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HIGH-SPEED INLET RESEARCH PROGRAM AND SUPPORTING ANALYSES

Robert E. Coltrin

ABSTRACT

A Mach 5 cruise aircraft was studied in a joint program effort by NASA Lewis, NASA Langley, and Lockheed. The propulsion system chosen for this aircraft was an over-under turbojet/ramjet system. The ramjet portion of the inlet is to be tested in NASA Lewis' 10 X 10 SWT. To test the Mach 5.0 design in this facility, which has a maximum Mach number capability of 3.5, the 1/3-scale inlet model is to be mounted under a large plate at a negative angle of attack. By this means, the Mach 3.5 freestream flow is expanded up to the desired speed on the inlet first ramp. Goals of the test program are to obtain performance data and bleed requirements, and also to obtain analysis code validation data. The inlet was designed by using a conventional method of characteristics approach with boundary layer correction.

Supporting analysis of the inlet using a three-dimensional parabolized Navier-Stokes code (PEPSIS) indicates that sidewall shock/boundary layer interactions cause large separated regions in the corners underneath the cowl. Such separations generally lead to inlet unstart, and are thus a major concern. This sidewall glancing shock/boundary layer interaction has been previously documented with fundamental research in the Lewis 1 X 1 SWT. As a result of the analysis, additional bleed regions have been added to the inlet model sidewalls and cowl to control separations in the corners. A two-dimensional analysis incorporating bleed on the ramp is also presented.

Supporting experiments for the Mach 5 program have been conducted in Lewis' 1 X 1 SWT. A small-scale model representing the inlet geometry up to the ramp shoulder and cowl lip was tested to verify the accelerator plate test technique and to obtain data on flow migration in the ramp and sidewall boundary layers. Another study explored several ramp bleed configurations to control boundary layer separations in that region.

Design of a two-dimensional Mach 5 cruise inlet represents several major challenges including multimode operation and dual flow, high temperatures, and three-dimensional airflow effects.

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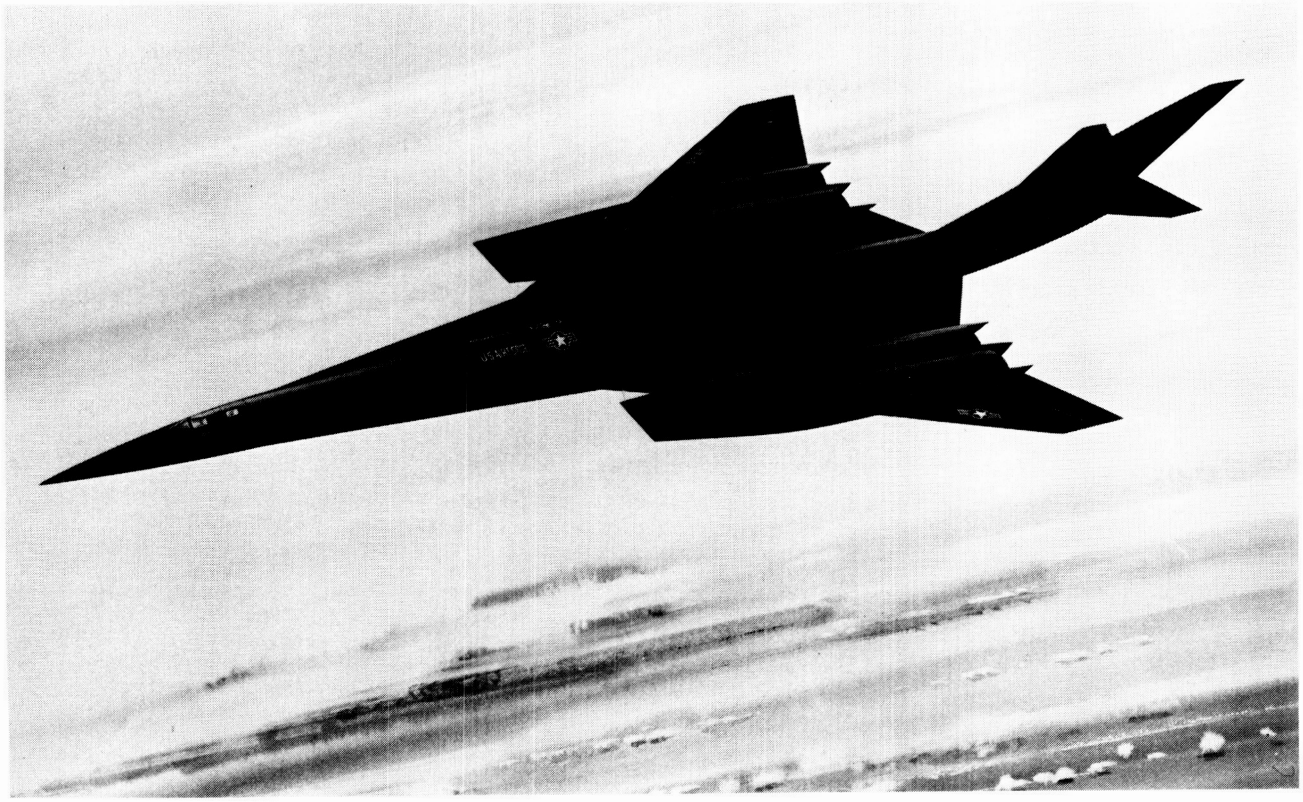
MACH 5 CRUISE AIRCRAFT STUDY

In 1980, a joint NASA Lewis, NASA Langley, and Lockheed California (with P&W as subcontractor) program was initiated. The purpose of this study was to define an aircraft capable of sustained high-speed cruise, and specifically, to define the propulsion system for this aircraft. The final configuration from this study is shown in the figure. The aircraft would employ four propulsion modules (two under each wing). The propulsion system chosen for this aircraft is an over-under turbojet plus ramjet system with a two-dimensional dual flow inlet and nozzle.

MACH 5 CRUISE AIRCRAFT STUDY



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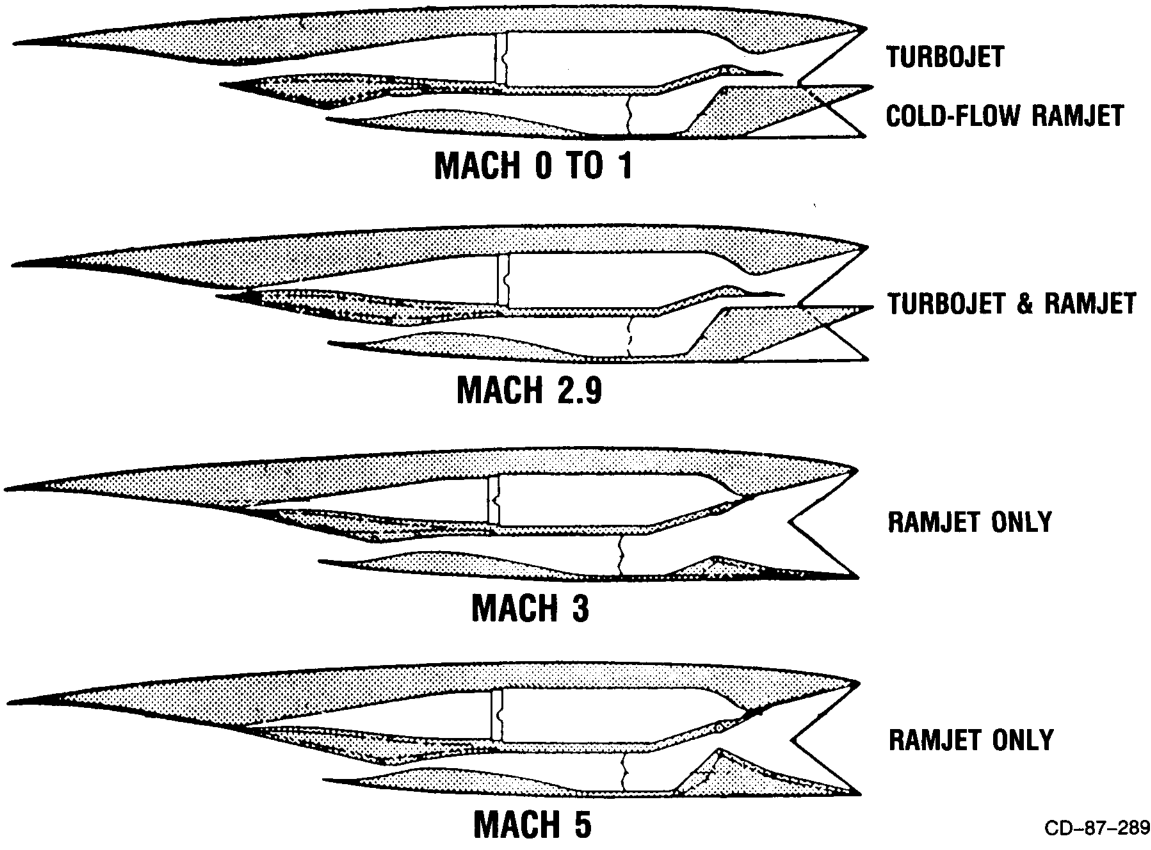
OVER-UNDER TURBOJET/RAMJET

The various modes of operation for the over-under turbojet plus ramjet are illustrated in the figure. At subsonic flight speeds, the turbojet powers the aircraft, with cold flow through the ramjet. Near Mach 1.0 the ramjet is ignited, and both systems are operating until the aircraft approaches Mach 3.0. Between Mach 2.5 and 3.0, the turbojet spools down and the upper duct of the inlet is closed off. From Mach 3.0 to cruise speed, the aircraft is powered by the ramjet only.

OVER-UNDER TURBOJET/RAMJET



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DESIGN METHODOLOGY

The ramjet (lower duct) portion of the inlet was designed by using a conventional method of characteristics (MOC) approach with boundary layer correction. One of the main driving factors in the design was length minimization, so as to reduce the weight as much as possible. The cowl shock is to be cancelled at the inlet shoulder, and the design throat Mach number is 1.6 inviscidly, which is reduced to approximately 1.2 when boundary layer corrections are made. The compression split is about 85 percent external (with four ramps) and 15 percent internal. The inlet employs variable ramp geometry for off-design operation.

DESIGN METHODOLOGY

- **DESIGNED BY METHOD OF CHARACTERISTICS WITH BOUNDARY LAYER CORRECTION.**
- **DESIGN MACH NUMBER = 5.0**
- **DESIGNED FOR MINIMUM LENGTH DUE TO WEIGHT CONSIDERATIONS.**
- **COWL OBLIQUE SHOCK CANCELLED AT RAMP SHOULDER.**
- **THROAT MACH NUMBER AT DESIGN CONDITIONS: INVISCID $M_T = 1.6$**
  WITH B.L. $M_T = 1.2$
- **COMPRESSION: EXTERNAL (85 PERCENT): 4 RAMPS**
  INTERNAL (15 PERCENT): COWL SHOCK
  DISTRIBUTED ISENTROPIC COMPRESSION
  TERMINAL SHOCK
- **VARIABLE RAMP GEOMETRY FOR OFF-DESIGN OPERATION**

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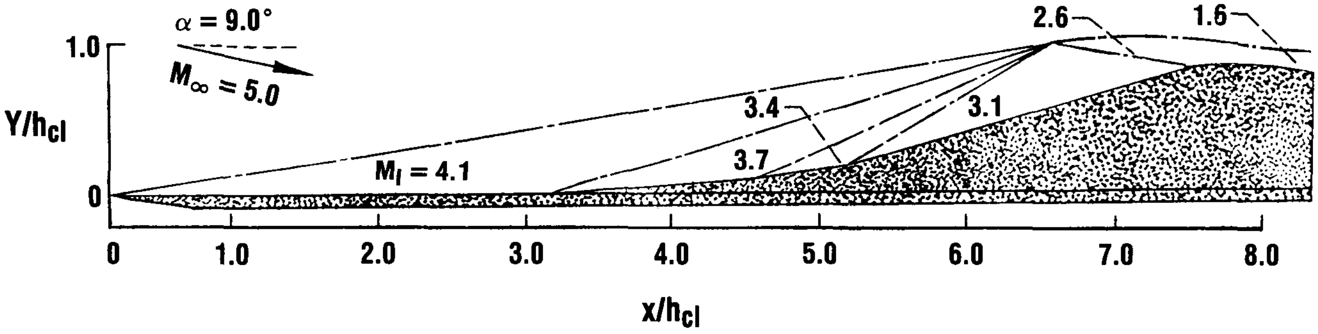
Mach 5 INLET AERODYNAMIC DESIGN CONFIGURATION

The aerodynamic design of the inlet is shown. X- and Y- dimensions are nondimensionalized to cowl lip height. Mach numbers in the various flow regions are shown for the cruise (Mach 5) condition. At cruise conditions, the initial wedge angle of the inlet is at 9°.

MACH 5 INLET
AERODYNAMIC DESIGN CONFIGURATION



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Mach 5 TWO-DIMENSIONAL INLET CHALLENGES

At high supersonic/low hypersonic speeds, several challenges face the inlet designer. The problems of multiple modes of operation and dual flow must be solved. High temperatures must be considered. Shock stability is not easily achieved; and the effects of three-dimensional flow, including corner flow and sidewall shock boundary layer interaction require complex bleed control systems. Inlet bleed and leakage cause serious performance penalties at the high speed conditions. Drag at off-design conditions is a problem, and weight reduction is a constant concern.

MACH 5 TWO-DIMENSIONAL INLET CHALLENGES

- MULTIPLE MODE/DUAL FLOW OPERATION
- HIGH TEMPERATURE
- SHOCK SYSTEM STABILITY
- GLANCING SIDEWALL SHOCK/BOUNDARY LAYER INTERACTIONS
- THREE-DIMENSIONAL CORNER FLOWS
- INLET BLEED AND LEAKAGE PENALTIES
- WEIGHT REDUCTION
- OFF-DESIGN DRAG
- BOUNDARY LAYER CONTROL

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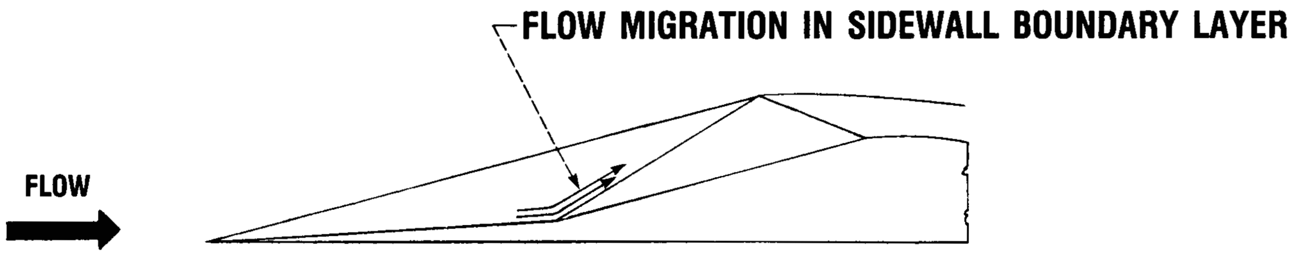
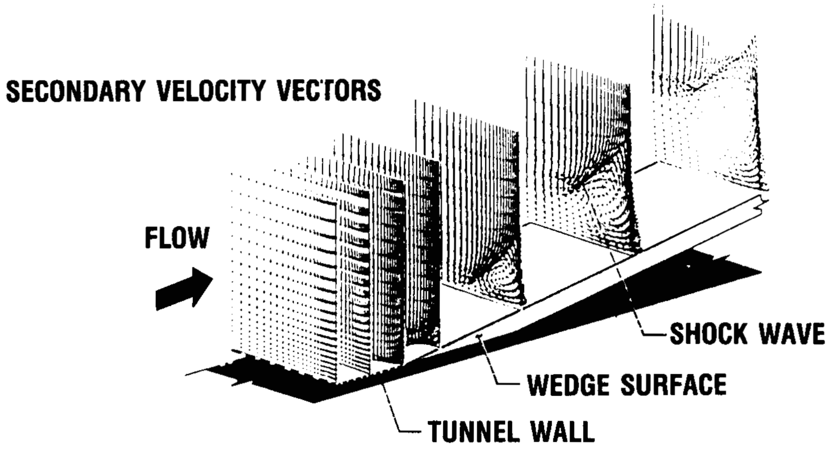
SIDEWALL BOUNDARY LAYER-GLANCING SHOCK WAVE INTERACTION

One problem with two-dimensional inlets is three-dimensional flow effects. Basic studies and analysis have shown that flow migration occurs in the boundary layer near regions where an oblique shock wave impinges on an adjacent sidewall. With thick boundary layers on an inlet sidewall, the higher pressure downstream of a sidewall-glancing shock can influence the upstream flow through the subsonic boundary layer. The result of this influence is a migration of the boundary layer along the oblique shock rather than parallel to the downstream ramp surface. A simple sketch showing the migration and analytical results are shown. This flow migration has a cumulative effect, with large regions of low-energy flow sweeping up the sidewalls as the flow moves aft toward the cowl.

SIDEWALL BOUNDARY LAYER-GLANCING SHOCK WAVE INTERACTION



TYPICAL TWO-DIMENSIONAL INLET



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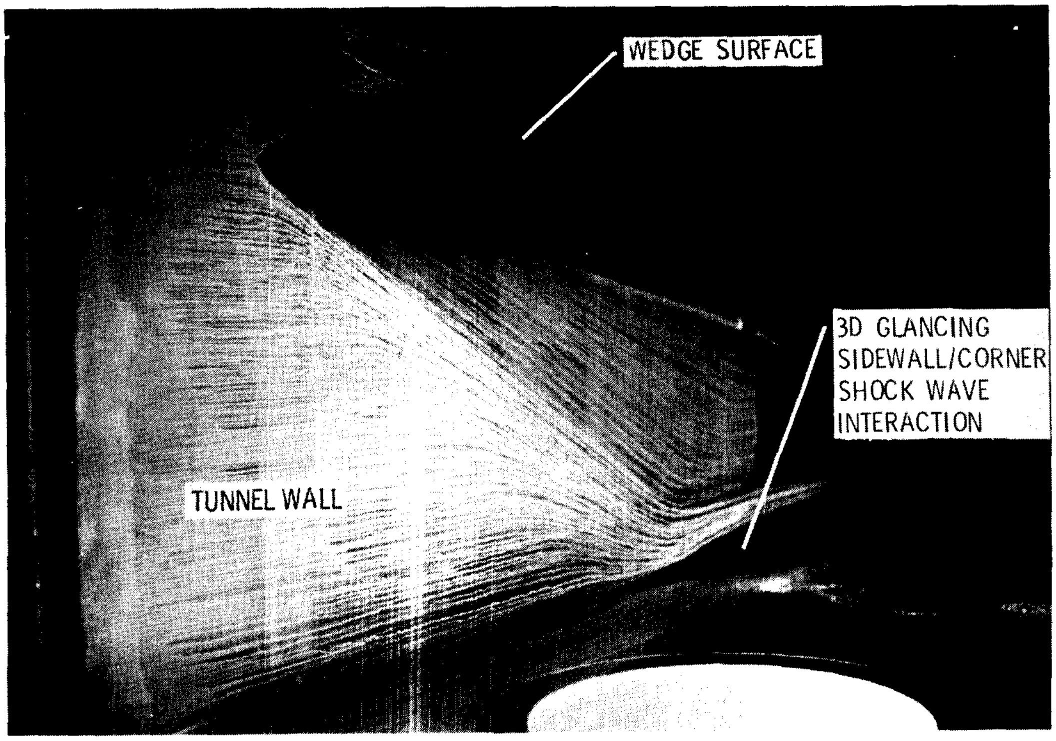
THREE-DIMENSIONAL SIDEWALL SHOCK INTERACTION
EXPERIMENTAL SURFACE OIL FILM PATTERNS

The figure shows a simple compression wedge installed on the flat wall of a supersonic wind tunnel. The oblique shock from this wedge interacts with the tunnel boundary layer which has a thickness of approximately one inch. The surface oil film shows flow patterns in the boundary layer. The oil flows indicate that the boundary layer on the wall ahead of the oblique shock and a large portion of the boundary layer flow aft of the shock is influenced and is turned in a direction along the oblique shock angle rather than parallel to the wedge surface.

THREE-DIMENSIONAL SIDEWALL SHOCK INTERACTION
EXPERIMENTAL SURFACE OIL FILM PATTERNS



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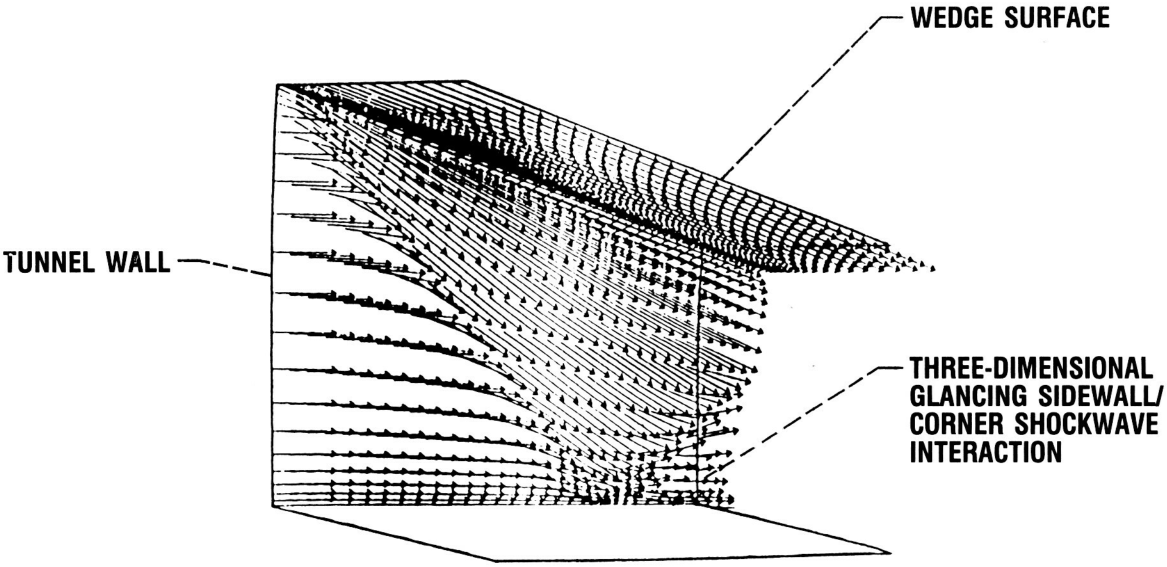
THREE-DIMENSIONAL SIDEWALL SHOCK INTERACTION
ANALYTICAL SURFACE OIL FILM PATTERNS

A three-dimensional parabolized Navier-Stokes (PEPSIS code) solution for the simple case shown in the previous figure is presented below. The velocity vectors show that the boundary layer flow tends to turn in the direction of the shock wave.

THREE-DIMENSIONAL SIDEWALL SHOCK INTERACTION
ANALYTICAL SURFACE OIL FILM PATTERNS



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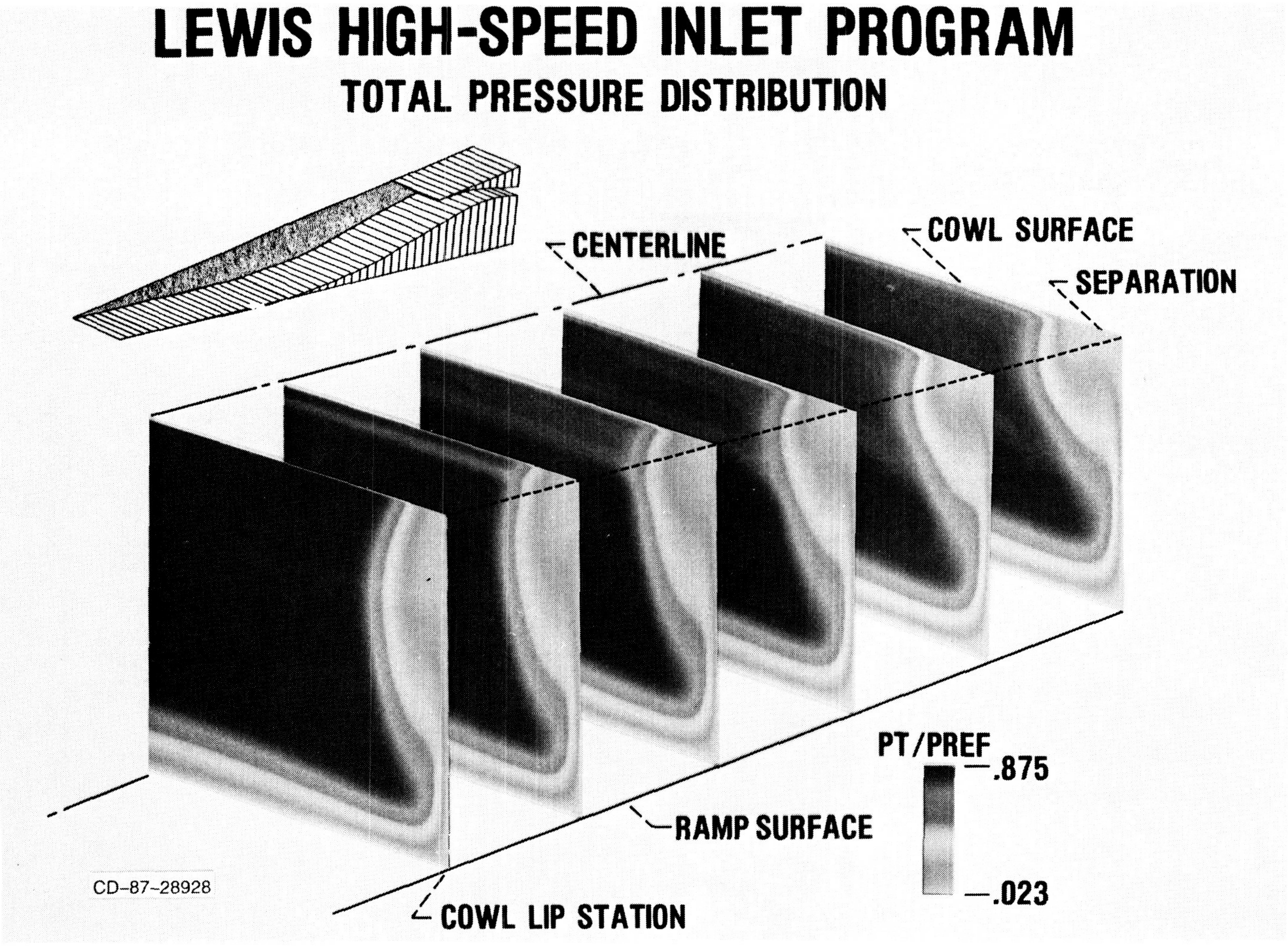
LEWIS HIGH-SPEED INLET PROGRAM
TOTAL PRESSURE DISTRIBUTION

PEPSIS analyses have shown that sidewall shock boundary layer interactions will have a dominant effect on the Mach 5 inlet. The figure shows total pressure distributions on cross-planes at several stations in the inlet aft of the cowl lip. Only half-planes are shown, as flow is symmetrical. Low energy flow swept up the sidewalls is captured by the cowl, resulting in a large separation region in the cowl-sidewall corner at a location forward of the inlet ramp shoulder. Such large separations will cause the inlet to unstart (expel the terminal shock out of the inlet), and thus are a major concern.



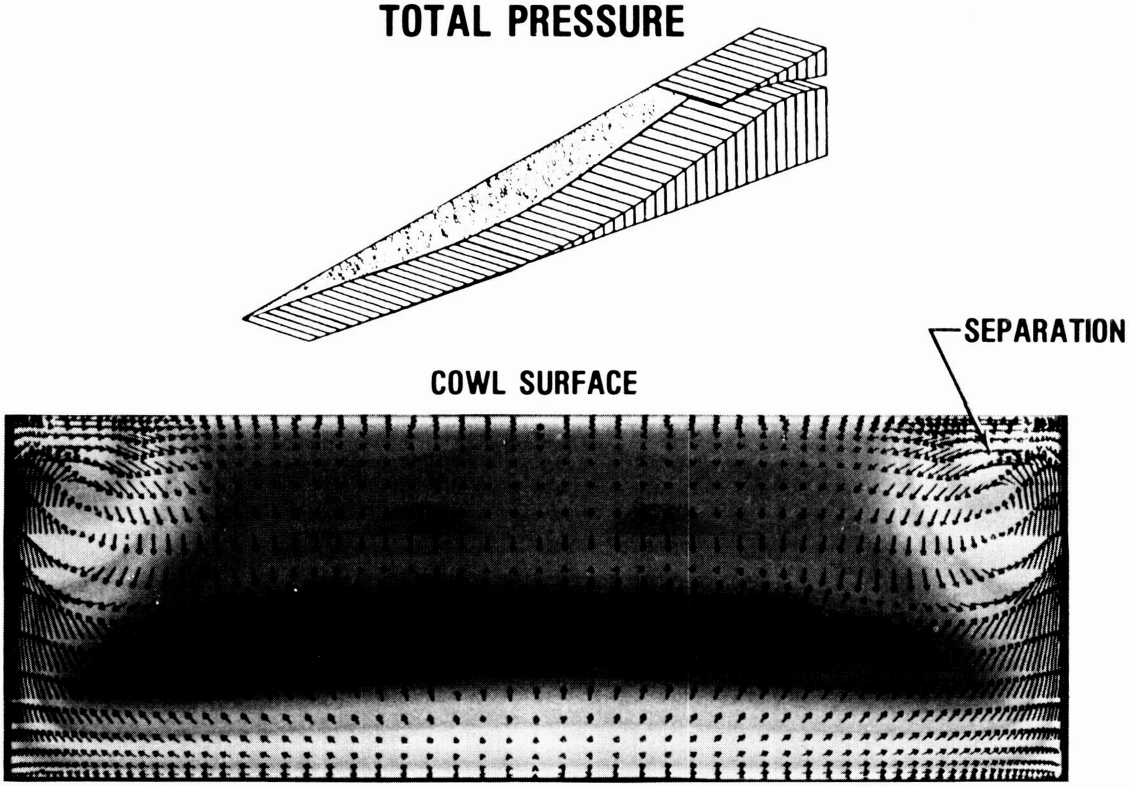
LEWIS HIGH-SPEED INLET PROGRAM

TOTAL PRESSURE DISTRIBUTION

LEWIS HIGH-SPEED INLET PROGRAM
TOTAL PRESSURE

The figure shows the total pressure distribution for a cross-section of the inlet just aft of the cowl lip. Velocity vectors are superimposed on this pressure distribution, showing recirculation in the corner separation region. The influence of the cowl oblique shock on the mid-stream flow can also be seen.

LEWIS HIGH-SPEED INLET PROGRAM
TOTAL PRESSURE



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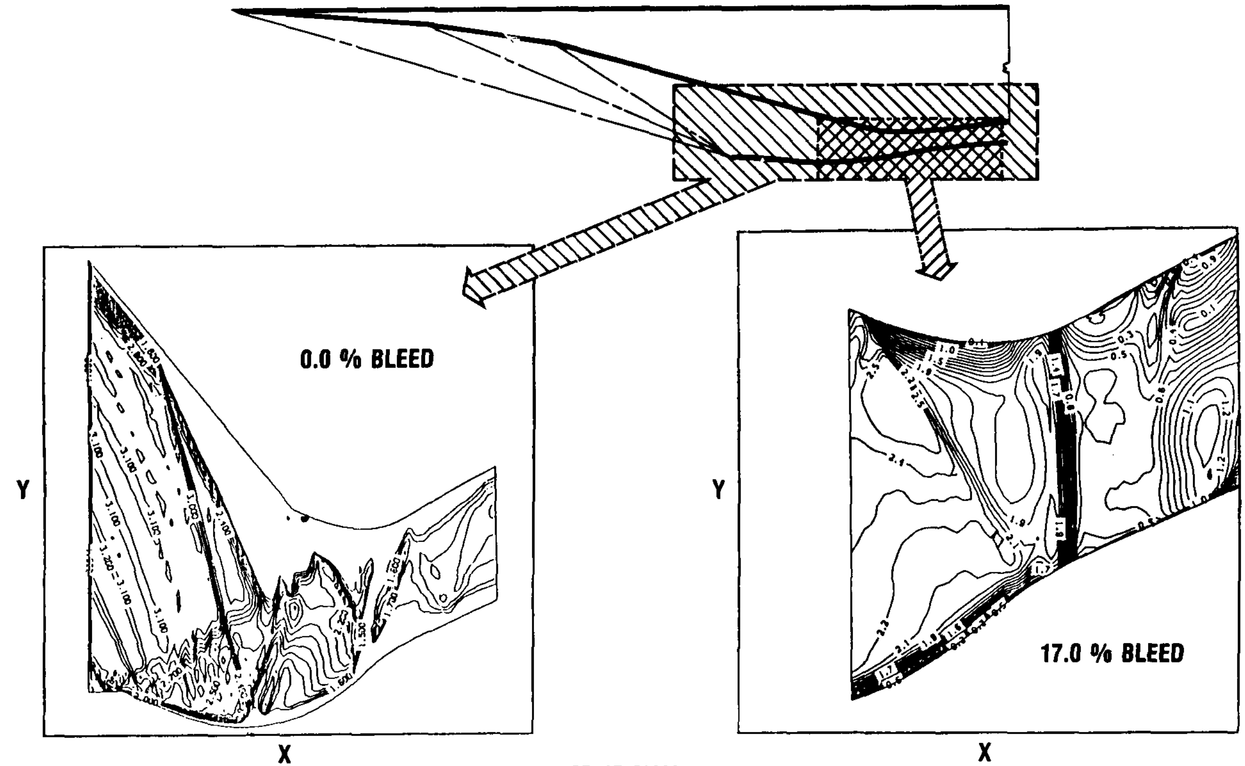
TWO-DIMENSIONAL KUMAR CODE ANALYSIS: Mach NUMBER CONTOURS

A two-dimensional analysis of the Mach 5 inlet, showing the benefits of boundary layer bleed on the ramp and cowl was carried out by W. Rose and E. Perkins of Rose Engineering and Research, consultants to Lockheed on the Mach 5 project. The analytical code was developed by A. Kumar of the NASA Langley Research Center. The Mach number distribution for the no-bleed case shown on the left represents the area encompassed by the large dashed box in the inlet sketch at the top. These contours show very large, separated regions on the ramp. The inlet will not operate in a started mode with these conditions, but would operate with the normal shock external to the cowl lip. The Mach contours on the right, with 17 percent bleed distributed through the inlet, represent the area in the inlet throat region on the sketch above. Bleed has prevented the large separations, and a normal shock has been stabilized in the inlet.

TWO-DIMENSIONAL KUMAR CODE ANALYSIS: MACH NUMBER CONTOURS



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BENEFITS TO BE OBTAINED FROM INLET TEST PROGRAM

A 1/3 scale model of the Mach 5 inlet is to be tested in the NASA Lewis 10 x 10 SWT. The main goals of this test plan are to: (1) provide data for code validation and for the development of inlet design codes, and (2) determine overall inlet performance and bleed requirements.

BENEFITS TO BE OBTAINED FROM INLET TEST PROGRAM

PROVIDE FUNDAMENTAL AND DESIGN DATA FOR CODE VALIDATION

- GLANCING SIDEWALL SHOCK/ BOUNDARY LAYER INTERACTION
- THICK BOUNDARY LAYER/MULTIPLE AND OBLIQUE SHOCK INTERACTION
- THICK BOUNDARY LAYER/NORMAL SHOCK INTERACTION
- CORNER FLOW
- INLET DESIGN CODE DEVELOPMENT DATA

DETERMINE OVERALL INLET PERFORMANCE

- DESIGN AND OFF-DESIGN AERODYNAMIC CHARACTERISTICS
- BLEED REQUIREMENTS
- UNSTART/RESTART CHARACTERISTICS
- CONTROL DATA SIGNALS
- VERIFICATION OF INLET DESIGN TECHNIQUE
- VERIFICATION OF ACCELERATOR PLATE TEST TECHNIQUE

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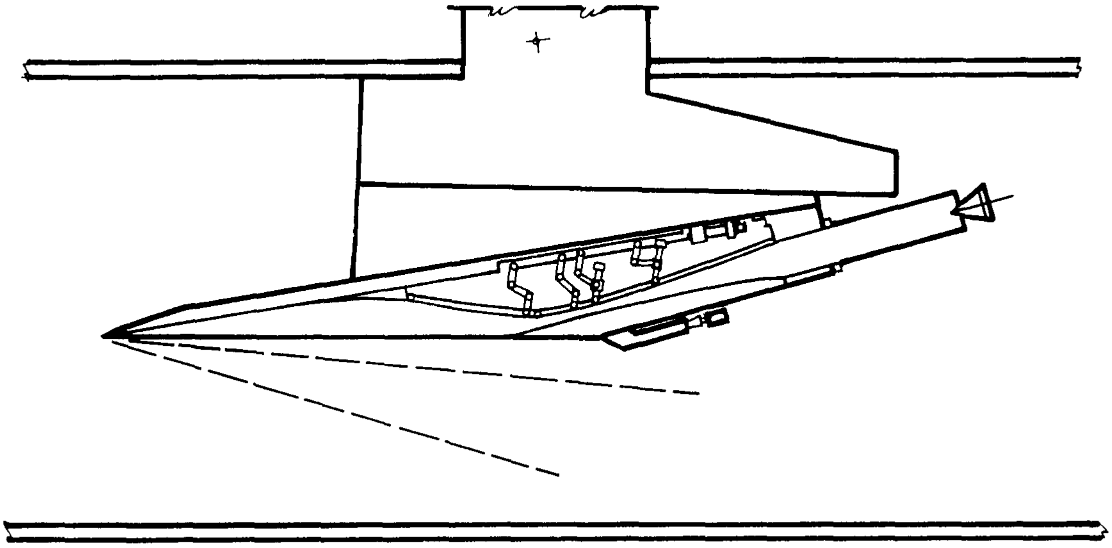
INLET RESEARCH

The Lewis 10 x 10 SWT has a maximum Mach number capability of 3.5. Therefore, to test the inlet at design conditions, the Mach 5.0 design freestream flow which is compressed to Mach 4.1 on the first ramp, is to be simulated by expanding the Mach 3.5 tunnel flow to Mach 4.1 underneath a plate at negative angle of attack. This "accelerator plate" test technique duplicates the actual inlet flow conditions with the exception of the initial oblique compression shock. The data will be corrected for the total pressure loss for this initial compression.

INLET RESEARCH



TWO-DIMENSIONAL INLET INSTALLED IN 10 × 10 SWT

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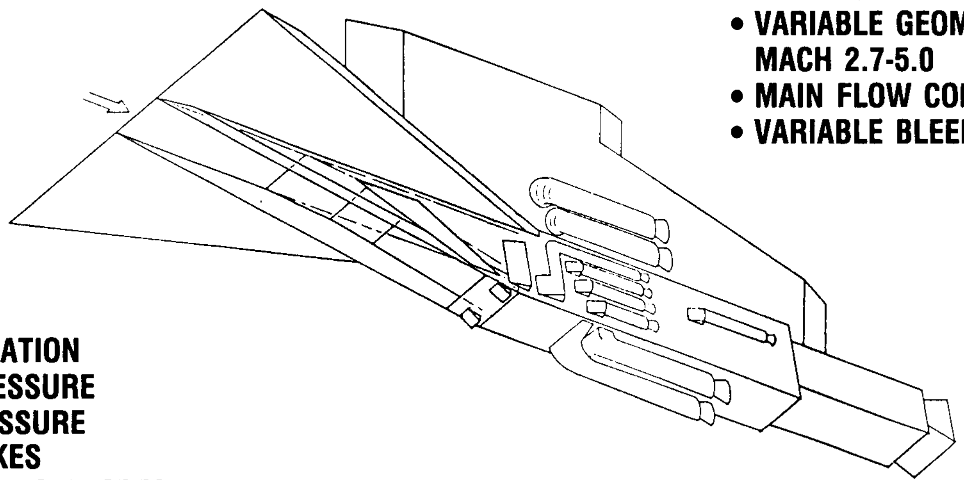
MACH 5 INLET MODEL

An isometric sketch of the model to be tested in the NASA Lewis 10 x 10 SWT is shown. The model incorporates remotely variable ramp geometry, main duct mass-flow control, and bleed exit plugs. The model is extensively instrumented with static pressure taps, total pressure rakes, translating flow angularity probes, and dynamic pressure transducers. It is a very large model, with the accelerator plate being 100 in. wide and an overall model length of about 20 ft. The cowl lip height is 16 in. with a capture width of 16 in.

MACH 5 INLET MODEL



REMOTE CONTROL:
- **VARIABLE GEOMETRY RAMP MACH 2.7-5.0**
- **MAIN FLOW CONTROL**
- **VARIABLE BLEED EXITS (15)**

INSTRUMENTATION
- **STATIC PRESSURE**
- **TOTAL PRESSURE**
  - **-FIXED RAKES**
  - **-TRANSLATING PROBES**
- **DYNAMIC PRESSURE TRANSDUCERS**
  - **-STATIC**
  - **-TOTAL**

DIMENSIONS
- **PLATE WIDTH = 100 in.**
- **COWL LIP HEIGHT = 16 in.**
- **LENGTH = 20 ft.**
- **CAPTURE WIDTH = 16 in.**

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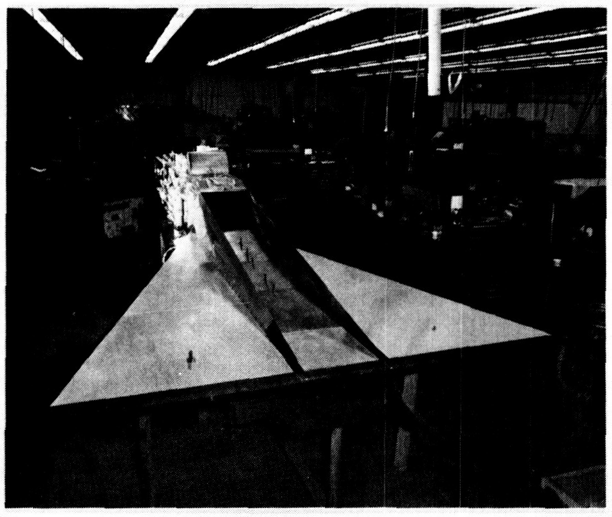
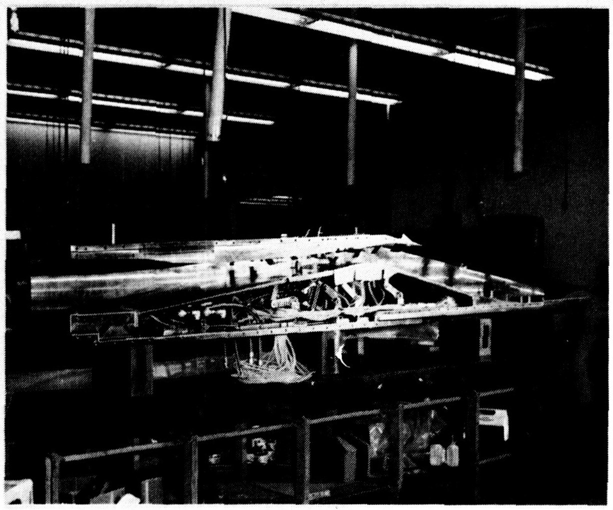
MACH 5 INLET TEST MODEL

Two views of the Mach 5 inlet model are shown. The model is made of stainless steel, except for the accelerator plate, which is aluminum. On the right, a side view of the inlet is shown with the sidewall removed to show variable ramp mechanisms. A single, large pair of actuators raises and lowers all moveable sections of the ramp simultaneously. The inlet duct is entirely two-dimensional, from leading edge to mass-flow control plug. All bleed regions are compartmented to prevent recirculation. Collapsible bellows are used to duct the compartmentalized ramp bleed through the ramp plenum.

MACH 5 INLET TEST MODEL





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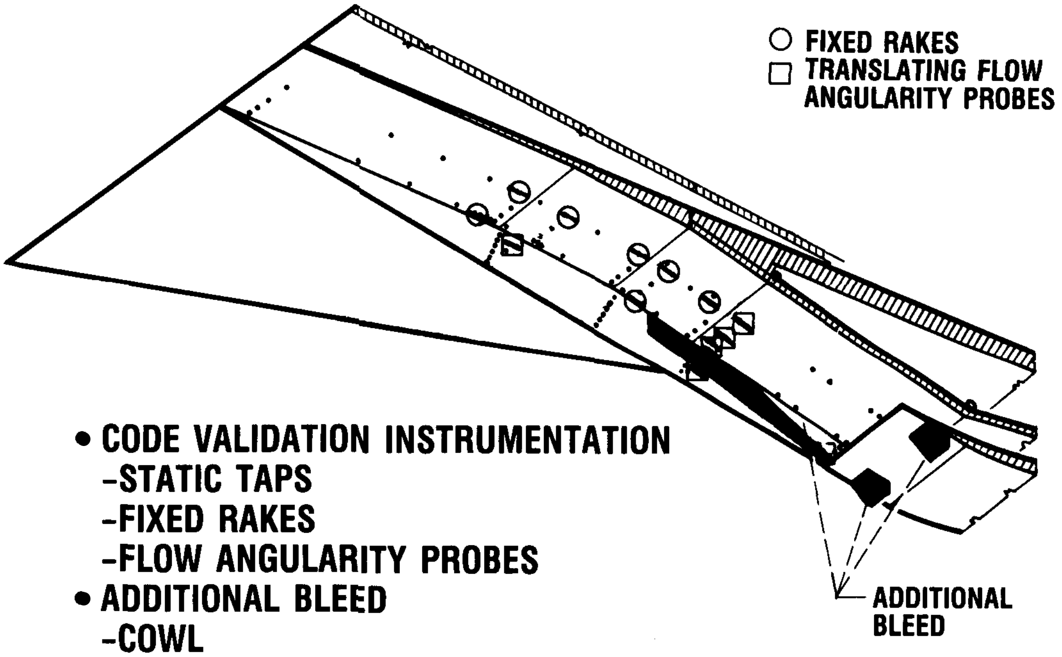
IMPACT OF "PEPSIS" ANALYSIS ON MODEL INSTRUMENTATION AND BLEED

As a result of the computational analysis indicating separations due to boundary layer migration from sidewall shock boundary layer interactions, modifications were made to the original model design. Additional instrumentation was added on the ramp and sidewall to map the flow migration phenomena and, also, to provide some code validation data. Additional bleed regions were added on the inlet sidewalls and on the cowl in the corners just aft of the cowl lip. This bleed was added to help control and/or eliminate corner separations.

IMPACT OF "PEPSIS" ANALYSIS ON MODEL INSTRUMENTATION AND BLEED



- **CODE VALIDATION INSTRUMENTATION**
  - -STATIC TAPS
  - -FIXED RAKES
  - -FLOW ANGULARITY PROBES
- **ADDITIONAL BLEED**
  - -COWL
  - -SIDEWALL

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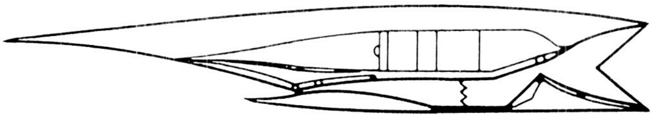
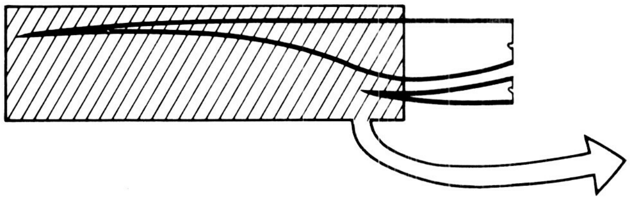
SMALL-SCALE PLATE/RAMP MODEL: 1 X 1 SWT

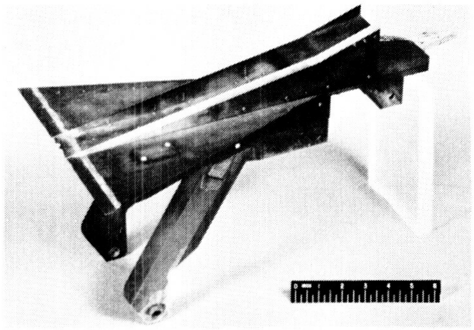
A simple, small-scale model of the high-speed inlet was tested in the NASA Lewis 1 x 1 SWT to provide some calibration data for comparison with analytical predictions. This model had capture dimensions of 1.6 in. by 1.6 in. and duplicated the inlet geometry to the cowl lip and ramp shoulder. Aft of these stations, the inlet was opened-up to allow inlet starting. The Schlieren photo on the lower left is for design flow conditions, and oblique shock waves from the second, third, and fourth ramps, as well as the cowl shock can be seen. The surface oil film photograph at the right is for an off-design Mach number (Mach 3.0 on the first ramp). For the condition shown in the photograph, the inlet was unstarted, as indicated by the ramp flow near the cowl lip station. However, upstream of this location the sidewall boundary layer flow migration that results from the boundary layer-glancing shock interaction can be seen.

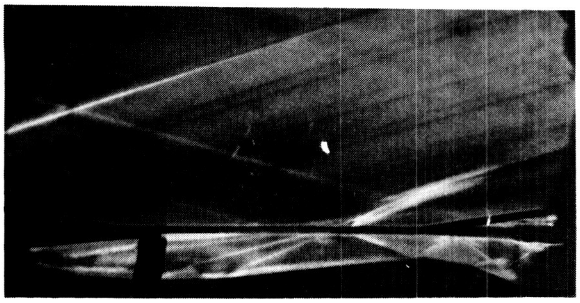
SMALL-SCALE PLATE/RAMP MODEL: 1 × 1 SWT

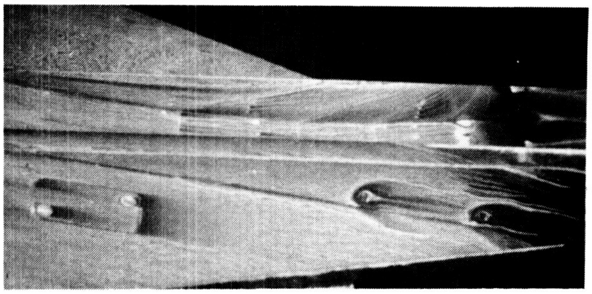
TURBOJET AND RAMJET









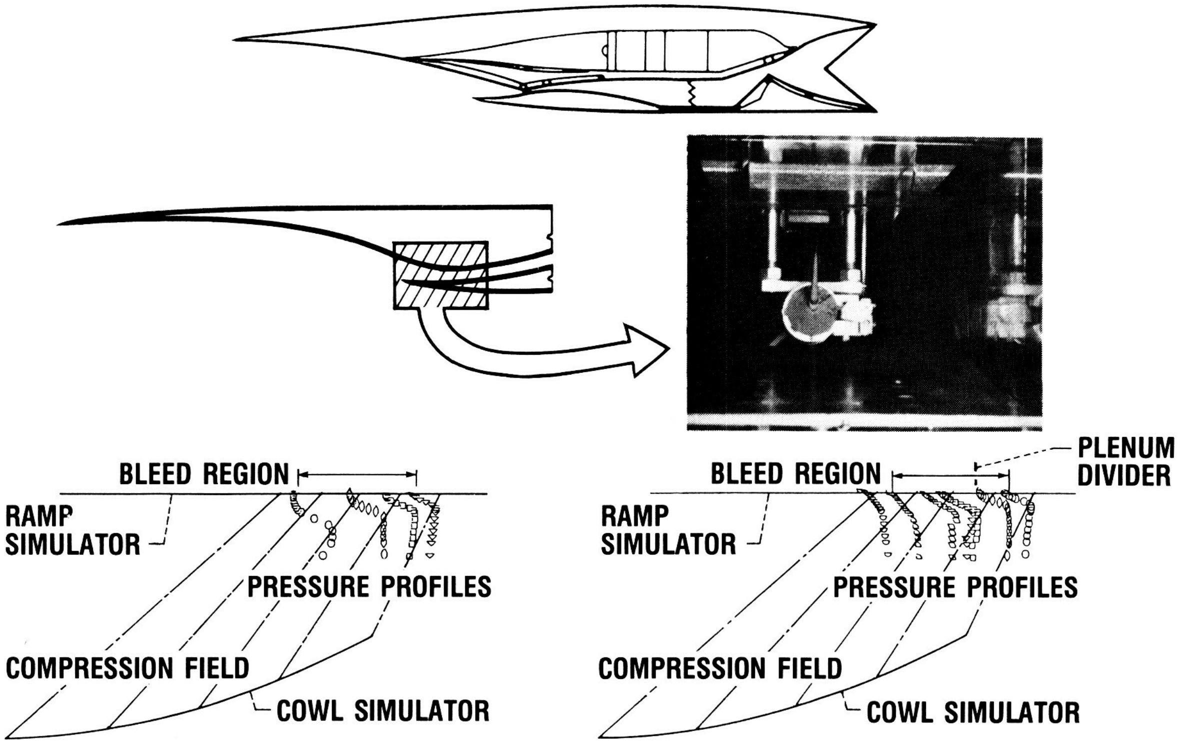


SCHLIEREN CD-87-28936 **OIL FLOW VISUALIZATION**

BLEED CONTROL STUDIES: 1 X 1 SWT

An aerodynamic design approach that may be used to reduce the weight of an inlet is to decrease the length over which the distributed cowl compression intersects the ramp surface. This is accomplished by increased curvature of the cowl and results in a large pressure rise over a short distance on the ramp. However, these large pressure gradients with large approach boundary layers can result in separation. A simple experimental program was conducted to study ramp bleed configurations to control the interaction of the pressure gradient-boundary layer in this region. For this test, the cowl was simulated by a contoured compression plate and the ramp by the tunnel wall (photo on the upper right in the figure). The tunnel wall incorporated a bleed plate in which various bleed patterns could be studied. A translating probe was used to survey the flow field. Surveys for a distributed porous bleed configuration are shown. Note that a separation occurs in the left-hand figure, due to recirculation in the bleed plenum. When the bleed is compartmentalized (as shown on the right) boundary layer is successfully controlled.

BLEED CONTROL STUDIES: 1 × 1 SWT



DISTRIBUTED POROUS BLEED

DISTRIBUTED POROUS BLEED (COMPARTMENTALIZED)

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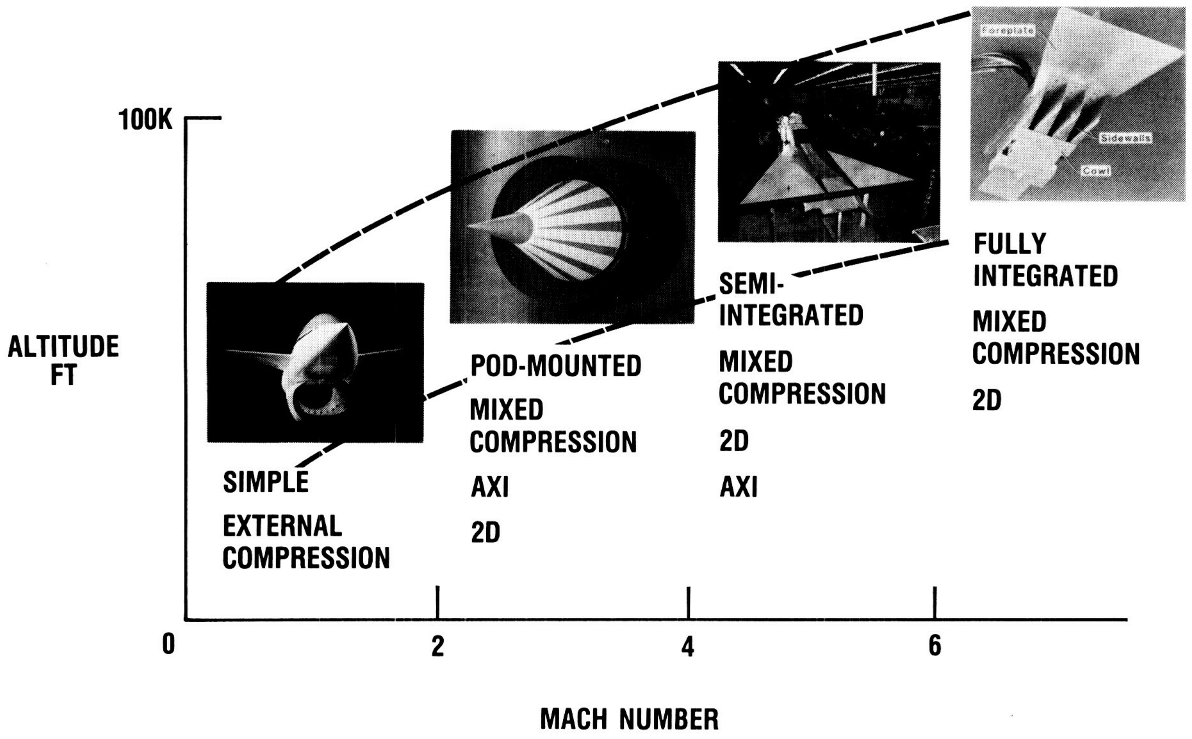
HIGH-SPEED CRUISE INLETS

The figure shows a plot of flight Mach number compared to altitude. Wind tunnel models of four representative inlets for different Mach numbers and altitudes are shown in the photographs. In the low supersonic speed range, inlets tend to be simple in geometry, and often have entirely external compression. The external compression HiMAT inlet is shown on the left. For aircraft operating in the Mach 2 to 4 range, inlets are usually pod-mounted and have mixed compression. Such an inlet, with axisymmetric geometry, is shown in the second photo from the left. This inlet incorporates a collapsing variable-diameter centerbody. In the Mach 4 to 6 range, inlets tend to be more integrated into the airframe. A two-dimensional Mach 5 inlet model is shown in the third photo from the left. Inlets for hypersonic (Mach 6+) aircraft are fully integrated into the airframe, and are normally two-dimensional rather than axisymmetric. A scram inlet model with sidewall compression is shown in the photograph at the right.

HIGH-SPEED CRUISE INLETS



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