SOME EVENTS IN SUCTION STABILIZATION OF THE LAMINAR BOUNDARY LAYER OR ANYONE FOR 100% LAMINAR FLOW?

By Bruce H. Carmichael

Presented to the SSA

INTRODUCTION

In 1904 when Ludwig Prandtl established the concept of the boundary layer, he also demonstrated experimentally that suction applied to the boundary layer could also delay separation in the adverse pressure gradient on blunt objects. In 1928, B. M. Jones of England was the first to suggest that boundary layer suction through a wing surface might be employed to extend the laminar boundary layer further than it would naturally occur. The flight experiments of Jones had previously shown that a sufficiently smooth wing surface could enjoy more extensive laminar flow than previously believed, that flow acceleration on the forward wing was helpful in increasing this and that the ambient turbulence in the atmosphere was lower than in wind tunnels and not of a frequency dangerous to the Laminar boundary layer. Jones suggestions were to become the trigger to the lifetime work of Dr Werner Pfenninger first in Zurich, Switzerland and later in the United States.

FIRST PROOF OF LAMINAR BOUNDARY LAYER EXTENSION BY SUCTION

In 1940-4-1, Dr. Pfenninger, student of Ackeret at ETH Zurich, extended laminar flow to the trailing edge of a 6.75% thick (at 39%chord) airfoil with a single suction slot at 77% chord yielding a profile drag coeflicient of 0.0037 at a Reynolds number of 1 million and a lift coefficient of 0. 3. Without suction the value was 0.0047, (figure 1). He also presented data of a 10.5% thick section with suction on both sides with a drag coeff. of 0.0017 at 3 million Reynolds number. In the same series of experiments in the early 1940's he presented test results on a 14% thick non-suction section with cruise flap and a drag coeff. of 0.005 at 1.07 million RN. He also showed data on a 6% thick section at Reynolds numbers from 700,000 down to 123,000 and used a step disturbance to trip the boundary layer and prevent separation. By 1946 this outstanding work was translated into English and was available in the United States as NACA Technical Memorandum 1181. Prof Ackeret told Pfenninger that only in the United States could he obtain backing for such an expensive development. Copies of this work were sent to all the aircraft companies in the U.S., but

NACA TM No. 1181

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL MEMORANDUM NO. 1181

INVESTIGATIONS ON REDUCTIONS OF FRICTION ON WINGS, IN PARTICULAR BY MEANS OF BOUNDARY-LAYER SUCTION*

By Werner Pfenninger

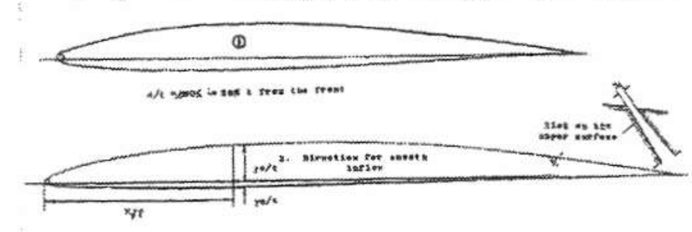
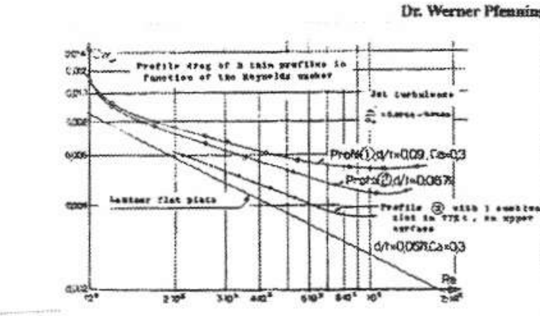


Figure 17.- Laminar suction profile 2 with a single suction slot on the upper surface. d/t = 0.0675 in 0.394 t from the front. Profile 1, d/t = 0.09, without suction.



Dr. Werner Pfenninger, Prophet of the Future

Fig 1 .- Laminar suction profile 2 (fig. 17). Minimum slot width s = 0.9 millimeter $c_{w_{opt}}$ (Re) without and with boundary-layer suction, $c_{w_{\infty}}$ (Re) of profile 1.

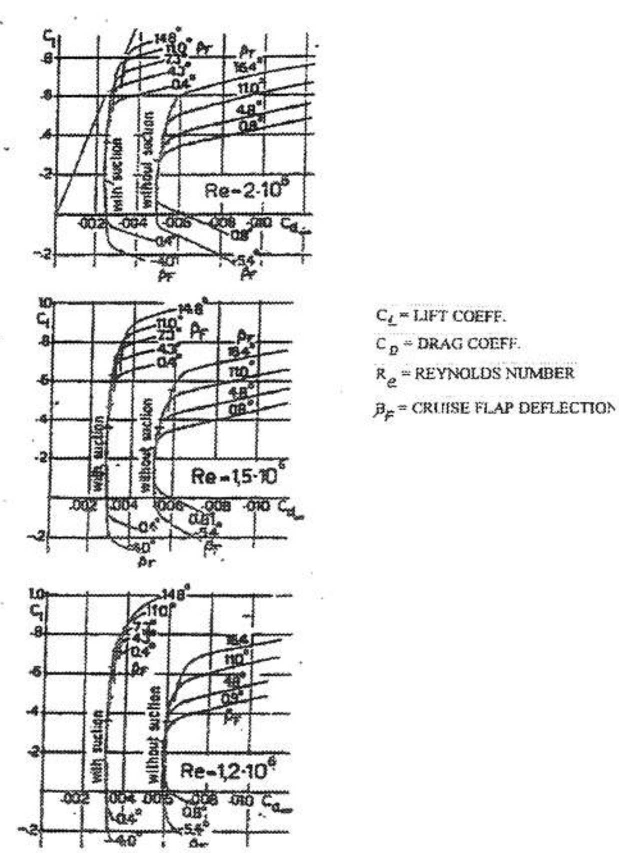
only one man had the understanding and vision to respond. Jack Northrop invited Dr. Pfenninger to join Northrop Aircraft. A special research building separate from the main plant was provided. A group of engineers and craftsmen willing to work under strong direction to evolve theory, design research models and build them to Pfenningers exacting requirements produced rapid advances in the decade of the 1950s.

It should be noted that in the years 1942-44, Bussman, Pretch and Ulrich had solved the boundary layer equations with uniform distributed suction which yielded after a short run the asymptotic profile and predictions of required suction quantity and effective drag coefficient including the drag equivalent of the suction power. In America, Pfenninger soon published experimental results on a 17% thick airfoil with suction slots on both surfaces. The effective drag coefficient was 0.003 at a RN of 1 million and 0.0025 at a RN of 2 million. (figure 2).

SUCTION STABILIZED LAMUNAR FLOW TO A SAILPLANE TRAILING EDGE - 1951

In 1949 when I met Dr. August Raspet at a sailplane meet in Texas, he had already set up a Flight Research Facility at Starkville, Mississippi using sailplanes as a tool for aerody-

Fig. 2 17% AIRFOIL POLARS WITH AND WITHOUT SUCTION PFENNINGER 1949 ZURICH WINDTUNNEL TESTS



namic and meteorological research. We see him (figure 3) with Mel Swartsberg chief pilot, craftsman, and department manager, and George Tabery tow pilot and craftsman. An inboard section of the NACA 4416 upper wing surface of the low wing TG-3 sailplane was smoothed up to the spar. Multiple ribblets were installed aft of the spar to smooth the transition from plywood to fabric. The initial experiment was intended to investigate the use of a single suction slot at the trailing edge as a control device. When it proved no-effective (figure 4), Dr. Raspet applied distributed suction from spar to trailing edge to help it along. Although the control device was unsuccessful, in the process Gus established laminar flow to the trailing edge. He punched rows of 0.018 inch diameter holes at 19 per inch using a window screen as a template. He chose the chordwise spacing of the rows based on how far laminar flow coasted aft of the last row punched. An outstanding example of letting the experiment guide the evolution of the solution.

In 1952, Dr. Raspet invited me to join him in this development. We eventually converted the section to three compartments and with the aid of Joy axivane fans and formed a bump at the exit to produce a negative exit pressure we extended the experiment up to 100 m.p.h. At this time the large wave at the plywood to fabric transition was faired to eliminate the need for the very dense suction in this region. A piece of the sacred pelt or fabric from the initial experiment is shown in figure 5. We had now gone as far as possible with the sailplane and sent a proposal to ONR to continue flight experiments with a jet aircraft. Meanwhile Dr. Pfenninger at Northrop had submitted a similar proposal

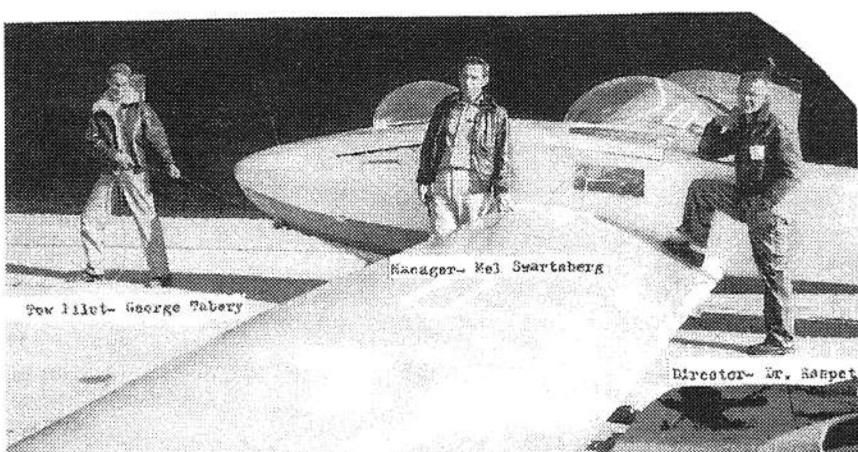


Fig. 3 Mississippi Research Colleagues

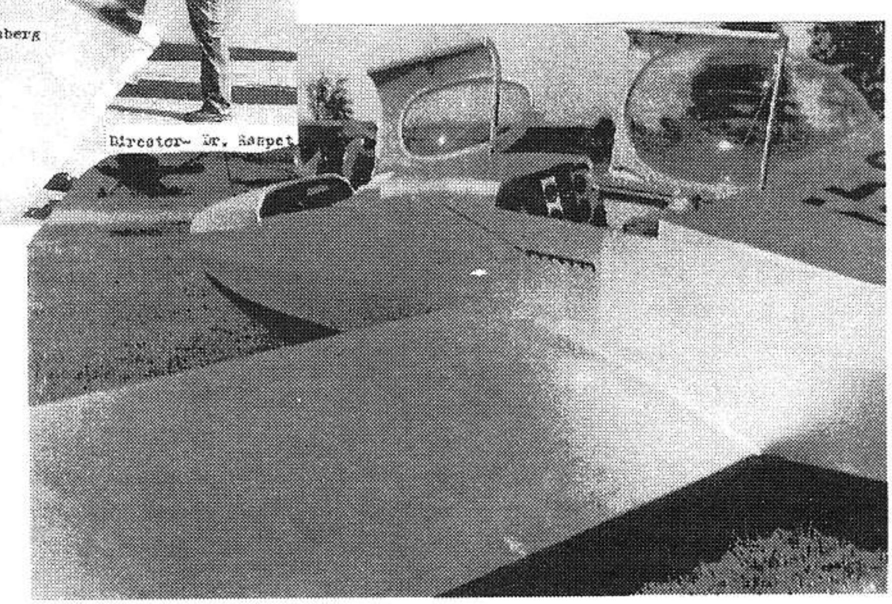


Fig. 4 Single suction slot

Fig.5 Perforated Fabric- Raspet 1951 Flight Experiment

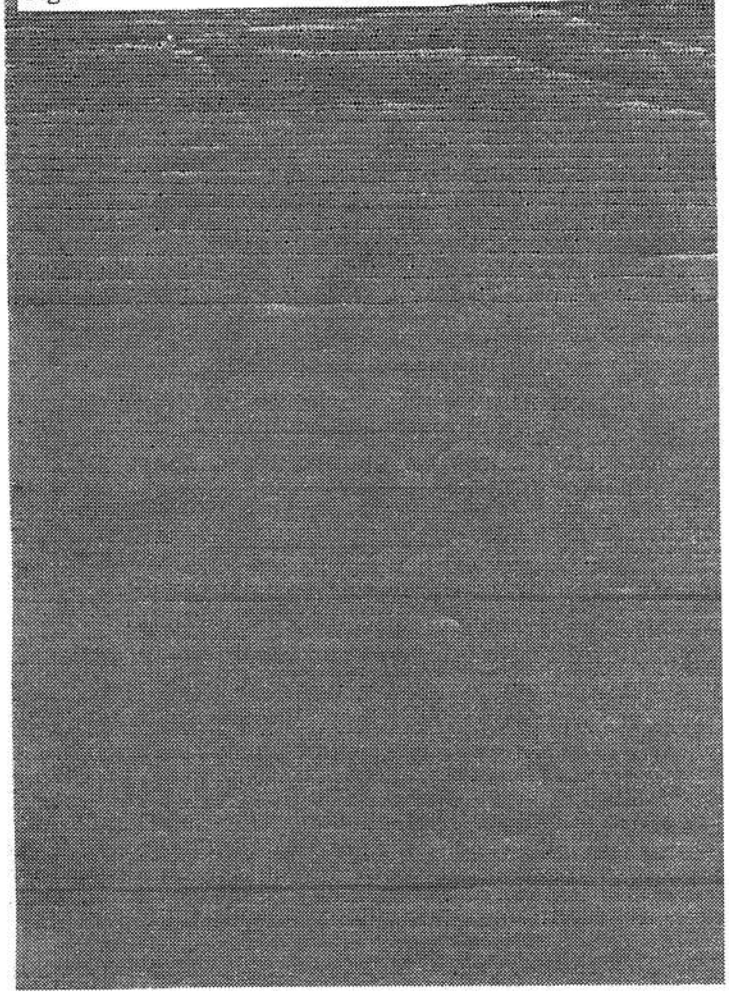
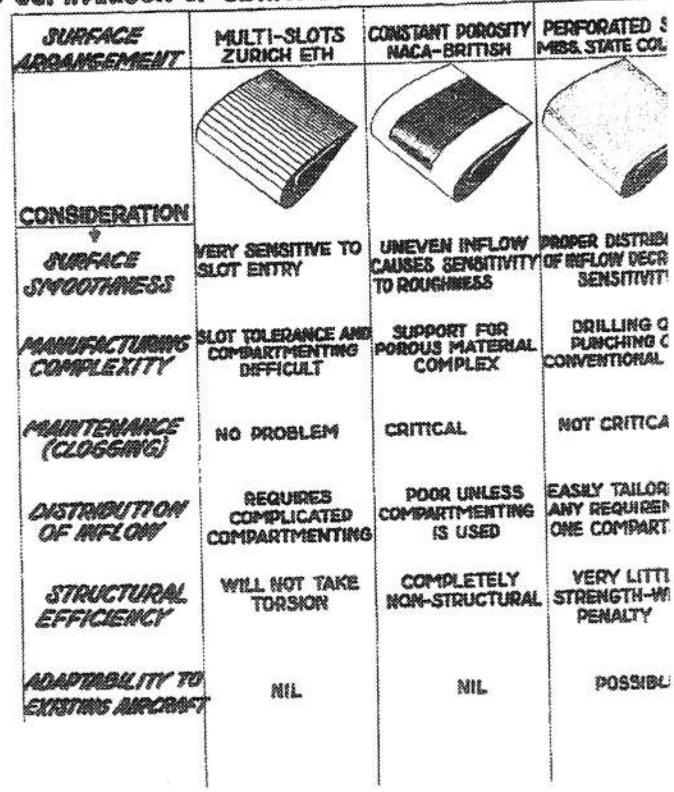


Fig. 6 COMPARISON OF SURFACES FOR DISTRIBUTED SUCTIO



SURFACE ARRANGEMENT	MULTI-SLOTS ZURICH ETH	CONSTANT POROSITY NACA-BRITISH	PERFORATED S MISS. STATE COL
CONSIDERATION			
SURFACE SMOOTHNESS	VERY SENSITIVE TO SLOT ENTRY	UNEVEN INFLOW CAUSES SENSITIVITY TO ROUGHNESS	PROPER DISTRIB OF INFLOW DECR SENSITIVIT
MANUFACTURING COMPLEXITY	SLOT TOLERANCE AND COMPARTMENTING DIFFICULT	SUPPORT FOR POROUS MATERIAL COMPLEX	DRILLING O PUNCHING C CONVENTIONAL
MAINTENANCE (CLOGGING)	NO PROBLEM	CRITICAL	NOT CRITICA
DISTRIBUTION OF INFLOW	REQUIRES COMPLICATED COMPARTMENTING	POOR UNLESS COMPARTMENTING IS USED	EASILY TAILOR ANY REQUIREN ONE COMPART
STRUCTURAL EFFICIENCY	WILL NOT TAKE TORSION	COMPLETELY NON-STRUCTURAL	VERY LITTI STRENGTH-W PENALTY
ADAPTABILITY TO EXISTING AIRCRAFT	NIL	NIL	POSSIBL

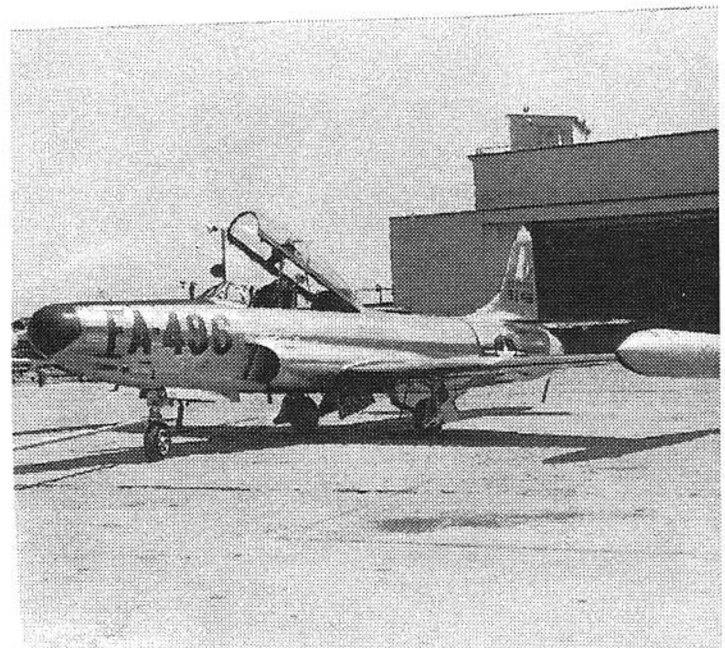


Fig. 7 F94-A SUCTION GLOVE TEST AIRCRAFT

to Wright Field and was funded. As part of our Mississippi proposal, I had written a tutorial on low drag suction boundary layer control. including a comparison of Pfenningers Zurich ETH large slots, the British and NASA constant porosity attempts and our Mississippi perforated skins, pointing out that the first two were impractical for an actual airplane, (figure 6). Pfenninger told me when I joined their effort that this nearly shot them down but that it forced them to develop a practical design. Dr. Pfenninger had always conducted his own experiments but Northrop realized that if they lost him in the fairly early days of jets that they would lose millions in research contracts. They needed an expendable with experience in the field which brought me to the promised land of California and North Base Muroc.

LOW DRAG SUCTION B.L.C. IN FLIGHT TO 36 MILLION RN 1955 -1957

An NACA 65 2 13 airfoil cuff was placed on the wing of an F-94A Jet Interceptor with a suction pump mounted beneath the fuselage, (figure 7). The upper surface only was provided with suction. The initial expermients were performed with 12 wide formed slots since this cuff had been prepared before the practical design had been achieved, (figure 8). Designer Bill Slag rapidly developed a two-layer skin as a practical solution, (figure 9). The thick inner skin has a spanwise trench of partial depth with spaced holes providing passage for suction air to an inner compartment while retaining structural integrity. Fine slits

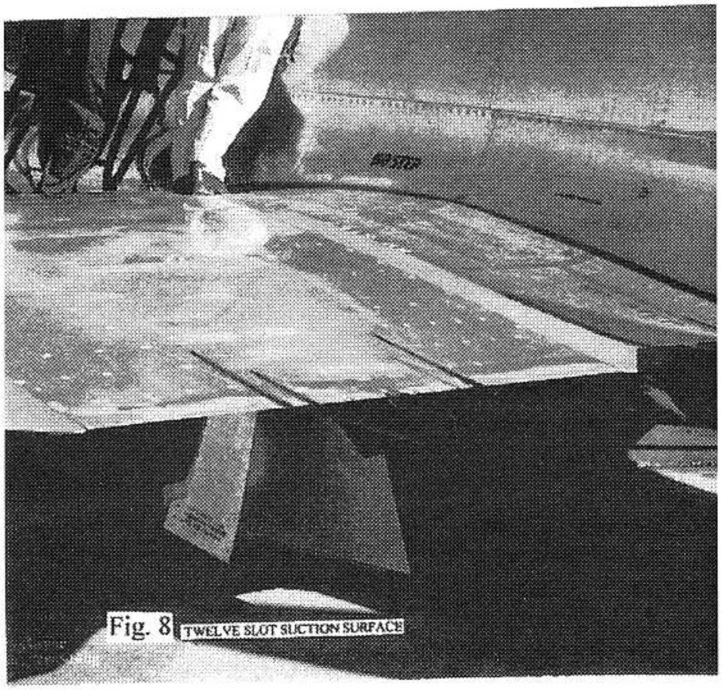


Fig. 8 TWELVE SLOT SUCTION SURFACE

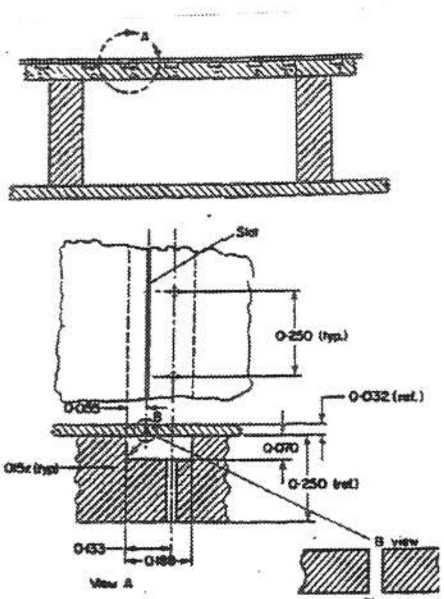


Fig. 9 NORTHROP STRUCTURALLY FEASIBLE SUCTION SURFACE

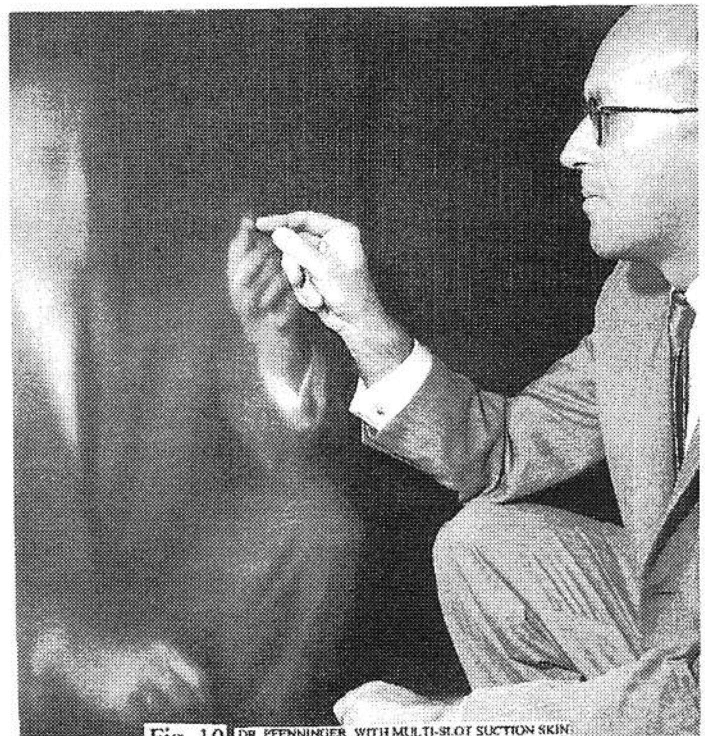


Fig. 10 DR. PFENNINGER WITH MULTI-SLOT SUCTION SKIN

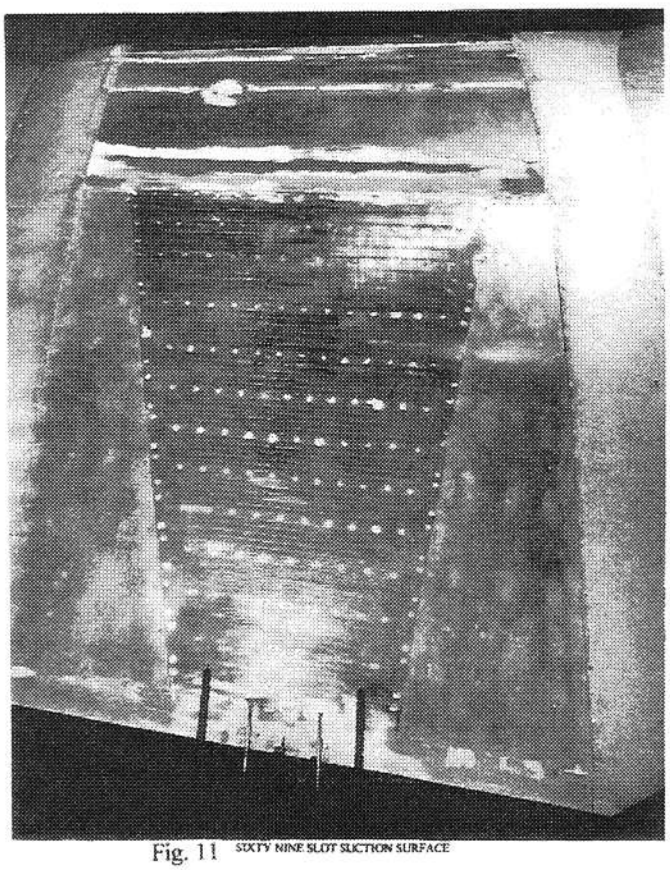


Fig. 11 SIXTY NINE SLOT SUCTION SURFACE

of 0.004 to 0.0055 inch width are cut in the thin outer skin which has been bonded to the inner skin. In figure 10 we see Dr. Pfenninger with such a multi-slitted wing skin. The wide slot section was successful to 25 million chord RN. It was then replaced with a 69 slot practical construction skin with suction starting at 40% chord and employing the same 12 compartments (figure 11). Laminar flow was maintained to the trailing edge up to 36 Million RN over a restricted range of lift coefficient, Mach number and altitude. At my suggestion suction was extended further forward resulting in an 81 slot panel. This opened up the flight envelope and the laminar lift coefficient increased from 0.37 to 0.56. In all these experiments laminar flow was lost at a flight Mach number of O.7 when the Mach number at the minimum pressure point reached 1.04.

The upper surface effective drag coefficient is shown in upper figure 12, decreasing from 0.001 at 12.5 million RN to 0.000475 at 30 million RN. The suction coefficient in middle figure 12 falls from 0.00055 at 12.5 M to 0.00029 at 30 M RN or 0.03 of 1% of flight speed. The upper surface effective drag coefficient is found to be 29% of the best natural laminar upper surface drag coefficient. At 32.7 million RN the suction drag is 72% and the wake drag 28% of the total. The suction drag is ideal and computed from the flow quantity and the pressure rise from the compartment to that at free stream without further losses or pump inefficiencies.

These experiments had the advantage of low turbulence in the upper atmosphere.

Flight test costs required use of a leading edge bug cover which was jettisoned after climb above the bug level.

In the decade of the 1950's, the Boundary Layer Research Group under the direction of Dr. Pfenninger established 100% laminar flow on models of straight wings, swept wings, bodies of revolution and in flow tubes. These were conducted in low turbulence wind tunnels at Northrop, U. of Michigan, NASA Ames and NASA Langley. When the ideal suction drag was added to the remaining wake drag and plotted against RN, the total wetted area drag coefficient ran parallel to and about 25% above the laminar friction line.

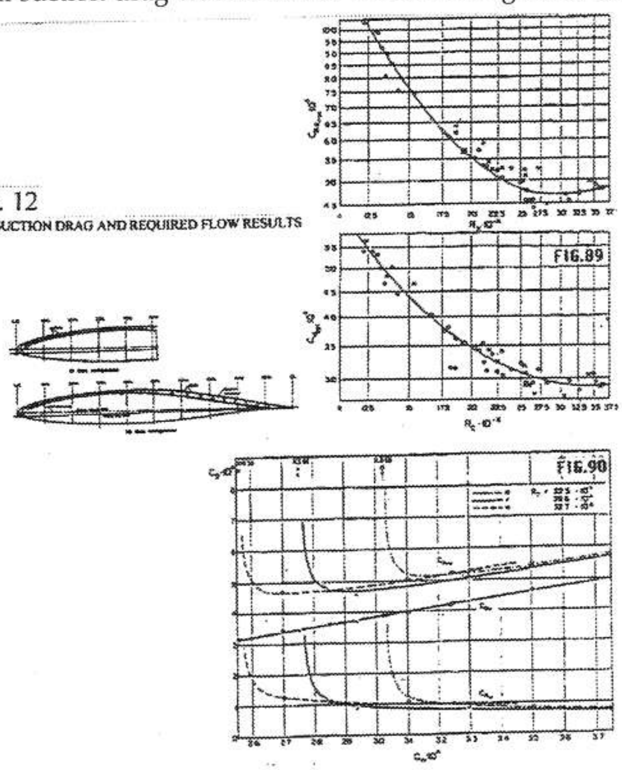


Fig. 12
F-94 SUCTION DRAG AND REQUIRED FLOW RESULTS

RB-66 FULL UPPER SURFACE SUCTION WING

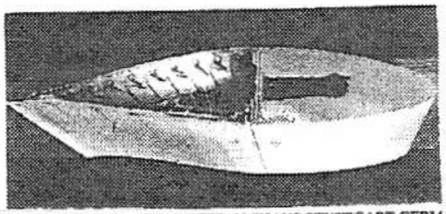
In the 1960s the research returned to flight with the suction system applied to the complete upper wing surface of a modified RB-66 jet bomber. The engines were shifted to the rear fuselage and a larger new suction wing was fitted with modified wing fuselage intersection. Metering of the full span suction was accomplished by gathering the flow of several spanwise spaced holes with plastic tubes under the skin terminating in a trimable nozzle to adjust the local flow. A special doubler design was used as structural joints to prevent a wavey surface under load. A.M.O. Smith, frustrated over a joint in a wind tunnel model which tripped the laminar flow said, " There is no such thing as a laminar joint. I suggested we purchase a tavern as a club for unemployed aerodynamicasts and call it "The Laminar Joint". On the RB-66 it was necessary to employ a GasterAW to prevent turbulent fuselage flow from going out the wing stagnation line and tripping the entire wing. After many difficulties, laminar flow was extended to the trailing edge over 75 % of the upper wing surface. Fabrication and maintenance costs were sufficiently high to discourage further application.

MORE RECENT WORK DIRECTED TO SAILPLANES

The Wortmann/Althaus wing model with perforated suction from 40% chord to the trailing edge of 1964 is shown in upper figure 13. When I spoke to Wortmann shortly before he passed away, he was discouraged over suction stabilization being applied to production sailplanes. Some of the reasons are that very low profile drag coefficients can be achieved with favorable pressure gradients. This extent of natural laminar flow leaves only 30% of the wetted area remaining to be treated by suction. At sailplane Reynolds numbers, the difference in laminar and turbulent friction is only a factor of 3. Suction stabilized laminar surfaces are equally vulnerable to bug strikes with loss of laminar flow. A better solution to the bug problem is required.

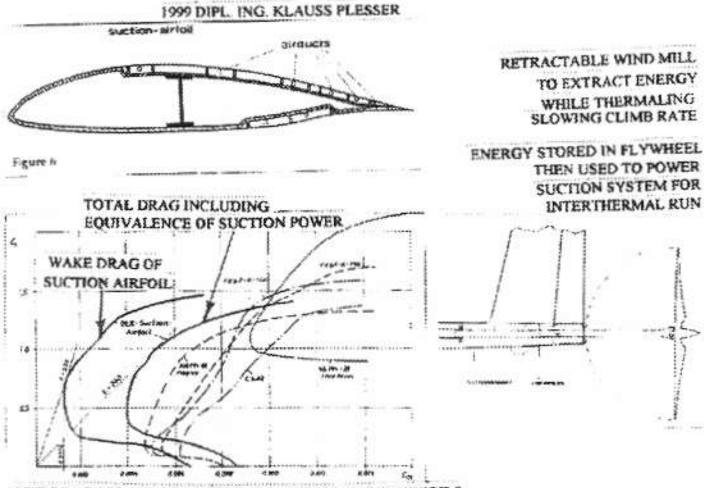
The Plesser article of April 2000 Technical Soaring (lower figure 13) shows a wake drag coefficient of 0.00 12 and an effective drag coefficient including the ideal cost of suction to be 0.004. Using a suction airfoil concept designed by Horstmann, Quast and Maughmer at DLR Braunschweig, Plesser suggests a retractable windmill to extract energy in the climb in thermal, store it in a flywheel and use it to power the suction system during the run between thermals. With this scheme, the wake drag alone is the effective profile drag coefficient in the high speed run since the suction power has already been paid for in the reduced thermal climb rate.

Fig. 13 SUCTION BOUNDARY LAYER CONTROL EXPERIMENTS FOR SAILPLANES



1964 F.X. WORTMANN AND DIETER ALTHAUS STUTTGART GERMANY
PERFORATED SURFACE SUCTION AFT OF 47% CHORD

1999 DIPL. ING. KLAUSS PLESSER



LIFT DRAG POLARS OF 4 NATURAL LAMINAR FLOW AIRFOILS
AND A SUCTION AIRFOIL WITH & WITHOUT DRAG EQUIVALENCE OF SUCTION POWER
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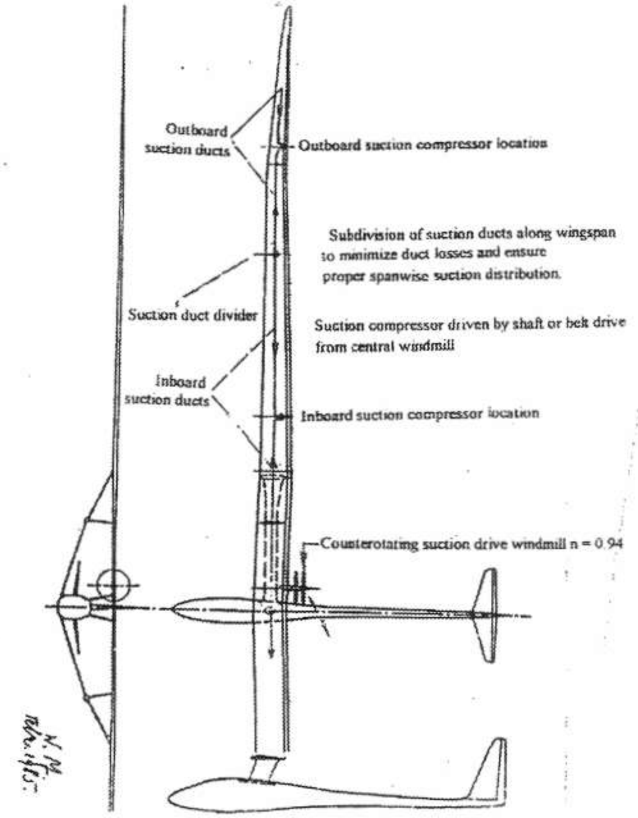

Fig. 14 DR. WERNER PFENNINGER'S ALL LAMINAR SAILPLANE DESIGN

Performance No Ballast	Performance With Ballast	Characteristics
L/D = 91.4 at 65 m.p.h.	L/D = 98.5 at 86.5 m.p.h.	Span = 106.3 ft.
Sink = 0.89 f.p.s. at 47 m.p.h.	Sink = 1.08 f.p.s. at 65.4 m.p.h.	Area = 208.7 sq. ft.
Sink = 2.9 f.p.s. at 117 m.p.h.	Sink = 4.07 f.p.s. at 166 m.p.h.	AR = 54 t/c = 0.128
L/D = 37.5 at 166 m.p.h.	L/D = 46 at 203.5 m.p.h.	W/S = 7.38 & 12.3 #/s.f.

Dr. Werner Pfenninger's all laminar sailplane study published in the October 1987 Technical Soaring (figure 14) describes in detail the pains that must be taken in optimizing the windmill, suction pump, wing surface and internal ducting and metering. His 32.4 meter span, 54 aspect ratio at 12 p.s.f. wing loading, projected an L/D of 98.5 at 87 m.p.h., a minimum sink of 1.08 ft./sec. at 60 m.p.h. and at 203 m.p.h. the L/D was still 46.

ONGOING SUCTION PROFILE DRAG REDUCTION WORK

OSTIV President Loek Bormans of Delft University has chosen this subject as his Doctoral work and reported on present progress to the Western Workshop of the American Sailplane Homebuilders in August 2002. He explained that profile drag reduction had reached a limit with 65% chord laminar on upper surface and 90% on the lower surface. Attempts to increase the extent on the upper surface results in dangerous non-linear lift and moment curves. Loek first investigated the British method with pressure recovery at a single large slot at 80%chord and flow acceleration downstream. The drag equivalent of the suction power just canceled out the reduction in wake drag. His present studies are with distributed suction through a perforated surface using solar cells to provide the pump power. His calculations indicate that this would increase a modern 60 L/D sailplane to a value of 90. If the power were applied directly to a propeller, the L/D would be less at a value of 80. New perforation methods can rapidly produce 0.1 mm diameter holes although they do not have to be this small at sailplane Reynolds Numbers. Perforations can even be applied through a wing covered with solar cells. He will soon test his wing model in his low turbulence wind tunnel.

SUMMARY

Perhaps the work of Loek Boermans will bring to reality a sailplane application of the dream of the previous workers in this field. The ultimate of 100% laminar flow is a beckoning goal. While cost and complexity may long delay application to production sailplanes, a research craft may lie within the realm of possibility.