Dryden Flight Research Center
Edwards, California 93523

Technical Support Package

The X-36 Program: a Test Pilot's Perspective on UAV Development Testing

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Technical Support Package

for

THE X-36 PROGRAM: A TEST PILOT'S PERSPECTIVE ON UAV DEVELOPMENT TESTING

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FLIGHT TESTING THE X-36—THE TEST PILOT'S PERSPECTIVE

Prepared by:
Laurence A. Walker (F)
Boeing AS&T Phantom Works
St. Louis, Missouri

Prepared for:
NASA Dryden Flight Research Center
Edwards, California
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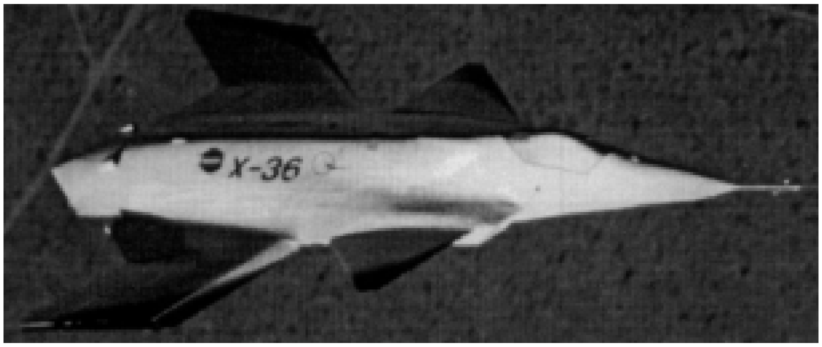

From the beginnings of aviation, designers have sought ways to create faster, lighter, more maneuverable designs. Tailless designs have had the promise of reducing structural weight, aerodynamic drag and cost, but at the increased complexity of a complicated control system and nontraditional control surfaces. Recently, stealth has also become an important design consideration. Fortunately, two key enabling technologies have made a blend of these attributes possible. These are digital flight control technology and the vast advances in computational analysis which permit integration of low observable technologies and advanced aerodynamic design. The X-36 represents a radical integration of these technologies into a practical research aircraft.

The X-36 Program is a cooperative research and demonstration program between NASA Ames Research Center and Boeing AS&T Phantom Works. Funding is based on a roughly 50-50 cost sharing arrangement; the cost for developing, fabricating and flight testing the X-36 is estimated at about $20 million.

Cost was a major driver in the decision to demonstrate these technologies in a subscale research aircraft. Since cost correlates strongly with size, the costs could be reduced by an order of magnitude. Unfortunately, the primary tradeoff was risk—a subscale aircraft would mean a single-string flight control system, trading risk for reduced cost by not having the multiple redundancy appropriate for a manned aircraft. Aircraft systems could also sacrifice redundancy to achieve lower weight and complexity. From an aerodynamic standpoint, demonstration of torsional agility at high angle of attack could be achieved nearly as well as it could with a full-sized aircraft. These tradeoffs are shown in Figure 1, with a 28% scale, powered demonstrator being chosen for the program.

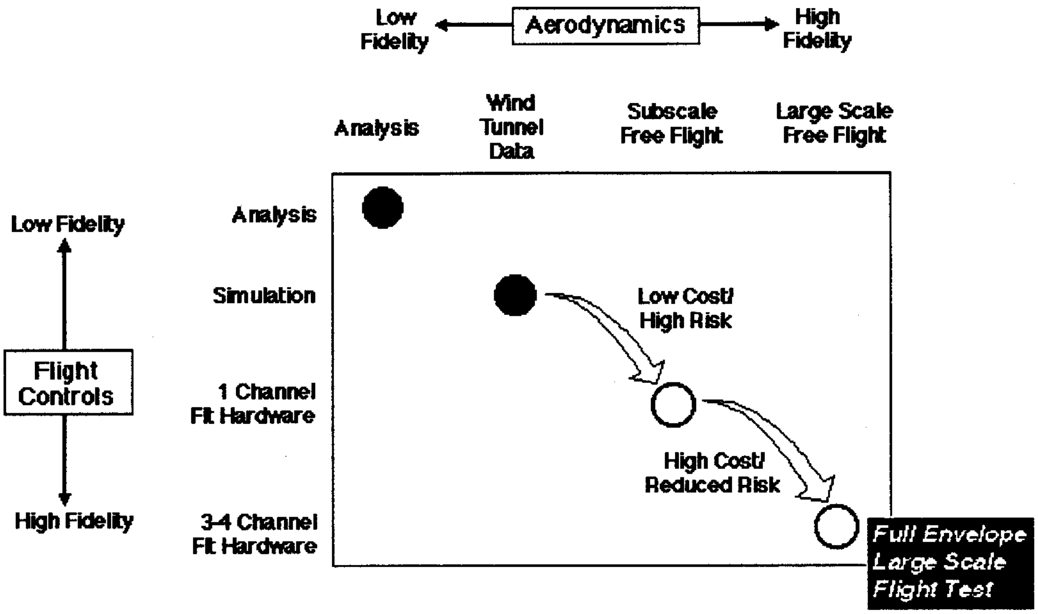

Figure 1
Technology Validation Approach

From the standpoint of program redundancy, risk was mitigated by having a second aircraft. To reduce the risk to each airframe, an onboard recovery parachute provided a last chance of emergency recovery. However, accepted risk, as it extended to the aircraft and onboard systems, did not extend to processes which included qualification testing of hardware and software. It was also extremely important to have done the necessary work to ensure that the flight test and air vehicle teams were well practiced in procedures and training. Although it may have been easy to conduct a full flight test program with the same engineering and core personnel, the documentation of our processes, software, and hardware was a real challenge which consumed more time than we had expected. The benefit of this increased emphasis on procedures and training was to be highlighted on flight 2 when loss of data link created our first major emergency.

A. AIRCRAFT DESCRIPTION

The X-36 is a 28% scale, remotely piloted research aircraft designed to demonstrate tailless, high angle of attack, fighter agility with a stealthy design. As a test pilot, it was disappointing to realize that flight testing would be without the usual joys of actually flying. Also, I feared that my cockpit control suite might consist of a model airplane radio control box, but after selling the advantages of a full-sized cockpit and displays, the program embraced this idea, and it contributed strongly to the success of the program.

The X-36 is shown in Figure 2. Length is nearly 18 feet including the noseboom; weight is approximately 1,250 lb. Wing span is nearly 11 feet; for power it uses a modified Williams International F-112 advanced cruise missile engine which supplies approximately 700 lb of thrust.

Weights

TOGW	1,245 lb
O.W.E.	1,083 lb
Usable Fuel	162 lb
Thrust Class	700 lb
Density	28.3 lb/ft^3

Performance

Mach Number	≤0.6
G_{Limit}	5 g's
q_{Limit}	200 psf
Landing Gear	14 fps
$V_{Approach}$	112 KEAS
Max AOA	~ 35°

Materials

Skin - Carbon Epoxy and Aluminum
Bones - Machined Aluminum
Assembly - Mechanical Attachment
Nozzle - Cast Chem Mill Titanium

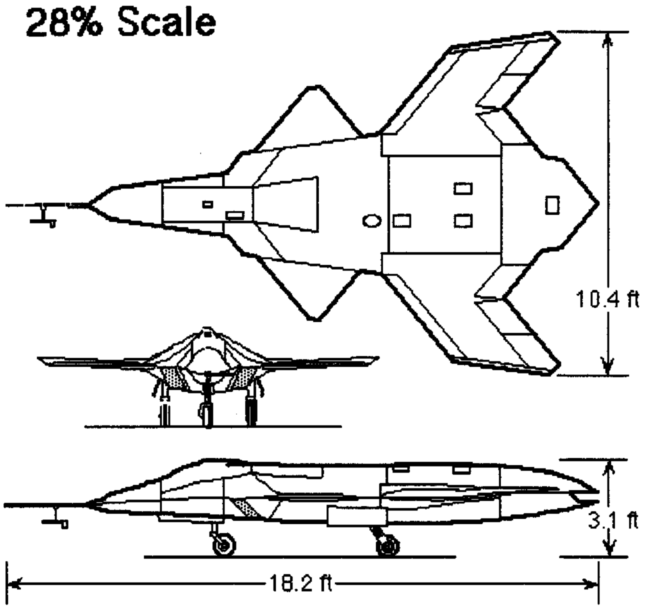

Figure 2

X-36 Description

The control system consists of canards, split ailerons, leading and trailing edge flaps, and thrust vectoring. The control system also provides speed brake and aerobraking functions. As would be appropriate for a subscale demonstrator, there are three flight control modes: the first is designed for takeoff and landing and feels comparable to a full-sized aircraft such as the F/A-18 with the landing gear extended. The second mode consists of up and away gains comparable to a full-sized fighter aircraft; the last provides still higher gains and rates which, when scaled to 100%, represent a full-sized fighter aircraft.

1. COCKPIT DESIGN

With a subscale, remotely piloted vehicle (RPV), the natural tendency might be to reduce the cockpit control and display suite. Actually, the best practice is just the opposite, primarily because the pilot will have less natural cues of peripheral vision, sounds, and kinesthetic feedback. Therefore, the challenge was to provide replacements for these cues and create overall situational awareness comparable to a full-sized aircraft. Ruling out motion bases and buffet simulation cues, we limited our effort to audio, visual, and Head-Up Display (HUD) cues. A full-sized stick, rudder pedals and their respective feel systems, throttle, and a full compliment of HOTAS switches complete the cockpit control effectors. Fortunately, this hardware had been salvaged from the aborted A-12 effort.

2. DISPLAYS

Two large 20-inch monitors provide the visual displays to the pilot, as well as being redundantly located throughout the Ground Control Station (GCS). The downlinked video from a canopy mounted camera is shown as background on the forward viewing monitor. When used as a simulator, a synthetic terrain data base shows the Edwards Air Force Base vicinity and includes main and lakebed runways. A fully functioned HUD overlays the video with embedded flight test features.

The second monitor shows a God's-eye-view HSI, engine and fuel displays, control surface deflections, yaw rate and a host of warnings, cautions, and advisories. An audio attention getter ("tweedle-dee") alerts the pilot to the arrival of any new warnings or cautions. An adjacent monitor, shared by the test director and GCS engineer, serves as a backup should either of the pilot's monitors fail.

3. HEAD-UP DISPLAY (HUD)

The HUD, shown in Figure 3, has a number of key features. Most importantly, the HUD was designed to overlay exactly the downlinked video and to have 1:1 registration with the outside world. The distance from the pilot's eye to the monitor was even selected to distend the same visual angle to match the video and HUD pitch ladder dimensions to avoid any visual distortion which would differ from a manned aircraft. Digital readouts of airspeed, altitude, AOA, and Nz are typical of the F/A-18 and F-15E HUDs. Navigational bearing and distance to the selected steerpoint shows in the NAV block; steering points are selectable by HOTAS.

Flight test HUD includes an analog specific power (Ps) indicator to the left of the airspeed box. This was extremely valuable to enable the pilot to set quickly the proper throttle setting to achieve a trim point.

The flight test HUD also includes an analog vertical line which shows both AOA and Nz information on opposite sides of the line. This combination helped considerably to see both Nz and AOA placard indicators simultaneously since both may be moving quite rapidly in a wind-up turn with negative Ps. A selectable (by the GCS engineer) fence symbol along this line shows the current positive and negative Nz and AOA limits; a target circle indicates the desired AOA or Nz for the current maneuver. Since placard observance is very important in a test program, we added warnings on the HUD to indicate exceedences of Nz (in either direction), AOA, and speed placards, as well as other customary warnings.

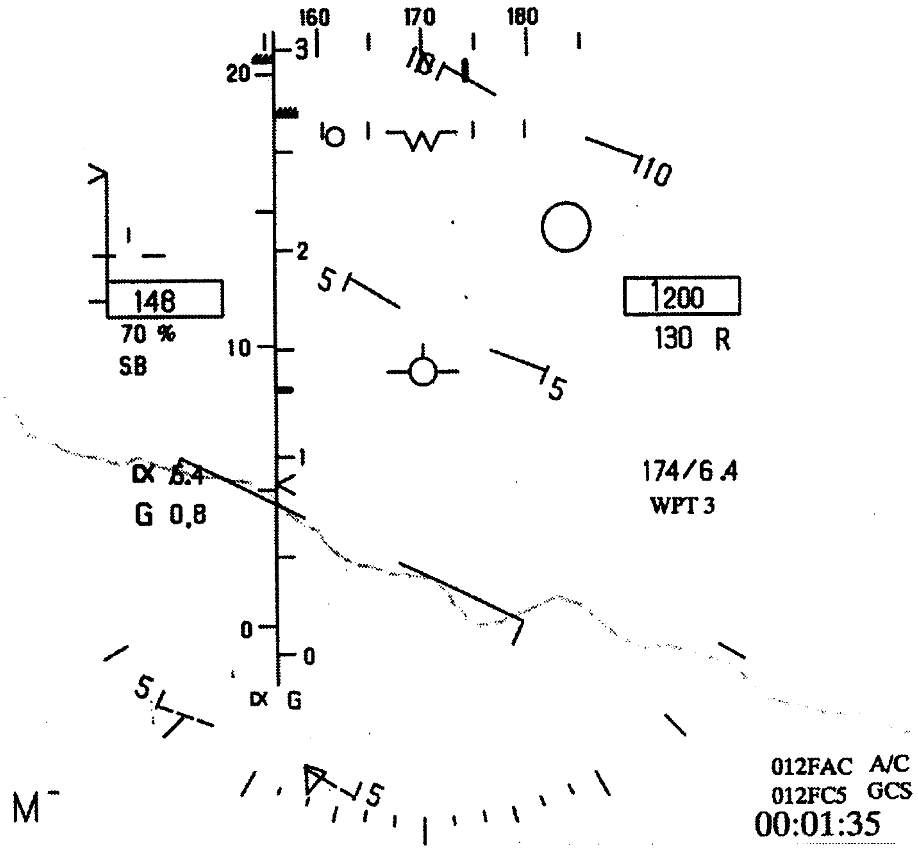

Figure 3

X-36 Head-Up Display

The HUD's velocity vector is designed to register accurately to the outside world and to the pitch ladder. The real inertial vector is shown as a ghost symbol when it is beyond 2° laterally from centerline. The normal inertial velocity vector symbol is caged laterally because at the slower speeds of the X-36, winds can cause large drift angles.

A true airmass velocity vector is the default velocity vector when airborne and can be toggled to an inertial velocity vector by HOTAS. An airmass vector indicates relative wind and is driven by corrected AOA and sideslip. The rationale for its incorporation was that since the X-36 is divergent in both pitch and yaw, that the airmass velocity vector position on the HUD would provide earlier pilot recognition of any developing divergence tendencies since the pilot would not have the benefit of cockpit sideforce or normal g. Additionally, the airmass velocity vector was very useful to see developing sideslip during rapid rolling maneuvers.

4. AUDIO CUES

Many times in the past in flight simulators, I have noticed that lack of sound increased the difficulty of setting power and hurt situational awareness. Accordingly, we included jet noise and wind noise in our simulations. Taking this idea a step further, we also included it in the aircraft by adding a microphone in the X-36 "cockpit" area. This downlinked audio proved to be a highly valuable cue and alerted the team, more than once, to problems such as screech at high-power settings and engine stalls before they became serious.

5. FLIGHT TEST PILOT CARDS

Although it may sound trivial, test card shuffling by the pilot was considerably more challenging than in a manned airplane. The primary problem is that the HUD monitor is the sole cue of attitude. With an aircraft that can roll at extremely high rates, is more gust susceptible than a larger aircraft, and has a mild spiral divergence, the test pilot's scan must spend far more time watching the HUD. Attempts to flip or shuffle cards on a kneeboard could result in significant deviations in attitude since there was no kinesthetic cue to alert the pilot of the deviation. Accordingly, we made a tray immediately at the lower edge of the HUD monitor to hold the test cards for easy viewing by the pilot and arranged the sheets like a hand of playing cards so that the completed top sheet could be pulled off without looking away from the HUD.

6. PILOT ISOLATION

Since the pilot's crew station is in the center of the GCS trailer, distraction by movements and sounds in the GCS had the potential to hurt situational awareness. We addressed the problem by creating a tent-like frame over and down both sides of the pilot's "cockpit" to keep his attention focused on his displays. The back side was left uncovered so that a "wizzo" could monitor progress of the flight and assist with any necessary emergency procedures from the flight manual. Additionally, a "flight comm" loop was created which included only the test director, pilot and radios, leaving the technology engineers free to discuss test results and anomalies without disturbing the pilot.

B. TEST RESULTS

1. TEST ENVELOPE

Due to the lack of flight control redundancy and the fact that the X-36 is divergent in both pitch and yaw, the testing envelope was intentionally limited to 160 knots to avoid a possible structural failure should a flight control failure and subsequent divergence occur. This approach would permit subsequent recovery of the intact airframe by an onboard recovery parachute which limited the sink rate to a gentle 14 feet per second.

2. PREFLIGHT TESTING - DATALINK

A critical element of RPV flying is ensuring that the data links are robust since they are the "control cables" that connect the pilot to the airplane as well as downlinking the flight data to the GCS to maintain situational awareness. Fortunately, our instrumentation system virtually came with the datalink, since all key parameters such as airdata, rates, accelerations, and positions were embedded in the data. Only a few extra parameters were needed such as temperature and system sensors appropriate to a new aircraft. Datalink checks included tow tests to check every planned runway for datalink dropouts. Secondly, a crane hoist test of the X-36 was made on the lakebed to verify antenna patterns and any potential losses due to destructive multipath interference. Lastly, a helicopter test with the X-36 suspended underneath was flown to the limits of the ranges to ensure that the range of the datalink was satisfactory within the operating areas.

3. HIGH-SPEED TAXI TESTS

The high-speed taxi tests went very well with no problems noted. Braking checks, braking doublets, rudder pedal doublets, lateral stick doublets, and pitch rotation tests all matched the simulation.

4. FIRST FLIGHT

First flight was flown on May 17, 1997. After much rehearsal and practice, the test team and aircraft were ready. The scheduled takeoff time was selected to be 0630 on a Saturday to avoid any conflict with main base traffic. Additionally, winds would be calmer and less of a factor. The UAV operating areas had been extended by special request to the base to provide additional operating area close to the datalink antenna.

Takeoff was just as had been simulated with the aircraft lifting off right on the airspeed numbers. Climb angle was quite good at about 15°, even considering that the gear and flaps were left down. However, after about 2 minutes, a temperature caution occurred. Downlinked data showed that the nozzle-bay temperatures were climbing and an immediate abort followed.

I knew nearly immediately after takeoff that the airplane was flying well. Control responses appeared immediate and the damping appeared good. No obvious deficiencies were noted. Unfortunately for the team, there was no time for any classic test maneuvers as the remaining time was spent repositioning for an immediate landing.

Since the airmass velocity vector was our airborne default, I noticed the first problem now with it—it wasn’t yet accurate enough to use as a glide slope reference. The theory was that if the velocity vector was placed about 1° down, then sink rate should be about 1/60th of the true airspeed. However, this was not to be the case. Since I had never made a lakebed landing with a sight picture only 3 feet above the lakebed, I was cautious to avoid the sinkhole illusion and tried to fly the airmass velocity vector to set sink rate. After about half the runway disappeared behind me, it appeared that I had virtually no sink rate and I reset the velocity vector about 2-1/2° low. This appeared to do the trick as the X-36 made an uneventful, but gentle touchdown and rollout.

In retrospect, the upwash predictions were about 1-1/2° too low with the effect that the airmass velocity vector showed about 1-1/2° lower than the actual flight path. Until the new upwash data could be incorporated, we selected the inertial velocity vector for all remaining landings.

5. FLIGHT 2

After incorporating two small scoops to aid nozzle-bay cooling, flight 2 gave us our most significant problem. About 10 miles away at 12,000-ft altitude, the video and downlink signals suddenly became very weak with the presence of static and video noise. A break X then appeared which meant that the X-36 had gone into lost link autonomous operation. It was almost frightening to suddenly realize that a new $20M aircraft was suddenly on its own and all I had was a frozen display with a big "X." The team instantly went into its recovery procedures to regain link. The independent NASA range safety display was a big help to track the air vehicle while the GCS engineers attempted to regain links.

In the autonomous mode, the aircraft turns to the nearest steering point and then navigates back on a preplanned return route to the autonomous orbit point located over the northern part of Rogers Lakebed. As bad luck would have it, the nearest autonomous steering point was behind the aircraft, farther away from the station. A couple of times, I regained control momentarily only to lose links in a matter of seconds. Each time the link was briefly regained, the aircraft was seen in a turn towards the more distant, but closer (to the aircraft), steering point. Each glimpse of the intermittent link showed a yet steeper angle of bank, well beyond what we had yet flown. Even so, the autonomous autopilot handled it well, although it was much more aggressive than we had seen in our simulation of this type of emergency. (Adjustment of its aggressiveness would also be high on our work list!) Fortunately, the X-36 returned to the autonomous orbit point where control was finally regained and an uneventful, but stress filled, landing was made.

After much additional ground testing, it was determined that the loss of the link was due to a temperature sensitivity problem in the low-noise amplifier. Apparently the LNA was OK at both low and high temperature where it was qualified, but at mid-range temperatures, this LNA lost enough sensitivity to cause link loss. After the problem was finally corrected, we had no further datalink problems.

A considerable amount of data was gathered in Phase 1 (Figure 4). Real-Time Stability Margin (RTSM) and Parameter IDentification (PID) maneuvers were flown with the aid of automated control sweeps, singlets, and doublets which were uplinked to the aircraft. When the pilot squeezed the trigger, the maneuver started and was complete in a matter of seconds. Throughout, the pilot could still control the X-36, although the engineers preferred as little pilot input as possible. These automated maneuvers greatly facilitated envelope expansion.

Phase 1 Flight Test - Thrust Vectoring ON
(100–160 knots, 0 to 15 degrees AOA, Nz 0.2 to 3 g)

- **Initial Handling Quality Assessment**
- **Functional Checkout**
- **Real-Time Stability Margin Assessment (RTSM)**
- **Air Data Calibration**
- **Parameter IDentification (PID)**
- **360 Degree Rolls**

Achieved:

  - **Upper Level 2 Handling Qualities**
  - **2 g, 20 Degree AOA, 160 KEAS**
  - **8 Flights, 4 Hours Flight Time**

Figure 4

Phase 1 Flight Test

Rolling maneuvers at three different speeds completed the testing of Phase 1. Handling qualities were remarkably good but a bit of pitch bobble caused Cooper-Harper ratings of HQR-4 for the pitch attitude capture task. Bank angle capture was assessed at HQR-3. There was also an unusual spiral divergence which tended to steepen all bank angles and required some lateral stick deflection towards wings-level for all turns. Considerable pilot attention was required. I was very glad that we had invested the extra effort to provide good situational awareness and minimize pilot distraction.

The last four flights of Phase 1 were flown in only four working days, attesting to the excellent reliability of the X-36.

6. PHASE 2

Phase 2 testing expanded the flight envelope as shown in Figure 5. With the new control laws, stability margins were improved and better derivatives were available. This resulted in still better flying qualities, increasing to Level 1 ratings in all axes.

Phase 2 Flight Test

(60–160 knots, 0 to 35 degrees AOA, Nz 0.2 to 5 g)

- **Elevated g Agility ~120 knots**
- **2A: Air Data Calibration, RTSM, PID**
- **2B: Incorporate 2A Results**
- **Agility Demo - Thrust Vectoring ON**
- **Agility Demo - Thrust Vectoring OFF**

Achieved:

  - **Level 1 Handling Qualities**
  - **4.8g, 40 Degree AOA, 177 KEAS**
  - **22 Flights, 10.9 Hours Flight Time**

Figure 5

Phase 2 Flight Test

With the new improvements, accelerated g bank-to-bank rolls, or RPOs (rolling pullouts) were flown at mid-range speeds at up to 4.8 g. Whether lateral stick was used, or rudder pedal, roll rates were spectacular and exceeded the program goals by a significant margin as shown in Figure 6. These rates exceeded those of any aircraft I've flown by a dramatic margin.

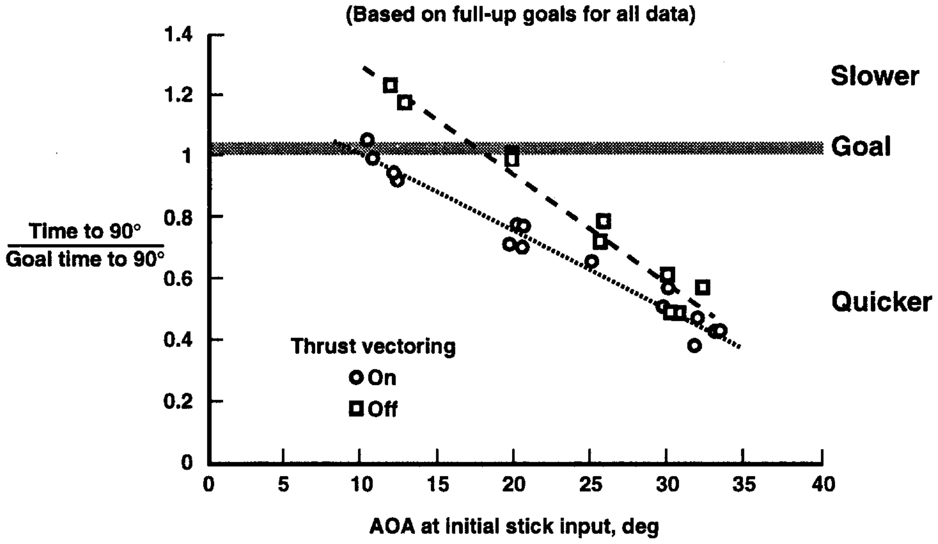

Figure 6

Normalized Time to Roll 90°

Reliability was also very good in this phase with 14 flights completed in only 35 calendar days. Seven of those were flown in only 8 working days.

6. PRECISION LANDINGS

As a footnote, with the prospect of El Niño and potentially flooded lakebeds, we wanted to have the option to conduct our operations from the main base runway. Surprisingly, we were asked if our landing accuracy was adequate to handle the (15,000-ft long) main base runway. Accordingly, we had the airfield personnel mark a 60-foot long "H", 600 feet down the right edge of lakebed runway 23 with a 20-foot wide gap in the cross bar. The object was to land in the center of the H. After completing 6 precision landings, I am pleased to report an average deviation of only 32 feet, facilitated by the excellent handling and HUD display symbology. Landing rollouts with aerodynamic and moderate braking averaged about 2,000 feet.

C. LESSONS LEARNED - CHALLENGES OF RPV FLYING

Without a doubt, the challenge of a successful flight test program with a remotely piloted aircraft far exceeded my estimation. Due to the lack of normal pilot cues, cockpit design was especially important as the quality of the design must help replace the missing flight cues.

The value of a trained test pilot to the operation was, of course, very high. The high degree of agility that was demonstrated requires familiarity with fighter maneuvers, as well as familiarity with the necessary cues and displays to do that kind of testing. With a test pilot, the team also had a high degree of flexibility to address problems, real-time, in emergency situations which might be otherwise impossible with a totally autonomous system.

In retrospect, perhaps the single most aggravating aspect of this program was the idea that the test vehicle was somehow expendable. Although this was really done to make sure that upper management understood the risks, the team never viewed the aircraft in that light. If a crash had occurred because of the accepted risk created by lack of redundancy, this could be accepted. However, if a crash occurred because of a failure to properly prepare and execute, this could never be acceptable. Fortunately, that "expendable" thinking did not adversely affect our team's preparation. In the end, process and safety proved to be exceedingly important and were key ingredients to this successful flight-test program.

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