



Volume II

Appendix D.9

Data Review and Timeline Reconstruction Report

This appendix contains the basic timeline data that was used to reconstruct the final minutes of *Columbia*'s re-entry on February 1, 2003. The version in this appendix contains all of the timeline events, but in condensed form.

The timeline organized the re-entry data. As such, this appendix contains no conclusions or recommendations. A visual presentation of the timeline has also been included on the CD that contains this appendix. It shows the timeline laid over a map of the United States along the ground track that *Columbia* flew during the re-entry.

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Data Review and Timeline Reconstruction Report

Don L. McCormack, Jr., NASA Team Leader, David W. Camp, Boeing Co-Team Leader,
and Joyce Seriale-Grush, NASA Co-Team Leader

NSTS 37376
June 3, 2003



Data Review and Timeline Reconstruction Team Final Report

in support of the
Columbia Accident Investigation

June 3, 2003

Submitted by:

/s/ Don L. McCormack, Jr.
Don L. McCormack, Jr., NASA
Team Leader

/s/ David W. Camp
David W. Camp, Boeing
Co-Team Leader

/s/ Joyce Seriale-Grush
Joyce Seriale-Grush, NASA
Co-Team Leader



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EXECUTIVE SUMMARY

The Date Review and Timeline Reconstruction Team was one of many Technical Integration Team sub-teams created in support of the Orbiter Vehicle Engineering (OVE) Working Group (WG) investigation into the *Columbia* accident. The team's charter was to review the available telemetry and recorded data from *Columbia* and develop a timeline of events leading up to the loss of *Columbia* and its crew.

This report defines and documents the process that the Data Review and Timeline Reconstruction Team used to develop the STS-107 entry timeline. It also defines and documents the team's products and interfaces.

The scope of the data review included all available real-time telemetry from *Columbia* and all recorded data from the Orbiter experiments (OEX) recorder. Available data from all mission phases – ascent, on-orbit, and entry – were reviewed for the discovery of timeline events. The vast majority of the off-nominal events were discovered in the review of entry data and subsequently the entry timeline is the principle product. The few off-nominal events discovered during the ascent data review were delivered to personnel in the Space Shuttle Program (SSP) Systems Integration group who were responsible for ascent timeline reconstruction.

The primary ground rule established by the Data Review and Timeline Reconstruction team was that the team was to identify off-nominal performance from a review of the available flight data, describe that off-nominal performance as events on a timeline and make the timeline available to the pertinent Technical Integration Team sub-teams. Detailed analysis to determine the cause of the events was then performed by the pertinent sub-teams.

The timeline also included nominal Orbiter events, a time reference from entry interface (EI), and ground-track locations so that the off-nominal events could be more easily placed into the proper time and space reference.

The Data Review and Timeline Reconstruction Team consisted of a core group that were responsible for the generation of the timeline and conducting the data reviews. The data reviews were performed by the various Orbiter subsystem managers (SSMs) and/or subsystem engineers (SSEs). The data review and the reconstruction of the timeline began in the first hours following the *Columbia* accident. It began with quick look reviews of subsystem entry data conducted in the Mission Evaluation Room. From these reviews the initial versions of the entry timeline were developed. More formal data reviews were subsequently conducted at the Boeing Houston facility. These reviews were supported by personnel from Boeing (technical management and SSMs/SSEs), the Johnson Space Center (JSC) Engineering Directorate, the JSC Mission Operations Directorate (MOD),

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the JSC and contractor Safety, Reliability and Quality Assurance (SR&QA) organizations, and the JSC Astronaut Office.

The timeline is documented in the Appendices. In Appendix A.1 is a summary entry timeline that groups events and shows only the more significant events to present the timeline in a more manageable form. Appendix A.2 is the master entry timeline that shows all of the entry events. Appendix B provides supporting data for the events on the entry timeline. Appendix C documents a graphical version of the entry timeline that is based on the summary entry timeline. The results of the subsystem data reviews are documented in Appendix D. Appendix E provides measurement data (description, source, type, location, range, sample rate) for each of the measurements associated with events on the timeline. Finally, Appendix F lists the names of many of the people who contributed in some way to this effort.

Utilizing the results of thorough reviews of all available flight data, as well as the review of videos of *Columbia's* entry and the results of the aerodynamic reconstruction, the Data Review and Timeline Reconstruction Team developed a thorough STS-107 entry timeline. This timeline provided a basis for the investigation and as such proved to be a valuable tool in the investigation of the *Columbia* accident.

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1.0 INTRODUCTION

The Date Review and Timeline Reconstruction Team was one of many Technical Integration Team sub-teams created in support of the Orbiter Vehicle Engineering (OVE) Working Group (WG) investigation into the *Columbia* accident. The team's charter was to review the available telemetry and recorded data from *Columbia* and develop a timeline of events leading up to the loss of *Columbia* and its crew.

The primary source of data for the timeline reconstruction was real-time telemetry from *Columbia* and recorded data from the Orbiter experiments (OEX) recorder that was discovered during the search for debris. Individual subsystem teams reviewed the data for off-nominal events based on the team's knowledge of expected subsystem performance and the comparison of STS-107 flight data with previous flight data.

The review included flight data from throughout the mission; ascent, on-orbit and entry. Obviously, the vast majority of off-nominal events were discovered in the review of entry data and those events are documented in the entry timeline. This timeline was baselined and configuration controlled by the OVE WG. The few off-nominal events discovered during the ascent data review were delivered to personnel in the Systems Integration group who were responsible for ascent timeline reconstruction. There were no off-nominal events related to the *Columbia* accident discovered in the review of on-orbit data.

Another source of data included the evaluation of videos received from individuals across the western United States who had recorded *Columbia's* entry. From these videos, debris shedding events were characterized and documented in the entry timeline. Additionally, aerodynamic events derived by the analysis of the entry trajectory were included in the timeline. These events show the changes in aerodynamic coefficients during entry. Finally, the timeline also included nominal Orbiter events, a time reference from entry interface (EI), and ground-track locations so that the off-nominal events could be more easily placed into the proper time and space reference.

2.0 PURPOSE AND SCOPE

This report defines and documents the process that the Data Review and Timeline Reconstruction Team used to develop the STS-107 entry timeline. It also defines and documents the team's products and interfaces.

The scope of the data review included all available real-time telemetry from *Columbia* and all recorded data from the OEX recorder. Available data from all mission phases – ascent, on-orbit, and entry – were reviewed for the discovery of

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timeline events. The vast majority of the off-nominal events were discovered in the review of entry data and subsequently the entry timeline is the principle product. The few off-nominal events discovered during the ascent data review were delivered to personnel in the Space Shuttle Program (SSP) Systems Integration group who were responsible for ascent timeline reconstruction. There were no off-nominal events related to the *Columbia* accident discovered in the review of on-orbit data.

In addition to the development of the timeline (Appendix A), a graphical version of the entry timeline was developed (Appendix B), a data package was compiled with data for each event on the timeline (Appendix C), a report summarizing the results of the subsystem data reviews was generated (Appendix D), and a table with measurement information for each measurement referenced on the entry timeline was generated (Appendix E).

3.0 GROUND RULES AND ASSUMPTIONS

The primary ground rule established by the Data Review and Timeline Reconstruction team was that the team was to identify off-nominal performance from a review of the available flight data, describe that off-nominal performance as events on a timeline and make the timeline available to the pertinent Technical Integration Team sub-teams. Detailed analysis to determine the cause of the events was then performed by the pertinent sub-teams.

There are exceptions to that ground rule in that two classes of events are actually products of the analyses conducted by two of the sub-teams. The Image Analysis Team screened over 140 videos received from the public. Approximately 25 contained good records of debris emanating from *Columbia*'s plasma envelope. The Image Analysis Team's emphasis was to obtain the most accurate times possible for the debris observations. A characterization of those observations and the times at which they occurred were included in the entry timeline.

Additionally, the Integrated Entry Environments team derived events for the timeline from entry trajectory reconstruction analyses. These events characterized changes in aerodynamic coefficients that occurred over the final 7-minutes of *Columbia*'s entry.

Finally, the timeline also included nominal Orbiter events, a time reference from entry interface (EI), and ground-track locations so that the off-nominal events could be more easily placed into the proper time and space reference.

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4.0 PROCESS DEFINITION

The Data Review and Timeline Reconstruction Team consisted of a core group that were responsible for the generation of the timeline and conducting the data reviews. The data reviews were performed by the various Orbiter subsystem managers (SSMs) and/or subsystem engineers (SSEs). The data review and the reconstruction of the timeline began in the first hours following the *Columbia* accident. It began with quick look reviews of subsystem entry data conducted in the Mission Evaluation Room. From these reviews the initial versions of the entry timeline were developed.

More formal data reviews were subsequently conducted at the Boeing Houston facility. These reviews were supported by personnel from Boeing (technical management and SSMs/SSEs), the Johnson Space Center (JSC) Engineering Directorate, the JSC Mission Operations Directorate (MOD), the JSC and contractor Safety, Reliability and Quality Assurance (SR&QA) organizations, and the JSC Astronaut Office. The initial focus of the review was on the entry data but it subsequently expanded to include ascent and on-orbit data. The review also included a 32-second period of real-time telemetry data that was not initially accepted by the Orbiter Data Reduction Complex (ODRC) due to the high bit error rate. This period of data was reconstructed so that it could be processed by the ODRC for review. The 32-second period consisted of approximately 5-seconds of data at the start of the period, an approximate 25-second data gap, and approximately 2-seconds of data at the end of the period.

The early revisions of entry timeline were considered preliminary as the events on the timeline matured through the process of more thorough and complete data reviews. Revision 12 of the timeline was subsequently baselined at the OVE WG on February 10, 2003, for configuration control. From that point on, changes could only be made to the timeline by re-baselining revisions at the OVE WG.

Timeline events were also received from two other sources, the Image Analysis Team and the Integrated Entry Environments Team. The Image Analysis Team screened videos received from the public, of which approximately 25 contained good records of debris emanating from *Columbia*'s plasma envelope. From these videos, the team was able to characterize off-nominal events with a description of the events and the times at which they occurred. The Integrated Entry Environments team derived events for the timeline from entry trajectory reconstruction analyses that characterized changes in aerodynamic coefficients that occurred over the final 7-minutes of *Columbia*'s entry.

In March, the OEX recorder was found and the data on the recorder was recovered. On the last weekend of March, the review of that data was begun. The process followed was that same as that established for the review of the real-

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time telemetry data. Initially, a separate entry timeline was developed from the OEX data. As with the timeline developed with the real-time telemetry data, the early revisions of this timeline were considered preliminary as the events on the timeline matured through the process of more thorough and complete data reviews. Revision 17 of the entry timeline subsequently merged revision 16 of the entry timeline with the entry timeline developed from the OEX data. Revision 17 of the entry timeline was baselined at the OVE WG on May 7, 2003.

In the weeks leading up to the release of this final report, minor changes were made to the entry timeline. These changes were primarily editorial in nature but did include changes to debris event times just prior to breakup of the vehicle. Therefore the version of the timeline documented in Appendix A of this report is revision 19 of the entry timeline.

Throughout the process, a graphical version of the timeline was developed and maintained. Additionally, each revision of the timeline was distributed to each of the Technical Integration Team sub-teams and other groups involved in the *Columbia* investigation. The Vehicle Data Mapping Team developed several products to more graphically illustrate the events during entry. The timeline was also used by the Scenario and Fact Database Teams and was used for the development of integrated ground track/timeline charts generated by organizations in JSC Engineering and MOD.

5.0 RESULTS

The Data Review and Timeline Reconstruction Team conducted data reviews of all available data from all phases of the STS-107 mission. From the results of these reviews and inputs from the Image Analysis and the Integrated Entry Environments Teams, an entry timeline was developed.

Revision 19 of the entry timeline is documented in the Appendices. In Appendix A.1 is a summary version of the entry timeline that groups events and shows only the more significant events to present the timeline in a more manageable form. In Appendix A.2 is the master entry timeline that shows all of the entry events.

A great amount of data was compiled and reviewed in support of this effort. Although all of that data is not documented here, Appendix B provides a brief verbal description and supporting data for each of the events on the entry timeline.

Appendix C documents a graphical version of the entry timeline that is based on the summary entry timeline. Note that other graphical versions were developed by other teams/organizations. The Vehicle Data Mapping Team developed both 2D

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and 3D products to visually show the events and organizations in JSC/Engineering and MOD integrated the entry timeline into ground track maps.

The results of the subsystem data reviews are documented in Appendix D. The reports summarize the results of the data reviews conducted by each of the subsystem teams. The reports cover all mission phases and indicate that although there was evidence of the impending catastrophic failure in the data, all of *Columbia*'s active systems were performing nominally until the final minute prior to breakup.

Appendix E provides measurement data (description, source, type, location, range, sample rate) for each of the measurements associated with events on the timeline.

Finally, Appendix F lists the names of many of the people who contributed in some way to this effort.

6.0 CONCLUSIONS

Utilizing the results of thorough reviews of all available flight data, as well as the review of videos of *Columbia*'s entry and the results of the aerodynamic reconstruction, the Data Review and Timeline Reconstruction Team developed a thorough STS-107 entry timeline. This timeline provided a basis for the investigation and as such proved to be a valuable tool in the investigation of the *Columbia* accident.

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Appendix D
Subsystem Data Review Summary Report
D.30 AIR DATA TRANSDUCER ASSEMBLY HARDWARE PERFORMANCE
EVALUATION

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Subsystem Data Review Summary Report
D.1.0 INTRODUCTION

The results of the subsystem data reviews are documented in Appendix D. The report summarizes the results of the data reviews conducted by each of the subsystem teams. The report covers all mission phases and indicate that although there was evidence in the data of the impending catastrophic failure, all of the Columbia vehicle active systems were performing nominally until the final minute prior to breakup.

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Subsystem Data Review Summary Report
D2.0 AUXILIARY POWER UNIT PERFORMANCE EVALUATION

D2.1 Executive Summary

The auxiliary power unit (APU) subsystem performed nominally during all phases of the mission. During entry, all APU parameters were nominal at loss-of-data.

Data during entry through the initial Orbiter loss of signal (LOS), prior to the 32-second (LOS+32) period of reconstructed data, showed nothing off nominal except for one-bit data hits in nine measurements. Data obtained from the final 32-second period of reconstructed data were comprised of an initial 5-second period, followed by a 25-second period of no data, concluding with a final 2-second period of data. The 5-second and 2-second data periods contained many data hits, which required extensive evaluation to extract valid data. Evaluation concluded that all three APUs were operating properly at normal speed through the final loss of all data (LOS+32 seconds) with all three hydraulic systems having lost all hydraulic main-pump pressure.

The APU subsystem had no off-nominal events, deviations from nominal, or unusual data other than one-bit data hits through the initial LOS period. Analysis indicates that no APU subsystem hardware contributed directly or indirectly, or was in any way associated with the cause of the loss of the Orbiter.

D2.2 Pre-launch/Ascent Performance

APU subsystem performance was nominal during the pre-launch/ascent phase. Two minor observations are noted in the following paragraphs.

A small-temperature-drop in the APU 2 injector tube temperature, which was recorded at approximately 16:15:39 G.m.L., was initially reported as caused by a suspected loose spring clip. However, following an investigation of the hydraulic loads data during this period and a comparison with data from the previous mission (STS-109) of this vehicle, it has now been concluded that the temperature drop was a normal APU response to a drop in hydraulic load.

Movement of a small amount of hydrazine in the APU 2 fuel pump seal cavity drain line is suspected to have caused a small temperature rise and drop in the APU fuel pump drain line temperature 2 near main engine cutoff (MECO). This event is not considered to be anomalous.

D2.3 On-Orbit Performance

APU subsystem performance was nominal during the on-orbit phase. The APU heater systems maintained all APU systems within the nominal temperature

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Subsystem Data Review Summary Report
D2.4 Entry Performance

range. APU 1 operated satisfactorily during the flight control subsystem (FCS) checkout.

D2.4 Entry Performance

The APU subsystem had no off-nominal events, deviations from nominal, or unusual data other than one-bit data hits through the final loss of data at 32:14:00:04 G.m.L. (LOS +32 seconds). Analysis indicates that no APU subsystem hardware contributed directly or indirectly, or was in any way associated with the cause of the loss of the Orbiter.

The thrust vector control (TVC) isolation valves of two of the three hydraulic systems are opened during hydraulic normal pressure to stow the Space Shuttle main engine (SSME). These periods of load on the corresponding APUs are evidenced in the APU turbine-speed and chamber-pressure plots. APU performance was nominal during the stowing of the SSMEs on the STS-107 mission.

Subsystem performance during the final 32-second period (LOS+32) of reconstructed data was within specifications and was as expected except for lower APU lubrication oil and bearing temperatures in the final 2-second period. This may be attributed to loss of all hydraulic loads as a result of loss of all hydraulic main pump pressure in all three hydraulic systems and/or possibly to a hydraulic water spray boiler (WSB) overcooling condition.

The APU group performed a review of the APU 1 revolutions per minute (RPM) signature during the final 2-second segment of the 32 seconds period of reconstructed data. The latest version (07) of the 32-second period of reconstructed data was used, and all APU parameters were re-reviewed. The 5-second segment and final 2-second segment indicate that the three APUs were functioning nominally to the end of data (32:14:00:05 G.m.L.).

Specifically with regard to the last 2 seconds of the reconstructed data, the APU 1 RPM signature was somewhat different than normal, and warranted special review, including consultation with the vendor, Hamilton Sundstrand Corp. (HSC). The portion of the cycle obtained is only the ramp-down, or turbine wheel spin-down. It was different from other cycles in that it started at a higher speed (112.9-percent) and ramped down slower (105.5-percent at end of data and still decreasing).

From an operational viewpoint, the APU is speed-controlled by a digital controller operating an on-off valve that sends pulses of fuel to the APU at a frequency of approximately once per second. The actuation of an elevator or any other increase in hydraulic load will cause the valve-pulsing frequency as well as the valve-on-time to increase because of the increased hydraulic load. The controller set points for normal-speed operation are 102-104 percent, which results in a

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Subsystem Data Review Summary Report

turbine-speed-band of about 102-110 percent, based on the designed valve response time and a programmed controller response time. When APU high-speed operation is selected in the cockpit, the controller set points are 112-114 percent, with resulting turbine-speed-band of about 112-117 percent.

The 112.9-percent data point is not indicative of high-speed operation, but is assessed as a data hit (bad data) for the following reasons:

1. The speed continues to ramp down below the high-speed set points and high-speed band;
2. The drop from 112.9 to 109.6 percent is 5 time-bit values, but would be only one or two for a real spin-down;
3. The remaining good data (109.6-105.5 percent) is a good, smooth, normal-speed signature, but at a slower spin-down rate, and it did not reach the lower set point by the end-of-data. This latter fact is the result of the loss of hydraulic fluid in the hydraulic system sometime during the 25-second gap in the period of reconstructed data. The APU is spinning an empty pump without load or pressure; this same effect was seen during an APU test at White Sands Test Facility June 5, 2001, when the hydraulic pump lost fluid and ran for 21 seconds before shutdown;
4. The 112.9-percent data point was extracted from a section of telemetry data for which a low-level of confidence exists for its accuracy;
5. The high-speed switch-scan data showed normal speed for APU 1. The switch-scan data were suspect for APU 2, and the switch-scan data were not available for APU 3; and,
6. No APU caution and warning indications occurred throughout the entry run, thus giving additional confirmation that the three APUs were operating nominally in normal speed and were not switched (commanded) to high speed.

However, in the remote possibility that the 112.9-percent data point were real data, it could possibly be explained by events in the Orbiter causing the controller set point to drift, degrading the valve response time, or perhaps causing a mechanical binding that could induce a shut off valve internal leak to the gas generator. It would not be indicative of high-speed operation.

In summary, the turbine speed was nominal for all three APUs up until loss of data at 32:14:00:04.7 G.m.t., and was indicative of normal speed. In addition, APU 2 exhibited a chamber pressure pulse that ended at this time; this pulse was typical of normal-speed pulses. Switch scans did not show a switch to high-speed. Although a switch position change could have been executed during the 25-second gap, the subsequent three RPM signatures and the one pulse signature indicate normal speed. The hydraulic system reservoirs were shown to have no oil at this time (last two seconds), with the APUs driving empty pumps, lubricated by residual hydraulic fluid.

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Subsystem Data Review Summary Report

D.3.0 HYDRAULICS/WATER SPRAY BOILER SUBSYSTEM PERFORMANCE EVALUATION

D3.1 Executive Summary

The hydraulics/water spray boiler (HYD/WSB) subsystem performed nominally during all phases of the mission. However, evidence of the event that led to the loss of the Orbiter was apparent in hydraulic subsystem parameters during the entry. Initially, this evidence was the loss of data from four left-hand elevon return-line temperature sensors and the anomalous temperature rise of eight temperature sensors in the left-hand wheel well. Finally, this evidence included the indication that the hydraulic subsystem had been breached and all three systems were lost.

All HYD/WSB subsystem parameters were functioning nominally and all subsystem parameters were within nominal ranges up until vehicle LOS. The HYD/WSB MER personnel were aware of the off-scale low (OSL) indication on the four left-hand elevon return line temperature sensors when the OSL indication occurred in flight. Post-flight analysis indicated that a total of 12 hydraulic subsystem thermal sensors had anomalous indications. These sensors included the four left-hand elevon return-line temperature sensors that went OSL and eight temperature sensors in the left-hand wheel well that indicated off-nominal increases in temperature. The off-nominal responses indicated by the 12 hydraulic subsystem temperature sensors is not indicative of any anomaly in the HYD/WSB subsystem operation but are an indication of an entry thermal event that led to the loss of the Orbiter.

The post-LOS reconstructed data covered a time period of 32 seconds and consisted of 5 seconds of data followed by a gap of 25 seconds followed by a final 2 seconds of data. Although both the 5- and 2-second data strings provided additional insightful data, both segments were characterized by, in some cases, multiple data hits. The final 2 seconds of data indicated that sometime in the previous 25-second data gap, the hydraulic subsystems were apparently breached. The final 2 seconds of data indicated hydraulic subsystem main pump (system) pressure at 0 psia on all three systems. The hydraulic reservoir pressures likewise indicated 0 psia and indicated reservoir quantities of 0 percent on all three systems.

D.3.2 Pre-launch/Ascent Performance

The hydraulics/water spray boiler (HYD/WSB) subsystem performed nominally during the pre-launch and ascent phases of the mission.

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Subsystem Data Review Summary Report

Circulation pump operation during pre-launch was nominal. Two bootstrap accumulator recharges occurred during the pre-launch operations. The first recharge occurred in system 1 (2192 to 2465 psia) and the second in system 3 (2143 to 2465 psia).

The three HYD/WSB systems were activated at T minus 5 minutes prior to launch. During ascent, the three thrust vector control (TVC) isolation valves were open. The three priority valves cracked within the required time limit of less than 1 second. The three hydraulic systems pressures were within the required range of 3050 - 3200 psia. The reseating of the priority valves at APU shutdown was nominal.

The water spray boiler system cores were loaded with approximately 5.0 lb of the additive mixture (53-percent water; 47-percent Propylene Glycol Monomethyl Ether (PGME). The WSB-ready indication was exhibited on all three WSB systems shortly after the water spray boiler gaseous nitrogen (GN₂) isolation valves were opened during pre-launch operations. Nominal WSB cooling performance was observed on all three HYD/WSB systems. System 3 initiated spray cooling approximately 6 seconds after MECO while systems 2 and 1 started approximately 32 seconds and 1 minute 32 seconds after MECO, respectively. No APU lubrication oil overcooling or undercooling conditions occurred. Water spray boiler water usage during ascent for spray cooling was within allowable limits.

D.3.3 On-Orbit Performance

The HYD/WSB subsystem performed nominally throughout the on-orbit phase of the mission. No deviations from the nominal were observed during the on-orbit operations.

D.3.4 Entry Performance

The HYD/WSB subsystem performed nominally throughout the entry phase of the mission until loss of data. The data review indicates that no HYD/WSB subsystem hardware contributed directly or indirectly, or was in any way associated with the cause of the loss of the Orbiter. However, evidence of the event that led to the loss of the Orbiter was apparent in hydraulic subsystem parameters and is discussed in this section.

Post-mission analysis of the HYD/WSB subsystem data involved plotting high-rate data for all system parameters and examining the high-rate data for any anomalous indications. The data analysis indicated a thermal effect in the Orbiter vehicle left-hand main landing gear (MLG) wheel well as indicated by eight hydraulic system thermal sensors. It was determined that all HYD/WSB entry/landing operations and thermal sensor responses appeared nominal up to 32:13:52:17 G.m.t. Analysis of the data indicated that the left MLG brake-line

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temperature sensor D began an anomalous rise in temperature at 32:13:52:17 G.m.t. Within 24 seconds, at 32:13:52:41 G.m.t., the left MLG brake-line temperature sensors A and C also initiated a temperature rise.

Four Orbiter vehicle left-side elevon actuator hydraulic return-line thermal sensors indicated an off-scale low (OSL) temperature of -76 °F. The sensors indicating OSL were as follows:

1. System 3 left outboard elevon (LOE) actuator return line;
2. System 1 left inboard elevon (LIE) actuator return line;
3. System 1 LOE actuator return line; and
4. System 2 LIE actuator return line.

The hydraulic system reservoir fluid quantities and all HYD/WSB subsystem temperatures and pressures appeared stable, indicating no subsystem leaks or instability. At that time, the water spray boilers were operating and the spray cooling was nominal. Initial discussions of the situation led to the conclusion that the data dropout of the elevon actuator return lines was caused by a dedicated signal conditioner (DSC) card dropout. Continued monitoring of the in-flight data indicated nominal HYD/WSB subsystem operation, despite the four elevon return-line temperature-sensor dropouts. The data analysis indicated that the four elevon-actuator sensor dropouts were slightly staggered within a time span of approximately 26 seconds, beginning at 32:13:53:10 G.m.t. The system 3 LOE actuator return-line and the system 1 LIE actuator return-line went OSL within 1 second of each other followed by the system 1 LOE actuator return-line and the system 2 LIE actuator return-line going OSL within 2 seconds of each other beginning 24 seconds after the first sensor began going OSL (system 3 LOE actuator return line) and 1 minute, 19 seconds following the first indicated anomalous temperature sensor rise indication in the left MLG wheel well.

Within 10 seconds of the last elevon-actuator return-line sensor going OSL, the left MLG brake-line temperature sensor A began an increase in rise rate, 1 minute, 5 seconds following the initial temperature increase on this sensor. Within 23 seconds, at 32:13:54:10 G.m.t., the left MLG brake-line temperature-sensor B initiated a temperature increase, the first anomalous response indicated on this sensor. Within the next 1 minute, 2 seconds, the left MLG strut actuator sensor and the left MLG system 3 brake-line return line temperature also initiated an indicated rise in temperature. At this point, it was 2 minutes, 55 seconds elapsed time since the first anomalous thermal sensor temperature increase indicated in the left-hand wheel well.

At 32:13:56:16 G.m.t., 3 minutes and 59 seconds after the first anomalous condition was noted in the hydraulic subsystem, the left MLG uplock actuator sensor initiated an anomalous rise in temperature. Within the next 37 seconds, the following four thermal sensors exhibited a change to an increasing rate of rise in temperature:

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1. Left MLG system 3 brake return line sensor; and
2. Left MLG brake-line temperature sensors C and B, and the left MLG strut actuator sensor.

At this point, it was 4 minutes, 36 seconds since the first anomalous thermal sensor temperature increase was indicated in the left-hand wheel well. Within 1 minute, 1 second, at 32:13:57:54 G.m.t., the system 2 left-hand brake switch valve return line initiated an anomalous rise in temperature. This was the last of the eight anomaly-affected sensors in the left-hand wheel well to indicate a rise in temperature. At 32:13:58:16 G.m.t., the left MLG brake-line temperature sensor D indicated a change to a rapid increase in the temperature. Sixteen seconds later, the system 2 left-hand brake switch valve return line also initiated a rapid increase in the temperature rise-rate. This sensor indicated the most rapid rise rate of all the left-hand wheelwell thermal sensors, indicating a rate of approximately 40 °F/min. This occurred at an elapsed time of 6 minutes, 15 seconds since the first hydraulic subsystem thermal sensor temperature increase was indicated in the left-hand wheel well.

Loss-of-signal from the vehicle occurred at 32:13:59:32 G.m.t., at which time all hydraulic subsystem sensor downlink data were lost. The elapsed time from the indication of the first sensor temperature indicating an anomalous temperature rise in the left-hand wheel well to LOS was 7 minutes, 15 seconds. At LOS, all of the thermal sensors within the left-hand wheel well, though rising, were all still below redline limits.

It should also be noted that, unlike other sensors that were still trending upward at LOS, the system 2 brake switching-valve return-line temperature sensor and the left MLG brake-line temperature sensor A, which had exhibited the greatest temperature rise rate, very briefly flattened and then exhibited a decrease (approximately 3 °F) prior to LOS. The reason for this is unknown.

The post-LOS period of reconstructed data covered a time period of 32 seconds and consisted of 5 seconds of data followed by a gap of 25 seconds followed by a final 2 seconds of data. Although both the 5- and 2-second data strings provided additional insightful data, both segments were characterized, in some cases, by multiple data hits. The initial 5 seconds of post-LOS reconstructed data indicated that all three hydraulic subsystem main pump pressures were still within nominal ranges (2700 - 3400 psia). All three hydraulic system reservoir volumes were within nominal range (46 - 90 percent) as were reservoir pressures (60 - 95 psia) and temperatures (less than 220 °F). All three hydraulic system bootstrap accumulator pressures were between 3050 psia and 3200 psia, which is within the nominal range. The eight left-hand wheel well thermal sensors discussed previously indicated relatively flat temperatures during the initial 5-second data period, and no data on any of these sensors were indicated in the

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final 2 seconds of data. All water spray boiler data was within the nominal range during the initial 5 seconds of post-LOS data. The water spray boiler system 1, 2, and 3 GN₂ tank pressures indicated nominal pressures of 2537 psia, 2452 psia and 2506 psia, respectively, at LOS.

The final 2 seconds of data indicated that sometime in the previous 25-second data gap, the hydraulic subsystems were apparently breached. The final 2 seconds of data indicated hydraulic system main pump (system) pressure at 0 psia on all three systems. The hydraulic system reservoir pressures likewise indicated 0 psia and indicated reservoir quantities of 0 percent on all three systems. Each of the three hydraulic system bootstrap accumulators showed a pressure below 2000 psia on the liquid side of the bellows, indicating that a less-than-nominal pressure was still locked up downstream of each of the system priority valves. The nominal bootstrap accumulator reset pressure following a nominal main pump shutdown is not less than 2675 psia and is controlled by the priority valve (system 1 - 1970 psia, system 2 - 1920 psia and system 3 - 1860 psia). The fact that the three bootstrap accumulator pressures were less than 2675 psia is consistent with the hydraulic system reservoir pressures being at 0 psia and reservoir quantities at 0 percent. The water spray boiler system 1, 2, and 3 GN₂ tank pressures still indicated pressure integrity during the final 2 seconds of post-LOS data, and the pressures were 2530 psia, 2450 psia, and 2510 psia, respectively, at the last salvaged data bit. The decreasing water spray boiler lubrication oil return line temperatures during the 32-second period of reconstructed data is attributed to reduced APU loads because of breached and depleted hydraulic systems. The APUs were spinning empty pumps without a load or pressure sometime during the 25-second period of LOS. The APU spin data are consistent with White Sands Test Facility test data for a depleted hydraulic pump. Depleted hydraulic systems and off-loading the APUs are consistent with decreasing APU bearing and lubrication oil outlet temperatures as well as water spray boiler lubrication oil return temperatures and increasing water spray boiler hydraulic heat exchanger temperatures. The data indicate that the water spray boilers did not experience a typical overshoot/overcool condition.

In summary, typical mission entry data in the timeframe of the observed anomaly indicates MLG wheel well thermal sensors leveling off to trending downward, not rising as occurred during the STS-107 event. Based on the data analysis, it is believed that the loss of the four elevon actuator return line thermal sensors to OSL was due to the destruction of the instrumentation wiring at some point in the wire routing. Discussions have led to the understanding that the wiring bundle carrying the left-hand elevon actuator instrumentation wiring is routed from the actuators to the vehicle left sidewall and around the outboard perimeter of the left-hand wheel well. The eight hydraulic subsystem sensors that indicated an anomalous temperature rise are located on hydraulic lines in the left-hand wheel well aft-portion inboard sidewall and on the left MLG strut and actuator. The maximum temperature change from the initiation of the temperature rise occurred on the left MLG brake-line temperature sensor A, indicating a rise from

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approximately 124 °F to 172 °F (48 °F change). This was also the highest temperature recorded in the left-hand wheel well prior to LOS. The minimum temperature change occurred on the left MLG brake-line temperature D, indicating a rise from 88 °F to 100 °F (12 °F change). The left MLG strut actuator temperature indicated a temperature of 76 °F at LOS.

Although showing evidence of the event leading to the loss of the Orbiter, the HYD/WSB parameters were all within nominal ranges and maintained apparent nominal operation up until the final 2 seconds of reconstructed data that indicated all three hydraulic systems had been lost.

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D4.0 MAIN PROPULSION SYSTEM PERFORMANCE EVALUATION

D4.1 Executive Summary

The main propulsion subsystem (MPS) performed nominally during all phases of the mission. During entry, all MPS parameters were nominal until loss of data.

D.4.2 Prelaunch/Ascent Performance

The MPS performed nominally during the pre-launch and ascent phases of the mission. No MPS anomalies or significant events were noted in the review of the ascent data.

D.4.3 On-Orbit Performance

The MPS performed nominally during the on-orbit phase of the mission. No MPS anomalies or significant events were noted during the review of the on-orbit data.

D.4.4 Entry Performance

The MPS performed nominally during the entry phase of the mission. No MPS anomalies or significant events were noted during the review of the entry data.

MPS helium system decay from reconfiguration until LOS was nominal. Some of the tanks for the helium systems for SSME 2, and 3 are located on the left side of the midbody. These systems did not indicate any temperature or associated pressure rise in the systems prior to LOS.

The LH₂ manifold was vented to vacuum for the duration of the flight prior to opening the return to launch site (RTL) dump valves, so no pressure decay was noted upon opening the valves.

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D.5.0 ORBITAL MANEUVERING SUBSYSTEM PERFORMANCE EVALUATION

D.5.1 Executive Summary

The orbital maneuvering subsystem (OMS) performed nominally during all phases of the mission. During entry, the OMS performance was nominal and without incident until the final 2 seconds of the 32-second period of reconstructed data. At that time, there was a significant loss of instrumentation on the left OMS pod.

D.5.2 Pre-launch/Ascent Performance

The OMS performed nominally during the pre-launch and ascent phases of the mission. No deviations or significant events related to the OMS were noted during the review of the ascent data.

D.5.3 On-Orbit Performance

The OMS performed nominally during the on-orbit phase of the mission. No deviations or significant events related to the OMS were noted during the review of the on-orbit data.

D.5.4 Entry Performance

During entry, the OMS performance was nominal and without incident until the final 2 seconds of the 32-second period of reconstructed data. At that time, there was a significant loss of instrumentation on the left OMS pod.

The overall performance of the left and right OMS was nominal, with no exceptions prior to LOS at 32:13:59:32 G.m.t. The left OMS experienced a loss of instrumentation when data came back for approximately 2 seconds before the final LOS at 32:14:00:05 G.m.t.

Starting at 32:13:59:30 G.m.t. (just prior to LOS), all the OMS parameters were reading nominal values and the values remained at nominal levels until 32:13:59:37.4 G.m.t. (end of the first 5-second period of reconstructed data). When data came back at 32:14:00:03 G.m.t., it was seen that most of the pressure and temperature measurements in the left OMS pod were reading an off-nominal value. In most cases, the data were at an off-scale low value, although some off-scale high measurements were observed. Some measurements were not available at all because of the intermittent nature of the data caused by data hits. However, there was one good reading of the left OMS engine GN₂ pressure that had the same reading as at 32:13:59:36 G.m.t. (during the first 5-second period of reconstructed data).

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The data during this final 2-second period of reconstructed data can be interpreted as showing the left OMS as having been breached because the available pressure data show the systems at dramatically reduced pressures. This interpretation is also supported by three primary avionics software system (PASS) fault summary messages concerning the left RCS and one backup flight system (BFS) fault message concerning the left OMS that was not on the PASS summary. There were no fault messages, or at least none in the buffer, for the right OMS. The fault messages, the criteria the GPCs use to generate them, and possible causes/interpretations of the messages are detailed in the following paragraphs.

There was no PASS message in the Queue for the left OMS; however, the BFS had an L OMS TK P message that was time-tagged at 32:14:00:03.470 G.m.t. The time tag is suspect data because of data errors in the time-word. The PASS will annunciate this message when the propellant tank ullage pressures are either high (> 288 psia) or low (< 234 psia). The BFS will annunciate this message for the propellant tank ullage pressures being either high (> 288 psia) or low (approximately 234 psia), or if the helium or GN₂ tanks fall below 1500 psia or 1200 psia, respectively, or the GN₂ accumulator pressure falls below 299 psia or exceeds 434 psia.

The error code for this message showed it was either the oxidizer and/or fuel tank that caused this message to be generated. There were no BFS data for the helium or GN₂ system during the final 2 seconds of the reconstructed data before the final LOS. On the PASS, there was only one data sample for only one left OMS tank pressure during this time period that was the left OMS oxidizer ullage pressure of 37.6 psia at 32:14:00:03 G.m.t. If this value drove the BFS fault; however, the PASS should have also annunciated a fault message, but none was recorded.

Since there were no right OMS fault messages and no left OMS pod data were available immediately prior to the final LOS, it is clear that something occurred in the left OMS pod during the 25-second data gap prior to the final 2-second period of reconstructed data. Without more data, any further explanations are speculation.

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D.6.0 REACTION CONTROL SUBSYSTEM PERFORMANCE EVALUATION

D.6.1 Executive Summary

The reaction control subsystem (RCS) performed nominally during all phases of the mission. During entry, the RCS performance was nominal and without incident until the final 2 seconds of the 32-second period of reconstructed data.

The overall performance of the forward RCS and the left and right RCS was nominal, with no exceptions prior to LOS at 032:13:59:32 G.m.t. The left RCS, housed in the left OMS pod, had experienced a significant loss of instrumentation, for some unknown reason, when data came back for approximately 2 seconds (reconstructed data period) before the final LOS at 032:14:00:05 G.m.t.

D.6.2 Pre-launch/Ascent Performance

No deviations or significant events related to the RCS were noted during the review of the pre-launch and ascent data.

D.6.3 On-Orbit Performance

No deviations or significant events related to the RCS were noted during the review of the on-orbit data.

D.6.4 Entry Performance

The overall performance of the forward RCS and the left and right RCS was nominal during entry, with no exceptions prior to LOS at 32:13:59:32 G.m.t. The left RCS, housed in the left OMS pod, had experienced a significant loss of instrumentation, for some unknown reason, when data came back for approximately 2 seconds before the final LOS at 32:14:00:05 G.m.t.

At 32:13:59:52.114 G.m.t., the PASS had a message that there was a leak in the left RCS. Subsequently at 32:14:00:01.54 G.m.t. and 32:14:00:03.47 G.m.t., the BFS had messages of a left RCS leak. A low-level of confidence exists for the time tags for the two BFS messages. This message is generated when the difference between the oxidizer and fuel quantities, as calculated by the RCS quantity monitor software, is greater than 9.5 percent based on pressure, volume and temperature (PVT) derived values. The unit percent-PVT is used to distinguish the quantity from percent gage where the latter implies a physical gage (found within the OMS tanks) and the former implies a thermodynamically derived value (in this case, the RCS quantity).

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At 32:14:00:02.654 G.m.t., the PASS had a message that a thruster in the left RCS had failed (L RCS LJET). No similar message was received from the BFS. This message is generated when an RCS thruster on the left OMS pod has failed. This can be a fail off, fail on, or fail leak. The crew would use their computer to determine the failure mode.

At 32:14:00:03.637 G.m.t., the PASS had a message that the left RCS PVT was not operating correctly (L RCS PVT). The BFS does not generate this message. This message is generated when the RCS quantity monitor software does not have enough input data to process, and therefore cannot calculate a quantity for either the oxidizer or fuel tanks. This means that at least one input and its backup have fallen outside the reasonableness limits for those particular inputs, and the software has suspended the quantity calculation.

The obvious analysis of the RCS leak message is that there was a leak, either oxidizer or fuel or both. However, there are also other things that can generate the message because the quantity message is based on tank pressures and temperatures. If the temperatures and/or the pressures give erroneous readings that satisfy the reasonableness limits, then the software will treat the values as good and calculate a quantity. For the data from STS-107 at LOS (approximately 032:13:59:32 G.m.t.), if both the left RCS oxidizer and fuel tank temperatures gave erroneous readings of 120 °F instead of the actual 80 °F, then the quantity monitoring software would have computed quantities which differed from each other by 9.5 percent PVT and a leak message would have been generated. However, if an input falls outside the reasonableness limits for that particular input, then the software uses a backup input. This allows a less accurate quantity to be calculated. In the previous example, the 120 °F temperature for the propellant tank is still within the reasonableness limits.

During the review of entry data past the first LOS at 032:13:59:32 G.m.t., it was determined that the left RCS data were nominal until approximately 32:13:59:37 G.m.t. (end of the 5-second period of reconstructed data). When data returned for a brief time at approximately 32:14:00:03 G.m.t. (final 2-second period of reconstructed data), the analysis showed that most of the left RCS operational instrumentation (OI) data and the limited downlist data that was available had values of OSL, OSH (off-scale high) or an off-nominal value. The data from the right RCS and the forward RCS on the other hand had nominal values, with a limited number of exceptions.

The analysis indicates that something caused the loss of data from the left RCS. The LEAK and PVT messages could have been caused by a mere lack of data resulting from the wires being severed by some means. The messages could also have been caused by an actual leak either through thruster valves (a thruster valve that did not completely close), or because of a breach of the system (ruptured propellant tank, broken propellant line, ruptured helium tank,

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broken helium line). Thus, the following two possible scenarios are provided and both are equally valid because of the paucity of data.

1. The first scenario is based on the premise that the left RCS had a leak that resulted in a quantity divergence of greater than 9.5-percent PVT between the fuel and oxidizer and, thus, generated the first message. This leak would be of such magnitude that the resulting propellant tank(s) would not be capable of supporting thruster firings causing the left thruster (LIET) message. Finally, enough propellant leaked out that the resulting propellant tank pressures fell outside the reasonableness limits and the PVT gaging calculation was suspended for the left RCS (the third message, L RCS PVT).
2. The second scenario is based on the premise that there was no leak. Instead, system instrumentation was being lost. In this scenario, some instrumentation loss caused a degradation of the PVT calculation and generated the first message. Then instrumentation for the thrusters themselves was lost and this loss resulted in the general purpose computer (GPC) being unable to confirm that the thrusters were firing in response to the reaction jet driver (RJD) outputs; thus the second message. Enough instrumentation was finally lost that the PVT gaging calculation was suspended for the left RCS, which resulted in the third message.

In response to questions that have been asked on the subject of calculating the amount of RCS propellant used, and therefore, gage the amount of thruster activity during the 25-second data gap before the final 2-second period of reconstructed data. Inadequate data exists from the left RCS oxidizer system to determine a final quantity. The left RCS fuel has one more measurement than the oxidizer, but that measurement is still not enough to accurately gage the propellant quantity. The gage readings are present just before final LOS (end of 2-second period of reconstructed data) and show the oxidizer and fuel quantities as 17.8 percent PVT and 31.8 percent PVT, respectively. This difference of more than 9.5-percent PVT shows that the left RCS leak message was generated, and the Master Alarm had been triggered. However, inadequate data exist from the telemetry to determine with any degree of certainty the cause the left RCS PVT message.

PASS data from the right RCS during the period from 32:13:59:36 G.m.t. to 32:14:00:03 G.m.t. shows that the quantities changed by an average value of 7.4-percent PVT. For the right RCS, there are no PASS pressure or temperature data for any tank during the final 2-second period of reconstructed data. The downlisted PASS quantities for the oxidizer and fuel tanks had values of 35.2-percent PVT and 31.2-percent PVT, respectively, while the BFS values were 33-percent PVT and 32-percent PVT, respectively. The cause of this

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difference is that the BFS uses slightly different quantity equations and initial conditions than the PASS.

The BFS had values for the helium P2 and propellant tank outlet pressures and tank quantities for the right RCS during the final 2-second period of reconstructed data. Using the available BFS pressures and adding the bias seen earlier in the mission to estimate the redundant pressure measurement, and assuming the tank temperatures had not changed in the previous 30 seconds, the PASS algorithm computes values of 31.8-percent PVT and 30.2-percent PVT in the oxidizer and fuel tanks, respectively. These values are reasonably close to the BFS values. These results give some confidence in the data quality of the downlisted propellant quantities. Since STS-1, it has been observed that periods of heavy RCS propellant usage cause the PVT gaging program to show a lower-than-actual quantity, because the helium and propellant temperature readings are slow to show the actual average temperatures. Once the thruster usage ceases, these temperatures "move" toward the actual average temperature of the tank contents, and the calculated propellant quantities likewise change in the direction of the actual propellant quantities. This phenomenon is referred to as "bounce-back".

An estimate of the bounce-back effect can be made from the forward RCS quantity bounce-back ratio seen after the forward RCS dump on STS-107. For this case, it is seen that for every 1-percent of propellant used the gage indicates 1.2775-percent PVT used. The 2, 3, and 4 thruster flow-rates found in the Shuttle Operational Data Book (SODB) are also used. As there are no data available to show how many thrusters actually fired and for how long, an estimation of the total thruster-on time for the right RCS during the LOS before the final 2-second period of reconstructed data is shown in the following table. The estimate is bounded using different propellant flow rates both with and without the bounce back effect. The results are given for seconds of time beyond 32:13:59:36.6 G.m.t.

Number of Thrusters Firing	Without PVT Bounce-Back	With PVT Bounce-Back
2	26 seconds	20 seconds
3	18 seconds	14 seconds
4	13 seconds	10 seconds

As for the forward RCS, with the exception of the ullage pressures that appear to be data hits, the pressures and temperatures of all the forward RCS tanks were unchanged from their former values when data was acquired for the final 2 seconds of reconstructed data.

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D.7.0 FUEL CELL POWERPLANT SUBSYSTEM PERFORMANCE EVALUATION

D.7.1 Executive Summary

The fuel cell powerplant (FCP) subsystem performed nominally during all phases of the mission. During entry, all FCP parameters were nominal until 2 seconds prior to the final loss-of-data. There were no gross system operation anomalies that could be confirmed in the final 2 seconds of reconstructed data. The changes seen appear to be a result of other events that were taking place on the vehicle.

D.7.2 Pre-launch/Ascent Performance

The FCP subsystem performed nominally during the pre-launch and ascent phases of the mission.

During powered flight, the electrical load peaked to approximately 23 kW immediately prior to Solid Rocket Booster (SRB) separation. All fuel cell measurements (current, voltage, temperatures, pressure, flow rates, and sub-stack differential voltages) were nominal. The fuel cell water relief and purge system temperatures were nominal. There were nominal heater cycles on the fuel cell alternate water lines.

During vent door opening at approximately T-18 seconds during pre-launch operations, the fuel cell 2 hydrogen (H₂) motor status jumped for one data sample approximately 0.1 V from 0.59 to 0.69 V. This change did not violate the Launch Commit Criteria (LCC) limit of 1.0 V. The voltage returned to the normal level on the next data sample one second later. Fuel cell operation continued to be nominal. This indication appears to be associated with the suspected ac bus 2 B-phase anomaly.

D.7.3 On-Orbit Performance

The FCP subsystem performed nominally during the on-orbit phase of the mission.

The voltage change discussed in the previous paragraph was also observed during a seat adjustment as well as during the payload bay door opening. These indications appear to be associated with the suspected ac bus 2 phase-B anomaly.

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D.7.4 Entry Performance

The fuel cell powerplant (FCP) subsystem performed nominally during the entry phase of the mission. During entry, all FCP parameters were nominal until 2 seconds prior to the final loss-of-data. The fuel cell subsystem performance during the period from 32:13:00 G.m.t. through LOS + 5 seconds of the reconstructed data were nominal. There are no direct or indirect findings or associations with the problem that caused the loss of the vehicle.

During the last 2 seconds of the 32-second period of reconstructed data, the fuel cell 3 hydrogen/water pump was operating on 2 phase ac current rather than the usual 3 phases, all loads on the fuel cells were increasing, the oxygen purge vent line temperature was experiencing an unexpected rise, and there were conflicting indications that manifold 1 had lost oxygen pressure (possibly instrumentation). No gross system operation anomaly is confirmable in the last 2 seconds of the reconstructed data. The changes of fuel cell parameters appear to be a result of other events that were taking place on the vehicle.

During the last 2 seconds of the 32-second period of reconstructed data, it was unreliable because of data hits with many fuel cell telemetry measurements missing from the "STS-107 EDIT" data. The basic conclusions derived are:

1. Fuel cell 3 hydrogen separator/water pump was operating on 2 phases based upon the pump motor status reading of about 4.5 Vdc;
2. All 3 fuel cells displayed load increases. Fuel cell 1 increased about 120 amps; fuel cell 2 increased about 44 amps; fuel cell 3 increased about 48 amps;
3. Fuel cell 3 and main bus C voltage both experienced a 0.5-Vdc drop during the last portion of the 2-second data before the final LOS;
4. Fuel cell oxygen purge-line temperature rose 84 °F from the LOS + 5 second data to the last 2 seconds of data. Only 1 sample of fuel cell telemetry was deemed to be of good quality by the Data Verification Team (DVT); and
5. PRSD oxygen manifold 1 pressure indicated off-scale low and fuel cell 1 coolant pressure (provides fuel cell indication of oxygen pressure) indicated OSL. No manifold -2 pressure indication was available to verify the readings. No other confirming cues were present to verify the loss of oxygen pressure in the manifold such as the fuel cell 1 oxygen reactant flow meter indicating good reactant flow; no other fuel cell coolant pressures had dropped; no tank pressures had dropped.

Nominal H₂ tank heater cycles in tanks 1 and 2 occurred to maintain nominal manifold pressure to support fuel cell operations. The O₂ manifold pressure was decaying at a nominal rate to support fuel cell operations and crew breathing. No oxygen tank heater cycles were required during entry up to the end of the 32-second period of reconstructed data, but nominal heater cycles were

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occurring prior to the entry phase. All tank internal fluid and heater assembly temperatures were nominal.

The total Orbiter power produced by the three fuel cells was nominal for LOS + 5 second data at about 20.5 kW. All fuel cell measurements (current, voltage, temperatures, pressure, flow-rates, and substack voltages) were nominal. The fuel cell water relief nozzle temperature was increasing as expected after entry interface because of aerothermal heating. The fuel cell product water line temperatures were beginning to decrease in a nominal fashion due to convective cooling caused by entering the atmosphere.

During the last 2 seconds of the 32-second period of reconstructed data, the total Orbiter power level had increased to about 23 kW. Current on all 3 three fuel cells was increasing; fuel cell 3 had 2 phase ac operation on its hydrogen/water pump; an off-nominal 84 °F rise in the oxygen purge vent line temperature was noted; and fuel cell 1 coolant pressure and oxygen manifold pressure 1 were reading OSL.

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D.8.0 POWER REACTANT STORAGE AND DISTRIBUTION SUBSYSTEM PERFORMANCE EVALUATION

D.8.1 Executive Summary

The power reactant storage and distribution (PRSD) subsystem performed nominally during all phases of the mission. During entry, all PRSD parameters were nominal at loss-of-data. The PRSD subsystem performance during the period from 32:13:00 G.m.t. through the LOS + 5-second period of reconstructed data were nominal. There are no direct or indirect findings or associations with the problem.

During the last 2 seconds of the 32-second period of reconstructed data, the fuel cell 3 hydrogen/water pump was operating on 2 phase AC current rather than the usual 3 phases, the oxygen purge vent line temperature was experiencing an unexpected rise, and conflicting indications were observed that manifold 1 had lost oxygen pressure (possibly instrumentation). No gross system operation anomaly is confirmable in the last 2 seconds of data. The changes of PRSD parameters appear to be a result of other events that were taking place on the vehicle.

D.8.2 Pre-launch/Ascent Performance

The PRSD subsystem oxygen (O₂) and hydrogen (H₂) tank sets 1 and 2 heater switches were in nominal ascent configuration. The O₂ and H₂ tanks 1 and 2 'A' heaters were in AUTO. All of the seven other tank set heater switches were configured to OFF. All four manifold isolation valves were open. The extended duration Orbiter (EDO) pallet, installed in the aft part of the payload bay with four tank sets, was deactivated. An O₂ offload was performed to reduce the nominal end-of-mission (EOM) landing weight. Oxygen tanks 1, 2 and 3 were offloaded by approximately 100 lb each and tanks 4 and 5 were offloaded by approximately 25 lb each for a total O₂ offload of approximately 350 lb.

The main buses were untied for ascent. The main bus B (MNB) to main bus C (MNC) cross tie was performed at 16:16:56:48 G.m.t., for nominal on-orbit SpaceHab load distribution. The water line heaters were on the A system.

The O₂ and H₂ manifold and tank pressure decay rates were nominal to support fuel cell operations and crew breathing. The oxygen manifold pressures reached the tank 1 and 2 control band and these tanks began nominal heater cycles at 16:16:28 G.m.t. The hydrogen manifold pressures did not reach their tank 1 and 2 control band during the ascent-data evaluated.

All tank internal fluid and heater assembly temperatures were nominal.

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D.8.3 On-Orbit Performance

All of the PRSD system tank pressure cycles that were regulated by internal electrical heater operation were nominal, and were controlled by the heater AUTO function. All of the tank internal fluid and heater assembly temperatures were nominal for the entire on-orbit operation. The EDO pallet was activated throughout the on-orbit operations, and was deactivated during deorbit preparations.

A hydrogen manifold pressure spike occurred when manifold pressure control was switched to H₂ tank 3 after H₂ tanks 4 and 5 were depleted. This was a nominal signature seen previously in all orbiters when control is switched from low-quantity tanks to high-quantity tanks with colder, denser fluid. The manifold pressure did not reach the manifold relief valve crack pressure.

The Operations and Maintenance Requirements and Specification Document (OMRSD) in-flight checkout of the tank heater current sensors was performed. Nominal sensor operation was verified on all of the tank heaters except for O₂ tank 7. During this test, the O₂ tank 7 heater-A manual-command failed to energize the A heater. Later in the mission, however, the heater sensor for O₂ tank 7 was verified during tank heater operation in the AUTO mode.

D.8.4 Entry Performance

The overall entry performance of the PRSD subsystem was nominal, with the exception of several abnormalities seen in the last 2 seconds of the 32-second period of reconstructed data that was recovered. These abnormalities are the rise in temperature of the fuel cell purge line and the conflicting indications that O₂ manifold 1 had lost pressure. These abnormalities are discussed in section D.7.4. Events that occurred during the entry timeline period were evaluated. The 32:13:00 G.m.t. through LOS + 5-second data was confirmed to be nominal system operations and PRSD measurements experienced no data loss. Other than some telemetry parameters beginning to become unreliable because of data hits before the 25-second period on no data, all PRSD measurements were nominal.

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D.9.0 ATMOSPHERIC REVITALIZATION SUBSYSTEM PERFORMANCE EVALUATION

D.9.1 Executive Summary

The atmospheric revitalization subsystem (ARS) performed nominally during all phases of the mission. During entry, all ARS parameters were nominal at loss-of-data.

D.9.2 Pre-launch/Ascent Performance

The ARS performed nominally during the pre-launch and ascent phases of the mission. No anomalous conditions were noted in the data during this phase of operations.

D.9.3 On-Orbit Performance

The ARS performed nominally during the nominally during the on-orbit phase of the mission.

D.9.4 Entry Performance

The ARS performed nominally during the entry phase of the mission. No anomalous conditions were noted in the data during this phase of operations.

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D.10.0 PRESSURE CONTROL SUBSYSTEM PERFORMANCE EVALUATION

D.10.1 Executive Summary

The pressure control subsystem (PCS) performed nominally during all phases of the mission. During entry, all PCS parameters were nominal at loss-of-data.

D.10.2 Pre-launch/Ascent Performance

Review of the PCS pre-launch/ascent data indicated nominal system performance with no anomalous conditions observed.

D.10.3 On-Orbit Performance

Review of the PCS on-orbit data indicated nominal system performance with no anomalous conditions observed.

D.10.4 Entry Performance

The PCS operated nominally during the entry phase. Additionally, subsystem performance gave no indications of anomalous performance in other subsystems.

The 14.7-psia cabin pressure regulator inlet valves were closed and the pressure control system was inactive for nominal cabin pressurization for entry with the exception of oxygen supply to the Launch and Entry Helmets (LEH) and g-suits. Nominal activation and oxygen use by the crew for the g-suits was evident in the data evaluated.

There were no data for most of the 32-second period of reconstructed data following LOS. Based on the limited data for all measurements (PPO₂, O₂ percent, cabin pressure, cabin temperature and PPCO₂), the cabin parameters were nominal at the end of the first 5-second period of data and it appears that the cabin pressure integrity was intact throughout the 32-second period of reconstructed data.

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D.11.0 ACTIVE THERMAL CONTROL SUBSYSTEM PERFORMANCE EVALUATION

D.11.1 Executive Summary

The active thermal control subsystem (ATCS) performed nominally during all phases of the mission. During entry, all ATCS parameters were nominal at loss-of-data.

D.11.2 Pre-launch/Ascent Performance

Review of the ATCS pre-launch and ascent data indicated nominal system performance with no anomalous conditions observed.

D.11.3 On-Orbit Performance

Review of the ATCS on-orbit data indicated nominal system performance with no anomalous conditions observed.

D.11.4 Entry Performance

The ATCS performed nominally during the entry phase of the mission. Normal flash evaporator water use was observed in the analysis of the data. No ATCS anomalous conditions were noted in the data.

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D.12.0 SUPPLY AND WASTE WATER MANAGEMENT SUBSYSTEM PERFORMANCE EVALUATION

D.12.1 Executive Summary

The supply and wastewater management (SWWM) subsystem performed nominally during all phases of the mission. During entry, all SWWM parameters were nominal at loss-of-data.

D.12.2 Pre-launch/Ascent Performance

Review of the SWWM subsystem pre-launch and ascent data indicated nominal system performance with no anomalous conditions observed.

D.12.3 On-Orbit Performance

Review of the SWWM subsystem on-orbit data indicated nominal system performance with no anomalous conditions observed.

D.12.4 Entry Performance

The SWWM subsystem indicated nominal operation during the entry phase and no anomalous conditions were observed.

An out-of-family condition was observed in the supply water dump nozzle and vacuum vent nozzle temperatures during entry. Supply water dump nozzle entry heating rates on temperature sensors A and B increased from 33.5 °F per minute to 43.25 °F per minute. After 2 minutes and 17 seconds, the increase rate changed to 30.47 °F per minute. Vacuum vent nozzle entry heating rate increased from 0.88 °F per minute to 7.49 °F per minute in 26 seconds and then changed to 1.33 °F per minute. All past flight entry nozzle temperatures were reviewed, and there was no past flight with similar signatures to those observed on STS-107.

The wastewater dump nozzle temperature was nominal throughout this period. Due to the physical proximity of the wastewater dump nozzle to the other two nozzles, it might be expected that all three nozzles would behave similarly to the aerodynamics of entry. This inconsistency between the three nozzle temperatures may provide further clues as to the aerodynamic/aerothermal events and timing of those events during STS-107.

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D.13.0 AIRLOCK SUBSYSTEM PERFORMANCE EVALUATION

D.13.1 Executive Summary

The airlock subsystem performed nominally during all phases of the mission. During entry, all airlock subsystem parameters were nominal at loss-of-data.

D.13.2 Pre-launch/Ascent Performance

Review of the airlock subsystem pre-launch and ascent data indicated nominal system performance with no anomalous conditions observed.

D.13.3 On-Orbit Performance

Review of the airlock subsystem on-orbit data indicated nominal system performance with no anomalous conditions observed.

D.13.4 Entry Performance

The airlock subsystem performed nominally during the entry phase of the mission. No in-flight anomalies were identified in the data analysis.

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D.14.0 SMOKE AND FIRE SUPPRESSION SUBSYSTEM PERFORMANCE EVALUATION

D.14.1 Executive Summary

The smoke and fire suppression subsystem performed nominally during all phases of the mission. During entry, all smoke and fire suppression subsystem parameters were nominal at loss-of-data.

D.13.2 Pre-launch/Ascent Performance

Review of the smoke and fire suppression subsystem pre-launch and ascent data indicated nominal system performance with no anomalous conditions observed.

D.13.3 On-Orbit Performance

Review of the smoke and fire suppression subsystem on-orbit data indicated nominal system performance with no anomalous conditions observed.

D.13.4 Entry Performance

The smoke and fire suppression subsystem performed nominally during the entry phase of the mission. No in-flight anomalies were identified in the data analysis.

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D.15.0 PASSIVE THERMAL CONTROL SUBSYSTEM PERFORMANCE EVALUATION

D.15.1 Executive Summary

The passive thermal control subsystem performed nominally during all phases of the mission. During entry, some passive thermal control subsystem parameter temperatures were off-nominal at loss-of-data.

From the real-time operational instrumentation (OI) data, it could be seen that abnormal temperature rises occurred in the left main landing gear compartment and left-side structure, and that sensors failed on the hydraulic actuator return-lines of the left inboard and outboard elevons, lower elevon bondline and left upper and lower wing bondlines. Also, an off-nominal signature (change in temperature rise rate) occurred in the supply water dump nozzle and vacuum vent nozzle.

From the operational experiment (OEX) recorder data, many off-nominal thermal responses were noted. These included off-nominal temperature-rises of the left wing front spar at reinforced carbon carbon (RCC) panel 9 and the left wing RCC panel 9 lower-outboard attachment clevis. Additionally, there were off-nominal temperature responses of several thermal protection subsystem (TPS) surface measurements on the left side of the vehicle and all of the left wing temperature measurements failed.

D.15.2 Pre-launch/Ascent Performance

The passive thermal control subsystem pre-launch and ascent temperature responses were nominal and compared favorably with those of previous missions. No in-flight anomalies were identified in the evaluation of the data for this phase of the mission.

D.15.3 On-Orbit Performance

The on-orbit performance of the passive thermal control subsystem was nominal and compared favorably with that of previous missions. The on-orbit temperature responses for the bottom bondline and main landing gear were nominal. Attitude adjustments were made for the nominal end-of-mission thermal conditioning for water production and radiator protection concerns. This attitude change had no adverse effect on the vehicle thermal performance. Heaters enabled for the deorbit phase of the mission operated nominally. No in-flight anomalies were identified in the evaluation of the data.

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D.15.4 Entry Performance

The entry performance of the passive thermal control subsystem was nominal with the exception of abnormal temperature rises and temperature sensor failures.

During entry, the bondline structure OI data increases in temperature because of entry heating. From plots comparing the STS-107 bondline temperature response with selected flights, the right-hand side fuselage and bottom centerline temperature responses were nominal. However, the left-hand side fuselage temperature data responded nominally with three exceptions that were:

1. Mid fuselage compartment sidewall temperature at Xo1215;
2. Mid fuselage sill longeron temperature at Xo1215; and
3. Aft fuselage compartment sidewall temperature at X1410.

At 32:13:54:22 G.m.t., the temperature rise rates at these locations began faster than previously experienced on comparison flights. Also, uneven temperature responses occurred between port and starboard side at the same Xo location; symmetrical heating and temperature rise rates were expected.

The temperature rises on the portside fuselage structure measurements (mid sidewall, longeron, and aft sidewall) indicate higher-than-nominal environmental heating.

From the OEX data, off-nominal temperature responses were noted very early during entry. The left wing front spar at RCC panel 9 started an off-nominal increasing temperature trend at 32:13:48:59 G.m.t. [entry interface (EI) plus 270 seconds], and the left wing RCC panel 9 lower outboard attachment clevis started an off-nominal increasing temperature trend at 32:13:48:59 G.m.t. Within the next 70 seconds, the TPS surface temperatures on the left side of the vehicle and the left OMS pod began off-nominal responses when compared to previous flights. This response continued to LOS. Finally, during the period from 32:13:52:21 to 32:13:53:47 G.m.t., all of the left wing temperature measurements failed.

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D.16.0 MECHANICAL SUBSYSTEM PERFORMANCE EVALUATION

D.16.1 Executive Summary

The mechanical subsystem performed nominally during all phases of the mission. During entry, all mechanical subsystem parameters were nominal at loss-of-data.

There were two unexplained occurrences of additional current draw on ac bus 1, but it is not believed that these were in any way related to the loss of the crew and vehicle.

D.16.2 Pre-launch/Ascent Performance

No anomalies were noted in the mechanical systems during the pre-launch and ascent phases of the mission. All mechanisms operated in nominal dual-motor time with all limit switches transferring properly.

D.16.3 On-Orbit Performance

The overall performance of the mechanical systems was nominal during the on-orbit phase of the mission and no anomalies were noted. The port radiator was deployed and stowed twice, and all involved mechanisms operated in nominal dual-motor time with all limit switches transferring properly.

During the vent-door opening, payload bay door (PLBD) opening and Ku-band antenna deployment, an intermittent signature occurred on ac bus 2, phase B where the current was slow to increase at motor startup. This anomaly is discussed in D.19.0 Electrical Power Distribution and Control subsystem section of this appendix.

D.16.4 Entry Performance

The overall performance of the mechanical systems was nominal during the entry phase up to the loss of the vehicle

There were two unexplained occurrences of additional current draw on ac bus 1, but it is not believed that they were in any way related to the loss of the crew and vehicle.

Motor control assembly (MCA) operational status (Op Stat) indications show that the appropriate MCA relays were operating to supply ac power to the motors. During deorbit preparation and entry, all mechanisms operated in nominal dual-motor time with all limit switches and op stats transferring properly.

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During payload bay door (PLBD) closure, after starboard door closure had been stopped for the nominal alignment check, a 0.7-second period of additional current draw occurred on ac bus 1. The amplitude and signature of the trace appear to correspond to starboard door drive motor 1. However, a scenario could not be determined that would explain why one door drive motor would run without the bulkhead latches running as well. Because the sample rate for limit switch and op stat data is only 1 Hz, it is impossible to determine whether any changes occurred in these indications within the 0.7-second time period.

During vent door closure, a 0.1-second period of additional current draw was noted on ac bus 1 phases A and C. It is possible that a momentary limit switch failure could have caused a motor to drive for this short period. Because the ac current sample rate is 0.1 Hz and the op stat and limit switch data sample rate is only 1 Hz, this could have occurred without showing up in the phase B, op stat, or limit-witch data.

All data reviewed indicated nominal performance of mechanical systems hardware from deorbit preparations through entry and LOS+32. The two unexplained occurrences of additional current draw on ac bus 1 are not believed in any way related to the loss of the crew and vehicle.

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D.17.0 LANDING AND DECELERATION SUBSYSTEM PERFORMANCE EVALUATION

D.17.1 Executive Summary

The landing and deceleration subsystem performed nominally during all phases of the mission. However, evidence of the event that led to the loss of the Orbiter was apparent in landing and deceleration parameters during the entry.

1. Left-hand MLG tire pressure measurements failed OSL prior to LOS;
2. Left-hand inboard and left-hand outboard wheel temperature measurements went OSL prior to LOS; and
3. Left MLG down-lock indication transferred and remained on through LOS.

D.17.2 Pre-launch/Ascent Performance

This system was not active throughout the pre-launch and ascent phases of the flight, and no anomalies were noted in the data that was reviewed.

D.17.3 On-Orbit Performance

This system was not active throughout the on-orbit phase of the flight, and no anomalies were noted in the data that was reviewed. All data reviewed indicated nominal performance of landing and deceleration hardware throughout the on-orbit phase.

D.17.4 Entry Performance

The overall performance of the landing/deceleration subsystem was nominal throughout entry and the LOS+32-second period of reconstructed data with the exceptions noted in the following paragraphs.

The left-hand main landing gear tire pressure measurements failed off-scale-low (OSL) prior to loss of signal (LOS). The data review showed that the loss of the primary measurements occurred prior to the loss of the secondary measurements. This appears to indicate an instrumentation failure as opposed to a loss of tire pressure.

The left-hand inboard (LHIB) and left-hand outboard (LHOB) wheel temperature measurements went OSL prior to LOS. There are no redundant measurements for wheel temperature. Prior to the failure of the instrumentation, all indications were in the nominal range for landing.

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The left MLG down-lock indication transferred on at 32:13:59:05.877 G.m.t. and remained on through LOS. This appeared to be an erroneous output because all other available data indicated that the gear was up and locked during this time.

Based on redundant sensors and other indications; all observed anomalies appear to be due to instrumentation failures and not hardware. The following is a discussion of the instrumentation data of the landing system.

The left-hand inboard (LHIB) 1 and left-hand outboard (LHOB) 1 tire-pressure measurements went OSL (230 psia). The trend toward OSL started at 32:13:58:33.171 G.m.t. for both measurements. The LHOB 1 went OSL at 32:13:58:40.194 G.m.t. and LHIB 1 went OSL at 32:13:58:38.225 G.m.t. Prior to this event the pressures were at a nominal value of 350 to 355 psia, which is consistent with the expected pressures adjusted for wheel-well environmental conditions given the post top-off tire pressures and leak rates obtained prior to launch.

Both LHIB and LHOB wheel temperature measurements went OSL (-75 °F). The trend toward OSL started at 32:13:58:35.730 G.m.t. for the LHIB and at 32:13:58:33.201 G.m.t. for the LHOB. The LHIB went OSL at 32:13:58:44.219 G.m.t. and the LHOB went OSL at 32:13:58:39.783 G.m.t. Prior to this event, the temperatures were at a nominal 35 °F. The data were consistent with the on-orbit thermal conditioning performed to maintain minimum nominal end of mission (NEOM) tire pressures.

The right-hand inboard (RHIB) 1 and right-hand outboard (RHOB) 1 tire pressure measurements appeared to dip approximately 3 psi and then recover to a nominal 355 psia. The first pressure drop started at 32:13:58:37.316 G.m.t. for RHIB 1 and at 32:13:58:38:304 G.m.t. for the RHOB 1. This condition lasted for approximately 10 seconds after which the pressures recovered until LOS. Prior to this event, the pressures were at a nominal value of 350 to 355 psia, which is consistent with the expected pressures adjusted for wheel-well environmental conditions given the post top-off tire pressures and leak rates obtained prior to launch.

The LHIB 2 and LHOB 2 tire pressure measurements went OSL (230 psia). The trend toward OSL started at 32:13:58:33.171 G.m.t. for both of these measurements. The LHIB 2 went OSL at 32:13:58:44.192 G.m.t. and LHOB 2 went OSL at 32:13:58:54.189 G.m.t. Prior to this event, the pressures were at a nominal value of 350 to 355 psia, which is consistent with the expected pressures adjusted for wheel well environmental conditions given the post top-off tire pressures and leak rates obtained prior to launch.

The RHOB 2 tire-pressure measurement appeared to dip approximately 3 psi and then recovered to a nominal 355 psia. The pressure drop started at 32:13:58:45.199 G.m.t. This lasted for approximately 10 seconds after which the

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pressure recovered until LOS. Prior to this event, the pressure was at a nominal 355 psia, which is consistent with the expected pressure adjusted for wheel well environmental conditions given the post top-off tire pressure and leak rate obtained prior to launch.

The left MLG down-lock indication transferred on at 32:13:59:05.877 G.m.t. and lasted through the LOS+32 period of reconstructed data. All other indications showed the gear was still up and locked during this time. Testing of the proximity sensor circuit has shown that it is possible for this indication to fail in this manner when wires are burned through.

At the beginning of the post-LOS 25-second data gap, the left MLG brake line temperature A measurement, located on the strut, indicated 103 °F, while at the end of the gap it indicated 278 °F. Although the downlinked data has been verified to contain no errors, this is considered an erroneous measurement because the brake line B measurement, which is located beside the A measurement, indicated exactly the same value (118.6 °F) as before the gap. In addition, there is no significant change in the C and D measurements, which are located on the wheel-well wall near the hydraulic switching valve.

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D.18.0 PURGE, VENT, AND DRAIN SUBSYSTEM PERFORMANCE EVALUATION

D.18.1 Executive Summary

The purge, vent and drain (PV&D) subsystem and hazardous gas detection subsystem (HGDS) performed nominally during all phases of the mission. During entry, all PV&D and HGDS parameters were nominal at loss-of-data. The vehicle drain system is passive; there is no telemetry to monitor or review.

D.17.2 Pre-launch/Ascent Performance

The PV&D subsystem and HGDS performed nominally during the pre-launch and ascent phases of the mission. The purge temperatures and flow rates were set to predetermined levels and stayed within nominal tolerances. Orbiter circuit 2 was supplied with a higher-than-normal flow rate (225 lb./min) because of the extended duration Orbiter (EDO) pallet requirement agreed to in the payload integration plan. The higher flow rate was within Orbiter purge system certification. During the T minus 9-minute hold, the circuit 2 flow-rate was reduced to 170 lb./min to alleviate the need for a post-flight inspection of the Orbiter T-0 purge-circuit quick-disconnect flappers. The inspection is required if separation occurs at a flow rate at or above 180 lb./min.

D.17.3 On-Orbit Performance

The PV&D subsystem and HGDS performed nominally during the on-orbit phase of the mission, as the subsystems are inactive during the on-orbit period.

D.17.4 Entry Performance

The PV&D subsystem and HGDS performed nominally during the entry phase of the mission.

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D.19.0 ELECTRICAL POWER DISTRIBUTION AND CONTROL SUBSYSTEM PERFORMANCE EVALUATION

D.19.1 Executive Summary

The electrical power distribution and control (EPDC) subsystem performed nominally except for the sluggish ac 2 bus phase B current response initially noted post-ascent. During entry, all EPDC subsystem parameters were nominal at loss-of-data.

The ac 2 phase B sluggish current response (STS-107 MER Problem 1) was not present during PLBD closing or during entry, and had no effect on the Orbiter contingency. Prior to the last 2 seconds of reconstructed entry data, no EPDC measurements were lost, and there were no ac or dc bus shorts or losses.

D.19.2 Pre-launch/Ascent Performance

The EPDC subsystem pre-launch and ascent responses were nominal with the exception of the in-flight anomaly discussed in the following paragraph. This in-flight anomaly had no impact on mission accomplishment.

During vent-door opening, PLBD opening and Ku-band antenna deployment, the ac 2 bus phase B current exhibited a sluggish response. The phase B current increased to about one-half of the expected value, then increased to its nominal value within 0.5 to 1.5 seconds. During this time period, the ac 2 bus phases A and C current increased a similar amount. During steady-state periods, there were periodic occurrences of smaller magnitude signals of the same type (phase B dropping, phases A and C increasing). As before, most of these occurrences lasted between 0.5 and 1.5 seconds, and the phase B drop was between 0.2 and 0.3 ampere (between 3 and 4 telemetry counts). Water-loop pump cycling on the ac 2 bus sometimes triggered the described response. The occurrence of this condition was very sporadic and unpredictable. During a couple of 24-hour periods, no occurrences were noted. The cause of this anomaly was believed to be the ac 2 bus phase B inverter or the wiring between the ac 2 phase B inverter and panels L4 and MA73C.

D.19.3 On-Orbit Performance

The EPDC subsystem on-orbit operations were nominal with the exception of the anomaly discussed in the previous section. This in-flight anomaly had no impact on mission accomplishment.

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D.19.4 Entry Performance

Off-nominal indications were identified in the last 32 seconds of reconstructed data. These are:

1. The 5-seconds of the reconstructed data had numerous data hits throughout the period. Based on the ASA 4 failure times during the 5 seconds of reconstructed data, three signatures were found on the aft main buses that could be 5-ampere remote power controller (RPC) trip signatures. The RPCs performed as designed.
2. In the 2-second period of reconstructed data, some of the EPDC data were missing, some data were available for only one data sample and some data were in conflict with confirming data. Three conclusions from the data are:
 - a. There was a general upward shift in fuel cell and forward main bus amperes and a general downward shift in main bus voltages.
 - b. Several confirming parameters indicate that the ac 3 phase A inverter was disconnected from its ac bus, and there was an increasingly high voltage and current load on ac 3 phases B and C.
 - c. The fuel cell 1 amperes and single data samples indicate the possibility of a high load on ac 1 phase C.

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D.20.0 DATA PROCESSING SYSTEM PERFORMANCE EVALUATION

D.20.1 Executive Summary

The data processing system (DPS) pre-launch, ascent and on-orbit operations were nominal. During entry, all DPS parameters were nominal at loss-of-data.

D.20.2 Pre-launch/Ascent Performance

No unexpected general-purpose computer (GPC) errors occurred during pre-launch or ascent operations. The mass memory unit (MMU) hardware was used successfully during the OPS 1 transition at T-20 minutes on launch day as the program was obtained from MMU 1 area 1 on the tape. Prior to launch, the Kennedy Space Center (KSC) performed a dump and compare of the entire software of GPC 1 with no mismatches identified. The multiplexer/demultiplexer (MDM) hardware performance was satisfactory as exhibited in the data review conducted after the contingency.

D.20.3 On-Orbit Performance

All DPS hardware performed satisfactorily during the on-orbit operations, and no in-flight anomalies were noted in the analysis of the data.

D.20.4 Entry Performance

The DPS entry operations were nominal. Fault messages were generated and are discussed in the appropriate sections of this appendix.

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D.21.0 FLIGHT CONTROL SYSTEM HARDWARE PERFORMANCE EVALUATION

D.21.1 Executive Summary

The flight control system (FCS) pre-launch, ascent and on-orbit operations were nominal. During entry, all FCS parameters were nominal at loss-of-data.

The 32-second period of reconstructed data indicate that there was an anomaly involving aerosurface actuator (ASA) 4. This condition has been evaluated and determined to be the result of a wiring short in the aft of the left wing.

D.21.2 Pre-launch/Ascent Performance

At all times, the Solid Rocket Booster (SRB) thrust vector controllers (TVC), MPS TVC, and aerosurface actuators were positioned exactly as the GPC commands were given with normal driver currents, secondary differential pressures, and elevon primary differential pressures. The reaction jet driver (RJD) operation was also normal with no thruster-fail indications or other anomalies noted. The rotational hand controller (RHC) and translation hand controller (THC) were both used and exhibited normal channel tracking.

At no time during the ascent of STS-107 did the flight controls fail to accomplish the task of implementing GPC commands. Actuator positions closely tracked GPC commands, and at no time did secondary differential pressures used in the fault detection mechanism approach the limits that would initiate a failure response.

D.21.3 On-Orbit Performance

The flight control hardware on-orbit performance was nominal. No anomalies were found in the data. The limited aerosurface data available also showed no anomalies. Flight control hardware performance during the on-orbit flight control system checkout was nominal. No anomalies were found in any of the tests or checkout prior to entry.

D.21.4 Entry Performance

The FCS performance during the entry phase was nominal until the final seconds before LOS.

The STS-107 aerosurface actuator performance was nominal until the final second before LOS, when the ASA 4 anomaly began to appear. Aerosurface position did follow GPC commands, even after the occurrence of the ASA 4 anomaly and until LOS + 5 seconds. Aerosurface actuator secondary differential

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pressures were well below the bypass level and normal until the ASA 4 anomaly appeared.

At 32:13:59:31.7 G.m.t., aerosurface channel 4 positions either were at their null value or were transitioning toward their null value. Less than one second later at 32:13:59:32.396 G.m.t., the power was current-limiting and the voltage had dropped sufficiently for both remote power controllers (RPCs) for ASA 4 to drive the RPC trip measurement (1 Hz). Secondary differential pressure data indicates channel 4 on the right outboard elevon, right inboard elevon, left inboard elevon, left outboard elevon, rudder, and speedbrake were bypassed. The channel 4 fail flag was raised on the right outboard elevon, right inboard elevon, left inboard elevon, left outboard elevon, rudder, and speedbrake at 32:13:59:32.1 G.m.t. (1-Hertz measurement).

The channel 4 driver currents on the right outboard elevon, right inboard elevon, left inboard elevon, left outboard elevon, and speedbrake were non-zero (driving the channel 4 servo valve). A force fight occurred between channel 4 and the other 3 channels on the left outboard elevon from 32:13:59:32.597 G.m.t. to 32:13:59:34.318 G.m.t., as indicated by secondary differential pressure data. This force fight began when the bypass valve on channel 4 reopened (non-bypassed state) and allowed the servo valve to become active.

At 32:13:59:34.536 G.m.t., speedbrake channel 1, 2, and 3 secondary differential pressures indicate a force fight against channel 4. The secondary differential pressure on channel 4 was at null. The isolation valve power RPC was tripped at this point, removing power from the bypass valves on all actuators for channel 4. At 32:13:59:35.077 G.m.t., the actuator fail flags from ASA 4 had turned off.

At approximately 32:14:00:04 G.m.t., just prior to final LOS, aerosurface switching valves are indicated to be in their secondary positions, while the valves are expected to be in their primary positions with zero hydraulic pressure in all three hydraulic systems. In the same time period (32:14:00:04 G.m.t.), all aerosurface position indications read zero volts. Also in the same time period, ASA 1, 2 and 3 RPC indications show that they are off while the ASA 1, 2 and 3 power-on commands show on. In the same time period (32:14:00:04 G.m.t.), there are valid hydraulic reservoir temperatures, rudder/speedbrake actuator return line temperatures, right elevon actuator temperatures, body flap temperatures and MPS TVC return line temperatures, but no valid left elevon actuator temperatures or hydraulic return line temperatures.

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D.22.0 INERTIAL MEASUREMENT UNIT PERFORMANCE EVALUATION

D.22.1 Executive Summary

The inertial measurement unit (IMU) pre-launch, ascent and on-orbit operations were nominal. During entry, all FCS parameters were nominal at loss-of-data.

D.22.2 Pre-launch/Ascent Performance

The IMU pre-launch and ascent performance was nominal. The IMUs measured and reflected the Orbiter changes in attitude and velocity due to the nominal ascent activities. Review of the IMU pre-launch and ascent data did not show any anomalous conditions.

D.22.3 On-Orbit Performance

The IMU on-orbit operations were nominal. The IMUs measured and reflected the Orbiter changes in attitude and velocity due to the nominal on-orbit operations. Review of the IMU on-orbit data did not show any anomalous conditions.

D.22.4 Entry Performance

The overall performance of the three IMUs during entry was nominal. The IMUs measured and reflected the Orbiter changes in attitude and velocity due to the nominal entry activities. The deorbit firing and energy reduction maneuvers were accurately tracked by all three IMUs. The post-LOS data indicated continued nominal velocity changes, but large attitude changes were noted between the first few seconds of data and the small sample of data at the end.

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D.23.0 STAR TRACKER SUBSYSTEM PERFORMANCE EVALUATION

D.23.1 Executive Summary

The star tracker subsystem was powered off during ascent and no subsystem data are available. The star tracker subsystem performance on-orbit was nominal. The star tracker was powered off during entry.

D.23.2 Pre-launch/Ascent Performance

The star tracker subsystem was powered off during ascent and no subsystem data are available.

D.23.3 On-Orbit Performance

The star tracker subsystem performance on-orbit was nominal. Review of the star tracker subsystem data from the on-orbit period indicated no anomalous or off-nominal performance.

D.23.4 Entry Performance

The star tracker subsystem was powered off during entry and no subsystem data are available.

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D.24.0 NAVIGATIONAL AIDS SUBSYSTEM PERFORMANCE EVALUATION

D.24.1 Executive Summary

All navigational aids subsystem (NAVAIDS) operations were nominal during the pre-launch, ascent and on-orbit operations. During entry, all NAVAIDS parameters were nominal at loss-of-data. Based on the analysis of the data, the conclusion is that the NAVAIDS were nominal and had no involvement in the catastrophic failure that preceded the loss of the *Columbia* during the entry phase of the STS-107 mission.

D.24.2 Pre-launch/Ascent Performance

The overall performance of the NAVAIDS was nominal during pre-launch and ascent operations. All three tactical air navigation (TACAN) systems remained locked on to KSC during the ascent and broke lock when the station was out of range. The NAVAIDS were powered off after the operational sequence (OPS) 2 transition.

D.24.3 On-Orbit Performance

The NAVAIDS are normally powered off during the on-orbit phase until the transition to OPS 8 for the FCS checkout approximately 24 hours prior to the predicted landing. All of the NAVAIDS successfully passed the self-test during the FCS checkout. The NAVAIDS were then powered off after the OPS 2 transition. No deviations or significant events were observed in the NAVAIDS performance.

D.24.4 Entry Performance

All NAVAIDS subsystems were powered on at 32:09:30:05 G.m.t., and were functioning nominally prior to loss of signal (LOS). The TACAN systems had locked on to various channel 111X ground stations during the pass over the United States just prior to the de-orbit maneuver and that was nominal operation. The TACAN systems were in the search mode, but were out-of-range of the KSC ground station when LOS occurred at 32:13:59:32:174 G.m.t. The TACAN systems remained in the search mode during the extra 32 seconds of telemetry data that were later recovered. At 32:13:47:37 G.m.t., radar altimeter 1 locked on to plasma. At 32:13:47:39 G.m.t., radar altimeter 2 locked on to plasma. At 32:13:48:53 G.m.t., radar altimeter 2 broke lock on the plasma and remained unlocked until 32:13:59:26:20 G.m.t., when one sample indicating 800 feet was observed. Radar altimeter 1 remained locked on to the plasma until 32:13:58:45:00 G.m.t., and then broke lock until 32:13:59:34:30 G.m.t., when one sample indicating 5200 feet was observed. The 800 feet and 5200 feet indications were proven to be invalid and were disregarded. The radar altimeter

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data were compared with the data from previous OV-102 missions, including STS-109, STS-93 and STS-90. Similar radar altimeter signatures were observed for these flights when compared with the data from STS-107. The radar altimeter performance was determined to be nominal. The three microwave-scanning-beam landing systems (MSBLS) were powered on but were out-of-range of the KSC ground station and did not lock on. The MSBLS indications were nominal. The MSBLS were still out-of-range of the ground station during the extra 32 seconds of telemetry data that were later recovered.

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D.25.0 S-BAND SUBSYSTEM PERFORMANCE EVALUATION

D.25.1 Executive Summary

All S-Band subsystems and processors including S-Band phase-modulated (PM) system 2 and S-Band frequency modulated (FM) system 1 performed nominally during the pre-launch, ascent and on-orbit phases of STS-107. During entry, all S-Band subsystem and processor parameters were nominal at loss-of-data.

D.25.2 Pre-launch/Ascent Performance

The overall performance of the communications and tracking (C&T) subsystems during the pre-launch and ascent phase was nominal. The payload signal processor (PSP) was configured and tested satisfactory during pre-launch and then powered off per procedures prior to launch. S-Band PM system string 1 and 2 and the S-Band FM system were powered on and a checkout of these systems was completed prior to launch. The S-Band PM system string 2 provided nominal S-Band Orbiter telemetry and air-to-ground (A/G) voice communication coverage during the pre-launch, launch, and ascent phases. There were no off-nominal telemetry indications from any S-Band subsystems or processors.

D.25.3 On-Orbit Performance

The overall performance of the C&T subsystems was nominal during the on-orbit phase. The PSP was powered on, configured for SpaceHab support, and operated nominally until powered off at SpaceHab de-activation prior to the deorbit maneuver. During on-orbit operations, the S-Band FM system was occasionally powered on for operations recorder dumps via ground stations and powered off again when not in use. The S-Band PM systems string 2 provided nominal S-Band Orbiter telemetry and A/G voice communication coverage in the Tracking and Data Relay Satellite (TDRS) mode during the majority of the on-orbit phase. There were no off-nominal telemetry indications from either of the S-Band PM subsystems in any operational mode and S-Band communication coverage was nominal throughout the on-orbit phase.

D.25.4 Entry Performance

The overall performance of the C&T subsystems hardware during entry was nominal. The S-band communications coverage via the TDRS was as good as anticipated and very comparable to previous Shuttle entries at the same orbital inclination of 39 degrees. There were several S-Band return-link data dropouts during entry from 32:13:50:00 G.m.t. to 32:13:56:00 G.m.t. that cannot be explained. The antenna look-angles to the TDRS during this period would not typically result in dropouts. Data dropouts after this period until the final LOS

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were not unexpected based on the antenna look angles to the TDRS. There were no off-nominal telemetry indications from any C&T subsystem.

The recovered data after the 25-second LOS indicated the BFS software commanded a switch from the upper right aft (URA) antenna to upper right forward (URF) antenna at 32:14:00:04 G.m.t., and there were instrumentation indications of the execution of the commanded switch. This conclusion was based on the two antenna switch discretes and the analog value of power amplifier (PA) reflected power, which were consistent with the performance characteristics the URF antenna.

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D.26.0 Ku-BAND SUBSYSTEM PERFORMANCE EVALUATION

D.26.1 Executive Summary

The overall performance of the Ku-Band subsystem was nominal with no in-flight anomalies found during data analysis. During entry, all Ku-band subsystem parameters were nominal at loss-of-data.

D.26.2 Pre-launch/Ascent Performance

The overall performance of the Ku-Band subsystem during the pre-launch and ascent phases was nominal. The Ku-Band deployed assembly was stowed for ascent. Telemetry and operations indicate that the Ku-Band was still in its nominal ascent position prior to on-orbit deployment.

D.26.3 On-Orbit Performance

The overall performance of the Ku-Band subsystem during the on-orbit phase was nominal. The Ku-Band assembly was deployed at 16:17:54 G.m.t. in the expected dual motor time of 23 seconds. All telemetry measurements indicated the Ku-Band deployed assembly transitioned from the stowed to the deployed position. The Ku-Band system was activated at 16:17:58 G.m.t., passed the self-test, and functioned properly throughout the mission until it was nominally stowed and powered off at 32:01:47 G.m.t.

D.26.4 Entry Performance

The Ku-Band deployed assembly was stowed for entry. Telemetry indicates that the Ku-Band was still in its nominal position during entry.

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D.27.0 INSTRUMENTATION SUBSYSTEM PERFORMANCE EVALUATION

D.27.1 Executive Summary

The overall performance of the instrumentation subsystem during the pre-launch, ascent and entry was nominal with no in-flight anomalies identified during the data analysis. During entry, all instrumentation subsystem parameters were nominal at loss-of-data.

D.27.2 Pre-launch/Ascent Performance

The OI and Orbiter experiments (OEX) recorder subsystems performed nominally throughout the STS-107 pre-launch and ascent phases. No significant events or findings were found during the data analysis.

D.27.3 On-Orbit Performance

The overall performance of the instrumentation subsystem during the on-orbit phase was nominal. Review of the OI subsystem on-orbit data indicated no in-flight anomalies or anomalous conditions in the subsystem performance.

D.27.4 Entry Performance

The overall performance of the instrumentation subsystem during the entry phase was nominal until loss of signal. There were no indications of any anomalous performance in any of the subsystem hardware. A number of individual measurements failed or had anomalous readings in the minutes immediately prior to loss of signal. All of these are apparently related to the accident.

During entry operations, several of the hydraulic measurements failed to off-scale-low. These were:

Hydraulic system 3 left outboard elevon return line temperature;
Hydraulic system 1 left-hand inboard elevon actuator return line temperature;
Hydraulic system 1 left outboard elevon return line temperature; and
Hydraulic system 2 left outboard elevon return line temperature.

All tire pressure and wheel temperature measurements for the left-hand MLG were then observed to have drifted lower and failed to OSL. The left-hand outboard tire pressure 1 began drifting lower at 32:13:58:34 G.m.t., and failed OSL at 32:13:58:38 G.m.t. The left-hand inboard tire pressure 1 began drifting lower at 32:13:58:33 G.m.t. and failed OSL at 32:13:58:40 G.m.t. The left-hand inboard wheel temperature began drifting lower at 32:13:58:35 G.m.t., and failed OSL at 32:13:58:45 G.m.t. The left-hand inboard tire pressure began drifting

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lower at 32:13:58:41 G.m.t. and failed OSL at 32:13:58:48 G.m.t. The left-hand outboard wheel temperature began drifting lower at 32:13:58:35 G.m.t., and failed OSL at 32:13:59:40 G.m.t. The left-hand outboard tire pressure 2 began drifting lower at 32:13:58:39 G.m.t., and failed OSL at 32:13:58:54 G.m.t.

The failed measurements used multiple dedicated signal conditioners (DSC) with no more than one affected measurement using a single DSC card. Similarly multiple MDM cards in more than one MDM were used. The failed tire-pressure measurements used two different strain gage signal conditioners (SGSC).

Temperatures in the area of the midbody DSC's and SGSC remained nominal (50-55 °F) until loss of data. As the measurements utilized multiple DSC's, the source of the failures is not believed to be related to a signal conditioner. Temperatures at the wheel itself were increasing but not high enough to cause transducer failure. Furthermore, the staggered loss of the individual measurements suggests that the failures were measurement failures, rather than actual loss of tire pressure.

The source of the failures is consequently believed to be in the wire harnesses between the wheel area and the midbody. Since the measurements did not exhibit the characteristics observed with breakage of the wheel separation harness, it is more likely to be due to heat-related degradation of the wiring harnesses in the vicinity of the left-hand wheel well.

Review of the post-LOS data did not alter the conclusions reached, and no additional anomalies were identified.

The OEX recorder was recovered and the data were successfully retrieved indicating that the hardware performed nominally. These data were extremely helpful to the investigation as data were recorded until the breakup of the vehicle. The vast majority of the left-wing measurements failed apparently because of heat-related degradation of wiring harnesses in the left wing.

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D.28.0 DISPLAYS AND CONTROLS SUBSYSTEM PERFORMANCE EVALUATION

D.28.1 Executive Summary

Review of the Displays and Controls (D&C) subsystem pre-launch, ascent and on-orbit data indicated nominal system performance with no anomalous conditions observed. During entry, all D&C subsystem parameters were nominal at loss-of-data.

D.28.2 Pre-launch/Ascent Performance

The D&C subsystem was in the normal configuration and exhibited nominal operation during the pre-launch and ascent phase. All pre-launch master alarm occurrences were attributable to expected operations.

D.28.3 On-Orbit Performance

The D&C subsystem performed nominally during the on-orbit phase of the mission.

D.28.3 Entry Performance

The D&C subsystem exhibited nominal operation during the entry phase, including the additional 32-second period of reconstructed data. During the entry phase up to the additional 32-second time frame, the master alarms annunciated were correlated to the individual subsystems that triggered the alarms.

The downlisted data for the caution and warning master alarm subsystem shows evidence of the master alarm annunciating continuously from 32:13:59.33.863 to 32:14:00.04.760 G.m.t., which includes the additional 32-second period of reconstructed data. The data review indicates several subsystems could have triggered the master alarm. Each individual subsystem with possible master alarm triggers has been evaluated for validity of the master alarm data relative to that subsystems performance. A review of the BFS data reveals a correlation of the events with the downlisted caution and warning master alarm telemetry data.

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Appendix E STS-107 Mishap Investigation Timeline Instrumentation Data

Table with columns: No, IASID, OIB, Ch, Type, File, Location (X, Y, Z, Roll, Pitch, Yaw), Range, Sample Rate, Units. Includes notes on data format and calibration.

Notes: (*) = IASID is physically located on the Left/Right/Elevon actuator. Note 1: They are calling a Discrete-5 or Off or Off-Scale Low and Discrete-1 or On or Off-Scale High. Note 2: While this is listed in the database as VDC, it is not downloaded as such. Note 3: Same as Note 2 except with MCC Calibrations. Selected Elevon FDBK is converted to degrees (DEG).

Appendix F List of Contributors

A great many people participated in the review and analysis of flight data from STS-107. The following is a list of some of the many people who contributed to the review of the STS-107 data and the generation of the entry timeline. The Data Review and Timeline Team thanks all of those who contributed to this effort and apologizes to those who have been inadvertently left of this list.

Core Team (conducted data reviews and represented their organizations at the data reviews, generated timeline, compiled supporting data, generated report, etc.)

- Don L. McCormack, Jr. NASA/MV
David W. Camp Boeing
Joyce Seriale-Grush NASA/EA
Tim Reith Boeing
Don Peck Boeing
Randy Moore Boeing
Lonnie Jenkins Boeing
Tony Leba Boeing
Chuck Armstrong Boeing
Tom Davies Boeing/Cimarron
Walter Scott Boeing/Cimarron
Joe Mechelay Boeing/Cimarron
Scott Altman NASA/CB
George Zamka NASA/CB
Eric Boe NASA/CB
David Moyer NASA/MV
Bert Wagster USA
Jon Olansen NASA/NC
Al Arnold GHG
Ross Engle SAIC
Jeff Kling NASA/DF
Howard Wagner NASA/EP
Robert W. Fricke, Jr. LMSO

Auxiliary Power Unit Subsystem

- Ken Smith Boeing
Paul Grout Boeing
Mike Houle Boeing
Tom Reuland Boeing
Mel Friant NASA/DF
Eddie Eskola USA

Hydraulics Subsystem

- Bob Rauch Boeing
Jeff Goza Boeing

Appendix F List of Contributors

- Charles Rittrivi Boeing
David Beaugh Boeing
Farzad Rezayat Boeing
Francisco Hernandez NASA/EP
Mike Snyder USA

Main Propulsion Subsystem

- David Rigby Boeing
Jeff Sinnott Boeing
Tina Martingano Boeing
Mohammed Jebri Boeing
John Chan Boeing
Scott Baird NASA/EP
John Melcher NASA/DF
Thomas Arnold NASA/DF

Orbital Maneuvering and Reaction Control Subsystems

- Brian Werner Boeing
Steven Arrieta Boeing
James Garza Boeing
Ed Fitzgerald Boeing
Mickie Eguia Boeing
Courtney Dorris Boeing
Dean Lenort USA/MOD

Fuel Cell and Power Reactant Storage and Distribution Subsystems

- Danny Fitzgerald Boeing
Ken Adams Boeing
Johnny Wong Boeing
Tim North Boeing

Environmental Control and Life Support Subsystems

- Jordan Metcalf NASA/EC
Bruce Harkness USA
Don Sanderfeld Boeing
Chris Hoffman Boeing
Isaac Andu Boeing
Carmelo Ascunzion Boeing
Menghis Hagos Boeing
Thomas Londrigan Boeing
Vince Reyes Boeing
Marco Lorenzano Boeing
Keith Mosall NASA/EC
Chau Pham NASA/EC
Darren Fasbender USA/MOD

Appendix F List of Contributors

- Michael Fitzpatrick USA/MOD

Passive Thermal Control Subsystem

- Harry Chang NASA/ES
Diana Coronado Boeing
Shannon Belknap Boeing
Tim Davies Boeing
David Russell Boeing
Dan Reynolds Boeing
Guadalupe Gonzales Boeing

Mechanical / Landing and Deceleration Subsystems

- Robert Davis NASA/ES
Bill Heitzman USA
Tom Hoffman Boeing
Link Salvador Boeing
Ruben Smith Boeing
Jeff Goodmark Boeing
Chip Heintl Boeing

Purge, Vent and Drain Subsystem

- Doug Cline Boeing

Electrical Power Distribution and Control Subsystem

- Larry Minter Boeing
Mark Fugitt Boeing
Pete Peterson Boeing
Kenneth Utley Boeing
Mike Danielson Boeing
Mark Welch USA/MOD
Angela Bauer NASA/DF

Flight Control Subsystem

- Don McCorvey Boeing
Rich Kawaga Boeing
Vester Purkey Boeing
Stephen Choi Boeing
Jeff Wyrick USA/MOD
Kyle Belton USA/MOD
David Weiler USA/MOD
Vic Untalan NASA/DF

Inertial Measurement Unit Subsystem

- Mike Reves Boeing
Mike Rodgers Boeing

Appendix F
List of Contributors

Star Tracker Subsystem
Phil Perkins Boeing

Avionics Subsystems
Denise Romero NASA
Kevin Dunn NASA
John Hunt USA

Data Processing Subsystem
Jon Cummings USA
James Cooley Boeing
Vinh Nguyen Boeing
Lynna Wood Boeing
Jennifer Hagin NASA/DF

Navigational Aids Subsystems
Lance Borden Boeing
Billy Cowan Boeing

Communication Subsystems
Jeff Stafford Boeing
Ken McCrary Boeing
Marty O'Hare Boeing
Martha May Boeing
Laura Hoppe USA/MOD
Daryl Brown NASA/DF
Cathy Sham NASA/EV
Chip Kroll NASA/EV
John Boster Lockheed
Antha Atkins Lockheed

Instrumentation / Recorders Subsystem
Dwight Favors Boeing
Steve Woods Boeing
Rey Rivas Boeing
Patrick Ngo Boeing
Mike Garske NASA/MV

Displays and Controls Subsystem
Brian Kang Boeing
Andy Farkas Boeing

Multifunction Electronic Display Subsystem
Jim Newsome NASA

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Appendix F
List of Contributors

Danny Siner NASA
Brent Bynum Boeing
Chris Gentz Boeing
Debra Owen Boeing

Entry Aerodynamics
Jim Harder Boeing
Olman Carvajal Boeing
Brandon Redding Boeing
Georgi Ushev Boeing

Stress Analysis
Mike Dunham Boeing
Shawn Sorenson Boeing

Image Analysis
Greg Byrne NASA/SX
Jon Disler LM

Safety
Alan Peterson Boeing
Mike Dye Boeing
Bruce Stewart Boeing
Jeremy Verostko SAIC
Meagan Bell GHG
Michael Penney SAIC

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