Volume I

Report of Findings
X-43A Mishap

By the
X-43A
Mishap Investigation Board

Volume I

Table of Contents

Table of Figures

Table of Tables

Appendices

Volume II

Volume II is comprised of Appendices A, B, and C. Volume II Appendix A contains the fault tree used by the X-43A Mishap Investigation Board (MIB) in resolving the X-43A mishap. In electronic format, Volume II Appendix B contains the plans, closeout forms and supporting data used to disposition each fault. This appendix also contains hardcopy examples of a plan and closeout. In electronic format, Volume II Appendix C contains the MIB schedule used for planning and monitoring the MIB activities. This appendix also contains a hardcopy of the top level schedule.

Volume III

Volume III contains the Corrective Action Plan to be submitted under separate cover by the X-43 Project Office.

Volume IV

Volume IV contains the lessons learned from the X-43A Mishap Investigation. Lessons learned are presented in the NASA Lessons Learned Information Systems (LLIS) format obtained from the LLIS website. These lessons learned are provided per NPG: 8621.1 paragraph 6.1.1 and as directed in the charter for the MIB (Volume I, Section 1).

Volume V

Witness statements and testimony taken in support of the X-43A Mishap Investigation are being retained by the Mishap Board Chairman. These witness statements and testimonies had no direct bearing on any of the contributors to the mishap.

1 BOARD CHARTER

The Associate Administrator for Aerospace Technology formally appointed the X-43A Mishap Investigation Board (MIB) through a letter of appointment on June 8, 2001. The MIB assumed responsibility for the investigation on June 5, 2001 based on verbal direction from the Associate Administrator.

The letter of appointment established the following charter for the MIB.

The Board will:

- Obtain and analyze whatever evidence, facts, and opinions it considers relevant.
- Use reports, studies, findings, recommendations, and other actions by NASA officials and contractors. The Board may conduct inquiries, hearings, tests, and other actions it deems appropriate. The Board may take and receive statements from witnesses.
- Impound property, equipment, and records as necessary.
- Determine actual cause(s) or if unable, determine probable cause(s) of X-43A Mishap, and document and prioritize their findings in terms of (a) the dominant root cause(s) of the mishap, (b) contributing root cause(s), and (c) significant observation(s).
- Develop recommendations for preventive or other appropriate actions.
- Provide a verbal report to Associate Administrator for Aerospace Technology as soon as possible, and a final report by August 31, 2001, in the format specified in NASA Procedures and Guidelines (NPG) 8621.1. (Due to the complexity of the X-43A mishap investigation, this date was amended by the Associate Administrator for Aerospace Technology to permit the board to complete its activities.)
- Provide a proposed lessons learned summary. (Proposed corrective action implementation plan is to be provided by the X-43A project office.)
- Perform any other duties that may be requested by the Associate Administrator for Aerospace Technology.

2 SIGNATURE PAGE

/s/
Robert W. Hughes
MIB Chairman
Chief Engineer, Space Launch Initiative
Marshall Space Flight Center

/s/
Joseph J. Lackovich, Jr.
MIB Executive Secretary
Deputy Director, ELV Launch Services
Kennedy Space Center

/s/
Frank H. Bauer
Chief, Guidance, Navigation & Control Center
Goddard Space Flight Center

/s/
Michael R. Hannan
Control Systems Engineer
Space Transportation Directorate
Marshall Space Flight Center

/s/
Luat T. Nguyen
Deputy Director, Airborne Systems Competency
Langley Research Center

/s/
Victoria A. Regenie
Deputy Director, Research Engineering Directorate
Dryden Flight Research Center

/s/
Karen L. Spanyer
Lead, Strength Analysis Group
Engineering Directorate
Marshall Space Flight Center

/s/
Pamela F. Richardson
Manager, Aeronautics Mission Assurance
Office of Safety and Mission Assurance

/s/
Accept: NASA HQ / Code R
Jeremiah F. Creedon
Associate Administrator
Office of Aerospace Technology

/s/
Approve: NASA HQ / Code Q
Bryan D. O'Connor
Associate Administrator
Office of Safety and Mission Assurance

Advisors
Office of Chief Counsel: DFRC/ Chauncey Williams
Office of Public Affairs: DFRC/ Fred Johnsen

3 ACKNOWLEDGMENTS

The X-43A MIB wishes to thank the members of the Mishap Investigation Team (MIT) and associated organizations for their committed efforts in the support of the X-43A MIB activities. Determining the cause of the X-43A mishap was a complex effort requiring a significant commitment of time and resources. The successful resolution of this mishap would have been impossible without the total cooperation, openness and commitment of the entire MIT. Key factors in the mishap resolution were the technical and programmatic competence, positive attitude and sustained support displayed by the Hyper-X Program team. The outstanding support provided by the expert consultants from both industry and NASA was equally important to understanding the complex technical issues associated with this mishap.

Organizations with members who participated actively in the MIT were:

- Dryden Flight Research Center (DFRC)
- Goddard Space Flight Center (GSFC)
- Kennedy Space Center (KSC)
- Langley Research Center (LaRC)
- Marshall Space Flight Center (MSFC)
- Orbital Sciences Corporation (OSC)
- Micro Craft Corporation

The X-43A MIB would also like to recognize and thank the managers and staffs at DFRC, LaRC and OSC for their assistance and hospitality during the MIB residence in their facilities. The dedicated support from these organizations during MIB operation in their facilities was a major contributor to the success of the investigation.

Finally, the MIB would like to thank Jackie Sneed and Jon Rick for their outstanding support in the scheduling, coordination and documentation of MIB activities. The daily efforts provided by Jackie and Jon were the key activities that enabled the MIB to function efficiently.

4 BOARD MEMBERS

Board Position/Responsibility	Function(s)
Chairperson Board: R. Hughes	Board Organization and Implementation
Executive Secretary Board: J. Lackovich	Alternate Board Chairperson / Fault Tree Organization and Scheduling
Control and Aerodynamics Board: L. Nguyen, F. Bauer, V. Regenie Board Consultants: C. Hall, M. Hannan	Aerodynamics and Controls Investigation Organization and Implementation
Avionics and Electronic Systems Board: F. Bauer	Avionics and Electronics Investigation Organization and Implementation
Processing and Operations Board: J. Lackovich	Processing and Operations Investigation Organization and Implementation
Systems and Software Board: V. Regenie	Systems and Software Investigation Organization and Implementation
Propulsion Board: R. Hughes Board Consultant: B. Neighbors	Propulsion Investigation Organization and Implementation
Stress and Environmental Analyses Board Consultant: K. Spanyer	Stress and Environmental Analyses Investigation Organization and Implementation
Structures and Aeroelastic Effects Board Consultant: K. Spanyer	Structures and Aeroelastic Effects Investigation Organization and Implementation
Mechanical Systems Board: R. Hughes	Mechanical Systems Investigation Organization and Implementation
Safety and Mission Assurance and Management Processes Ex O: P. Richardson	Safety and Mission Assurance and Evaluation of Management Processes
Board Organization and Report Development Assoc.: J. Sneed, J. Rick	Organization of Daily Board Processes, Report Development and Fault Tree Control

5 EXECUTIVE SUMMARY

NASA initiated the Hyper-X Program in 1996 to advance hypersonic air-breathing propulsion and related technologies from laboratory experiments to the flight environment. This program was designed to be a high-risk, high-payoff program. The X-43A was to be the first flight vehicle in the flight series. The X-43A was a combination of the Hyper-X Research Vehicle (HXRV), HXRV adapter, and Hyper-X Launch Vehicle (HXLV) referred to as the X-43A stack. The first X-43A flight attempt was conducted on June 2, 2001.

The HXLV was a rocket-propelled launch vehicle modified from a Pegasus launch vehicle stage one (Orion 50S) configuration. The HXLV was to accelerate the HXRV to the required Mach number and operational altitude to obtain scramjet technology data. The trajectory selected to achieve the mission was at a lower altitude and subsequently a higher dynamic pressure than a typical Pegasus trajectory. This trajectory was selected due to X-43A stack weight limits on the B-52.

During the first mission, the X-43A stack was released from a B-52 carrier aircraft one hour and 15 minutes after takeoff. This corresponds to 0.0 seconds mission time. The HXLV solid rocket motor ignition occurred 5.19 seconds later and the mission proceeded as planned through the start of the pitch-up maneuver at 8 seconds. During the pitch-up maneuver the X-43A stack began to experience a control anomaly (at approximately 11.5 seconds) characterized by a diverging roll oscillation at a 2.5 Hz frequency. The roll oscillation continued to diverge until approximately 13 seconds when the HXLV rudder electromechanical actuator (EMA) stalled and ceased to respond to autopilot commands. The rudder actuator stall resulted in loss of yaw control that caused the X-43A stack sideslip to diverge rapidly to over 8 degrees. At 13.5 seconds, structural overload of the starboard elevon occurred. The severe loss of control caused the X-43A stack to deviate significantly from its planned trajectory and the vehicle was terminated by range control 48.57 seconds after release.

The X-43A Mishap Investigation Board (MIB) was convened at DFRC on June 5, 2001.

The mission failure was attributed to the HXLV.

Root Cause: The X-43A HXLV failed because the vehicle control system design was deficient for the trajectory flown due to inaccurate analytical models (Pegasus heritage and HXLV specific), which overestimated the system margins.

- The key phenomenon that triggered the mishap was the divergent roll oscillatory motion at a 2.5 Hz frequency.
  - The divergence was primarily caused by excessive control system gain.
- A second phenomenon that was a consequence of the divergent roll oscillation was a stall of the rudder actuator that accelerated the loss of control.
- Neither phenomenon was predicted by preflight analyses.
- The analytical modeling deficiencies resulted from a combination of factors.

Note: Models include system architecture, boundary conditions and data.

The mishap occurred because the control system could not maintain the vehicle stability during transonic flight. The vehicle instability was observed as a divergent roll oscillation. An effect of the divergent roll oscillation was the stall of the rudder actuator. The stall accelerated loss of control. The loss of control resulted in loss of the X-43A stack. The rudder actuator stalled due to increased deflections that caused higher aerodynamic loading than preflight predictions. The deficient control system and under prediction of rudder actuator loads occurred due to modeling inaccuracies.

Determining the cause of the X-43A mishap was a complex effort requiring a significant commitment of time and resources. This effort consisted of in-depth evaluations of the Pegasus and HXLV system and subsystem models and tools as well as extensive system level and subsystem level analyses. To support the analyses, extensive mechanical testing (fin actuation system) and wind tunnel testing (6 percent model) were required.

The major contributors to the mishap were modeling inaccuracies in the fin actuation system, modeling inaccuracies in the aerodynamics and insufficient variations of modeling parameters (parametric uncertainty analysis). Pegasus heritage and HXLV specific models were found to be inaccurate.

- Fin actuation system inaccuracies resulted from:
  - Discrepancies in modeling the electronic and mechanical fin actuator system components
  - Under prediction of the fin actuation system compliance used in the models.
- Aerodynamic modeling inaccuracies resulted from:
  - Error in incorporation of wind tunnel data into the math model
  - Misinterpretation of wind tunnel results due to insufficient data
  - Unmodeled outer mold line changes associated with the thermal protection system (TPS).
- Insufficient variations of modeling parameters (parameter uncertainty analysis) were found in:
  - Aerodynamics
  - Fin Actuation System
  - Control System

Less significant contributors were errors detected in modeling mass properties. Potential contributing factors were found in the areas of dynamic aerodynamics and aeroservoelasticity.

Linear stability predictions were recalculated using the corrected nominal models. Stability gain margins were computed for all axes. Aileron gain margin (roll axis) was examined in particular and showed a sizeable reduction from the 8 dB preflight prediction. Model corrections led to a revised prediction of less than 2 dB at nominal conditions. This was well below the requirement of a 6 dB gain margin. Although this reduction was very significant and close to instability boundaries, the revised prediction was still stable. This meant that the nominal model corrections alone were insufficient to predict the vehicle loss of control and that parameter uncertainty had to be included. Accounting for parameter uncertainties in the analyses replicated the mishap. This was confirmed by nonlinear time history predictions using the 6-degree of freedom (6-DOF) flight dynamics simulation of the X-43A stack.

No single contributing factor or potential contributing factor caused this mishap. The flight mishap could only be reproduced when all of the modeling inaccuracies with uncertainty variations were incorporated in the system level linear analysis model and nonlinear simulation model.

6 HYPER-X PROGRAM OVERVIEW

This section is written in the past tense to express the status of the Hyper-X Program and X-43A mission as evaluated by the MIB. The use of past tense is not intended to reflect the current status of the Hyper-X Program.

6.1 Overview

The Hyper-X Program was a collaborative effort between NASA LaRC and DFRC with shared mission success responsibilities. To execute the program, NASA awarded industry contracts for the design, development and fabrication of the flight test vehicles. OSC was the contractor for the Hyper-X Launch Vehicle (HXLV) and Micro Craft was the contractor for the Hyper-X Research Vehicle (HXRV) and HXRV adapter. These contracts included launch services and flight test support.

6.2 Program/Project Objectives

The Hyper-X Program was designed to be a high-risk, high-payoff program. NASA initiated the program in 1996 to advance hypersonic air-breathing propulsion and related technologies from laboratory experiments to the flight environment. The primary program goal was to demonstrate and flight validate analytical design tools, computational methods and experimental techniques required for the development of a hypersonic, air-breathing aircraft. Accomplishing this goal required flight data from a scramjet-powered vehicle. The scramjet vehicle configuration was designated the X-43A Hyper-X Research Vehicle (HXRV). The X-43A HXRV was designed and built to fly at hypersonic speeds (greater than Mach 5). Three X-43A flights, each with a non-recoverable HXRV, were planned. The first X-43A flight attempt was conducted on June 2, 2001.

6.3 Configuration

The X-43A HXRV was designed to be accelerated to its operational altitude and Mach number using a rocket-propelled launch vehicle, designated the Hyper-X Launch Vehicle (HXLV). The HXRV was attached to the HXLV via the HXRV adapter. The HXRV adapter also provided services to maintain the desired HXRV environmental conditions during mated flight and to separate the HXRV from the HXRV adapter for scramjet operation. This combination of the HXLV, the HXRV adapter and the HXRV was designated the X-43A stack (Figure 6-1). The X-43A stack was integrated to the B-52 carrier aircraft and was flown to the launch area for deployment (Figure 6-2).

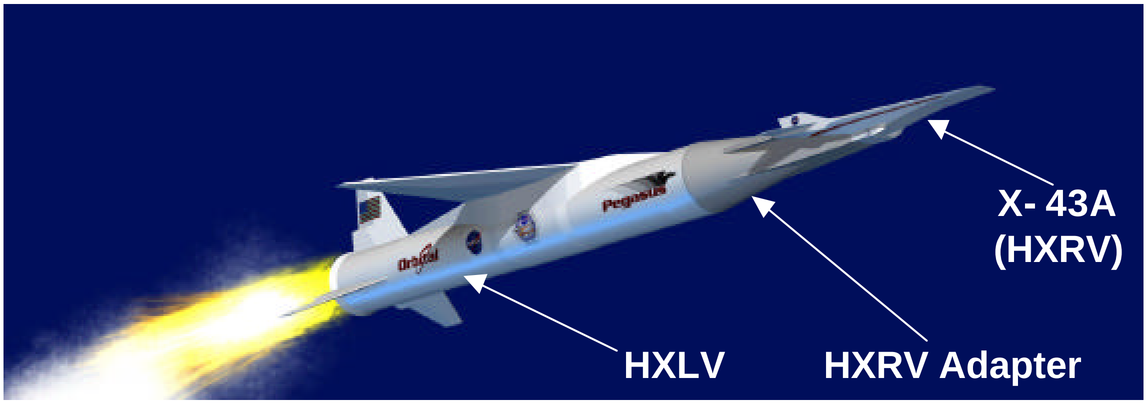


Figure 6-1. X-43A Stack

Figure 6-2. B-52 Carrier Aircraft with X-43A Stack

6.4 Description of X-43A Flight Hardware and Mission

6.4.1 B-52 Carrier Aircraft

The carrier aircraft was the NASA DFRC B-52B (52-008).

6.4.2 X-43A Hyper-X Research Vehicle (HXRV)

The HXRV was 12 feet long, 5 feet wide, 2 feet high, and weighed about 3,000 pounds. It was powered by a single hydrogen-fueled, dual-mode, airframe-integrated scramjet propulsion system.

6.4.3 Hyper-X Launch Vehicle (HXLV)

The HXLV was derived from a modified Pegasus launch vehicle stage one (Orion 50S) configuration. Modifications to the Pegasus configuration for the X-43A mission are depicted in Figure 6-3.

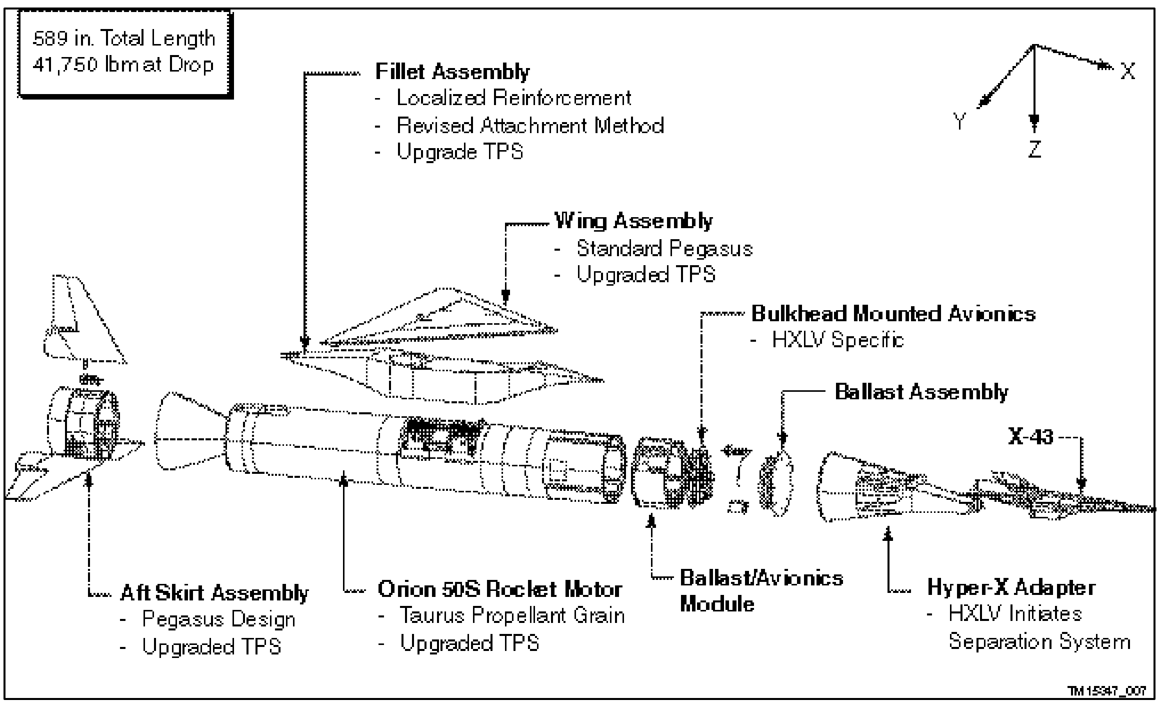


Figure 6-3. X-43A Stack with Modifications from Pegasus

6.4.3.1 Environments: HXLV versus Pegasus

The HXLV was launched and flown in an environment that was significantly different from previous Pegasus experience. At the time of failure, 13.5 seconds, the HXLV altitude was 22,244 feet, whereas a typical Pegasus altitude for the same flight duration would have been approximately 40,000 feet. In addition, at Mach 1, near the failure point, the HXLV dynamic pressure was 650 psf whereas a typical Pegasus dynamic pressure for the same Mach number would have been approximately 300 psf. This increase in dynamic pressure at transonic conditions was a major factor in the mishap.

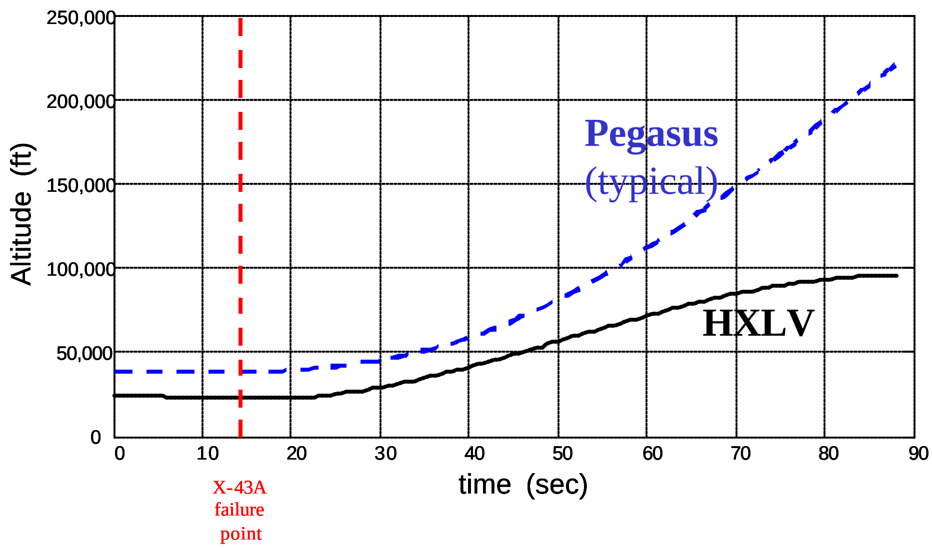


Figure 6-4. Altitude vs. Time

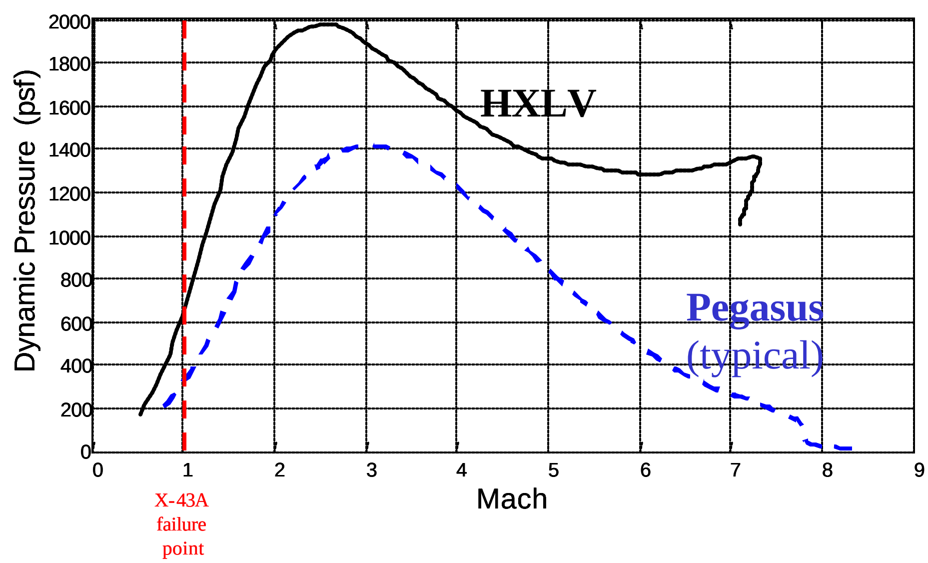


Figure 6-5. Dynamic Pressure vs. Mach

6.4.3.2 HXLV Control System

The HXLV control system was a closed-loop feedback system (Figure 6-6). The HXLV control system consisted of an inertial measurement unit (IMU) that sensed the X-43A stack accelerations and rates; an autopilot that translated the output from the IMU into steering commands; an electronic control unit (ECU) that translated the autopilot commands into fin (elevons and rudder) position commands; and an electromechanical actuator (EMA) that rotated the fins to the commanded positions. A sensor measured fin actuator position that the ECU used as feedback for servo control. The ECU also filtered the sensed actuator position and transmitted it to the autopilot (talkback). The ECU and the EMA comprised the Fin Actuation System (FAS).

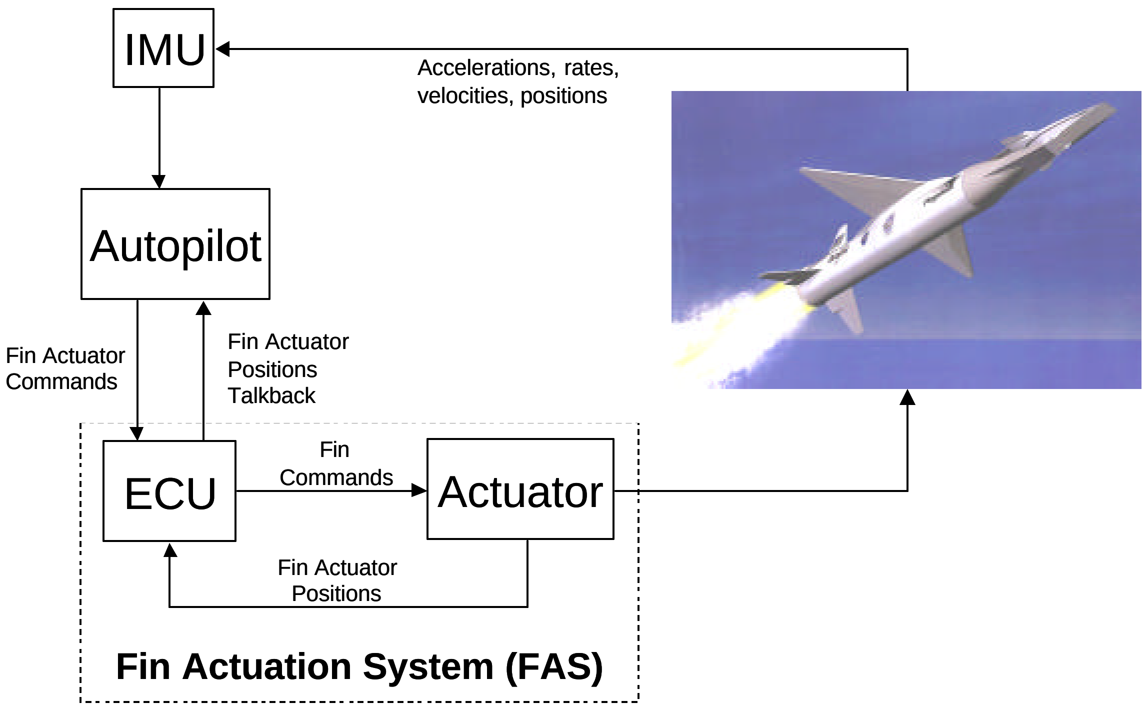


Figure 6-6. HXLV Control System Diagram

6.4.3.3 HXLV Control System Modeling

The analysis of the HXLV control system was performed using two systems level models:

- The linear analysis model
- The 6-degree of freedom (6-DOF) nonlinear simulation model.

These systems level models were developed from multiple supporting models (Figure 6-7). Three of the supporting models (FAS, aerodynamics, mass properties) were determined to be contributors to the mishap.

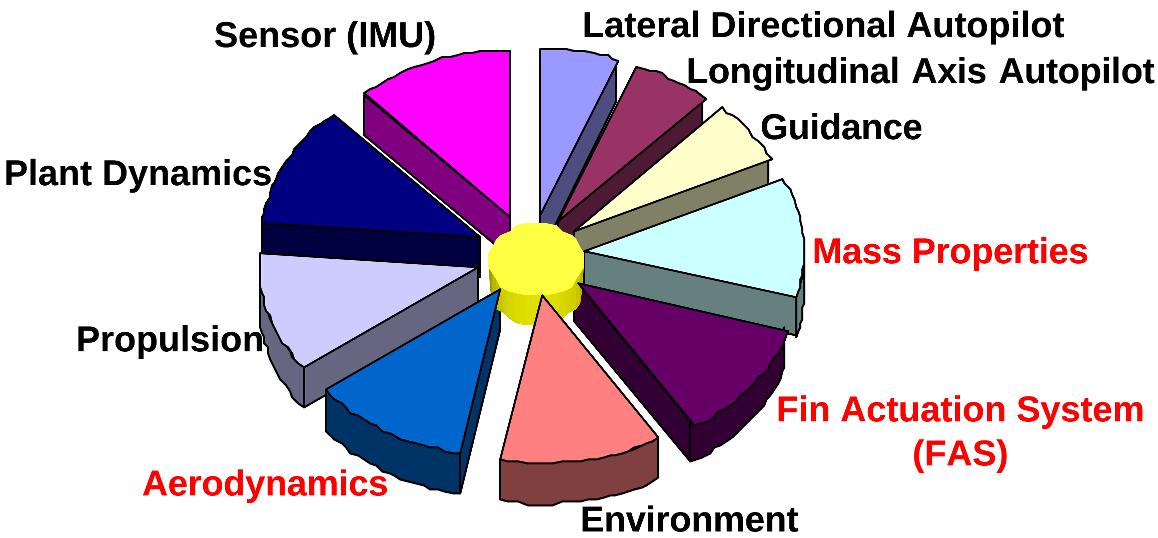


Figure 6-7. Subsystem Models Comprising the System Level Models

6.5 Mission Profile

Figure 6-8 shows the planned mission profile with flight events for the X-43A mission.

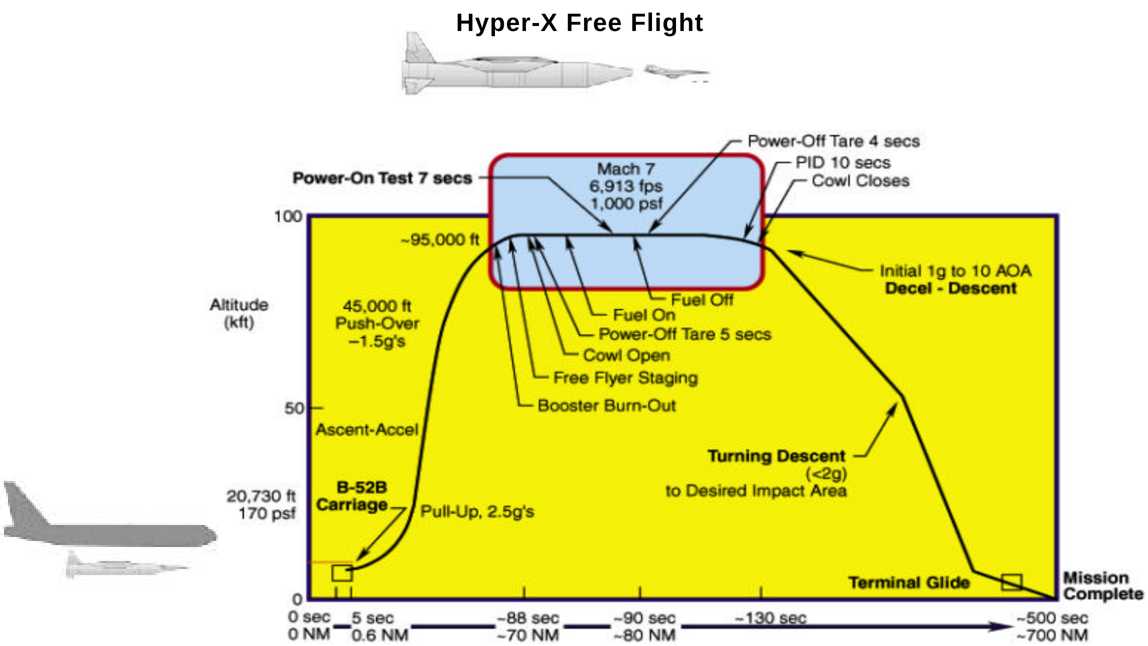


Figure 6-8. X-43A Mission Profile

6.6 Mission Operations

All flight operations in the Pacific Sea Range were conducted in accordance with U.S. Navy requirements per RCC319-92 and met DFRC/Air Force Flight Test Center Range Systems Safety Office requirements.

7 DESCRIPTION OF X-43A MISHAP

7.1 Captive Carry

At 12:28 p.m. PDT on June 2, 2001, the X-43A stack (HXLV, HXRV and HXRV adapter) was attached to the DFRC B-52 (008) and carried to the Point Mugu sea range. The captive carry of the X-43A stack on the B-52 was nominal, with the exception of an alternator on the B-52 that failed prior to take-off. The two F-18 chase planes, 846 and 852, followed the B-52, operating per standard procedures throughout the flight. Chase plane 846 provided live video, while chase plane 852 provided still photos.

7.2 Release and Flight

A detailed timeline is presented in Table 7-1. This table indicates the times that data for events were received on the ground. Critical event times that were used in the analysis (including time histories) of the mishap were adjusted for data latencies. The adjusted times are denoted with an asterisk (*). Also listed in the table are anomalies recorded during the investigation of the mishap. These anomalies are discussed in Volume I Appendix B.

The following paragraphs describe the events of the release and flight until the time of data loss.

The X-43A stack was released from the B-52 one hour and fifteen minutes after takeoff. This corresponded to 0.0 seconds mission time. The HXLV autopilot was enabled at 0.38 seconds. The HXLV solid rocket motor ignition occurred 5.19 seconds mission time. These events were nominal and occurred as planned.

Between 6.23 seconds and 7.1 seconds, the HXRV adapter gaseous nitrogen (GN_2) pyro valve opened. The regulator malfunctioned and uncontrolled GN_2 venting began. This uncontrolled venting incident was recorded as an anomaly but determined to have no contribution to the mishap. At 10.18 seconds, the HXLV path steering guidance was engaged. During the pitch-up maneuver, at approximately 11.5 seconds, a divergent oscillation primarily in the roll axis was observed at a 2.5 Hz frequency. At 13.02 seconds, the rudder actuator reached its current limit of -36.7 amps and no longer responded to commands, indicating a rudder actuator stall. Shortly after the rudder actuator stalled, the starboard fin departed from the vehicle, quickly followed by the port fin, then the rudder and wing.

The HXRV left wing linkage failed at 18.84 seconds. At 20.87 seconds, the HXLV telemetry stream was lost and one minute later the HXRV telemetry data was lost. At 48.57 seconds, the flight termination system (FTS) was initiated. Flight termination was successful and the vehicle stayed within the Point Mugu range.

Table 7-1. Detailed Timeline

Anomaly No.	Mission Time: Time from Separation (sec) *Adjusted for Latencies	Event Description
A-10	-1:57	B-52 loss of alternator (right forward)
	-0.33	Pylon adapter pushrods begin to move
A-09	-0.25	Hook movement has released preload, stack load still present. ~B-52 launch lock indication loss
	-0.23	Stack begins to drop from B-52
	0.00	Physical separation of umbilical connectors
	0.03	B-52 release sense by the flight management unit
	0.16	HXLV flight computer separation sense
	0.18*	HXLV sequencer reset
	0.34*	Initialize HXLV autopilot filters (phase count=24)
	0.38*	Enable HXLV autopilot (phase count=25)
	5.19	Motor ignition
A-06	5.22	HXLV motor start debris
A-07	5.24	Change in HXRV vertical/lateral accelerometer
A-04	6.23	HXRV adapter GN_2 pyro valve opened (SV-19)
A-05	7.10	GN_2 venting due to pressures exceeding relief valve setting
	10.18*	Enable HXLV path steering guidance (phase count=31)
	11.50*	Divergent roll oscillation begins
A-02	13.02*	HXLV rudder actuator reaches current limit (-36.7 A)
A-01	13.30	Starboard fin shaft strain gauge goes to positive maximum value indicating broken gauge wiring
	13.46	Starboard actuator motor temperature value goes to maximum, indicating broken gauge wiring
	13.48	Starboard fin leading edge temperature value goes to maximum, indicating broken gauge wiring
	13.62*	Starboard actuator position value goes to zero, indicating broken actuator wiring
	13.70	Port actuator motor temperature value goes to maximum, indicating broken gauge wiring
	13.74*	Rudder actuator begins to be back driven, as indicated in position and current monitor changes from stall
	13.78*	Port actuator position value goes to zero, indicating broken actuator wiring

Anomaly No.	Mission Time: Time from Separation (sec) *Adjusted for Latencies	Event Description
	13.80	Port fin shaft strain gauge value goes to positive maximum, indicating broken gauge wiring
	13.83	Rudder shaft left side strain gauge value goes to positive maximum, indicating broken gauge wiring
	13.85	Rudder shaft right side strain gauge value goes to positive maximum, indicating broken gauge wiring
	14.26	Rudder right side temperature value goes to maximum, indicating broken gauge wiring
	15.00	Wing leading edge compression strain gauge value goes to maximum, indicating broken gauge wiring
	15.65	LBIT1010 failure - PPT B3 power-up failure
	15.65	LBIT1011 failure - PPT B4 power-up failure
	17.57	LBIT1005 failure - PPT A3 power-up failure
	18.84	HXRV left wing failure
	20.87	Loss of HXLV data stream
	45.37	HXRV adapter H_2O pyro valve opened (SV-15)
	48.57	FTS
	49.31	HXRV separation from HXRV adapter
	49.63	Aft S-band come on
	58.85	LBIT 0101 failure - U-gyro reasonableness fail
	75.17	LBIT 0107 failure - U-gyro dither gain fail
	75.17	LBIT 0115 failure - U-gyro health status fail
	77.57	Loss of HXRV data stream

7.3 Flight Data

Figure 7-1 shows vehicle flight parameters [Mach, angle of attack (alpha), sideslip (beta) and dynamic pressure (q)] for the time period between 9 and 14 seconds. Also denoted on this figure are the key phenomena that triggered this mishap. The first phenomenon was the divergent roll oscillatory motion that started at approximately 11.5 seconds. The second phenomenon was the rudder actuator stall at approximately 13 seconds. Data shown in Figure 7-1 for Mach, angle of attack (alpha) and dynamic pressure (q) indicate that these parameters remained nominal until after the rudder actuator stalled at 13 seconds. Sideslip (beta) was within the expected range until 12.5 seconds but began a rapid divergence at 13 seconds when rudder actuator stall occurred.

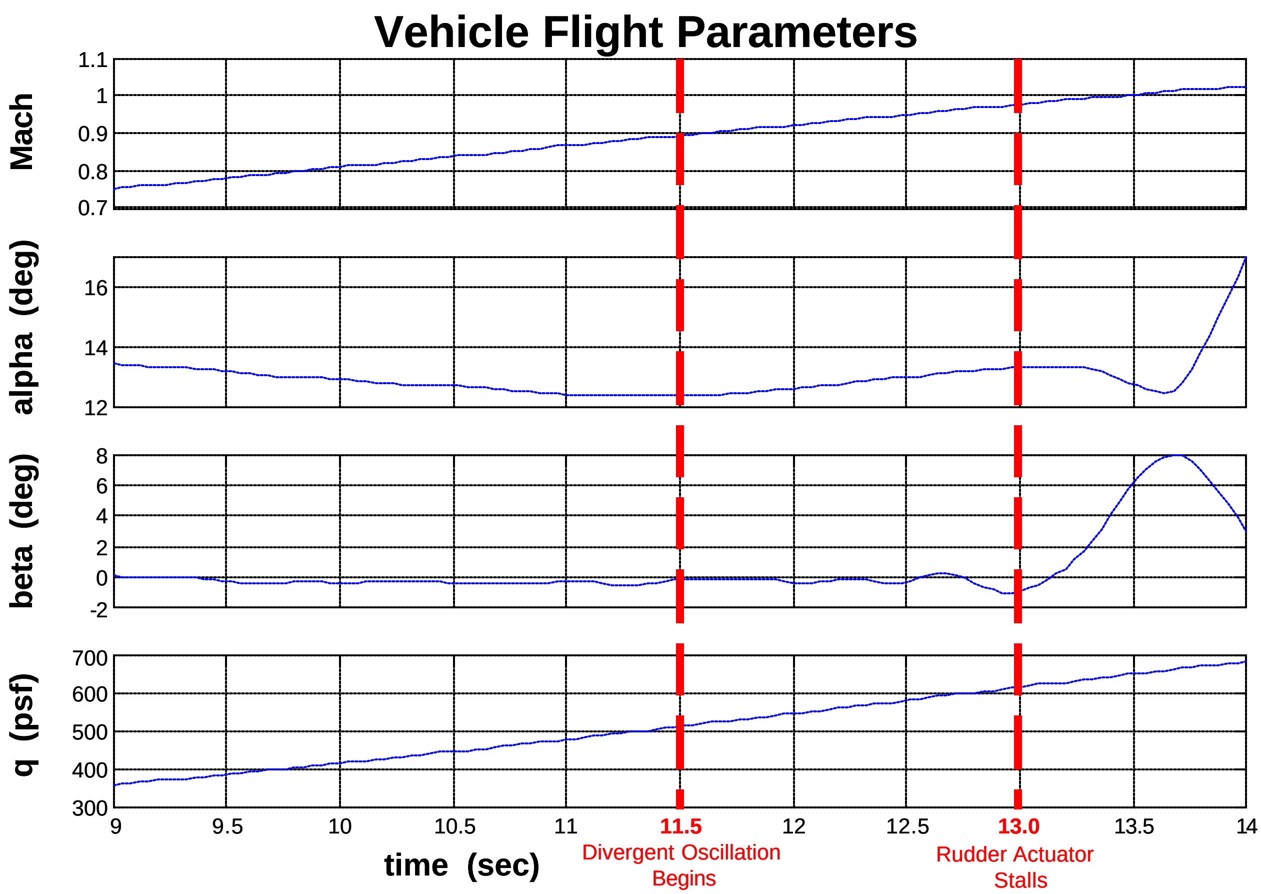


Figure 7-1. Vehicle Flight Parameters

Figure 7-2 shows the control surface positions (rudder and elevon) and vehicle roll rate for the time period between 9 and 14 seconds. The data for rudder deflection (rudder), and differential elevon deflection (elevon) and roll rate remained within the expected range until 11.5 seconds when the divergent oscillation began. At that point, rudder deflection, differential elevon deflection and roll rate began an oscillatory increase at 2.5 Hz. At approximately 13 seconds, rudder actuator stall occurred and differential elevon and roll rate increased dramatically. At approximately 13.5 seconds the starboard elevon departed from the vehicle.

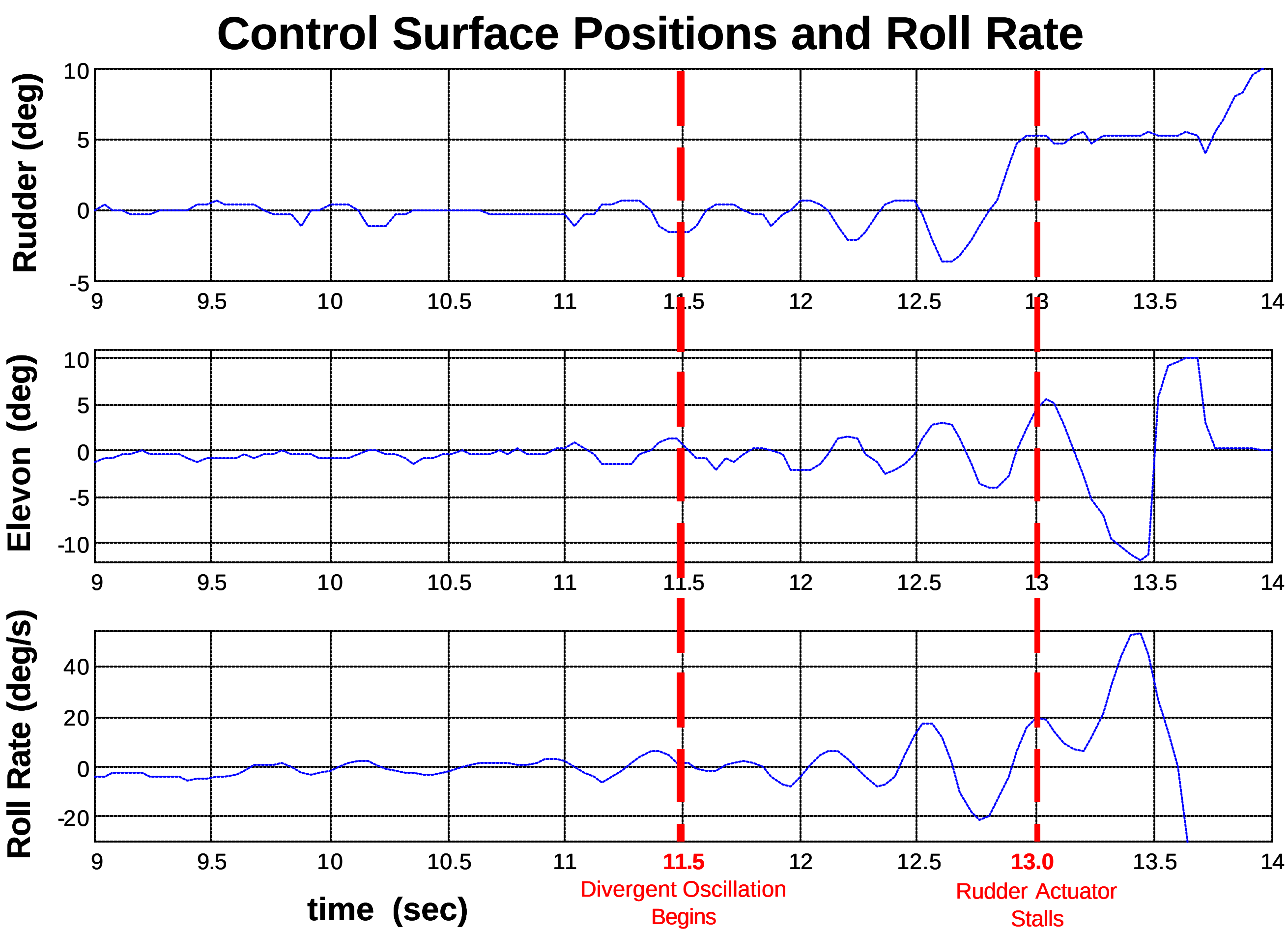


Figure 7-2. Control Surface Positions and Roll Rate

8 METHOD OF INVESTIGATION, BOARD ORGANIZATION, SPECIAL CIRCUMSTANCES

The Associate Administrator for Aerospace Technology formally appointed the X-43A Mishap Investigation Board which assumed responsibility for the investigation on June 5, 2001. The basic guidance used in implementing and executing the X-43A mishap investigation was per NPG: 8621.1, NASA Procedures and Guidelines for Mishap Reporting, Investigating, and Record Keeping, dated June 2, 2000. The investigation implementation was adjusted as required to reflect the situations and conditions specific to the MIB. The intent of NPG 8621.1 was met.

A special circumstance associated with the X-43A mishap investigation was:

- The X-43A mishap resulted in the physical evidence from the flight vehicle being dropped into the Pacific Ocean in approximately 1,200 feet of water. No attempt was made to recover physical evidence from the flight hardware.

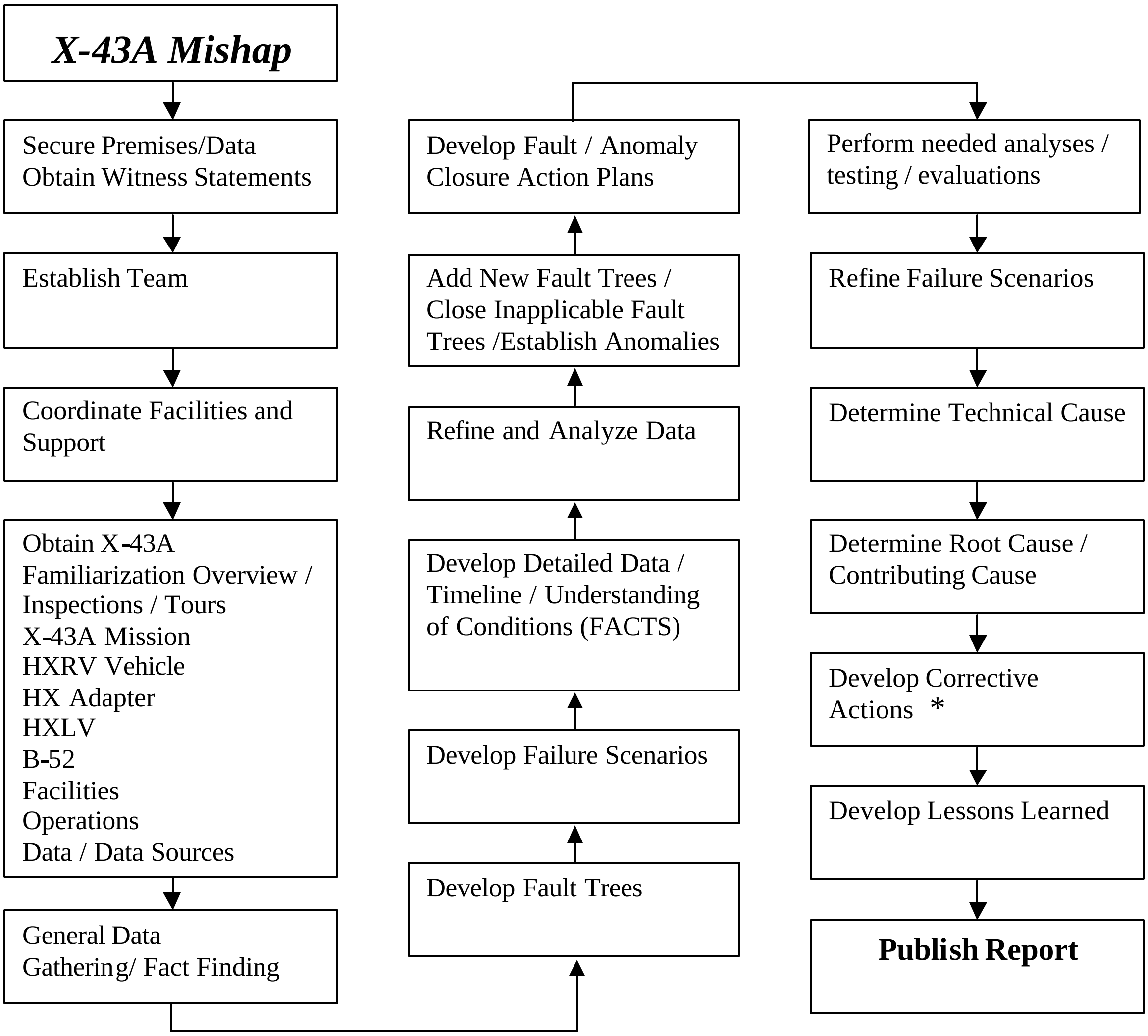
The initial MIB meetings were conducted at the DFRC from June 5, 2001 through June 23, 2001. Data reviews were held daily as the flight data was processed and interpreted. The MIB relocated to Orbital Sciences Corporation in Chandler, Arizona from June 23, 2001 through August 31, 2001 to focus on the HXLV failure scenarios of the investigation. The MIB relocated to the LaRC from September 10, 2001 through December 7, 2001 to support wind tunnel testing. The final efforts of the investigation were completed through teleconferences and electronic communications. The verbal report for the X-43A mishap was presented to the Associate Administrator for Aerospace Technology on February 7, 2002 and the Report of Findings was submitted to NASA Headquarters for approval in March, 2002.

8.1 Methodology

A fault tree-based investigation methodology was chosen for the X-43A mishap. The basis for this choice was the complexity of the X-43A physical and functional systems, the multi-organizational character of the X-43A team, the availability of fault trees used in risk assessments by the X-43A Project and the familiarity of the MIB with the fault tree investigation process.

8.2 Process

The MIB followed a rigorous process during investigation of the X-43A mishap (Figure 8-1).



* Corrective Actions are to be developed by the Project

Figure 8-1. X-43A Mishap Investigation Board Process

8.3 Board Organization

The MIB consisted of those individuals formally appointed by the Associate Administrator, expert consultants and administrative support personnel. The MIB was organized to permit the MIB members to support the fault tree based investigation in their specific areas of expertise. Technical teams were formed to support the MIB in the investigation. These technical teams were formed in conjunction with the existing integrated product teams (IPTs) of the X-43A Project and were supplemented by independent experts from NASA Centers and contractor organizations. The MIB and the technical teams collectively formed the MIT.

8.4 Board Operation

The general operation of the MIB encompassed three basic responsibilities: Overall planning and management, technical investigation and presentation and report formulation.

The overall planning and management was the exclusive function of the MIB. This function was implemented through daily MIB sessions where the investigation process, planning, scheduling and execution strategy were decided.

The management of the technical investigation was accomplished through daily team meetings with the MIT where status reports of the ongoing activities were provided. Presentations that included supporting analyses and data were provided to assess fault tree scenarios. In addition, the MIB held periodic data reviews, which summarized the multi-disciplined fault tree analyses, performed to support possible failure scenarios.

Monthly status reports were provided throughout the investigation. Presentation and report formulation included the interim report to management, a formal presentation and the final report of findings.

8.5 Implementation

The implementation of the fault tree investigation involved the identification of potential mishap faults or causes. Initially, this was done at a high level based on assessments of the physical, functional, engineering, and operational characteristics of the X-43A program in relation to the data from the mishap. This effort involved the MIB and the MIT leads. When high level faults were deemed credible, lower level or subtier faults that might have precipitated the higher level fault were developed. These lower level faults were developed using potential scenarios for the specific high level fault. No fault was added or removed from the fault tree without MIB review and approval.

Technical evaluation of each lower level fault constituted the building blocks of the investigation and yielded the information that, when assessed in a total systems environment, permitted understanding of the mishap.

The result of each lower level fault evaluation was a determination of the potential for the individual fault to have contributed to the final mishap. A color-code was assigned to each fault based on the potential of that fault to have contributed to the final mishap. The key to the color-code is as follows:

- Green (G) - A confirmed non-contributor
- Yellow (Y) - A potential contributor that cannot be assigned a confirmed quantifiable contribution
- Red (R) - A contributor with a confirmed quantifiable contribution

The top level fault tree developed for the X-43A mishap is shown in Figure 8-2. A total of 613 faults were evaluated. Of these, eleven were determined to be direct contributors to the mishap and three were determined to be potential contributors. The entire fault tree used in this investigation is shown in Volume II Appendix A.

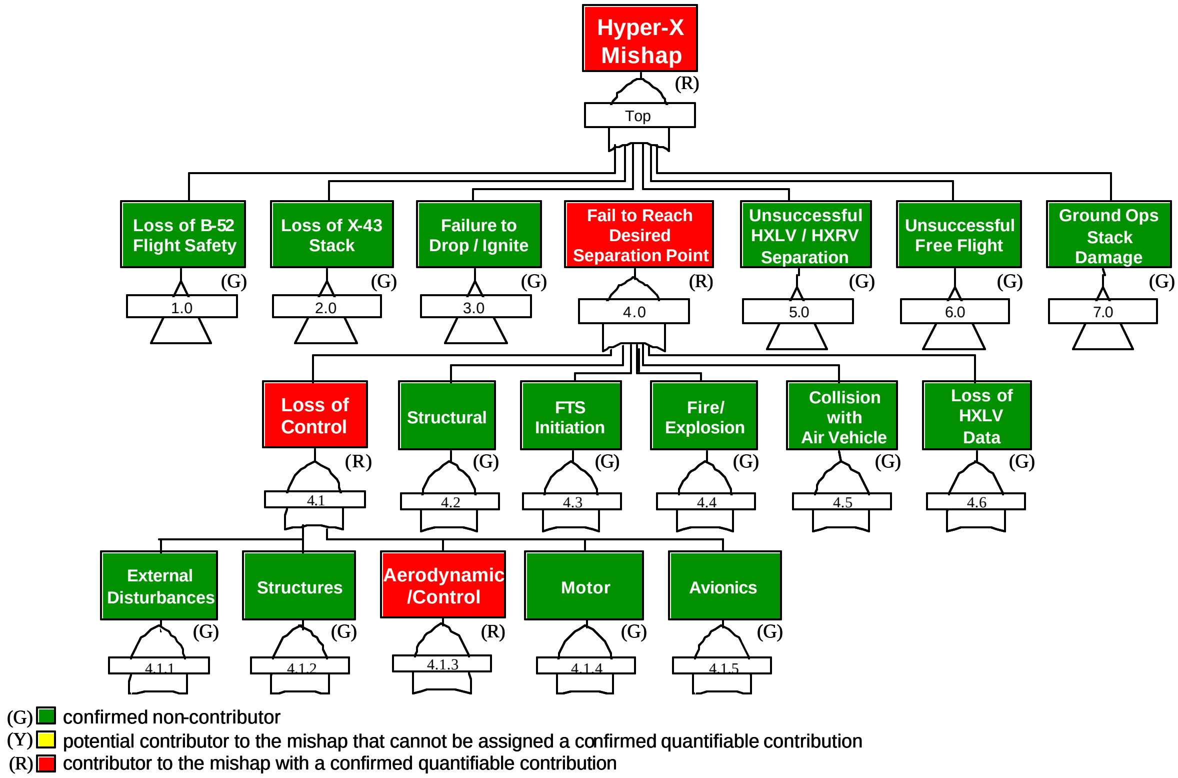


Figure 8-2. Top Level Fault Tree

The critical branch of the fault tree is shown in Figure 8-3.

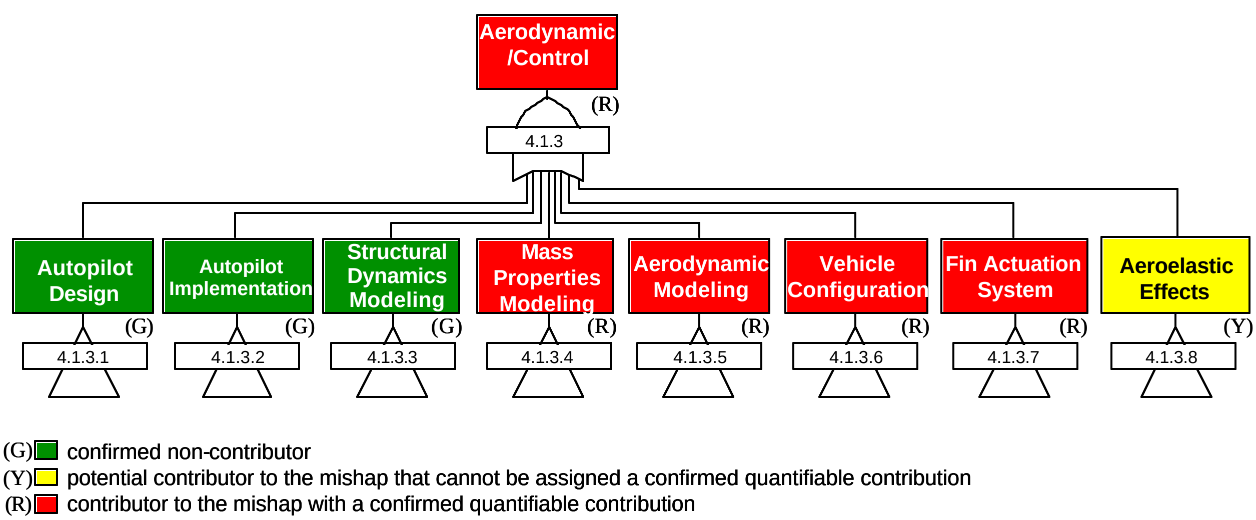


Figure 8-3. Critical Fault Tree Branch

8.6 Data Sources

Data used by the MIB was taken from monitoring sources on board the B-52 carrier aircraft; sites receiving flight downlink from the X-43A stack; data developed during the preflight manufacture, test and checkout of the X-43A stack; postflight testing of X-43A stack software and hardware; postflight evaluation of the FAS/Fin (elevon(s) and/or rudder) system; postflight aerodynamics testing of the X-43A stack; postflight evaluation of X-43A analytical models, systems, subsystems and processes; and special analyses performed in support of the investigation.

8.7 Other Data Sources

The MIB used other sources to improve their understanding of the X-43A mishap.

These other sources included applicable failure reports and anomaly reports from previous Pegasus missions. The WIRE mission flown from Vandenburg Air Force Base on March 4, 1999 was used as a benchmark. During the transonic flight regime (approximately 6-12 seconds after release from the carrier aircraft, Mach 0.9-1.2, approximately 40,000 feet) a significant attitude disturbance was observed in which the vehicle experienced large sideslip and bank excursions. The excursions began in roll, and then quickly coupled into yaw and finally pitch. As the vehicle left the transonic region it recovered from the disturbance and the WIRE mission successfully achieved the proper orbit. Following this anomaly, changes to the autopilot, improvements in aerodynamic modeling and upgrades to fin actuation system modeling were implemented. The significantly higher launch altitude and reduced dynamic pressure was a key difference between all other Pegasus flights and the X-43A trajectory.

Subsequent Pegasus missions with these modifications were successful.

As a part of this investigation, failures of vehicles related to the X-43A (Pegasus and Taurus) were evaluated for applicability to the mishap.

9 FINDING, ROOT CAUSE, CONTRIBUTING FACTORS, RECOMMENDATIONS - *EXPORT CONTROLLED*

10 SIGNIFICANT OBSERVATIONS, ANOMALIES, RECOMMENDATIONS - *EXPORT CONTROLLED*

11 DEFINITION OF TERMS AND ACRONYMS

6-DOF	6 Degree of Freedom
A, Amps.	Amperes
AIT	Aircraft Integration Trailer
Alpha, α	Angle of Attack
ATP	Acceptance Test Procedure
Backlash	Total rotational and radial motion (stop-to-stop) that occurs in the output gear of the FAS gear train when the input gear is held fixed
BET	Best Estimated Trajectory
Beta, β	Angle of Sideslip
B/AM	Ballast/Avionics Module
CAD	Computer Aided Design
CFD	Computational Fluid Dynamics
CG	Center of Gravity
C_{hm}	Hinge moment coefficient
Clda, $Cl\delta a$	Rolling moment coefficient due to aileron (differential elevon) deflection
Clp	Rolling moment coefficient due to roll rate (roll damping derivative)
Clr	Rolling moment coefficient due to yaw rate
CM	Configuration Management
Cnp	Yawing moment coefficient due to roll rate
Cnr	Yawing moment coefficient due to yaw rate (yaw damping derivative)
CPU	Central Processing Unit
δ_{elv}	Elevon deflection
δ_r	Rudder deflection
dB	Decibels
Deg	Degrees
DFRC	Dryden Flight Research Center
DR	Discrepancy Report
ECU	Electronic Control Unit
ELV	Expendable launch vehicle
EMA	Electromechanical Actuator
ERB	Engineering Review Board
EXP	Experiment
FAS	Fin Actuation System
FEM	Finite Element Model
Fin	Elevon(s) and/or rudder
FTS	Flight Termination System
G	Green – Non-contributor to the mishap
GN_2	Gaseous Nitrogen
GN&C	Guidance, Navigation, and Control

GSFC	Goddard Space Flight Center
GVT	Ground Vibration Test
H_2O	Water
HQ	NASA Headquarters
HXLV	Hyper-X Launch Vehicle
HXRV	Hyper-X Research Vehicle
Hz	Hertz
IMU	Inertial Measurement Unit
INS	Inertial Navigation System
IPT	Integrated Product Team
KSC	Kennedy Space Center
LaRC	Langely Research Center
LBIT	Latched Built-in-Test
LFRC	Load Friction
LOS	Loss of Signal
M	Mach
MassProp	Mass Properties
MDL	Mission Data Load
MIB	Mishap Investigation Board
MIT	Mishap Investigation Team
MOI	Moment of Inertia
MSFC	Marshall Space Flight Center
MST	Mission Sequence Time
NASA	National Aeronautics and Space Administration
NPG	NASA Procedures and Guidelines
NRTSim	Non-Real-Time Simulation
OD	Outer Diameter
PID	Parameter Identification
PPT	Precision Pressure Transducer
PR	Pressure Regulator
PSS	Premature Separation Sense
PWM	Pulse Width Modulation
q	Dynamic Pressure
QA	Quality Assurance
R	Red – Contributor to the mishap
RCC	Range Commanders' Council
RTCL	Real Time Closed Loop
RTS	Ready-To-Separate
RV	Relief Valve
Sigma, σ	Sigma (Standard Deviation)
SNI	San Nicolas Island
SPR	Software Problem Report
SRS	Software Requirements Specification
SV	Servo Valve
SWAS	Sub-millimeter Wave Astronomy Satellite
TM	Technical Memorandum

TO	Technical Order
TPS	Thermal Protection System
VDD	Version Description Document
WIRE	Wide-Field Infrared Explorer
Y	Yellow – Potential Contributor to the mishap