The X-43 Fin Actuation System Problem – Reliability in Shades of Gray

Curtis Peebles[*]

NASA Dryden Flight Research Center, Edwards, California, 93523-0273 USA

Following the loss of the first X-43 during launch, the mishap investigation board indicated the Fin Actuator System (FAS) needed to have a larger torque margin. To supply this added torque, a second actuator was added. The consequences of what seemed to be a simple modification would trouble the X-43 program. Because of the second actuator, a new computer board was required. This proved to be subject to electronic noise. This resulted in the actuator latch up in ground tests of the FAS for the second launch. Such a latch up would cause the Pegasus booster to fail, as the FAS was a single string system. The problem was corrected and the second flight was successful. The same modifications were added to the FAS for flight three. When the FAS underwent ground tests, it also latched up. The failure indicated that each computer board had a different tolerance to electronic noise. The problem with the FAS was corrected. Subsequently, another failure occurred, raising questions about the design, and the probability of failure for the X-43 Mach 10 flight. This was not simply a technical issue, but illuminated the difficulties facing both managers and engineers in assessing risk, design requirements, and probabilities in cutting edge aerospace projects

Nomenclature

CPLD = Complex Programmable Logic Devices

ECU = Electronic Control Unit

EMA = Electromechanical Actuator

FAS = Fin Actuation System

FET = Field Effect Transistors

HXLV = Hyper-X Launch Vehicle

IMU = Inertial Measurement Unit

MIB = Mishap Investigation Board

psf = Pounds per Square Foot

[*] Historian, P.O. Box. 273, MS 4839.

I. Introduction

Of the many challenges facing the engineers working on the Hyper-X project, the Fin Actuation System (FAS) problem could be considered the most frustrating. It had its roots in the selection of the modified Pegasus first stage as the Hyper-X Launch Vehicle (HXLV). The Hyper-X program was conducted under NASA Administrator Daniel S. Goldin's "faster, better, cheaper" philosophy. This approach was rooted in the use of existing technology to support low-cost/high-risk/short-term research endeavors. In this case, the goal was to demonstrate the operation in flight of an airframe-integrated scramjet engine.

The function of the HXLV was to get the X-43A research vehicle to planned flight test conditions for a scramjet-engine experiment. A single HXLV configuration had to be capable of accommodating planned separation speeds of Mach 7 and Mach 10 as well as dynamic pressures and flight path angles that differed from those of a standard Pegasus launch, and be compatible with the B-52B launch vehicle's weight limitations. This effort would be based on the existing Pegasus database derived through wind tunnel tests and control system models. The exception to this use of off-the-shelf systems would be for Hyper-X-specific elements such as separation.

II. The HXLV Guidance System

The HXLV guidance system was based on the closed-loop feedback design of the existing Pegasus hardware. The guidance system used a "single-string" design, meaning that there was no backup system for any of its elements. This was due to size, cost, and the difficulty of integrating two control systems, and meant that any failure would result in the loss of the HXLV and payload.

The inertial measurement unit (IMU) was a Litton LN-100LG GPS-Aided Inertial Navigation System. The IMU measured the accelerations, rates, velocities, and positions of the HXLV from activation and alignment before launch from the B-52B through X-43A separation. The IMU output is sent to the flight computer, a 68030-based computer with a pair of 68302-based communications boards. The flight computer took the IMU's pure inertial measurements and translated the output into path-steering commands for the control surfaces at the HXLV's aft end.[1]

The FAS had two elements. The first was the Electronic Control Unit (ECU), which included the signal conversion and power output boards that received steering commands from the flight computer. The ECU then converted the computer's commands into analog signals, which then were sent to the second element, an electromechanical actuator (EMA) that moved the fin. The EMA consisted of a permanent magnet motor, reduction gear train, position potentiometer, and metal housing. Each of the three control surfaces had an individual EMA actuator. A thermal battery supplied electrical power during the HXLV's ascent. The three EMA units were mounted in the aft skirt assembly, a two-part aluminum cylinder attached to the aft end of the ATK Orion 50S rocket motor.

As an EMA moved a fin, the potentiometer measured the change in its position and reported this back to the ECU, which filtered the sensed actuator position measurements. This "fin actuator position talkback" was sent by the ECU to the flight computer. Simultaneously, the IMU measured changes in the flight path caused by the fins' movements and generated new outputs for the flight computer.[2]

This back-and-forth transfer of data and commands introduced electronic delays into the control system. The IMU took a small amount of time to measure the vehicle's movements then compare these to the planned flight path, determine the differences, and generate the output for the flight computer. The flight computer also took time converting the IMU output into fin actuator commands, and sending those to the ECU. Additional time was required for the ECU to convert these into analog signals for the actuator. Similar delays occurred on the feedback half of the loop.

Beyond these electronic delays, there also were mechanical factors, called "compliance." It took time for the actuators to move the fins to the commanded position. The fins also operated in a highly dynamic environment; during the X-43A boost phase, the HXLV fins were subjected to a dynamic pressure approaching 1,000 pounds per square foot (psf). These aerodynamic forces would cause the fins to bend and the linkages to flex. The effects of such compliance had to be correctly modeled if the HXLV were to be stable in flight. Operating conditions for the HXLV were more demanding than those for more stable vehicles. In these vehicles compliance errors had the potential to "eat up" margins.[3]

Existing Pegasus compliance and structural models were used as the basis for adapting the first rocket stage to the new HXLV profile. The Pegasus was regarded as off-the-shelf equipment, and the Pegasus wind tunnel model

was one example of how such heritage data was utilized. There seemed no reason to build an entire new model of the rocket for use with the Hyper-X. The existing model was modified with the X-43A shape attached to the nose. The model had movable horizontal roll control fins adjustable in five-degree increments.

The model was tested first at a specific angle of attack with a zero-degree fin deflection, then with the fins at plus or minus five degrees, and finally at a plus-or-minus-ten-degree deflection. This was repeated for each angle-of-attack value, along with differing amounts of sideslip, to build the aerodynamic database. From this data, Hyper-X engineers could determine the booster's roll authority. For fin positions between the increments, engineers would interpolate by taking the measured roll authority and dividing by two to find the linear average.[4]

Another factor now entered the picture. To better qualify the scramjet design tools, NASA managers decided on a three-flight test series with the X-43A. The series would consist of two Mach 7 missions, to test the scramjet's ability to provide positive acceleration, and a single Mach 10 flight to test its maximum design cruise speed. The decision to make a pair of Mach 7 flights raised a significant problem. These Mach 7 flights had a problem with the burnout speed of the HXLV. A standard 40,000-foot altitude for launch from the B-52B would result in a Mach 10 burnout speed; some means of slowing the HXLV to a Mach 7 burnout speed would have to be developed.

The design team evaluated two approaches: a drop at about 21,000 feet at a lower Mach number, with additional ballast, versus an HXLV with a reduced propellant load at standard launch altitude and speed. Ultimately, program engineers decided that using the first launch of a booster with a significant propellant offload on the first flight of the X-43A vehicle added too much risk to an already risky operation. They opted instead for a low-altitude/low-speed launch of a ballasted HXLV.[5]

The major change introduced by the new launch altitude was the increase in dynamic pressure the HXLV would experience during ascent. A standard Pegasus had a dynamic pressure of about 300 psf at transonic speed. In contrast, the HXLV would experience a dynamic pressure of about 650 psf in the lower flight regime. This increase in dynamic pressure was due to higher air density at the lower launch altitude. And because of the lower-altitude launch conditions, the HXLV also would take longer to reach Mach 1 than would a standard Pegasus. Wind tunnel data indicated that the lower/slower/higher-dynamic-pressure launch profile of the HXLV could be successfully executed.[6]

III. Failure and Aftermath

The first X-43A launch was made June 2, 2001. The HXLV's rocket ignited 5.19 seconds after release from the B-52B. The HXLV began to accelerate, then pitched up into the ascent flight path at 8 seconds after launch. At 11.5 seconds after launch, the HXLV began a divergent roll oscillation. This 2.5 Hz-frequency roll oscillation continued to diverge for the next second and a half. The rudder's EMA then stalled and ceased responding to the flight computer commands. With the loss of rudder control at about 13 seconds after launch, the vehicle began to yaw, reaching a sideslip of more than 8 degrees. The resulting high aerodynamic forces caused a structural overload of the starboard elevon 13.5 seconds after launch. The elevon then broke off, followed by the other two fins. Following the loss of control, the range safety officer activated the flight termination system.

The X-43A Mishap Investigation Board (MIB) was convened on June 5, and worked for the next nine months. The board concluded that the failure was due to modeling inaccuracies in the FAS and aerodynamics, both Pegasus-heritage and HXLV-specific, as well as insufficient variations in the modeling of the parametric uncertainty analysis.[7]

A new HXLV wind tunnel model was built, with fins that could be moved in 2.5-degree increments (rather than in the five-degree increments of the original model). Wind tunnel tests at these fixed fin positions showed nonlinearities in the vehicle's rolling moment. This had *not* been predicted by the original five-degree-increment tests.

The MIB also identified errors in the compliance element of the actuator model. Post-mishap testing indicated that both the fins and the linkages were more flexible than the Pegasus heritage model had predicted. As a result, the fins' angle of attack was greater than predicted due to the aerodynamic loads. Not only had the rolling moment been under predicted, but the extra angle of attack contributed still more.

Had the control system detected this error, a correction for it could have been made. But the flexibility in the linkage had occurred in a part of the system where it could not be detected by the actuator position feedback potentiometer. As a result, the control system could not compensate for a compliance error it could not "see."

Another factor playing a minor role in the failure was the inherent delay in the control system. The HXLV control system was designed using the Pegasus model. As with other heritage elements, this proved inadequate for the HXLV application. The HXLV system delay was longer than predicted, resulting in a further worsening of the

situation since the booster rolled farther than expected because the system delay meant corrections could not be accomplished quickly enough. [8]

The lower and slower HXLV launch also figured into the loss. During earlier Pegasus launches, oscillations similar to those seen on the first X-43A launch had appeared but stopped after one or two cycles. The reason for this was that the Pegasus was launched at 40,000 feet and a speed of Mach 0.8, leaving only a brief interval before the booster reached Mach 1. Once it went supersonic, the center of pressure on the fins moved aft and the aerodynamic loads went down. The oscillations immediately ended. The HXLV, however, was launched at a speed of Mach 0.51, and spent more time at transonic speeds in denser air than would have been the case in a standard Pegasus launch. The oscillations continued, and the HXLV roll became divergent.[9]

The HXLV's rudder moved in an attempt to damp out the roll instability. Aerodynamic forces on the rudder were greater than the torque the EMA actuator could produce. The rudder was actually driven back by the aerodynamic pressure, resulting in a loss of control. Before the flight, data indicated that the fins could experience a gain from eight to ten decibels higher than predicted and the HXLV would remain stable. The MIB report indicated there was a gain margin of about -4 decibels. Even after the analysis was completed, about two decibels of gain still were unaccounted for or were missing for the entire system.

Project engineers believed that increasing the torque capability on the actuator system would provide a fix to increase the margin. Although they knew this would be difficult, what was looming larger in their minds was the even more problematic option of offloading HXLV propellant to allow a 40,000 foot/Mach 0.8 launch and Mach 7 burnout speed. The FAS modification seemed, by contrast, to be a simple fix. Paul Reukauf, the Dryden X-43A deputy project manager, said later, "...it turned out that [the FAS modification] was the fix that almost killed the program."[10]

IV. No Good Deed Goes Unpunished

Hyper-X engineers wanted a 50 percent torque margin, in the worst-case scenario, to ensure that the HXLV fins would not stall under unexpectedly high dynamic pressures. The contractor indicated that this could be accomplished by removing a brake on each EMA and replacing it with a second actuator motor in a torque-summing configuration. These modifications would increase the hinge torque from 1,850 foot-pounds to over 3,000 foot-pounds.

This required significant modification to the Pegasus ECU, which consisted of a signal conversion board, control board, pre-driver board, three powerboards (one for each fin), and motherboard. To handle the doubled current produced by two actuators, the powerboard and pre-driver board had to be redesigned. The new powerboards replaced the analog design of the original Pegasus with a digital system. The new ECU used complex programmable logic devices (CPLDs) to control the direction of the fin's movement. The CPLDs activated opposing pairs of field effect transistors (FET) mounted in an "H-Bridge" configuration. The opening of an FET pair would cause the motor to rotate in the desired direction, while the amount of current determined the extent of the fin's movement. To reverse the fin movement, the initial pair of FETs would be closed and the other pair activated.

The powerboard and pre-driver board for each ECU now were "Hyper-X specific" rather than Pegasus-heritage designs. The new design posed several challenges. The CPLDs were low-voltage logic devices, which control high electrical currents. All the hardware was collocated on a powerboard. In addition, the high-current switching could create electrical effects that might cause CPLD failure. But though engineers felt none of the dread at the prospect of the FAS redesign that they did over offloading HXLV propellant, those working on the project realized that the redesign would be difficult nonetheless.[11]

The first sign of a problem with the FAS modifications came in early October 2003. An ECU failed during a cold-soak test simulating temperatures at high altitudes. The failures occurred when the actuators were commanded to slew at a high rate. Instead, the CPLD ceased processing, which is known as a "latch up" condition. Should this occur in flight, the fins would stop moving, HXLV control would be lost, and the mission would fail.

The unit was returned to the vendor for analysis. The contractor attempted to reproduce the failures with the ECU instrumented for diagnostic data. Although several cold-temperature cycles were made, each time the channel controlling the fin operated normally.[12] Corpening recalled that, "as soon as you hooked up your diagnostic equipment, it wouldn't [latch up] anymore. So the problem was so subtle that as soon as you interfered in any way with the circuitry, it wouldn't [latch up]."[13]

Langley, Dryden, contractors, and subcontractors were the initial participants in the FAS investigation. By mid-November 2003, they were joined by engineers from the NASA Goddard and Marshall centers and the CPLD manufacturer. A fault tree provided a structure for their investigations. The prime contractor's reliability laboratory

examined the powerboard components, while a subcontractor checked the integrated circuits and programmable devices for low-temperature design issues. Monday, Wednesday, and Friday teleconferences were held to coordinate activities.[14]

Not until January of 2004 was the problem resolved. The latch-up was triggered by excessive electronic noise in the ECU powerboards during "current-limit states." These occurred when the maximum electrical current value was being sent to the field effect transistors. The CPLDs, which were the control devices for the FETs, were adversely affected by the noise. Once the noise reached a certain level, it would cause the CPLDs to latch up.

The failures could be reproduced in ground tests, even though the exact process through which the electronic noise caused the latch-up was not entirely clear. Engineers also concluded that this failure mode could occur at only two points during the planned flight profile. The first was soon after ignition, when the HXLV pitched up into the ascent path, putting the maximum stress on the FAS during the flight. The second was after the solid rocket burned out and X-43A separation had occurred. When the HXLV was at hypersonic speeds prior to separation, the fin movements were small and did not reach the current-limit state.

Two changes were made to solve the problem. The CPLD firmware was changed to eliminate programming that could not function properly across the required temperature range. Resistors also were added to the CPLD outputs, which controlled the FETs. These resistors minimized (but did not eliminate) the electronic noise in the output signals. Although the investigation was time-consuming and extremely thorough, the actual fixes were minor.

The FAS to be used on the second flight underwent pre-flight testing. This consisted of 200 five-degree command step inputs – during which the current-limit state was attained each time – at cold, ambient, and hot temperatures, for a total of 600 cycles. These tests created much greater stress on the FAS than would the planned flight profile. The FAS latch-ups occurred only under these stress-test conditions and never during a standard flight profile.

A final check would be performed before the launch. The fin sweep test was modified to put stress on the FAS, to replicate the conditions under which it latched up. The downlink telemetry also would give indications if the FAS were beginning to fail. If these indications appeared, the drop could be cancelled. Otherwise, the launch would proceed.[15]

Resolving the flight 2 FAS problem delayed the second launch by nearly six months. Ironically, the propellant offload that had caused such concern was a non-issue. Not until March 27, 2004, was the second flight made. The launch went without a hitch, and the HXLV flew the correct ascent profile with no FAS problems. Reaching the separation point, the X-43A successfully cleared the booster, ignited the scramjet, and was able to accelerate as planned. It achieved a top speed of Mach 6.83 at about 95,000 feet. Scramjet data indicated that the engine's operation was close to ground test predictions. This was the first free-flight data from a scramjet vehicle. After more than four decades of plans and disappointments, it was a monumental event.

V. The FAS Problem Revisited

With a successful flight completed and the data analyzed, program engineers turned their attention to the third, Mach 10 flight. They felt confident that this could be accomplished in a short time, largely because all believed that the FAS problem had been solved during preparations for the second flight.[16]

During low-temperature testing in early June of 2004, however, two ECU boards latched up. These failures occurred at significantly lower temperatures than those seen during previous flights. The recovery plan called for replacing the two failed boards with spares. To prevent the ECU from becoming too cold, a heater plate was added to maintain an ambient temperature during the second flight. This would be completed in mid-July, with the third launch still possible in September.[17]

The replacement FAS hardware was delivered to the subcontractor for qualification testing, but failed its initial room-temperature test on June 30. Two of the channels passed successfully but the third latched up. In contrast, the earlier problems had occurred during the low-temperature test phase. Clearly, the fix developed for the Mach 7 flight had not worked for the identical Mach 10 FAS hardware.[18]

As the investigation progressed, it became clear that the boards for the third flight were not identical to those of the previous FAS. Laurie Grindle, Dryden chief engineer for the third X-43A flight, observed, "...some of the components on the [flight 3] board were from a different lot than the other and this lot seems to be noisier than the other. And so the fixes we had in place that worked fine for flight 2 wouldn't stand up to the noise they were getting from flight 3. So we had to basically go right back to the drawing board with another design cycle."[19]

The solution was to add "more of the same fix" to eliminate the electronic noise in the CPLD output to the FETs. By the third week of July, the fix had been determined and the boards had successfully completed low-temperature testing. With the FAS problem apparently solved, the fix was accepted by government and contractor engineers.[20]

Then, on August 16, a powerboard undergoing acceptance testing suffered an altogether different type of malfunction High-current flow through the FETs caused the powerboard to burn up, leaving it severely damaged. The same NASA/industry team that had investigated the original failure was reassembled and reviewed the FAS design. As part of this effort, a fault tree was developed to assist with determining the root cause.

Despite an extensive analysis effort, failure simulations, and development testing, a root cause for the failure could not be conclusively determined. Several likely causes were proposed, and these became the basis for modifications. Analysis indicated that the electronic noise also would disrupt the CPLD's timing of the opening and closing of the field effect transistor pairs. This, in turn, controlled the movement of the fin. The switching of the two pairs of FETs had overlapped. Both went on, and the high current flow shorted them out, literally melting them.

To reduce the potential for this timing error the CPLD firmware was modified to increase deadband time between switching, providing additional margin. The gate resistance also was increased to reduce the time it took for the FETs to turn on. In addition, researchers decided to add a ground jumper wire to connect the ECU heat sink and the powerboard, to minimize ground noise. Changes to the test procedures were made to avoid damaging the systems while at the same time providing the necessary level of stress testing.[21]

This stage of analysis also revealed a thus-far overlooked problem. The flight 2 analysis showed that a latch-up would occur only when a current-limit state had been reached. The data now indicated that a failure could occur at any time after the FAS was activated. This vulnerability had been present during the second flight without engineers realizing it. As Reukauf later commented on the dilemma, "Well, since we didn't really fix the system for Mach 7, did we just get lucky at Mach 7, and can we take the risk for Mach 10 or can't we?"[22]

Reukauf's query about a Mach 10 flight's viability was decided in the affirmative. The X-43A project managers, the Flight Readiness Review Board, and the Airworthiness and Flight Safety Review Board all were convinced that the third X-43A flight was safe and could be successfully accomplished. On November 16, 2004, the launch was made. After all the work and debate, the boost went exactly as planned. The separation conditions were very close to those predicted. The top speed was Mach 9.6 at an altitude of 109,000 feet. The scramjet sustained cruise flight at the vehicle's maximum design speed.

VI. Reliability in Shades of Gray

The FAS problems highlight the difficulties in assessing risk in research aircraft programs. The Hyper-X program made use of existing systems, including the Pegasus booster and its associated flight models. To meet the demands of the X-43A mission profile, however, these existing systems had to be modified. And modifications inevitably mean some loss of certainty, if not increased risk. Yohan Lin, a NASA engineer at Dryden involved in the checkout of all three X-43A vehicles summed up the prospects. He noted, "Whenever you tweak a system that's already working...you're always asking for problems, because...the system is balanced and...you upset that balance...you introduce elements in there that were never there or intended, unknowns will come out, or new problems will arrive...."[23]

As a result, the heritage of the existing systems is lost. Program engineers, managers, and contractors can no longer rely on the reliability data for the production systems, as the products were now one-of-a-kind units. These systems may, as a result, have to undergo extensive development work, analysis, and checkout procedures. Such work must be allowed for in both the program's schedule and budget.

The problems experienced with the FAS serve as an example. The FAS used on the second and third flights was not the Pegasus FAS, but a redesigned system. That there would be difficulties with the redesigned FAS was understood. What had not been expected was how complex those difficulties would prove to be.[24] Hard-pressed to find a better explanation, Corpening dryly noted, "At one point I think we were having things go wrong so much that the only thing we could attribute it to was that at that time Mars was as close to the Earth as it had been in thousands of years. We figured it was the influence of Mars."[25]

Yet even after all the analysis was complete and the decision to proceed with a third flight had been made, the engineers were not 100 percent certain they knew what was causing the problems. The assurances that X-43A personnel could provide to the different review panels were not conclusive. The latch-up was due to the different sensitivities of lot variations among components. By careful selection of components, engineers were confident that the FAS would work in flight for the approximately 90 seconds required. Dryden X-43A project manager Joel Sitz later noted that though this had worked, it was not an elegant way to deal with the issue.

Engineers could replicate most of the failures under similar conditions in ground tests. Even if the reasons for the failure were not clear, they *did* know under what conditions the failure would occur. They also knew that the FAS had never failed under planned flight conditions; the failures had always occurred under the much-higher stress case conditions of the ground tests. A step input about 15 seconds after the HXLV ignition put the greatest stress on the FAS of the entire third flight. But even this did not reach the stress level of the tests.

The confidence that X-43A engineers had in prospects for the flights' success was based on this, even though they did not know the specific "why" of the problem. They could reproduce the failure conditions, *and* were able to show that the FAS would not experience these conditions during ascent *and* there was an adequate margin for uncertainties. The FAS for the second and third flights had been tested nearly a thousand times each under high-stress conditions. The large number of tests indicated that predictions for the flights' success were valid. The various review boards' and technical groups' decisions to fly or not fly were made based on such "shades of gray" assessments.[26]

VII. Conclusion

The impact of lessons learned from the FAS problem extends beyond the aeronautical research community. None of those who worked on the X-43A project could give an accurate numerical value for the probability of mission success. The best that could be given were solid estimates. This reflected the research nature of the Hyper-X project. Only three X-43As were built, while each of the HXLV boosters and their FAS were unique. Each of the three vehicles made one flight only after extensive test and checkout. This situation differs dramatically from that of a production fighter or airliner, which may fly several times a day for several hours at a time.

I believe it is important that the society at large understand that aerospace research carries with it the risk of failure. It has long been a truism that one can learn more from failure than from success. Progress is where the focus needs to be kept, and progress is derived from failures as well as successes. Progress is evolution and growth derived from all available sources. Dr. Hugh L. Dryden, for whom the Dryden Flight Research Center is named, once observed that flight research separates "the real from the imagined." Sometimes, this means that five years' worth of work is lost in 13.5 seconds.

The FAS problems were only one of the challenges faced by the Hyper-X team. Ultimately, their efforts were successful. The team had remained together, through hard times and setbacks. When success was finally achieved, it was all the sweeter.

Acknowledgments

References

[1] Phillip J. Joyce, John B. Pomroy, and Laurie Grindle, "The Hyper-X Launch Vehicle: Challenges and Design Considerations for Hypersonic Flight," AIAA 2005-3333, p. 4.

[2] X-43A Mishap Investigation Board, "Report of Findings: X-43A Mishap Volume I," p. 12.

[3] Ibid, p. 11, and Griff Corpening history interview, NASA Dryden Flight Research Center History Office, p. 44-46.

[4] Corpening history interview p. 30, 31, 44.

[5] Joyce, Pomroy, and Grindle, "The Hyper-X Launch Vehicle: Challenges and Design Considerations for Hypersonic Flight," p. 6.

[6] "Report of Findings: X-43A Mishap Volume I," p. 11, and Paul Reukauf history interview, NASA Dryden Flight Research Center History Office, p. 26, 42.

[7] "Report of Findings: X-43A Mishap Volume I," p. 5, 6.

[8] Ibid, p. 5, 6, Corpening history interview p. 44, 45, and Reukauf interview, p. 46. The new HXLV model also took into account the effects of the additional thickness of thermal protective material on the HXLV fins.

[9] "Report of Findings: X-43A Mishap Volume I," p. 7.

[10] Reukauf history interview, p. 45, 46, 71, 72, and e-mail from Yohan Lin, July 5, 2006, Subject: db info.

[11] David E. Reubush, Lual T. Nguyen, and Vincent L. Rousch, "Review of X-43A Return to Flight Activities and Current Status," p. 5, Yohan Lin history interview, NASA Dryden Flight Research Center History Office, p. 62, and additional information from Lin.

[12] Aerospace Projects weekly reports, October 3, 2003, p. 3, and October 31, 2003 p. 2, 3.

[13] Corpening interview, p. 48.

[14] Aerospace Projects weekly report, November 14, 2003, p. 2.

[15] Aerospace Projects weekly report, January 9, 2004, p. 3, additional information from Dryden X-43A project manager Joel Sitz, Lin, and Reukauf, and e-mail from Yohan Lin to Curtis Peebles, June 27, 2006, Subject: Your Paper.

[16] Reukauf interview, p. 57, 58.

[17] Ibid, June 10, 2004, p. 3, 4.

[18] Ibid, June 25, 2004, p. 3, and July 2, 2004, and Reukauf interview, p. 58.

[19] Laurie Grindle interview #3, NASA Dryden Flight Research Center History Office, p. 9.

[20] Aerospace Projects weekly reports, July 23, 2004, p. 3 and July 30, 2004, p. 4.

[21] Ibid, August 20, 2004, p. 3, and August 27, 2004, p. 3. Additional information provided by Lin.

[22] Grindle interview #3, p. 15, 16, and Reukauf interview, p. 58, 59.

[23] Lin interview, p. 60. The title and section heading were inspired by a comment by Linda Soden, who worked on X-43A configuration control: "Reliability comes in 256 colors of gray." Linda Soden history interview, NASA Dryden Flight Research Center History Office, p. 45.

[24] Joel Sitz interview notes, June 2, 2004.

[25] Corpening interview, p. 49.

[26] Sitz interview notes, June 2, 2006.

Figure 1. Orbital Sciences Corporation's Pegasus booster under the wing of the B-52.

Figure 2. NASA's B-52 launch aircraft flies over the Pacific Ocean carrying the third X-43A vehicle on November 16, 2004.
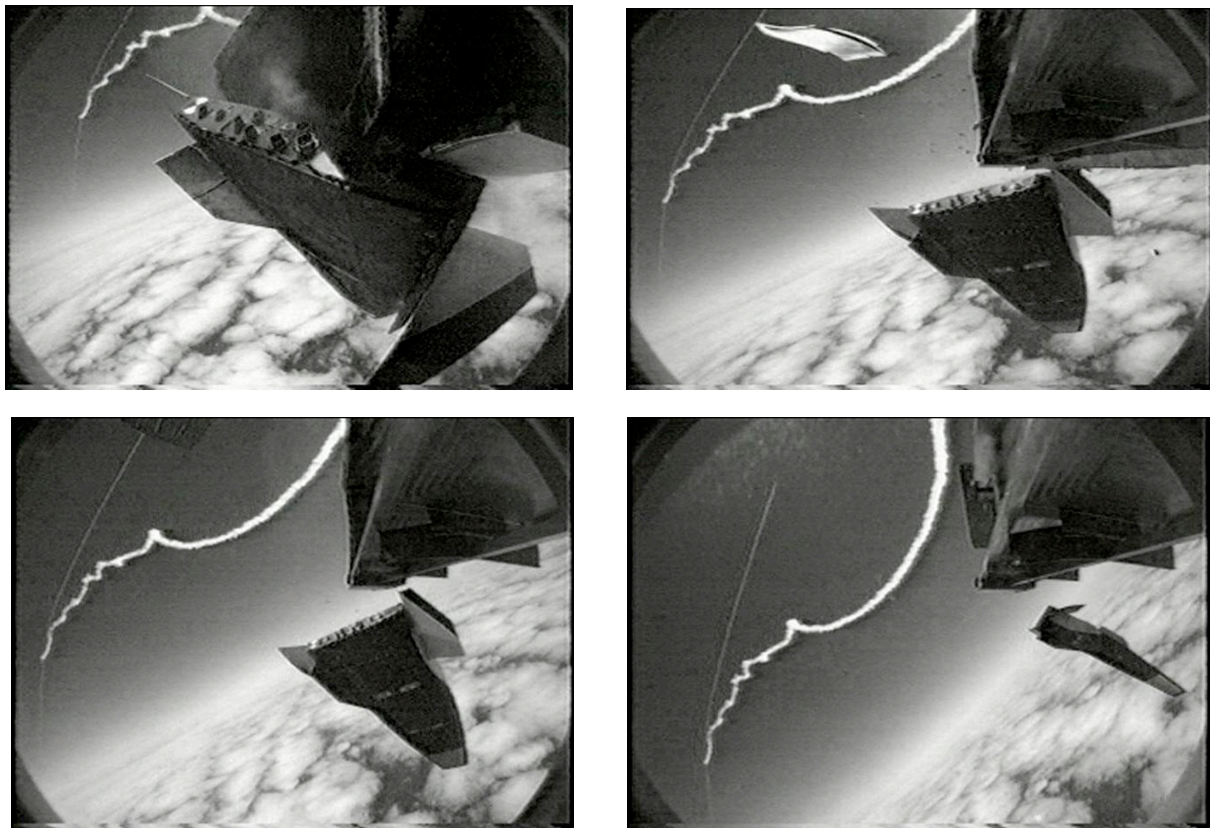
Figure 3.   This series of images shows the first X-43A as it breaks free of the HXLV.

Figure 4. The second X-43A and its modified Pegasus booster accelerate after launch from NASA's B-52B over the Pacific Ocean.

Figure 5. NASA engineers monitor mission progress from a Dryden control room prior to launch of the third X-43A on November 16, 2004.

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