X-31 High Alpha Conference

X-31 Post-Stall Envelope Expansion

and

Tactical Utility Testing

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Dave Canter

NAWC-AD Patuxent River, MD

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Good morning. I'm Dave Canter and I'm from the Naval Air Warfare Center's Aircraft Division at Pax River, MD.

I was a member the X-31 international test organization at NASA Dryden during calendar years 92 and 93.

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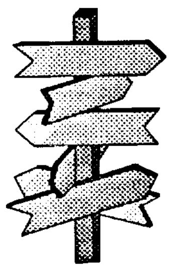

Lessons Learned

Non-Technical

Technical

Tactical Utility Results

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I will discuss some of the lessons that were learned along the way and end with some of the results achieved during tactical utility testing.

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Organizational Lessons Learned

- Test Team Building
- Streamlined Flight Clearance Process
- Consistent Leadership

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The first lesson is that test team building takes a lot of time. The X-31 test team is made up of a very diverse mix of government agencies and contractors from the US and from Germany. It took approximately six months of working together before we became a cohesive team where there was a bond of trust between the government and contractor engineers. Trust was critical to creating positive working relationships and to put an end to redundant efforts that had been going on as government engineers worked to verify the results achieved by the contractors. The only way to build a cohesive team is through working together over an extended period of time. To get the organizational bugs worked out, we think its a good idea to get your team physically co-located at least 3 months prior to the start of flying.

2nd point: NASA has a streamlined flight clearance process, referred to as a Tech Brief, where the test team briefs representatives from engineering, flight ops, and management on planned testing. If all questions are satisfactorily answered at the Tech Brief, permission is received to commence testing. This approach is much faster than requiring a formal written document to be reviewed by a long chain of individuals.

3rd point: The ITO was blessed with consistent leadership. When a chief engineer from one of the team member organizations left the program, they were replaced by someone from within the organization. This continuity in leadership meant that our way of doing business did not have to change through the course of testing.

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Logistical Lessons Learned

- 90% of Test Team On-Site
- Collocated Assets
- Six Project Pilots Not Too Many

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The program also had some logistical factors working in its favor. Approximately 90 % of the test team was on-site at Dryden. Early on, the flight hardware in the loop simulator was moved from Rockwell's Downey facility up to Dryden. The majority of the test team was located in one building, NASA's Integrated Test Facility or ITF. Along with the engineers, the ITF was home to half of the X-31 test pilots, the simulator, and the jets. This setup greatly improved communications and efficiency. It was amazingly easy to try things out on the simulator or to go into the hangar and do on-aircraft testing.

For the majority of the last two years, the ITO used six test pilots - basically one from each of the major organizations involved. Early on, there were fears that it wouldn't be possible to keep that many pilots proficient for high AOA envelope expansion. This was not a problem, because the pilots were all very experienced, they were able to get proficiency flying in other types of aircraft, and they could get as much simulator time as they needed.

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Technical Lessons Learned

High AOA Aerodynamics

- Wind Tunnel Does *Not* Give Complete Picture
- Small Differences Have Large Impact
- Precise Air Data Required for Flight Control Laws

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Now, I'll switch to some of the technical lessons learned. Depending on which projects you've been involved with, some of these will not be new to you. In the area of high AOA aerodynamics, we saw that there were many nuances that were not discovered in the wind tunnel. The primary effect that was not identified was the strength of the symmetric vortices coming off the nose of the aircraft.

We also saw that very small changes to the aircraft's nose dramatically changed the plane's stability and control at high AOAs. These small changes to the aircraft's nose would be very difficult to duplicate on a small-scale wind tunnel model. When we started flying above 50° AOA, the aircraft underwent sideforce kicks which the pilots called lurches.

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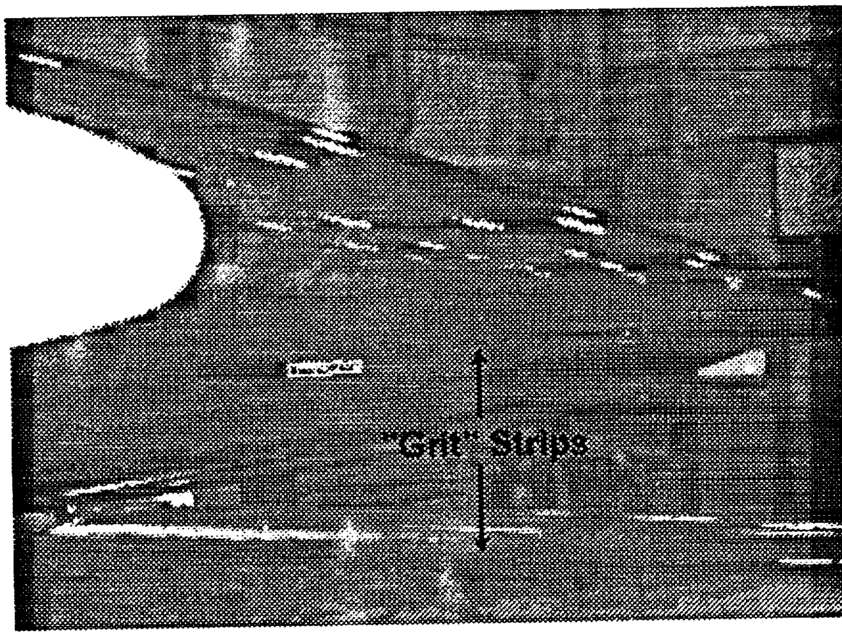

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We added narrow 1/4 inch wide strips of grit - small grains about the size of bird seed, to the aircraft's noseboom and radome. These grit strips reduced the randomness of lurches, and we were able to finish 1 g envelope expansion to the design AOA limit of 70°. When we started elevated g entries to post-stall, which the X-31 defines as AOAs above 30°, we had an unintentional departure from controlled flight at 58° AOA during a split-s maneuver. Analysis determined that the departure was caused by a very large yaw asymmetry which overcame the available thrust vectoring control power. It was realized that the grit strips alone were not a powerful enough effector of the forebody aerodynamics.

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Based on previous high AOA research and new wind tunnel testing with the X-31 model, we added 6/10 in wide by 20 in long strakes to the nose and also blunted the nose tip from essentially a zero radius of curvature to a radius of curvature of 3/4 of an inch. The strakes were added to force symmetric transition of the forebody vortices and the nose tip was blunted to give lower yaw asymmetries. These changes to the nose made a major improvement to the aerodynamics of the aircraft.

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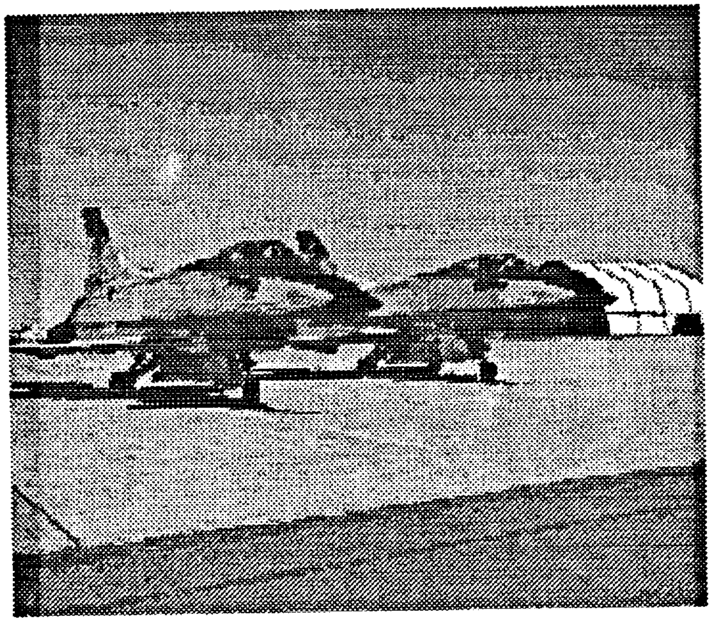

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Despite the fact that the X-31's were built with the same external dimensions, aircraft 2 had considerably stronger yaw asymmetries than aircraft one. This lead to aircraft two being referred to as the "evil twin". By testing aircraft two with several lengths of extended nose strakes, we found that we were able to get it to fly like aircraft one by lengthening the strakes by 8 1/2 inches. Longer nose strakes than this proved undesirable because they created a de-stabilizing nose-up pitching moment. Since the longer nose strakes were added to aircraft two, it is no longer an "evil twin".

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Technical Lessons Learned

High AOA Aerodynamics

- **Wind Tunnel Does *Not* Give Complete Picture**
- **Small Differences Have Large Impact**
- **Precise Air Data Required for Flight Control Laws**

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Due to the low basic stability of the aircraft at high AOA, it had a low tolerance for sideslip buildup. That made sideslip a very important feedback to the flight control system. The source of sideslip was the inertial navigation unit, or INU. Below 30° AOA, the INU was updated with air data from the noseboom. When we started spending extended periods of time above 30° AOA, we got large values of sideslip from the INU which were not true sideslip, but were calculated due to drift caused by changes in wind direction and magnitude. This meant that we needed to continue to update the INU with air data all the way to 70° AOA. This lead to the incorporation of an unusual noseboom configuration.

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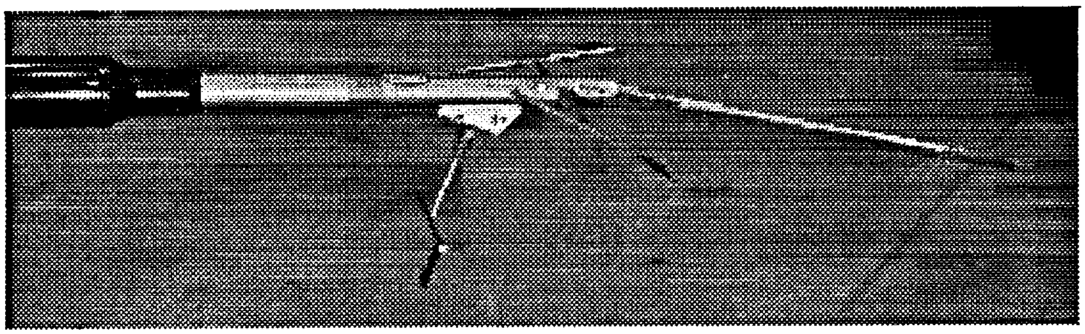

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We have a Kiel type pitot-static probe instead of the standard NACA type probe in order to get better behavior at high AOAs. To get desired accuracy all the way to 70°, we actually bent the kiel probe down 10° relative to the noseboom. We also had to add a edge to rotate our sideslip vane down 20° from the noseboom. This was required to counter a 4 Hz oscillation of the sideslip vane which occurred at 62° AOA. Canting the vane down effectively lowered the AOA that the sideslip vane saw by 20° and thus eliminated the oscillations. With these modifications to the noseboom, we were able to use air data to update the INU throughout the entire AOA envelope. This eliminated the problem of INU calculated sideslip drift at high AOA.

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Technical Lessons Learned

Flight Control System

- **Greater Control Power Required**
- **Multiple Control Law Changes**
- **Rapid Software V&V *The* Key**

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Many changes were made to the flight control system before we achieved the desired level of controllability. The departure taught us that more control power was needed to counter the yaw asymmetries. Fortunately, we had additional control power available. We were able to increase the thrust vector vane travel into the engine exhaust plume from 26 to 35°. But: this was a very big change, because with over 26° of travel into the plume, there was the potential for vane-to-vane impact. Once the vane travel was increased above 26°, only the software kept the vanes from impacting. The software did work and we haven't had a vane-to-vane impact.

Throughout the course of envelope expansion, as we learned more about the plane, many control law modifications were required. The main factor which forced these changes was the fact that the aerodynamics were different from what had been seen in the wind tunnel. Fortunately, we were able to make these changes very quickly and the envelope expansion process was rarely slowed down.

The key to our rapid incorporation of new control laws was the software V & V process. The V&V process was sped up by some of the factors that have been mentioned previously: we had the flight-hardware-in-the-loop simulation and aircraft on-site with engineering, and we had lots of pilots available for piloted sim V&V. One other item which helped tremendously was automated testing. Automated test cases were run for a variety of control inputs and flight conditions. Time history plots of data using the current software were overlaid with data from the new control laws. Engineers were then able to study these overlay plots to verify that the software change had the intended effect. Minor software changes were often made in under two weeks.

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Technical Lessons Learned

Flight Test Technology

- **Thrust Vectoring Clouds Build-Up Approach**
- **Pilot-Selectable AOA Limiter Beneficial**
- **Real-Time Kill Determination Saved Test Time**

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We saw that having thrust vectoring clouded the traditional build-up approach. Traditionally, you would complete a test block at high altitude and then repeat the block at a lower altitude. This approach works fine for an aircraft whose control comes strictly from aerodynamic surfaces; since, for low airspeeds, the control power is primarily a function of dynamic pressure. So, the same calibrated airspeed can be flown at 30,000 ft before testing at 20,000 ft, for instance. However, if a large portion of your control power comes from engine thrust, you have a different situation: at high altitude, the air is less dense and the engine has lower thrust - directly lowering your control power. As you come down in altitude, you have more thrust and thus more control power. We saw that there were some maneuvers that we couldn't complete at 30,000 ft that we could do at 20,000 ft. This lead us to modify our buildup approach. For instance, we would start a test block at 30,000 ft and proceed until our control margins got too low, based on control room strip chart analysis. Once this happened, we would re-start the block at 20,000 ft. If the control margins remained high enough, we would go all the way to 70° AOA, even though we may have only been able to test up to 50° AOA at 30,000 ft. This approach worked for us, but it did require good real-time analysis by our flying qualities and flight control engineers.

During one early flight, when our limit was still 50° AOA, one pilot inadvertently overshot to 62° AOA. This was caused primarily by high stick sensitivity. It was thought that the sensitivity would be okay for the tactical testing but that it was too high for the clinical envelope expansion. To overcome this problem, our engineers developed a pilot - selectable AOA limiter. This proved to be a major benefit during envelope expansion. The AOA limiter could be set in 5° increments between 30 and 70°. This not only took away the problem of inadvertent AOA overshoots, but it also greatly improved the repeatability of gathering test data, which in turn, simplified the data analysis.

For our tactical utility testing, we had both the X-31 and F-18 adversary aircraft instrumented. Both aircraft were equipped with C-band beacons to improve the accuracy of tracking by ground based radars. Using aircraft and space-position data, we were able to determine valid firing positions for simulated missile shots. This allowed us to tell the pilots whether or not they had a scored a kill within seconds after they had squeezed the trigger. This saved valuable test time since the pilots would knock off the engagement once a kill was scored. This capability helped us to accomplish many more engagements per flight than would have been possible otherwise.

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Technical Lessons Learned

Analysis Tools

- **Improved Analysis of Model Fidelity**
- **Simulator Lagged Behind Flight Data**
- **3-D Visualization Tool Improved Understanding**

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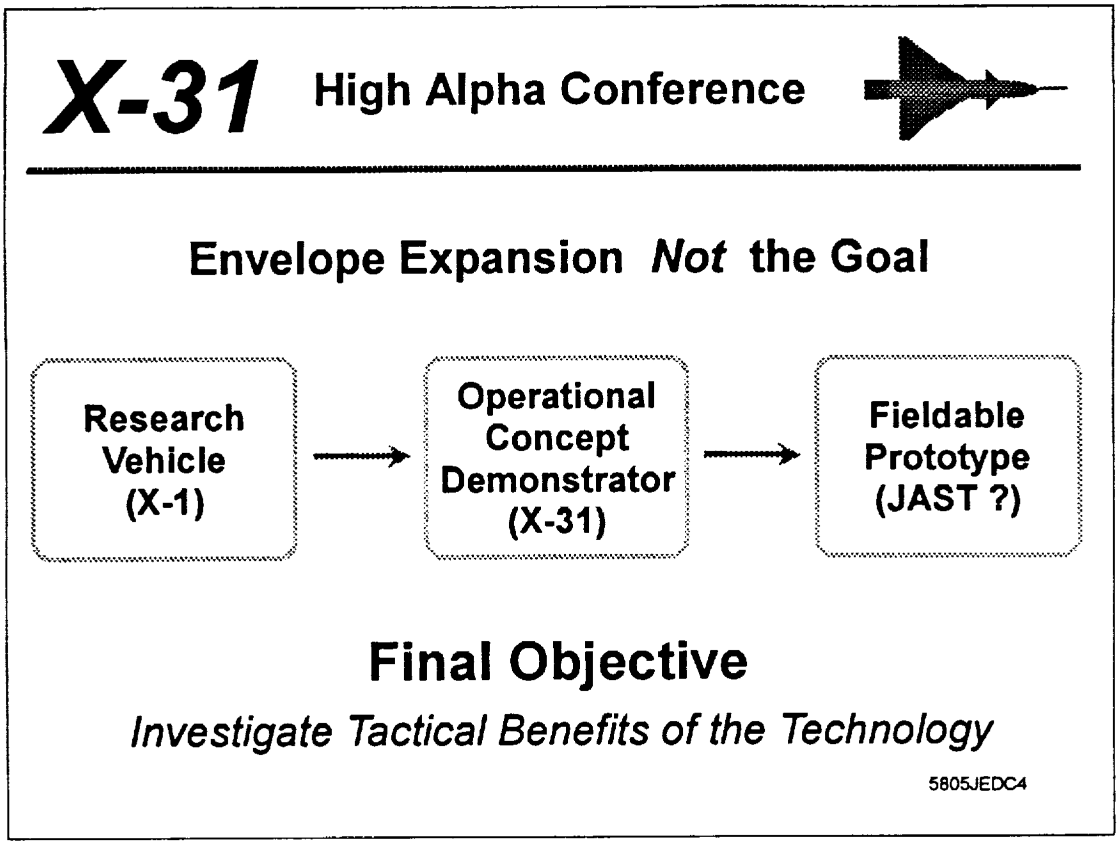
Concerning our analysis tools, we saw that the ability to drive the simulation with inputs from flight data greatly improved the process of evaluating the fidelity of the aircraft model. This capability, combined with the constant AOA provided by using the AOA limiter, allowed us to do direct time history overlays of flight data with simulator data. The overlay plots helped us to determine the corrections required to account for the yaw asymmetries. The fidelity of the simulation was quite good, but it DID always lag behind the flight data. This was most dramatically illustrated by the fact that the departure was not predicted ahead of time.

We found pseudo three-dimensional visualization programs to be very useful. These programs were able to show us what both aircraft were doing during close-in combat engagements. We used these programs both real-time and post-flight. Real-time, the program helped to enhance the situational awareness of the test team in the control room. The program was very helpful post-flight for pilot de-briefs, study by the engineers and for presentations such as this one, as I'll demonstrate in a few minutes.



I'd like to make some observations myself about what the program represents as a model for the future. It was not your typical "X" program strictly designed to prove what is possible. As an operational concept demonstrator, the program's prime directive was to demonstrate what application the technology and post stall maneuvering could have for future fighter designs. I would like to stress that since we also were tasked with taking a low cost, rapid, and off the shelf approach, we are not a fieldable prototype you sometimes see discussed as the future of R&D efforts; where you subject a piece of equipment to battlefield stresses. Put another way; we didn't want to just perform an experiment, we wanted to show implications, but we weren't prepared to lead the way in replacing current equipment.

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Implications of this Approach

Separate Pseudo - Operational Test Plan

Adapted to What was Achievable

Brute Force Fixes to Meet the Goal

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For our international test team, this operational demonstrator concept meant we were running two parallel efforts. We had almost a separate, test planning venture underway that relied on simulation to try and get a feel for what the final, pseudo-operational testing might look like. We were counting on this close linkage with realistic manned simulation campaigns to prevent any expensive flight test pitfalls. But envelope expansion was taking a greater chunk of time and budget than we hoped, so the final Close in Combat test plan was scrubbed and adapted to what was realistically achievable within the program's remaining funding. Equally as important, was the give and take from the envelope expansion players who gave us only brute force solutions and the minimal acceptable speed and altitude combination to move ahead and meet the first cut demonstration goals.

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Video:

X-31
Close-In Combat:
Sample Engagements

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That's enough of the philosophical stuff, let's look at some real results. What you are about to see are two sample close in combat engagements between the X-31 and an F/A-18 adversary. The starting conditions for this first engagement is what we called the High Speed Line Abreast; referring to a starting condition of about 100 knots above our maximum post stall entry speed. As the engagement progresses, notice how the adversary pilot takes what I would describe as a "bite" so as to press the advantage and turn the fight into a rolling scissors, but seeing that, the X-31 pilot counters with a deep post stall maneuver that stops his down range travel coupled with a high velocity vector roll rate that brings the nose to bear threatening the adversary and forcing the fight down into what's been described as a funnel of minimum radius turns. Where the X-31, with it's higher agility is actually slower, performing smaller radius turns, and descending at a lesser rate than the adversary. Which allows him to bring the nose to bear for a close in guns kill represented by the blue trigger squeeze line.

This second engagement includes the HUD view and starts with the X-31 in a very defensive position with the adversary behind his wingline with his nose on. Performing a rapid, decelerating, post stall reversal the X-31 flushes the adversary out above and slightly in front. But notice, he must release the aggravated angle of attack condition to avoid falling too far below the adversary. At this point in the fight, the X-31 has extricated himself from the defensive situation and then slowly turns it to his advantage using some of the same capabilities and techniques described in the first engagement. Now switch your attention to the HUD display projecting in the upper right hand corner and you can sense how this high angle of attack velocity vector rolling capability looks to the pilot like a controllable flat spin.

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Implications of the Technology

- Not Necessarily a *Revolution*
- New Possibilities for:
  - Pointing (*Killing*)
  - Positioning (*Driving the Fight*)
- CAREFREE Needs New Methods of Pilot Feedback
- Achievable Today without Major Trade-Offs

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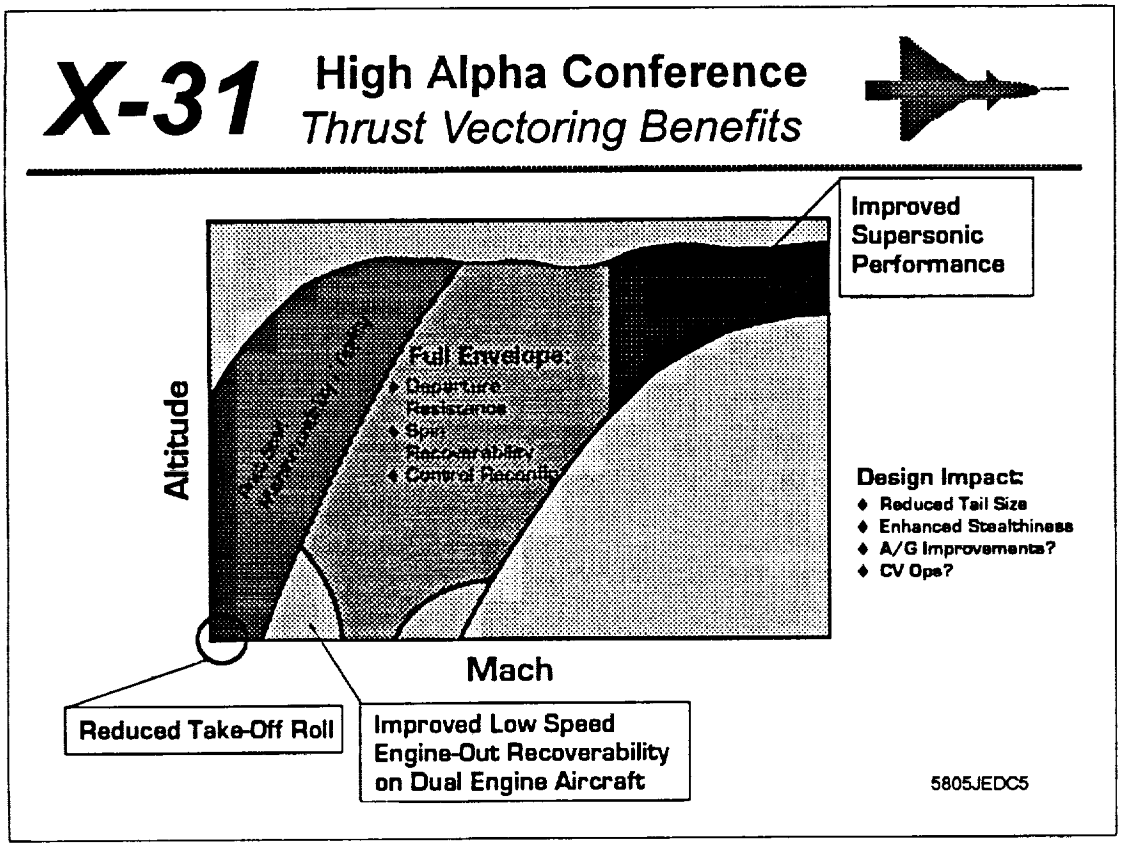
But on to the question of what it all means. All of the pilots on the program had strong military backgrounds. One point they agreed on is the X-31 does not necessarily represent a total revolution in air combat. They would not advocate trading off any other important fighter characteristics just to acquire this capability. Rather, they concluded that the enhanced pitch pointing and velocity vector maneuvering provided by post stall opened new options for the pilot to use in close in combat. These options involved using post stall maneuvering as a repositioning tool to drive the fight, or as a way to optimally rotate and point the vehicle for a weapons employment when the opponent can't counter you. But you must use it in a selective and timely manner in order to be successful.

One other important point to consider that isn't immediately obvious from the movie. The X-31 is the only aircraft designed from day one to operate in the post stall arena. This design has resulted in an aircraft that has virtually carefree handling throughout it's entire envelope. With carefree handling comes a problem of having cues of your energy state. Unlike most conventional aircraft, there are no changes in buffet level or flying qualities to provide the pilot with a seat of the pants gut feel of how he's maneuvering his aircraft. So how to interject those tacit feedback cues back into the cockpit operator will be a challenge for future designs.

One issue future designers will not have have to wrestle with though is the penalty of thrust vectoring incorporation. The F-16 MATV has ably demonstrated that incorporation of 3 dimensional vectoring is achievable today without any significant trade-offs.



The one unfortunate problem with 3 dimensional thrust vectoring is that it has become synonymous with flying controllably beyond the lift barrier; thus extending the flight envelope only to the left. Please keep in mind that it has applications throughout the flight envelope. In the middle as a stall/spin preventer or recovery device. In the high/fast region for enhanced directional stability and in the low slow region where carrier pilots are always looking for more control power, wherever they can find it.

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Future Testing Possibilities

ARPA Support

- HMD / SIM Links

JAST Support

- *High / Fast*
- *Low / Slow*

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So where are we now? That is the $6.4 million dollar question. Let's just say that it's my firm desire and hope that the program can continue. There are plans in place to use us for another ARPA sponsored effort that relates to information technology and fusing real and virtual targets over multiple sites via computer networks. We have a Helmet Mounted Display system which would prove useful for this testing.

And there appears to be interest in having some near term thrust vectoring experiments performed in both corners of the envelope. So keep watching the aviation trade publications for word of our progress.

Thank you for your interest, and I can take a couple of questions.