Status of F16XL SSLFC Numerical Design Validation

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The F-16XL SSLFC Program is a joint ongoing effort involving Rockwell's North American Aircraft Division, NASA Ames-Dryden Flight Research Facility, and NASA Langley Research Center. The objectives of the program are to demonstrate that laminar flow can be obtained on a highly swept wingat supersonic speeds, validate the capabilities of a numerical methodologydesigned to predict boundary layer transition and validate the capabilities of the methodology in the design of active and passive LFC concepts.

The F-16XL SSLFC Program consists of the design, fabrication, installation, and flight test of an active laminar flow control glove for the F-16XL. The glove design emphasized the active (suction) control of attachment line and crossflow boundary condition instabilities. The glove design envelop was constrained by the existing geometry, safety of flight considerations, and space requirements for the suction mechanism. The leading edge extension of the glove was limited to 10 inches for consideration of asymmetric flying qualities and the glove height above the existing surface restricted to two inches. The active (suction) portion of the wing extends to nominally 25% chord. The glove was constructed of a micro-perforated titanium sheet (hole diameter = .025 inches, spacing ratio = 1/8, sheet thickness = .0025 inches). The glove design includes 22 separate chambers to allow suction variation in the chordwise direction. The F-16XL SSLFC program is currently in the flight test phase.

SLK-DSK114-91 0430 4
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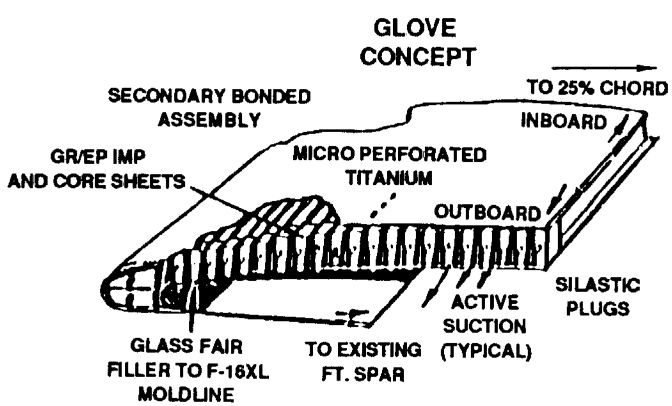
SUPERSONIC LAMINAR FLOW CONTROL EXPERIMENT

- Objective
  - Demonstrate supersonic laminar flow for highly swept planforms
- Approach
  - Validate design methodology through flight demonstration of an F-16XL at M = 1.6, 44K feet



COOPERATIVE EFFORT

- Rockwell International North American Aircraft
- NASA Ames-Dryden Flight Research Facility
- NASA Langley Research Center

MGE-910501-5663

The presentation will briefly address the design of the active glove and the glove fabrication and will emphasize the Computational Fluid Dynamics (CFD) methodology, ongoing flight test program, and tentative future plans for the program.

PRESENTATION OUTLINE

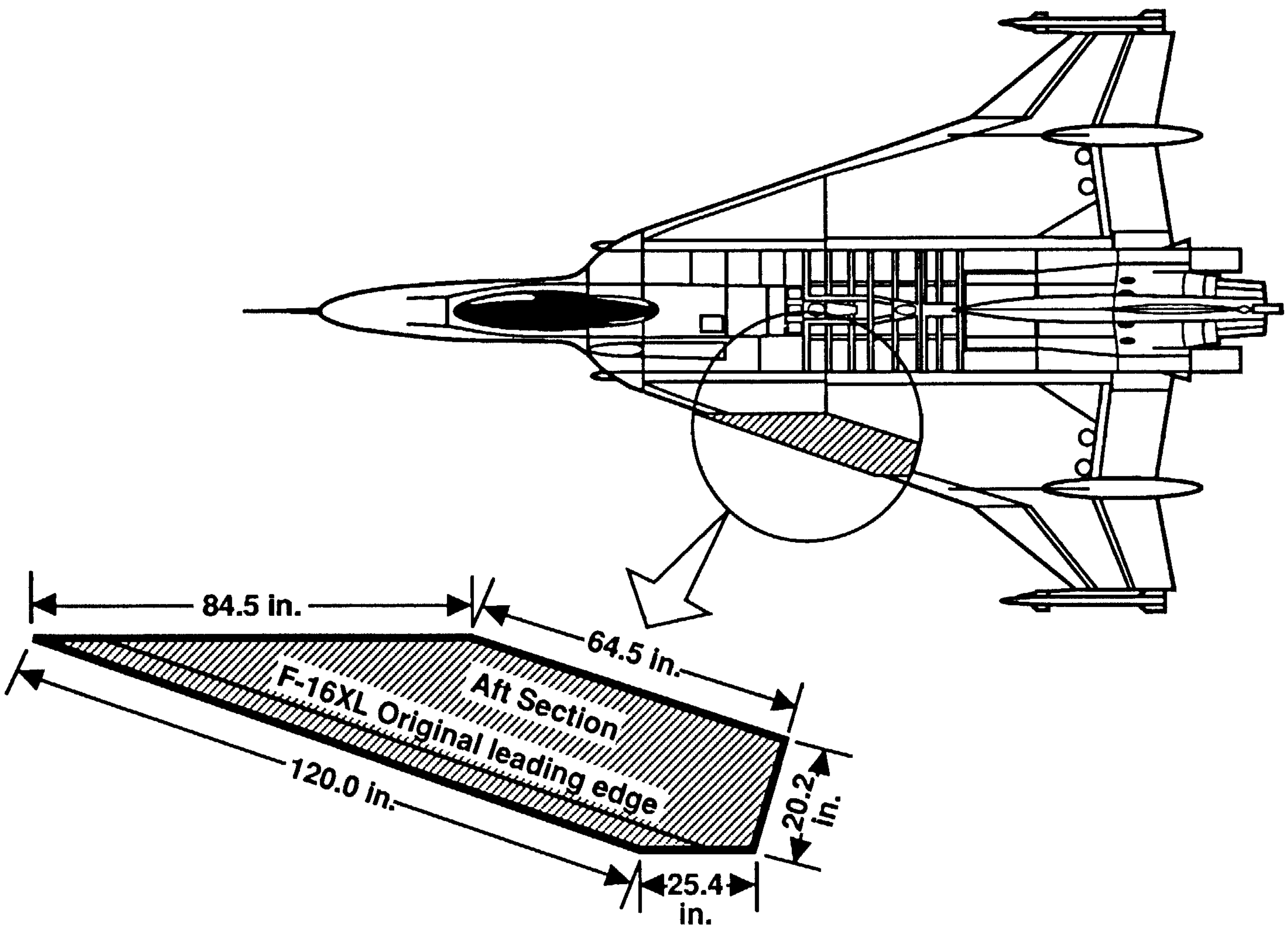
- LFC design for the F-16XL
- F-16XL glove fabrication and installation
- CFD approach
- Flight test results
- Future plans

SLK-DSK114-91 0430 5
Revised 05-07-91

The active glove was mounted on the inboard of the left wing of the F-16XL vehicle where the leading-edge sweep is 700 (the sweep of the outboard portion of the wing is 500). The active glove begins just aft of the leading edge on the lower surface, wraps around the leading edge and continues to nominally 25 % chord of the original wing. The flight design condition for the F-16XL SSLFC program was Mach number = 1.6, angle-of-attack = 20, and an altitude of 44,000 feet.

F-16XL SSLFC GLOVE

DESIGN CONDITION: MACH = 1.6, ALPHA = 2 DEG., ALT = 44K FT



MGE-910502-5680

The glove was designed with emphasis in avoiding attachment line transition and cross-flow transition. To achieve laminar flow at the design condition a smooth favorable pressure gradient augmented by suction was designed.

The design criterion for avoiding leading edge attachment line contamination was to keep the compressible momentum thickness Reynolds number at the attachment line below a value of 114. Based on empirical data the attachment line momentum thickness Reynolds number below which disturbances decay, was taken to be 114* and at values of 265* natural transition was assumed to occur. Between these limits the boundary layer state is affected by propagation of turbulence from the fuselage andinboard wing and the critical Reynolds number is configuration specific.

The criterion for control of crossflow instabilities was to keep the amplification factor below 6. An amplification factor of 6 is a conservative value (10 is commonly used). The amplification factor is a measure of the relative growth in amplitude of a disturbance seeded in the boundary layer.

Another consideration in the design was to minimize the suction hole velocity to avoid any disturbances due to the suction.

A series of codes including two-dimensional and three-dimensional Euler codes, boundary layer programs, and stability codes were used in an iterative design procedure to arrive at the final glove shape and suction distribution.

*Poll, D. I. A., "Transition Description and Prediction in Three-Dimensional Flows," AGARD Report R-709, Paper 5 March 1984.

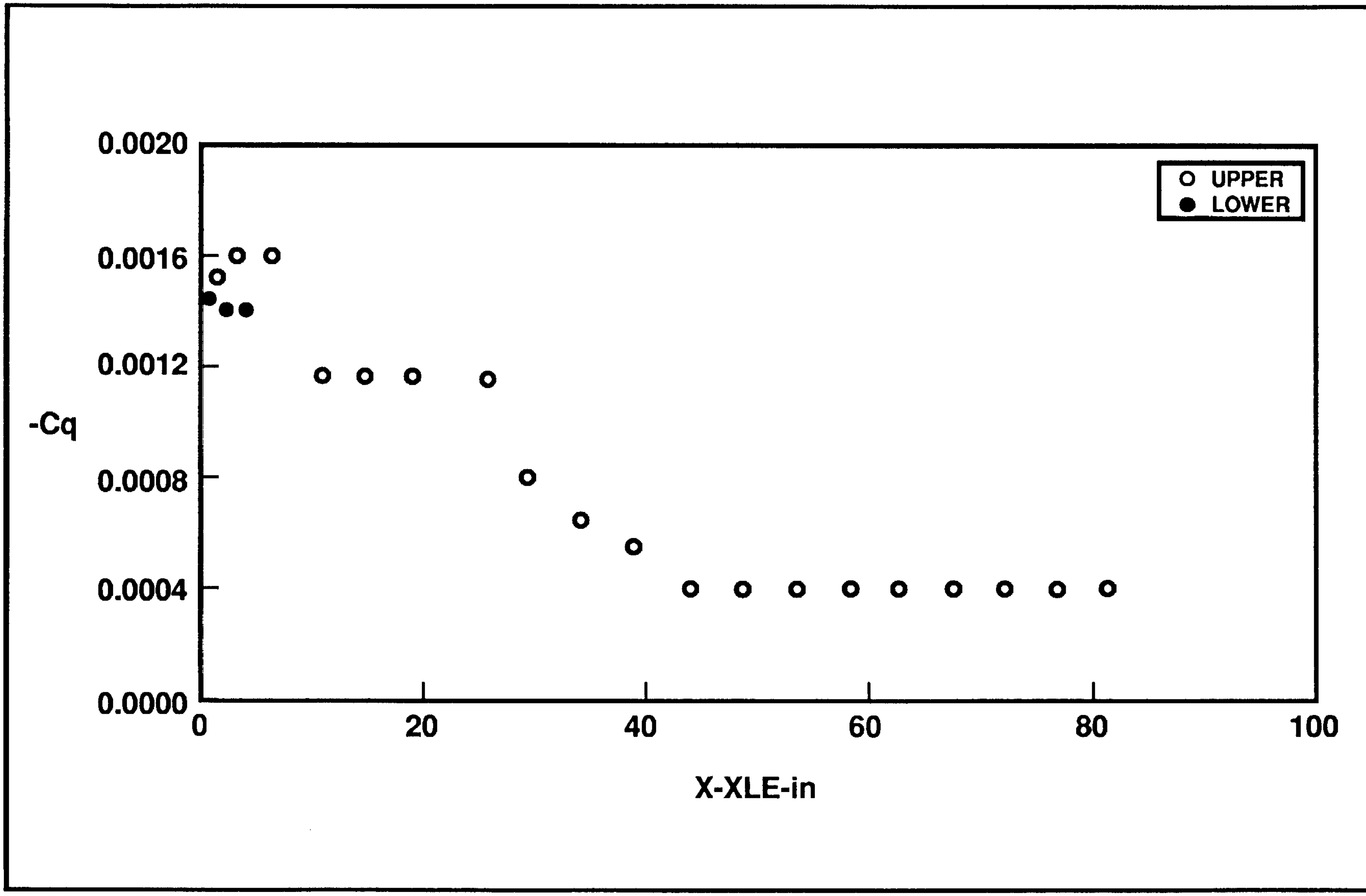
GLOVE DESIGN

- Design Criteria
  - Attachment line
    - Compressible $Re_\theta < 114$
  - Crossflow instabilities
    - Amplification factor $N < 6$
  - Minimize suction hole velocity
- Methodology
  - 2D Euler (yawed wing)
  - 3D Euler (space marching)
  - Boundary layer programs
  - Stability analysis

SLK-DSK114-91 0430 9
Revised 05-07-91

Restrictions on the minimum allowable bending radius (.25 inches) of the titanium sheet required suction coefficients of between -.001 and -.002 in the leading edge region to meet the momentum thickness Reynolds number criteria. The suction strength in the chordwise direction decreased meeting requirements of amplification factors less than 6 for crossflow instabilities. The variation in chordwise suction distributions was achieved through the twenty-two chordwise suction flutes.

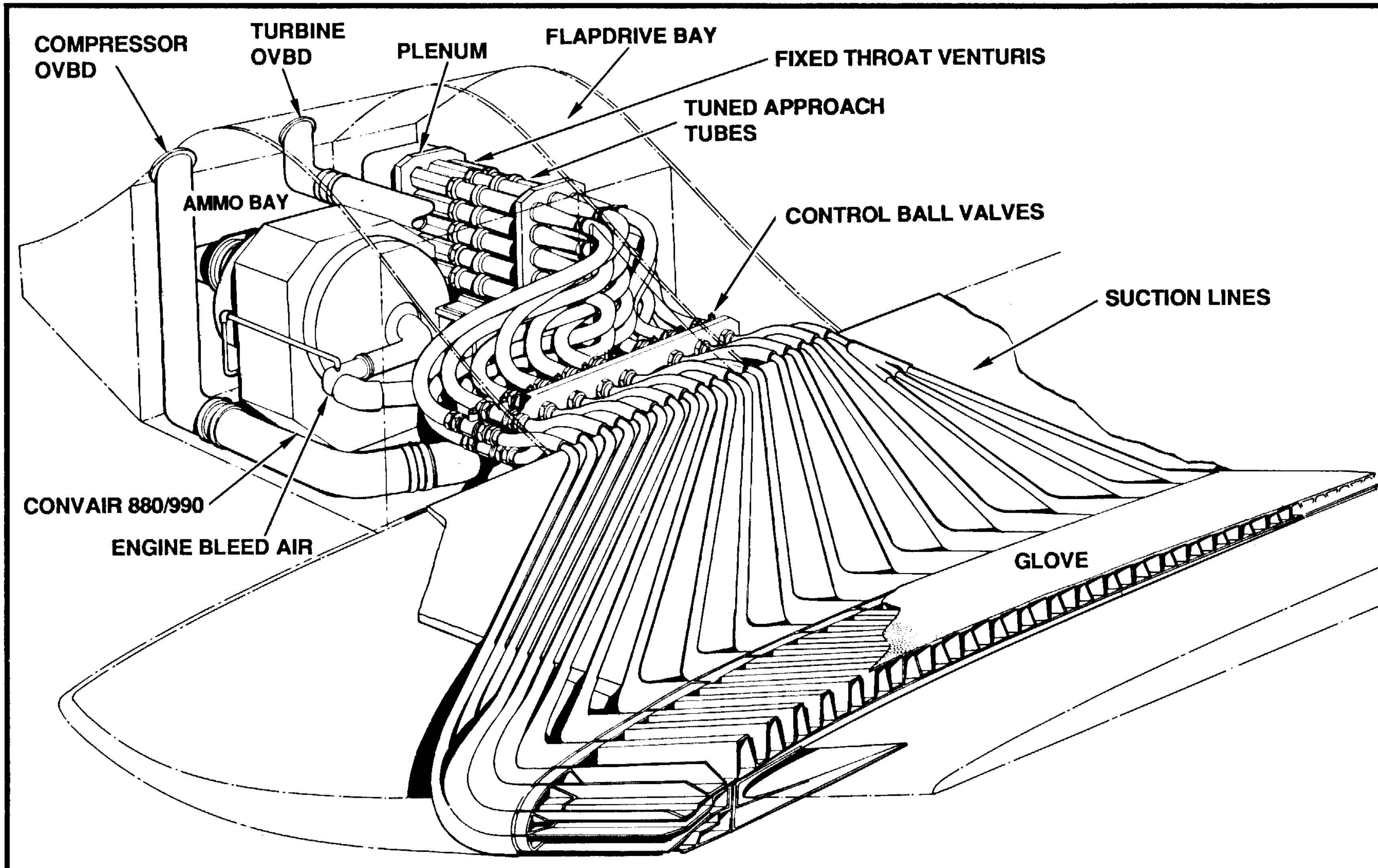
SUCTION DISTRIBUTION AT MIDSPAN



MGE-910502-5670

The suction subsystem was designed around a Convair 880 Auxiliary Power Unit (APU) compressor that was used as the suction pump. The pump was mounted in the ammunition bay behind the canopy. 17 fixed throat venturis were connected between the pump and the chordwise flutes in the active glove. The venturis were designed to achieve the design suction distribution in a choked mode.

SUCTION SUBSYSTEM DESIGN



DS-91-5660

The numerical approach developed and currently being validated as part of the ongoing F-16XL SSLFC program was based on the coupling of a Navier-Stokes code and a linear compressible boundary-layer stability method.

The Navier-Stokes method used was the Unified Solution Algorithm (USA) code developed by Rockwell's Science Center*. The USA code is based on a finite -volume implementation of an upwind Total Variation Diminishing (TVD) formulation embedded in a multi-block structured-grid bookkeeping framework.

The Compressible Stability Analysis (COSAL) code developed by Malik** was used for temporal theory applications to calculate an amplification factor. The application of the stability theory to transition prediction consists of the computation of laminar profiles with superimposed small perturbations and the resultant integration of the disturbance amplitude growth rates. Transition occurs when the amplification factor reaches a prescribed value N. Stability theory does not provide the absoluteamplification level, so the N-factor is extracted from experimental correlation.

The USA and COSAL codes were coupled in such a way to enable stability calculations to be made for arbitrary three-dimensinal flows. The COSAL interface was modified to replace the essentially two-dimensional profile definition with a general three-dimensional search and interpolation procedure. The analysis follows the streamline if no instability exists and the direction of the group velocity vector if an unstable mode is encountered.

The development of the computational methodology and its application to the F-16XL SSLFC program is discussed in detail in AIAA Paper 91-0188***.

* Chakravarthy, S. R., Szema, K. Y, and Haney, J. W., "Unified 'Nose-to-Tail' Computational Method for Hypersonic Vehicle Applications," AIAA Paper 88-2564, June 6-8, 1988.

** Malik, M. R., "COSAL - - A Black-Box Compressible Stability Analysis code for Transition Prediction in Three-Dimensional Boundary Layers," NASA CR 165925, May 1982.

*** Woan, C. J., George, M. W., "CFD Validation of a Supersonic Laminar Flow Control Concept," AIAA Paper 91-0188, January 7-10, 1991.

COMPUTATIONAL METHODOLOGY

CFD ANALYSIS (USA)

- Navier-Stokes equations
- Finite volume formulation
- 3rd order accurate TVD scheme
- Roe's flux-difference splitting

Stability Analysis (COSAL)

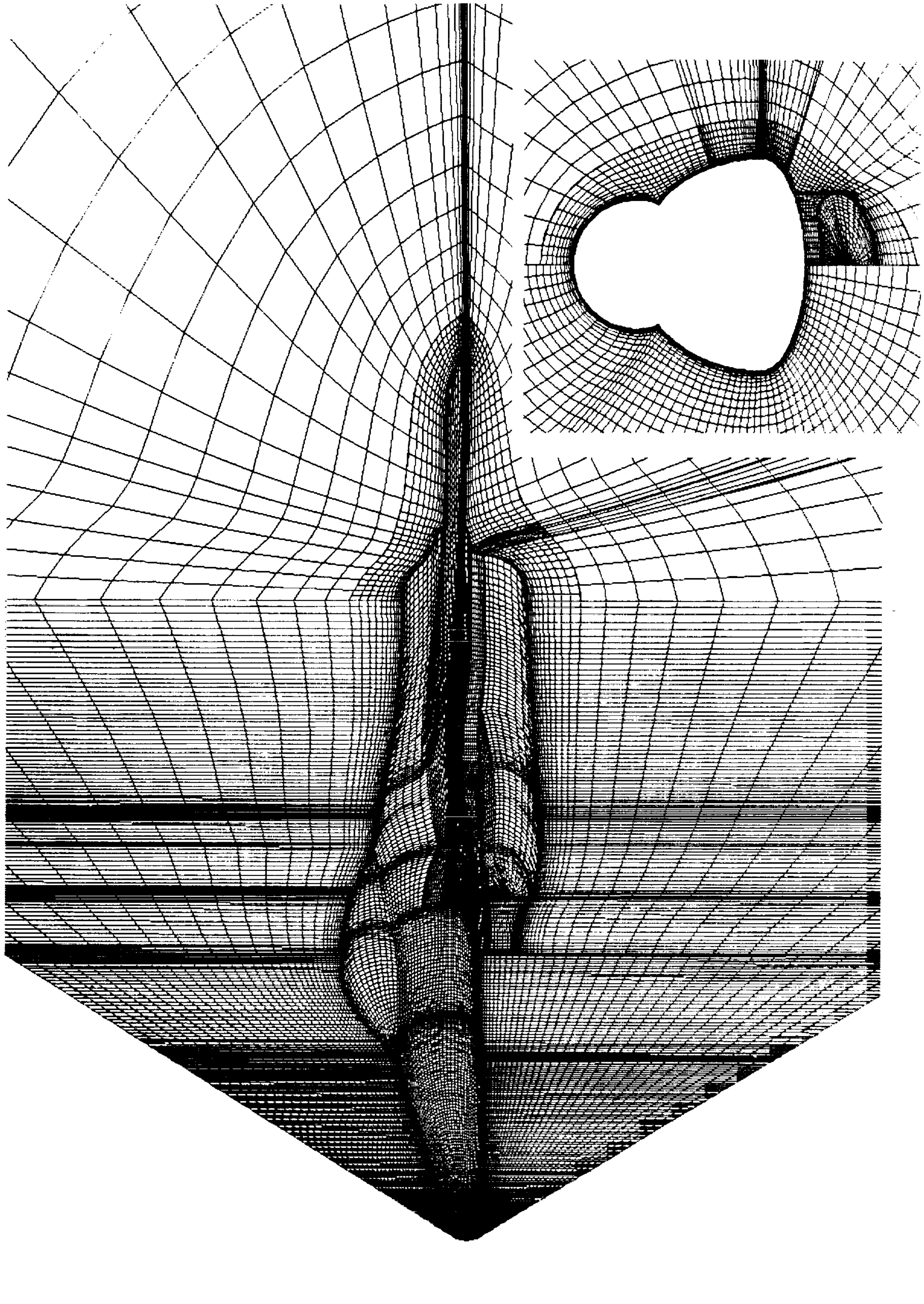
- 3D linear compressible BL stability theory
- Temporal theory
- Computation of amplification factor N
- Design for swept tapered wing

USA/COSAL Coupling

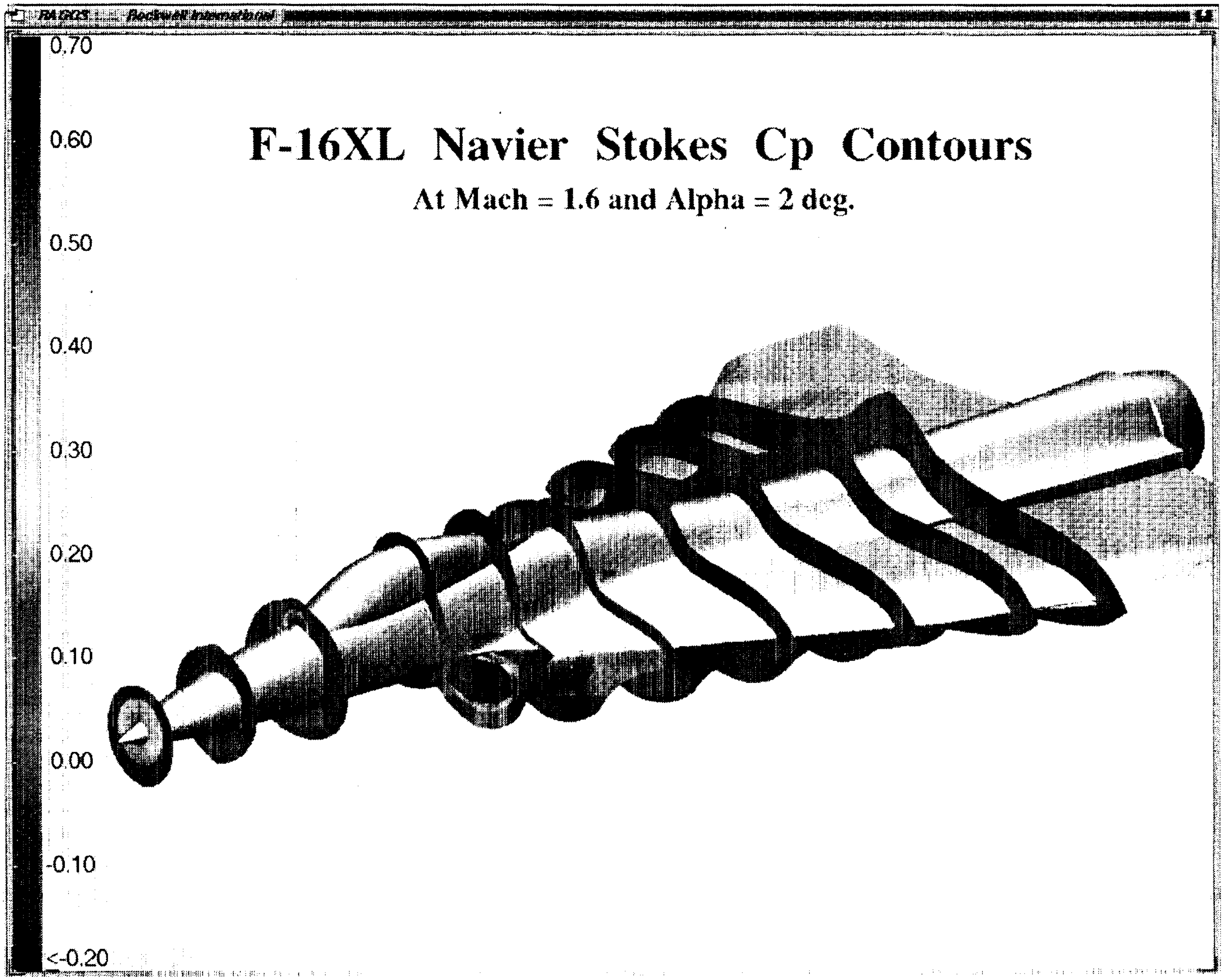
- Generalize 3D input BL profiles
  - Along the external streamline if no instability exists
  - Along the group velocity vector direction if unstable mode is encountered

The grid topology used to numerically represent the F-16XL SSLFC consisted of four major blocks in the streamwise direction. Each major streamwise block was further divided into sub-blocks resulting in 21 blocks with approximately one million grid points. To capture the complexity of the geometry, a non-aligned bock grid approach was used and applied at the interface of blocks 3 and 4. The non-aligned block interface was located upstream of the inlet plane to avoid strong gradients.

F-16XL SSLFC GRID TOPOLOGY



For the LFC calculations it was important to capture the effects of the wing, body, canopy, inlet, diverter, and environmental control inlet (ECS). Of specific concern were the shock systems emanating from the fore and aft regions of the canopy and from the main and ECS inlets. To study the effect of grid density two grids were utilized, with approximately 750,000 and 1,000,000 grid points. The larger grid had ten additional nodes in the boundary layer.


RAGGS
Rockwell International
F-16XL Navier Stokes Cp Contours
At Mach = 1.6 and Alpha = 2 deg.
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
-0.10
<-0.20

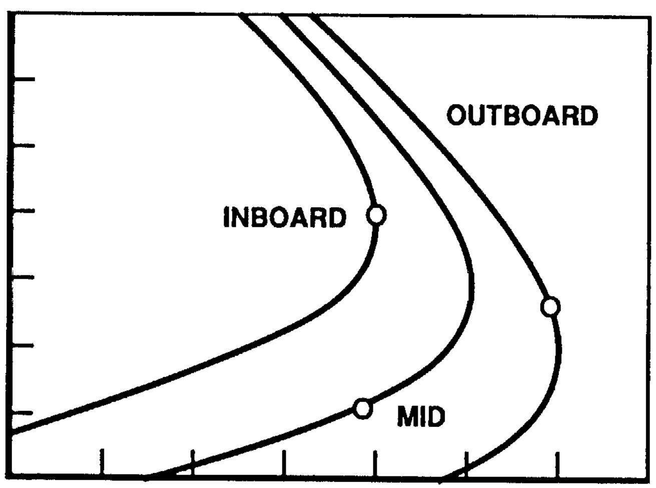
Results of the Navier-Stokes code indicated that the attachment line location and momentum thickness Reynolds number at the attachment line deviated from the design goals. The desired location for the attachment line was the nose of the wing sections. The nose is the location of maximum curvature resulting in minimum momentum thickness Reynolds number. The attachment line at the inboard of the active glove was located on the nose and proceeded to move onto the lower surface as a function of spanwise direction and then back onto the upper surface at the outboard wing section of the active glove. The deviation of the attachment line from the nose of the wing sections resulted in an increasing momentum thickness Reynolds number in the spanwise direction. The resultant values of the momentum thickness Reynolds number are slightly over the design goal of 114 but are well below the natural transition value of 265.

265 is the value of Reynolds number above which transition occurs due to freestream turbulence levels and 114 is the value below which turbulence or disturbances emanating from the wing-body junction would decay along the attachment line. The values of 265 and 114 are arrived from experiment and represent the limits of the band of scattered experimental data.

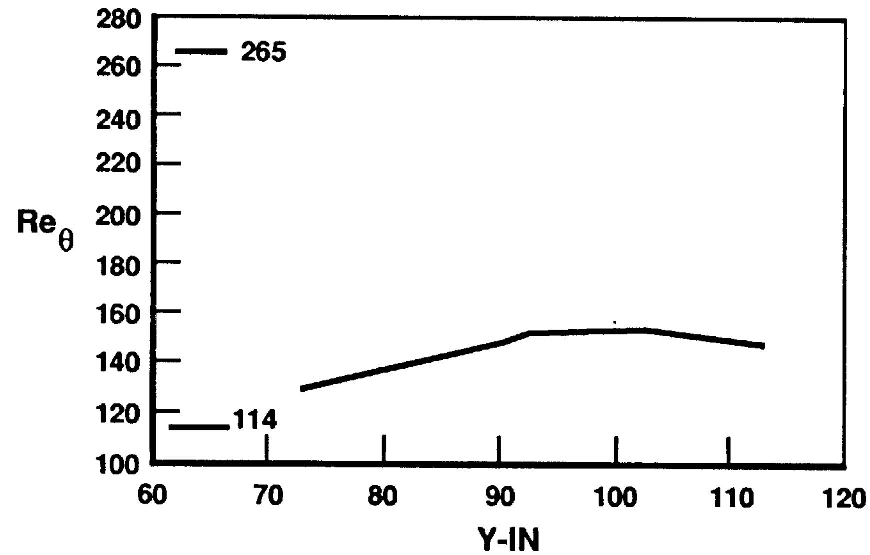
In between the values of 114 and 265, whether transition occurs or not at the attachment line will depend on the upstream disturbance levels.

ATTACHMENT LINE CHARACTERISTICS

ATTACHMENT LINE LOCATION



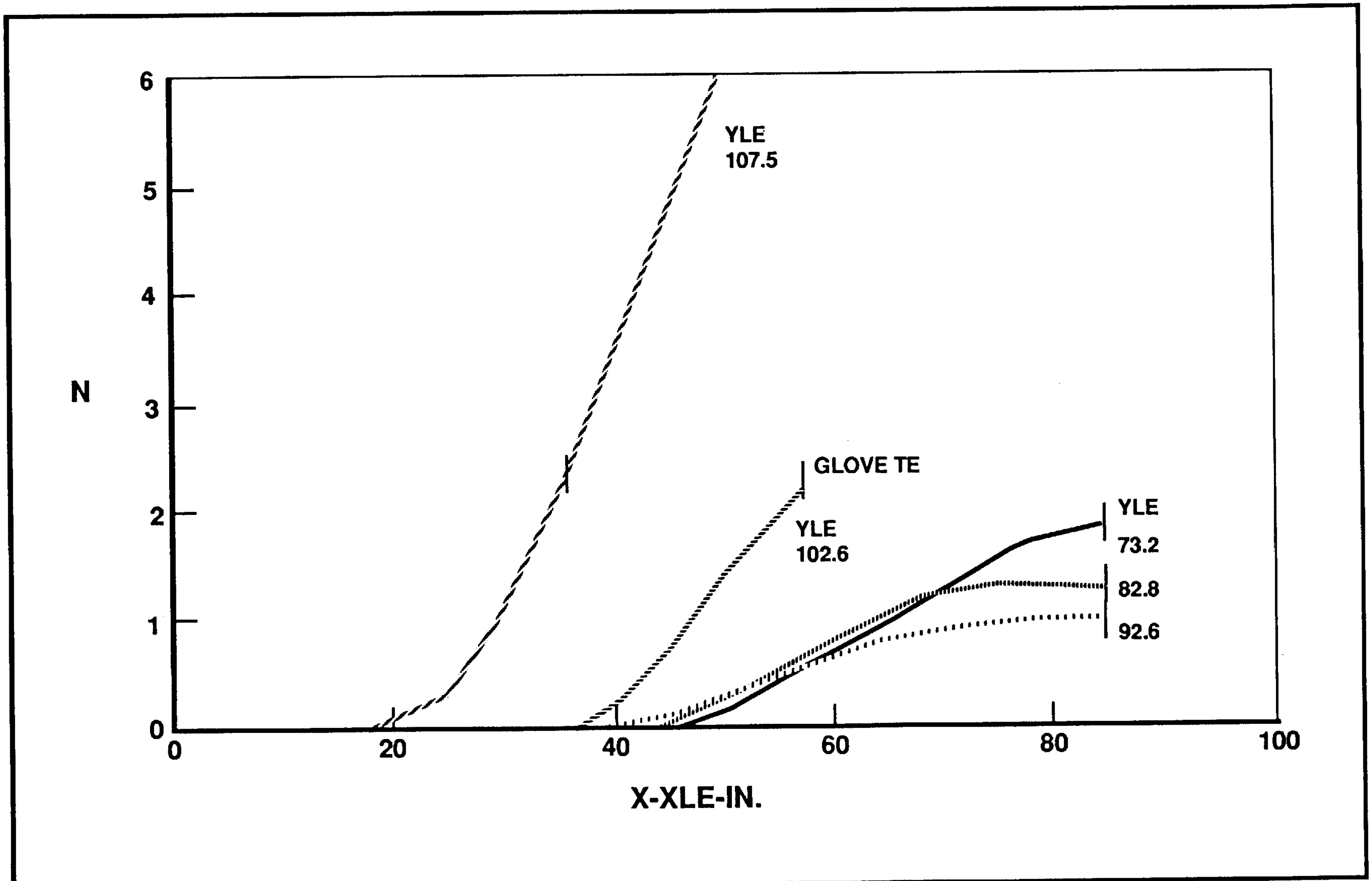
MOMENTUM THICKNESS
REYNOLDS NUMBER



MGE-910501-5662

The stability predictions resulting from the coupling of the Navier-Stokes code and the stability analysis code indicated that laminar flow would be obtained over the entire glove. The maximum amplification factor N reached on the glove was less than 3.

STABILITY PREDICTION OVER ACTIVE GLOVE



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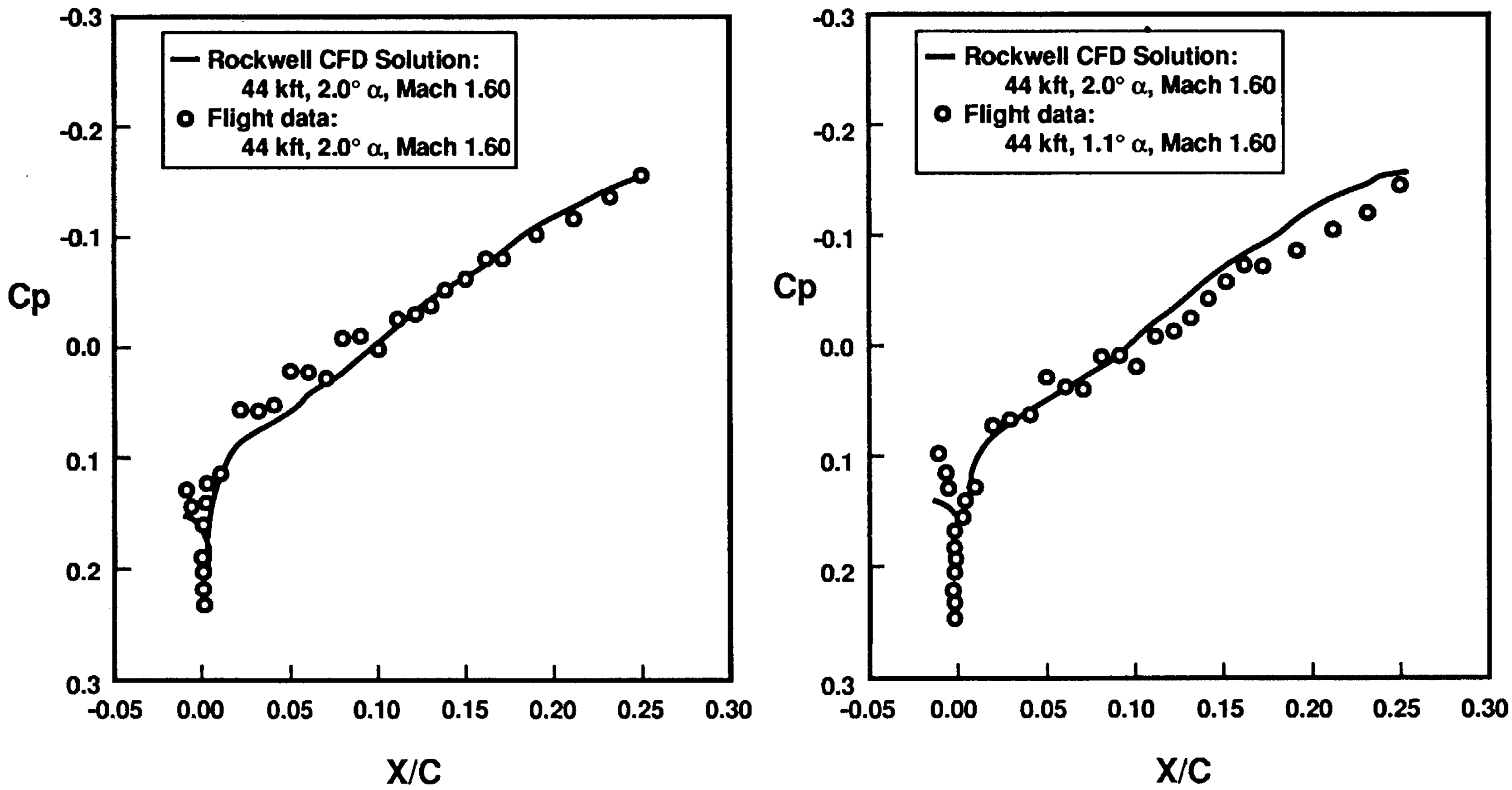
Two rows of pressure taps were placed on the F-16XL SSLFC vehicle. The rows were located at the inboard and outboard edges of the active suctionglove.

The comparison of the Navier-Stokes pressure results with the flight test results indicate relatively good agreement at the inboard station. The flight test pressure results contained a series of chordwise oscillations that have not been explained to date.

F-16XL-SSLF EXPERIMENT CFD TO FLIGHT DATA COMPARISON

INBOARD ORIFICE ROW

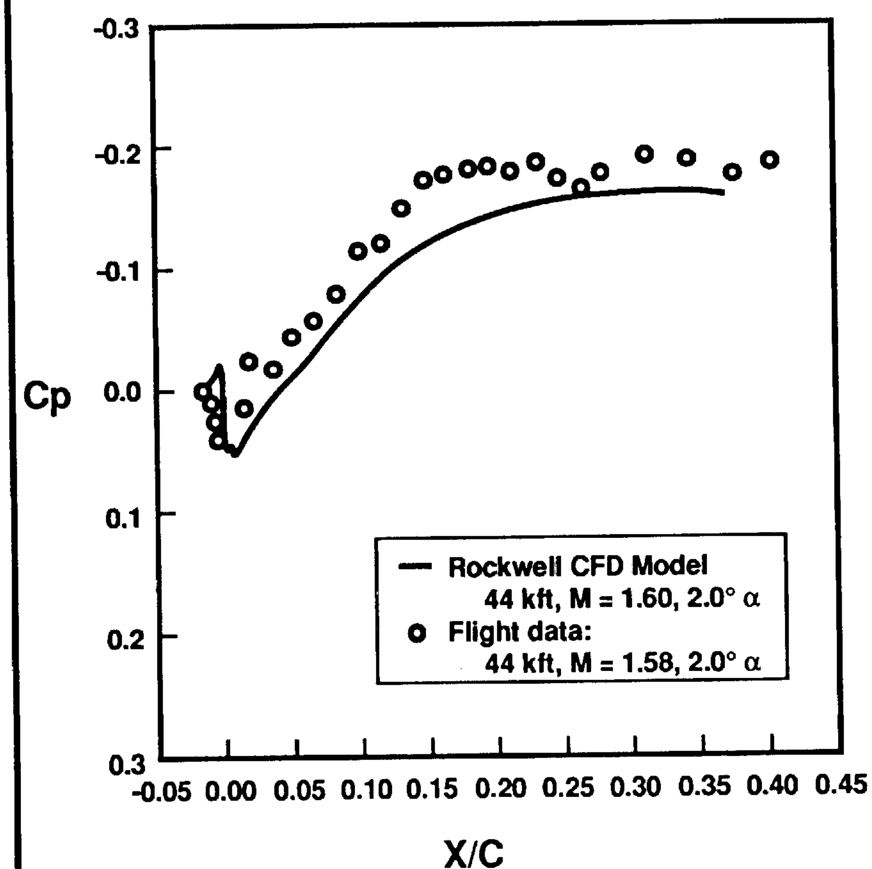


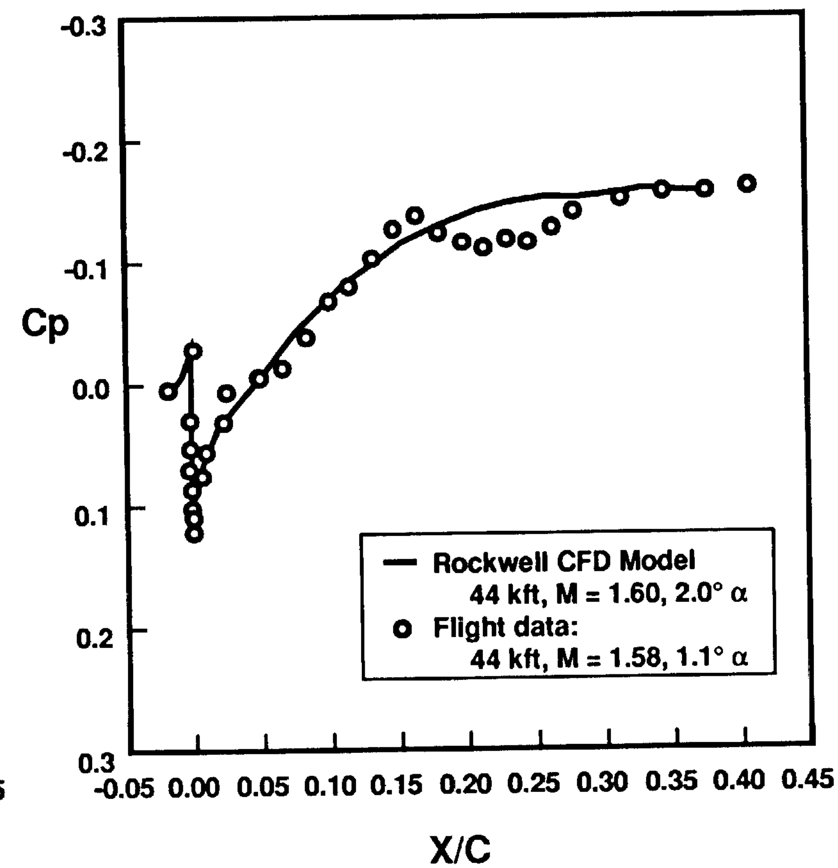
MGE-910502-5659

The comparison of the Navier-Stokes pressure results with the flight test results for the outboard pressure row were not as good as the inboard comparisons. The comparisons indicate a possible twist difference of approximately one degree between the numerical model and flight vehicle.

F-16XL-SSLF EXPERIMENT CFD TO FLIGHT DATA COMPARISON

OUTBOARD ORIFICE ROW





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F-16XL SSLF INSTRUMENTATION LAYOUT

The left wing of F-16XL Ship 1 has been modified with a Supersonic Laminar Flow Control Glove (dark section). The edges of the active glove have been instrumented to measure surface static pressures for pressure distribution documentation. Using relocatable hot-film sensors, researchers can detect the character (laminar or turbulent) of the flow anywhere on the gloved wing surface in flight.

For initial flight tests, as many as 18 hot-film sensors were located as shown. By locating sensors along the outboard and trailing edges of the glove, researchers can determine if the entire glove is laminar at design condition. By locating sensors on the passive glove immediately inboard of the active glove, and on the active glove inboard edge, researchers can determine if the small step between the passive and active gloves has a significant effect on the amount of laminar flow detected.

The unusual angle of alignment for the hot-film sensors (approximately 30 degrees to the streamline) was determined to be necessary to prevent disturbances shedding from a forward sensor, from affecting the measurements of the sensors behind it.

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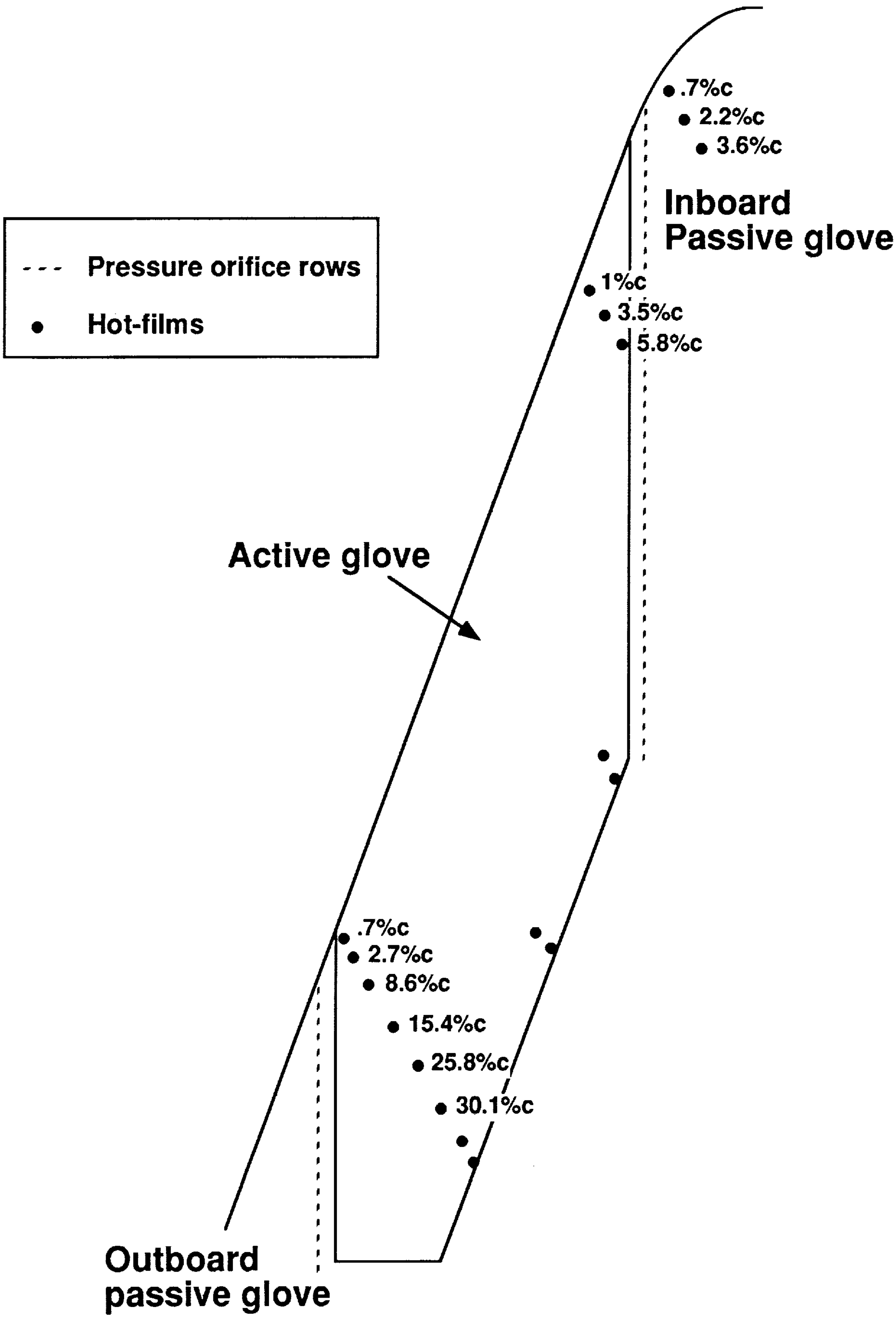
TEST MATRIX
Completed Test Points

Shown is the limited flight envelope of the F-16XL Ship 1 with the completed test points. Flight data for various Mach numbers, altitudes, and angles of attack from these test points were used to determine the character of the attachment line (with no active suction), the location of transition (with and without suction), and the pressure distributions at 2 span stations (inboard and outboard of the active glove).

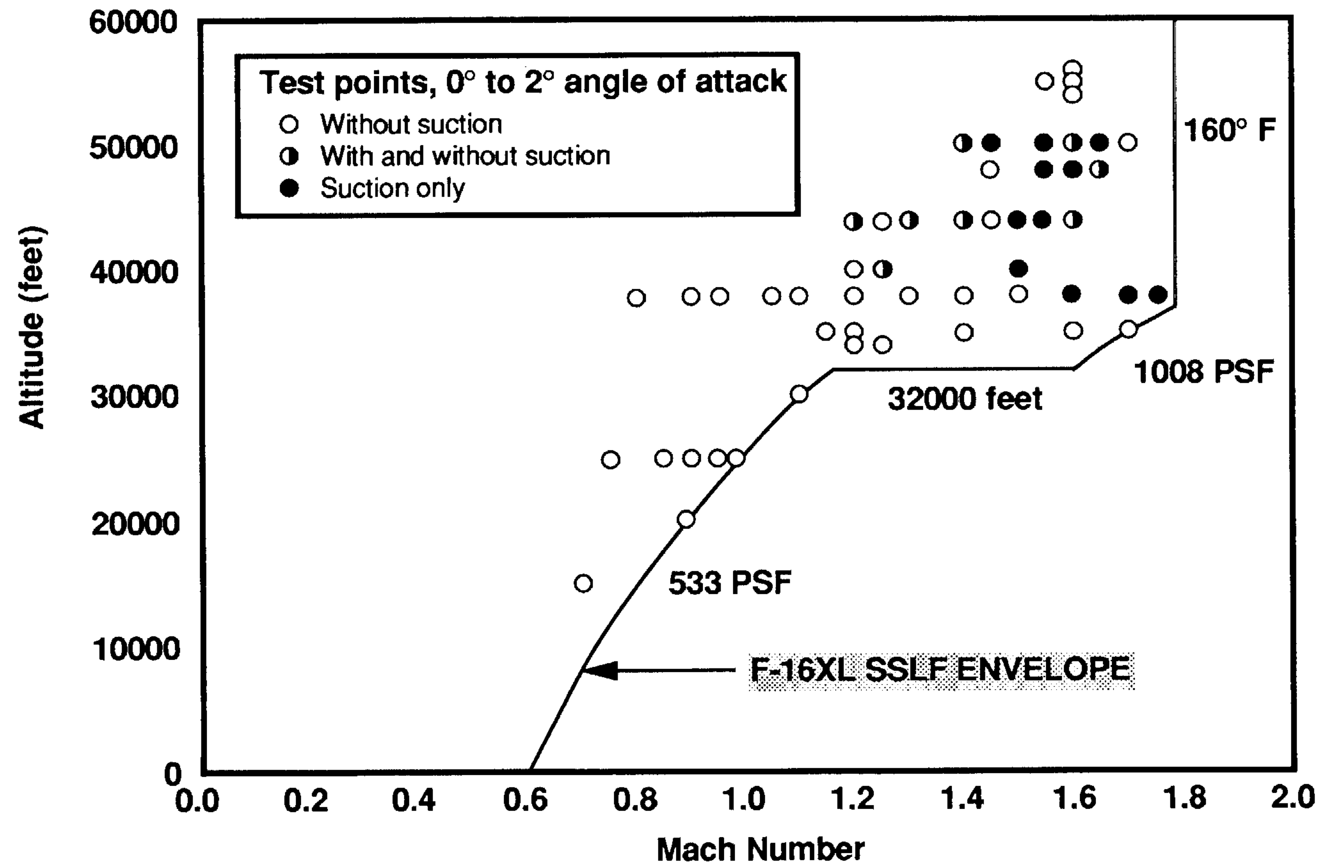
The solid circles are test points completed with active suction. (The suction pump was installed and operating.) The open circles are test points completed without active suction. (The suction pump was removed from the aircraft, however, some air may have been passing through the porous skin.) The half-solid circles are test points completed once with active suction and repeated after the suction pump was removed.

Some of the results from these flight tests are shown in the succeeding charts.

INSTRUMENTATION LAYOUT



Phase I Test Matrix - Completed Test Points



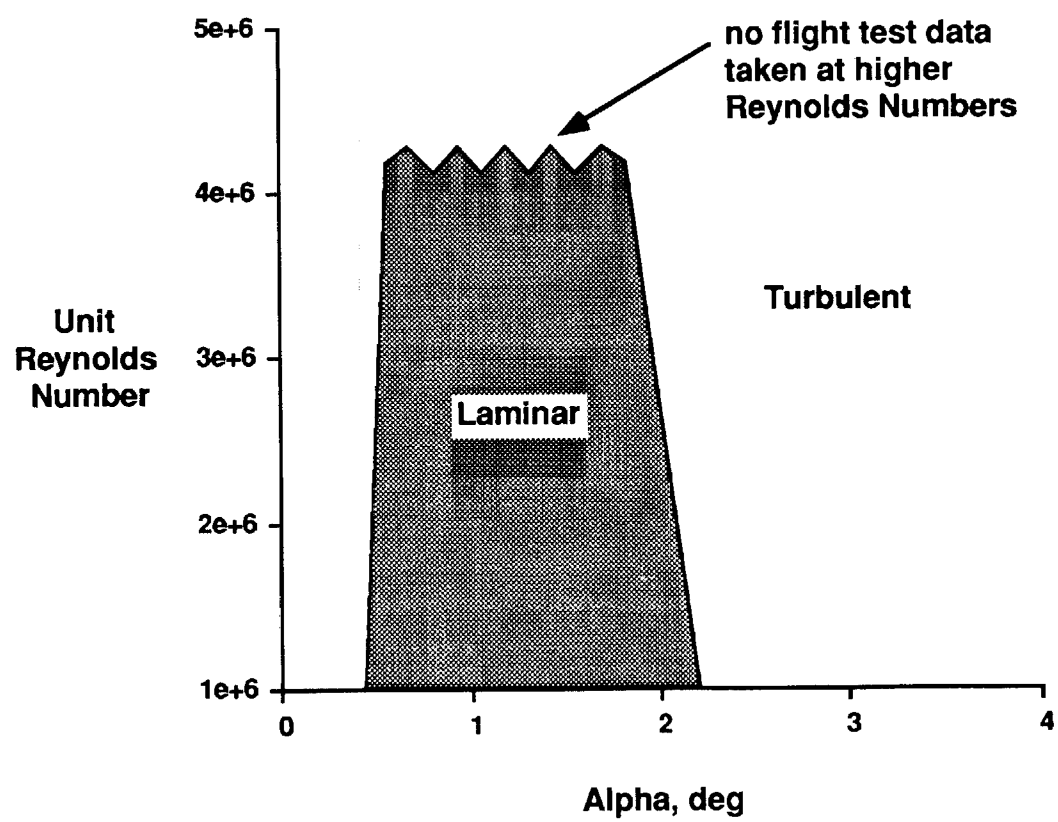
FLIGHT CONDITIONS FOR A LAMINAR ATTACHMENT LINE
Passive Glove - Inboard

The unit Reynolds Number, as a function of angle of attack (α), at which transition occurs on the inboard passive glove, is shown.

Within the boundaries of the shaded region, a laminar attachment line exists on the inboard passive glove to .7% chord. The passive glove attachment line was found to be laminar to a unit Reynolds number of at least 4 million. The 'jagged' top of the shaded region is intended to indicate that although no flight data has been obtained at higher unit Reynolds numbers, there is a possibility that a laminar attachment line exists beyond a 4 million unit Reynolds number.

It is interesting to note that a laminar attachment line exists for an α range from about 1/2 to 2 1/4 degrees. Beyond the α boundaries a turbulent attachment line exists. This wide angle of attack envelope of laminar attachment on the inboard passive glove was not expected, due to the relatively small leading edge radius of the glove. These data indicate that maintaining a laminar attachment line for a small leading edge may be easier than predicted by stability codes.

Flight Conditions for a Laminar Attachment Line
Passive Glove - Inboard



FLIGHT CONDITIONS FOR A LAMINAR ATTACHMENT LINE

Active Glove - Typical (without active suction)

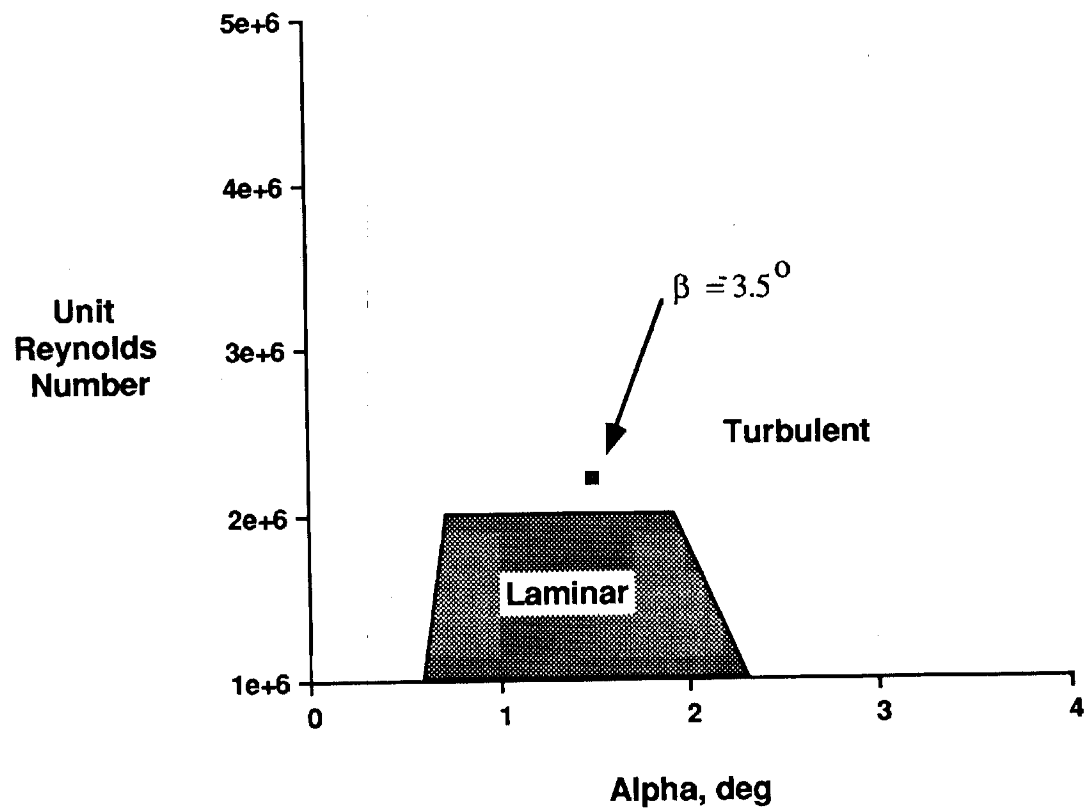
The unit Reynolds number, as a function of angle of attack (α), at which transition occurs on the 'typical' active glove section (inboard or outboard), is shown. All test points were flown without active suction.

Within the boundaries of the shaded region, a laminar attachment line exists on the active glove inboard and outboard to 1 and to .7% chord respectively. The unit Reynolds number limits shown represent the maximum unit Reynolds numbers for a laminar attachment line. The flat top of this region is indicative of the finding that for this typical active glove section the attachment line is not laminar beyond a Reynolds Number of approximately 2 million.

One series of test points were flown with -3.5 degrees side slip, effectively unsweeping the left wing from 70 degrees sweep to 66.5 degrees sweep. This reduction in sweep increased the unit Reynolds number, for a laminar attachment line, to approximately 2.2 million.

Flight Condition for Laminar Attachment Line

Active Glove - Typical (without active suction)



PRELIMINARY TRANSITION DATA
Outboard Active Glove, 1.4 M

Glove transition results are based entirely on interpretation of hot-film signals, which is discussed in detail in NASA TM 100444 "Techniques Used in the Variable Sweep Transition Flight Experiment" (Anderson et al, 1988)

The transition location at the outboard active glove station, as a function of α, for Mach 1.4, 50,000 ft (1.7 million unit Reynolds number) is shown for a limited suction and a no active suction case. The term, 'limited suction' is used in lieu of 'maximum suction' to indicate the case when the suction pump was operating, but was providing only a small percentage of the maximum suction. (Actual mass flow and Cq is not available.)

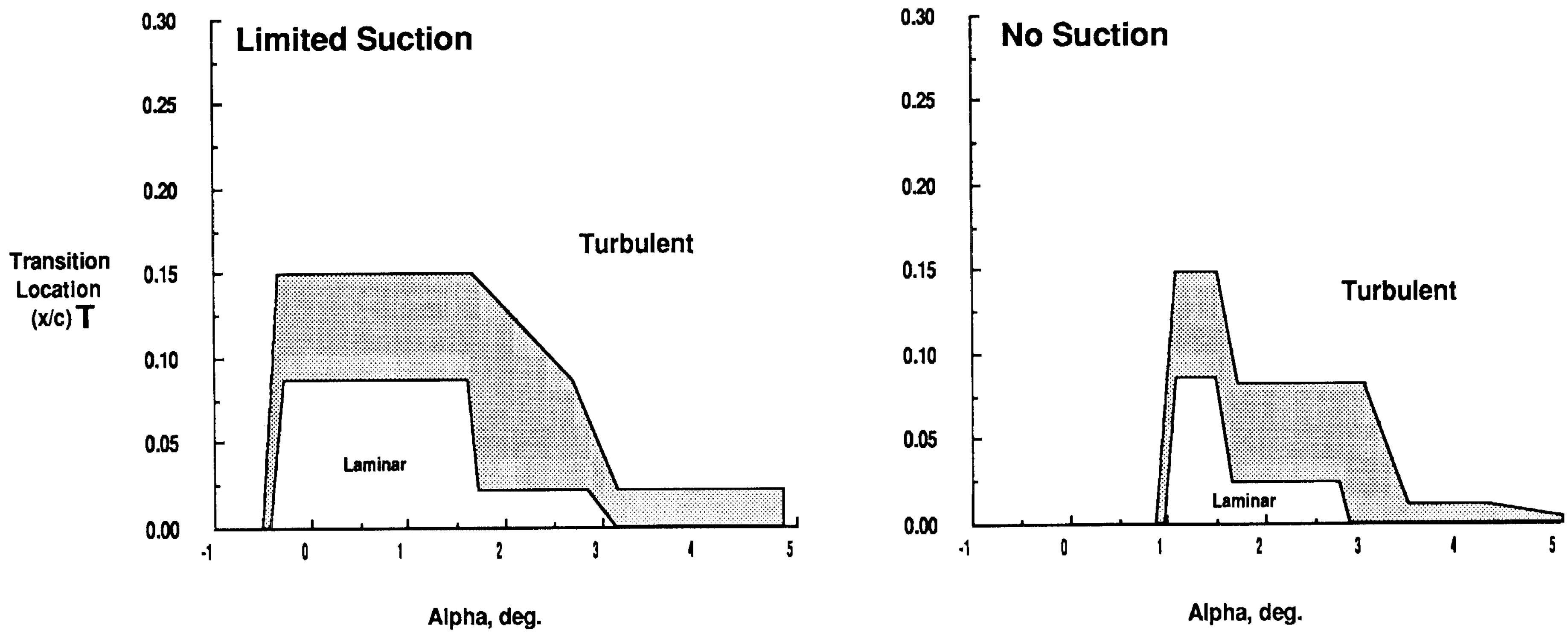
The shaded region represents the zone in which transition occurs. Because of size and space limitations on the active glove, the hot film sensor array used provided transition information for specific locations only. Thus, the shaded region indicates that transition occurred somewhere between 8.6 and 15.4 % chord. (The signal was laminar at 8.6% chord, but turbulent at 15.4% chord.) Beyond the α boundaries, a turbulent attachment line exists.

In a comparison of the limited suction and no suction case, one effect of suction can clearly be seen in this chart. By adding some suction, the maximum extent of laminar flow did not increase, however, the angle of attack range increased significantly.

Preliminary Transition Data

Outboard Active Glove

Mach = 1.4
Alt = 50,000 ft
Re/ft = 1.7 million



PRELIMINARY TRANSITION DATA
Outboard Active Glove, 1.6 M

Outboard active glove station transition location for Mach 1.6, 50,000 ft (1.9 million Reynolds number) is shown for maximum and no suction condition. 'Maximum' suction indicates that the suction pump was operating normally. (Actual mass flow and Cq is not available.)

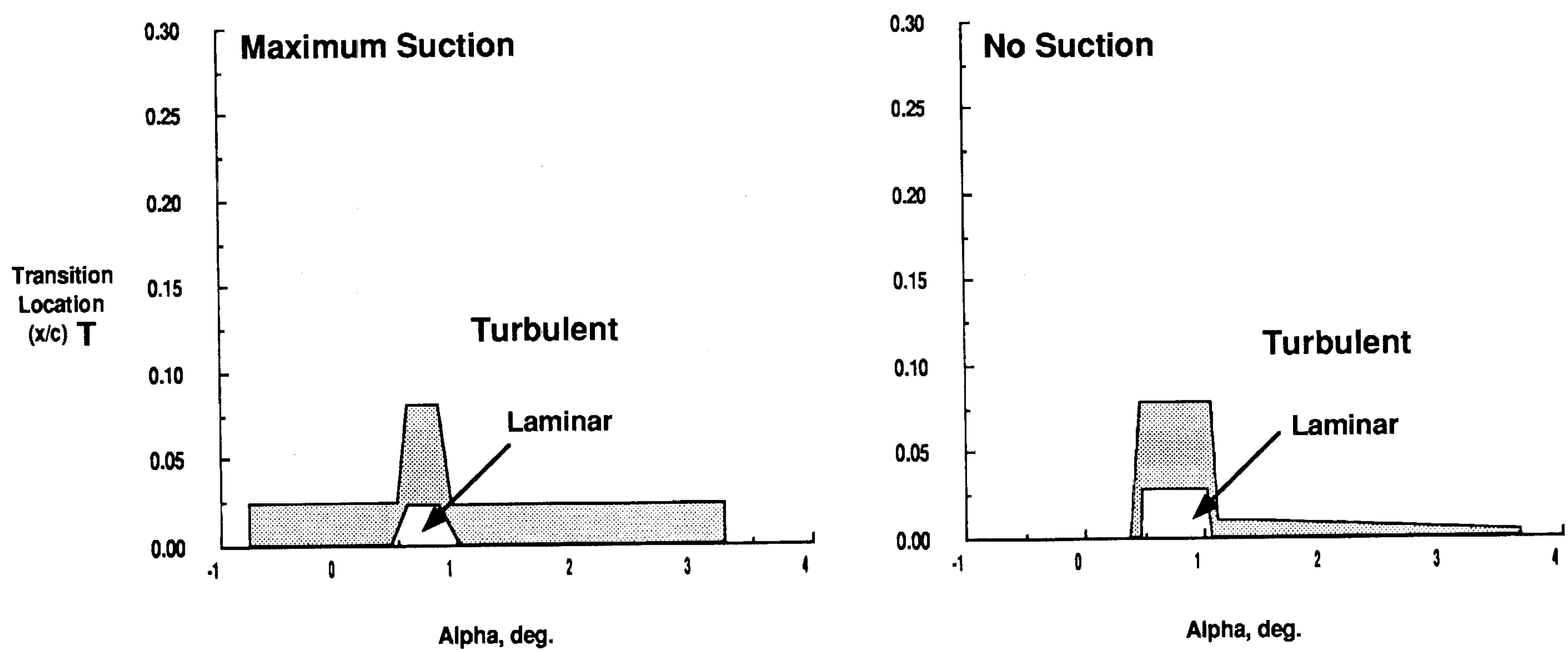
Like the Mach 1.4 case, the shaded region represents the zone in which transition occurs.

A comparison of the maximum suction and no suction results indicates that the extent of the laminar region does not change significantly with or without suction. It appears, in fact, that the maximum extent of laminar is slightly greater without suction. Since only one data point was available for this comparison, further flight testing is required.

The apparent difference in the transition region (shaded region) for the two cases may be related to instrumentation layout differences. That is, for the maximum suction case, the first hot-film sensor was at 2.7% chord, whereas, for the no suction case, the first hot-film was at .7% chord. Transition may occur further forward in the maximum suction case. Further flight testing is required to determine the actual transition location for the maximum suction case.

Preliminary Transition Data
Outboard Active Glove

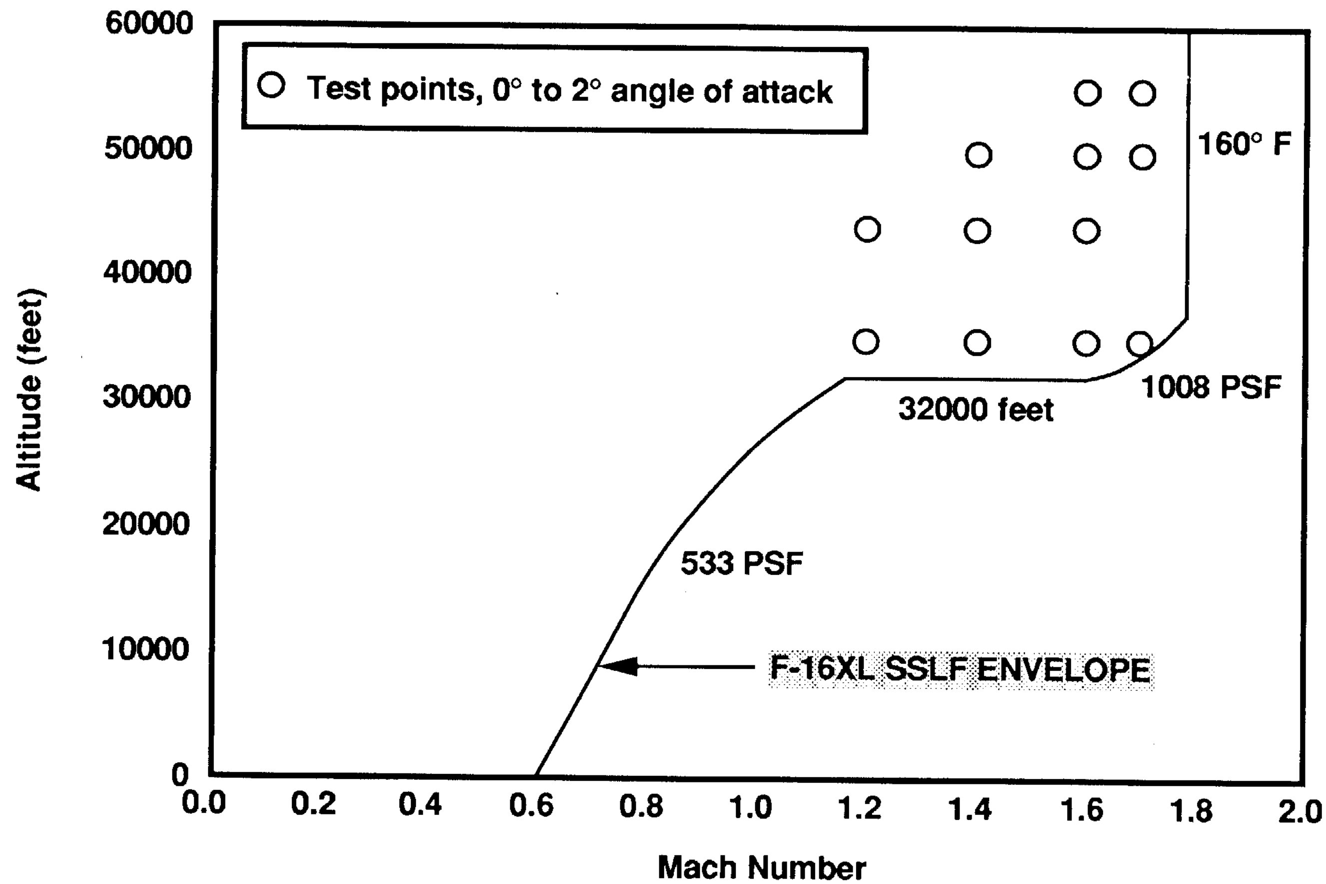
Mach = 1.6
Alt = 50,000 ft
Re/ft = 1.9 million



TEST MATRIX
Remaining Test Points

Continued flight evaluation of this glove with and without suction is required. Shown is the flight envelope of the F-16XL Ship 1 with the planned test points. For each test point shown, various angles of attack will be examined with the suction pump providing maximum and no suction. The hot-film sensor array will be changed as necessary to document transition location both span and chordwise. In addition, the α boundaries for attachment line transition will be documented. It is expected that this evaluation will require 10-12 research flights.

Phase I Test Matrix - Remaining Test Points



F-16XL SSLF
Proposed Follow-On Activities

A number of objectives for follow-on research are shown. The accomplishment of these follow-on activities will provide researchers with additional information on suction effects, as well as additional data for code validation.

Currently, NASA Ames-Dryden and NASA Langley are developing the procedures and plans to accomplish the six stated objectives by January 1992. Specific details on how these objectives will be achieved are not available at this time.

F-16XL SSLF Proposed Follow-on Activities

Objectives

- Conduct suction distribution studies for code validation
- Evaluate techniques for controlling attachment line turbulence
- Evaluate effects of 2-D and 3-D roughness on transition
- Evaluate flow visualization techniques to detect transition and cross flow disturbances
- Assess effects of advanced sensors on transition
- Evaluate noise levels in laminar and turbulent boundary layers

SUMMARY OF RESULTS TO DATE

The flight evaluations to date have resulted in several findings. Those findings are summarized in this chart.

Summary of Results to Date

- Laminar flow was achieved supersonically.
- A laminar attachment line was maintained over a wider range of alphas than anticipated.
- The attachment line remains laminar on the passive glove to a higher unit Reynolds number than on the active glove.
- Reducing sweep increased the unit Reynolds number for a laminar attachment line on the active glove.
- The effect of suction is inconsistent and not quantified. Further flight testing is necessary.
- Planned follow-on activities will provide additional information on suction effects as well as code validation data.

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