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# FLIGHT EVALUATION OF PNEUMATIC FOREBODY VORTEX CONTROL IN POST-STALL FLIGHT

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DRYDEN FLIGHT RESEARCH CENTER
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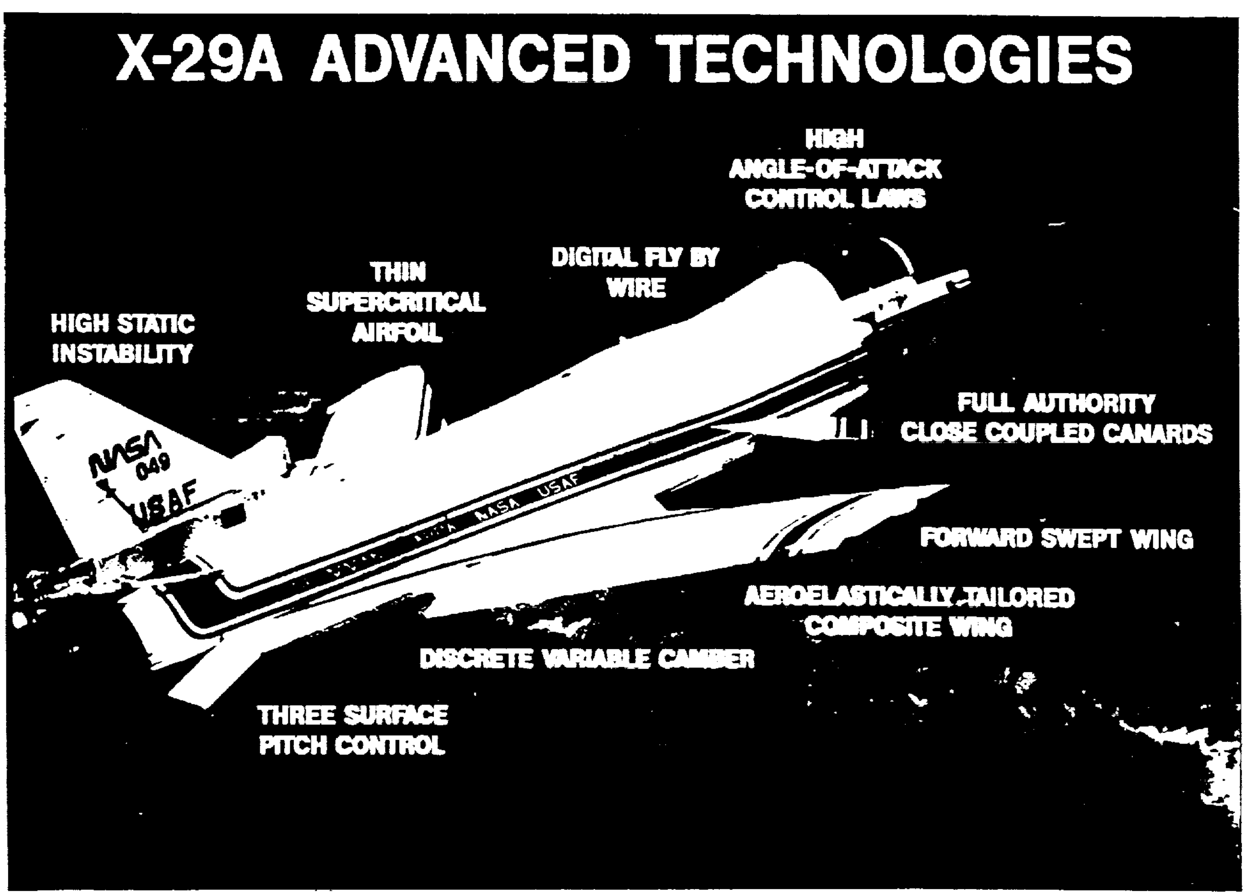
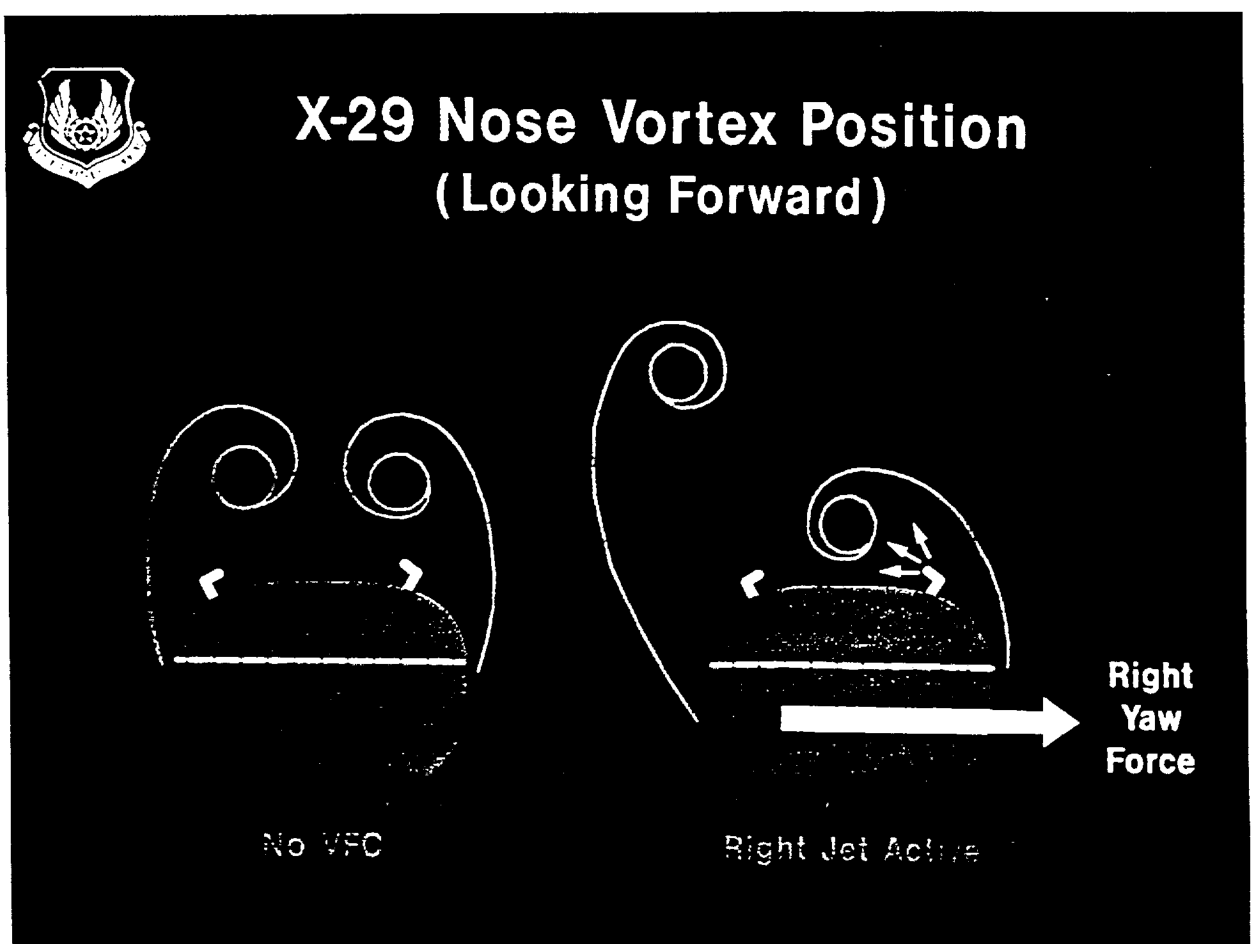
The high angle-of-attack research vehicle used in this flight test was the X-29A Ship 2. Many of you have seen previous reports on this aircraft's capabilities. This chart should refresh your memories on the technologies on-board. The most notable, of course, is the forward-swept wing. The close-coupled canards were selected to make the aircraft 35 % statically unstable. The digital flight control system employed high alpha control laws which permitted trimmed 1G flight to about 50 degrees and maneuvering flight to about 40 degrees angle of attack.



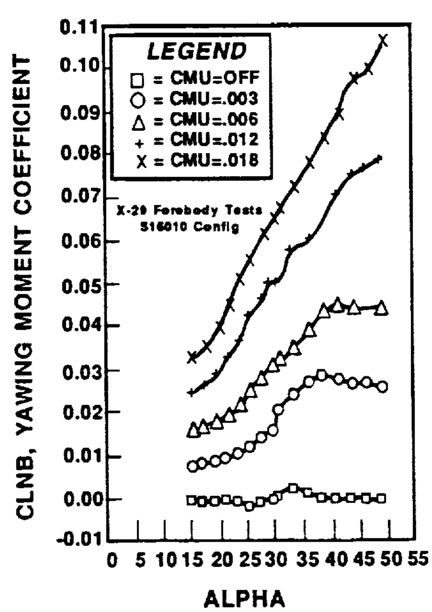
Before we get into the discussion of results of the ground and flight tests, let me say some words about the specific technology upon which I'm reporting. Vortex Flow Control is an aerodynamic concept for producing directional control power at angles of attack where the conventional rudder loses its effectiveness. By using high pressure air jets, located symmetrically on either side of the upper nose section, the vortices shedding off of the nose at high AOA can be moved on command. Blowing on the right side lowers the static pressure there, moving the right vortex closer to the surface. Entrainment of air blows the opposite vortex away from the nose, raising the pressure on the left side. The net result is a nose-right force acting on a long moment arm from the aircraft CG, providing a substantial yawing moment.



# X-29 VFC WIND TUNNEL RESULTS
## FOREBODY ONLY

Now some results, starting with our ground tests. The first phase of the program was done in the wind tunnel. We used a 1/8- scale forebody model of the X-29 to perform nozzle optimization studies. Parameters of specific interest included the nozzle size and shape, its location and orientation on the nose, and the blowing coefficient. The data clearly showed that a significant yawing moment could be generated with blowing from AOA of 15 to 55 degrees. Low blowing rates which were of practical interest for flight test produced almost constant effectiveness between 35 and 55 degrees angle of attack.

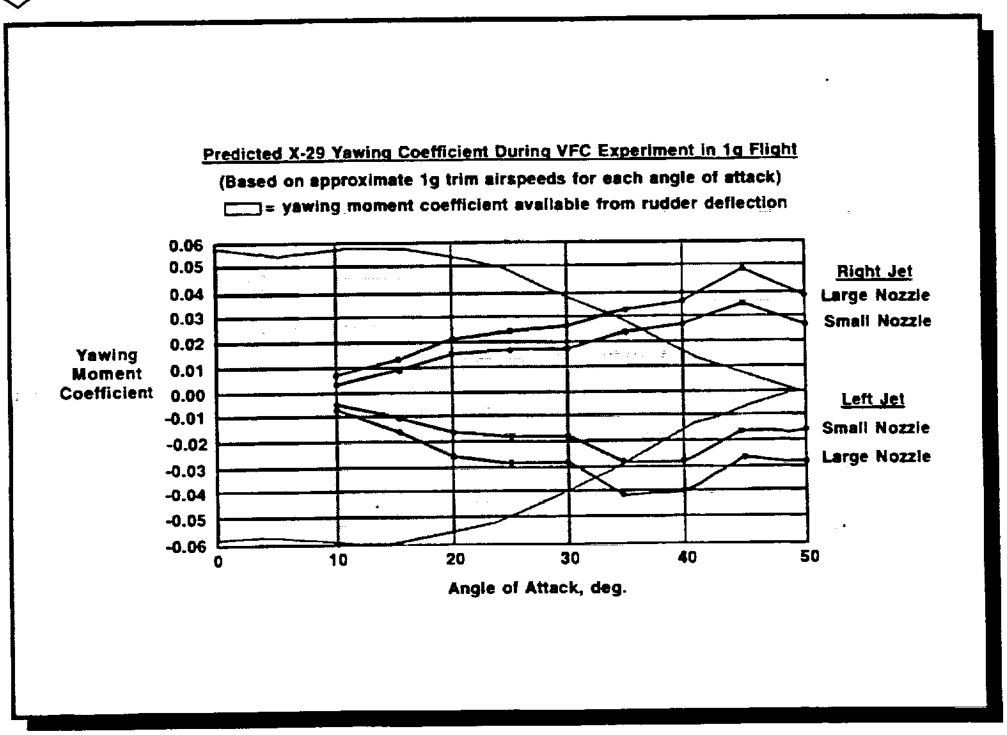
## X-29 VFC WIND TUNNEL RESULTS



X-29 VFC WIND TUNNEL RESULTS
FULL CONFIGURATION YAWING MOMENT

Buoyed by our success with the forebody model, we tested a 1/8-scale full aircraft model in the Grumman Low Speed wind tunnel. In order to vary the mass flow coefficient, we used two different size nozzles, both of the same basic configuration. This chart shows some synergistic benefit from the full configuration aircraft model. Besides creating side force on the fuselage, the manipulated vortex swept the canopy, providing about 10% more moment than seen in the forebody-only testing. The data shown here have already been transposed to flight test conditions. As you see, we can recover a large portion of the lost rudder power above 30 degrees angle of attack.

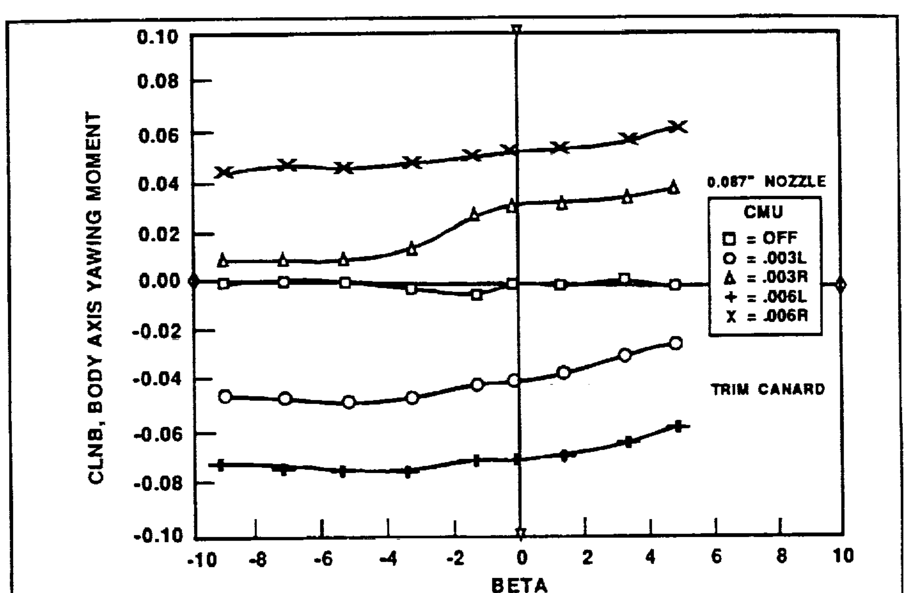
## X-29 VFC PROGRAM
### YAWING MOMENT PREDICTION



## X-29 VFC WIND TUNNEL RESULTS
## FULL CONFIGURATION $C_n$ WITH SIDESLIP

To complete the wind tunnel static data picture, we need to look at both the sideslip effect on induced yawing moment and the pitching moment effects caused by the vortex manipulation. This slide shows that the yawing moment is quite well-behaved with sideslip on the model. The data were taken at 35 degrees AOA and appear almost independent of sideslip.

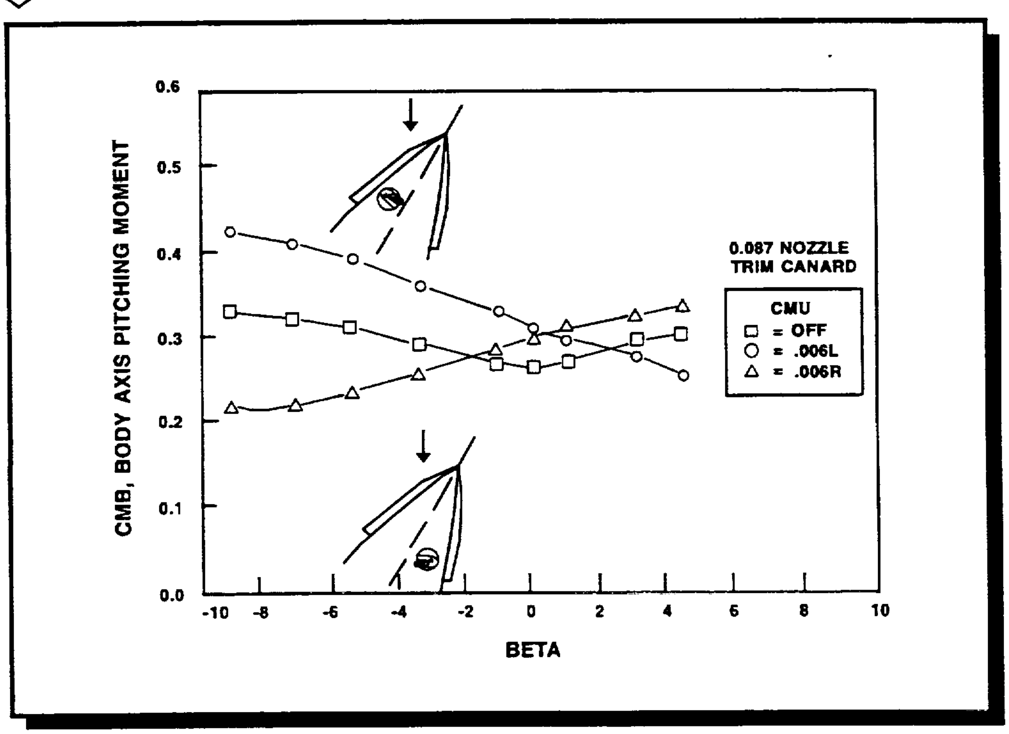
# X-29 VFC WIND TUNNEL RESULTS



# X-29 VFC WIND TUNNEL RESULTS
# FULL CONFIGURATION PITCHING MOMENT

Aircraft pitch control power is a critical parameter at very high angle-of-attack conditions and pitching moment increments due to forebody vortex control can aggravate the problem. This slide presents the effects on the pitching moment versus sideslip at 40 degrees angle of attack. A nose-up increment was observed at zero beta on the order of $\Delta C_M = 0.05$. The increments at sideslip depended on whether the upwind or the downwind jet was active. The downwind jet, which is the one responsible for initiating and maintaining the sideslip condition, generated a desirable nose-down pitching moment. The upwind jet, which would return the aircraft to zero beta, generated an undesirable nose-up increment. The observed increments are substantial, but fall within the nose-down authority of the X-29 aircraft up to 50 degrees AOA.

## X-29 VFC WIND TUNNEL RESULTS

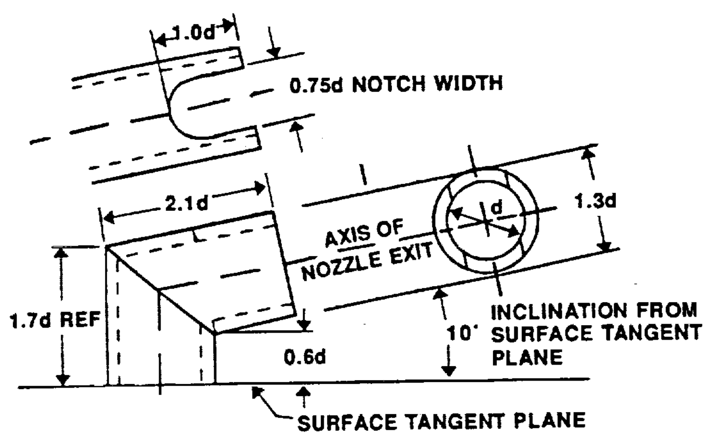


VFC OPTIMIZED
NOZZLE DETAILS

These next two slides show you the specific nozzle configuration which produced the results just presented. The important thing to notice on the nozzle detail is the slot and the 10 degree inclination. This concept produced a sheet of air, creating a much larger influence on the vortices than the round jet with which we started.

# VFC OPTIMIZED NOZZLE DETAILS

d = NOZZLE INTERNAL DIAMETER, SELECTED FROM SUPPLY PRESSURE AND MASS FLOW REQUIREMENTS.
ALL OTHER DIMENSIONS AS FRACTIONS OF "d".

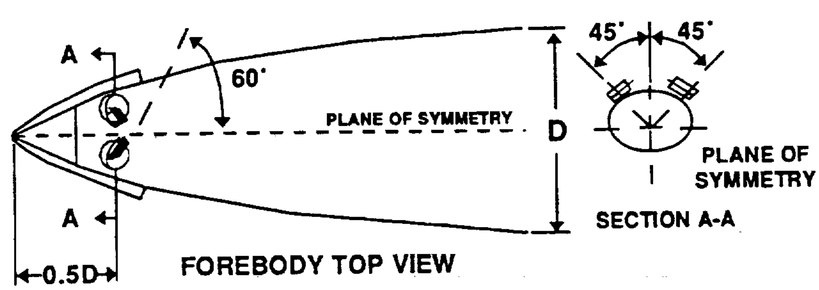


# X-29 FOREBODY
# NOZZLE CONFIGURATION

The control of the vortices was also sensitive to nozzle location on the forebody. A position too close to the apex of the forebody or the trailing edge of the chines disrupted the formation and shedding of the vortices. Further, it was determined that canting the nozzles in-board sixty degrees helped to pull the active-side vortex further around the fuselage, with the resulting low pressures influencing more of the surface and cross-feeding more external air into the opposite vortex. It should be noted here that our solution is not by any means the only possible combination of nozzle shape, size and location.

## X-29 FOREBODY NOZZLE CONFIGURATION

D = FOREBODY MAXIMUM DIAMETER FROM WHICH THE FOREBODY FINENESS RATIO IS DETERMINED.
THE AXIAL LOCATION OF NOZZLES IS SPECIFIED AS A FRACTION OF THIS DIAMETER.

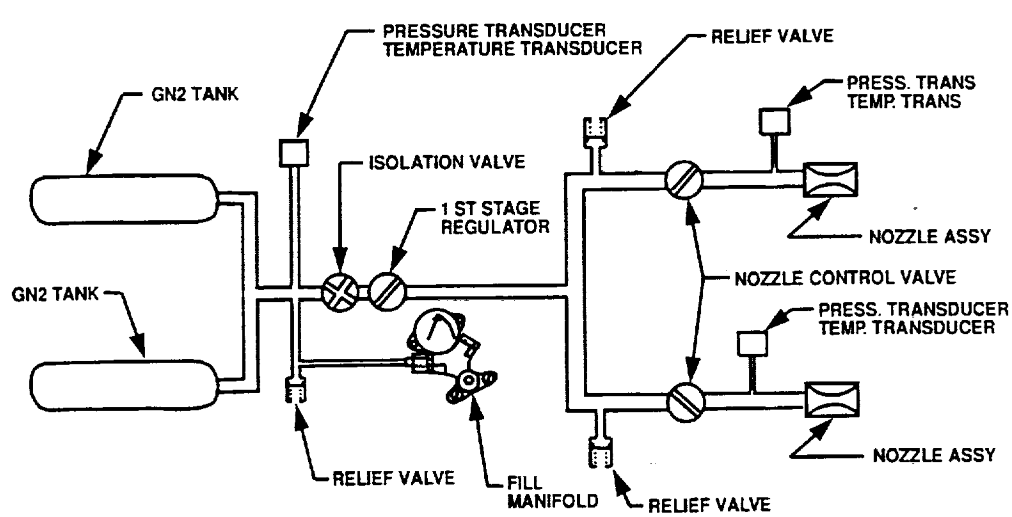



AXIS OF NOZZLE EXIT POINTED 60 DEGREES INWARD TOWARD PLANE OF SYMMETRY.

# X-29 VFC SYSTEM
# STORED GAS SCHEMATIC

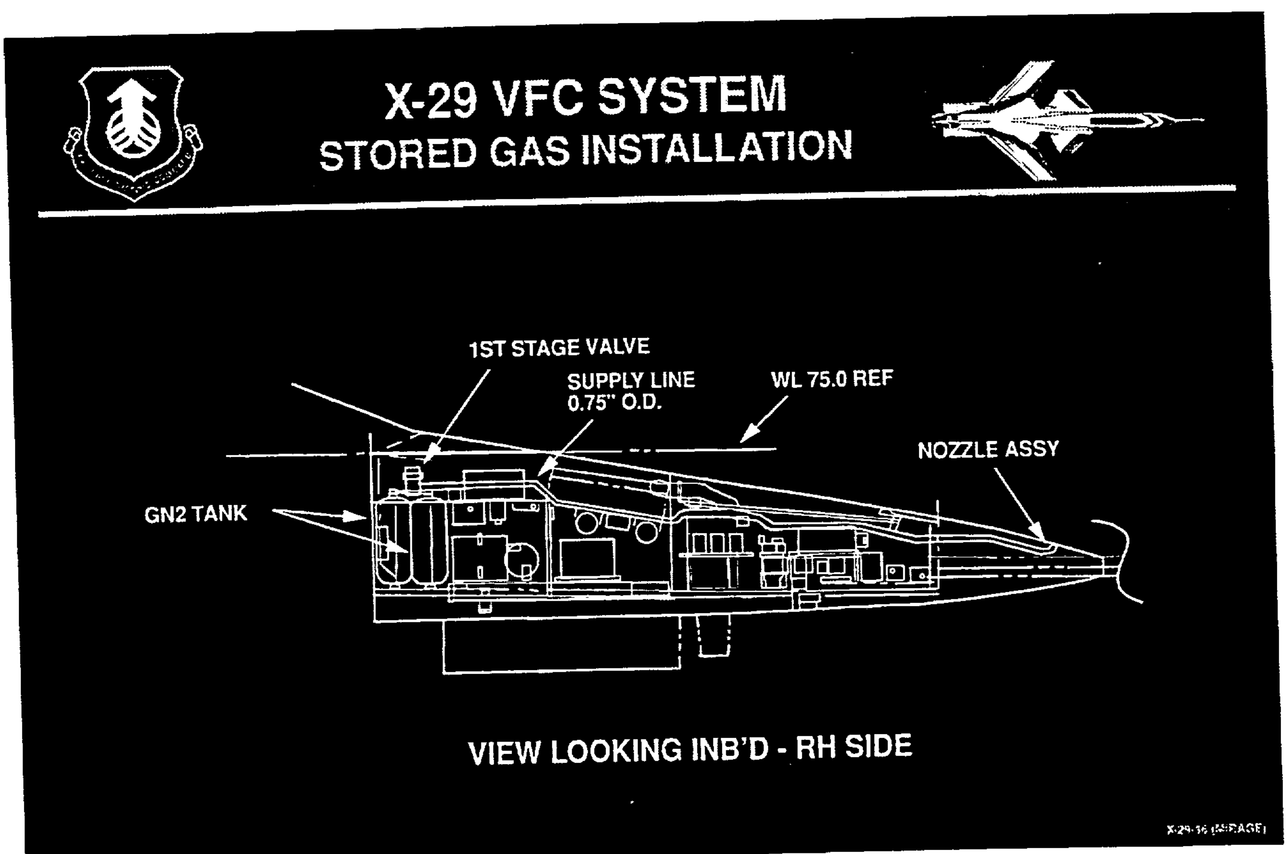
Let's turn our attention now to the VFC flight test program. The mechanization of an on-board blowing system is shown here. The system was designed to support a proof-of-concept experiment and as such had limited capability. Two Kevlar-wrapped, aluminum-lined storage bottles carried up to 13 pounds of 6000 psi gaseous nitrogen ($GN_2$) aloft. When the system was activated, gas pressure was reduced through two stages of regulation to a nozzle reservoir pressure of 400 psi. Flow was directed by the pilot through the left, right, or both nozzles. Weight flow was calculated from pressure and temperature measurements at two locations -- near the storage tanks and a very precise calculation just upstream of the calibrated nozzles.

**X - 29 VFC SYSTEM**
**STORED GAS SCHEMATIC**



# X-29 VFC SYSTEM
## STORED GAS INSTALLATION

Location of the system in the X-29 is shown in this slide. The storage bottles were located just forward of the cockpit fire wall along with the first stage of pressure reduction and the fill valve. The air was routed forward along the top of the nose and into the nose cone attachment compartment. At this point, final pressure reduction to 400 psi was accomplished and individual shutoff valves directed the nitrogen to the side of the aircraft commanded by the pilot.

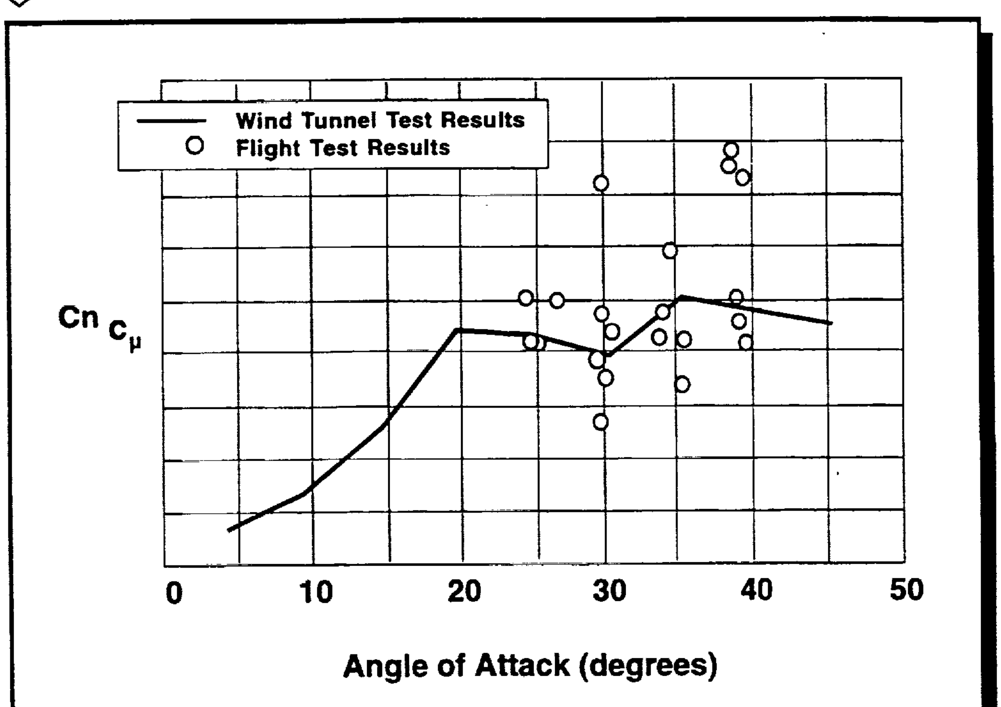


## VFC EFFECTIVENESS AT ZERO SIDESLIP

The best measure of the effectiveness of VFC is the control derivative of yawing moment due to blowing, $Cn_{C_\mu}$. The chart shows the results obtained from one second pulses of the VFC system during stabilized 1G high alpha test points with less than one degree of sideslip. Three nozzle sizes were tested to cover a range of mass flows (0.202, 0.286, and 0.350 in. dia.). Inertial coupling and engine gyroscopic effects were subtracted from the total flight-measured accelerations to yield the flight values of the aerodynamic coefficients. Measured control surface positions, body-axis rates, and flight conditions were then used to query the aerodynamic database for predicted time histories of the coefficients. An example of the two results is shown here. At angles of attack above 35 degrees, the wing rock and zero sideslip asymmetries of the basic aircraft complicated the analysis of the VFC flight data, resulting in the increased scatter that can be seen at 40 degrees angle of attack.

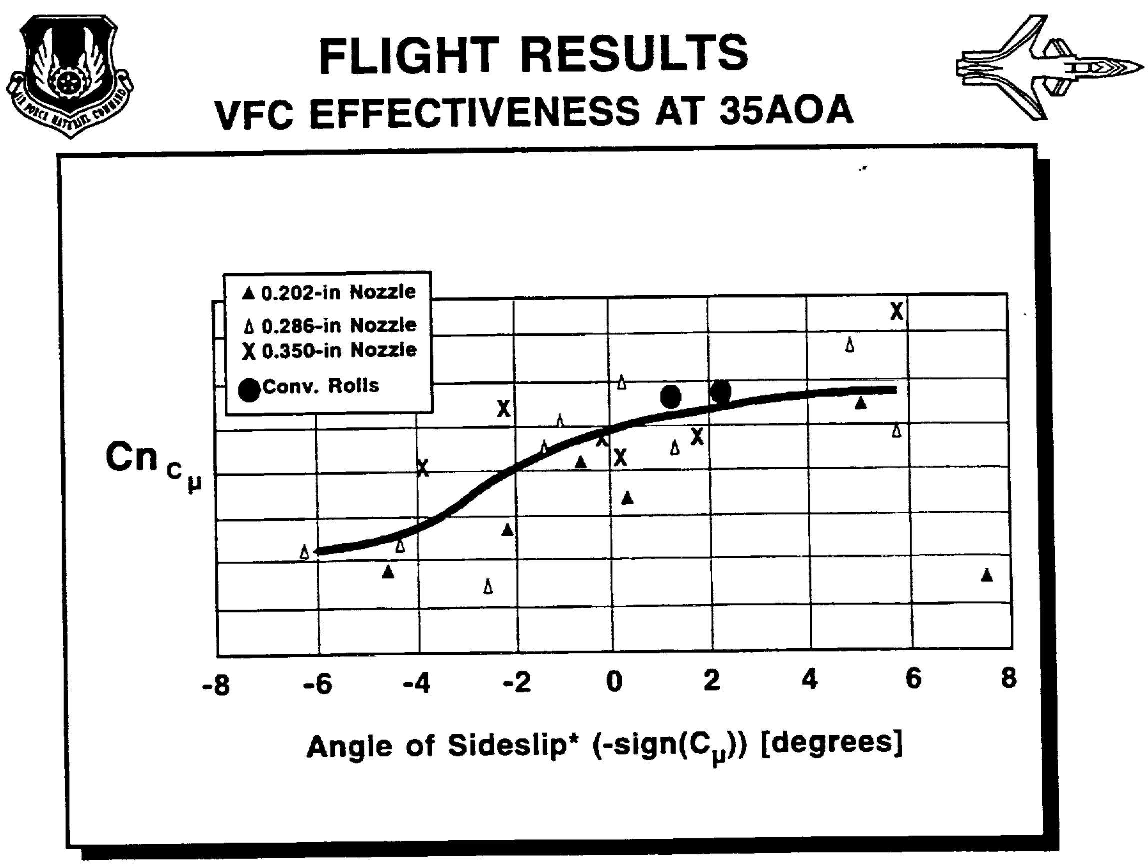
# FLIGHT RESULTS

### VFC EFFECTIVENESS AT ZERO SIDESLIP



# VFC EFFECTIVENESS AT 35 AOA
# WITH SIDESLIP

This slide shows the VFC effectiveness at 35 AOA due to sideslip. Again, results are from one second pulses. The points on the left resulted from blowing to reduce the pre-established sideslip. Points on the right occurred when blowing was used to increase sideslip. VFC strength does not decrease much when blowing on the same side as the pre-established sideslip; its strength does degrade somewhat when blowing on the opposite side. This suggests that while VFC may be very useful for extended-duration maneuvers, during which VFC causes moderate increasing sideslip, it will not be as effective in reducing a pre-existing sideslip condition. Also shown are the results of two "conventional roll" maneuvers, in which a short VFC pulse was used to oppose the yaw rate generated by a full-stick roll. The data show that aircraft rates do not significantly influence effectiveness.

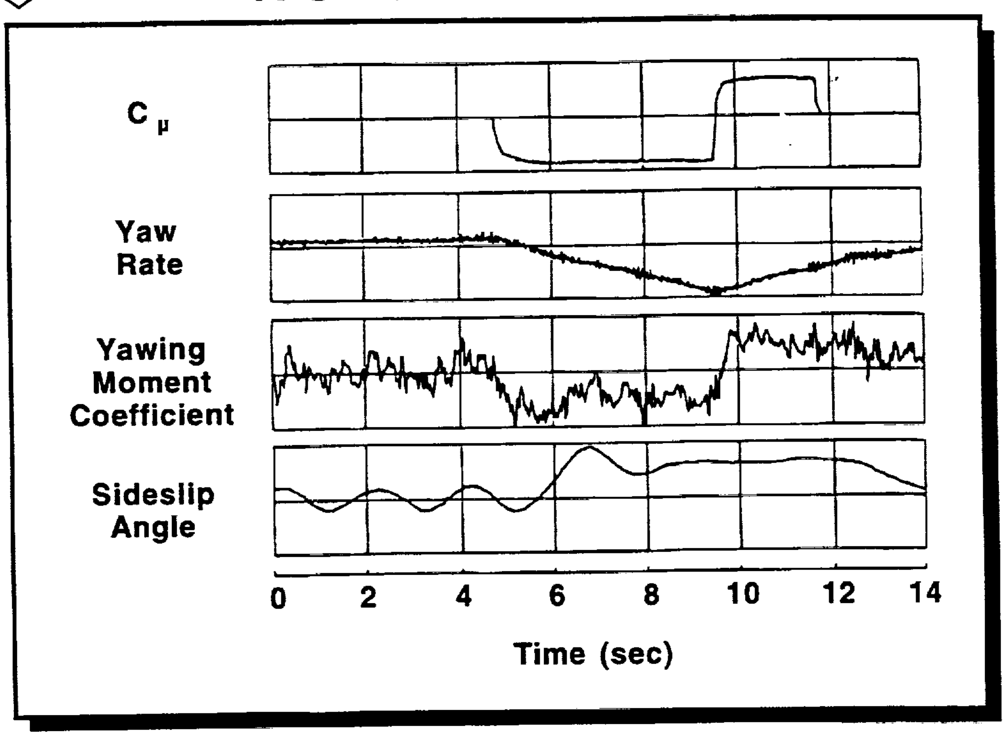


# "VFC ROLL" AT 40 AOA

Here are the results of a "VFC-Roll" at 40 degrees AOA. The maneuver consisted of stabilizing the aircraft in 1G flight at the target angle of attack, activating the left VFC nozzle until a target yaw rate was reached, and then switching to the right nozzle in order to stop the VFC-induced rate. The maneuver was flown with the lateral stick and rudder pedals neutral. The purpose of this maneuver, beyond the demonstration of a pure-VFC roll, was to determine the aerodynamic time delay associated with switching from one nozzle to the other. This data is essential for the design of a VFC-based flight control system and can not be obtained from static wind tunnel tests. As can be seen, the time for the full reversal of the yawing moment was less than one half second. Further, the yaw acceleration after the reversal was as strong as the initial acceleration.

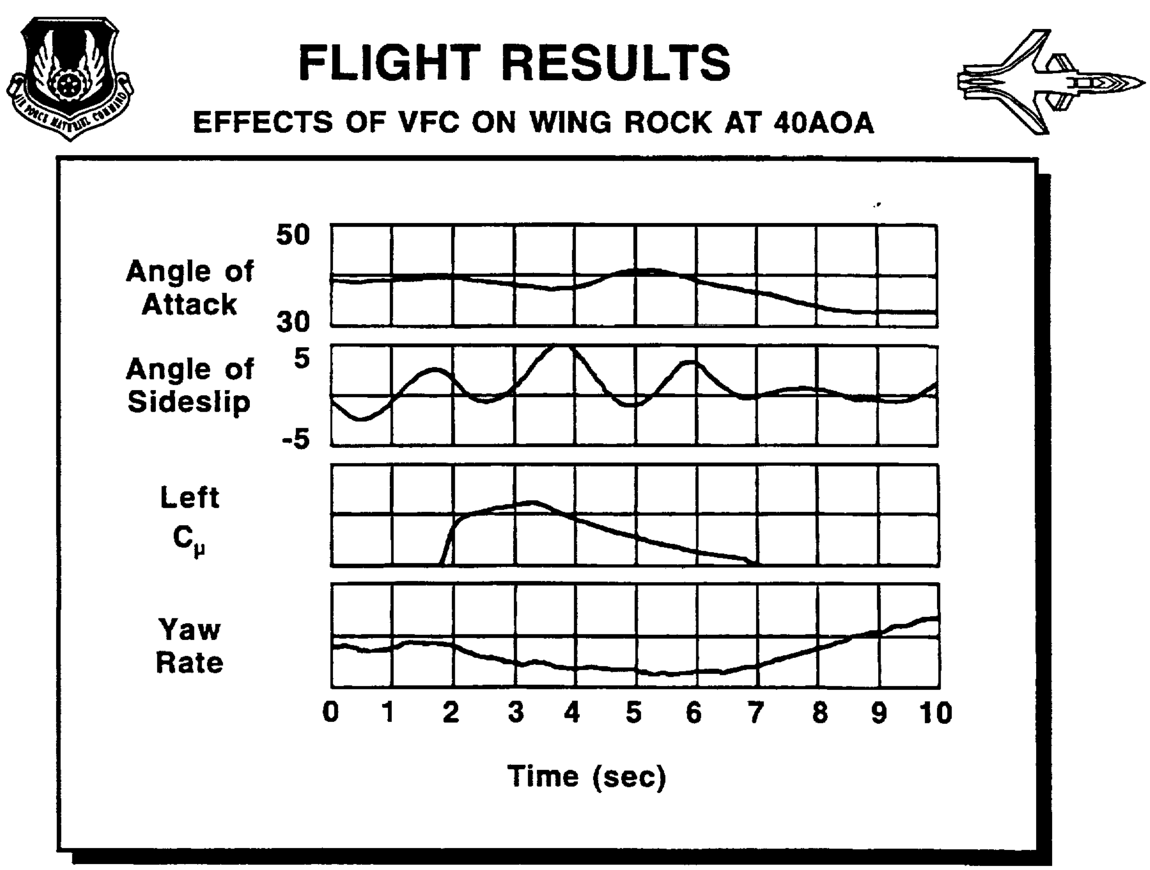
**FLIGHT RESULTS**

**"VFC-Roll" at 40AOA**



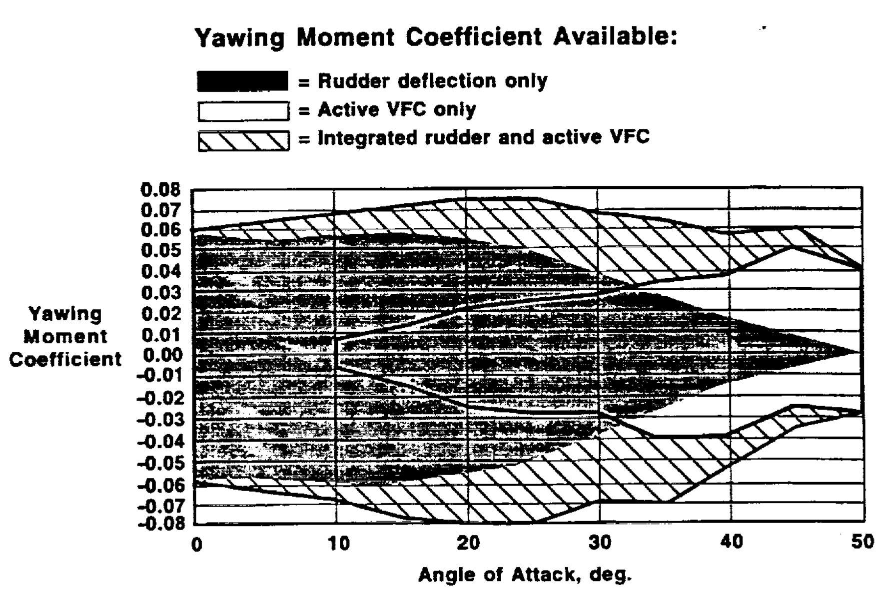
# EFFECTS OF VFC ON WING ROCK

One of our program goals was to determine the effects of VFC on wing rock. Wing rock behavior is actually a body rock caused by the oscillatory motion of the forebody vortices. The plot shows the time-history of a 1.5 second VFC pulse at 40 degrees angle of attack. As seen in the sideslip data, this maneuver begins with typical wing rock at 0.5 Hz with a magnitude of ±2 degrees sideslip. The average sideslip angle shifts slightly nose-left, but the frequency and amplitude of the wing rock remain relatively constant. A very careful look at the data reveals a slight reduction in wing-rock amplitude towards the end of the blowing pulse. Our plan to examine wing-rock effects at 40 alpha in the absence of sideslip required short pulses which rendered our results inclusive. By countering the sideslip and roll coupling with aero surfaces at 35 alpha, blowing longer may indeed have eliminated wing rock.



How can we use what we've learned to enhance the capability of an advanced weapon system? It seems clear that the best way to include active blowing is to imbed it within the primary control laws. Since forebody blowing serves as a roll coordinator and sideslip regulator, functions satisfied by the rudder at low angles of attack, it behooves the designer to integrate $\gamma Cn_{c\mu}/\gamma t$ (blowing) with $\gamma Cn_{\delta r}/\gamma t$ (rudder) over the entire flight envelope of the aircraft. The combined system would then produce the yaw control power displayed here. The system would be robust enough to coordinate any rolling maneuver within the confines of the aircraft's operational envelope.

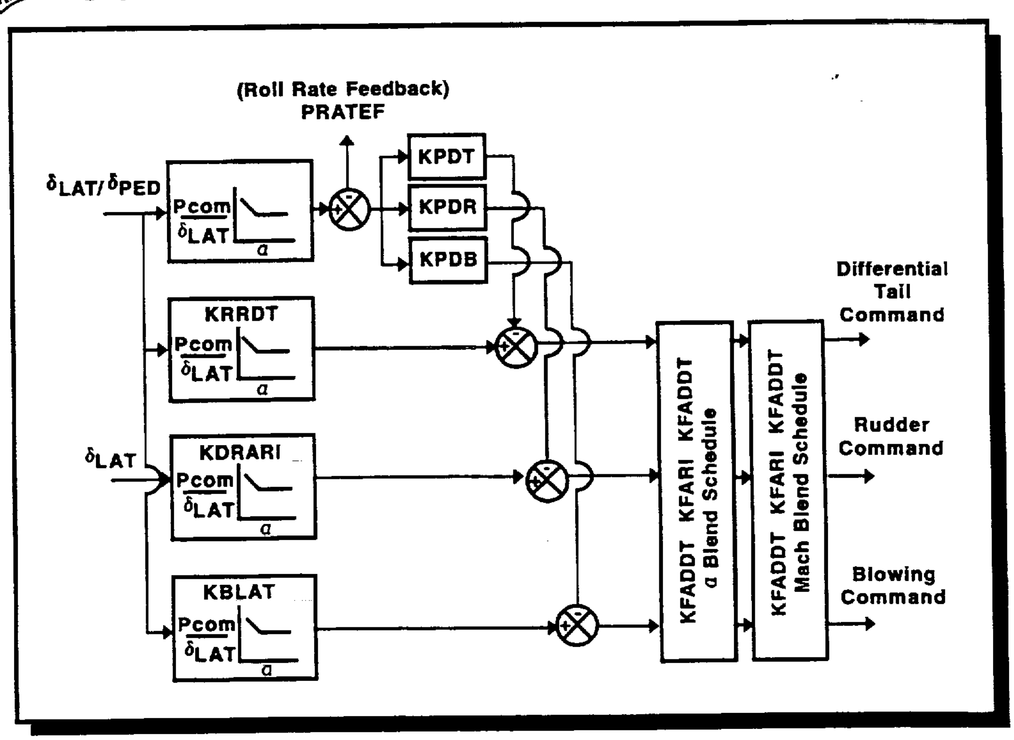
## INTEGRATED YAWING MOMENT PREDICTION FOR RUDDER AND ACTIVE VFC



PROPOSED F-15 LATERAL CONTROL
LAWS WITH ACTIVE VFC

An example of this integration is shown in this slide. This is the modified lateral control law for an F-15 aircraft. Note that forebody blowing has been blended with both the horizontal tail and rudder. A six degree of freedom (SDF) solution of the equations of motion using this blended blowing model was performed.

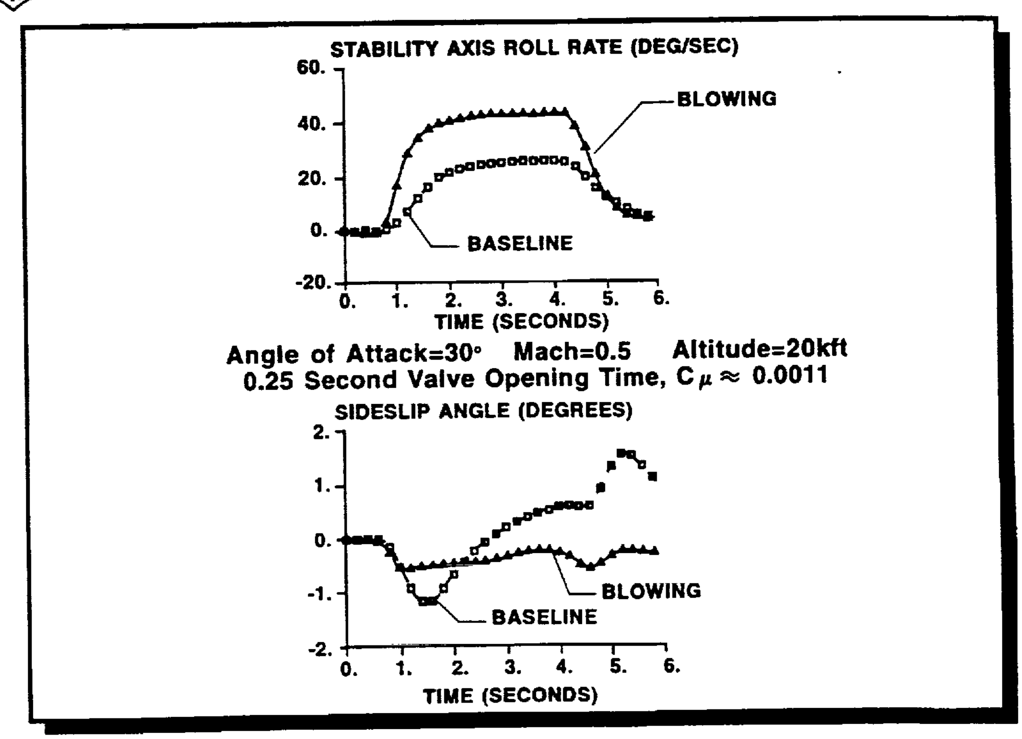
## PROPOSED F-15 LATERAL CONTROL LAWS WITH ACTIVE VFC



# SIMULATED F-15 ROLL PERFORMANCE WITH ACTIVE VFC

Just a reminder that one of the prime uses of Vortex Flow Control is the coordination of lateral commands. This slide shows the results of the simulation using the integrated control law. The data clearly show a 100 % improvement in stability axis roll rate while at the same time providing excellent coordination. Further, the roll acceleration has tripled over the baseline.

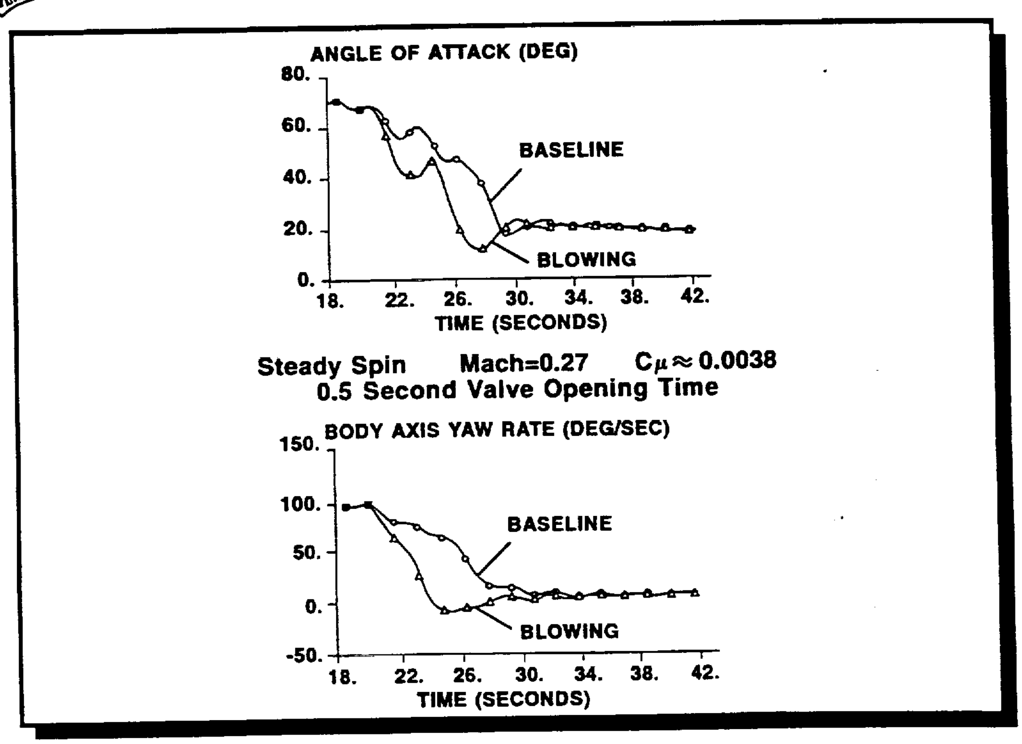
## SIMULATED F-15 ROLL PERFORMANCE WITH ACTIVE VFC



# SIMULATED F-15 SPIN RECOVERY WITH ACTIVE VFC

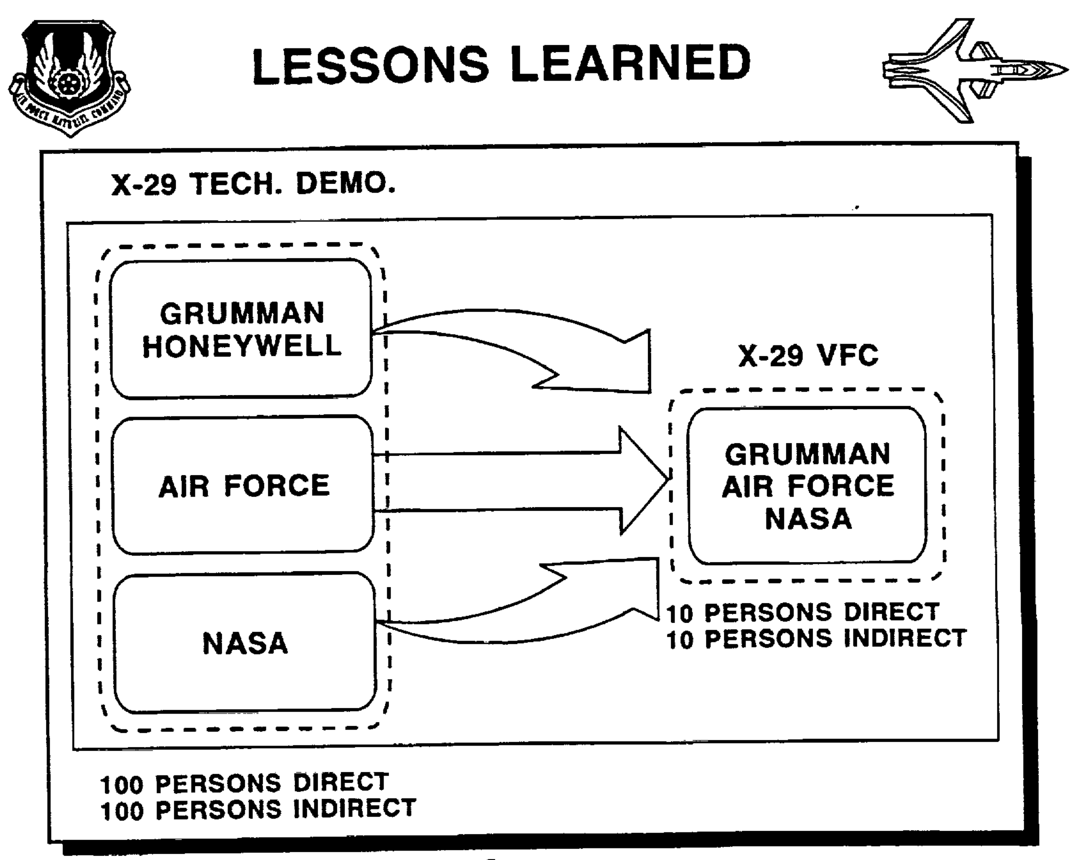
A fully-developed spin was simulated in order to compare baseline and VFC-enhanced control laws. The baseline configuration was used to recover the aircraft. At full recovery, the residual angle of attack was 20 degrees. The task was then repeated using the VFC-enhanced controls. But the task was now arbitrarily redefined to recover the aircraft to a 20 degree alpha condition. The angle of attack chart shows the two solutions give the same overall time to accomplish, about ten seconds. Note on the yaw rate chart that VFC actually ended the spin about five seconds sooner than the baseline control laws. At this point in time, the pilot had to leave his 40 degree angle-of-attack condition and capture the task-selected 20 degrees. So if the task was to simply recover the aircraft, VFC-enhanced controls were significantly superior.

SIMULATED F-15 SPIN RECOVERY WITH ACTIVE VFC



LESSONS LEARNED
TEST TEAM RESTRUCTURING

The final portion of my presentation will address a few "lessons learned" on the VFC program. The management of our critical experiment was our first hurdle. The X-29 Technology Demonstration Program had employed up to 200 people. The VFC experiment was a relatively small program which had a relatively small budget and had to be completed in a very short time. The trick was to establish a team with the right mix of technical people who could work effectively and efficiently together. We accomplished this with only ten full time engineers ranging from aerodynamicists to mechanical designers. The entire program from beginning of tunnel testing to the conclusion of flight test reporting was a mere 14 months.



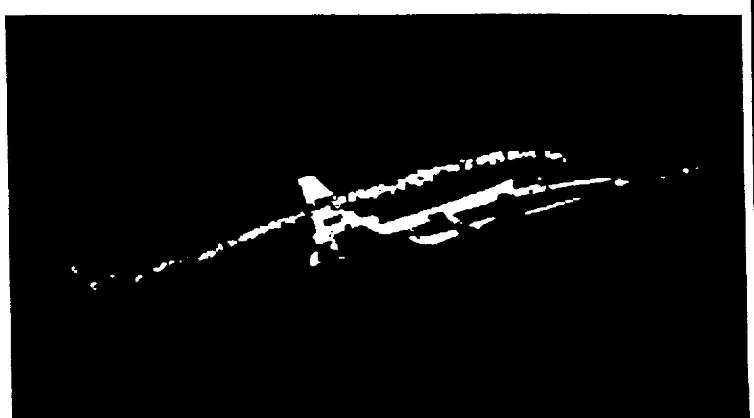
LESSONS LEARNED
TESTBED SELECTION

From a technical point of view, the VFC program needed a testbed with a high AOA, low speed capability, the flight regime where VFC was most effective. The X-29 was directionally stable at angles to almost 45 degrees and had a strong dihedral characteristic to counter the destabilizing effects of the asymmetric blowing. After seven years of test flights throughout the envelope, the aircraft had a large and well-understood data base.

## LESSONS LEARNED

### X-29

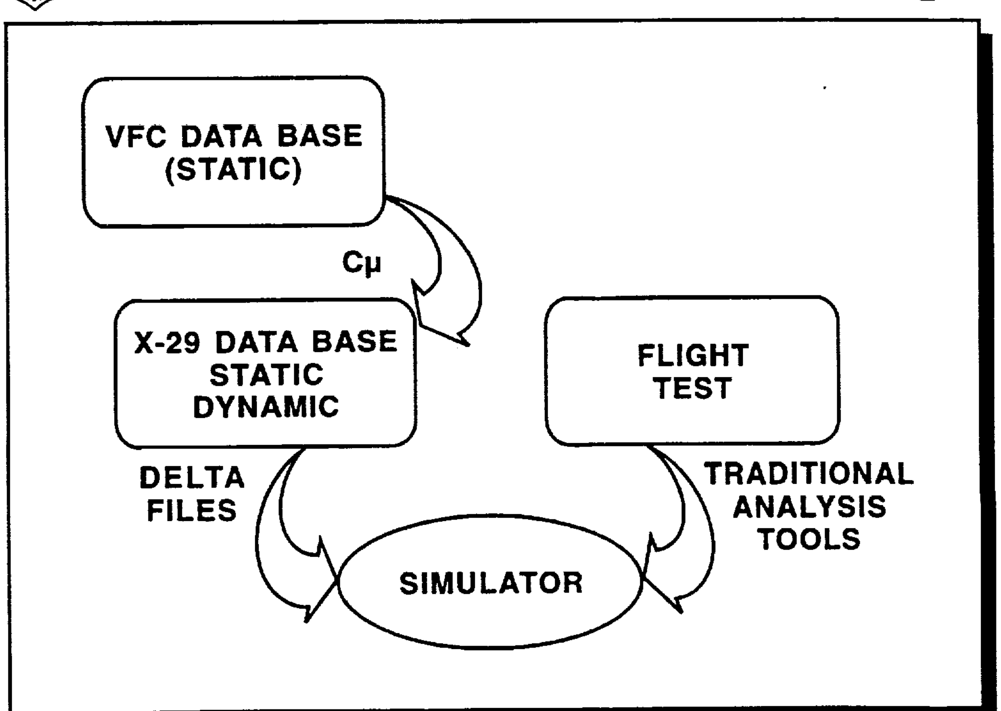
CAPABLE AIRFRAME
EXCELLENT DATABASE
STRONG DIHEDRAL TO
COUNTER VFC



## LESSONS LEARNED
## SIMULATION FOR RISK REDUCTION

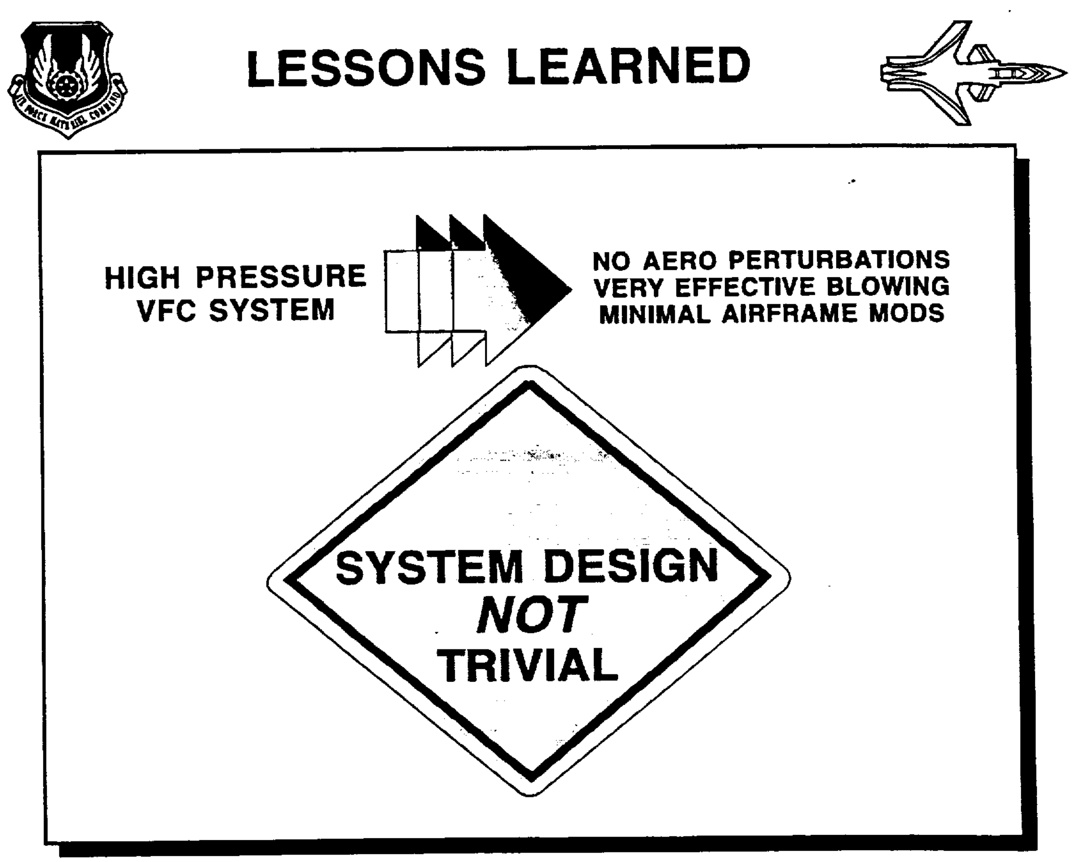
Up front it was considered somewhat of a risk to fly the VFC technology with only static wind tunnel data to predict performance. After much consideration we concluded that our X-29 flight validated simulation was of sufficient fidelity to warrant using the testbed to answer questions on dynamics. So we took our static data base, combined it with the aircraft's dynamics, and used the delta file approach to query the simulator on safety and performance of proposed flight test points. Following each flight, the aircraft model was updated if necessary. By doing this flight-to-flight, we minimized the risk of straying too far from actual aircraft performance.

## LESSONS LEARNED

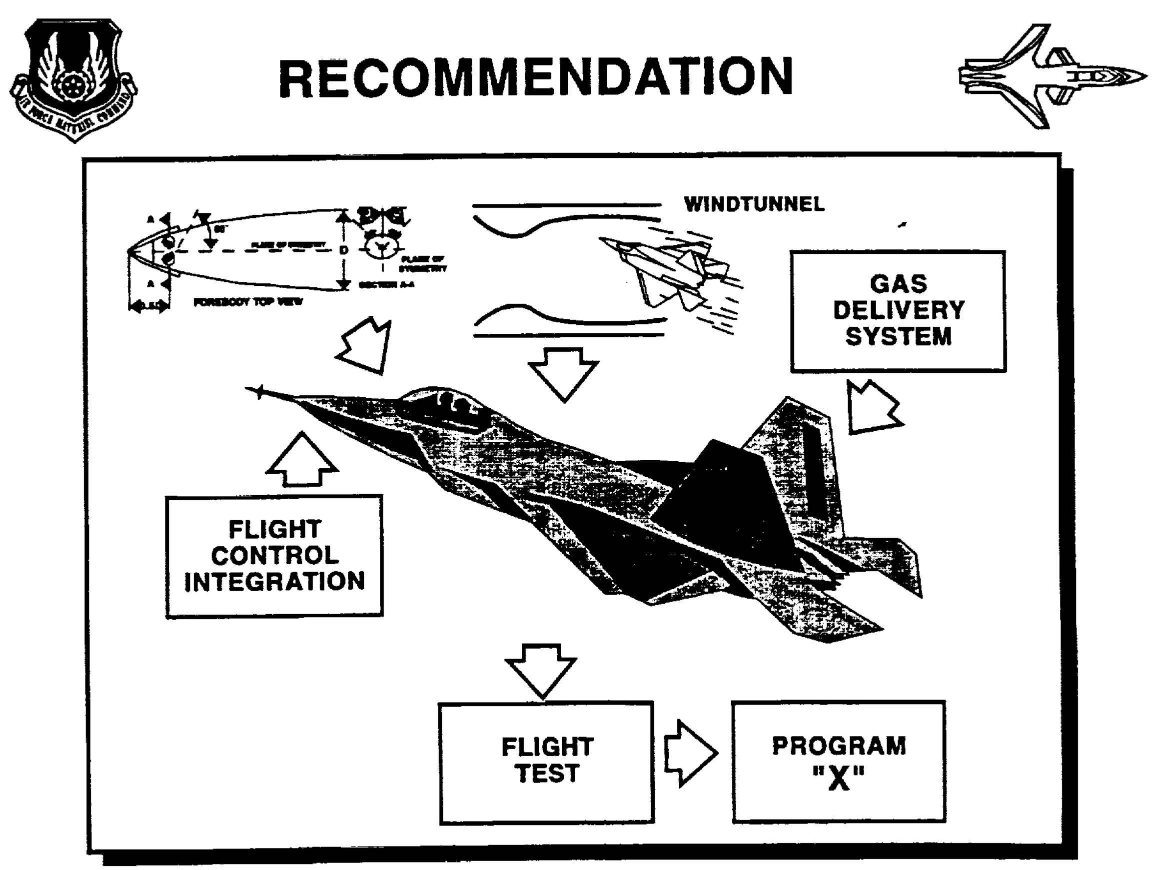


LESSONS LEARNED
BENEFITS OF HIGH PRESSURE SYSTEM

Early in the design phase of the program, we chose the high pressure delivery system as the most effective way to supply the nitrogen needed to power the VFC nozzles. A significant factor in this selection was the ability to store an adequate quantity of gas on board to conduct a meaningful experiment. Based on our results, a high pressure system would be the choice for an operational fully integrated system on an advanced or retrofitted fighter aircraft. High pressure translates to small hardware. Our small nozzles were very effective and caused no aerodynamic perturbations on the baseline characteristics. Further, aircraft modifications were minimized. High pressure in an operational environment does complicate the design process since additional compression devices and heat exchangers would be required, no trivial task!



The next step in pursuing the VFC technology as a viable option for incorporation on an operational aircraft is to fully integrate it into the flight control system and vehicle subsystems on a candidate testbed. This step requires three distinct yet interrelated tasks. The on-board gas delivery supply system, probably using engine bleed air, must be developed. Static and dynamic wind tunnel data must be acquired for the candidate testbed configuration. Finally, the testbed itself must be designed, including it's upgraded flight control laws, modified or built, and flight tested throughout its total operating envelope. A well-laid-out program should produce results which lend credence to the hypothesis that VFC is a mature technology ready for application.



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The goal of the Fourth High Alpha Conference, held at the NASA Dryden Flight Research Center on July 12–14, 1994, was to focus on the flight validation of high angle-of-attack technologies and provide an in-depth review of the latest high angle-of-attack activities. Areas that were covered include, high angle-of-attack aerodynamics, propulsion and inlet dynamics, thrust vectoring, control laws and handling qualities, tactical utility, and forebody controls.

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