NASA/TM—2014–218414

The Human Factors of an Early Space Accident: Flight 3-65 of the X-15

Immanuel Barshi
NASA Ames Research Center

Irving C. Statler
NASA Ames Research Center

June 2014

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Immanuel Barshi
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NASA Ames Research Center

*National Aeronautics and
Space Administration*

*Ames Research Center
Moffett Field, California*

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Acknowledgement

The authors would like to express their deep appreciation to Jeb Orr for his excellent engineering advice on all X-15 technical matters and his tireless support throughout this investigation. The many exchanges and discussions with Jeb made this analysis much better than it would have been otherwise. Many thanks also to Cynthia Null and Jolene Feldman for their comments on an earlier draft of this report. All remaining errors are ours alone.

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Contents

Figures and Tables

Acronyms

α	angle of attack
β	angle of roll
ADI	Attitude Director Indicator
AFCS	adaptive flight control system
AIB	Accident Investigation Board
BCS	ballistic control system
FCS	flight control system
fps	feet per second
km	kilometer
km/h	kilometers per hour
IFDS	Inertial Flight Data System
IMU	inertial measurement unit
NASA	National Aeronautics and Space Administration
PAI	Precision Attitude Indicator
PIO	pilot- induced oscillation
psf	pounds per square foot
PST	Pacific Standard Time
RCS	reaction control system
SAS	Stability Augmentation System
SD	spatial disorientation

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Immanuel Barshi and Irving C. Statler

Abstract

The X-15 was a critical research vehicle in the early days of space flight. On November 15, 1967, the X-15-3 suffered an in-flight breakup. It was the 191st flight of the X-15 and the 65th flight of this third configuration (X-15-3). It was the only fatal accident of the X-15 program. This paper presents an analysis, from a human factors perspective, of the events that led up to the accident. The analysis is based on the information contained in the report of the Air Force-NASA Accident Investigation Board (AIB) dated January 1968.

The X-15-3 was the only configuration of the X-15 equipped with an early experimental adaptive flight control system (the Minneapolis Honeywell MH-96) that provided automated variation of the gains of the vehicle's controls as a function of the dynamic pressure. During a critical phase of the flight, the MH-96 had been malfunctioning for 3 minutes before the pilot became aware of his inability to control the vehicle. The AIB's analysis addressed, primarily, the events that occurred subsequent to the pilot's switching from controlling the vehicle through the MH-96 Adaptive Flight Control System (by using the right-hand control stick) to direct control of the reaction control system (by using the left-hand control stick). The analysis described here suggests that all of the events that caused the accident occurred well before the moment when the pilot switched to direct control. Under the given conditions, by the time the pilot recognized the need to switch to direct control, the destruction of the vehicle was inevitable. Consequently, the analyses and conclusions regarding the causal factors of, and the contributing factors to, the loss of Flight 3-65 presented in this paper differ from those of the AIB based on the same evidence.

Although the X-15 accident occurred in 1967, the results of the presented analysis are as relevant today as they were 47 years ago. We present the main points of our analysis and discuss their implications for the safety of space operations.

Forward

The X-15 (Figure 1) was a rocket-powered aircraft built by North American Aviation and operated jointly by NASA, the U.S. Air Force, and the U.S. Navy. It was the first manned vehicle to probe the lower edges of space for data on material, human factors, and hypersonic stability and control that helped to make human spaceflight possible.

Figure 1. The X-15-3 in flight (USAF Photo).

The X-15 was launched from a B-52 at about 45,000 ft. and 434 knots and its rocket engine then fired for the first 80-120 seconds in the boost phase of the flight. The rest of the 10–11 minute flight was powerless and ended with a 174-knot glide landing at Edwards Air Force Base, California (Figure 2).

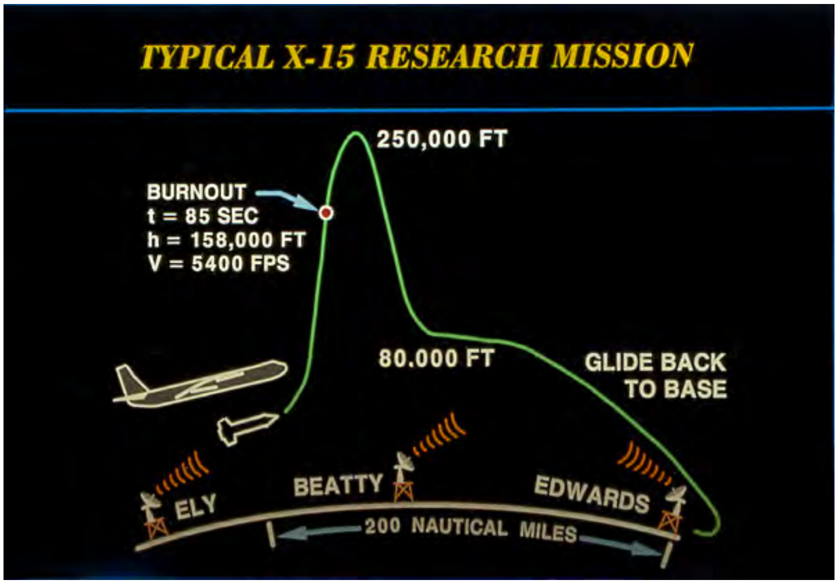

Figure 2. A typical X-15 mission profile (picture Courtesy of X-15 Pilot Astronaut Bill Dana).

Between 1959 and 1968, the X-15 aircraft made 199 flights and it still holds the world record for the highest speed ever reached by a manned, powered aircraft of 3,928 knots (7,275 km/h). Thirteen flights exceeded the Air Force's spaceflight criterion of 50 miles (80 km) altitude and qualified the pilots for astronaut status. During these flights, X-15 pilots routinely experienced several minutes of microgravity. The program has been acknowledged as one of the most successful flight research programs in history. The one exception was the disintegration at altitude of the X-15-3 aircraft during Flight 3-65 on November 15, 1967, when its experimental automated flight control system entered into a pitch instability that produced limit-cycle oscillations at high rates of all the aerodynamic control surfaces. [2]

The X-15-3 was the first hypersonic vehicle to be flown with an adaptive flight control system. Recently, the NASA Engineering and Safety Center undertook a new review of the 1967 X-15-3 accident to obtain an assessment of the role of the automated flight control system in that accident, of the risks associated with the use of adaptive flight control systems, and of the relevance of this experience to the deployment of adaptive control in modern aerospace applications. [8]

This report is a part of that review [8], specifically addressing the human factors issues entailed in the destruction of the X-15-3. Even though the analysis presented in this report is based on the information contained in the report of the Accident Investigation Board (AIB) [1], the conclusions as to the causal and contributing factors in the accident presented here differ from those of the Board. It must be noted that care has been taken to rely only on information and knowledge that were available at the time of the accident and its original investigation rather than assume current knowledge that has accumulated since the time of the accident.

1.0 The X-15-3 Aircraft

The X-15 was a research program and changes were made to various systems over the course of the program and between the three different models: X-15-1 (56-6670), X-15-2 (56-6671), and X-15-3 (56-6672).

All three airplanes had some type of 3-axis (roll, pitch, and yaw) Stability Augmentation System (SAS)—also called the roll, pitch, or yaw damper—that used the aerodynamic controls at low altitudes and high dynamic pressures. The SAS had to have a variable gain on its control authority to accommodate the large change in dynamic pressure and aerodynamic-control-surface effectiveness during the flight. On the X-15-1 and X-15-2, the pilot had three selector knobs with which he could select 10 gain settings for each axis. The aerodynamic SAS was critical during reentry into the atmosphere because handling qualities were very poor and the piloting task was very demanding without it.

At high altitudes and low dynamic pressures when the aerodynamic controls were no longer adequately effective to maintain aircraft control, the X-15 had a reaction control system (RCS, also referred to as BCS for ballistic control system) that consisted of small rocket thrusters in the aircraft nose and wingtips and a control stick mounted on the left side of the cockpit for the pilot's control of these thrusters. On the X-15-1 and X-15-2 a system was added, completely separate from the SAS, that used aerodynamic controls which provided rate damping and attitude hold using the RCS. The pilot had to manually engage and disengage this system when he transitioned between using the aerodynamic controls and the left side stick to operate the RCS.

Unique to the X-15-3 was an adaptive flight control system (AFCS) called the MH-96 developed by Minneapolis-Honeywell which was designed to perform automatically some of the functions that the pilot performed manually on the previous configurations. On X-15-3, the MH-96 was intended to provide:

1. Automatic control of the gain of inputs to the aerodynamic control surfaces in all three axes as a function of dynamic pressure.
2. Automatic engage/disengage of the reaction controls.
3. Ability to use the right hand side stick for both aerodynamic and reaction controls.
4. Attitude/angle of attack hold modes with both aerodynamic and reaction controls.
5. Increased reliability through dual-channel fault-tolerant architecture.

The MH-96 was an experimental system. The X-15-3 was the first aircraft to be flown with an AFCS and several potentially serious problems had been identified during the 64 flights prior to Flight 3-65 [3, 4, 5]. During Flight 3-65 the automatic control of the gains (Item 1 above) and the automatic access to the RCS (Item 2 above) malfunctioned, such that the pilot's ability to use the right hand side stick for both aerodynamic and reaction controls (Item 3 above) was intermittent. The attitude/angle of attack hold modes (Item 4 above) were not used prior to or during Flight 3-65. The fault detection circuits providing the supposed increased reliability (Item 5 above) detected false positives and exacerbated the situation during Flight 3-65.

The MH-96 continuously predicted the aircraft's control response at its current speed and altitude using the characteristics of the control surface servo-actuators—essentially by detecting the external dynamic pressure as the control surfaces vibrated slightly about their trim positions. The system then drove the aircraft to match an ideal model response by automatically adjusting the gain of electrical signals sent to the servomotors driving the aerodynamic controls (i.e., elevator, ailerons, and rudder) on the pitch, roll, and yaw axes in response to the pilot's movements of the control stick and rudder pedals and the aircraft rotational velocities. As aircraft altitude increased and dynamic pressures decreased, the MH-96 automatically increased gain levels. As aircraft altitude decreased and dynamic pressures increased, the MH-96 would reduce gain levels to prevent the system (pilot included) from overstressing the aircraft as denser air was encountered and aerodynamic control surfaces became more effective.

At high altitudes and low dynamic pressures, when the normal aerodynamic controls were no longer adequately effective to maintain aircraft control, the X-15 had a RCS that consisted of small rocket thrusters in the aircraft nose and wingtips and a control stick mounted on the left side of the cockpit for the pilot's control of these thrusters. In addition to automatically varying the gains of inputs to the aerodynamic controls when they were effective, the MH-96 was also designed to automatically 'blend' the transition of control from using the aerodynamic elevator, ailerons, and rudder control surfaces at low altitudes to using the RCS at high altitudes when the aerodynamic controls were ineffective. When the total gain of the three aerodynamic control channels reached 90% of its maximum value and the aerodynamic controls became ineffective, the MH-96 automatically opened the gateway for signals to the RCS. The side stick on the right side of the X-15-3 cockpit was used for the pilot's control inputs to the MH-96, which were incorporated into the computations of the AFCS before the signals were transmitted to the RCS. Although direct control of the RCS was always available to the pilot by way of the side stick mounted on the left of the cockpit just as in the X-15-1 and X-15-2, the X-15-3 pilot was discouraged from using it without first disabling the AFCS because of the extra rocket fuel consumed when there were two independent inputs to the RCS from the pilot and from the AFCS. When the MH-96 sensed a total gain less than 75% based on the dynamic pressure, it shut off the pilot's access to the RCS through the right side stick control so as to conserve rocket fuel.

Among the many changes made to the X-15 during the program were those to the displays in the cockpit. The pilot's display panel in the X-15-3 (Figures 3a, 3b, and Table 1) was significantly different from the displays in the other two X-15 aircraft.

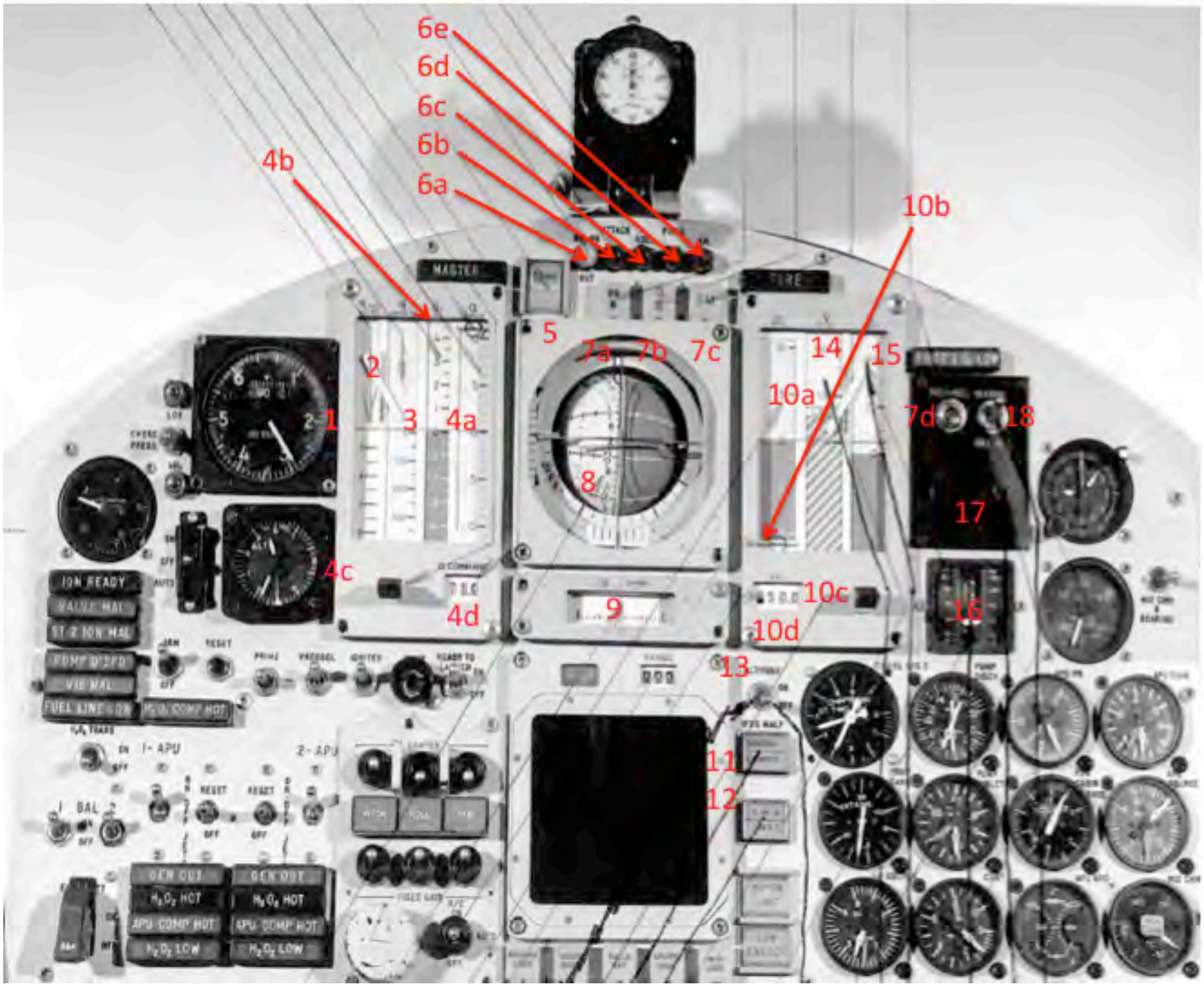

Figure 3a. Pilot's display panel in the X-15-3 (Figure 3a in AIB report).

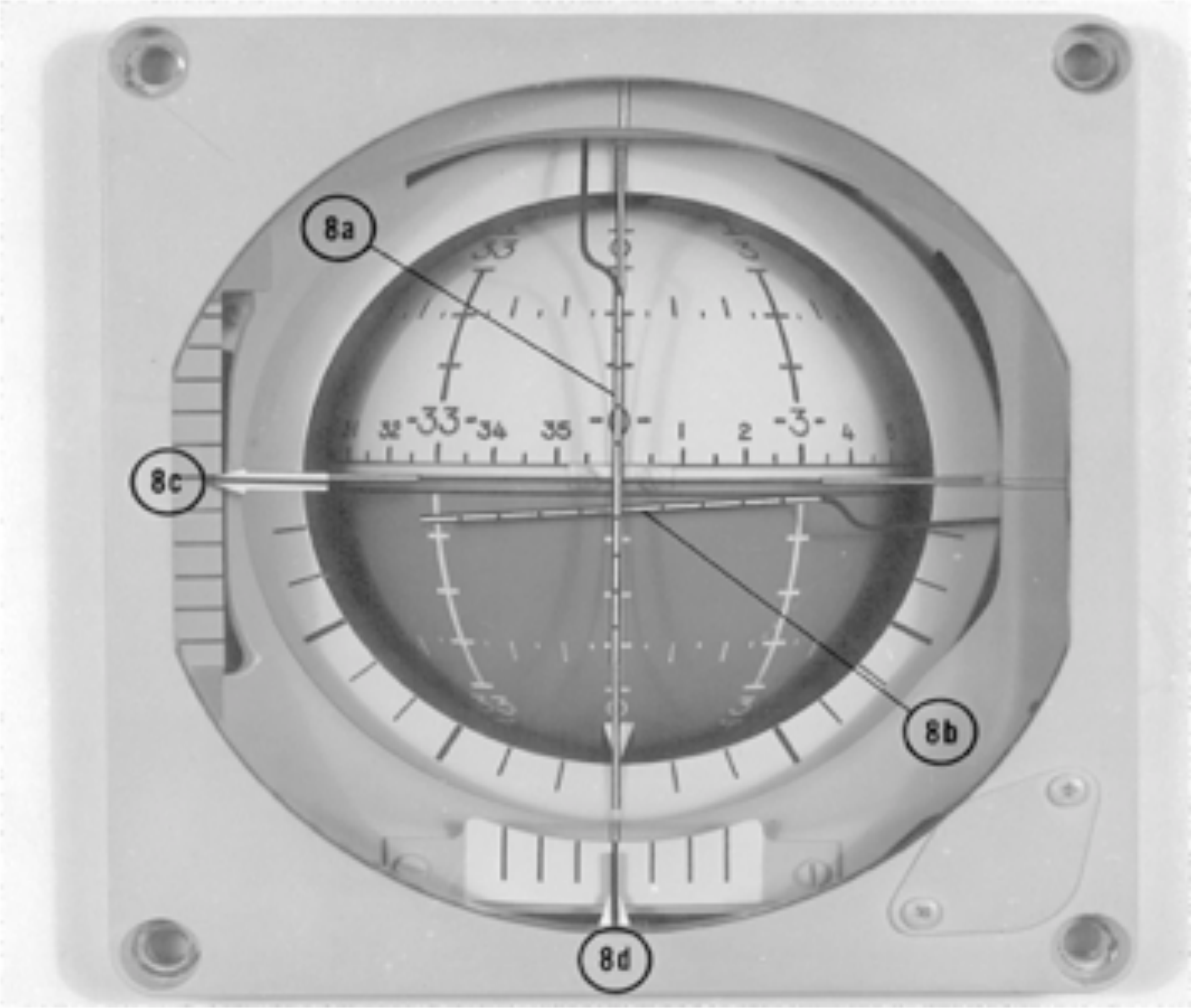

Figure 3b. The Attitude Director Indicator in the X-15-3 (Figure 3b in AIB report).

In the usual normal operation of all three configurations of the X-15, the pilot's Attitude Director Indicator (ADI) in the center of the control panel (Item 8 in Figure 3a) was a standard freely rotating sphere called the '8-ball' and its faceplate displayed a fixed reference aircraft symbol (Figure 3b). The sphere itself was bisected into white and black areas representing sky and earth, respectively. The ADI was a critical instrument because the typical X-15 ballistic flight profile prevented pilots from seeing Earth's horizon until re-entry and the degree of precision flying required by the mission demanded constant reference to flight instruments until landing. Moreover, the pilot was dependent on the ADI to perform the maneuvers required for the experiments with the X-15-3 with the required precision. Normally, the needles labeled 8a and 8b in Figure 3b indicated sideslip error from zero and angle of attack error from preset, respectively. Needle 8c displayed error from a ground preset of the desired climb attitude. Needle 8d indicated error from a ground-preset heading.

Table 1. Description of the Pilot's Display Panel in X-15-3

Item # in Figures 3a and 3b	*Description*
1	Info solely pre-launch
2	Dynamic pressure
3	Normal acceleration
4a-4d	Angle of attack (a); Selector index (b); Toggle switch (c); Index setting (d)
5	Switch for pilot to change source of angle of attack and angle of yaw from 'ball nose' to inertial computed when dynamic pressure <~50 psf
6a-6e	MH-96 status lights
7a-7d	Selection switches for needle function on Attitude Indicator
8a-8d	Attitude Director Indicator (ADI) (See text on next page)
9	Sideslip angle independent of ADI
10a-10d	10a vertical velocity; 10b–10d not operational on 3-65
11	Warning light: Top half red = IFDS malfunction; Bottom half amber = computer malfunction
12	Warning light. Energy management malfunction. Not operational on 3-65
13	Altitude switch changes source from B-52 to inertial computer
14	Flight path velocity magnitude in fps
15	Altitude in 1,000s of feet
16	Horizontal stabilizer position indicators
17	Knob to set desired values of precision pitch and roll attitudes presented on Attitude Indicator when 7d is activated
18	Not used on Flight 3-65

However, the ADI in the X-15-3 aircraft was modified to enable the pilot to select an alternate display configuration called the Precision Attitude Indicator (PAI) that was needed to perform certain scheduled experiments with the desired precision. The switches at 7a–7d in Figure 3a controlled the functions of the horizontal and vertical needles independently so that in the PAI mode they indicate the pitch- and roll-attitude errors, respectively, rather than pitch and yaw in the ADI's normal mode. This was a major design departure for a performance instrument considered critical to maintaining controlled flight—it was done because the X-15 instrument panel had limited area available.

An additional complexity of the ADI in either of its modes was that the standard ball nose air data system, which provided a measurement of angle of attack and sideslip was not reliable at dynamic pressures less than about 50 psf. When the pilot received the displayed information that the dynamic pressure was less than 50 psf he was expected to use a switch (Item 5 in Figure 3a) to change the source of angle of attack and sideslip data for the ADI displays from the ball nose to an inertial-based computed source.

2.0 Flight 3-65

Flight 3-65, the 65th flight of the X-15-3 airplane and the 191st X-15 flight, was planned for a maximum altitude of 250,000 ft. and a maximum velocity of 5,100 fps. Flight 3-65, with U.S. Air Force Major Michael J. Adams as its pilot, was a high-altitude flight and the aircraft was in nearly the same configuration as the two flights of the X-15-3 immediately preceding it, which were also high-altitude flights. The flight plans for the three flights were similar and they all involved use of the ADI in its normal mode in the climb and descent phases of flight and in its PAI display mode to perform certain experimental maneuvers. The plan for Flight 3-65's ten-minute duration was packed with a full schedule of experiments, which included bow-shock standoff measurement, solar-spectrum measurements, ultraviolet exhaust-plume measurements, and micrometeorite collection.

The differences in the configuration of the X-15-3 for Flight 3-65 compared with the previous two flights were: (1) a panel of ablative material was added to the left-hand upper speed brake to test the adhesive and insulating properties of a material proposed for use on the Saturn launch vehicle; and (2) a traversing probe in the pod of its right wingtip was operated for the first time on the X-15-3 aircraft in a high-altitude flight. The traversing probe was used in an experiment called a bow-shock standoff measurement. It was driven by a 115-volt, 400-cycle electric motor. Although this probe had been used in 1963 on X-15-1 at a lower altitude, neither the probe nor the motor had ever undergone thorough qualification tests for their ability to withstand the low pressures, high temperatures, and other environmental factors that it would encounter during Flight 3-65. No requirements for such environmental testing prior to flight existed at that time if the equipment was considered isolated from the safety-critical components of the aircraft.

At about 10:00 am PST on November 15, 1967, Major Adams waited inside the cockpit of the X-15-3 as the B-52A carried it to launch altitude. Launch from the B-52 took place at 10:30:07.4 PST at 45,000 ft. altitude with all systems operating normally; the pilot ignited the boost rocket, and the X-15-3 accelerated into a steep climb. The data show that during the final 40 seconds of the power-on phase, a sideslip to about $\beta = 5.0^{o}$ (nose left) developed gradually. This deviation was attributed to engine-thrust misalignment, had been seen on previous flights, and was considered fairly normal.

At 10:31:07, when the aircraft reached about 90,000 ft., arcing from the motor drive of the traversing probe caused an electrical disturbance to the aircraft's electrical system that continued until 10:33:53. Figures 4 and 5 show that the telemetered traces for pitch, angle of attack, normal acceleration,, roll, yaw, and sideslip all became erratic at 10:31:10 and remained so until the cessation of the electrical disturbance. Figure 5 shows a note that the Inertial Flight Data System (IFDS) computer malfunctioned at 10:31:28.

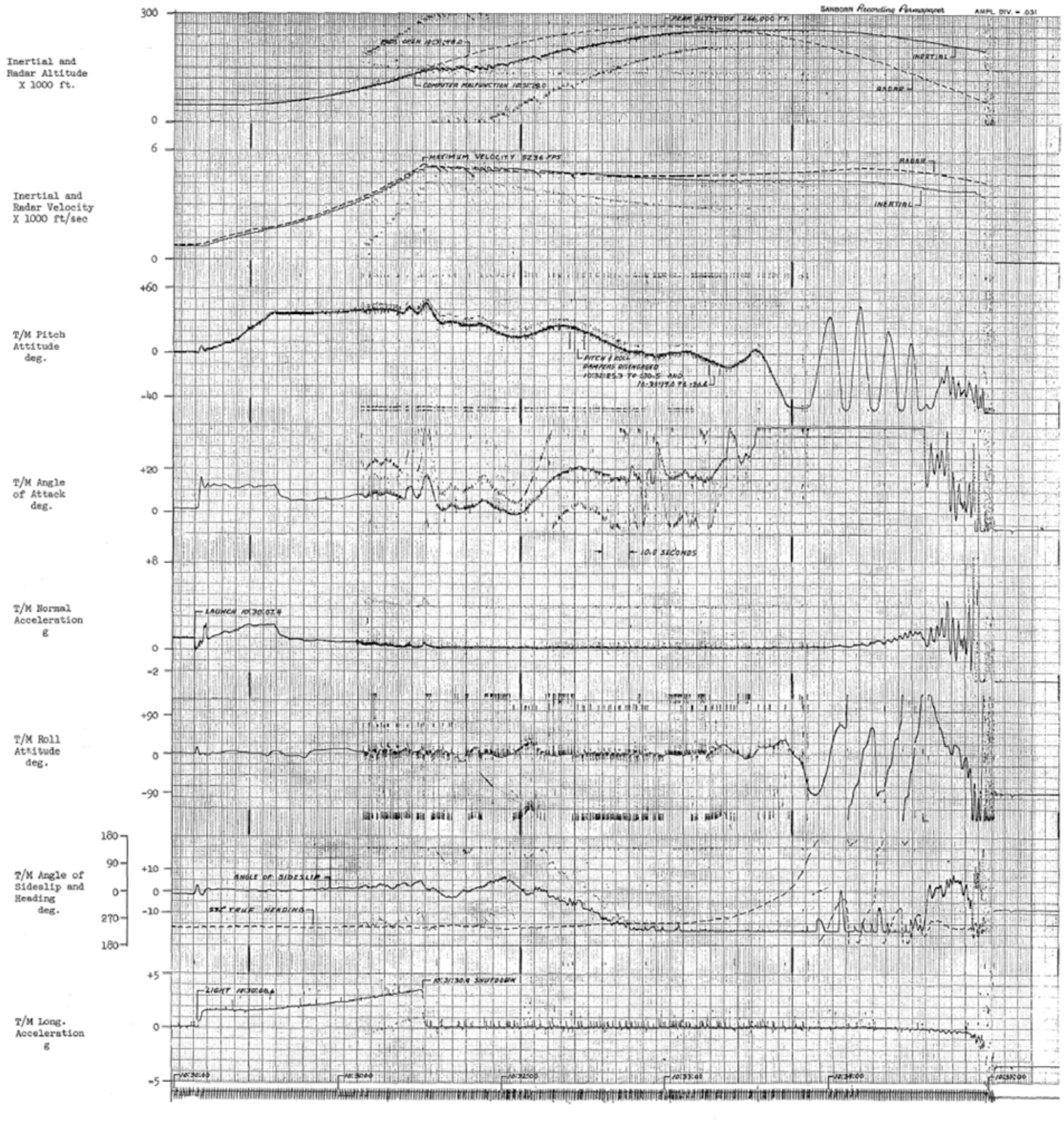

Figure 4. Time history of Flight 3-65 (Figure 6 in AIB report).

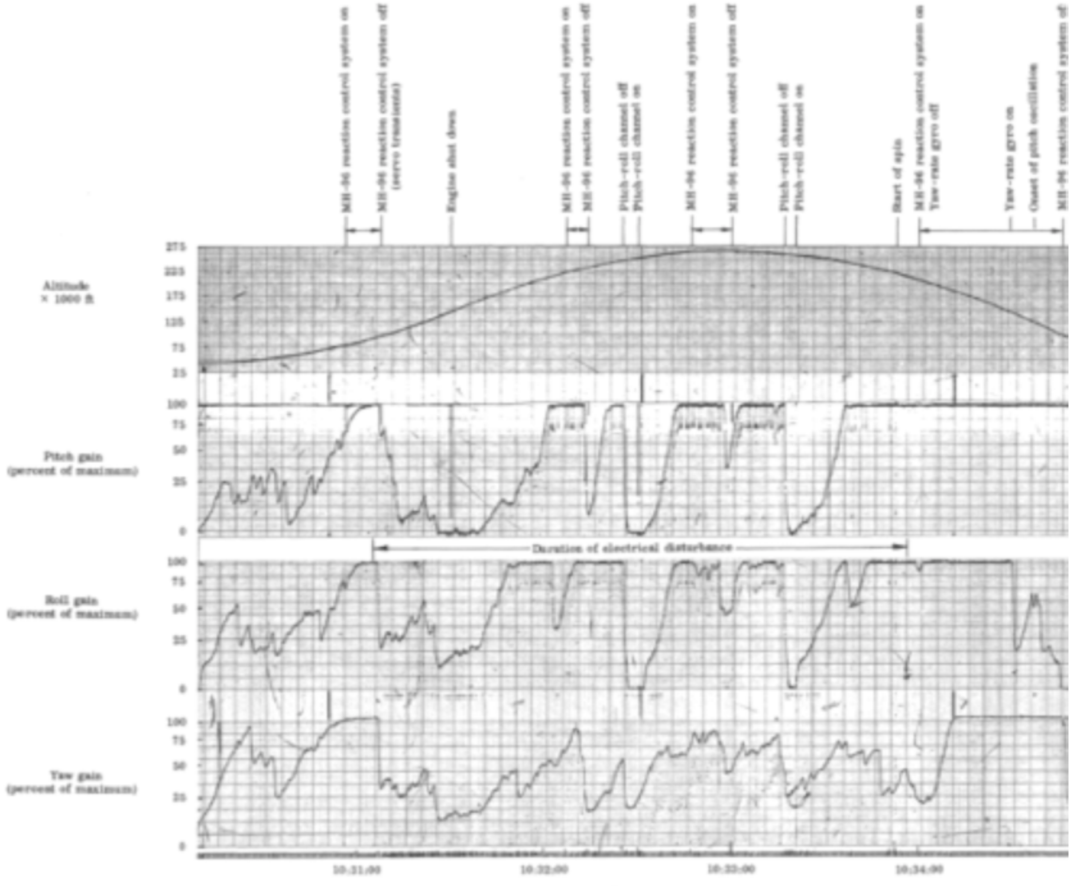

Figure 5. Time history of MH-96 control system gains during Flight 3-65 (Figure 17 in AIB report).

The electrical disturbance caused cascading failures of the computer in the IFDS[1] [6], of components of the MH-96 AFCS, and of electrical components of the aircraft's flight-control system that included spurious electrical signals to the servo-valve torque motor. The MH-96 AFCS that varied the control gains as a function of dynamic pressure used feedback from the servos, which was a function of the aerodynamic loads on the control surfaces and, therefore, of the dynamic pressure, as the measure of dynamic pressure. Consequently, the spurious electrical signals to the servomotors caused erroneous fluctuations in the automated gain control from maximum to minimum as seen in Figure 5, which caused the pilot's accessibility to the RCS through the right side stick to be intermittent throughout the 2 min, 46 sec duration of the electrical disturbance.

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[1] The IFDS installed in the X-15 consisted of an inertial measurement unit (IMU), a computer, and pilot's displays of pitch, roll, and heading, total earth reference velocity, rate of climb, and geometric height, pitch, roll, and heading, total earth reference velocity, rate of climb, and geometric height.

Figure 6[2] diagrams the time line of what is considered to have been the key events during the 3 minutes following the initial arcing. Appendix A presents a detailed sequence of the events from the moment of launch that includes an annotated transcript of the radio communications between ground control and Major Adams. Note how much was going on during that short time!

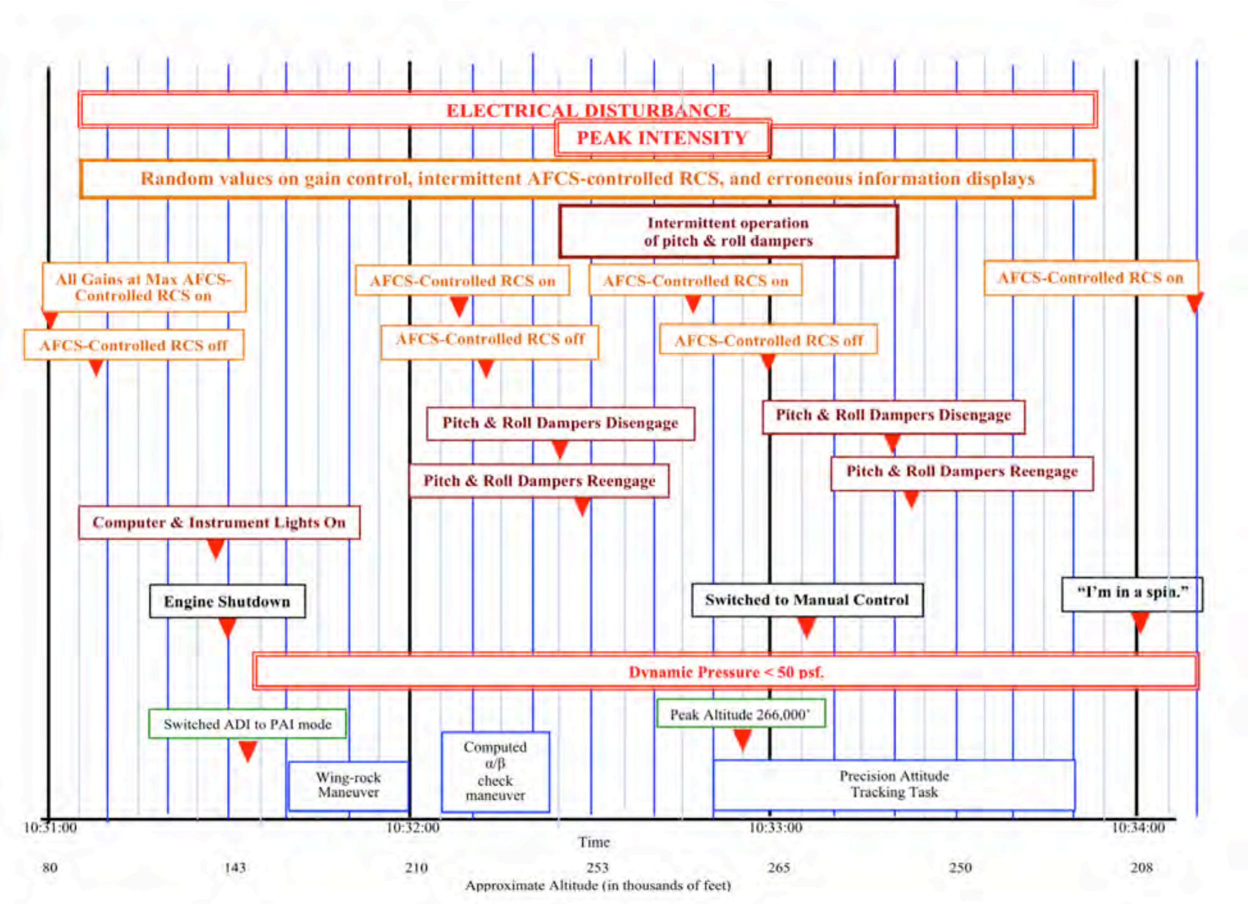

Figure 6. Time line of critical events leading up to entry into spin.

As seen in Figures 5 and 7, at 10:31:00 all three gains on inputs to the aerodynamic controls were at their maximums so that the MH-96 had automatically opened the gateway for inputs to the RCS and the pilot's right-hand side stick was operational at that point. Seven seconds later, the total gain of the three aerodynamic controls had decreased below 75% of its maximum so that access to the RCS was closed by the MH-96. From then on, the pilot's right-side-stick control of the RCS was intermittent because of the erratic fluctuations in the automated gain controls due to the continuing electrical disturbance. The pilot was unable to detect this intermittency of control for nearly 3 minutes, which is not surprising given the on-off nature of the RCS and the intermittent nature of the failure. Cockpit indicators showed that the engagement of the pitch and roll dampers were also intermittent during the electrical disturbance.

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[2] Figure 6 was developed from data taken from Figures 6, 8, 9, 10, and 17, and from Attachment K in the AIB report including the transcript of radio communication.

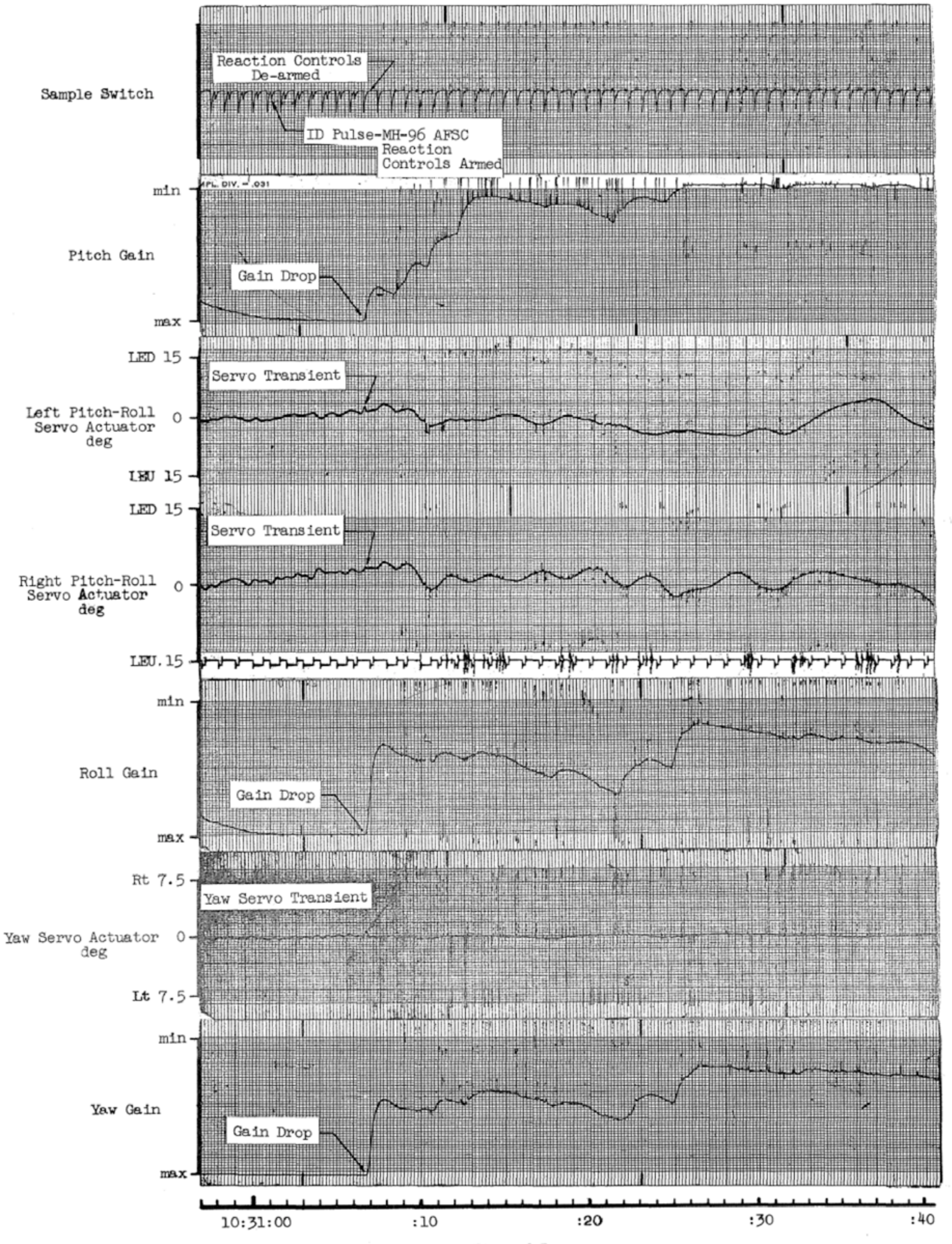

Figure 7. Time history of control-system servo-actuator motions and gains showing effect of electrical disturbance (Figure 10 in AIB report).

At 10:31:28 (2 seconds before engine shutdown) at about 140,000 ft. (Figure 8), Major Adams reported that the IFDS computer- and the instrument-malfunction lights had come on. Eight seconds later, the pilot attempted to reset the light but it stayed on and at 10:31:58 he again reported that the computer- and the instrument-malfunction lights were on. Ground control acknowledged the pilot's reports.

At 10:31:34 and about 154,000 ft. (Figure 8) the pilot received instruction from ground control to switch the ADI to the PAI mode (which Major Adams had already done) in accordance with the flight plan in preparation for the scheduled experimental maneuvers. At about the same time, when the dynamic pressure fell below 50 psf, he switched to the IFDS as the source of information for angle of attack (α) and angle of roll (β) as well as for altitude and velocity even though the computer malfunction light was still on.

At 10:31:42, the Flight Controller (i.e., ground control, identified as NASA 1 in the radio transcript in Appendix A) called for the wing-rock maneuver for the exhaust plume measurement even though malfunction lights were still on. Major Adams had already initiated the maneuver at 10:31:40 and he completed it at 10:32:00 despite the intermittent control throughout but he had exceeded the bank angles specified in the flight plan and the airplane had started a slow yaw drift to the right. During the performance of the wing-rock maneuver, the trouble on-board became clear to the engineer monitoring the telemetry of the MH-96 AFCS and radar track and he called to the Flight Controller that the pilot was "having control problems"!

At 10:32:08 and about 220,000 ft. (Figure 8), Major Adams was instructed by ground control to perform the scheduled experiment of the computed α/β-check maneuver, which required the use of the display of IFDS computed angle of attack and computed angle of sideslip, even though the Flight Controller had acknowledged the pilot's prior reports that the IFDS computer was malfunctioning. The pilot performed this maneuver until 10:32:23.

At 10:32:27, Major Adams reported that the pitch and roll dampers had tripped out. He was able to reset them at 10:32:32 but they disengaged again at 10:33:20.

At about 10:32:50, the pilot initiated the Precision Attitude-Tracking Task in accordance with instructions from ground control. At 10:32:51.2, the Flight Controller reported *"Over the top at about 261"* [actually, 266] and at 10:33:01.4 the Flight Controller told the pilot that he was looking *"real good"*. However, at 10:33:05 and about 263,000 ft. (Figure 8), the pilot apparently noticed for the first time the aircraft's lack of responsiveness due to the intermittent, and ultimately the deactivation of, access to the RCS through the right side stick and he switched to direct control bypassing the AFCS using the left side stick. Normally, the procedure for switching to direct manual control would have involved deactivating the 'auto' mode of the RCS or disabling the MH-96 but Major Adams did not execute this step.

By the time the pilot switched to direct manual control of the RCS, the aircraft had rolled left and the precision roll indicator (of the PAI) showed the need for the aircraft to be rolled to the right. Rather than effecting the needed right-roll control, the pilot applied right-yaw control, even though the yaw angle was already off heading by 15° to the right due to the slow drift that started 40 seconds earlier. The aircraft started yawing to the right again in response to the pilot's control, thereby further increasing the deviation from heading. Meanwhile, Major Adams continued to try to perform the precision attitude-tracking task.

Despite the many indications of various malfunctions of the aircraft systems and concerns voiced by members of the ground control team, the Flight Controller seemed to be unaware of Major Adams' severe situation (or he was completely focused on accomplishing the flight plan) and at 10:33:25 he once again assured the pilot that he was *"a little bit high"* but in *"real good shape."*

Fourteen seconds later, at 10:33:39 and about 240,000 ft., the pilot reported that the aircraft control seemed *"squirrelly"* and 22 seconds after that, at 10:34:01, Major Adams said, *"I'm in a spin."* Ground control did not acknowledge either of these transmissions. Major Adams repeated *"I'm in a spin"* at 10:34:16. At 10:34:17 the Flight Controller said *"Say Again."*

At 10:34:17 the aircraft was in descent at 184,000 ft. with a velocity of 3,022 knots (5,100 fps; see Figure 8). It was pitched up at about 40^o, had a roll rate of about 20^o per second, and at more than 90^o off of its intended heading (see Figure 4). The dynamic pressure was still less than 20 psf, which meant that the aerodynamic controls and the ball-nose indicator were ineffective.

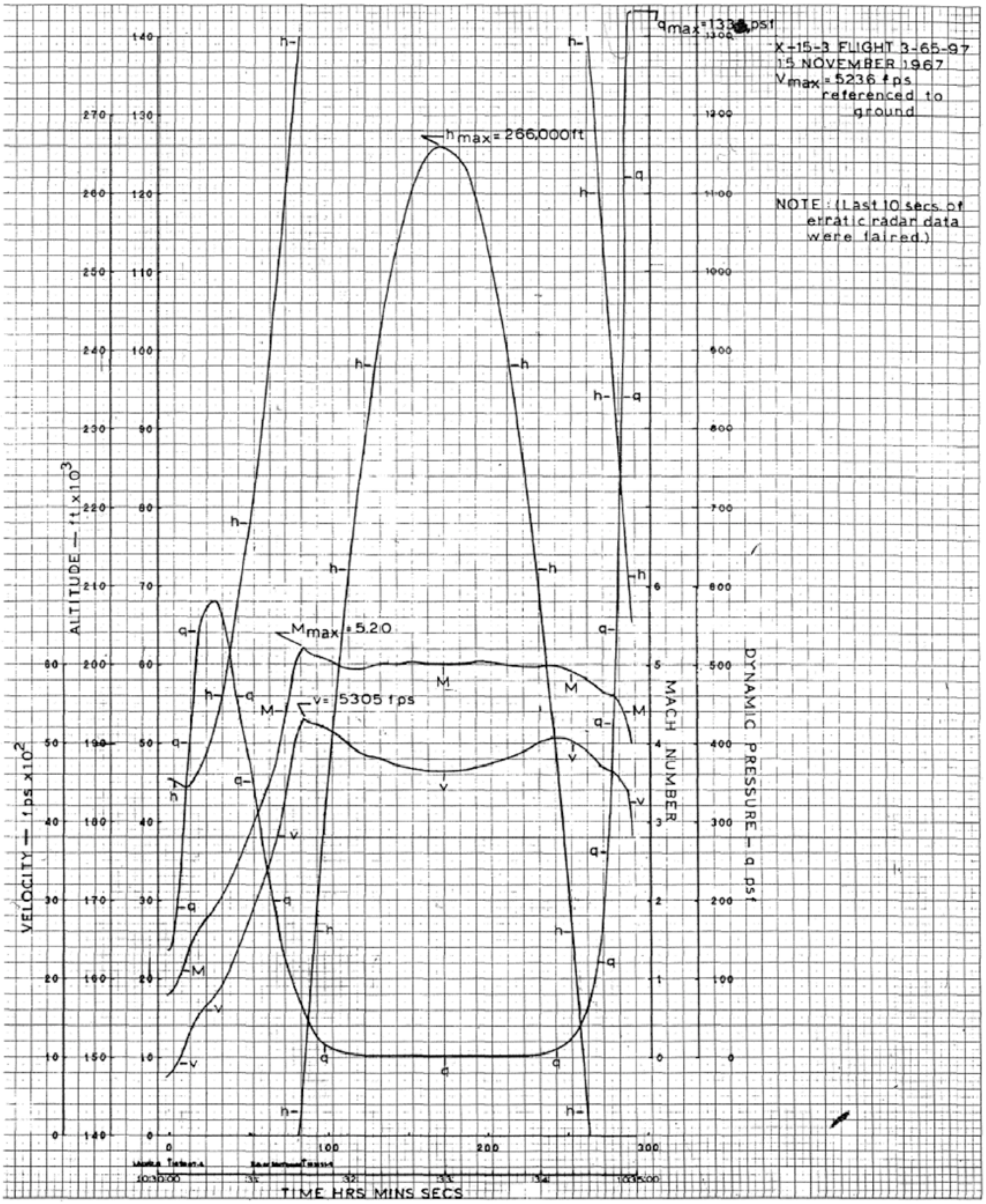

Figure 8. Variation of altitude, Mach number, and dynamic pressure during Flight 3-65 (Figure 8 in AIB report).

No procedure had been developed to recover from a hypersonic spin. Ground control could not help. From the moment the aircraft entered into a spin, the ensuing events were inevitable. After the aircraft had completed three revolutions, it came out of the spin and went into a 45-degree inverted dive. Major Adams did not have sufficient time to recover from the dive.

At about 10:34:37, within seconds after the aircraft went into an inverted dive, the MH-96 AFCS entered into a limit-cycle instability in the pitch axis forcing the horizontal stabilizers into rapid, cyclic oscillation to their limit of travel at their maximum rate of 26^{o} per second. As dynamic pressure increased during rapid descent, the motions of the horizontal stabilizer produced rapidly increasing accelerations both in pitch (plus and minus 15 gs) and in yaw (plus and minus 8 gs) that exceeded the aircraft's structural limits. The severe oscillations and massive g forces Major Adams encountered likely resulted in his incapacitation. He was unable to eject or recover control. Within 20 seconds—by 10:34:54—the aircraft began to break up. The largest pieces impacted the ground at 10:34:58, just 56 seconds after the aircraft entered a spin.

3.0 The Causal and Contributing Factors

As in most accidents, the destruction of the X-15-3 during Flight 3-65 was due to a confluence of **latent** and **proximate** factors. This human factors review of the events leading to the in-flight breakup of the X-15-3 identified these **latent** and **proximate causal factors** and also some **contributing factors**. The **contributing factors** were those that exacerbated the causal factors. Although it was quite unlikely, it is conceivable that if certain of these contributing factors had not occurred the pilot might have been able to recover control of the aircraft and effect a safe landing.

3.1 The Causal Factors

A **latent causal factor** of the Flight 3-65 accident was management's decision to permit the installation of experimental equipment (namely, the apparatus for the traversing-probe experiment) without requiring it to be environmentally tested.[3] The consequences of the arcing of the traversing–probe motor on Flight 3-65 show that the management and procedures for designing and testing X-15 experimental flight equipment were inadequate. As was demonstrated by the successes of the previous two flights of the X-15-3 in which this experiment was not deployed, this accident would not have occurred had management required an environmental test of the traversing probe prior to flight. Therefore, management's failure to require the appropriate environmental testing of experimental equipment before it was installed on the aircraft was a causal factor of the accident.

A **proximate causal factor** was the confluence of the failures of the aircraft system design and of ground control to alert the pilot to the possibility of control problems and erroneous data as soon as indications of malfunctions were detected or observed. The entire system, including X-15 management, ground control for Flight 3-65, and the designs of the aircraft's AFCS and of the displays, contributed to Major Adams' illusion that his aircraft was operating properly during almost 3 minutes when the electrical systems were all malfunctioning. The pilot and ground control should have recognized that the inability to reset the IFDS computer and instrument malfunction lights was an indication of a system malfunction but it seems that the program (including the pilot and ground control) tended not to consider the IFDS to be critical. While there was an indicator of the failure of the IFDS computer on the pilot's display, and while the MH-96 could detect and alert the pilot to numerous types of major component failures, there was no display to indicate that the MH-96 gain control was erratic. If the pilot had been alerted so that he would have changed to direct manual control and reverted to the fixed-gain mode of the MH-96 in a timely fashion (e.g., when ground

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[3] Moreover, the condenser used in the traversing probe on the X-15-3 aircraft was rated for 200 volts when the specification had been for a 1,000-volt rating. Even though post-accident tests showed that electrical arcing would have occurred with a condenser of proper voltage rating, it is added evidence of the failure on the part of the management of Flight 3-65.

control observed indications of control problems during the wing-rock maneuver), he very likely could have brought the aircraft to a successful landing. Therefore, the failure of the *system* to alert the pilot to the problem in the aircraft's control and displays was a causal factor of the accident.

- There were no provisions in the system design for alerting the pilot to the erratic behavior of the automated flight control system or to the erroneous information on aircraft angles of attack, sideslip, altitude, and altitude rate generated by the malfunctioning IFDS computer. Also, the intermittent aspect of the access through the AFCS to the RCS (which is already an inherently 'on-off' system) caused the pilot to be deluded into believing that the system was operating properly for several minutes. As the AIB report [1] states, access to the automated RCS was *"propitiously"* operating during the few brief instants when the pilot moved the right side stick control as he performed the first two tasks (i.e., the wing-rock maneuver and the computed α/β-check maneuver) and as he initiated the precision attitude-tracking task. The report states: *"Since the MH-96 provides no visual indication to the pilot of reaction control system status, i.e., whether or not the system has been automatically selected, the pilot must rely on being able to detect rocket operation by sound, visual exhaust observation, or control response to determine if the reaction controls have been properly selected. Since no attitude-rocket firing occurred during the initial 11-second engage time of the MH-96 reaction controls on flight 3-65, it would have been virtually impossible for the pilot to detect that the system had automatically engaged and then disengaged 11 seconds later"* (pg. 41). Consequently, with no visual display of the failure there was little possibility that the pilot, on his own, would have recognized the intermittency of his control based solely on aircraft response.

- Ground control was a party to this proximate causal factor because its primary principle was not followed. The AIB report [1] states: *"The philosophy associated with X-15 research flights is to discontinue the research objectives when aircraft malfunctions impair safe recovery of the aircraft or when the pilot has become so overloaded with aircraft malfunctions and/or experiment tasks that he is unable to do either"* (pg. 36). This is indeed the proper philosophy for flight-testing. It is regrettable that it was not effectively implemented during Flight 3-65.

  In describing the monitoring function of ground control, the AIB report [1] states that "*All the aircraft systems are monitored, and the pilot is advised if any unusual occurrences are noted on telemetry and is asked to verify and in some cases requested to take particular action*" (pg. 14–15). Again, ground control failed to fulfill this critical function. Although many *"unusual occurrences were noted on telemetry,"* the pilot was not advised, not asked to verify, and no particular action was requested of him.

  The AIB report [1] states that ground control did not have access to all the information needed for effective and timely detection of problems. If in fact this was the case, then ground control was unable to perform its primary function of protecting the safety of the aircraft and pilot in accordance with the philosophy the AIB had already noted. It is hard to understand why the status of the critical automated reaction control system was not being monitored on the ground, whereas the servomotors of the aerodynamic control system were being monitored. It is especially disturbing, as the MH-96 AFCS should have still been viewed as experimental equipment having experienced problems in previous flights. Ground control's key role is safety backup to the pilot in such an experimental flight. Therefore, all critical flight information should be available to ground control regardless of whether or not it is available to the pilot.

  However, despite of the lack of certain key information, ground control had plenty of evidence of problems with Flight 3-65. The continuing fluctuations in all of the telemetered data along with the indications of the IFDS malfunction should have been enough evidence of problems to mandate at the least a report to the pilot of a problem if not an order to abort the mission. Within 1 minute and 20 seconds after the start of the electrical disturbance, ground control already had several indicators of serious problems on the aircraft. Following are the indications of problems of which ground control was aware and the times at which they became aware of them:

- At 10:31:07 (only 1 minute after launch), all of the telemetered data suddenly became erratic and remained so for several minutes (see Figure 4). For example, ground control was aware of continuing anomalous servo transients from these telemetered data. The AIB report [1] states: *"The transient motion of the three servos was not due to pilot inputs or aircraft motion, but was apparently electrical and was of sufficient frequency content and amplitude to drive all three control gains well below their normal values for the particular flight conditions at which it occurred. The gain reduction in all three channels was great enough to cause the primary reaction controls to automatically disengage"* (pg. 38).
- Starting at 10:31:07, the telemetered data on altitude and velocity differed from the radar data. Testimony shows that the difference was sufficient that it had been noted by ground-control personnel.
- Twenty-one seconds later (10:31:28), the pilot reported that the IFDS computer and instrument malfunction lights were on.
- At 10:31:58, the Flight Controller acknowledged the pilot's report that the IFDS computer was malfunctioning.
- About 20 seconds later, during the wing-rock maneuver, a member of ground control reported to the Flight Controller that the pilot was having a control problem based on his observations of larger than normal pitch-roll servo excursions.
- At 10:32:26, disengagement of the pitch and roll dampers was reported by the pilot and acknowledged by the Flight Controller.

Even just a suspicion of a problem—which ground control certainly had—should have been sufficient to alert the pilot and abort the mission regardless of any belief that the pilot had detected the problem. Ground control's responsibility for safety was its first priority. The proactive approach to safety is to advise the pilot of a problem as soon as there is any indication of that possibility. Such a warning is mandatory even if it may be redundant. The failure of ground control to notify the pilot of a possible control problem as soon as they had a suspicion of a problem was a grave error and a causal factor in the loss of Flight 3-65.

Despite all the evidence of problems, ground control not only failed to inform the pilot of their awareness of possible control problems and of erroneous data, the Flight Controller continuously assured him that he was on the planned flight profile and instructed him to proceed with planned experiments. For instance, consider the following transmissions from NASA 1 (see also the detailed transcript in Appendix A):

10:30:45 – *"We have you right on track, on the profile."*

10:31:13 - *"Okay, right on track."*

10:31:21 - *"On profile, on heading."*

10:31:50 – *"On heading, on profile."*

10:32:19 - *"Right on the track."*

10:32:43 - *"You are looking real good, right on the heading, Mike."*

10:33:01 - *"Your heading is going in the right direction, Mike, real good."*

10:33:25 – "*A little bit high, Mike, but real good shape."*

10:34:01 – Pilot reports *"I am in a spin!"*

10:34:03 - *"Let's get your experiment in and the camera on."*

It is particularly interesting to note the many references to being "on heading." According to the AIB report [1], ground control did not have heading information and was strictly relying on radar track data. In fact, the very first recommendation the AIB made in the conclusion of their report says: "*A telemetered indication of airplane heading should be placed in the X-15 control room where it is visible to the flight controller*" (pg. 75). Given the high workload inherent in these very short, very busy test flights, compounded by multiple failures and control difficulties, it's small wonder that Major Adams didn't correct his yaw angle with all these assurances that he was "on heading."

Not only did ground control thereby enforce the pilot's illusion that all was well and cause him to discount the computer and instrument malfunction lights and the disengagement of the pitch and yaw dampers, but they also added to the pilots' problems and workload by instructing him to execute the experiments rather than focus on the problems.

– At 10:31:40, the pilot was instructed to perform the wing-rock maneuver even though it relied on the IFDS computer and even though Major Adams' report that the computer and instrument malfunction lights were on had been acknowledged by ground control.

– During the wing-rock maneuver, it became apparent to ground personnel monitoring the telemetry records that something was amiss in the control of the airplane. Nevertheless, the Flight Controller instructed the pilot to continue with the computed α/β-check maneuver. This experiment was a part of a continuing study to determine the highest altitude at which the ball-nose display could still be considered reliable by comparing the ball-nose indications of angle of attack and sideslip to the values calculated by the IFDS computer. Ground control already knew that the IFDS computer was malfunctioning and that there was a control problem, yet the pilot was instructed to proceed with this experiment that relied on the IFDS computed angle of attack and computed angle of sideslip.

After 190 successful flights, the ground-control personnel and, in particular the Flight Controller of Flight 3-65, may have become complacent and apparently chose to ignore the evidence of a problem on board the aircraft. The Flight Controller appears to have been so focused on completing the flight as planned that he was unable to recognize the integrated significance of the several indications of problems that were reported to him by the pilot and by ground-control personnel. Evidence of this attitude on the part of the Flight Controller is in the following examples of witness testimony in the AIB report [1]:

– A member of the ground control team during Flight 3-65 testified" *"The first problem indication was the computer malfunction light call from the pilot. I did not hear him call reset. The next thing was pitch-roll damper dropout, and reset...With the apparent A/C problems I asked the controller to have the experiments closed....*" (pg. G-25).

- Another member of the ground control team stated: *"During a period when the pilot was performing a wing rocking maneuver, the pitch-roll servos were going through large motions–from stop-to-stop. This in self is not abnormal or unusual, however, I felt that the duration that the servos were against the stops was unusually long and I called out to the Flight Controller that 'he (the pilot) was having control problems'"* (pg. G-18).
- Yet another member of the ground control team testified: *"Upon initiation of the planned roll maneuvers, the pilot appeared to have a roll control problem as evidenced by larger than normal pitch-roll servo excursions...stop to stop excursions continued on the pitch-roll servo traces. In addition, the ball nose β indication moved off scale, showing the aircraft nose right"* (pg. G-26).

It seems that the Flight Controller did not consider these sufficient evidence of continuing serious control problems.

Even after he had been informed of a likely control problem that was recognized during the wing-rock maneuver, the Flight Controller permitted the pilot to complete the wing-rock maneuver, and, moreover, instructed him to proceed with the computed α/β-check maneuvers and then with the precision attitude-tracking task experiment. In addition, the Flight Controller continually assured the pilot that all was OK, that he was *"on track"* and *"on heading"* (see the radio transcripts of NASA 1 in Appendix A).

For over two minutes, until Major Adams himself recognized he had problems, ground control encouraged him to operate the aircraft even though it was known that the control system had failed and that much of the displayed information on aircraft states was probably erroneous (see the radio transcripts of NASA 1 in Appendix A).

It seems that the Flight Controller permitted his dedication to performing the flight plan to cloud his watchfulness for the possibility of a safety problem.

3.2 The Contributing Factors

During the nearly three minutes after the electrical arcing from the traversing probe that precipitated the events leading up to the destruction of the X-15-3, there were several factors that exacerbated the causal factors of those events. It is conceivable that the pilot might have regained control of the aircraft and effected a safe landing had certain of these factors not prevailed at the time.

- One of these **contributing factors** was the design of the adaptive gain control in the MH-96 that allowed a failure in the AFCS to interfere with the pilot's ability to control the aircraft without any indication to the pilot of the failure other than a reliance on his noticing a lack of response to his control inputs.
    - To conserve control-rocket fuel, the system was designed so that the RCS could only be engaged by the pilot (through the right side stick control) or by the AFCS whenever the sum of the gains to the aerodynamic control surfaces for pitch, roll, and yaw exceeded 90% of maximum and would become disengaged from any inputs whenever the total gain for the three controls decreased to 75% of the maximum. (These gains were functions of dynamic pressure by way of feedback from the control surfaces' servomotors.) Consequently, at the start of the electrical disturbance that caused

spurious signals to the servos, the pitch-, roll-, and yaw-control gains all dropped precipitously from their maxima as shown in Figures 5 and 7 and the access (for both the pilot and the AFCS) to the RCS was automatically disengaged. Subsequently, as the total value of the three gains randomly exceeded 90% or fell below 75% of the maximum value, inputs to the RCS through the adaptive gain control were permitted or prohibited intermittently.[4]

  - Another manifestation of this poor design concept in the MH-96 that interfered with the pilot's ability to control was that whenever there was a disengagement of the pitch and roll dampers (as occurred multiple times during Flight 3-65), the adaptive gain control was reduced to its minimum value in order to prevent large engage transients to the aerodynamic controls when the channel was reset. Also, the MH-96 was designed so that after each such disengagement of the dampers about 20 seconds would elapse before the MH-96 AFCS allowed the pilot to have access to the reaction controls through the right side stick (although this is not apparent in the gain variations shown in Figures 5 and 7). This is an acceptable design feature as long as it does not prevent the pilot from exercising control with, perhaps, additional effort (as was more or less the case when the pilot used the aerodynamic controls). However, this feature of the MH-96 AFCS caused a delay in re-opening the gateway for the pilot's inputs to the RCS using the right side stick when control depended on the RCS. Although this aspect of the MH-96 design had merit for protection of the aerodynamic controls, the designers apparently failed to consider the negative impact of the delayed re-engagement of the pitch and roll dampers on the controllability when the only control useful to the pilot was the RCS.

  - The pilot of Flight 3-65 was dealing with an ineffective right side control stick from 10:31.07 until 10:33:50 because his access to the reaction controls was being denied by the automated system behaviors designed into the MH-96 with no indication to the pilot. The intermittency of this ineffectiveness was particularly insidious because with no other signal of malfunction, in combination with a rocket reaction control which is inherently an 'on-off' system, the pilot's recognition of the failure was obfuscated.

- A second **contributing factor** due to the design of the MH-96 AFCS was the complexity of the pilot's interface with the system.

  - The main problem with the AFCS' interface was the lack of interface. Several key functions of the AFCS had no interface with the pilot. Thus, when the AFCS started malfunctioning at 10:31:07 with the first electrical disturbance there were no indications to the pilot of that failure.

  - The problem of understanding the functioning of the AFCS (and the potential for misunderstanding) is exemplified by the following instructions in the Pilot's MH-96 Manual:

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[4] As long as the dynamic pressure was sufficiently high for effective aerodynamic control, the adaptive gain control never prevented the pilot's access to control. Even with a failure of the adaptive gain control, the pilot could still control the aircraft, although he might work harder. However, when the dynamic pressure fell below about 50 psf., the MH-96 became a gatekeeper for the pilot's access to the RCS. When the adaptive gain control failed in this case, the pilot's connection to the RCS was cut.

> *"If the damper switches are down and the lights are out, power for the system is off. If the damper switches are down and the lights are on, the system is disengaged but in a state of readiness to be engaged. If the damper switches are up (DAMPER position} and the lights are out, the dampers are engaged. If the damper switches are up and the lights are on, only the fixed-gain portion of the dampers are engaged"* (pg. H-27 of the AIB report [1]).

This is the kind of design that is conducive to human error.

– The procedure to switch from control of the RCS through the MH-96 to direct manual control was similarly complex. The Pilot's Manual states that before the pilot switches to the left side stick for direct access to the RCS he must first turn off the MH-96 AFCS otherwise the automated system would oppose the pilot's commands. The pilot would be expected to take this action when he recognized that the AFCS has failed. However, the MH-96 provided no indication of its status. When the MH-96 failed as it did on Flight 3-65, the pilot would have had to rely on the aircraft response to recognize that the reaction control system is not being activated by his right side stick inputs. However, as was pointed out previously and as noted in the AIB report, the small control inputs required for the experiments and the propitious intermittent effectiveness of control made it virtually impossible for the pilot to detect the failure. Also, even had Major Adams recognized that the AFCS was not functioning properly, it is questionable whether he could have identified and taken all the necessary steps to disengage it under the stressful conditions and the large aircraft motions that existed at the time he entered into the spin. There was no single-button override of the MH-96.

– The MH-96, particularly as it was used in the X-15-3 with adaptive control gain, was experimental equipment and provision should have been made for instantaneous disengagement in case of any malfunction. There should have been a single, well-identified button (and a clear display/message of when to push it) that would put the aircraft into its basic non-experimental configuration using the MH-96 in its backup flight system mode with fixed gain on the controls and normal display in the ADI.

- A third **contributing factor** due to the design of the MH-96 AFCS was that it had a known tendency to go into limit-cycle oscillations that drove all the controls to their maximums at very high frequencies when the system was operating at or close to maximum gain. On Flight 3-65 it was the pitch control-system instability that caused the destruction of the aircraft.[5] The possibility of this mode of failure (having experienced it on a prior flight) should have resulted in a suspension of flight operations using the MH-96 until the design issue was resolved and documented. While the previous incidence of this failure was concerning but caused no damage, in this case it destroyed the aircraft. During post-accident simulations to duplicate the aircraft motions and control-system operation during the period immediately following the recovery from the spin, this pitch control-system instability was induced at some point on nearly every attempt and the resulting recovery attempts were unsuccessful. The post-accident simulations confirmed that there was nothing that Major Adams could

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[5] A recent analysis [8] concluded that the cause of the instability was most likely a latent design error in a structural notch filter and was unrelated to but exacerbated by the adaptive gain mechanism. The mode of failure was a rate-limit instability involving the power actuator not unlike a classical pilot-induced oscillation (PIO).

have done to save the flight. Because of automated system behaviors that had been designed into the MH-96 and as long as it was still engaged, the entry into the spin sealed the fate of the aircraft. Although this pitch control-system instability resulted in the destruction of the X-15-3, it is considered a contributing factor because the instability would have been avoided if Major Adams had remembered to disengage the AFCS when he switched to direct manual control just prior to entering the spin.

- Another **contributing factor** was in the design of the pilot's display that used a single critical instrument, the ADI, in two different modes: one a normal mode used most of the time, the other a mode (PAI) that was used only occasionally.
    - Even though this instrument had been flown successfully on previous X-15-3 flights, it was a fundamentally poor design from a human factors perspective. In its normal configuration, the horizontal and vertical needles of the ADI indicated angle of attack and angle of sideslip, respectively. When the ADI was switched to the PAI mode for periods of certain maneuvers, the horizontal needle indicated pitch angle and the vertical needle indicated roll angle. Using such a critical display in two different configurations without a clear and salient mode indication is conducive to mode confusion, especially when the pilot is under stress and high workload.
    - Further, the mode indicator light on the display panel was innocuous. There were four attitude-indicator-deviation-needle function switches (switches 7a–7d in Figures 3a and 3b). Two of these were push-to-select switches related to normal ADI configurations and one was a push-to-select switch related to energy management that was not operational on Flight 3-65. Each of these switch faces illuminated with a small white light when that particular function was selected. The fourth was a toggle switch to select the PAI mode when it was in the up position. This toggle switch did not have an indicator light; the position of the switch was the only indication of whether the PAI mode was on or off. When one function was activated, the previously selected mode was automatically disengaged. This was an inadequate display of modes. The indication of the mode should be on the display itself, not on the mode activation switch. In the case of the X-15-3, the entire ADI should have been clearly marked for each of the modes in which that display was used.
- Yet another **contributing factor** was that during the time period and the altitudes at which most of the critical events occurred, information displayed came from the IFDS computer which was known to have failed while the only other source (the 'ball nose') was known to be unreliable. There was no provision for backup source of reliable information for the pilot at high altitude in case of failure of the IFDS computer.
    - When the dynamic pressure became less than about 50 psf, the normal procedure for the pilot was to push a switch on the display panel (switch 5 in Figure 3a, the bottom half of which flashes amber to alert the pilot) that changed the source of data for the angle-of-attack and angle-of-sideslip from the aerodynamic source of the 'ball nose' to the IFDS computer. On Flight 3-65, the dynamic pressure fell below 50 psf at about 155,000 ft. at 10:31:35, by which time the IFDS computer had already failed and the computer and instrument malfunction light had come on. Although he did not make a verbal report, the post-accident examination of the cockpit film shows that Major

Adams pushed the data-source switch as planned[6] despite the IFDS computer malfunction light. After switching the source, many of the pilot's displays of the aircraft state were erroneous, although the sideslip indication was (correctly) indicating off-scale nose-right. When the dynamic pressure increased to above 50 psf with the switch in the computed mode, the pilot was similarly reminded to switch to the ball-nose-derived angle-of-attack and angle-of-sideslip information. On Flight 3-65, the dynamic pressure did not increase above 50 psf until well after Major Adams reported he was in a spin. The cockpit film indicates that he never switched back to the aerodynamically driven source of aircraft data and he may not have been able to make that switch once the aircraft had entered into a spin.

- Finally, the evidence in the AIB report was reviewed to ascertain what actions taken or not taken by Major Adams during the critical three minutes may have been contributing factors in the X-15-3 accident.
    - It was not until two minutes after the access to the RCS through the right side stick had become intermittent that Major Adams realized the aircraft was not responding to his inputs to the right side stick and switched to the left side stick control. The MH-96 did not provide the pilot with any indication of the status of the system. Propitiously the controls worked when he called upon them while he performed the wing-rock and the computed α/β-check maneuvers. This coincident response contributed to the deception that his controls were operating normally. It was not until he was trying to maintain the precise control for the precision attitude-tracking task that he found that the access to the RCS through the AFCS from his right side stick was not working. The delay in his ability to recognize the failure contributed to the accident.
    - Major Adams failed to correct the error in yaw when he switched to direct control of the RCS through the left side stick. The AIB report attributes this failure to the pilot's misinterpretation of the PAI after he had selected that mode for the ADI earlier. However, the AIB report [1] states: *"Since it did not require excessive control inputs to keep the needle close to center, the pilot may not have realized his error until it was too late or he may never have realized his error, in that he could not or did not recognize any problem with his attitude control"* (pg. 36). It is important that the AIB recognized the pilot might not have been able to discern that the aircraft had reached a large yaw error until he discovered that he had no control. Major Adams' failure to correct the yaw error or his inability to detect it probably contributed to the accident.

      The evidence suggests that Major Adams' control inputs when he switched to the left hand stick control of the RCS were consistent with an ADI mode display rather than the PAI mode. Thus, it has been claimed that he forgot that he was in the PAI mode and misinterpreted the display. However, at the moment he switched control, he was performing the precision attitude-tracking task (Figure 9) and he continued to try to complete that task after he switched hands. It is hard to believe that Major Adams would have forgotten he was in the PAI mode while he was in the process of performing the very maneuver for which the PAI mode was specifically designed.

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[6] The first time the AIB report mentions this switching to the IFDS in the report was when it occurred at 230,000 ft. but this was during the performance of the computed α/β-check maneuver and may have been part of that experiment.

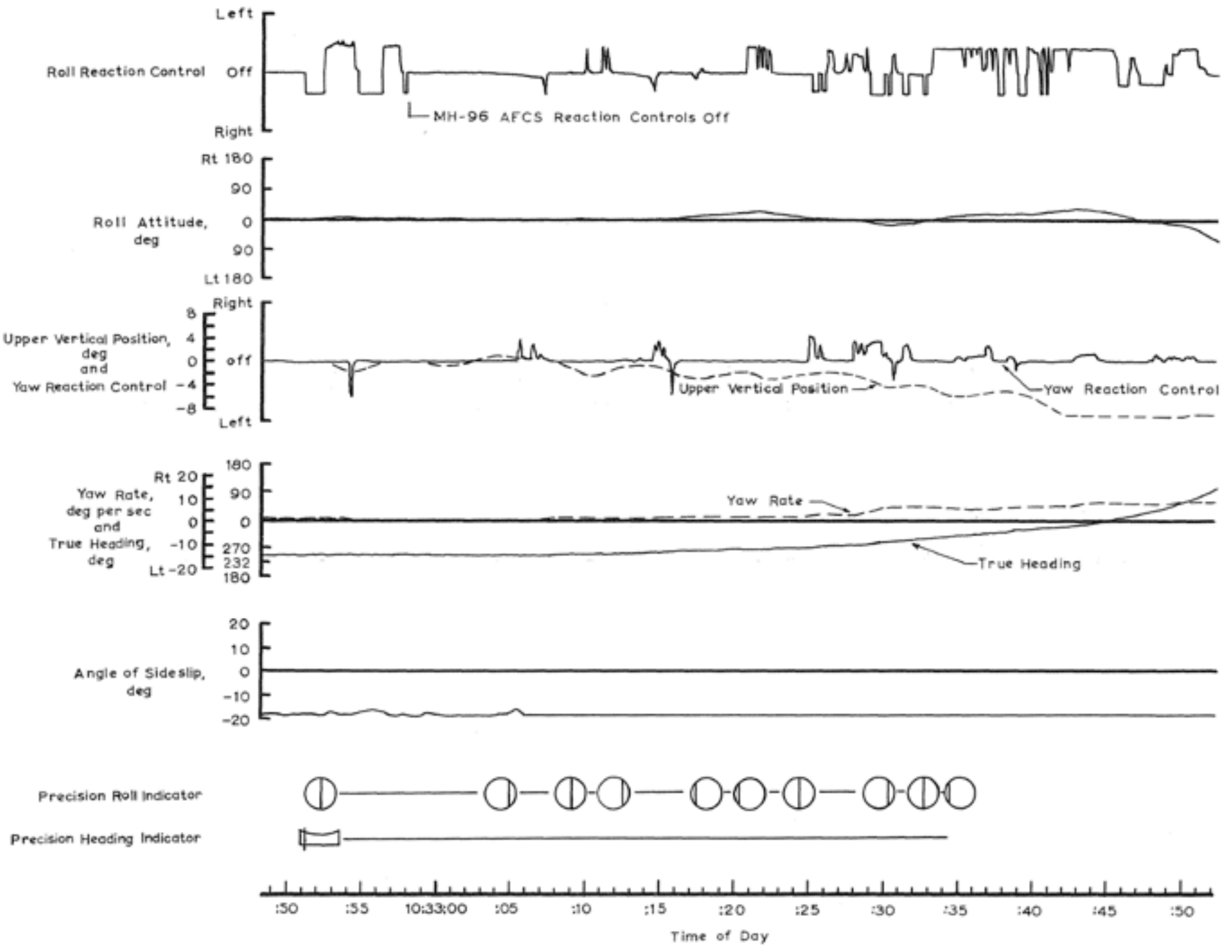

Figure 9. Time history of precision attitude tracking task at peak altitude (Figure 13 in AIB report).

– The evidence indicates that Major Adams did not disengage the MH-96 AFCS as he was supposed to when he switched to the left side stick control. This was a very important failure because the subsequent instability would have been avoided if Major Adams had remembered to disengage the AFCS when he switched to direct manual control and recovery from the dive might have been possible.[7]

Major Adams's apparently impaired performance at this point might be explained by the high stress and workload at the moment that he switched controls. By the time Major Adams realized that he had no control using the right side stick and changed to direct manual control of the RCS through the left side stick, he also must have recognized that the aircraft had attained large angles and angular velocities in pitch, roll, and yaw (Figure 4), the computer and instrument malfunction lights were still on, and that the displayed information was suspect. Major Adams suddenly found himself trying to cope with recovering from having had an uncontrolled aircraft and questionable information just as he was starting into the critical descent phase while he

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[7] The disengagement was part of the pre-flight captive carry checkout procedure but it doesn't appear on the radio transcript and may have been skipped to save time. It might have been more fresh in Major Adams' mind if it had not been skipped.

was still trying to complete the precision-attitude tracking task. The aircraft was at an altitude at which the aerodynamic controls were still ineffective and the AFCS was still behaving erratically and sending signals that intermittently activated the RCS in opposition to the inputs from the pilot. Also, just a few seconds after switching to manual control the pitch and roll dampers disengaged once again. Coping with these multiple problems could very well have demanded all of Major Adams' attention possibly causing him to overlook actions he had taken (such as switching the ADI mode to PAI) or should have taken (such as disengaging the AFCS).

– A speculation has been that Major Adams' susceptibility to Type II Spatial Disorientation (SD)—that the AIB report refers to as *"vertigo"*—was a **contributing factor** in the scenario of this accident. However, there was no evidence that SD affected Major Adams' performance during the boost phase or in his preparations for and performance of both the wing-rock and the computed α/β-check maneuvers. Nor was there evidence that he was misinterpreting the PAI during the performance of these two experiments.

However, at the moment that the pilot switched to direct manual control he had just come *"over the top"* at about 266,000 ft. and had been in a zero-g condition since the end of the engine burn. Under these circumstances, Major Adams' susceptibility to SD may have contributed to his forgetting to switch off the AFCS, especially as it seems he was still focused on completing the precision attitude-tracking task. As the AIB report [1] states: *"Vertigo* [SD] *could have coupled with the added workload of sorting the various malfunctions"* (pg. 36) and perhaps caused his lack of recognition of the yaw attitude if he did, in fact, misinterpret the ADI in its PAI mode during his subsequent actions.

Most of Major Adams' experience in this aircraft had been with a normal ADI (i.e., with the vertical needle indicating yaw) whenever he had used the left side stick for the RCS.[8] When he switched to manual control he was under stress and high workload, and it is a common human tendency under such conditions to revert to the basics in which one is most highly trained. Thus, Major Adams may have mentally reverted to the normal mode of the ADI when he switched to manual control.

It is also possible that, at that moment, Major Adams was confused as to what to believe in the displays. Pilots are trained that the only way to overcome SD is to fly basic instruments and disregard the attitudes suspected by their physical senses. Major Adams had been taught that the ball-nose did not provide reliable information at dynamic pressures less than about 50 psf. He knew he had switched to the IFDS computer for the source of data to his displays when the panel display light indicated that he should do so and he knew that the IFDS computer- and instrument-malfunction lights were on. However, the assurances from ground control that all was OK and the instructions to perform experiments that relied on the IFDS computed data would have contributed to the confusion.

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[8] Moreover, even the simulator on which he trained for this mission only had a wooden mockup of the PAI mode of the ADI.

The AIB report [1] states: "*The pilot seemed unaware of a gross heading deviation in spite of three separate correctly reading instruments... . He apparently was concentrating on a single instrument, the vertical needle of the ADI, as a pilot might do if he were trying to overcome vertigo* [SD]*"* (pg. 37). When some instruments are displaying erroneous information it may be hard to tell which instruments are correct and which are not. When the pilot is focused on a specific instrument for the sake of the particular maneuver that is to be performed, other instruments receive lower priority. And when ground control continuously assures you that you are *"on heading"* there may be little need to pay particular attention to heading. Furthermore, tunneled attention and disregard for other displays (including audible alarms) are well-known tendencies of humans under high stress and workload regardless of SD. [7]

4.0 Conclusions

The following conclusions have been drawn from this human-factors analysis:

1. The accident was precipitated at 10:31:07 when the electrical disturbance from the arcing motor of the traversing probe experiment caused the gain control in the MH-96 AFCS to malfunction so that control inputs from neither the pilot nor the AFCS were delivered consistently to the RCS. Consequently, control through the automated RCS was intermittent from that time on and intermittent control could have been worse than total failure. It is highly challenging to maintain precise control with an on-off system like the RCS even when it operates normally. It becomes much more difficult to maintain control through an on-off system when access to that control is intermittent. Furthermore, intermittent operation can delude the pilot into thinking an on-off system is operating properly. Given the latent factors, the lack of environmental testing, the attitude of the operators, the lack of telemetered data, and the design choices, the flight assumed numerous unnecessary risks above and beyond the risks inherent in such flight-testing. Adding to that, the proximate factor of the failure to inform the pilot of problems and to abort the mission made the accident happen.

2. Despite any possible indications aboard the aircraft of the problems that started with the first electrical arcing at 10:31:07, the pilot did not acknowledge failure of the RCS and revert to manual control until 10:33:05. At this time, the aircraft has been in an uncontrolled and uncontrollable state for almost 2 minutes, which was not apparent to the pilot. The AIB report [1] states it would have been highly unlikely that the pilot would have been able to recognize the failures because of their intermittency and because of the little need for precise attitude control during most of this time. Furthermore, the continuous encouragement from ground control assuring him that he was *"on track"* and *"on heading"* and should continue with his maneuvers could have easily masked any concerns Major Adams might have had.

3. The pilot had no reliable control after 10:31:07 with which to correct any errors of which he may have been aware. Moreover, it is possible that he was uncertain about the reliability of his displays as he had switched from the 'ball nose' to the IFDS computer for the source of certain data on aircraft state and he knew that the IFDS computer had failed.

4. Had ground control aborted the mission when they had clear indications of malfunctions the flight would have very likely been recoverable. The entire system (in the air and on the ground) obfuscated the possibility of the pilot's recognizing the problems on his aircraft until he found he

was unable to perform the precision attitude-tracking task and switched to manual control. The failure of ground control to advise the pilot of the possibility of problems as soon as they saw that all of the telemetered traces suddenly became noisy and unreliable, or when it was observed that the servos were not acting properly, are indications of some complacency on the part of ground personnel and an inappropriate dependency on the pilot—perhaps as a result of having had 190 successful flights of the X-15.

5. By the time Major Adams realized that he had no control using the right side stick and changed to direct manual control of the RCS through the left side stick, the aircraft had attained large angles and angular velocities in pitch, roll, and yaw, the computer and instrument malfunction lights were still on, the displayed information was suspect; within seconds, the pitch and roll dampers disengaged, and he was still trying to complete the precision attitude-tracking task. Moreover, at this moment the aircraft had just come 'over the top' at about 266,000 ft. just before beginning the free fall in the descent phase. Under these circumstances, Major Adams' susceptibility to Spatial Disorientation may have coupled with his high stress and workload in sorting out the various malfunctions and he failed, or was unable to, recover control to prevent entry into a spin.

6. Had Major Adams disengaged the MH-96 AFCS as he should have when he switched to manual control, the pitch instability, limit-cycle oscillations of the controls would not have occurred and he might have been able to recover from the dive and effect a safe landing.

7. The destruction of the X-15-3 was due to the extreme structural loads produced by the high frequency limit-cycle oscillations of the control surfaces induced by the AFCS. However, this behavior was inevitable due to the design of the MH-96 once the aircraft entered into a spin.

8. There are too many unanswerable questions to blithely place the blame on Major Adams' known susceptibility to Spatial Disorientation. In fact, the pilot maintained proper control of the aircraft from launch up to and through the wing-rock maneuver and the computed α/β-check maneuver. Spatial Disorientation was not evident in any degradation of his cognitive or motor-skill performance during that time. The focus of his attention on performing the precise roll maneuver using an intermittent RCS may well have distracted him from noticing any indication of the yaw angle he acquired during the boost phase. There is no doubt that multiple malfunctions can indeed be distracting.

5.0 Recommendations

This review of the human factors of the events leading up to the destruction of the X-15-3 in Flight 3-65 indicated several recommendations for consideration in future similar operations. Many of the following recommendations have been recognized and implemented as a result of experience gained in the 47 years since Flight 3-65.

1. All experiments and other equipment must be environmentally checked before being placed aboard any aircraft or space vehicle.

2. The primary responsibility of ground-control personnel (especially the Flight Controller) must be the safety of the test pilot and the vehicle.

3. Ground control must have access to all of the information on the aircraft-systems status needed to perform their primary responsibility of maintaining safety of operation.

4. Automation must be designed to provide for effective dynamic cooperation between the human and the non-human agents responsible for operating any complex system. Even though a great deal has been learned since 1967 in flying automated flight control systems in military and commercial aircraft, the continuing failure to design for human-machine *cooperation* continues to be a causal factor of incidents and accidents.

5. An experimental flight control system should have a fail-safe logic that disengages it and takes it off line as soon as it malfunctions, together with a salient indication of its malfunction.

6. A stability augmentation system must never be the cause of instability even under extreme flight conditions.

7. An automated system, the failure of which would compromise the safety and/or the operability of the aircraft, must not rely on a single source of aircraft or of environmental data for computation of its automated actions.

8. When an action taken by the pilot always requires another action, the follow-on action should be considered for automation. For example, the MH-96 Pilot's Manual states that when the pilot switches from the right side stick to the left side stick for access to the RCS, he must turn off the MH-96. This second step should have been automated.

9. Any piece of equipment that interacts with aircraft control should be considered critical and therefore have clear indicators of malfunction, redundancies, easy off switch, and extensive testing.

10. A limitation on the authority of the stability augmentation system should never limit the pilot's authority for control as it did in the MH-96 design. A failure of the stability-augmentation system should not limit or interfere with the pilot's ability to control the aircraft, although his workload may increase. If the stability augmentation system is required for controlled flight, it must be designed to satisfy appropriate requirements for redundancy and human rating.

11. A failure of the flight control system must be made evident to the pilot immediately and must not

interfere with his manual and direct control of the aircraft.

12. The pilot's interface with the FCS must be simple and immediately understandable to maximize performance even under high stress and workload.

13. Each display of critical aircraft data should have reliable automated recognition of malfunction and backup modes.

14. Using a critical display in two different configurations without a clear and salient mode indication is conducive to mode confusion, especially when the pilot is under stress and high workload. The indicator of the mode should be on the display not on the mode activation switch. In the case of the X-15-3, the entire ADI should have been clearly marked for each of the modes in which that display was used.

15. Susceptibility to Spatial Disorientation (SD) need not be the cause for disqualifying a candidate pilot. After several decades of humans in space, a great deal more is understood about dealing with SD than was known in 1967 when the X-15-3 AIB made its recommendation to avoid selecting pilots who demonstrate "labyrinth sensitivity" (pg. 75).

6.0 References

[1] NASA-USAF Accident Investigation Board. 1968. Investigation of the Crash of the X-15-3 Aircraft on November 15, 1967. NASA Flight Research Center, Edwards, California, January 1968.

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[7] Bilalić, Merim and McLeod, Peter. 2014. Why Good Thoughts Block Better Ones *Scientific American* vol 310, issue 3, March 2014.

[8] Dennehy, C. J., Orr, J. S., Barshi, I., & Statler, I. C. (2014). A comprehensive analysis of the X-15 Flight 3-65 accident. NASA TM-2014-218538.

Appendix A

Fight 3-65-97 Sequence of Events

(Attachment K of the AIB Report)

The radio transcriptions in the table below are identified as "NASA 1" for transmissions from ground control (i.e., the Flight Controller) and are identified as "Mike" for those from the pilot. Key events and transmissions are indicated by a bold face time entry, and in some cases – bold text.

TIME (PST)	EVENT
10:30:	
07.4	Launch
08.0	17.5° Rt. Roll-Off
08.5	Cham. Press. starts to rise
08.6	ß = 2.4° Nose Lt. (Angle of Sideslip)
09.0	Longitudinal Acceleration shows engine light
09.4	Computed $\alpha = 6^{o}$ (Computed Angle of Attack)
09.6	$\alpha = 15.3°$ (Angle of Attack) α average = 11° during rotation
10.0	Cham. Press. reaches maximum
11.4	Longitudinal Acceleration reaches value for l00% Thrust
12.0	NASA 1: Good light here, Mike.
14.0	NASA 1: Check Alpha, heading.
14.7	Inertial Velocity = 1000 fps
20.1	.4 sec. Boost Guidance dropout to zero null (can't distinguish on cockpit film)
21.0	NASA 1: Right on track, Mike, coming up on profile.
27.1	Inertial Velocity = 1500 fps
29.0	Radar Altitude ~ 50,000 ft.
30.5	NASA 1: Standby for Theta
33.0	NASA 1: How do you read, Mike?
34.1	Inertial Altitude = 50,000 ft.
34.7	Pitch Attitude = 37.3° Pitch Attitude average ~ 37.3° during climb-out

36.3	Normal Acceleration = 2.2g (Max during rotation)
38.3	NASA 1: Check Boost Guidance null, Mike. How do you read?
42.0	Inertial Velocity = 2000 fps
42.5	Radar Altitude = 60,000ft.
44.4	Inertial Altitude = 60,000ft.
45.3	NASA 1: OK Mike, we have you right on track, on the profile.
51.1	Radar Altitude = 70,000 ft.
52.4	Inertial Altitude = 70,000 ft. Velocity = 2500 fps
52.7	Mike: Roger
53·7	.7 sec. Boost Guidance dropout to zero (can't distinguish on cockpit film)
54.9	Yaw gain at max. for 11.9 sec.
56.0	NASA 1: OK
57·9	Radar Altitude = 80,000 ft.
58.2	Auto BCS (Ballistic Control System[9]) on
59·3	Inertial Altitude = 80,000 ft.
10:31:	
00.2	Roll gain at max. for 6.6 sec.
01.0	NASA 1: Standby for 83,000 ft., Mike.
01.8	Inertial Velocity = 3000 fps
04.5	Radar Altitude = 90,000 ft.
04.7	Pitch gain at max. for 2.1 sec.
05.6	Inertial Altitude = 90,000 ft.
06.8	±.25g Oscillation in normal Acceleration, blip in vertical and L/H horizontal stabilizer servos
07.0	Auto BCS off (control progressively gets worse from this point on)
08.2	Noise begins in all telemetered data channels
08.3	Traversing probe slows down frequency of Oscillation
09.4	Inertial Velocity = 3500 fps

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[9] BCS for Ballistic Control System is used in the AIB report interchangeably with RCS, Reaction Control System.

10.0	Radar Altitude = 100,000 ft. NASA 1: Do you read us at all, Mike?
11.1	Inertial Altitude = 100,000 ft.
13.0	NASA 1: OK, right on track.
15.0	Radar Altitude = 110,000 ft.
15.6	Inertial Altitude= 110,000 ft., Velocity= 4000 fps
16.0	NASA 1: Coming up on 110,000 ft.
17.7	α= 8.3° Computed $\alpha \sim 5^{o}$ (start of pre-shutdown pitch Oscillation)
20.0	Radar Altitude = 120,000 ft.
20.5	Inertial Altitude = 120,000 ft.
21.0	NASA 1: On profile, on heading.
22.6	Inertial Velocity = 4500 fps
23.3	α = 5.4° computed $\alpha \sim$ 3.6°
24.0	Radar Altitude = 130,000 ft.
24.6	Inertial Altitude = 130,000 ft. p 4.7°
25.0	NASA 1: Standby for shutdown.
25.9	Pitch gain at min. for 12.8 sec.
26.8	α = 11.5° computed α = 5.8° Pitch Attitude = 42.6°, p = 1.8° Nose Lt.
28.0.	**Computer and Instrument lights on**. Inertial Velocity= 5000 fps Radar Altitude = 140,000 ft.
28.5	Precision heading off scale (Nose Left)
29.1	Inertial Altitude = 140,000 ft. α = 5.9° Computed α = 3.6°
29.8	Boost Guidance dropped out and stayed at zero
29.9	Cham. Press. begins to decrease
30.0	Roll Attitude = +9.5°
30.3	ß max. at 4.6° Nose Lt. (thrust misalignment)
31.0.	Long. Acceleration indicates start of shutdown.
31.6	Cham. Press. at minimum.
32.0	Radar Altitude = 150,000 ft. (Inertial Altitude Rate = peak positive)
32.3	α = 16.5° Computed α = 7.5° Pitch Attitude $\sim 45.7^{o}$
32.8	Long. Acceleration indicates shutdown complete

33.0	Precision Attitude indication on, Inertial Velocity = 5200 fps (for 23.5 sec.) Roll Attitude= -6.5°
33.7	Inertial Altitude = 150,000 ft., ß & Precision Heading = 0
34.0	NASA 1: PAI; Mike.
35.2 ·	Normal Acceleration reaches 0g. ·
35.8	**Hand punches computer light (stays "ON")**
36.0	First of 61 noticeable computer dumps
37.0	Roll Attitude = +11° (first of 3 complete wing rock maneuvers)
38.3	α = .2° (stays around 0.5° for~ 50 sec.)
38.5	NASA 1: Alpha to zero. Precision Heading off scale (Nose Rt.)
40.0	Radar Altitude = 170,000 ft.
41.5	NASA 1: Rock your wings and extend your experiment, Mike.
42.2	ß max = -4.8° Nose Rt.
44.5	Radar Altitude = 180,000 ft.
45.4	Roll Attitude = -20°
45.5	ß and Precision Heading = 0°
46.5	First flash of computed α light
48.0	JPL experiment opens
48.2	Micrometeorite experiment opens. Radar Altitude = 187,200 ft.
50.2	Roll Attitude = +17.5°
50.5	NASA 1: On heading, on profile; have you going a little bit high; that's all right.
52.0	Roll gain max. for 10.5 sec.
53.8	Radar Altitude = 200,000 ft.
55.6	Precision Heading off scale (Nose Lt.)
56.5	Inertial Velocity starts down from 5200 fps.
56.8	Inertial Altitude = 160,000 ft.
58.5	Mike: OK, I 'm reading you now. **I've got a computer and instrument light.**
58.9	Servos hard over; Rt. roll. Radar Altitude = 210,000 ft.
59·5	Roll Attitude = -11°
10:32:	

01.3	ß max = +6.3° Nose Lt. Traversing probe slowed more.
02.0	Pitch gain at max. for 10.6 sec.
03.2	NASA 1: OK, Mike.
03.4	Inertial Altitude = 170,000 ft.
04.3	Radar Altitude = 220,000 ft.
04.4	Servos hard over; Pitch up
04.6	Micrometeorite cycled to 2nd collector face
06.9	Inertial Velocity = 5000 fps
07.7	Yaw Rate= +.6°/sec.
08.0	"We'll go ahead and try computed alpha at 230, Mike"
08.4.	Inertial Altitude = 180, 000 ft.
08.8	Auto on (2nd time on for 4. 3 sec.) (Fired once Lt. Roll; once Rt. Roll; once Lt. Yaw; once Rt. Yaw)
09.5	Roll gain at max. for 15.7 sec.
09.7	Left 2.1 sec. Yaw input; ß went from -3.2° to 0°
10.0	Heading change = 0° for last time
10.6	Roll Attitude = +28°
11.0	Radar Altitude = 230,000 ft.
13.1	ß and Precision Heading= 0°. Inertial Altitude= 190,000 ft. **Auto BCS off (2nd time)**
14.0	ß = +1.5, begins Oscillation; drift to Off-scale (Nose Rt.) in 33.4 sec.
14.4	Servos hard over; Rt. roll
14.5	NASA 1: Check your computed α now.
15.6	Hand poised at computed α light (switch)
18.2	Radar Altitude = 220,000 ft.
19.5	NASA 1: Right on the track, Mike.
20.0	Roll Attitude = -8° **(end of intentional wing rocks)** Heading change = +2°
20.4	Inertial Altitude = 200,000 ft.
21.6	Pitch gain at max. for 3.6 sec.
22.4	Servos hard over; Pitch down
22.7	Computed α light & switch "ON"

23.4	Precision Heading off-scale Nose Rt. (First noticeable heading drift on Ball)
25.3	Servos hard over; Lt. roll, Pitch & Roll Dampers disengage (Horizontal stabilizer trim~ -6°)
25.5	Pitch Attitude = +25°
26.2	ß Off-scale Nose Rt. (cockpit)
26.3	Damper disengage light seen for first time
27.0	Radar Altitude = 250,000 ft.
27.2	Pitch & Roll Dampers at min. for 4.8 sec.
28.3	α = 20.5°
28.5	**Mike: I lost my Pitch & Roll Dampers**
29.3	Inertial Altitude = 210,000 ft.
29.7	Damper off light seen; last frame
30.0	Heading Change = +7° (239° true heading)
30.2	NASA 1: OK Mike, let's try and get 'em on.
30.5	Pitch & Roll Dampers reset
33.3	Mike: They reset
34.0	NASA 1: Did they reset?
34.6	Inertial Altitude =220,000 ft.
35.8	Mike: "Yep".
37.8	NASA 1: I'll give peak altitude, Mike.
39·5	Radar Altitude : 260,000 ft.
40.0	Heading change =+12° (244°)
42.3	Servos hard over; Pitch up
42.7	Inertial Altitude = 230,000 ft.
42.8	Roll gain at max, for 5.2 sec.
43.5	NASA 1: Have you coming over the top; you're looking real good; right on the heading, Mike.
43.6	Pitch gain at max. for 13.4 sec.
47.1	Auto BCS on (3rd. time on for 10.6 sec.) (Fired: twice Lt. roll; once Lt. Yaw; Pitch Up, Down, Up, Down, Up)
47.4	ß On scale for 5.8 sec. (ß= -19.5°)
50.0	Heading change = +15° (247°) Inertial Altitude = 240,000 ft.

51.2	NASA 1: Over the top at about 261, Mike~
52.0	JPL off sun
52.3	α = -8.8°
53~7	Servos hard over; Lt. roll
54.4	α = 19.4º
54.8	ß on scale for 1.9 sec.(= l8.5°)
55.0	Yaw rate at zero for 10.6 sec.
55.1	NASA 1: Check your attitudes.
55.6	α = 12.5°
57.5	α = 33.5°
57.7	Auto BCS Off (3rd time)
58.0	JPL on sun
10:33:	
00.0	Peak radar altitude= 266,000 ft. Heading Change =+15° (247°)
00.6	Inertial Altitude = 250,000 ft.
00.8	Inertial Velocity= 4500 fps (for 62.4 sec.)
01.4	NASA 1: You're a little bit hot but your heading is going in the right direction Mike; real good.
03.3	Servos hard over; Rt. roll. α = 15.0°
03.6	Pitch and Roll at max. gain for 13.4 sec.
05.4	Three Rt. Yaw BCS inputs; **Left hand stick (first inputs).** Roll Attitude = -4.5°
05.6	Yaw rate leaves zero (last time at zero)
06.0	JPL off sun
07~2	NASA 1: Check your attitudes. Yaw Rate= +1.0°/sec.
07.7	α = 19.1"
10.0	Lt. Roll BCS input. Heading Change = +18° (250°)
10.5	NASA l: How do you read, Mike?
10.6	Servos hard over; Left roll
11.0	Two left roll BCS inputs
13.3	Yaw Rate= +.8°/sec

14.0	Roll Attitude = -.5°
14.4	NASA 1: OK, lets check your dampers, Mike.
14.5	Rt., Lt Yaw BCS inputs (Roll Attitude going positive at~ 3.5°/sec.)
14.6	Yaw Rate goes from +.8 to +1.4 to +1.2°/sec.
14.8	α = 13.2°
15.7	Yaw Rate= +2.3°/sec
16.1	Yaw Rate = +1.6°/sec for 7.3 sec.
16.9	1° Nose-Up Pitch Trim Command
17.0	Mike: They're still on. **Pitch and Roll Dampers disengage for 3.6 sec** (pilot check?)
18.4.	NASA 1: OK Inertial Altitude = 260,000 ft. (One damper light flash on cockpit film).
18.8	Pitch & Roll at min. gain for 1.8 sec.
20.0	Heading Change = +28 o (260°). Traversing probe returned to normal speed.
20.6	1.7 sec. Lt. Roll BCS input
20.7	Roll Attitude = +25.0°
21.4	Three Pitch Up BCS inputs
22.8	1.7 sec. Lt. Roll BCS input
23.5	Pitch Attitude= -12.0°. Inertial Altitude= 260,000 ft. (stays at max. alt. for 31.5 sec.)
23.7	α Off scale positive for 1.1 sec.
24.6	One Pitch up BCS pulse
24.9	Two Rt. Yaw BCS inputs. Roll Attitude =+5° (going negative at ~4.5°/sec
25.0	Yaw Rate= +1.2°/sec. NASA 1: Little bit high Mike but real good shape.
25.8	Yaw Rate= +2.5°/sec for 2.1 sec.
26.0	Four Lt. Roll BCS inputs
27.9	Rt., Lt., Rt. Yaw BCS inputs (Roll Attitude continuing negative)
28.3	α = 21.9°
29.3	Computed α = +.4°
29.4·	One Pitch Up BCS pulse
30.0	Heading Change= +53° (285°). Roll Attitude= -14° a = 26. T') Yaw Rate = +5 .6°
30.4	One Lt. Roll BCS input

31.2	α = 24.3° Radar Altitude = 250,000 ft.
32.0	3.2 sec. Nose Down BCS input
32.4	NASA 1: We've got you coming down hill now, your dampers still on?
33.1	12.5 seconds of almost full left roll BCS inputs.
33.2	Pitch Attitude = +4.6°
33.7	α off scale (positive) for 62.5 seconds.
33·9	Hard over servos; Lt. Roll
34.8	2.4 sec. small Rt. Yaw BCS input (Roll Attitude~ +15°)
34. 9	Yaw Rate= +4.4°/sec.
35.4	Nose Down Pitch BCS pulse
35.6	Roll Attitude = +l7.5o
35·9	Roll at max. gain for 5.3 sec.
36.7	Nose Down Pitch BCS pulse. Pitch at max. gain for 78.7 sec.
37.2	Yaw Rate= +5.6°/sec. for 4.2 sec.
37.8	Nose Down Pitch BCS pulse
38.2	Rt., Lt. Yaw BCS pulse. Roll Attitude = +20° Heading Change = +90° (322°)
39.4	**Mike: Yea, seems squirrelly.**
40.0	Radar Altitude = 240,000 ft; Heading Change = +100° (332°) Four Nose Up BCS pulses. Normal acceleration slowly begins to oscillate to "l g”
41.7	Hard over servos; Lt. Roll
41.8	Rudder hard over; airplane nose left
42.6	One Rt. Yaw BCS pulse (Roll Attitude = +28°)
43.0	Roll Attitude = +28°
43.6	Roll at max. gain for 46.4 seconds.
44.2	3.6 sec. Pitch Up BCS pulse
44.3	NASA 1: OK, have you coming back through 230, Ball Nose Mike.
44.6	Yaw Rate = 7.4° /sec
45.6	Inertial Altitude Rate = 0 fps
46.4	One Lt. Roll BCS input
47.1	Radar Altitude = 230,000 ft.

l.7. 6	Pitch Trim Command from ~ 0 to 5° Nose Up
47.9	One Rt. Yaw BCS pulse
48.0	Yaw Rate = +6.9°/sec
48.6	Two Up, Down, Up Pitch BCS pulses
48.7	One Lt. Roll BCS pulse
49.1	Hard over servos; Lt. Roll
49.2	2.4 sec. Lt. Roll BCS inputs
49.6	Heading Change= +180° (52°) (cockpit film shows Precision Heading changed sign)
50.0	Heading Change = +200° (72°). Computed α=> 40°.
50.8	Pitch Attitude = -56.7°
51.0	Yaw Rate= +8.6°/sec. NASA 1: Let's watch your alpha Mike; let's not keep it as high as normal with this damper problem.
51.2	Traversing probe stopped
52.8	Noise stopped on Telemetered Data channels
53.2	Yaw Rate= +7.2°/sec
53.3	Hard over servos; Nose Up. Radar Altitude = 220,000 ft.
54.1	Heading Change = +270° (142°)
54.9	Roll Attitude = -90°
56.0	ß on scale for 2.9 seconds (-13.5°)
57.1	One Pitch Up BCS pulse
58.1	6.1 seconds Rt. Yaw BCS pulses. NASA 1: Have you at 210, alpha beta and check your alpha Mike.
58.8	One Pitch UP BCS pulse
59.0	Radar Altitude = 210,000 ft.
59.2	Computed a = 13.5°
59·5	Yaw Rate off scale (positive) for 35.5 seconds (> 20°/sec)
59·9	Heading Change= +360° or 0°j once around (232°)
10:34:	
00.0	Heading Change = +3° (235°)
01.0	Pitch Attitude = +34.3°
01.5	**Mike: I'm in a spin Pete.**

02.4	1.9 sec. Lt. Roll BCS pulse
03.2	NASA 1: Let's get your experiments in and the camera on.
04.1	ß on scale for 2.5 seconds (+.2°)
04.5	Radar Altitude = 200,000 ft. Roll Attitude = +65°
04.9	Computed α = 38.2°
05.6	Heading Change = +101° (starts left)
06.3	Roll Attitude = +57^{o}
06.4	Large left yaw BCS input
06.6	Lt. Roll BCS pulse
07.2	Servos hard over; Nose Up. Pitch Attitude = -89°
08.0	Heading Change = -78° (starts right)
09.2	Radar Altitude = 190,000 ft. Servos hard over; Lt. Roll
09.8	Auto BCS on (last time) Fires: Pitch Up 26.8 sec. intermittent, Left Roll ·27.4 sec. constant, Left Yaw 27.3 sec. intermittent
11.4	Yaw gain at max. for 34.8 seconds
12.6	NASA 1: Now, let's watch your theta Mike. ß on scale for 1.0 second (-15.7°). Heading Change= 0° (232°), Pitch Attitude = +43°
14.2	Radar Altitude = 180,000 ft.
14.4	Computed α = 18.5°
16.2	Servos hard over; Lt. Roll
16.3	ß on scale for 0.7 second (-16.5°)
16.4	Roll Attitude through 360° to +61.2° (starts left)
16.6	**Mike: I'm in a spin.**
17.0	Heading Change = +90° (322°)
17.9	Pitch Attitude = -89°. NASA 1: Say again.
18.1	Heading Change= 180° (52°). Radar Altitude= 170,000 ft.
18.4	Computed α = 36.4^{o}
18.5	Heading Change = 270° (142°)
18.6	Roll Attitude = -90° (starts right)
18.7	ß on scale for 2.0 seconds (-7~2°)

19.1	**Mike: I'm in a spin (last positive transmission from Mike)**
20.5	NASA 1: Say again.
20.6	Servos hard over; Nose Up
22.2	ß on scale for 0.8 sec. (-15.8°)
22.6	Servos hard over; Lt. Roll. Radar Altitude = l60,000 ft.
23.1	Pitch Attitude = 21.3°
23.2	Heading Change = 360° or 0° (232°). 2nd full revolution
23.8	Computed α = 12.2°
24.2	Servos hard over; Lt. Roll, Roll Attitude = 0° (start of 2nd Full Lt. Roll)
25.2	Normal Acceleration reaches “l g"
26.8	Radar Altitude = 150,000 ft.
27.2	Heading Change = +72° (starts left)
27.4	Computed α = 31.6°
27.9	Pitch Attitude = -84°
28.2	NASA 1: OK, Mike you're coming through about 135 now.
28.8	Heading Change = -72° (starts right)
29.2	ß on scale for 0.4 second (=18.2°)
30.3	Radar Altitude = 140,000 ft.
31.2	ß comes on scale and begins an oscillation from ~ -20° to ~ +20° at loss of signal.
31.4	Normal Acceleration = 1.7g
31.6	Pitch Attitude = +11.4° (last time positive)
31.9	Heading change = ·0 ° (232^{o})
32.2	Computed α = 9. 7^{o}
32.3	Roll Attitude = 0° complete roll (2nd time)
34.0	Heading Change = +51° (starts left). Radar Altitude= 130,000 ft., NASA 1: Let's get it straightened out.
35.0	Computed α == 25.9°. Yaw Rate comes back on scale; oscillates towards positive side until it goes off scale at 10:34:56.8 (> 20°/ sec) converges for ~18 sec., then diverges for rest of data.
35.2	Pitch Attitude = -70° begins to oscillate converging toward~- 37^{o} at loss of signal.
36.4	Heading Change = -25° (207°) .. Horizontal stabilizer begins limit cycle.
37.2	Roll Attitude = +209° (starts left)

37.3	Long. Acceleration begins obvious deceleration from 0g to max. of -1.6g.
37.4	α back on scale (11. 2o)
37 6	Left Horizontal Stabilizer begins limit cycle
37.8	Heading Change = 0° (232°)
38.0	Radar Altitude = 120,000 ft.
38.7	Computed ß begins oscillation. Decrease from 22.6° to -3.0°
38.8	α = 33. 6o (oscillation ~ 20° for 6 sec.)
38.9	Normal Acceleration = 2.06g
39.0	Heading Change == +29° (261°) Oscillates from +20 to +30° for ~ 7 sec.
39.8	Mike (?): (KEYED MICROPHONE)
40.0	Normal Acceleration = .72g
4l.8	Radar Altitude = 110,000 ft .
42.4	NASA 1: OK, you got theta equal zero now.
42.7	Inertial Altitude Rate descent arrested
42.9	Normal Acceleration = 3.0lg
44.9	α off scale positive (> 40°)
45. 2	Pitch trim command from 5^o to 3.6°/sec. Nose Up
45.5	NASA 1: Let's get some angle of attack up.
45. 7	UV-l begins pressure build-up and oscillation
45.8	Heading Change = 0° (232°) Oscillates about zero for ~ 9 sec.
46.1	α = 0.1°· Roll gain to 0 for rest of data.·
46.4	Roll Attitude = 0°
47.0	α = 18.7^o
47.2	Auto BCS off' (last time) 6. 6 sec. Rt. Yaw BCS input
47.4	Roll Attitude = +27.4°
47.7	7.4 second Rt. Roll BCS (last roll BCS input)
48.1	Normal Acceleration = -l.0g, α = -0.3°
4.8. 2	One Pitch Up BCS pulse
49.0	Radar Altitude = 90,000 ft. Normal Acceleration = 2.75g, α = 13.5^o

50.4	One Pitch Down BCS pulse. Roll Attitude = -30°
50.8	α = 2.0° Normal Acceleration = 0g. Begins divergent oscillation
51.0	NASA l: Coming up to 80, 000 Mike.
51.4	α = 6. 0° • Normal Acceleration = 1. 3g
51.6	Roll Attitude = 0°
51.9	α = 1.2°
52.0	Normal Acceleration = -0.4g
52.6	Roll Attitude = -50°
52.8	One Pitch Down BCS pulse
52·9	Normal Acceleration = 4.7g
53.0	α = 14.5°
53.1	Last Upper Vertical Stabilizer CPT movement
53.3	Roll Attitude = -23°
53.4	Computed α = -1.3°
53.8	Normal Acceleration = -1.9g a = -2.5°
54.0	NASA 1: Let‘s get some α on it. JPL communicator changes signal.
54.2	One Pitch Down BCS pulse (last pitch BCS pulse)
54.3	Roll Attitude = -156°
54.4	Last cockpit film frame
54.6	Normal Acceleration off scale positive for .3 second (oscillates ±off scale for rest of data). Computed α = 20.0°
54.7	α = 32.3°. Flap position indicator transient & oscillation.
54.8	Heading Change = -32° (200°)
54.9	UV-1 goes off scale-on scale-off scale
55.0	2.6 sec. Rt. Yaw BCS pulse (last BCS pulse). Roll Attitude= -56°. Pitch gain to 0 for rest of data.
55.2	Computed α = 0.0~ Change in traversing probe signal. **Side-stick lateral force goes to zero.**
55·3	Pitch trim command from 3.6° Nose Up to 1.5° Nose Down. Micrometeorite cycled one face (3rd one) ?
55·4	α is off scale positive for . 6 second (> 40°)
55.5	Heading Change = +23° (255°)
55.6	Upper speed brake trace moves ~ 5° open

55·7	Roll Attitude = -166°
55.8	Lower speed brake trace moves ~ 4° open
56.0	Pitch and Roll servos lock-up
56.4	Roll Attitude = -88.6°
56.5	Heading Change= -29°. Computed α = 19.0°
56.6	α = 24.7°
57.0	Radar Altitude = 70,000 ft. Rudder servo lock-up. Roll Attitude = -159.1° (Rolling right)
57.2	Pitch gain at 0 for rest of data. α is off scale negative.
57 .6	Computed α = -4.5°
57.8	Roll Attitude= 0° (continuing right at~ 186°/sec)
57. 9	Heading Change = -17° (215°)
58.3	Computed α = 10.5°
58.7	Radar Altitude = 62,000 ft. (Velocity and dynamic pressure decreasing). Heading Change = +21° (253°). Computed α is off scale negative. Roll Attitude = +245^{o}
58.75	Loss of telemetry signal.