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Recent Progress in the Development of Laminar Flow Aircraft

F. S. Collier, Jr.
NASA Langley Research Center
Hampton, VA 23681-0001

Abstract

This paper presents an overview of wind-tunnel investigations and flight research activities in the United States and Europe devoted to advancing the state-of-the-art and reducing the risk associated with the application of laminar flow control (LFC) technology to commercial transports. The paper highlights LFC research conducted within the last five years.

Introduction

Drag reduction in the form of laminar flow control applied to future, advanced commercial and military transports across the speed regime offers breakthrough opportunities in terms of reductions in take-off gross weight (TOGW), operating empty weight (OEW), block fuel for a given mission, and significant improvements in cruise lift to drag ratio (L/D). Recent NASA studies (Ref. 1) on an advanced subsonic, twin-engine commercial transport with anticipated 1995 engine, structure, and aerodynamic technology improvements incorporated into the design indicate that the application of laminar flow to the wing upper surface, empennage, and engine nacelles would result in TOGW and OEW reductions of about 10 and 6 percent, respectively, when compared to the turbulent baseline as shown in Figure 1. The analysis included conservative estimates of the hybrid laminar flow control (HLFC) system weight and engine bleed air (to drive the suction device) requirements. Satisfaction of all operational and Federal Aviation Regulations (FAR) regulatory requirements, such as fuel reserves and balanced field length, was achieved. Also shown in Figure 1, projected year 2000 technologies applied to an advanced high-speed civil transport (HSCT) designed to carry 247 passengers at Mach 2.4 a distance of 6500 nautical miles with laminar flow over 40 percent of the wetted wing area results in impressive improvements in TOGW, OEW, and fuel burn of 12.6 percent, 9.8 percent, and 16.0 percent, respectively, when compared to the turbulent version of the concept (Ref. 2). Based upon a TOGW of 750,000 lbs. for the turbulent baseline HSCT aircraft, the projected reduction in TOGW for the laminar airplane is roughly equivalent to the payload fraction!

In order to compute potential savings in fuel costs or improvements in aerodynamic efficiency as a function of total laminarized surface area, one must be able to accurately predict the location of boundary-layer transition on complex, three-dimensional geometries. Pressure gradient, surface curvature, wall temperature, wall mass transfer, and unit Reynolds number are known to influence the stability of the boundary layer. To further complicate matters, there exists many environmental disturbances, any one of which can cause immediate transition to turbulent flow if "supercritical" in nature. For example, although rare, ice crystals of sufficient size and density in cirrus clouds encountered during flight are known to "trip" a laminar boundary layer causing premature transition. Under such conditions, conventional linear stability theory is not applicable. In any case, linear stability theory represents the current state-of-the-art for transition onset prediction for flows past complex, three-dimensional geometries at transonic, supersonic and hypersonic speeds. Several excellent reviews of recent advances in transition prediction methods are available; therefore, no further discussion of this topic will occur in this paper.

This paper will present an overview of wind-tunnel investigations and flight research activities in the United States and Europe devoted to advancing the state-of-the-art and reducing the risk associated with the application of laminar flow control (LFC) technology to commercial and military transports. The paper will focus on LFC research conducted within the last five years and will highlight activities devoted to the attack of "barrier" challenges.

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B757 Hybrid Laminar Flow Control Flight Experiment (1987-1991)

Laminar flow flight research in the 1950's and 60's demonstrated that manufacturing techniques needed to obtain the stringent surface smoothness and waviness criteria required for laminar flow aircraft presented a major challenge. Today, it is recognized that conventional production aircraft wing surfaces can be built to meet these design constraints. Furthermore, the most significant advance made in the development of the laminar flow technology is the concept of hybrid laminar flow control (HLFC), an idea which integrates the concepts of natural laminar flow (NLF) and full-chord laminar flow control (LFC), and which avoids the undesirable characteristics of both (see Figure 2). NLF is sweep limited and full-chord LFC is very complex. The key features of HLFC are (a) conventional spar box construction techniques are utilized, (b) boundary-layer suction is required only in the leading edge, (c) natural laminar flow is obtained over the wing box through proper tailoring of the geometry, and (d) the HLFC wing design has good performance in the turbulent mode. The Leading Edge Flight Test on the NASA Jetstar addressed HLFC leading-edge system integration and reliability questions and set the stage for a large, commercial transport demonstration of HLFC. To this end, NASA initiated a cooperative flight program with the U. S. Air Force Wright Laboratory and Boeing Commercial Airplane Group on a B757 transport aircraft in 1987.

Objectives

The B757 High Reynolds Number HLFC Flight Experiment was designed to meet three objectives: (1) perform high Reynolds number flight research on the HLFC concept, (2) develop a data base on the effectiveness of the HLFC concept applied to a large, subsonic commercial transport, and (3) develop and flight validate an integrated, practical high-lift, anti-ice, and HLFC system.

Technical Approach

A 20-foot span segment of the leading-edge box of the B757's port wing outboard of the engine nacelle pylon was replaced with an all metal construction, HLFC leading-edge box as shown schematically in Figure 3. This new leading edge consisted of a micro-perforated titanium outer skin, subsurface suction flutes and collection ducts to allow for boundary-layer suction to control cross flow disturbance growth aft to the front spar of the B757, as well as fully integrated high-lift Krueger /insect shield and hot air de-icing systems. The wing-box portion of the test area consisted of the original, production B757 surface and contour, and only required minor clean-up to meet surface waviness and smoothness requirements for the achievement of laminar flow. The design point for the flight tests was chosen as M=0.80 at a lift coefficient of 0.50. Parametric variations around the design point were performed to investigate extent of laminar flow as a function of Mach number, unit Reynolds number and lift coefficient. Flight testing began in February of 1991.

Instrumentation

The instrumentation package on board the aircraft included: (a) flush mounted (in the perforated leading edge) and strip-of-tube static pressure measurement capability for external Cp distribution, (b) hot-film gages for transition detection of the wing box and attachment-line boundary layers, (c) infrared camera for boundary layer transition detection (phase II only), and (d) wake survey probe for inferred local drag reduction determination. A schematic of the instrumentation set-up is shown in Figure 4. The state of the laminar boundary layer, the internal and external pressure distributions, and the health of the suction system were monitored in real time on board the aircraft during the conduct of the flight test.

Major Accomplishments

The flight-test phase of the program consisted of 31 flights and 150 flight-test hours. During the conduct of the flight test, it was shown that the HLFC concept was extremely effective in delaying boundary-layer transition to the rear spar. The state of the boundary layer is shown in Figure 5 at a sample test condition with most of the hot-film gages indicating laminar flow beyond 65-percent chord. In fact, the suction rates required to routinely achieve laminar flow to 65-percent chord were about one-third of those predicted during the design phase. As shown in Figure 5, the wake rake measurements indicated a local drag reduction on the order of 29 percent with the HLFC system operational, which results in a integrated 6-percent drag reduction for the aircraft.

Hybrid Laminar Flow Nacelle Demonstration on a Commercial Transport (1991-1992)

Building upon the success of the B757 HLFC Flight Experiment, General Electric Aircraft Engines initiated a project in 1991 with Rohr, Industries, Inc., Allied Signal Aerospace, and NASA directed toward the aerodynamic flight demonstration of the hybrid laminar flow control concept applied to the external surface of large, turbofan engine nacelles. The friction drag associated with modern, turbofan nacelles may be as large as 4 to 5 percent of the total aircraft drag for a typical commercial transport, and NASA and industry studies indicate potential specific fuel consumption reductions on the order of 1-1.5 percent for advanced nacelles designed to achieve laminar boundary layer flow.

Objectives

As stated in Reference 3, the main objective of the project was "to demonstrate the feasibility of laminar flow nacelles for wide-body aircraft powered by modern high-bypass engines"........... and was "geared to investigate the influence of aerodynamic characteristics and surface effects on the extent of laminar flow."

Technical Approach

A production GEAE CF6-50C2 engine nacelle installed in the number two (on the starboard wing) position of a Airbus A300/B2 commercial transport aircraft was modified to incorporate two hybrid laminar flow control panels, one inboard, and one outboard as shown in Figure 6. The panels were built to very stringent surface waviness specifications, and were fabricated of a micro-perforated composite material. The design was capable of providing suction from the highlight aft to the outer barrel/fan cowl juncture. Suction was applied to the surface utilizing subsurface circumferential flutes, a design proven in previous LFC programs, and was collected and ducted to an industrial turbocompressor (TC) unit (the suction source) driven by engine bleed. For conveinence, the TC unit was located in the storage bay of the aircraft. The flow through each flute was individually metered. The laminar flow contour extended aft over the fan cowl door, and was accomplished through the use of a non-perforated "scab on" composite structure which was blended back into the original nacelle contour ahead of the thrust reverser. No provisions were made for anti-icing or insect contamination avoidance systems.

Instrumentation

The instrumentation package on the aircraft included: (a) static pressure taps on the external surface and in the flutes, (b) a boundary-layer rake to quantify boundary layer buildup, (c) hot-film gages for boundary-layer transition detection, (d) surface embedded microphones to assess noise field influence on the state of the boundary layer, (e) a charge patch for measurement of atmospheric particle concentration, and (f) infrared imaging for global laminar boundary layer transition detection. Real-time monitoring and analysis of the state of the boundary layer and suction system was accomplished on board the aircraft.

Major Accomplishments

The flight test phase of the project extended over a period of 16 flights totaling 50 flight hours. As shown in Figure 6, the HLFC concept was extremely effective over the range of cruise altitudes and Mach numbers tested, resulting in laminar flow to 43 percent of the nacelle length (the design objective) independent of altitude. At this location, the static pressure sensors indicated the beginning of the pressure recovery region, which effectively transitions the laminar boundary layer to a turbulent boundary layer. Without suction, significant laminar flow was achieved; however, as shown in Figure 6, the extent of laminar flow decreased as altitude decreased (unit Reynolds number increased) for the case of no suction.

The European Laminar Flow Program

Since the mid 1980's, the effort in Europe directed toward the development of laminar flow to the point of application has accelerated. The following sections will highlight several recent LFC developmental efforts.

Dassault Falcon 50 Hybrid Laminar Flow Flight Demonstrator (1987-1990)

Objectives

The main objective of the flight tests on the Falcon 50 aircraft was the development of a new, laminar flow wing design in the highly three-dimensional region near the fuselage which could provide for leading-edge boundary-layer suction aft to 10-percent of the chord on the upper surface, anti-icing and insect contamination avoidance, and fuselage turbulence contamination avoidance along the attachment line (Refs. 4-5). Achievement of 30-percent chord laminar flow in this region was the design objective.

Technical Approach

A perforated stainless steel suction article was "gloved" over the existing inboard wing structure in close proximity to the fuselage of the Falcon 50 aircraft. The glove was faired into the existing wing with an epoxy resin fairing. Boundary-layer suction was generated with the use of an ejector/plenum arrangement and was distributed chord wise through six spanwise flutes (see Figure 7). In addition, a TKS anti-icing system was integrated into the design, and performed the additional task of insect contamination avoidance. Monopropylene Glycol (MPG) was the fluid chosen for use in this system.

The flight test phase was conducted with and without a Gaster bump styled turbulence diverter installed in the inboard region on the leading edge of the suction panel. Initially, without the Gaster bump, the primary objective of the flight investigation was the assessment of the TKS anti-icing/insect avoidance system. In addition, the location of the attachment line was measured for proper placement to the Gaster bump. In the second phase, the effectiveness of the Gaster bump for turbulence contamination avoidance along the attachment line was assessed, as well as the effect of boundary-layer suction and sweep angle on the chordwise extent of laminar flow. The flight tests were conducted such that the chord Reynolds number variation in the region of the test article was between 12 and 20 million. The leading-edge sweep angle of the test article was nominally 35 degrees; however, additional testing was conducted at sideslip of 5 degrees yielding a resultant leading-edge sweep angle of 30 degrees.

Instrumentation

The installed instrumentation package included: (a) 3 rows of pressure taps embedded in the suction article between the flutes for external pressure distribution, (b) 3 rows of twelve hot films each for transition detection flush mounted downstream of the suction article, (c) 2 multi-element hot-film sensor arrays oriented spanwise on either side of the attachment line for attachment-line boundary layer state detection (used only during the leading-edge transition measurements), (d) infrared and video capability, (e) sensors for free stream turbulence measurements, and (f) velocimeters coupled with static pressure taps for flute mass-flow inference.

Major Accomplishments

It was demonstrated that the TKS system was very effective for insect avoidance. During low-altitude flight tests over insect-infested areas, the port (untreated) side of the aircraft had 600 insects per square meter impact the leading edge in the region of interest, whereas on the starboard side treated with the MPG fluid, no insect contamination was noted.

The effectiveness of the Gaster bump for turbulence contamination avoidance along the attachment line is illustrated in Figure 3. With boundary-layer suction and without the bump, the whole test article was observed to be turbulent. For various Reynolds number and sweep angle combinations, the best case revealed only a very small area of intermittent boundary-layer flow outboard on the test article (Figure 8). With the Gaster bump installed on the leading edge 150mm from the side of fuselage, and with the same suction rates as in the case of no bump, it was observed that the boundary layer was mostly intermittent, a tremendous improvement over the first case (Figure 8). Finally, when the bump was moved to a position 300mm from the root, most of the test article became fully laminar, as can be seen in Figure 8. In this configuration, when the sweep angle was reduced to 30 degrees by side-slipping the aircraft, a further slight improvement was observed in the extent of laminar flow (Figure 8). As expected, when the boundary-layer suction was eliminated, the flow over the test article became completely turbulent (Figure 8).

European Natural Laminar Flow Nacelle Demonstrator (1992-1993)

In 1992 and 1993, a cooperative program was conducted by DLR, Rolls Royce, and MTU with the goal of investigating in flight the prospects of achieving extensive natural laminar flow on aircraft engine nacelles (Ref. 6). The test vehicle chosen for the project was the VFW-614/ATTAS aircraft which has twin Rolls/Snecma M45H Turbofans, as shown in Figure 9. The program had the goals of: (1) demonstration of drag reduction with NLF applied to a nacelle in flight,

(2) verification of CFD design methodology, and (3) verification of manufacturing techniques for laminar flow surfaces. Two new composite nacelles were constructed by Hurel-Dubois for the program; one which consisted of the baseline nacelle lines, and another with a new set of aerodynamic lines, as can be seen in the comparison of the baseline nacelle and NLF nacelle pressure distributions shown in Figure 9 for the isolated nacelle case. The flight test portion of the program consists of two phases; the first of which tested the composite NLF design and the second for testing the new composite baseline nacelle.

In September of 1992, the first phase of the program was completed with 38 flight hours acquired at conditions representative of commercial transports. The results of the program indicated the validity of CFD for laminar flow design purposes, successfully moving the transition location aft and realizing a drag reduction with the NLF nacelle. No results are available on Phase II of the program at this time.

European Laminar Flow Investigation (1989-1992)

The European Laminar Flow Investigation (ELFIN) project, initiated in 1989, consisted of four primary elements, each of which concentrated on the development of laminar flow technology for application to commercial transport aircraft: (1) a transonic wind-tunnel evaluation of the hybrid laminar flow concept on a large scale model, (2) the development of a boundary-layer suction device, as well as the development of new wind-tunnel and flight-test techniques, (3) development of improved computational methods for laminar to turbulent flow predictive capability, and (4) a partial-span flight demonstration of natural laminar flow utilizing a foam and fiberglass glove over existing wing structure (Ref. 7). The project team consisted of 24 organizations, including Deutsche Airbus, coordinator of the project, Alenia, Aerospatiale, British Aerospace, CASA, Fokker Aircraft/NLR, Dassault Aviation, Donier, SAAB/FFA, Steigerwald, Analysis Systems, Onera, CIRA INTA, DLR, and the Universities of Manchester, Bristol, Galway, Libson, Lyngby, Darmstadt, Delft, Madrid, and Zaragoza. This phase of ELFIN was completed in 1992.

VFW-614 HLFC Transonic Wind-Tunnel Experiment (1992)

Tasks 1 and 2 of the ELFIN program called for a transonic wind-tunnel evaluation of the hybrid laminar flow concept, evaluation of wind-tunnel test techniques and development of viable boundary-layer suction devices. To this end, in March and April of 1992, a 1:2 scale model of one of the VFW-614 wings capable of leading-edge suction was built by the ELFIN project team and tested in the French S1MA transonic tunnel, the first test of its kind in the facility (Ref. 8). The model had a span of 4.7m and a mean chord of 1.58 m. A schematic of the test set-up is shown in Figure 10, including a detailed view of the ejector system used to provide the boundary-layer suction.

The perforated leading edge was built into the mid-span region of the wing, and was about 0.95m in span and provided boundary-layer suction aft chord wise to about 15 percent chord on both the upper and lower surface. The titanium outer skin was 0.9mm thick and had holes which were 40 microns in diameter and spaced 0.5mm apart. The suction surface had average porosity of 44 percent. As shown in Figure 10, the leading edge consisted of 38 suction flutes ganged to 17 collection ducts. The suction flow rate through each collection duct was individually controlled and measured. Figure 10 shows the model installed in the S1MA wind-tunnel (Ref. 9).

In Figure 10, the chord-wise transition location measured with infrared thermography as a function of suction flow velocity for a given transonic test condition is illustrated. As can be seen, as the suction flow velocity is increased from zero, the transition front moves aft, an indication of successful control of the boundary-layer disturbance growth rates. Data gathered from the test will be used for suction system design criteria and calibration of the laminar flow predictive methodology. It was expected that further data analysis would occur in a new effort, conducted under ELFIN II.

Fokker 100 Natural Laminar Flow (NLF) Glove Flight Experiment (1991)

Building upon the success of VFW-614/ATTAS NLF wing flights tests conducted in 1987, the ELFIN project team embarked upon Task 4, choosing a Fokker 100 (Figure 11) transport aircraft for the partial-span NLF demonstration. The main objectives of this task were to measure the drag reduction associated with a natural laminar flow wing design, validate laminar flow CFD methodology, and to establish the upper limits (transition Reynolds number for a given leading-edge sweep angle) of NLF (Refs. 7, 10-12). As seen in Figure 11, the geometry and flight envelope of the Fokker 100 allows for the exploration of the NLF boundary.

The starboard wing was modified with a full-chord, partial-span natural laminar flow glove which was bonded to the original wing surface, and located between the flap track fairings as shown in Figure 12. Glove construction was of foam and fiberglass, was prefabricated in a very accurate mold, and designed to provide over 50-percent chord laminar flow. In addition, a wake rake was mounted aft of the NLF test section so that local drag reduction could be inferred from wake pressure profile measurements. The aircraft was instrumented with two infrared cameras for boundary-layer transition detection, one above and one below the wing (Figure 12). To facilitate transition detection with the IR cameras, a carbon-fiber heater mat was embedded in the glove to enhance the heat transfer process on the surface (Figure 12). The glove was further instrumented with chordwise, flush static pressure taps and embedded hot films for boundary-layer flow physics measurements, as well as an additional means of detecting transition.

The Fokker 100 flight-test phase conducted within ELFIN, consisted of 3 flights for a total of twelve hours (see Figure 12), and produced results which confirmed predictions of 15-percent drag reduction, thereby validating preflight high-speed, wind-tunnel investigations conducted at the Dutch National Aerospace Laboratory. Further efforts were expected to be conducted under ELFIN II.

The A320 Laminar Fin Program

A program consisting of theoretical analysis, a large wind-tunnel evaluation, and a flight test program geared toward the application of laminar flow to wing surfaces of future, advanced aircraft was initiated by Airbus, Industrie in close collaboration with ONERA and DLR in 1987 (see Figure 13). The vertical fin of the A320 aircraft was chosen as the candidate for evaluation of the feasibility of HLFC because of the availability of an aircraft for flight testing, simple installation, no de-icing system, attainment of flight Reynolds number in existing wind-tunnel facility (S1MA at Modane), and minimized cost (Refs. 13-15). Analysis of the pressure distribution of the existing A320 vertical tail and a proposed HLFC A320 vertical tail is shown in Figure 14. Results indicate that laminar flow is achievable to about 40-percent chord of the baseline A320 fin, and about 50-percent chord of the HLFC A320 fin for reasonable amounts of boundary-layer suction. Further analysis of these results revealed that 1.0-1.5% aircraft drag reduction is possible by laminarizing the vertical fin. The second phase of the program involved the testing of the the A320 vertical fin with leading edge suction in the ONERA S1MA facility. It is expected that a follow-on flight program of the HLFC fin design will occur in 1994 on an A320 aircraft.

Concluding Remarks

This paper has reviewed recent efforts in the U.S. and Europe directed toward solving barrier problems associated the application of laminar flow control to advanced, next generation aircraft. The technology has the potential to offer breakthrough improvements in aircraft efficiency, thereby leading to (1) significant reductions in aircraft fuel consumption or (2) significant extended range capability. Much progress has been accomplished toward the goal of commercial application. However, application of the technology leads to additional systems and maintenance requirements. There are still questions which must be resolved relative to long-term operational and reliability characteristics of current HLFC concepts, and these and other issues must be addressed before the customers of the technology can commit to the investment required for ultimate application of the technology.

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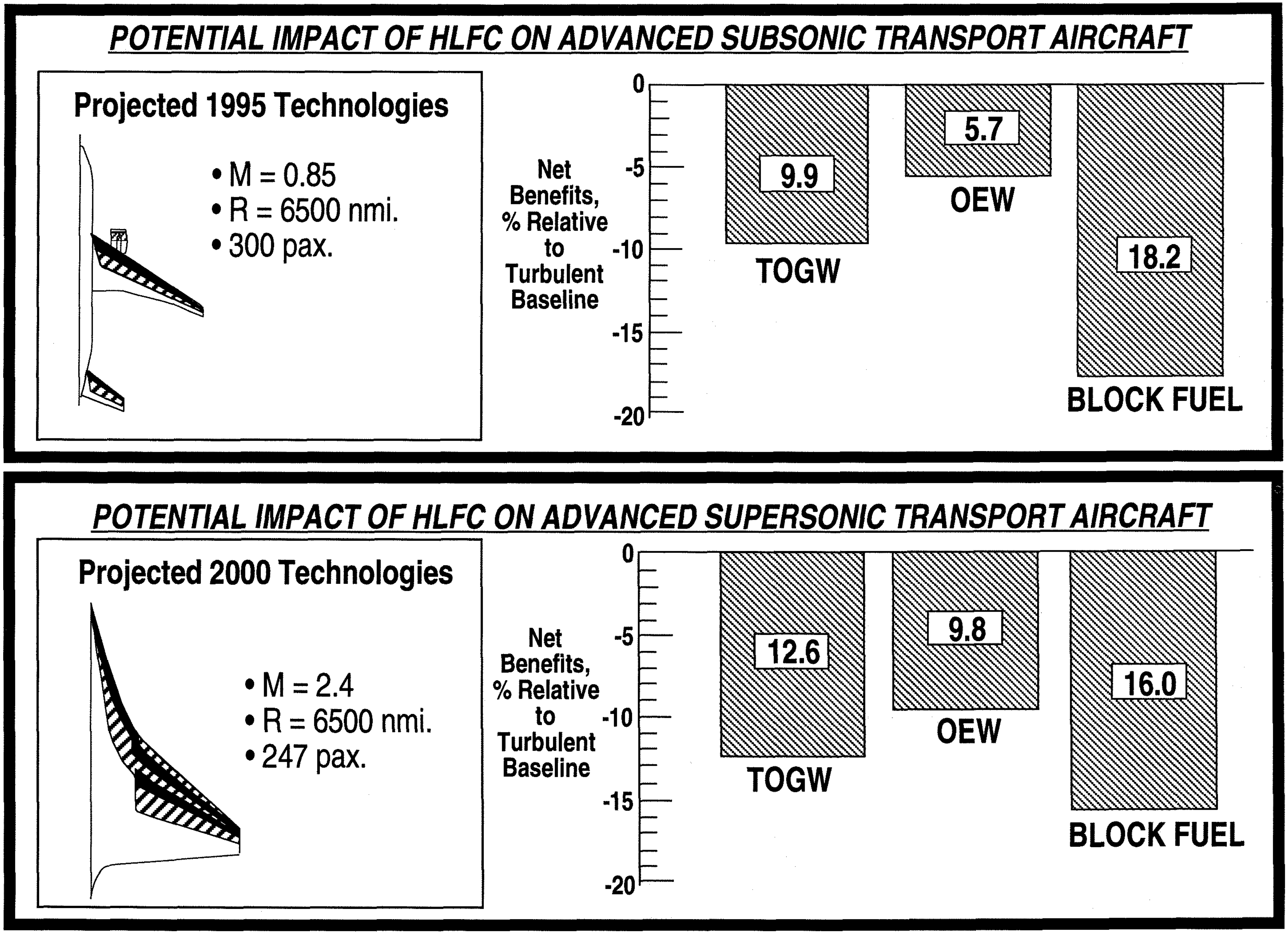
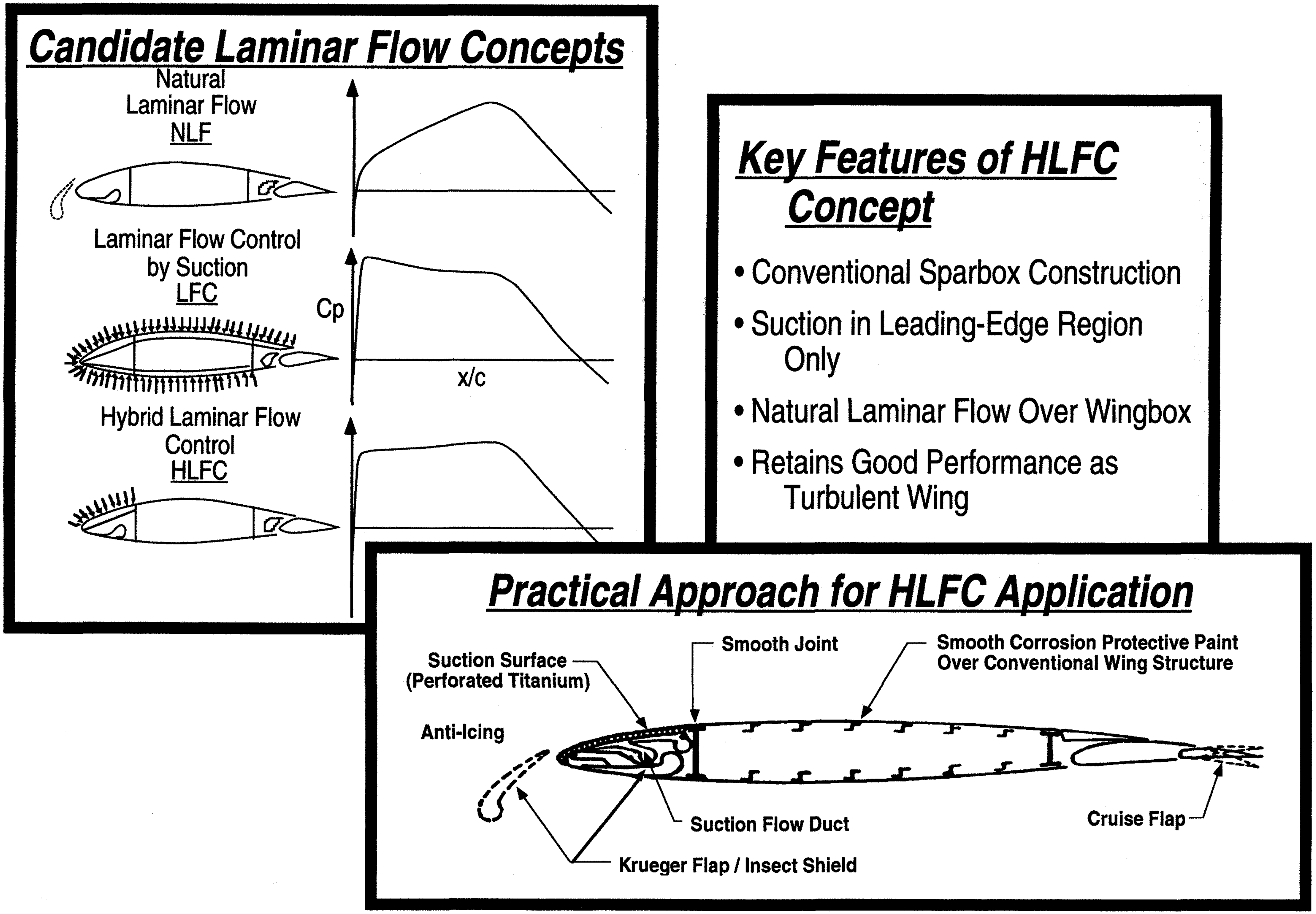


POTENTIAL IMPACT OF HLFC ON ADVANCED SUBSONIC TRANSPORT AIRCRAFT

POTENTIAL IMPACT OF HLFC ON ADVANCED SUPERSONIC TRANSPORT AIRCRAFT

Figure 1 - Potential Impact of Laminar Flow Control Applied to Advanced Aircraft Configurations



Key Features of HLFC Concept

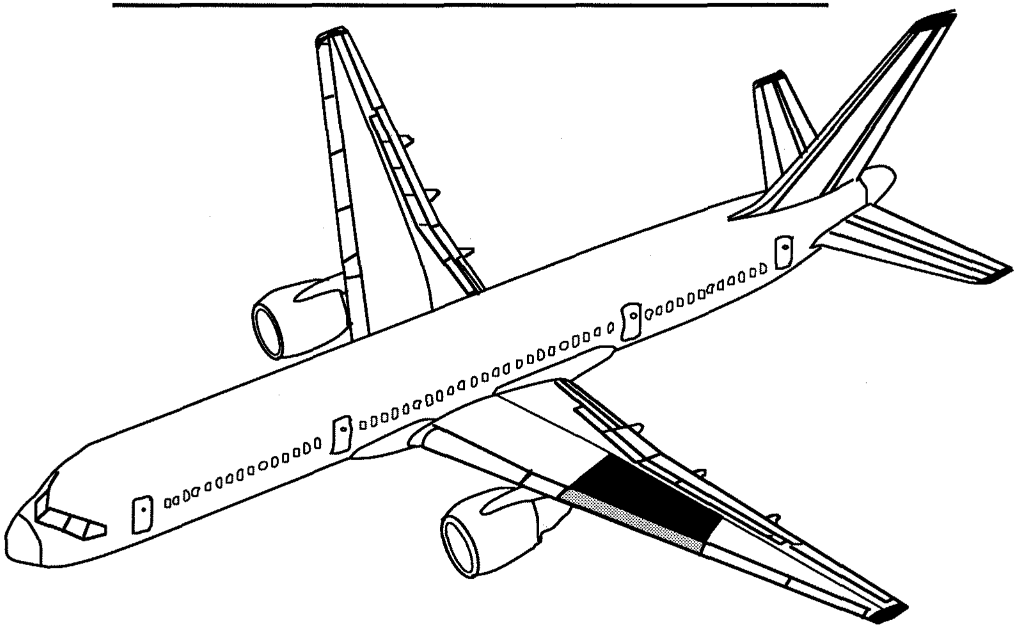
- Conventional Sparbox Construction
- Suction in Leading-Edge Region Only
- Natural Laminar Flow Over Wingbox
- Retains Good Performance as Turbulent Wing

Figure 2 - Candidate Laminar Flow Concepts and Schematic of the HLFC Concept

Technical Features

- Cruise Conditions
  - M = 0.80
  - RN = 30 million
  - Alt. = 34 to 42 kft.
- Laminar Flow Achievable (Design)
  - 38 to 62 percent chord
- Boundary-Layer Suction to Front Spar
- Microperforated Titanium Suction Surface
- All Metal Construction
- Operational Systems
  - Leading-Edge High-Lift Krueger/Insect Shield
  - Thermal Anti-Icing

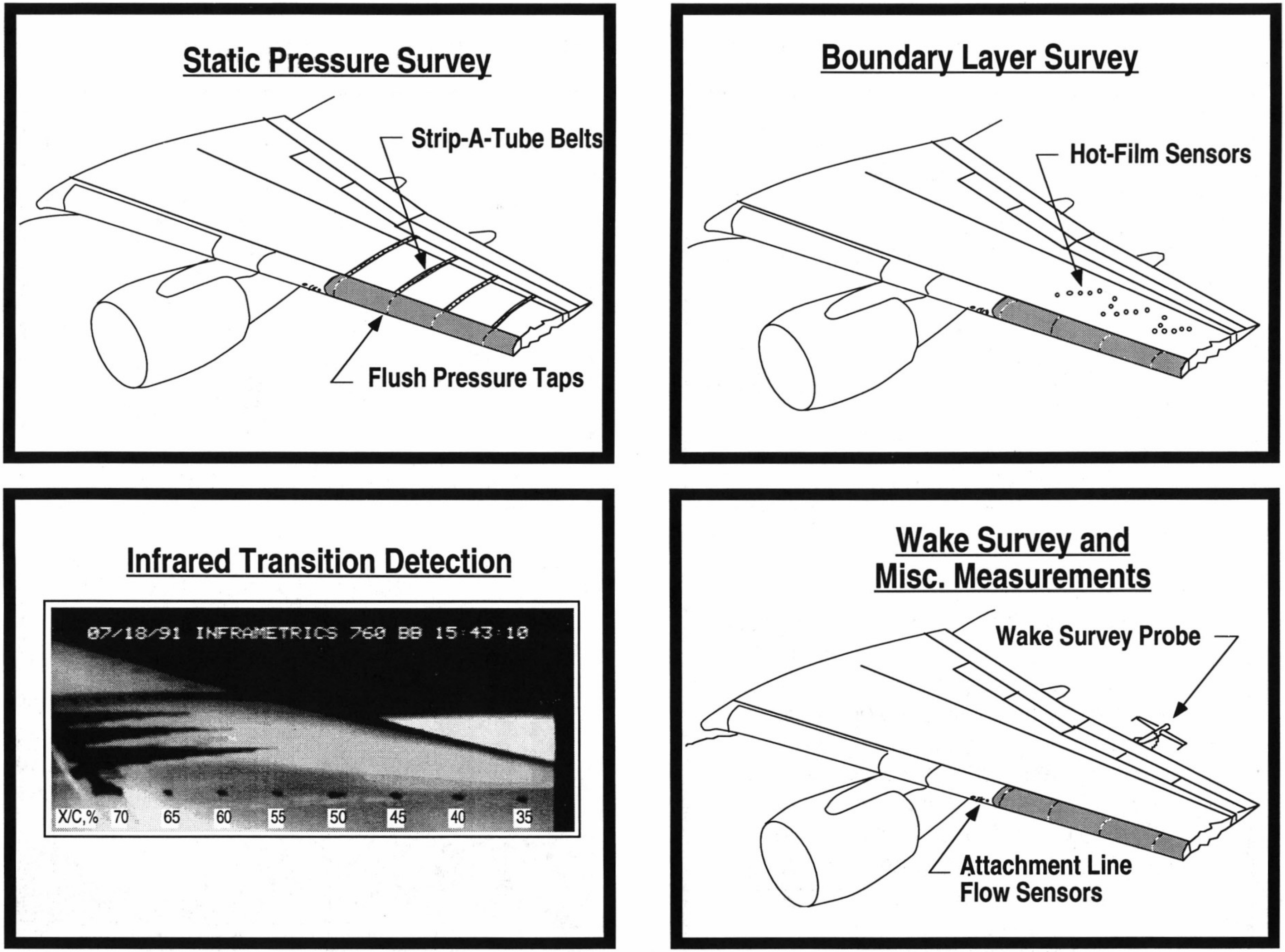
B757 HLFC Test Bed Aircraft



Critical Program Milestones

• Contract Award	Nov '87
• Critical Design Review	Dec '88
• First Flight	Feb '90
• Complete Phase I & II	Sep '91
• Complete Documentation	Jul '93

Figure 3 - Technical Features and Schematic Layout of B757 HLFC Test Bed Aircraft



Static Pressure Survey

Boundary Layer Survey

Infrared Transition Detection

Wake Survey and Misc. Measurements

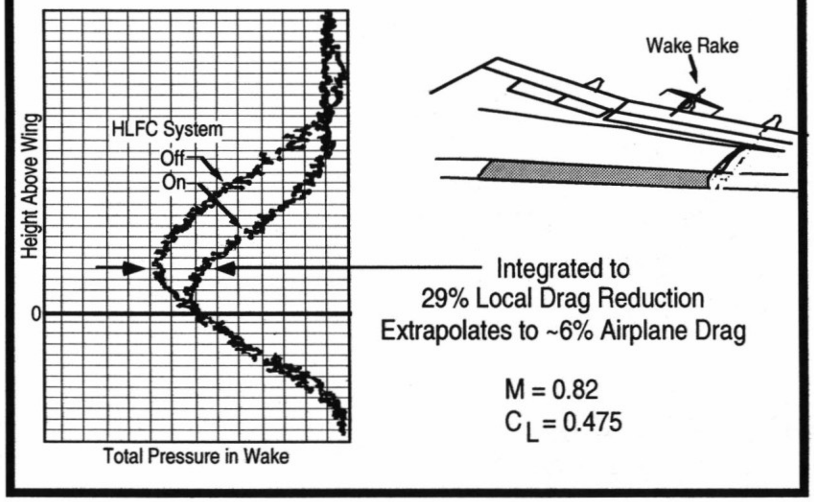
Figure 4 - Schematic of the Instrumentation Layout for the B757 HLFC Flight Tests

B757 HLFC TESTBED IN FLIGHT

ACCOMPLISHMENTS

- 31 Flights, 150 Flight Test Hours
- Installed Practical HLFC Systems into a Commercial Transport Leading Edge
  - Suction Panel, Ducting and Controls
  - Krueger High Lift/Insect Shield
  - Hot Air Deicing (did not demonstrate)
- Laminar Flow Routinely Achieved
- Maximum Extent of Laminar Flow Shock-Limited
- Calibrated Existing Predictive Methods

DRAG REDUCTION MEASUREMENTS



Integrated to 29% Local Drag Reduction Extrapolates to ~6% Airplane Drag

$M = 0.82$

$C_L = 0.475$

LAMINAR FLOW DETECTION

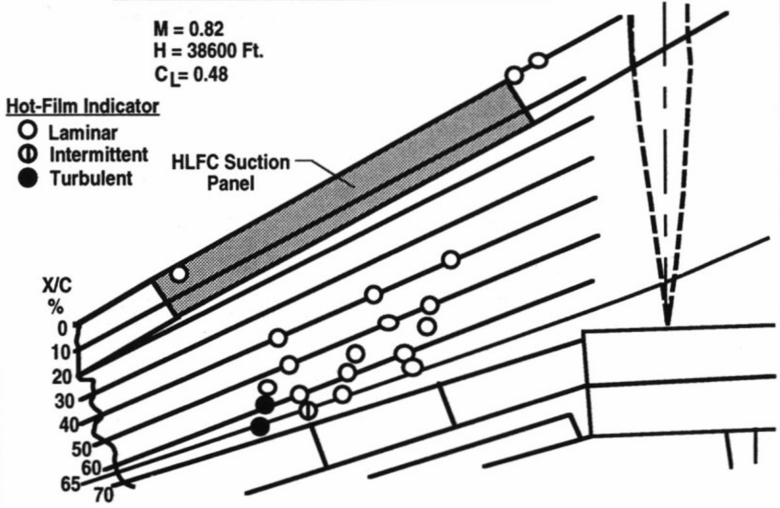


Figure 5 - B757 High Reynolds Number Hybrid Laminar Flow Control Program Results

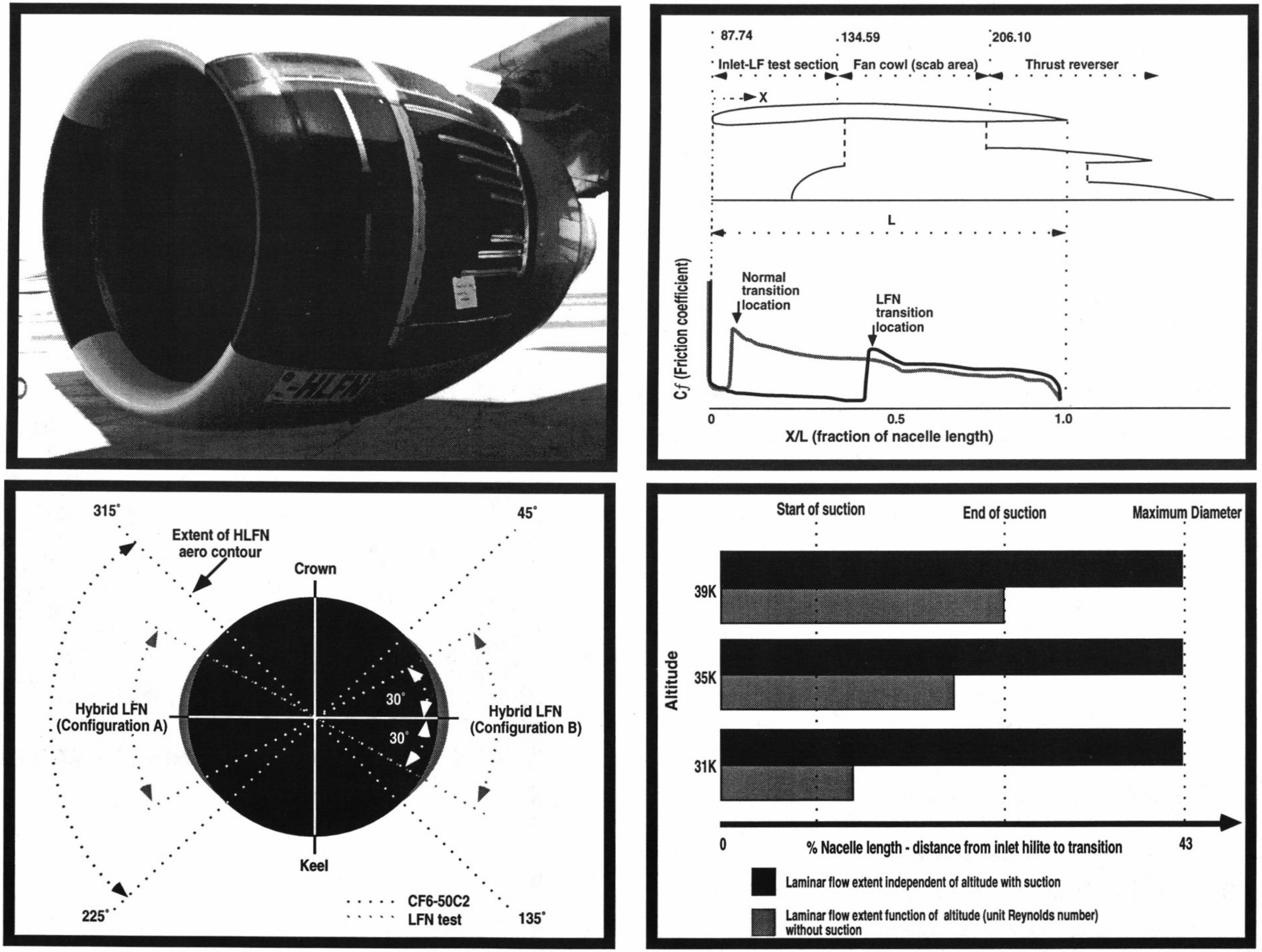
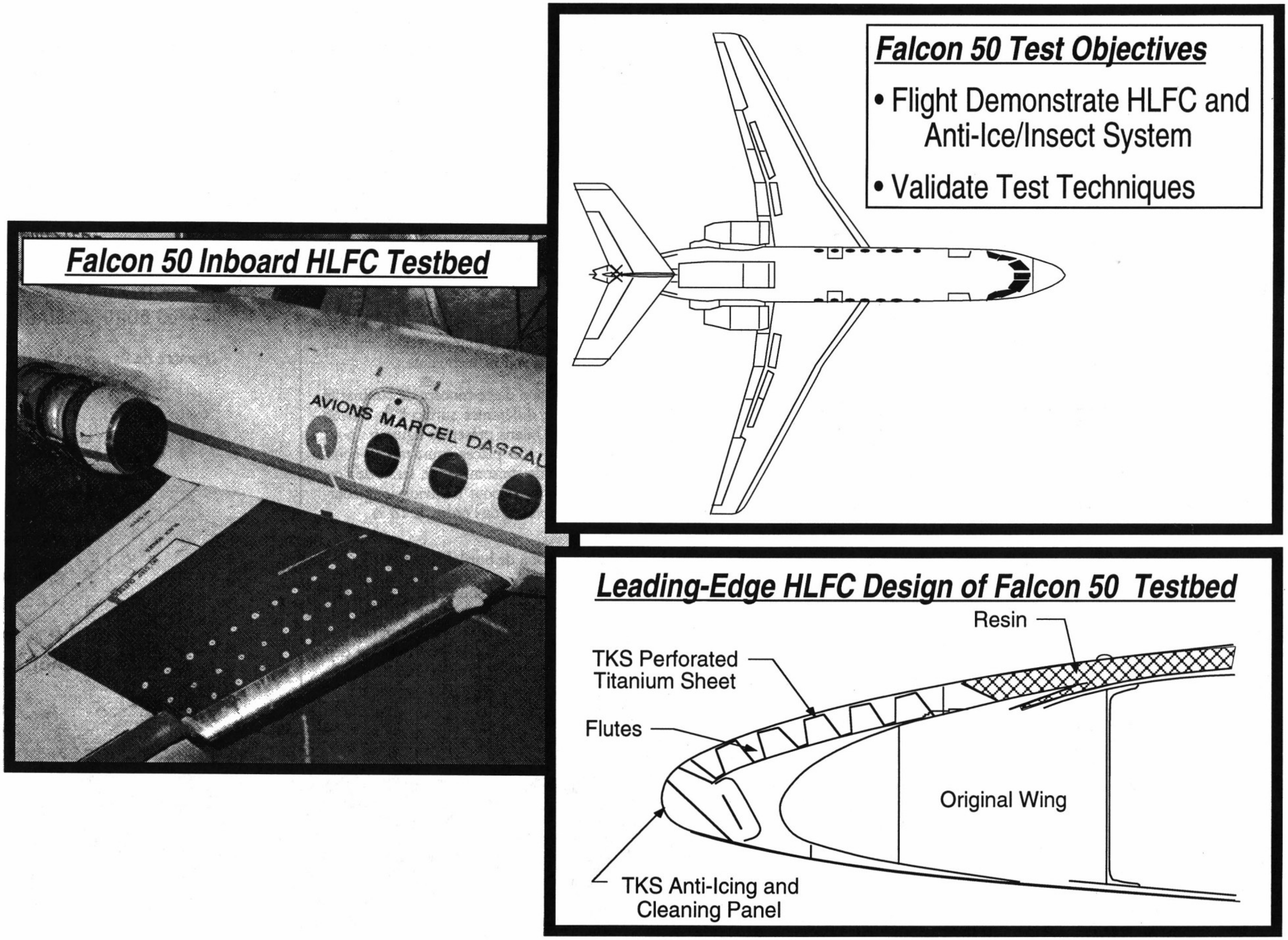


Figure 6 - General Electric Hybrid Laminar Flow Nacelle Program (Ref. 3)


Falcon 50 Test Objectives

- Flight Demonstrate HLFC and Anti-Ice/Insect System
- Validate Test Techniques

Falcon 50 Inboard HLFC Testbed

Leading-Edge HLFC Design of Falcon 50 Testbed

Figure 7 - Dassault Falcon 50 Hybrid Laminar Flow Flight Demonstrator (Refs. 4 and 5)

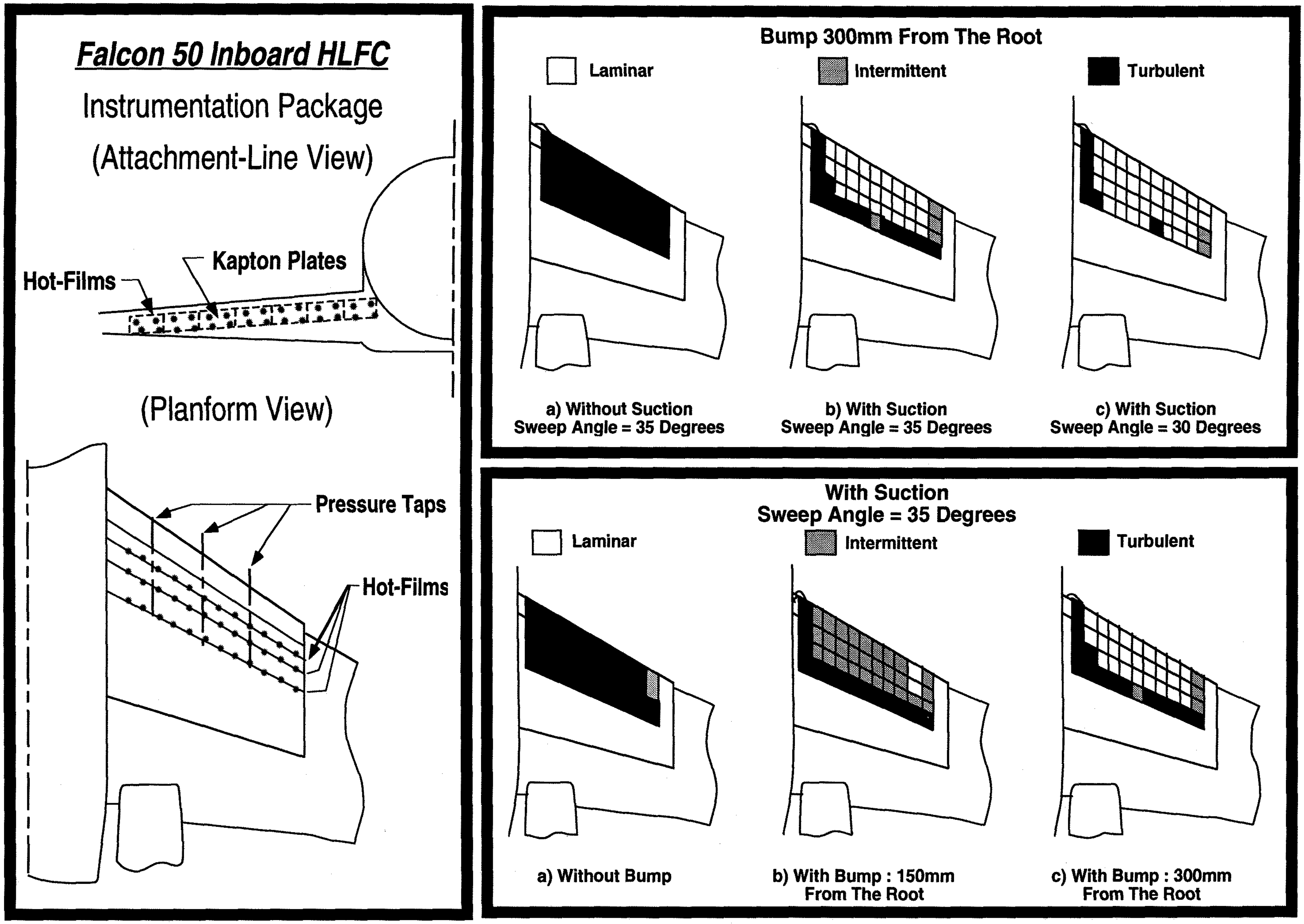
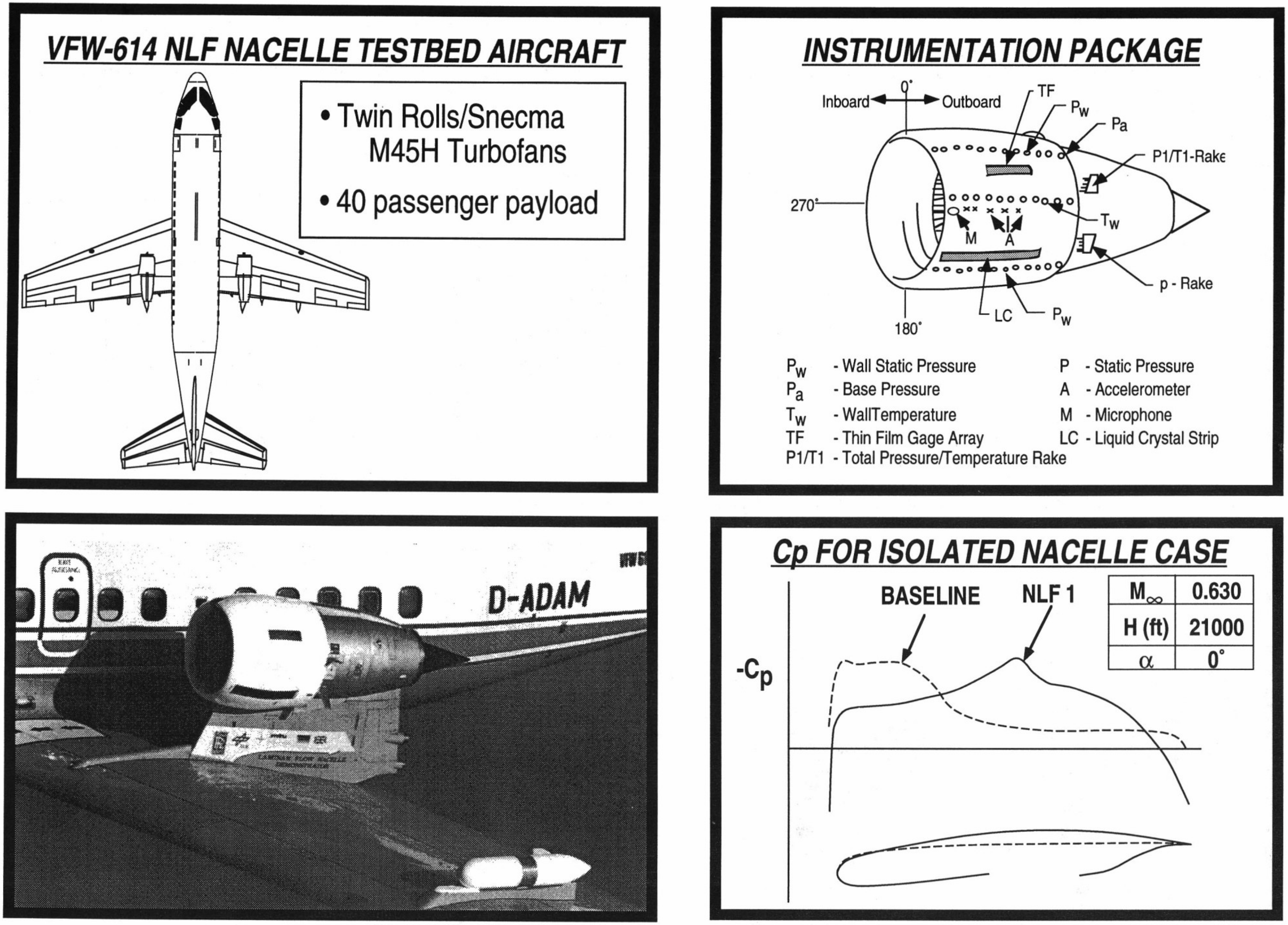


Figure 8 - Instrumentation Layout and Flight Test Results on Falcon 50 HLFC Demonstrator (Ref. 4)



VFW-614 NLF NACELLE TESTBED AIRCRAFT

- Twin Rolls/Snecma M45H Turbofans
- 40 passenger payload

INSTRUMENTATION PACKAGE

P_w	- Wall Static Pressure	P	- Static Pressure
P_a	- Base Pressure	A	- Accelerometer
T_w	- WallTemperature	M	- Microphone
TF	- Thin Film Gage Array	LC	- Liquid Crystal Strip
P1/T1	- Total Pressure/Temperature Rake		

Cp FOR ISOLATED NACELLE CASE

M_∞	0.630
H (ft)	21000
α	0°

Figure 9 - European Natural Laminar Flow Nacelle Demonstrator on the VFW-614/ATTAS (Ref. 6)

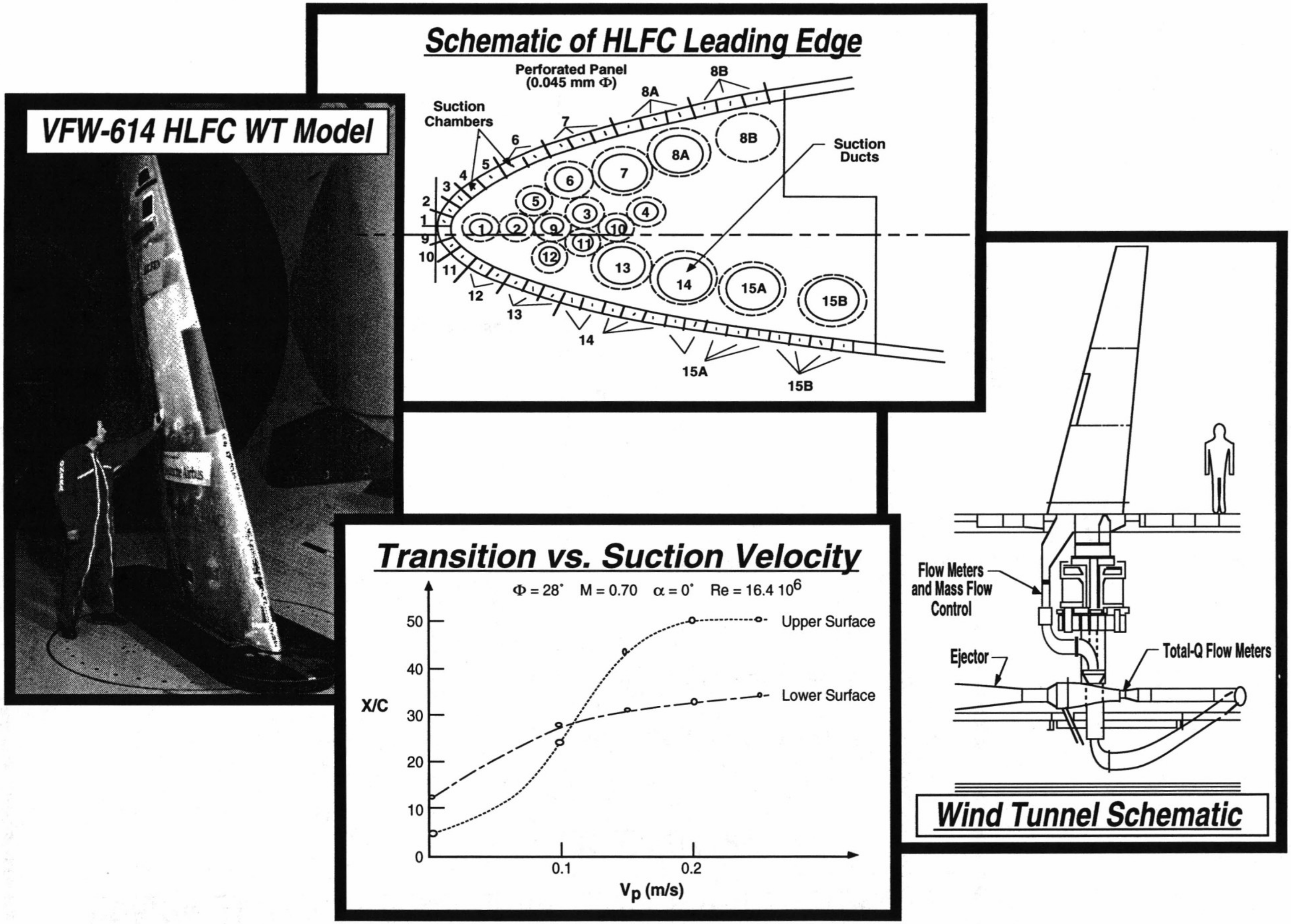
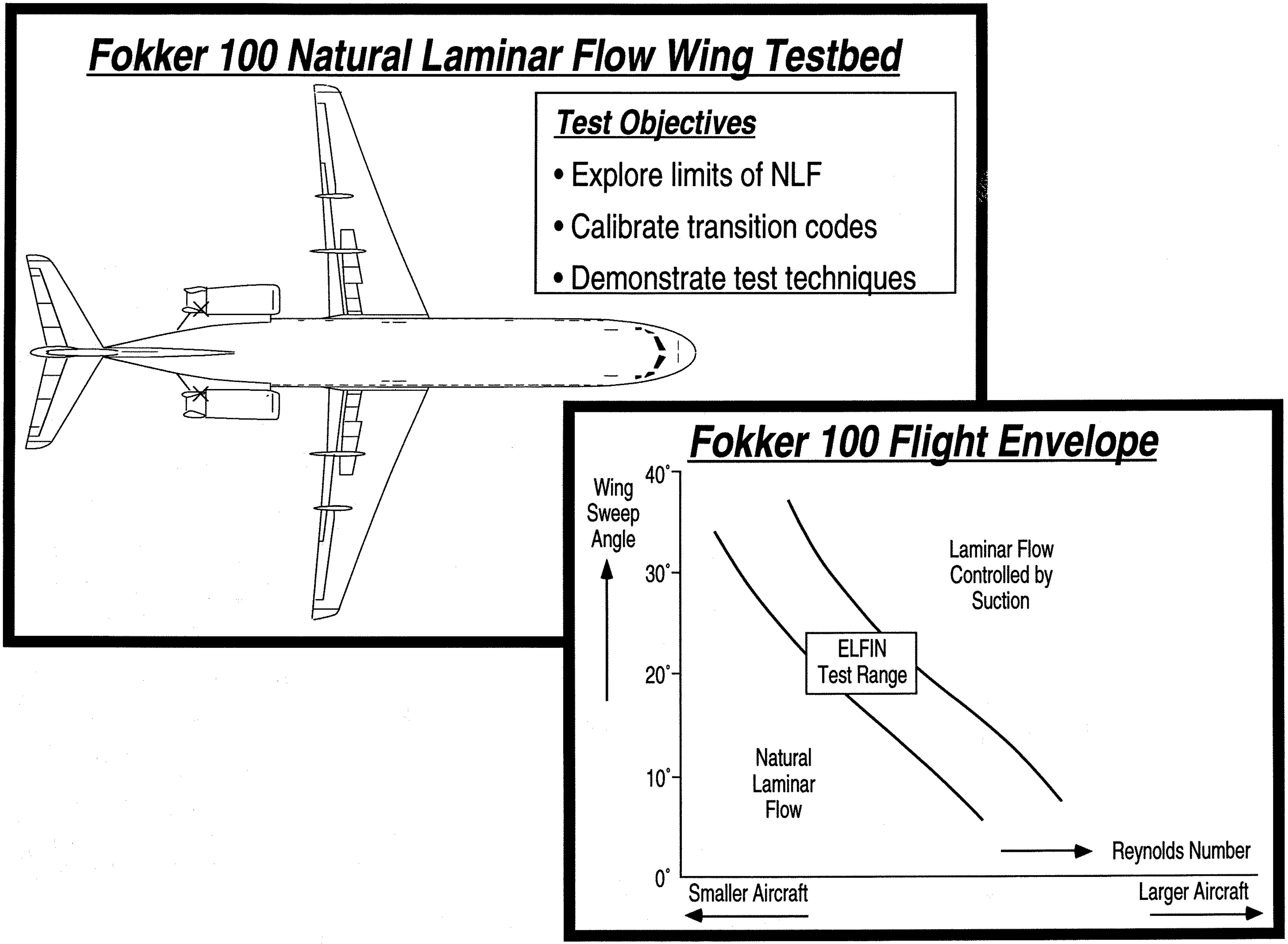


Figure 10 - ELFIN Large-Scale HLFC Wind-Tunnel Investigation in ONERA S1MA (Refs. 8 and 9)



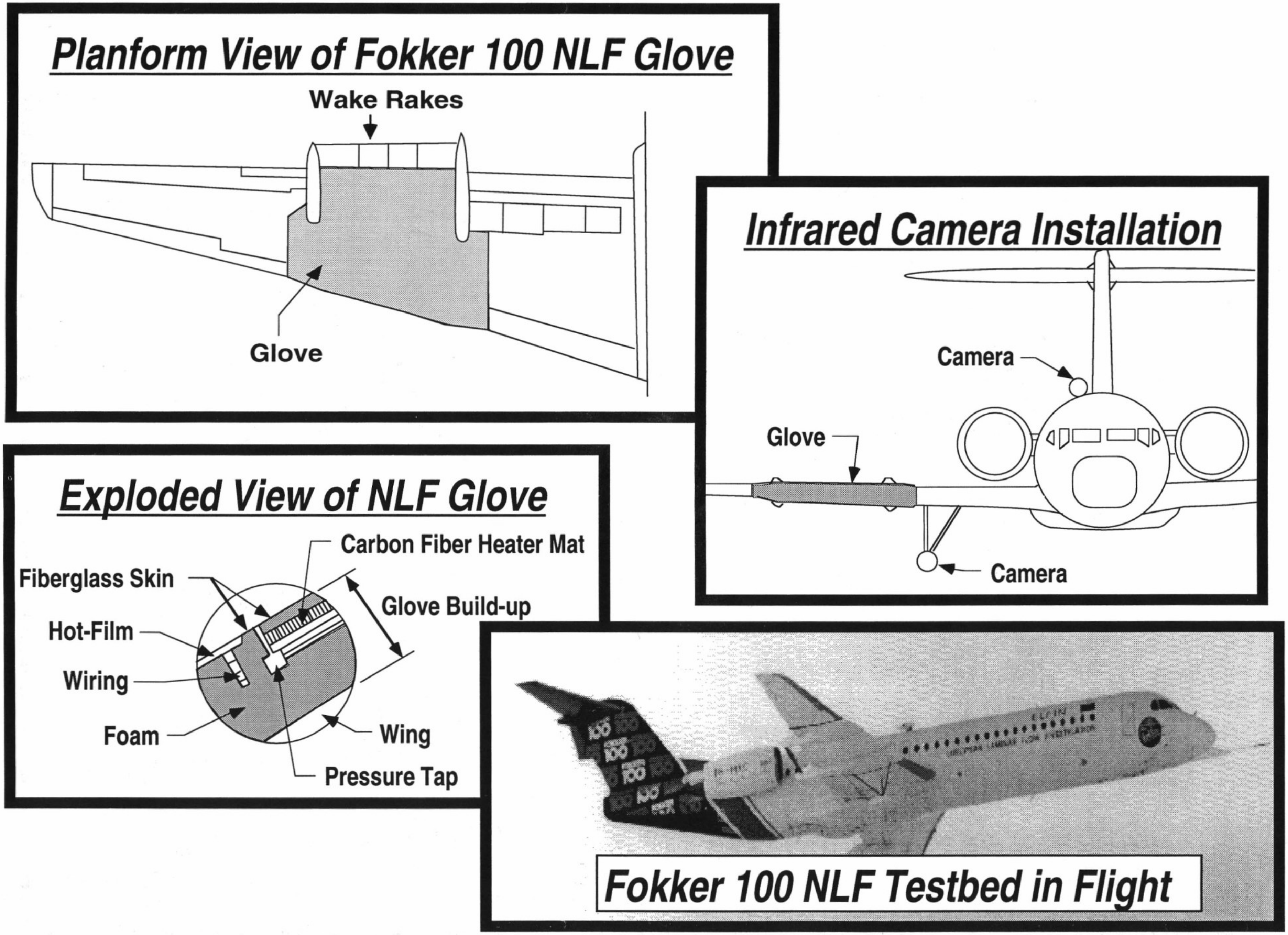
Fokker 100 Natural Laminar Flow Wing Testbed

Test Objectives

- Explore limits of NLF
- Calibrate transition codes
- Demonstrate test techniques

Fokker 100 Flight Envelope

Figure 11 - ELFIN Fokker 100 Natural Laminar Flow Test Objectives and Flight Envelope (Refs. 7, 10 - 12)



Planform View of Fokker 100 NLF Glove

Infrared Camera Installation

Exploded View of NLF Glove

Fokker 100 NLF Testbed in Flight

Figure 12 - ELFIN Fokker 100 NLF Instrumentation Layout, Glove Schematic and Test Bed (Refs. 7, 10 - 12)

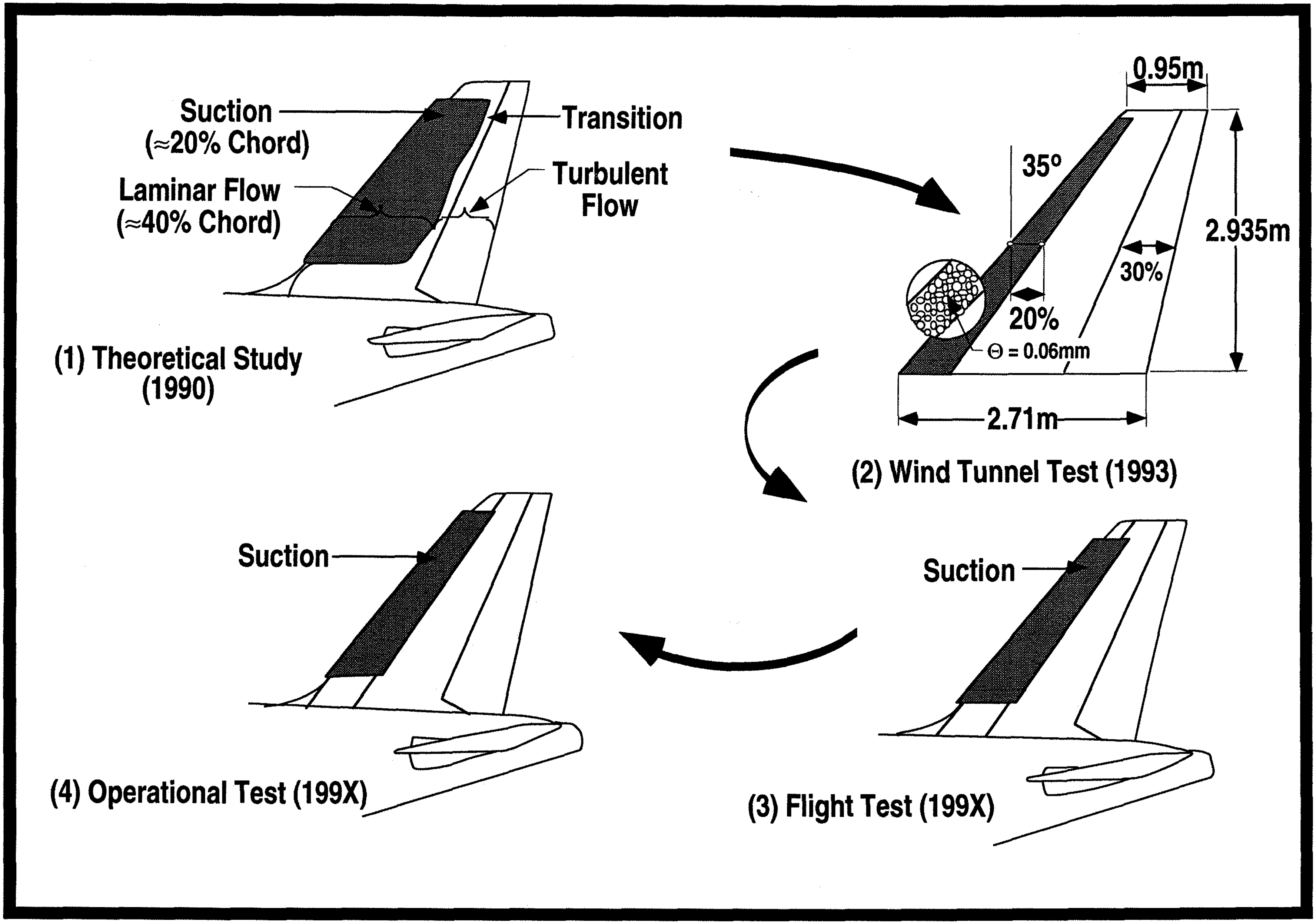


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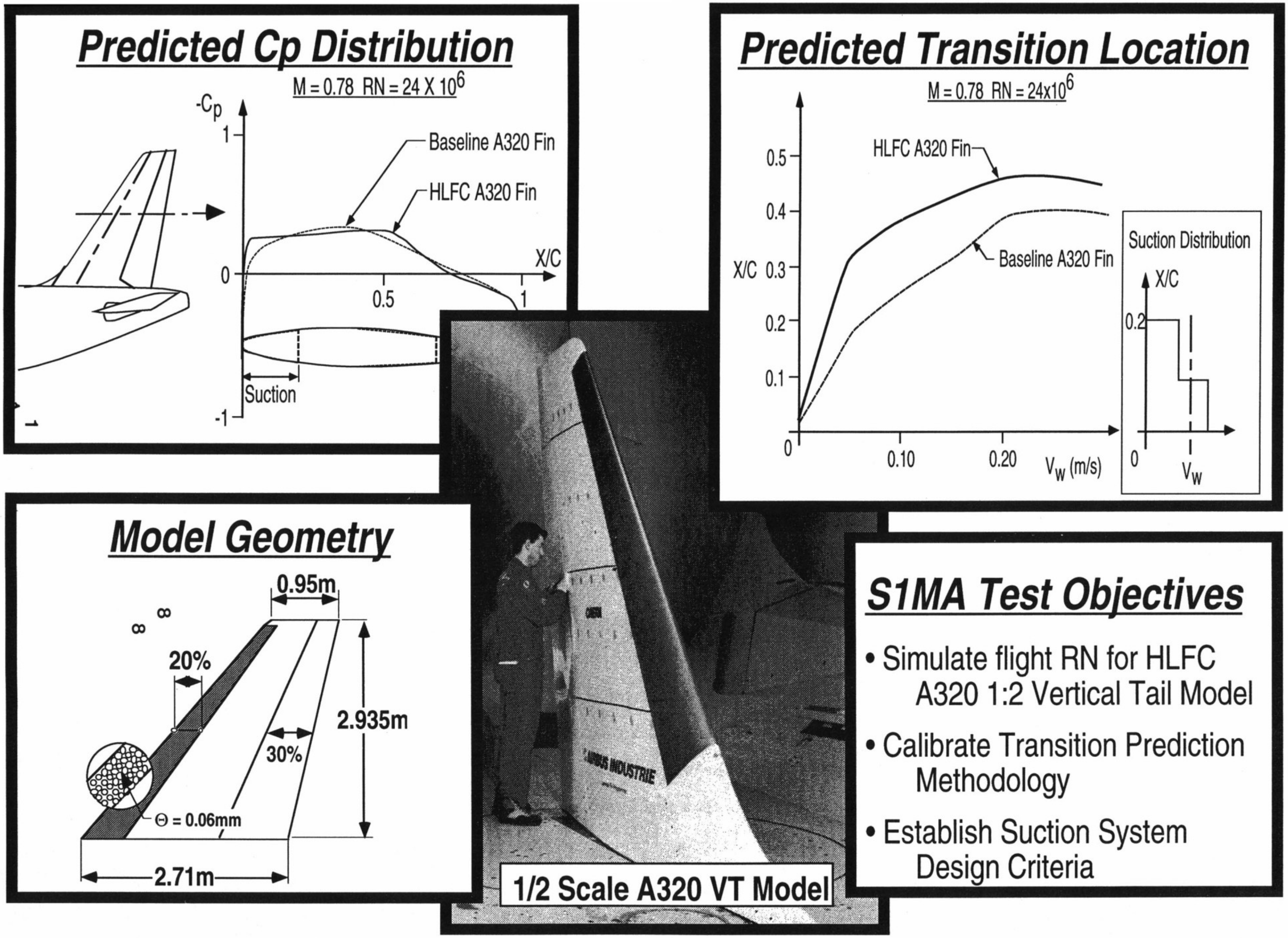
Figure 13 - A320 Hyrbrid Laminar Flow Control Vertical Fin Program (Refs. 13 - 15)



S1MA Test Objectives

- Simulate flight RN for HLFC A320 1:2 Vertical Tail Model
- Calibrate Transition Prediction Methodology
- Establish Suction System Design Criteria

Figure 14 - A320 HLFC Vertical Fin Analysis and Wind-Tunnel Investigation in ONERA S1MA (Refs. 13 - 15)