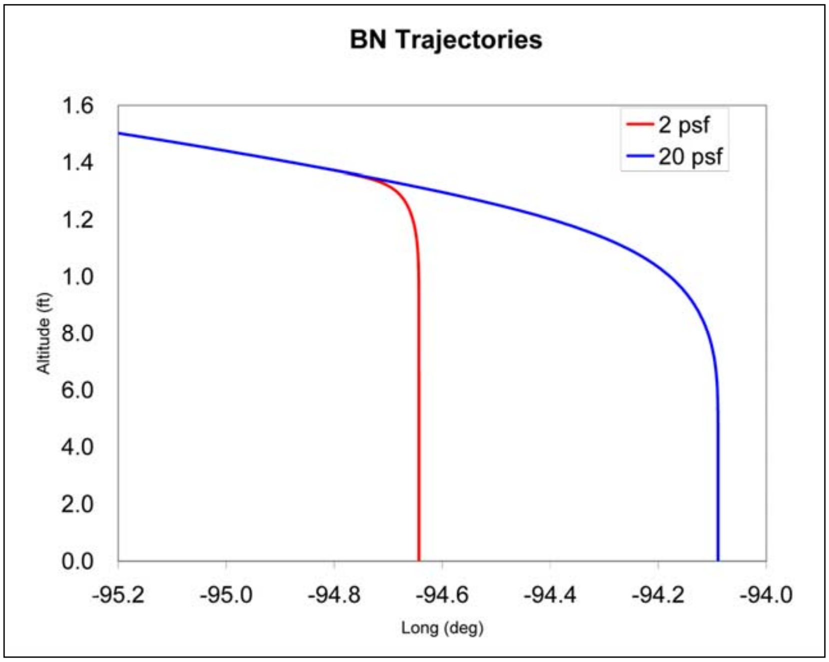
The ballistic number (BN) of an object can be thought as a measure of how far downrange the object will travel. The equation for the BN is

$$BN = \frac{W}{C_D * Area}$$

where W = weight

The units for BN are pounds per square foot (psf) (C_D does not have units associated with it).

Objects with large BNs will generally travel farther downrange than objects with smaller BNs. The plot below shows the trajectories for two objects with different BNs, 20 and 2 psf. The red line is the trajectory of the 2-psf objects and the blue line is the trajectory of the 20-psf object.

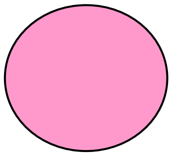


Let's look at how each of the parameters in the BN equation, weight, C_D, and area, affect the BN. First we'll look at weight.

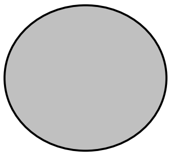
How Weight Affects BN

Two spheres, one is made of rubber and the other is made of aluminum. Both spheres have the same area and C_D.

Area = 0.087 ft^2 (a radius of 2 in.)
$C_D = 1$



Rubber
W = 1.3 lbs.
BN = 14.9 psf



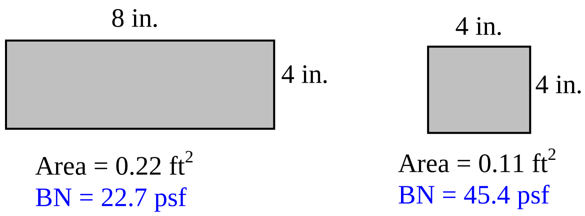
Aluminum
W = 3.3 lbs.
BN = 37.9 psf

The sphere with the larger weight, the aluminum sphere, will have a larger BN. If both spheres were released at the same altitude and velocity, the aluminum sphere would travel farther downrange than the rubber sphere because of its larger BN.

How Area Affects BN

For this example, there are two boxes, both made of aluminum. They have the same weight and C_D. The only difference is the area.

Weight = 5 lbs.
$C_D = 1$

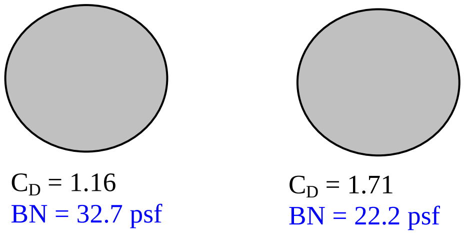


The box with the smaller area will have a larger BN. If both boxes were released at the same altitude and velocity, the box with the smaller area would travel farther downrange because of its larger BN.

How C_D Affects BN

Two spheres, both made of aluminum with the same weight and area. The only difference is that they are released at different velocities that give them different C_D's.

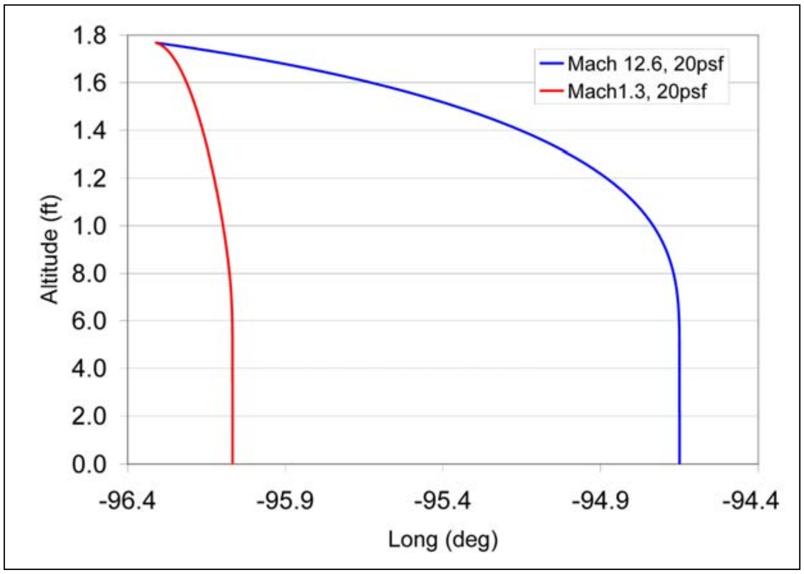
Area = 0.087 ft^2
Weight = 3.3 lbs.



The sphere with the smaller C_D will have a larger BN. But in this particular example, the sphere with the larger BN may not have the larger downrange distance because the initial velocities were different. The next section looks at how the initial velocity affects a ballistic trajectory.

How Initial Velocity Affects Ballistic Trajectories

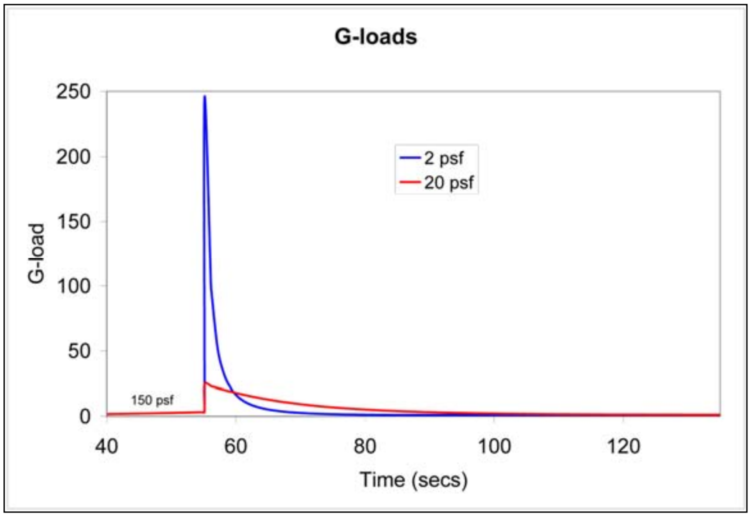
Two spheres have the same BN, which is equal to 20 psf, and are released at the same altitude. But they are released at different initial velocities, Mach 12.6 and Mach 1.3. The plot at the top of the following page shows the trajectories of each sphere. The red line shows the trajectory of the sphere that is released at Mach 1.3. The blue line shows the trajectory of the sphere that is released at Mach 12.6.



Even though both spheres have the same BN, the sphere that is released at the higher velocity will travel farther downrange. The initial conditions of the ballistic trajectory play a role in determining the downrange distance of an object.

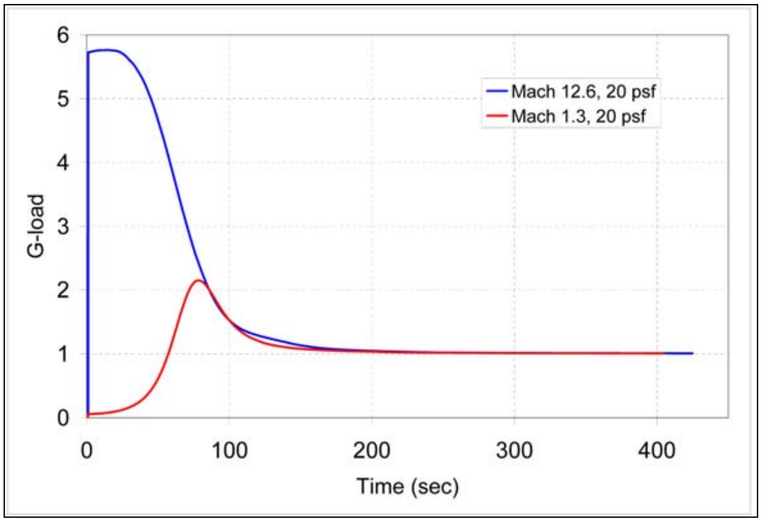
G-loads

Another topic that is related to BN is G-load. G-loads are the accelerations acting on an object divided by Earth's gravitational acceleration. When an object with a small BN is released from an object with a larger BN, the object with the smaller BN will experience a sudden change in the accelerations acting on it. This sudden change in the accelerations is called a G-load spike. As an example, let's go back to the 20 psf and 2 psf objects that we looked at in the beginning. Both of these objects are released from a larger 150-psf object. The plot below shows the sudden change in acceleration that each object experiences. The black line before the G-load spikes is the 150-psf object, the red line is the 20-psf object after release, and the blue line is the 2-psf object after release.



The 2-psf object experiences a much greater change in acceleration after being released than the 20-psf object. The greater the difference between the BNs of two objects, the greater the G-spike.

In a previous example, we examined the effect of initial velocity on two objects with the same BN. What would their G-loads look like? The G-loads for the Mach 12.6 and Mach 1.3 spheres are shown in the plot below. The red line is the Mach 1.3 object, and the blue line is the Mach 12.6 object.



The object with the higher release velocity had a larger G-load spike. The reason for this is found in the drag acceleration equation. It is a function of velocity squared. So, the higher-velocity object will experience a greater drag acceleration than the lower-velocity object.

$$Drag\ \ acceleration = -\frac{1}{2}C_D\frac{Area}{Mass}\rho v^2$$

But why did the G-load of the object at the lower initial velocity ramp up? That object’s velocity actually increased after release, increasing the drag acceleration, which increased the G-load.

To sum it up, a ballistic object has no control over its trajectory. The BN is a general measure of how far downrange an object will travel. The larger the BN, the farther downrange it will travel. G-load is a measure of the accelerations acting on an object. The larger the difference in BN between two objects, the larger the initial G-load, or G-load spike, will be at release. Initial conditions are important in ballistic trajectories. Different initial velocities for the same BN will generate different downrange distances and G-load profiles.

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