



Volume V

Appendix G.12

Crew Survivability

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Crew Survivability Report

Submitted by Group II

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PREFACE

Within two weeks of the STS-107 accident, NASA formed a Crew Survivability Working Group (CSWG) at the request of the Columbia Accident Investigation Board. The summary, which follows, was derived from investigation and analysis by the CAIB as well as the CSWG. The CSWG work dated 30 June 03 has been de-identified by crewmember and is attached as part of this appendix. The information presented in Volume 1 page 77 of the CAIB report, was drawn from this summary.

PURPOSE

While not the root cause of the mishap, understanding the cause of the loss of the crew will provide information that can be utilized in the design and planning of future space missions and vehicles to increase the probability of survival in the event of mishap.

VEHICLE INTEGRITY

In an effort to identify the integrity of *Columbia*'s pressurized cabin (the crew module – CM) prior to or during the catastrophic breakup of the vehicle, a detailed review of the environmental control and life support systems parameters that were down linked was performed. All cabin environmental parameters measured were nominal.

Although an additional 32 seconds of *Columbia*'s down linked data was recorded post LOS, there were no changes identified for the environmental control systems parameters over these 32 seconds. Additionally, the OEX accelerometer data during this period, and 17 seconds beyond, was not physiologically challenging and did not exceed any physiologic tolerance limits.

NO EVIDENCE OF AN EXPLOSION

Forensic evaluation of all recovered crew module / forward

fuselage (CM/FF) components does not provide evidence for an over-pressurization and/or explosion event. This conclusion is supported by both the lack of forensic evidence and by lack of a credible source. Water tanks from below the mid-deck floor, along with both Forward Reaction Control System (FRCS) tanks were shown not to have undergone explosive failure.

An analysis was performed to establish the maximum delta pressure that could be generated assuming a sufficient heat rate was provided to cause all five tanks to burst simultaneously. The analysis concluded, given the tank sizes, initial temperature and pressure conditions, and water volumes, that the maximum delta pressure that could be created within the volume where the water tanks are located is only 50 psia. Based on this, the water tank rupture as a contributing factor towards seat failures, was dismissed.

Additionally, explosives experts from the FBI reviewed the crew cabin hardware at KSC and came to the conclusion that an explosive force was not a factor in the failure of this hardware.

STRUCTURAL FAILURE

Separation of the CM/FF assembly from the rest of the vehicle likely occurred at the interface between the Xo576 and Xo582 bulkheads. Subsequent break up of the assembly occurred as a consequence of ballistic heating and dynamic loading events. Materials evaluation of fractures on both primary and secondary structure elements suggests that structural failures occurred at stress and strain rates that, absent high temperature, would not have resulted in failure.¹

MEDICAL AND LIFE SCIENCES

An extensive medical, crew health, STS-107 medical open items and in-flight anomaly review was completed. Space and Life Sciences Directorate Flight Readiness Review data were investigated. The Armed Forces Institute of Pathology

and Federal Bureau of Investigation conducted forensic analyses after recovery from the debris field. Death occurred after 14:00:19 (GMT) and was due to the physical environment associated with Crew Module catastrophic failure; death was due to blunt trauma and hypoxia with no evidence of lethal injury from thermal effects.

DATA FROM ORBITER AND OTHER SOURCES

CABIN ATMOSPHERE

In an effort to identify the integrity of *Columbia's* pressurized cabin prior to or during the catastrophic breakup of the vehicle, a detailed review of the environmental control and life support systems down linked parameters was performed. The cabin environmental data was nominal shirtsleeve environment. An additional 32 seconds plus two follow-on seconds of *Columbia's* down linked and GPC data, respectively, were recorded post LOS (Table 1), there were no changes identified for the environmental control systems parameters.

- | | |
|---------------------------|--|
| • Cabin Pressure | 14.64 psia |
| • Cabin Temperature | 71.6 deg F |
| • Humidity | 37.9% |
| • ppO2 Levels (3 Sensors) | 3.14 psia (Sensor A),
3.14 psia (Sensor B),
3.16 psia (Sensor C) |
| • DP/dt | 0.004 psi/min |
| • ppCO2 | 1.96 mmHg |
| • Cabin Temp Setting | 0 or full cool/full
HX flow |

- | | |
|-----------------------|--|
| • N2 Supply Pressures | 1011 psia (Sys 1),
1067 psia (Sys 2)
– Nominal |
| • O2 Supply Pressures | 822 psia (Sys 1),
809 psia (Sys 2)
– Nominal |

Table 1.

FLIGHT DYNAMICS

Trajectory Reconstruction Process

The fundamental objectives of this effort were twofold: to identify, as accurately as possible, 1) the point in the trajectory of the *Columbia* when the crew module separated from the rest of the vehicle and 2) when the crew module itself began to disintegrate. Therefore, for the most part, all efforts were concentrated on the forward part of the vehicle and the crew module. The procedure used in this process is very straightforward. A piece of debris-of-interest is identified and its weight, size, and aerodynamic characteristics are determined. Using this information, its ballistic number is calculated. Knowing the location on the ground where a piece of debris was found, a trajectory program is executed in an iterative fashion to determine at what point in *Columbia's* trajectory did that piece of debris have to have been released in order to land at that particular point on the ground. In other words, where do the trajectories of the piece of debris and the CM/FF intersect? It is at this point that the debris separated from the CM/FF.

Obviously, there are several assumptions made in the course

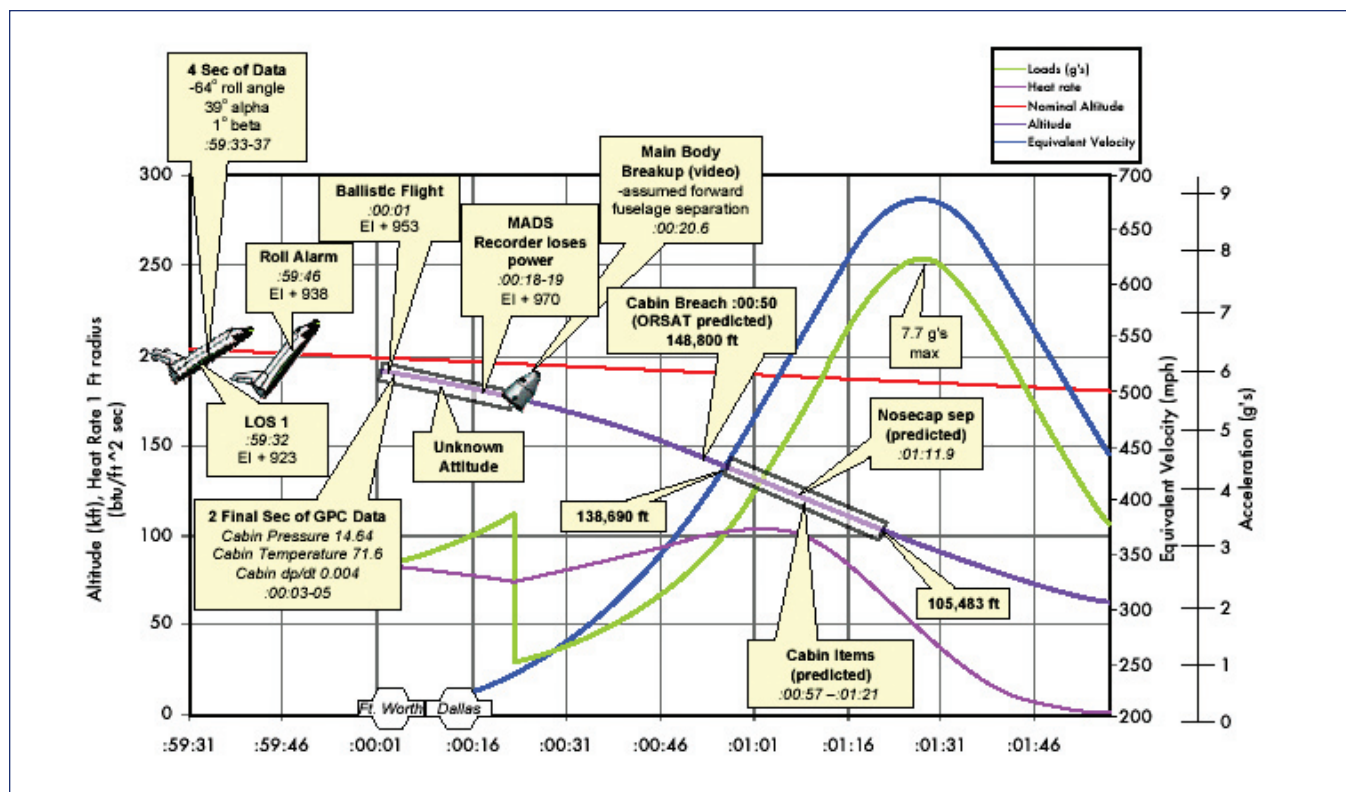


Figure 1.

of this process. The weight and area of the object as it was found may not be the same as when it became separated. Due to heating, structural loads, etc., the configuration of a given object may change. Similarly, defining the aerodynamic characteristics contains a certain amount of uncertainty since it is done computationally (although, at these altitudes, simple Newtonian assumptions are quite good). From that point of view, the most reliable objects would be spherical since the aerodynamic characteristics of a sphere are well known.

Data Sources

The first source of information was the official Rev 15 timeline and was continually refined as more data became available. All of the results derived from this process necessarily had to fit the official timeline or provide a strong rationale for revising it. Most of the information from the timeline are known quantities that were used as facts for this investigation.

Much information was gathered regarding debris and materials that originated from the crew module. This included crew equipment (helmets, radios, etc), objects definitely located in the crew module (toilet, racks, instrumentation, etc), and structural debris. These pieces were characterized as to weight, size, and aerodynamics and subjected to the iterative trajectory process mentioned above. The results were then plotted to determine their origin with respect to the orbiter's trajectory.

FLIGHT DYNAMICS

Trajectory Reconstruction

An overall summary of the disintegration scenario can be seen in Figure 1. In addition to the timeline markers are some predicted events as well as load and heat rate calculations for the crew module on its trajectory. The band superimposed on the trajectory (starting about 14:00:58) indicates the window within which all of the debris analyzed originates. This would indicate that the destruction of the crew module took place over approximately 24 seconds. It is significant to note that the heat rate peaks near the beginning of this period while the load environment is increasing throughout the period. Thus, it is postulated that the cabin was exposed to significant heat load together with an increasing load environment. This resulted in the complete destruction of the vehicle and is also consistent with the structural analysis of the CM debris.

In spite of the diversity of items analyzed, and the uncertainty in the circumstances of their release, the analysis demonstrates that they cluster about an area along the trajectory that is about 24 seconds long which began at an altitude of approximately 140,000 feet and ended at 105,00 feet. A thermal entry model, ORSAT, was used to predict when entry heating would cause structural failure of CM. ORSAT predicted approximately 140,000 feet, which is consistent with the independent aerodynamic model. Another corroborating piece of evidence of ORSAT's ability to accurately predict heat-induced damage is its prediction of the thermal damage to helmet visors. ORSAT forecasted that the laminate

helmet visor would experience melting of one laminate and not the other. Subsequently, when the helmets were located in the debris field, the damage observed was what ORSAT predicted. This leads to the conclusion that the crew module was breached early in that window and was in the process of continual disintegration throughout the 24 seconds.

GROUND BASED ANALYSIS

In addition to the trajectory analyses, the debris footprint on the ground was analyzed to see if there were any patterns that could be used to infer the sequence of events. This analysis was limited strictly to the crewmembers and the equipment they were closely associated with at the time of the event. The most western piece of crew equipment found was a helmet from the mid-deck. The breakdown as to location of the remaining crew equipment showed that the mid-deck crew equipment was the farthest west and the flight deck crew equipment was at the eastern end of the debris field. Therefore, it seems reasonable to conclude that the crew equipment on the mid-deck separated from the CM before the flight deck crew equipment.

It is also interesting to note the order in which debris was found on the ground. With one exception, and taking into account missing items, the debris pattern is repeatable between crew positions.

FORENSIC HARDWARE INVESTIGATION

CREW WORN EQUIPMENT

Based on recovery of the wrist rings from the ACES suits that were worn by the crew during entry it could be determined that 3 crewmembers were not wearing their gloves at the time of the mishap. Based on the recovery of the helmets, it was determined that one of the crewmembers was not wearing their helmet at the time of the mishap.

STRUCTURE

Recovered Debris

Approximately 45% of the original crew module mass was recovered. Some major structural elements recovered, included portions of the forward and aft crew module bulkheads, window frames, mid-deck floor components, airlock and hatches. About 70% of the flight deck panels, and 80% of the mid-deck floor were recovered. Less than 20% of locker metal structure and fragments of the plastic and composite material of the locker trays were recovered. The Mid-deck Access Rack (MAR) was found nearly intact. Although some foam, fabric and paper were recovered, the bulk of the items recovered consisted of metal, plastic and composite materials. It is estimated that less than 30% of items stowed in the lockers were recovered. The EVA tool and suit debris (stowed mostly in the airlock for entry) were weighed, with 40% of the original mass recovered. The condition of the recovered debris items varied widely; from highly melted, twisted and torn, to near pristine (Figure 2). Overall, the damage distribution of crew module debris is consistent with surrounding debris from the forward fuselage structure.



Figure 2.

Debris recovered from the crew module experienced noticeably less aerodynamic heating than other portions of the vehicle. Primary and secondary structure elements failures occurred at high temperatures evidenced by broomstraw² fractures. Five major attach points that suspend the crew module inside the forward fuselage were recovered, the port and starboard side fittings were recovered with evidence of high heating.³

Structural Failures

Separation of the CM/FF assembly from the rest of the vehicle likely occurred at the interface between the Xo576 and Xo582 bulkheads. Each fitting exhibited failures at both its crew module interface and Xo582 frame interface. The crew module interface failed at the longeron tab on both the port and starboard sides. On the Xo582 frame interface, the starboard side experienced a lug tensile failure while the port side fittings pulled through the Xo582 frame. Both the port and starboard side struts of the Y-linkage failed in tension at the clevis end fittings. The port side failed in proximity to the Xo582 ring frame, the starboard side in proximity to the Xo576 bulkhead. The Z-link failed at the attach point to the Xcm200 bulkhead. The joint failed by a combination of both fastener tensile failure and fastener insert pullout. This is similar to what happened in the *Challenger* mishap. Subsequent break up of the assembly occurred as a consequence of ballistic heating and dynamic loading events.⁴

Mid Deck Floor Structure

Approximately 80% of the mid-deck floor was recovered. Generally, mid deck floor panel and structure components experienced heating, but not of sufficient magnitude to cause melting of metallic components (with the exception of the LiOH door (Figure 3) and a few very localized areas on two recovered structure items). Heating was however sufficient to cause significant damage to the Aeroglaze topcoat (paint) and in some cases the Koropon primer.

Flight Deck Floor Structure

Unlike the mid deck floor, it is estimated that less than 10%



Figure 3.

of the flight deck floor was recovered. This is attributed to the substantial amount of heating experienced in this area.

Generally, only small portions of flight deck floor panels, structure, and seat components were recovered. In all cases, debris components are highly melted and/or deposited with splattered aluminum on all surfaces. None of the coating materials (topcoat or primer) survived.

The magnitude and distribution of heating experienced by flight deck components suggests a prolonged attachment to the larger crew module structure during re-entry (i.e. high ballistic number). Heating patterns on all debris components appears to be defined by the attachment to surrounding structure. This suggests these items were released from the crew module later in the break-up sequence as compared to items from the mid-deck locations. Ground plots of fallen debris also support this conclusion.

Crew Module Pressure Shell

Relatively speaking, some debris recovered from the crew module experienced noticeably less aerodynamic heating than other portions of the vehicle. No substantial portions of the CM shell were recovered. Those portions which were recovered such as pieces of the airlock, mid-deck LiOH door, and related structures showed failure and melting of thin sections where the contiguous ribbed sections were essentially undamaged indicating that the heating rate, duration of heating, and total energy input was not of such a magnitude to overcome the limited thermal capacity of the contiguous ribbed regions. Relatively speaking, more of the pressure shell was recovered from the lower crew module area than anywhere else

Heating was sufficient to burn away nearly all exposed thin sections of the exterior pressure shell (including bulkhead areas), and exposed thin section areas of internal components. Although some recovered debris has significant thermal damage, evaluation of heat patterns do not suggest any evidence that an internal cabin fire occurred before vehicle break-up.⁵

Seat Structure

A rather large collection of seat debris items was recovered. Since the majority of the lightweight seat design is common to all seven seat locations, positive seat assignment on most of the recovered seat debris was not possible. Major differences in the magnitude of thermal exposure were identified on flight deck vs. mid deck seat locations. As with the flight deck structure, flight deck seat components were highly melted and/or deposited with splattered aluminum on all surfaces. In contrast, mid-deck seat structural components did not experience any melting at all. The mid-deck seat 6 and 7 locations (Figure 3) did however collect significant deposits of melted aluminum from the LiOH door that these two seats were attached to. This melting appears to have occurred due to the LiOH floor panel having the seats and crew still attached at the time of separation from the CM.

Hardware Forensics Evaluation

Separation of the CM/FF assembly from the rest of the vehicle occurred as a consequence of heating and structural loading experienced outside of the vehicle design envelope. Although significant loading events initiated this separation, failure of the crew module structure was not instantaneous. Failure modes assessed on crew module structural components suggest that fractures occurred subsequent to and as a result of elevated temperature exposure (corresponding to a significant reduction of material properties). Thus, subsequent break-up of both the crew module and forward fuselage structure occurred as a consequence of the combined environments provided by ballistic heating and aerodynamic loading.

CONCLUSIONS

Acceleration levels seen by the crew module prior to its catastrophic failure were not lethal. LOS occurred at 8:59:32. The death of the crewmembers was due to blunt trauma and hypoxia. The exact time of death – sometime after 9:00:19 a.m. Eastern Standard Time – cannot be determined because of the lack of direct physical or recorded evidence. Failure of crew module was precipitated by thermal degradation of structural properties that resulted in a catastrophic sequential structural failure that happened very rapidly as opposed to a catastrophic instantaneous ‘explosive’ failure. Crew module separation from the forward fuselage is not an anomalous condition in the case of a vehicle loss of control as has been the case in both 51-L (*Challenger*) and STS-107 (*Columbia*).

SUMMARY

It is irrefutable, as conclusively demonstrated by items that were recovered in pristine condition whose locations were within close proximity to some crewmembers, that it was possible to attenuate the potentially hostile environment that was present during CM break-up to the point where physically and thermally induced harmful effects were virtually eliminated. This physical evidence makes a compelling argument that crew survival under environmental circumstances seen in this mishap could be possible given the appropriate

level of physiological and environmental protection.

1. Determine the cause of the loss of the crew – the loss of the crew occurred from blunt force and hypoxia. The exact time of death is indeterminate due to the lack of evidence of initiation and rate of cabin decompression.
2. Thermally induced degradation of structural properties of the CM resulted in its catastrophic structural failure. This failure subjected the crew to lethal environmental factors that included windblast, low atmospheric pressure and entry heating.

RECOMMENDATIONS:

NASA should investigate techniques that will prevent the structural failure of the CM due to thermal degradation of structural properties and determine their feasibility for application.

Future crewed vehicles should incorporate the knowledge gained from the 51-L and STS-107 mishaps in assessing the feasibility of designing vehicles that will provide for crew survival even in the face of a mishap that results in the loss of the vehicle.

Crew procedures and techniques for use of CWE should be standardized and complied with by all crewmembers.

Footnotes

- ¹ NSTS-60501, STS-107 *Columbia Reconstruction Report, Debris Assessment, Conclusion*, pg. 117, June 30, 2003
- ² NSTS-60501, STS-107 *Columbia Reconstruction Report, Appendix A*, pg. 147, June 30, 2003
- ³ NSTS-60501, STS-107 *Columbia Reconstruction Report, Debris Assessment Sub-Systems, Crew Module*, pg. 103, June 30, 2003
- ⁴ NSTS-60501, STS-107 *Columbia Reconstruction Report, Debris Assessment Sub-Systems, Crew Module*, pg. 103, June 30, 2003
- ⁵ NSTS-60501, STS-107 *Columbia Reconstruction Report, Debris Assessment Sub-Systems, Crew Module*, pg. 103, June 30, 2003

Note: This appendix contains draft recommendations that were reviewed by the Board. The conclusions drawn in this report do not necessarily reflect the conclusions of the Board; when there is conflict, the statements in Volume I of the Columbia Accident Investigation Board Report take precedence.

The information contained in the following pages was compiled by the CAIB/NASA JSC Crew Survival Working Group.

ASSUMPTIONS/FINDINGS

DATA FROM ORBITER AND OTHER SOURCES

Cabin Atmosphere

In an effort to identify the integrity of *Columbia's* pressurized cabin prior to or during the catastrophic breakup of the vehicle, a detailed review of the environmental control and life support systems downlinked parameters was performed. The following measurements (all nominal) were recorded at mission control at the time of loss of signal (LOS) from *Columbia*:

- Cabin Pressure 14.64 psia
- Cabin Temperature 71.6 deg F
- Humidity 37.9%
- ppO₂ Levels (3 Sensors) 3.14 psia (Sensor A),
3.14 psia (Sensor B),
3.16 psia (Sensor C)
- DP/dt 0.004 psi/min
(this is the zero point due to the sensor bias)
- ppCO₂ 1.96 mmHg
- Cabin Temp Setting 0 or full cool/full HX flow
- N₂ Supply Pressures 1011 psia (Sys 1),
1067 psia (Sys 2)
– Nominal
- O₂ Supply Pressures 822 psia (Sys 1),
809 psia (Sys 2)
– Nominal

An additional 32 seconds, plus two (2) follow-on seconds, of *Columbia's* downlinked and GPC, respectively, data were recorded post LOS, there were no changes identified for the environmental control systems parameters.

As far as the Modular Auxiliary Data System Recorder, which was recovered from the *Columbia* debris, there are no environmental control systems parameters recorded on this system.

Water Tank Analysis

When members of the CSWG initially reviewed the crew cabin debris at the Kennedy Space Center (KSC), some of the debris suggested there may have been an explosive force from below the middeck up toward the top of the vehicle. In particular, middeck seats failed in the middle of the leg posts, as opposed to the connection points on the middeck floor, which are the weakest point structurally.

Based in particular on the seat failure, an assessment was done to identify the hardware located below the crew cabin capable of generating an increased pressure (or force) due to high delta temperatures or pressures. The only hardware

identified was the four (4) potable water tanks and one (1) wastewater tank located immediately below the pressurized cabin.

An analysis was performed to establish the maximum delta pressure that could be generated assuming a sufficient heat rate was provided to cause all five (5) tanks to burst simultaneously. The analysis concluded, given the tank sizes, initial temperature and pressure conditions, and water volumes, that the maximum delta pressure that could be created within the volume where the water tanks are located is only 50 psia. Based on this, the water tank rupture as a contributing factor towards seat failures, were dismissed.

Additionally, explosives experts from the FBI reviewed the crew cabin hardware at KSC and came to the conclusion that an explosive force was not a factor in the failure of this hardware.

Cabin Depressurization

An analysis was performed to determine the time required for the cabin to depress to the altitude pressure at 200,000 feet (0.0028 psia) from a nominal 14.7 psia cabin pressure. Five (5) cases were analyzed, (a) bulkhead (BH) penetrations of 2.54 in², (b) BH penetrations + 2" diameter hole (equivalent to eject the Waste Collector Subsystem (WCS) Commode Control Handle (CCH) ball), (c) 36" diameter hole (equivalent to the Airlock "A" hatch), (d) 36" diameter hole + BH penetrations + 2" WMC penetration, and (e) 72" diameter hole + BH penetrations + 2" diameter WMC penetration.

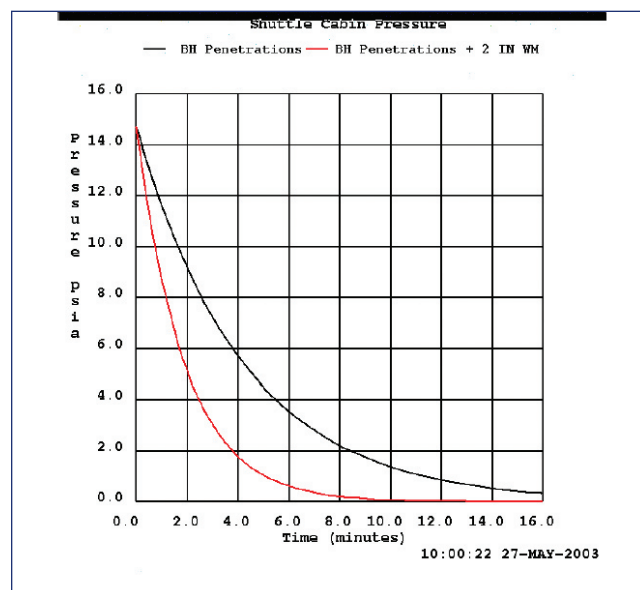


Figure XYZ Cabin Depressurization Cases (a) and (b).

Each case was selected to understand the range of possible depressurization rates, as a function of possible CM break-up scenario. Case (b) was selected as the WCS CCH ball was one of the furthest west CM item found. Case (c) was selected to simulated loss of the Airlock "A" hatch.

The analysis results are reflected in the graph below. Clearly, depress rate significantly varies, from minutes to seconds of useful cabin atmosphere. The CSWG is still analyzing data and hardware in an attempt to, at a minimum bound the depress rate. Depending on the scenario chosen, one can conclude whether or not the crew had or did not have time to execute various malfunction/contingency procedures.

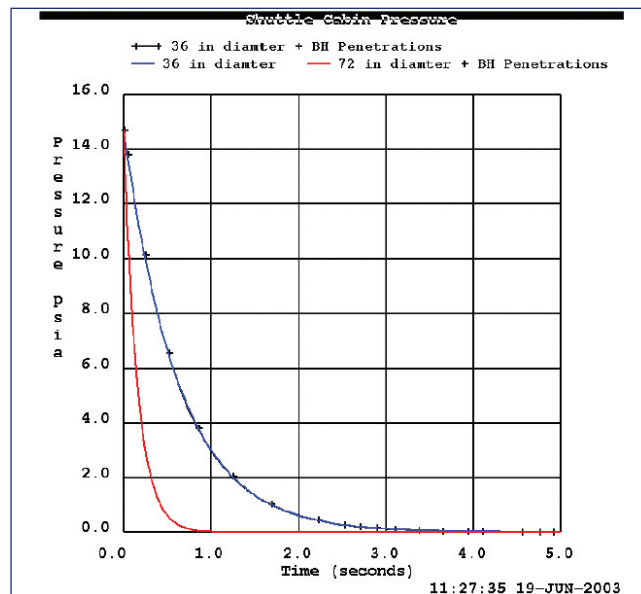


Figure XYZ Cabin Depressurization Cases (c), (d), and (e). Blue (or upper) curve contains both (c) and (d) cases.

FORENSIC HARDWARE INVESTIGATION

Shuttle Crew Escape Equipment (CEE)

Helmets and Suit-Disconnects

General Condition

Seven out of seven helmets along with six out of seven suit-side disconnects were recovered. Five of the seven helmets were recovered with the suit-side disconnect ring still attached. Thus, failure occurred predominantly between the suit-disconnect and suit fabric interface. Detailed inspection of all helmets and helmet to suit-disconnect interfaces suggests all but one crew member had their helmet on and properly installed at the time of crew module failure.

In general, the condition of each helmet shows effects from both mechanical and thermal loading. Effects from thermal loading were generally consistent across all helmets, except for the helmet that was not worn at the time of the mishap (much better condition). The effects from mechanical loading were generally consistent across all seven helmets. The magnitude and distribution of mechanical damage was not severe (except for that caused by ground impact).

Thermal Condition

Thermal effects were apparent throughout all helmet sur-

faces. Significant variations in general thermal condition were noted from helmet to helmet (both interior and exterior helmet surfaces). Reflective tape was missing from all outer helmet surfaces. Various amounts and depths of fiberglass delaminations were observed. Some white paint survived, outside of areas removed via fiberglass delamination. Residual paint on exterior helmet surfaces shows signs of damage consistent with impact from a large number of small debris items ("crater-like" pitting).

Both shallow and deep delaminations on helmet exterior surfaces appear associated with thermal effects. Significant variations in both location and magnitude of "hot spots" (i.e. stagnation points) were observed on exterior helmet surfaces:

Relatively small amounts of residual melted suit material were discovered, all of which was confined to the helmet / suit disconnect ring area. On all helmets except the one that was not worn, melted suit material was observed on both sides of the helmet / suit-side disconnect interface. Melted materials appear consistent with suit bladder materials (Nylon and Teflon), but not with Nomex. In all cases, the relative absence of Nomex material anywhere on internal or external helmet surfaces was noted. Close inspection of the suit / bladder clamp interface on the suit-side disconnect ring yielded only Nylon and Teflon materials (absent Nomex). As a result, it is suggested that the Nomex material failed mechanically before the chemical break-down temperature was reached (500°C). Thus, temperature may have degraded suit/helmet interface, yet the two were not melted apart. Deposition of melted suit material onto the helmet and suit-side disconnect areas appears to have occurred after mechanical separation of the helmet (small fragments of suit material were still clamped into suit-side disconnect upon mechanical separation).

On three of the seven helmets, the upper visor reinforcement bar survived with some Lexan / Plexiglass visor material still attached (large amount on helmet not worn). Upper and lower visor bars along with visor materials on each of the other four helmets did not survive. The visor is constructed of a two materials laminate: Polycarbonate and Polymethylmethacrylate. In all cases, the Polymethylmethacrylate flowed and the Polycarbonate did not. Subsequent laboratory analysis of visor materials suggests that helmet visor materials achieved temperatures between the range of 300 – 400 °C (572 - 752 F).

Mechanical Condition

In all cases, the helmet structure remained intact and the helmet profile was preserved in original form. Generically speaking, the helmets experienced a wide range of localized mechanical damage (fractures), but did not experience massive structural damage from external surface impacts (prior to ground impact). External helmet impacts were insignificant in size and random in distribution. Internal impacts were observed on all helmets.

Hold-down cables on each helmet (except the unworn helmet) were severed at the attach points to the cable guide



Recovered Glove Disconnects.

tubes (mechanical overload). All cable guide tubes (except the unworn helmet) experienced significant plastic deformation. Guide tubes display evidence of external contaminants (i.e. melted suit material) and thermal effects on top of fractures / localized deformation. This implies that mechanical loading was followed by exposure to thermal environment. Relative rotation of the helmet to suit-disconnect ring was observed all helmets (except the unworn helmet) anywhere from 90 to 180 degrees from forward nominal. Major cable guide tube deformation and helmet rotation supports evidence for a significant loading event, i.e. helmets were removed via mechanical (not thermal) mechanism.

Only one of the seven helmets (the unworn helmet) was recovered with the bailer bar still attached. All others were mechanically removed, yet the bailer bar cam mechanism remained in place (yet damaged) on both the starboard and port side helmet interfaces. The bailer bar latch mechanism on five out of seven helmets survived in good condition. This would not be expected if the crewmembers had achieved a “visor down” position (mechanical separation of bailer bar would also fracture latch assembly). The other two helmets experienced latch mechanism separation (fractured fasteners) before subsequent deposition of melted suit materials. This suggests sequence of events, i.e. latch separation followed by suit melting. Neither of these two helmets show evidence of indentation / deformation which could be associated with forces expected if the bailer-bar “ripped” the latch from the helmet-side disconnect ring. Thus, it is unlikely that any of the crewmembers achieved a helmet “visor down” position.

Glove Disconnects

A total of ten glove disconnect debris items were recovered

corresponding to six out of seven crewmembers. Exposure to entry heating environments is apparent throughout. However, the level of heating varied substantially from item to item. Items from some crewmembers experienced significantly greater heating than comparable items on other crewmembers. Also, significant differences in heating were noted from the left to right sides on some crewmembers equipment. Detailed inspection of recovered debris items suggests that three of the seven crewmembers did not have gloves properly installed during re-entry.

Melted aluminum material was deposited onto exposed glove disconnect rings in 5 of 7 cases. The source of this material appears to be external to the glove disconnect rings (i.e. surrounding structure).

Melted suit material was discovered on all recovered glove disconnect items. Close inspection of the suit / bladder clamp interface on the suit-side disconnect ring yielded mainly nylon and Teflon materials (absent Nomex). In all cases, minimal amounts of Nomex remained clamped at the interface. Overall, the amount of residual melted suit material appears to correlate with the general magnitude of heating (i.e. higher magnitude heating resulted in the pyrolysis of residual suit material). As with the helmets, deposition of melted suit material onto the glove disconnects areas appears to have occurred after mechanical separation (small fragments of suit material were still clamped into suit-side disconnect upon mechanical separation). Thus, failure modes at the suit-side disconnect ring (between the suit-side ring and suit material interface) were similar to those observed at the suit-side helmet disconnect location (see Helmet section above).

Emergency Oxygen System (EOS)

Two EOS bottle/reducer subassemblies are flown per crewmember and are located within the harness assembly. Ten total individual EOS bottle/reducers have been found to-date, each with no oxygen remaining. All 10 individual EOS bottle/reducers present similar appearances. Material of construction consists of an outer stainless steel, cryogenically formed, bottle and a metallic regulator assembly.

No Nylon material, from the harness that contains the EOS, was visibly found adherent to the bottle/regulator assembly. Minor evidence of elevated temperatures is visibly identifiable, however, directional burn marks and discrete externally induced impacts are visible. As with most *Columbia* hardware, ground-induced corrosion is also evident. X-ray revealed all regulators have been activated, however, this could have occurred with separation of the bottles from the harness. Final determination if any crewmember in-fact activated an EOS is still under analysis.

Overall appearance suggests 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, experienced ballistic heating and some metal pellet-like impacts

SEAWARS

Two SEAWARS are flown per crewmember (left/right) and are part of the Personal Parachute Assembly (PPA) risers, which interface to the harness. Six total SEAWARS have been found to-date, none auto-ignited, and those inspected with both male/female buckle sections still attached. All six SEAWARS present similar appearances, consisting of the SEAWARS assembly still attached to approximately 12" of Nylon harness strap remnant. Material of construction consists of an outer aluminum casing, plastic external components, various internal electronic components, and an interfacing Nylon harness strap.

Only two of six SEAWARS have been inspected to-date (remaining to-be inspected by end of JUL 2003). Each SEAWARS has evidence of directional melting, burning, and mechanical loading. Each SEAWARS was found with only the lower Nylon strap, a surviving length consistent with failure at the waist. While the terminating ends show evidence of melting, they do not suggest significant melting. Localized heating on the metallic SEAWARS Frost fitting (i.e., buckle) suggests intense heat exposure, perhaps ballistically induced, for a short duration. Final determination if any crewmember was wearing these during genesis of these melt features is still under analysis.

Overall appearance suggests each inspected SEAWARS experienced similar thermal and mechanical environments. Each SEAWARS was mechanically extracted from the harness webbing as temperatures were rising, then for a short duration and nearly simultaneously, experienced ballistic heating, followed by nearly no hot metal shower event

TSUB-A SARSAT

One TSUB-A SARSAT beacon is flown per crewmember and is located within the Personal Parachute Assembly (PPA). Six total TSUB-A SARSATs have been found to-date, none successfully auto-activated. All six TSUB-A SARSATs present similar appearances. Material of construction consists of an outer aluminum casing, plastic external switches, and various internal electronic components.

No PPA Nylon material was visibly found adherent to the outer aluminum casing. Various amounts of paint survived and displayed evidence of impact with multiple small hot metallic pellets, plus ground-induced corrosion. All external plastic has been melted, with some directional features possibly attributed to final component ballistic heating. Internal inspection revealed minor solder re-flow, with majority of components mechanically and electrically intact. Two units were externally powered and properly functioned.

Overall appearance suggests each TSUB-A SARSAT experienced similar thermal and mechanical environments. Each TSUB-A was mechanically extracted from the PPA as temperatures were rising, then for a short duration and nearly simultaneously, experienced high ballistic heating and a hot metal pellet-like shower.

AN/PRC-112

One AN/PRC-112 radio/beacon is flown per crewmember and is located within right side, ACES outer pocket. Four total AN/PRC-112s have been found to-date. All four AN/PRC-112s present similar appearances. Material of construction consists of an outer aluminum casing, plastic external switches, plastic external battery pack, and various internal electronic components.

No ACES Nomex material was visibly found adhered to the outer aluminum casing. Various amounts of paint survived and displayed evidence of impact with multiple small hot metallic pellets, plus ground-induced corrosion. All external plastic has been melted or missing, with some directional features possibly attributed to final component ballistic heating. Internal inspection revealed evidence of moderate burning, with center-most components only experiencing minor solder re-flow. Each AN/PRC-112's "control module" (which contains unique crew ID) was successfully extracted and externally powered to determine crew ID.

Overall appearance suggests each AN/PRC-112 experienced similar thermal and mechanical environments. Each AN/PRC-112 was mechanically extracted from the ACES external pocket as temperatures were rising, then for a short duration and nearly simultaneously, experienced high ballistic heating and a hot metal pellet-like shower.

Structure

Recovered Debris

Overall, approximately 40-50% of the original crew module mass was recovered. Some major structural elements were recovered, including major portions of:

- forward and aft crew module bulkheads
- window frames
- mid-deck floor components
- airlock and hatches

About 70% of the flight-deck panels and about 80% of the mid-deck floor were recovered. Less than 20% of locker metal structure was found, only plastic and composite material fragments of the locker trays. The Mid-deck Access Rack (MAR) was found nearly intact.

Although some foam, fabric and paper were recovered, the bulk of the items recovered consisted of metal, plastic and composite materials. It is estimated that less than 30 percent of items stowed in the lockers were recovered. The EVA tool and suit debris (stowed mostly in the airlock for entry) was weighed, and 40% of the original mass was recovered.

Generally, the condition of the recovered debris items varied widely; from highly melted, twisted and torn, to near pristine. Overall, the damage distribution of crew module debris is consistent with surrounding debris from the forward fuselage structure.

Heating

Relatively speaking, some debris recovered from the crew module experienced noticeably less aerodynamic heating than other portions of the vehicle. Heating was however sufficient enough to burn away nearly all exposed thin sections of the exterior pressure shell (including bulkhead areas), and exposed thin section areas of internal components. Although recovered debris components do show significant effects from heating, evaluation of heat patterns do not suggest any evidence that an internal cabin fire occurred before vehicle break-up.

No Evidence Supporting An Explosion Event

Forensic evaluation of all recovered crew module / forward fuselage components does not provide evidence for an over-pressurization and/or explosion event. This conclusion is supported by both the lack of forensic evidence and by lack of a credible source. (Water tanks from below the mid-deck floor, along with both Forward Reaction Control System (FRCS) tanks were recovered in good condition.)

Structural Failures

Separation of the crew module / forward fuselage assembly from the rest of the vehicle likely occurred at the interface between the Xo576 and Xo582 bulkheads. Subsequent break up of the assembly occurred as a consequence of ballistic heating and dynamic loading events. Materials evaluation of fractures on both primary and secondary structure elements suggests that structural failures occurred at high temperatures that reduced the material properties of the elements. Therefore, structural failure occurred at reduced levels of stress and strain rates than otherwise would have resulted in structural failure.

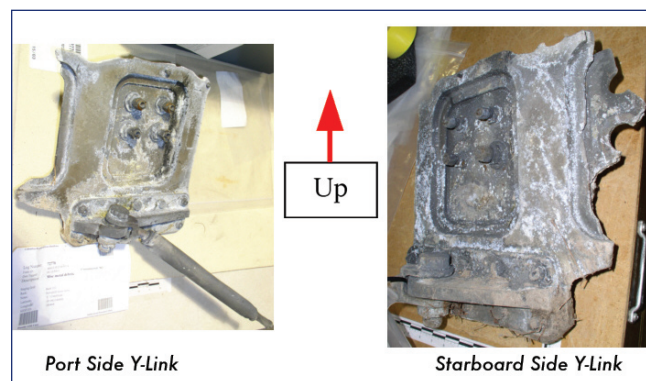
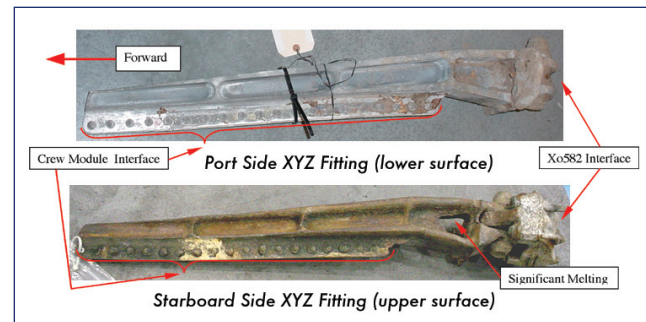
Crew Module Attach Fittings

Four major attach points that suspend the crew module inside the forward fuselage were recovered:

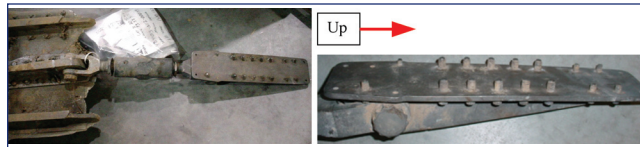
- Both the port & starboard XYZ-fittings (V070-332032) attaching the crew module longeron tab to the Xo582 frame
- The double strut Y-link attaching the lower center Xo576 bulkhead to the Xo582 frame
- The single Z-link attaching the Xo378 bulkhead to the Xcm200 bulkhead

Both the port and starboard side XYZ fittings were recovered intact with evidence of high heating. Both titanium fittings experienced significant thermal exposure / melting, predominantly on the upper surfaces. In comparison, the starboard side fitting experienced significantly greater heating than the port side.

Each fitting exhibited failures at both its crew module interface and Xo582 frame interface. The crew module interface failed at the longeron tab on both the port and starboard sides. Fasteners along the joint remained intact. On the Xo582 frame interface, the port side experienced a lug tensile failure while the starboard side fittings pulled through the Xo582 frame.



Both the port and starboard side Xo576 interfaces of the double strut Y-link assembly were recovered (the Xo582 side interface was not recovered). Both the port and starboard side struts of the Y-linkage failed in tension at the clevis end fittings. The port side failed in proximity to the Xo582 ring frame, the starboard side in proximity to the Xo576 bulkhead.



The Z-link failed at the attach point to the Xcm200 bulkhead. The joint failed by a combination of both fastener tensile failure and fastener insert pullout

Detailed inspection of each linkage failure suggests the failure mode was affected by a reduction in material properties associated with elevated temperatures.

Mid Deck Floor Structure

A substantial portion of the mid-deck floor was recovered (approximately 80%). In comparison with other crew module structure, more of the mid-deck floor was recovered than anything else. Generally, mid deck floor panel and structure components experienced heating, but not of sufficient magnitude to cause melting of metallic components (exceptions include the LiOH door and a few very localized areas on two recovered structure items). Heating was however sufficient to cause significant damage to the Aeroglaze topcoat (paint) and in some cases the Koropon primer.

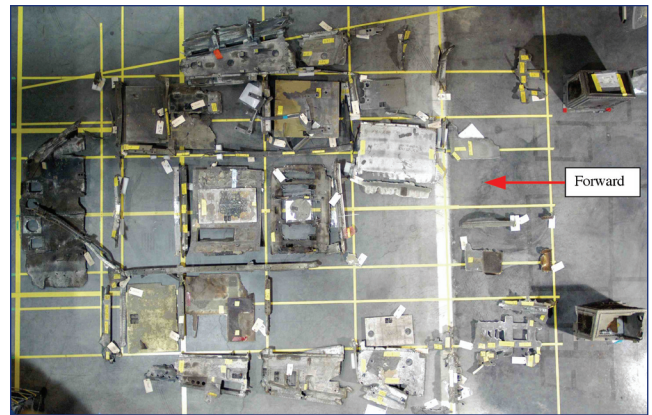
The magnitude and distribution of heating experienced by mid deck components suggests that these items were either:

1. Released from the crew module early in the break-up sequence
2. Shielded by surrounding structure until final separation

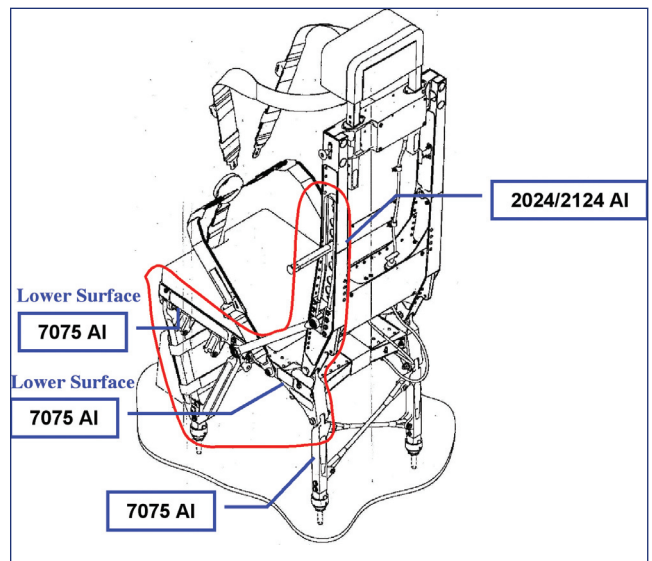
Assessment of debris field ground plots supports the former, not the latter scenario.

Heating patterns on all debris components appears to be independent of attachment to surrounding structure. This implies that the recovered debris items not only were released early, but that they separated quickly from the surrounding structure. Deceleration occurred quickly due to low mass/area ratios (ballistic numbers).

The only recovered mid deck floor item which experienced significant re-entry heating was the LiOH door floor panel, with the corresponding seat 6 and 7 attachments. The panel itself was highly melted, with thin sections completely missing. Detailed inspection of heat patterns suggest that directional heating occurred along a flow vector directed “bottom-up.” The mid deck seat 6 and 7 locations collected



Mid Deck Floor Debris (looking down).



Mid Deck: Materials Sampling Analysis on Recovered Seat Debris Items.



LiOH Door Floor Panel With Seat 6 & 7 Attach Points.

deposits of melted aluminum consistent with the mid-deck floor panel they were attached to (verified by materials analysis and consistent with the flow direction). Materials

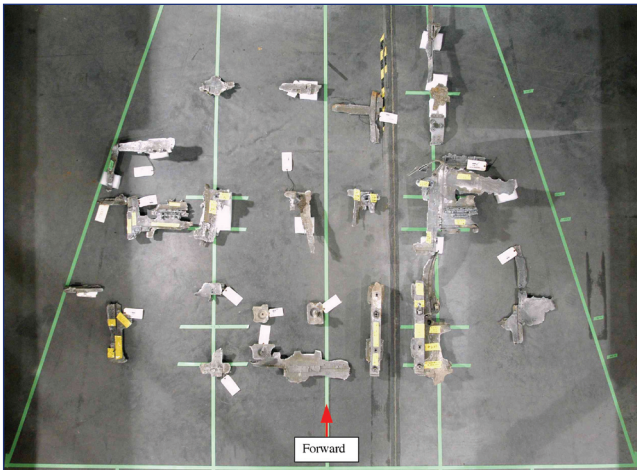
consistent with the surrounding pressure shell and/or structure were not found.

Thus, seats 6 and 7 remained attached to the LiOH door floor panel during thermal exposure, and experienced this environment completely separate from the surrounding structure. The magnitude of ballistic heating experienced on this debris item can be rationalized by the fact that this is by far the heaviest piece of recovered mid deck floor structure and thus possessed a high ballistic number when released from the crew module. The heating effects seen suggest that a ballistic number was higher than would be attributable to just the mass of the LiOH door and seats 6 & 7 alone.

Flight Deck Floor Structure

Unlike the mid deck floor, it is estimated that less than 10% of the flight deck floor was recovered. This is attributed to the substantial amount of heating experienced in this area.

Generally, only small portions of flight deck floor panels, structure, and seat components were recovered. In all cases, debris components are highly melted and/or deposited with splattered aluminum on all surfaces. None of the coating materials (topcoat or primer) survived.

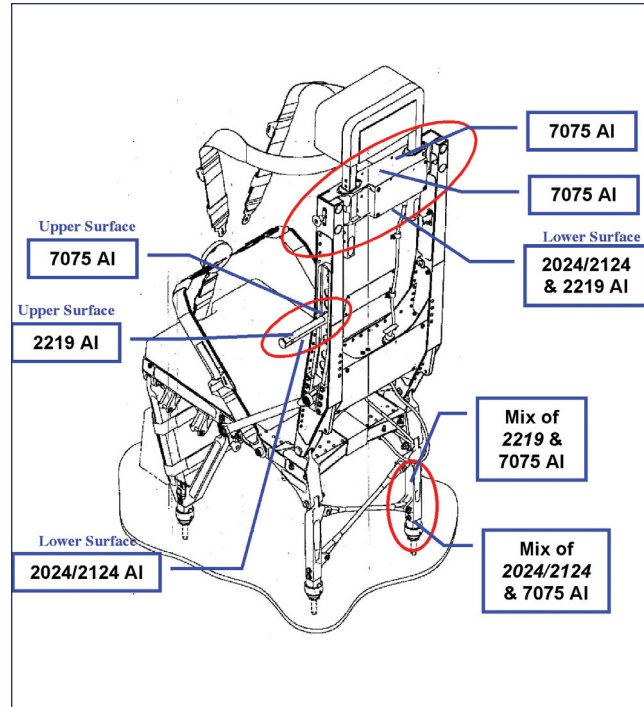


Flight Deck Floor Debris (looking down).

The flight deck seat locations collected substantial deposits of melted aluminum from locations throughout the cabin area (verified by materials analysis). Materials consistent with the bulkheads and outer pressure shell (2219 aluminum), the surrounding primary and secondary structure (2219, 2024, 2124, and 7075 aluminum), and the seat itself (2024 and 7075 aluminum) were discovered on both upper and lower surfaces of recovered seat debris. See below for a description of findings:

Thus, the flight deck seats remained attached to both flight deck floor panels and surrounding structure during thermal exposure.

The magnitude and distribution of heating experienced by flight deck components suggests a prolonged attachment to



Flight Deck: Materials Sampling Analysis on Recovered Seat Debris Items.

the larger crew module structure during re-entry (i.e. high ballistic number). Heating patterns on all debris components appears to be defined by the attachment to surrounding structure. This suggests these items were released from the crew module later in the break-up sequence than comparable items from mid deck locations. Ground plots of fallen debris also support this conclusion.

Forward Bulkhead Structure

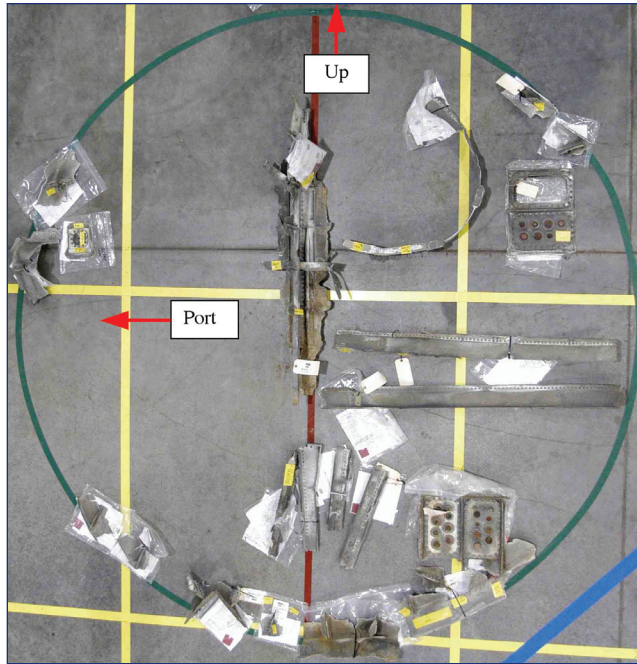
The failure mode of the forward bulkhead structure has not been determined. Debris items recovered from the forward bulkhead show heating patterns initiating from multiple directions. All of the recovered stiffeners appear to have sheared along their attach points, consistent with a bulkhead bending failure. Some failure modes appear to have been affected by elevated temperatures.

Further Analysis of the forward bulkhead structural failure is still in work.

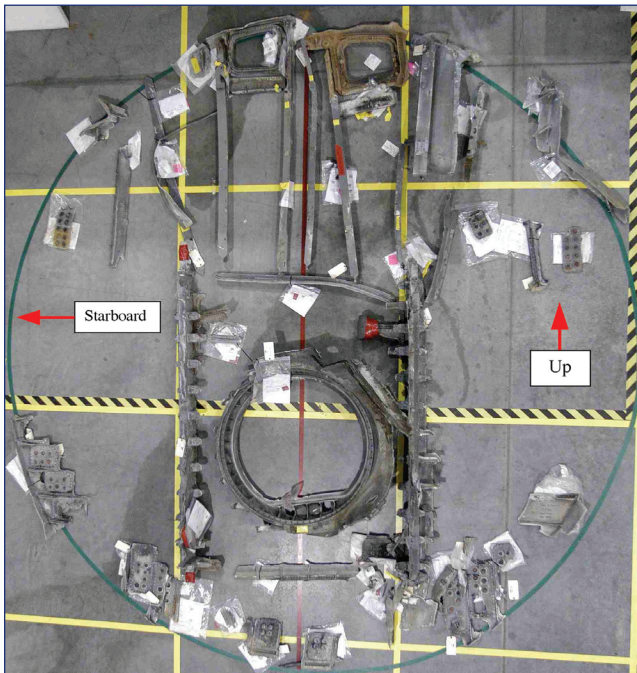
Aft Bulkhead Structure

The failure mode of the aft bulkhead structure has not been determined. Debris items recovered from the aft bulkhead show heating patterns initiating from multiple directions. All of the recovered stiffeners appear to have sheared along their attach points, consistent with a bulkhead bending failure. Some failure modes appear to have been affected by elevated temperatures.

Further Analysis of the forward bulkhead structural failure is still in work.



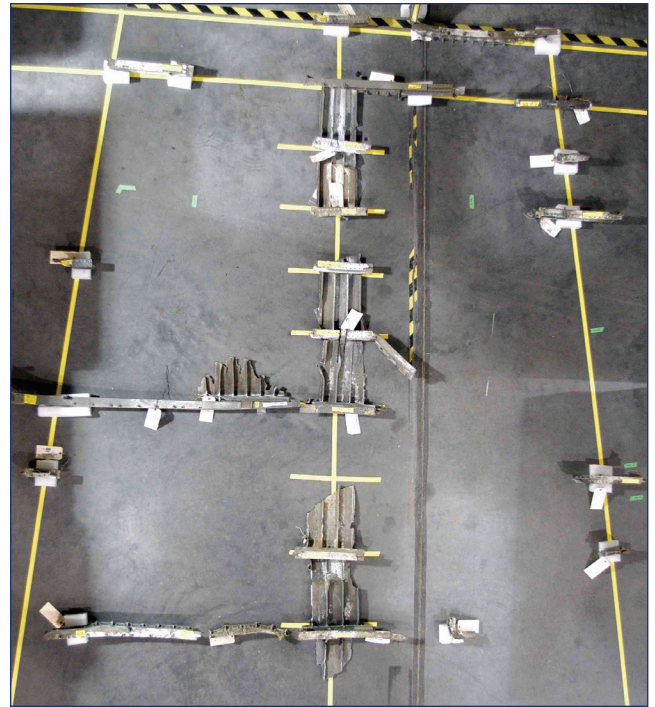
Forward Bulkhead Debris (looking forward).



Aft Bulkhead Debris (looking aft).

Pressure Shell

Barely ANY of the exterior pressure shell was recovered. Apparently, re-entry heating was sufficient to burn / melt away nearly all exposed thin sections (including bulkhead areas). In general, the only pieces of the pressure shell remaining were found attached to corresponding structure. Relatively speaking, more of the pressure shell was recovered from the lower crew module area than anywhere else .



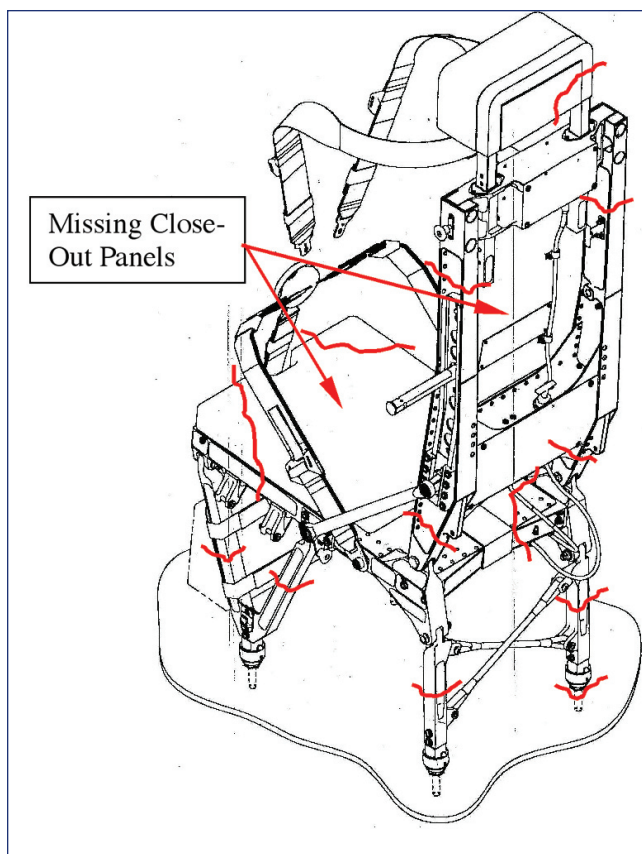
Lower Crew Module Pressure Shell Debris.

Seat Structure

A rather large collection of seat debris items was recovered. Since the majority of the lightweight seat design is common to all seven seat locations, positive seat assignment on most of the recovered seat debris was not possible. However, several key components were identified to seat locations on four flight deck (seats 1,2,3, & 4) and two mid deck (seats 6 & 7) locations. The only consistent piece of seat debris that was positively identified to each of the six seat locations was a failed portion of the upper seat back (see below for a detailed discussion).

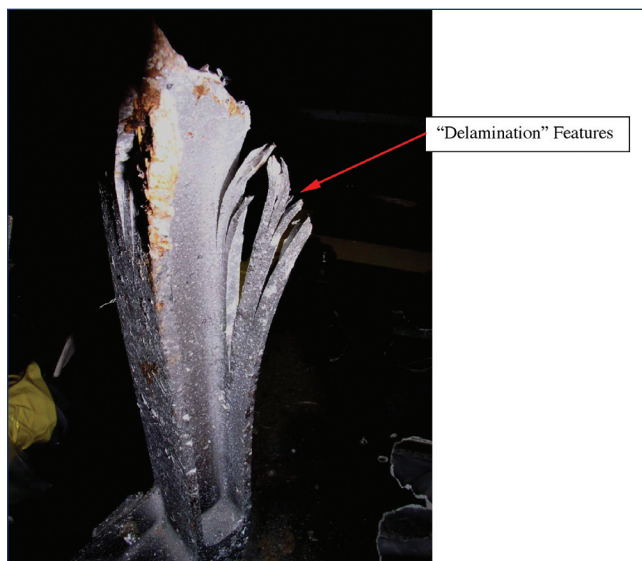
Generically, major differences in the magnitude of thermal exposure were identified on flight deck vs. mid deck seat locations. As with the flight deck structure, flight deck seat components were highly melted and/or deposited with splattered aluminum on all surfaces. In contrast, and consistent with most mid deck structure, mid deck seat structural components did not experience any melting at all. The mid deck seat 6 and 7 locations did however collect significant deposits of melted aluminum from the LiOH door that these two seats were attached to (see Mid Deck Floor section).

In nearly all cases, seat components generally fractured into relatively small pieces. It is noted that nearly all seat component fractures occurred at minimum thermal cross-sectional areas (minimum thermal mass), away from any large heat sink locations. It is also noted that nearly all thin-sheet aluminum materials (close-out panels on seat pan and seat back) are completely missing (i.e. overloaded / melted away). Common seat component fracture locations are shown below:



Common Seat Failure Locations (shown in red)
(NOTE: Mission Specialist seat shown; Components below seat pan on Commander/Pilot seat are different in design).

Upon inspection of fracture surfaces, a very unique “delamination” type fracture pattern was identified that is consistent throughout the seat component debris items. Several fractures almost appear as if the 7075 aluminum material is constructed of a laminate material (see below) when in ac-



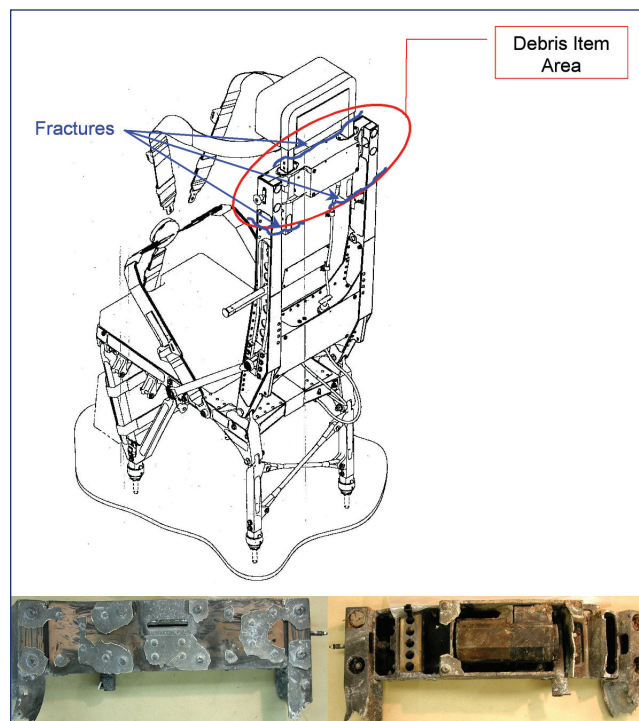
Example of “Broom-Straw” Fracture.

tual fact the material is solid aluminum plate not a laminate structure. This phenomenon was termed as “broom-straw” fractures (see Example below).

This fracture mode is consistent with elevated temperatures and relatively high strain rates. Metallurgical evaluation in proximity to, and away from crack surfaces discovered heavy grain boundary precipitation. Equiaxed grains were discovered along crack surfaces. These features are consistent with failures at high temperatures. Significant LACK of ductility surrounding fracture areas suggests failures occurred at relatively high strain rates for the thermal environment that was experienced. Thus, it is concluded that seat failure occurred as a result of thermal exposure (material property degradation) prior to mechanical overload.

Upper Seat Backs / Seat Restraint Recoil Mechanisms

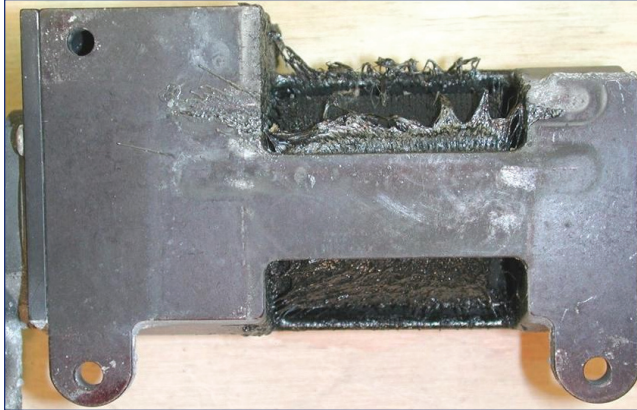
Six out of seven “Upper Seat Back” debris items were recovered (all but Seat 5). Each item was positively identified to a seat position. Each recovered upper seat back debris item contains the upper seat strap recoil mechanism and some amount of strap material, which had recoiled back into the mechanism subsequent to strap failure. A description of the debris location and an example of one recovered upper seat back debris item follows:



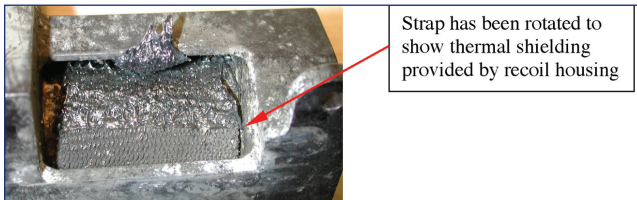
Schematic of “Upper Seat Back” Debris Location, and Example of Representative Debris Item (front and back shown).

In all cases, fractures at the upper seat back location occurred at the minimum thermal cross section, away from heat sinks on either side. These fractures are consistent with the general seat failure mechanism (thermal heating followed by mechanical overload).

In all cases, a significant amount of melted / splattered strap material was discovered internal to the upper back seat cavity. Melting appears associated with air flow entering the upper seat back strap entry point. Melt patterns suggest melting occurred AFTER the seat straps had been recoiled into the housing (i.e. post-failure). Thus, it can be concluded that crewmembers were removed prior to completion of thermal heating event.



Example of Strap Melt Patterns Surrounding Recoil Mechanism.



Close-Up of Strap Melt Patterns.

As the condition of the residual strap material contains evidence of thermal / loading history, each recoil mechanism was removed and disassembled to expose the straps for inspection. Upon inspection, strap failures occurred at varying positions along the strap length. Seat 1 & 2 experienced strap failures at or near the end of the strap, at the recoil mechanism (fully extended position). The seat 7 strap failed at approximately 50% of full extension. Seat 3 shows evidence that the strap experienced a significant dynamic loading event at the fully extended position ("bird-caging" near the recoil mechanism observed). All others straps failed at locations ranging from 50 - 90% of strap length (away from recoil attach point).

Comparing the ends of the recovered straps, 5 of 6 strap ends terminate along a "straight line" (all but seat 2). Away from the melted areas (in close proximity), the residual strap material remains flexible / resilient. This appears consistent with melting that occurred AFTER the strap had recoiled back into the housing (straight lines correspond to edges of the exposed strap pass-through areas). Had failure occurred by thermal means only, a thermal exposure gradient over some finite length would be expected. This was not present in any of the six recovered straps. It is thus concluded that all straps failed via mechanical overload of thermally com-

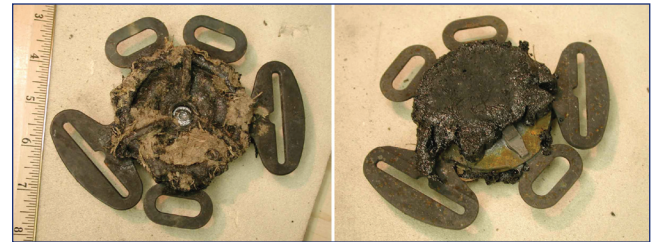
promised material.

Once the straps were fully extended for inspection, the presence of metallic debris material was discovered on both upper and lower strap surfaces. Overall, melted metallic material was deposited onto exposed seat harness strap material on 4 of 6 recovered upper seat back recoil mechanisms. Material deposition occurred BEFORE separation from seats, yet AFTER the crew module pressure shell had been breached.

Evidence from upper seat strap materials suggests that 4 of 6 straps were "extended" (50-100%) at the time of failure. 5 of 6 were fully extended at some point in time before catastrophic failure. Also, the presence of melted metallic material on extended straps suggests that the crew remained in their seats during exposure to the thermal re-entry environment.

5-Point Seat Belt Buckle

Only one of seven 5-point seat belt buckles was recovered. Positive identification was not possible. The one recovered buckle experienced significant re-entry heating. This resulted in substantial melting of the outer plastic housing. The structure however remained intact, with all five clasps still in place.



Recovered 5-Point Seat Belt Buckle (front and back shown).

Surprisingly, the two upper strap attach clasps were bent *outward* (away from the crewmember). All other clasps appeared nominal. The buckle assembly was disassembled in an attempt to locate "witness marks" which may have been caused by mechanical loading. Nothing was found.

Break-Up Sequence

Overall, crew module debris items experienced a significant variation in both the magnitude and direction of heating experienced during re-entry. The distribution of directional heating / splatter patterns observed throughout the recovered crew module debris items is essentially RANDOM. Minus the mid deck floor components, the magnitude and orientation of significant heating appears to be defined by the attachment to surrounding structure. In general, most failure modes are consistent with fracture at high temperature.

It can be concluded that the break-up of crew module structure was not instantaneous, but rather a sequential failure / separation of major structural components.

Hardware Forensics Evaluation: General Conclusions

Separation of the crew module / forward fuselage assembly from the rest of the vehicle occurred as a consequence of heating and structural loading experienced outside of the vehicle design envelope. Although significant loading events initiated this separation, failure of the crew module structure was not instantaneous. Failure modes assessed on crew module structural components suggest that fractures occurred subsequent to elevated temperature exposure (corresponding to a significant reduction of material properties). Thus, subsequent break-up of both the crew module and forward fuselage structure occurred as a consequence of the combined environments provided by ballistic heating and aerodynamic loading.

Failure modes assessed on crew module and/or forward fuselage components cannot be linked to the root cause of the STS-107 *Columbia* crash.

The information contained in this work was compiled by the CAIB/NASA JSC Crew Survival Working Group. The conclusions drawn in this work do not necessarily reflect the conclusions of the Board; when there is conflict, the statements in Volume I of the Columbia Accident Investigation Board Report take precedence.