NASA CR-152276

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SUMMARY OF PAST EXPERIENCE IN NATURAL LAMINAR FLOW AND EXPERIMENTAL PROGRAM FOR RESILIENT LEADING EDGE

BY B. H. CARMICHAEL

MAY 1979

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Prepared under Contract No. NAS2-10113

By: Low Energy Transportation Systems
34795 Camino Capistrano
Capistrano Beach, California 92624

for

Ames Research Center

National Aeronautics and Space Administration

(NASA-CR-152276) SUMMARY OF PAST EXPERIENCE IN NATURAL LAMINAR FLOW AND EXPERIMENTAL PROGRAM FOR RESILIENT LEADING EDGE (Low Energy Transport Systems) 50 p HC A03/MF A01 CSCL 01A G3/02

N79-26024

Unclas 28806

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1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA CR-152276		

4. Title and Subtitle	5. Report Date
Summary of Past Experience in Natural Laminar Flow and Experimental Program for Resilent Leading Edge	May 1979
	6. Performing Organization Code
7. Author(s) Bruce H. Carmichael	8. Performing Organization Report No.
	10. Work Unit No.
9. Performing Organization Name and Address Low Energy Transportation Systems 34795 Camino Capistrano Capistrano Beach, CA 92624	11. Contract or Grant No. NAS2-10113
	13. Type of Report and Period Covered Contractor Report
12. Sponsoring Agency Name and Address Technical Monitor: Jerry Barrack V/STOL Systems Technology Br. NASA Ames Research Center Moffett Field, CA 94035	14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

The practical achievement of a significant amount of natural laminar flow (NLF) offers the potential for significant drag reduction and, hence, efficiency improvement for future aircraft. Recent advances in materials, structural fabrication technology, and aerodynamic design optimization make the practical achievement of NLF appear more feasible. This is particularly true for the high aspect ratio, un-swept, shorter-chord wings on commuter transport aircraft. In order to better assess this potential, a study was conducted to summarize past experience with natural laminar flow. The objective of this study was to consolidate not only published data, but also unpublished data and personal observations of natural laminar flow researchers. Included in this summary are surface contour, waviness, and smoothness requirements, noise and vibration effects on boundary layer transition, boundary layer stability criteria, flight experience with natural laminar flow and suction stabilized boundary layers, and propeller slipstream, rain, frost, ice, and insect contamination effects on boundary layer transition. The resilient leading edge investigated by Dr. F. X. Wortmann appears to be a very promising method to prevent leading edge insect contamination.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Natural Laminar Flow Laminar Flow Wing Leading Edge Wing Aerodynamics	Unclassified - Unlimited STAR Category 02

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified	48	

*For sale by the National Technical Information Service, Springfield, Virginia 22161

NASA CR-152276

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SUMMARY

Commuter aircraft operating at Reynolds numbers per foot of 2 million and mean wing chord Reynolds number of 16 million could (under ideal conditions) achieve extensive natural laminar flow with profile drag coefficients in the range 0.003 to 0.004. The relatively high aspect ratio, unswept wing with moderately thick airfoils is ideally suited to such a goal. These low cruising profile drag coefficients are compatible with carefully designed modern full span extensible flap and spoiler lateral control systems. Thus the take-off and landing requirements need not cut into the performance gain attributable to the use of laminar airfoils. Profile drag coefficients of 0.003 have been measured in flight experiments in the past and modern transition prediction methods allow the design of airfoils maximizing the extent of laminar flow, at least under ideal conditions.

Construction of large wing sections of bonded honeycomb in female molds is now state-of-the-art and results in surfaces of sufficient stiffness, smoothness, and absence of waviness, together with light weight, which will meet the exacting demands of laminar flow. Major structural joints require special attention and access doors must be located to affect as little laminar surface areas as possible.

The twin tractor propeller configuration of many present day commuter aircraft would prevent the attainment of low profile coefficients in the propeller slipstream. Pusher propellers or aft fuselage propulsive pods should be employed to maximize cruise performance. Noise and vibration below presently ill-defined critical levels but within well defined critical frequencies should not, on the basis of limited past experiments, preclude extensive laminar flow.

Atmospheric turbulence is of too large a scale to have an adverse effect. Laminar flow is lost when flying in rain but is regained soon after leaving a rain area. Turbulence generated by frost particles traversing the boundary layer only seems to occur at altitudes above commuter aircraft levels. Leading edge de-icers must probably be of the thermal rather than mechanical type due to stringent surface smoothness requirements. Leading edge smoothness deterioration due to rain erosion must be carefully considered.

Serious design effort on an extensively laminar commuter aircraft wing must be preceded by a complete solution of the leading edge insect contamination problem. Promising methods, partially developed, include continuous water spray from the leading edge during take-off and climb, and the resilient leading edge pioneered by Dr. F. X. Wortmann. It is recommended that the later method be investigated first since it promises a more complete solution at a lower weight penalty. The crucial problem will be to find a resilient coating able to repell insects while retaining an adequate service life particularly against rain-caused erosion.

High performance production, man-carrying sailplanes have demonstrated extensive laminar flow and low profile drag coefficients for the past two decades. While they operate at lower unit and chord Reynolds numbers than commuter aircraft and do not have to contend with possible disturbances from propulsion systems, the experience does give promise of success for a program to extend such performance gains to powered aircraft.

NOTATION

C	Chord length parallel to flight path	ft
C'	Chord length perpendicular to constant percentage lines	ft
C_{D_o}	Profile drag coefficient $= D/q_\infty \cdot S$	-
C_L	Lift coefficient $= L/q_\infty \cdot S$	-
C_p	Pressure coefficient $= (p-p_o)/q_\infty$	-
D	Drag	pounds
e^n	Boundary layer disturbance amplification factor	-
h	Surface wave height	inches
K	Roughness particle height	inches
L	Laminar run length without wave (also lift force in pounds)	ft
p	Local surface pressure	pounds/ft^2
p_o	Ambient pressure	pounds/ft^2
q_∞	Free stream dynamic pressure $\frac{\zeta}{2} U_\infty^2$	pounds/ft^2
r	Leading edge nose radius	ft
R'	Reynolds number per foot of length $= U_\infty/\nu$	1/ft
R_c	Chord Reynolds number $= U_\infty C/\nu$	-
$R_{X_{TR}}$	Projected transition length RN $= U_\infty X_{TR}/\nu$	-
R_K	Roughness Reynolds number $= u_K \cdot K/\nu$	-
$R_{\delta}*$	Displacement thickness RN $= U\delta*/\nu$	-
S	Wing planform area	ft
t	Airfoil thickness	ft
u	Velocity at some height y in boundary layer	ft/sec

NOTATION (Cont'd)

u_k	Velocity at top of roughness particle	ft/sec
U	Velocity at outside edge of boundary layer	ft/sec
U_∞	Free stream or flight velocity	ft/sec
X	Projected distance in flight direction (also distance from leading edge to surface wave)	ft
X_{TR}	Projected distance to transition point	ft
Y	Distance measured perpendicular to surface	inches
α	Angle of attack	deg
λ	Length of surface wave	inches
λ'	Length of surface wave perpendicular to constant percentage lines	inches
ζ	Atmospheric density	pound sec^2/ft^4
u	Atmospheric viscosity	pound sec/ft^2
ν	Kinematic viscosity	ft^2/sec
Λ	Wing sweepback angle	deg
δ	Total boundary layer thickness	inches
δ^*	Displacement thickness $= \int_0^\delta (1 - \frac{u}{U})\, dy$	inches

(A) History of Natural Laminar Flow

The possibility of aircraft drag reduction through laminar boundary layer flow was clearly mentioned in the paper "The Streamline Aeroplane" read before the Royal Aeronautical Society by B. Melvill Jones[1] in 1929. Jones pointed out that the goal for aircraft drag should be the sum of drag due to lift and skin friction. He presented both laminar and turbulent friction curves and discussed the transition data available at that time.

In January of 1938, B. Melvill Jones delivered the First Wright Brothers Lecture[2] on the subject, "Flight Experiments on the Boundary Layer". This paper summarized results of profile drag and boundary layer transition location measurements in flight on several aircraft. The results were correlated with the Squire and Young[3] theoretical predictions at a chord Reynolds number of about 7 million. He concluded that transition could be delayed to 30% chord with a 30 to 35% reduction in profile drag if surface waviness was low and roughness grains larger than 0.002 inch height at $R_c = 10^7$ were avoided. He noted the forward and aft travel of the upper and lower surface transition points with increasing angle of attack. The consistency of the transition point locations as opposed to previous wind tunnel experience led him to suggest that the atmospheric turbulence was too low and of too large a scale to have much effect on transition. He found the laminar range of lift coefficients to be larger for thicker sections. The type of airfoil-Reynolds number combinations available to him led to transition occurring in the adverse pressure gradient.

Continuation of this work by Stevens & Craig[4] led to the important discovery that transition in flight at high Reynolds number would be limited to locations very near if not forward of the minimum pressure point and that it should be practical to design airfoils with minimum pressure at least as far aft as 50%.

The above two papers led to the development of laminar airfoils simultaneously in England[5], the United States[6], Switzerland[7], Germany[8], and Japan[9]. Early tests were devoted to establishing the lowest possible drag coefficient at the design lift coefficient. The phenomenally low values obtained at chord Reynolds numbers of 2×10^6 to 5×10^6 are tabulated in Table I. Values ranging from 0.0022 at 4% thickness to 0.0035 at 15% thickness represent giant reductions from the values possible with conventional airfoils. For example, the drag of the NACA 27-212 is only 41% of the drag of the conventional NACA 0012 at $R_c = 4.7 \times 10^6$.

Transition was delayed to very far aft locations on these early airfoils, occurring at 81% of chord on the 18-212 at 7.3×10^6 chord Reynolds number resulting in a transition arc length Reynolds number of 7.2×10^6 (based on local potential velocity at transition).

Some of the early sections suffered from very blunt trailing edge angles which produced excessively steep adverse pressure gradients and led to erratic lift and moment characteristics. The cusped trailing edge solution to these problems seems to have been first discovered by Jacobs[6] at NASA Langley.

The low turbulence two-dimensional wind tunnel at NASA Langley permitted the rapid development of systematic families of low drag airfoils[10] having useful thickness ratios and usable lift coefficient ranges. This facility also permitted testing to high Reynolds number of large chord airfoils at cruising lift coefficients. In particular, the NACA $65_{(412)}$-420 smooth model achieved drag coefficients between 0.004 and 0.005 for chord Reynolds numbers of 30×10^6 to 60×10^6 while a practical construction 65 (216)-3(16.5) wing section achieved values of 0.005 to 0.006 at chord Reynolds number of 15×10^6 to 35×10^6.[10]

The most striking drag reductions were obtained through flight measurements by the British in the famous King Cobra experiments of 1945[11]. Values of C_{D_0} of 0.0028 were repeatedly measured at a chord Reynolds number of 18 million. Reduction of surface roughness alone did not produce these results until the surface waviness was also reduced. A large wave at the main spar was faired out over a 10 inch wavelength. The test section was located outside the propeller slipstream but included an active but skillfully sealed aileron. A value of $R_{X_{TR}} = R_c \cdot X_{TR}/C$ of 11×10^6 occurred aft of the minimum pressure point leading authors to believe that this was not a limit for the 662-116 airfoil. Many additional conclusions regarding practical problems for laminar flow at high Reynolds numbers in flight were noted and will be covered in later sections of this report.

Between 1954 and 1957, high Reynolds number flight experiments[12] were conducted with a low drag airfoil cuff on the wing of an F-94 jet aircraft. These experiments were conducted by Roy Whites and the author under the direction of Dr. Werner Pfenninger. A 13% thick NACA 65 series airfoil was employed. Suction slots in the rear 60% of the airfoil permitted laminar flow to be maintained to the trailing edge up to limits available to this aircraft. At the maximum chord Reynolds number of 36 million, the forward impervious 40% reprented a value of natural $R_{X_{TR}}$ of 14.4 million. The degree of flow acceleration increased as the Reynolds number increased (and the lift coefficient decreased plus some help from compressibility), and this effect fortunately overcame the effect of increasing Reynolds number. The value of $R_{X_{TR}}$ noted above is believed to be the highest demonstrated for natural laminar flow on a wing section to date.

A family of bodies of revolution with a length to diameter ratio of 9 were suspended from the F-94A aircraft and instrumented for transition detection[13]. The elliptical body had a maximum value of $R_{X_{TR}}$ of only 4.5 million while the more pointed sears Haack and parabolic bodies had values of 6.2 and 6.5 million due to stronger flow acceleration. These values occurred at body length Reynolds numbers of 30 million. In a low turbulence wind tunnel at body length Reynolds numbers of 3 million, transition was aft of 80% for these bodies. A prolate spheroid of 7.5 length to diameter ratio in the Ames low turbulence wind tunnel achieved a value of $R_{X_{TR}}$ of 4.3 million[14].

In 1961, the author and Dr. Max Kramer tested a body of revolution of 3.3 length to diameter ratio with minimum pressure at 60% of length[15]. The drag was only 40% that of torpedoes of standard form. Transition location deduced from the drag data gave a maximum value of $R_{X_{TR}}$ of 18 million. The body shape was obtained by expanding the coordinates of an NACA 66 series airfoil. In more recent years, even higher values of $R_{X_{TR}}$ have been obtained by combining such low fineness ratio with more pointed shape to improve the flow acceleration. This data is not yet in the open literature.

In the early 1970's, Paul Bikle and L. Montoya conducted a large number of profile drag measurements in flight on a high performance sailplane[16]. The Wortmann FX-61-163 airfoil was modified in that the lower surface cusp was removed between 60 and 98% chord and a sealed 20% chord trailing edge cruise flap was incorporated. The conventional all metal wing incorporated an 0.032 inch aluminum skin, aluminum ribs spaced at 9 inches and a main spar at 35% chord. The deformation at the spar was faired out over a sufficiently large chord length to avoid a surface wave. The surface waviness of the entire section was reduced to ± 0.003 over a 2 inch wavelength and surface roughness was reduced by sanding with #400 paper. The cruise flap had a tape sealed lower surface hinge and a tight rub seal at the upper surface. The profile drag values were slightly lower than those obtained in a low turbulence wind tunnel on a "perfect" model (without flap) over the same Reynolds number-lift coefficient range: $1 \times 10^6 < R_c < 3 \times 10^6$, with C_L of 1.28 to 0.15, respectively. It should be remembered that this was a sailplane and that power plant noise and vibration were absent. Additional results from this program will be included in later sections.

Once the disturbance levels are sufficiently low, the limit on transition Reynolds number is mainly dependent on the magnitude of the flow acceleration or favorable pressure gradient. The author was involved in transition experiments on a 14 foot diameter buoyancy-propelled underwater body in 1971, 1972, 1977 and 1978. The scale of the experiment was sufficiently large to allow high values of $R_{X_{TR}}$ at locations sufficiently far forward to enjoy very high flow acceleration. Under these conditions, values of $R_{X_{TR}} = 48 \times 10^6$ were obtained. At such high Reynolds numbers, the flow is characterized by numerous turbulent bursts and the above value was based on a criteria of the flow being laminar 50% of the time. The minimum pressure point on this body (whose length to diameter ratio was 2.5) was at 35% of length but the maximum $R_{X_{TR}}$ values occurred at 23.5% of length. This data is not yet in the open literature. It is somewhat academic to the problem of natural laminar flow on a wing since such strong flow acceleration would be located so far forward that transition at such locations would not lead to extensive drag reductions.

Summing up the experimental evidence, we can say:

(1) Wing profile drag values as low as predicted by Squire Young theory (as a function of Reynolds number, thickness ratio, and transition location) have been obtained in flight.

(2) Moderate thickness airfoils with transition delayed to 60% on both surfaces can achieve profile drag coefficients as low as 0.003.

(3) Transition can be delayed to 60% chord or greater at least up to values of $U_\infty X_{TR}/\nu$ of 11×10^6 and perhaps as high as 18×10^6 for very thick airfoils with stronger flow acceleration.

(4) The above results are dependent on accurate wave free surfaces free of roughness and other disturbances as covered in later sections of the report.

Table I. Early Laminar Flow Airfoil Test Results

COUNTRY	AIRFOIL	THICKNESS	LIFT COEFF.	REYNOLDS NO.	DRAG COEFF.
England	EC 1250	0.12	-	5×10^6	0.0029
United States	18-204	0.04	0.2	4.2×10^6	0.0022
	18-209	0.09	0.2	5.3×10^6	0.0026
	27-212	0.12	0.19	4.8×10^6	0.0029
	27-215	0.15	0.2	4.6×10^6	0.0035
Switzerland	Pfenninger	0.10	-	2.2×10^6	0.0033
	Pfenninger	0.14	-	2.1×10^6	0.0040
Japan	TANI LB 24	0.10	0	3.2×10^6	0.0033

(B) Usefulness and Limitations of Theoretical Transition Predictions

Although the few available experimental results are indicative of what one may expect in practice, the conditions one is interested in seldom match the few experimental points available. When all external disturbances are sufficiently low, the Tollmein theory of amplification of very small disturbances seems to hold for unswept wings. The local degree of amplification is a function of the boundary layer Reynolds number and the local shape of the boundary layer velocity profile (in particular, the second derivative). Below a certain Reynolds number, no amplification is possible. Once this point is determined, the amplification of oscillations of various frequencies must be integrated for local conditions along the surface until a sufficiently high value of amplification occurs to cause transition. Attempts have been made to express the increment of boundary layer Reynolds number between start of amplification and transition on the basis of a mean value of flow acceleration and based on a few experimental results. This method while better than nothing is really not sufficiently accurate. The amplification integration method of A.M.O. Smith(17) is the most reliable transition prediction method available at this time. The limitation of this method if that it cannot account for starting disturbances higher than infinitesimal. One attempt to provide the influence of various levels of starting disturbances is found in Reference 18 where the boundary layer Reynolds number at transition has been estimated as a function of both average pressure gradient and level ot stream turbulence. An excellent summary of the complexity of the problem and limitations of the various approaches is contained in Reference 19.

At present, the most practical procedure for transition estimation for wings (where instability due to sweepback is not a factor) would be to employ the amplification method of Smith[17] until a value of e^9 or e^{10} is reached and consider this to be the upper limit in the absence of disturbances.

(C) Broadening the Laminar Bucket With Cruise Flap

An airfoil designed for very low profile drag at the design lift coefficient cannot retain the necessary favorable pressure gradients on both surfaces at values of lift coefficient largely different than the design value. This leads to rapid forward transition motion on one surface or the other with attendant rapid rise in drag. The favorable range of lift coefficients lying between the transition motion on upper and lower surface respectively is known as the low drag bucket. The width of the bucket diminishes with reduction in airfoil thickness, more aft location of the minimum pressure points, and increase in Reynolds number. A solution which permits low drag values over a broader range of lift coefficents is the trailing edge cruise flap. This essentially provides a variable camber airfoil allowing a range of lift coefficients to be attained at almost constant angle of attack, through moderate up and down deflections of the flap. Experimental data was first published by Pfenninger[7] on a 14% thick laminar airfoil at a chord Reynolds number of 1.07×10^6. At zero flap deflection, the bucket was limited to $0.3 < C_L < 0.5$. The bucket width was extended from $C_L = 0$ with a 10^o up flap detection to $C_L = 0.98$ with a 25^o down flap deflection. The trailing edge flap was 12.5% chord in length.

This work remained largely dormant for over two decades until Dr. F. X. Wortmann at Stuttgart developed a series of laminar airfoils specifically for sailplanes employing the short chord trailing edge camber changing flap principle[20]. These sections have become widely used on high performance sailplanes which require low profile drag at moderately high lift coefficients in order to circle in small diameter thermal currents and also at very low lift coefficients in the high speed linear dashes between thermals. These sections with thickness ratios of 15 and 17% chord and 17% chord trailing edge flaps allow very low drag values from C_L values as low as 0.1 and as high as 1.6 at chord Reynolds numbers from 3×10^6 to 0.7×10^6, respectively.

While the bucket width extension would be more limited at higher Reynolds numbers, a sizeable effect could still be retained if required. During a visit by the author to Stuttgart in August 1977, Dr. Eppler mentioned that the cruise flap was probably unnecessary on powered aircraft and that a better procedure might be to design an extensively laminar section for the cruise condition and equip it with a good high lift extensible flap for take-off and landing. He was of the opinion that the climb lift coefficient would be close enough to the cruise value to eliminate the complexity of a short chord cruise flap built into the extensible flap.

The question then becomes whether a good extensible flap can be made to have zero or very little drag penalty in the retracted position. Once again, we are indebted to the sailplane designers for a practical demonstration of this point. Dr. D. J. Marsden of the University of Alberta took an alternate approach to the design of a high performance sailplane of maximum speed range. He incorporated a 35% chord extensible flap with a Wortmann FX 61-163 airfoil. Tests in a low turbulence wind tunnel showed a profile drag penalty of only 0.0006 at low lift coefficient with the flap retracted and usable upper lift coefficient with 16^{0} flap deflection of 2.0 at a chord Reynolds number of 0.9×10^{6}. Marsden built a high performance sailplane with such a flap and confirmed that he could both outclimb other sailplanes and thanks to a higher permissible wing loading coupled with low profile drag with flap retracted, could easily outrun other sailplanes.

While comparable data is not available at higher Reynolds number, the idea of a low penalty in cruise, high lift trailing edge flap on a laminar airfoil appears at this point to be feasible.

(D) Surface Contour, Waviness, and Smoothness Requirements

The question of the required accuracy of the absolutes ordinates of a laminar airfoil is invariably raised. In general, it may be said that the absolute ordinates are less important than the smooth variation in surface curvature. It has been found that an inadvertent increase in section thickness ratio has little effect as long as it is spread smoothly over the entire contour(11). Rather radical changes such as cusp removal near the trailing edge have also been shown to have little effect on drag(16). The leading edge, however, remains a sensitive area. While the effect is negligible at design lift coefficient, there can be a sizable reduction in the width of the low drag bucket due to rather small leading edge contour changes. The Theodorson simplified leading edge plotting method used on the NACA 6 series airfoils produced premature pressure peaks which can be reduced by more modern contour fairing procedures.

Surface Waviness

The ability of small surface waves to limit the extent of laminar flow has been known since the early flight work of Jones[2]. The first systematic experiments were reported by Fage[22] in 1943 in which he found emperical expressions for the smallest surface wave which could move transition forward on a flat plate. For this special case of zero pressure gradient, he found it necessary to use a different expression for each of two regimes:

$$\frac{h}{L} = 13.5 \times 10^6 \; \frac{\left(\frac{X}{L}\right)^{\frac{1}{2}} \cdot \left(\frac{\lambda}{L}\right)^{\frac{1}{2}}}{\left(\frac{UL}{\nu}\right)^{3/2}} \quad \text{when} \quad \left(\frac{\lambda}{L}\right)^{\frac{1}{2}} \cdot \left(\frac{X}{L}\right)^{\frac{1}{2}} < 0.09$$

$$\frac{h}{L} = 9.0 \times 10^6 \; \frac{\left(\frac{\lambda}{L}\right)^{\frac{1}{2}}}{\left(\frac{UL}{\nu}\right)^{3/2}} \quad \text{when} \quad \left(\frac{\lambda}{L}\right)^{\frac{1}{2}} \; \left(\frac{X}{L}\right)^{\frac{1}{2}} > 0.09$$

Thus, it is necessary to account for wave locations X which are short compared to the wave-free laminar run L unless relieved by a large wavelength λ . It is interesting to note that the allowable wave height h is proportional to the square root of the wave length λ and inversely proportional to the wave-free laminar length Reynolds number to the 3/2 power.

The next series of surface wave experiments wereconducted on the 7.5 foot chord 13% thick 65 series airfoil cuffed upon the F-94 wing.

These were placed in a region of strong favorable pressure gradient. The formulas of Fage were used to pick the initial wave dimensions. Since the Reynolds number and pressure gradient were interrelated in these flight experiments [23], it was found that the increase in favorable pressure gradient predominated over the increase in Reynolds number permitting a sub-critical wave at high altitude and low Reynolds number to remain sub-critical at lower altitudes and higher Reynolds numbers than would have been the case at constant pressure gradient.

In later work in the low turbulence wind tunnel with a 7 foot chord swept suction wing[24], it was possible to check the effect of Reynolds number at constant boundary layer stability. The critical wave criteria were found to be independent of sweepback and the same criteria seemed to hold for both cases: the F-94 experiments where a strong pressure gradient existed in the absence of suction and the swept wing wind tunnel experiments where the boundary layer stability under low pressure gradient was augmented by suction through spaced fine slots[25]. For the case of single waves under strong boundary layer stability conditions, the critical size can be expressed by:

$$\frac{h^2_{Crit}}{\lambda' \cdot C'} \, R_C^{3/2} = 59{,}000 \text{ or}$$

$$\frac{h}{\lambda'} \cdot \left(\frac{\lambda'}{C'}\right)^{\frac{1}{2}} \cdot R_C^{3/4} = 244$$ where the wavelength λ' and chord C' are measured normal to the element line (for swept wings) but where the chord in R_C is measured along the flight path. Again as in the experiments of Fage, the allowable wave height was found to be proportional to the square root

of the wavelength. The allowable wave height was found to decrease markedly with the number of waves in a continuous multiple wave set.

Some typical critical wave-dimensions from the F-94 experiments can perhaps best be expressed as the following "equivalent" waves. In all cases, laminar flow could be maintained at a chord Reynolds number of 20×10^6, (Reynolds number per foot of 2.67×10^6) if the pressure gradient parameter, $\dfrac{C_{P_{.42C}} - C_{P_{.22C}}}{(X/C)_{.42} - (X/C)_{.22}}$ was equal to -0.52.

It should be noted that in the absence of waves, laminar flow could be maintained down to a value of this parameter of -0.365.

Wave Location	Number of Waves	Wave Height (Inches)	Wave Length (Inches)
0.28C	1	0.005	0.67
0.28C	1	0.009	2.00
0.28C	1	0.014	6.00
0.28C	2	0.008	2.00
0.28C	3	0.006	2.00
0.28C	4	0.0046	2.00
0.28C	6	0.0035	0.67
0.15C	1	0.010	2.0

At Reynolds numbers per foot between 2 and 3 million (typical of commuter plane operation), the above practical flight experience would indicate that single waves under strong flow acceleration could have height to wave length ratios greater than values normally encountered in modern aircraft construction. The flow acceleration near and aft of mid-chord on airfoils designed for really far aft minimum pressure could be considerably lower (when not augmented by compressibility) and this could cut allowable wave sizes by a factor of 2. Also, multiple waves could bring the allowables down by another factor of 2 so in practice, it is highly desirable to design for wave height not to exceed 0.002 inches at a 2 inch wavelength and with height proportional to the square root of wavelength at other wavelengths. This is not difficult to achieve in sandwich panel construction. The problem comes at major structural joints and at the edges of access panels. One has to consider possible deformation at major joints under flight loads. The Northrop X-21A laminar suction wing experiments established this as a major problem [26]. The problem of roll off at the edges of major structural panels lead to excessive waviness at panel joints. This was removed through use of various surface fillers but the filler tended to chip off under flexing in flight and was a continuous maintenance problem. Northrop recommended making all panels oversize and cutting off the edges as a solution to this problem. The detail design of the joint to limit distortion and flexing is also important.

Surface Roughness

The many studies of the minimum size of surface roughness necessary to cause premature transition to the laminar boundary layer have revealed that no single critical Reynolds number such as $R_K = \frac{u_K K}{\nu}$ is adequate. The result is also dependent upon the geometry of the roughness. It was found in References 27 and 28 that $R_{K_{Critical}}$ was larger for tall-small diameter cylinders than for short-large diameter cylinders.

The author carried out extensive cylindrical roughness tests [29] where pressure gradient, distance from leading edge, Reynolds number, cylinder height and diameter were varied. It was found possible to compress the data into a reasonably narrow band by plotting $R_{K_{Critical}}$ against $K^2/\theta d$. This bears some similarity to the wave results. Thus, it seems that various disturbances such as wires, steps, gaps, waves, beads, and cylinders all require separate roughness criteria. It is possible to define some practical guidance for the roughness problem.

(1) Roughness which protrudes above the surface is more critical than depressions or scratches in the surface.

(2) Critical values for a wing at a Reynolds number per foot of 2×10^6 to 3×10^6 are small but within achievable values for modern aircraft construction.

(3) The most critical region on an airfoil lies about 2 to 4% of chord from the stagnation point[28].

(4) For the most critical location, the value of R_K for <u>grit</u> type roughness is 600. A criteria even simpler to apply for a typical low drag airfoil is $R_{K_\infty} = \frac{U_\infty \cdot K}{\nu} = 680$[30]. Thus at a Reynolds number per foot of 2×10^6 spherical grit of 0.004 inch diameter would be sufficient to trip the boundary layer. A non-flush rivet with large diameter to height ratio would have a critical height of about 0.002 inch.

(5) Some typical critical roughness values from the F-94 flight experiments [23] include: a 0.007" single sphere at 2½% chord at a Reynolds number per foot of 1.92×10^6, 0.0033" single disk of 0.094" diameter at 2½% chord at 3×10^6, a single .0105" sphere at 22% chord at

2.22×10^6, a single .007" disk with 0.094" diameter at 22% chord and 1.99×10^6 and multiple .006" spheres at 22% chord at 1.94×10^6. These Reynolds number per foot are very close to those typical of commuter aircraft operation and thus the actual roughness heights are very close to those which will be critical.

(E) Effects of Sweepback and/or Taper

Following the success of the King Cobra flight experiments[11], the British, at the end of WWII, started development of a flying wing transatlantic airliner with extensive natural laminar flow. Their initial theoretical investigation indicated that the sweepback necessary for the flying wing design should not introduce any additional problems for extensive natural laminar flow. Tests of a scaled-down flying prototype revealed transition far forward. Experiments were rapidly conducted in flight on various swept wings and tail surfaces and in wind tunnels on models whose sweepback was variable. It was soon possible for them to obtain an empirical correlation for the Reynolds number for which transition first started to move forward and also a second value where transition leaped forward to the vicinity of the leading edge, in terms of the major variables[31]. The critical Reynolds number decreases with increasing sweepback, increasing airfoil thickness to chord ratio and increasing leading edge radius.

Once the emperically derived understanding was reached, a second theoretical approach provided an understandable physical explanation in terms of boundary layer phenomena. It was reasoned that in a plane normal to the flight path, for airfoils with non-constant pressure, there would exist a transverse pressure gradient, acting in-board for regions of falling pressure in the stream direction (forward portion of the airfoil) and acting outboard in regions of rising pressure (rear portion). This gradient acting on the retarded fluid in the boundary layer would produce a transverse velocity profile similar to a wake profile. The cross flow velocity is zero at the surface and far from the surface but attains a maximum value down in the boundary layer. Correlation of such boundary layer calculations with the emperically determined limits lead to a critical value for the transverse or cross flow Reynolds number in terms of the height of and value of the maximum cross flow velocity.

During the Northrop X-21 swept laminar flight experiments, a further difficulty was encountered. The 35^{0} swept X-21 wing had distributed suction boundary layer stabilization from a few percent of chord to the trailing edge. It was designed to keep the cross flow Reynolds numbers below critical values at all locations. Although complete laminar flow was obtained on the thin outer panels, transition initially occurred at the leading edge over much of the in-board portion of the wing. It was found that for very thick airfoils with strong leading edge sweep at high Reynolds numbers that turbulence originating, e.g., in the fuselage boundary layer would travel along the stagnation line producing turbulent flow over large portions of the wing(26). This problem was solved by applying suction at the leading edge keeping the stagnation region momentum thickness RN below a value of 100.

The unswept high aspect ratio wings planned for commuter aircraft should eliminate boundary layer sweep instability in spite of rather high values of taper ratio.

(F) Effect of Propeller Slipstream

The few data available on slipstream effects on transition and airfoil drag are not completely consistent. Early British data as well as the more detailed investigations of Reference 32 indicate transition within the first 10% of chord in the slipstream. Measurements are difficult to interpret in the slipstream but some NACA flight data indicates transition as far back as 20% chord and only moderate increases of drag.

A 27-212 extreme laminar airfoil was employed in the tests of Reference 32. A propeller 20% chord ahead of the leading edge forced transition at or ahead of 10% chord even at a thrust coefficient of zero. The effect was most severe near the propeller centerline with small reductions further out where the flow is disturbed a lower percentage of time. The adverse effect of the propeller encompassed a region with width at the leading edge equal to the propeller diameter and spreading at a 7.5° angle back along the wing chord from each propeller tip.

The same propeller mounted 20% chord aft of the trailing edge had no adverse effect on transition or drag over the full range of thrust coefficients.

For tractor propellers, regions outside the area described above seem to be unaffected by propeller effects as demonstrated in the King Cobra Tests[11].

The most common commuter airliner configuration at present is the twin tractor wing mounted arrangement. If extensive laminar flow is desired, this is the least desirable arrangement. The high wing aspect ratio will reduce the penalty to some degree. Pusher propellers or turbofan configurations should eliminate premature transition due to slipstream.

(G) Noise, Vibration and Panel Stiffness Considerations

A forward shift in the boundary layer transition point due to a controlled sound or noise field was observed in the classical experiments of Schubauer and Skramstad. The most effective frequencies were found near the upper neutral stability branch in terms of frequency and boundary layer Reynolds number which was in the range, R^*_δ = 1200 to 2800.

Transition tests of non-suction bodies of revolution in the Ames 12 foot pressure wind tunnel were found to be influenced by the noise spectrum of the tunnel.

The author conducted measurements (unpublished) in 1954 on a sailplane wing with distributed suction through rows of fine perforations. Sound from a loud speaker placed inside the wing was found to move transition from the trailing edge far forward at frequencies close to the upper neutral stability branch at chord Reynolds numbers from 1.5×10^6 to 5×10^6.

Unfortunately, most of the information on the influence of noise is in the form of qualitative observations and where specific experiments have been conducted, the models employed distributed suction boundary layer stabilization.

The most comprehensive experiments known to this writer are summarized in Reference 33 through 35. A 4% thick unswept wing of 17 foot chord with distributed suction through many fine slots as well as a 30° swept wing of 7 foot chord employing distributed suction served as the models. The unswept wing results[34] are most nearly applicable to the commuter aircraft. This wing was subjected to: external longitudinal and transverse sound waves, internal sound waves, and panel vibration. The sound waves were of both discrete frequencies and random noise in octave banes between 150 and 4000 cycles. Vibration experiments were at 100, 190, and 1240 cps. Largest effects were found for those frequencies predicted to be critical for T. S. amplification. With strong suction stabilization, the critical intensities decreased at a lower rate than $1/R_C$ while at low suction stabilization the dependency was at a greater rate than $1/R_C$. The critical sound intensity was as low as 108 dB at $R_C = 20 \times 10^6$ at the minimum suction quantity $C_Q = 1.1 \times 10^{-4}$. When suction was increased 80%, the critical intensity increased to over 130 dB. For the higher octave of frequencies 600/1200∿ suction had to be increased in the forward area to prevent transition. At 300/600∿ suction increase in the mid-region was required and for 150/300∿ suction increase in the rear region of the airfoil was most effective.

Similar experiments with boundary layer stabilization due to strong favorable pressure gradient (thick laminar airfoil) are not presently available but should be similar to these thin airfoil suction stabilized results.

(H) Effect of Atmospheric Turbulence

It was discovered very early that the scale of atmospheric turbulence was too large to constitute a source of instability to the laminar boundary layer. In spite of the lack of convenience of flight test over laboratory work, the ease of maintaining extensive laminar flow in flight compared to wind tunnel testing has been most striking to all who have experimented in both regimes.

The change in angle of attack upon entering a gust may cause a momentary forward movement of transition on extreme laminar airfoils with narrow low drag buckets.

The most encouraging data to date is that of Bikle[16] who found the profile drag of a laminar airfoil on a sailplane to be unaffected when circling continuously in rough thermal currents. These results were obtained by the wake survey method.

I. Problems of Rain, Frost, and Ice

It has been a universal experience that laminar flow is lost when flying in rain. Even flight in close proximity to clouds has been observed to result in loss of laminar flow due to condensation of moisture on the surface. The percentage of time that critical rain and moisture will be encountered in commuter operation is probably quite low in the southwest but may be a major nuisance in some portions of the country. It has been observed that once out of rain conditions, the moisture rapidly evaporates and laminar flow is restored within a minute or less.

Frost in the atmosphere can result in loss of laminar flow in two different ways. Frost crystals on the surface will generally be large enough to trip the boundary layer. Under certain conditions, frost may deposit on the surface while on the ground before take-off. This type could be removed before take-off. The writer experienced one instance of frost deposition on a laminar airfoil during a rapid descent from altitude in the F-94 experiments.

During the X-21 tests, laminar flow was occasionally lost for no apparent reason. With the assistance of the Meteorologist Dr. Paul McCready, a sampling device was installed which detected tiny frost crystals in the atmosphere. None were observed to adhere to the surface in these flights. It was speculated that some frost crystals passing the wing within the boundary layer might shed wakes which could introduce turbulence to the boundary layer. At a DARPA meeting in the Spring of 1979, the writer asked Dr. W. Pfenninger why we had never encountered this phenomena in the extensive F-94 flight work. He reminded me that the F-94 work was confined to altitudes of 36,000 feet and lower while the X-21 spent considerable time at and above 40,000 feet. McCready's survey showed the ice crystal phenomena to be confined to the higher altitudes just above the tropopause. As such, it should not constitute a problem to the commuter aircraft.

No one expects to maintain laminar flow under icing conditions. A more serious problem is that of the influence of any anti-icing device on laminar flow under non-icing conditions. The mechanical or rubber boot type has never to this writer's knowledge been installed in a smooth enough manner to avoid tripping the laminar boundary layer. Thermal de-icing would seem to be the method most likely to avoid this problem and could also be used to evaporate moisture, perhaps solving the problem of flying in proximity to clouds.

(J) Past Experience With The Leading Edge Insect Contamination Problem and Solutions Other Than The Resilient Leading Edge

The major problem preventing the application of decades of major drag reduction experience due to laminar flow has been boundary layer tripping by insect impingement at or near the leading edge. An excellent survey of the problem is found in Reference 36 with some additional detailed measurements in Reference 37. The insect population is confined to levels below cruise altitude for even commuter aircraft, still, take-off, climb, descent, and landing must be made through these levels. The accumulated insect remains in the first few percent of chord occurs at height several times that required to trip the boundary layer. One exception to this was found in a few of the F-94 flights where the very small insects found around the Mojave Desert would result in turbulent flow at low altitude but became sub-critical at altitudes above 28,000 feet. It is dissapointing that in the later measurements of Reference 38, the insects found over the alfalfa fields within 30 miles of the F-94 take-off site were sufficiently large that they did not become sub-critical at higher altitudes as in our earlier work. It must be concluded that insect encounters resulting in leading edge contamination will almost always cause turbulent flow even during later flight at cruising altitude.

The largest values of insect population per million ft^3 of air space are found at a temperature of 25°C and amount to 300 at ground level, 25 at 250 ft altitude, 10 at 1000 ft and negligible above 5000 ft (although a few insects are occasionally carried higher in strong thermal currents)[36]. This writer encountered one large insect over Mississippi at 14,000 ft as an exception that proves the rule.

The insect population falls to 20% of the maximum encountered at 25°C at both 5°C and 37°C, illustrating the sharp dependence of insect flight on temperature. The same can be said for wind speed where the population falls to 20% of the maximum encountered at 5 to 10 Mph by the time wind speed increases to 35 Mph. The temperature and wind velocity data apply to near ground level where 54% of the total population occurs. An additional 33% is found at altitudes between 250 ft and 1000 ft with the remaining 13% occurring between 1000 and 5000 ft.

The relative velocity at which insects will rupture and contaminate the surface upon impact varies with type of insect but all types rupture between 22.5 Mph and 44.9 Mph.

Typical height of roughness caused by impacting insects decrease from a maximum of 0.017 inch at 2% chord to 0.007 inch at 5% chord and zero by 30% chord on a 66-018 airfoil lower surface at 6° angle of attack at a chord Reynolds number of 6.9×10^6.

Typical chordwise limitation of contamination on a thick airfoil are: 13%C at 1°α and 6%C at 4°α for the upper surface and 17%C at 1°α and 32%C at 9°α for the lower surface. Thick airfoils tend to contaminate further aft than thin airfoils but the maximum thickness height is nearly independent of airfoil thickness. The critical thickness height to trip the laminar boundary layer is $R_{K_{crit}} = \frac{Ku_K}{\nu} = 200.$

The most effective method of preventing insect contamination is the paper leading edge cover which is wrapped about the leading edge, held with tape at the downstream ends, and cut with a string doubled about the paper at the leading edge after climb out to an altitude above the bug level.

This method was first used in the King Cobra experiments and later in the F-94 experiments and was 100% effective. A full span paper cover was investigated in the X-21 program and was successful but due to the low insect population at Edwards AFB on the Mojave Desert and the high flight altitudes of the X-21, was not required on the majority of the flights.

Since the paper leading edge cover is inconvenient and would probably raise problems about littering around busy airports, many other solutions have been investigated, particularly by the British[36]. Insects were found to penetrate to the surface and contaminate through both solid films which would sublimate away, and highly viscous films which evaporate in time. A 0.009 inch thick elastic spray on film was effective and could be removed by spraying water from the leading edge once above the bug level but required a weight of water of about ½% of gross weight.

Both the British and the recent NASA Dryden experiments have found that the leading edge can be kept clean by a continuous spray of water during take-off and climb. The British found 0.85# of water per minute per square foot of wing surface required at 35°C but this rose to 1.35# per min per ft^2 at 50°C.

A novel method due to the British entailed chilling the leading edge with dry ice before take-off resulting in a thin layer of ice. After eight minutes of flight, the ice had broken away carrying the insects with it. The complexity of the refrigeration system tends to discourage this approach and the same argument may be applied to the continuous water spray system.

The British also investigated sucking the turbulent boundary layer away at 20% chord thus permitting a laminar boundary layer to re-establish aft of this point. It was found necessary to remove slightly more than the complete boundary layer thickness and the suction power requirement was just equal to the savings in drag due to the re-laminarization. They noted that insect remains will erode away in flight from regions other than near the leading edge and that a more forward position of the suction slot would lead to a net drag reduction if erosion could be relied upon to remove insects aft of the slot.

The investigations of insect contamination prevention covered above were carried out during the 1940's, 1950's and 1960's. Recently, an extensive flight program was conducted by NASA Dryden using a Lockheed Jetstar aircraft as reported in Reference 38. The outboard leading edge flap was equipped with water spray nozzles spaced four inches apart on the lower surface which directed water over the upper surface. Boundary layer velocity probes spaced two inches apart were located near the trailing edge of the leading edge flap to determine whether the boundary layer was laminar or turbulent at this point. The flap was treated in five equal spanwise segments employing: (1) Teflon pressure-sensitive tape, (2) spray-on teflon coating, (3) organo-silicone hydrophobic coating, (4) random rain repellent coating, and (5) aluminum alloy untreated surface. Flights were conducted from airports in San Francisco, Sacramento, Drydon FRC, Los Angeles, and San Diego in California plus Houston and Ellington AFB in Texas and Orlando, Florida. Insect contamination was found to occur at all take-off sites. Erosion of insect remains during cruise conditions was found to be insufficient to remove the problem. None of the surfaces tested showed any significant reduction to the degree of contamination although the Teflon surfaces were easier to clean between flights. Water-detergent spray after contamination occurred was not effective in removing insect remains in flight. Intermittent use of spray in the insect levels was also not effective. Continuous water-detergent spray was found to be completely effective in preventing insect contamination and loss of laminar flow. It was estimated that less than 1% of gross weight would have to be allocated to the water and spray system for airline application. These experiments did not include investigation of the resilient leading edge concept of Dr. F. X. Wortmann. This basically different concept will be covered separately in Part N of this report.

(K) Material Selection and Detail Design Considerations

The ability to produce wing surfaces meeting the stringent requirements for laminar flow has improved remarkably in the decades following the original concept. At one time, the thin metal skins, multiple spanwise stringers, and countless fasteners at the surface dictated against any significant laminar flow unless large quantities of surface smoothers were employed. These fillers and smoothers were then liable to chip off under flexing caused by flight loads. The problem can be avoided by fabrication of very large panels of bonded sandwich construction in accurate female molds. This is now state-of-the-art. For example, the Tulsa Division of Rockwell makes large leading edge panels for the Boeing 747 by this method and inspects every square inch by an ultrasonic method to insure that there are no voids in the bonding. The bonded sandwich construction produces panels as wave free as the molds in which they are made with sufficient stiffness and lightness to insure against surface distortion and/or vibration in flight. The troublesome not-always flush rivets problem is also removed, now that reliable bonding methods are available.

The problem now shift to the structural joints between the large panels for example at spar locations. It is necessary to insure the fixety of such joints under load so that critical waviness does not occur at this point. It is desirable to place such potentially dangerous features as far aft as possible. Double rows of fasteners with adequate overlap in the joint is desirable to improve the fixety. Modern epoxy-type filler materials can be used to smooth main structural joints but are best avoided if possible because of the possible maintenance headaches such as occurred on the X-21 laminar wing. Many designs will require mechanical fasteners at major structural joints. One method of preventing the fasteners from becoming a surface problem is to allow a recess strip in the area of the fasteners. This can be filled flush with a thin metal surface strip bonded in place. If it should ever be necessary to disassemble the structural joint, the thin surface strip could be peeled off to allow access to the fasteners.

Access doors are the remaining major problem for the laminar wing designer. For partially laminar designs, it may be possible to provide access aft of the region where laminar flow is expected. To some extent, it will be possible to work out access locations having a minimum laminar area of influence. Serious studies are presently underway to design access doors meeting laminar flow requirements where the problem is compounded by incorporation of distributed suction through the súrface. Reports of these studies by Boeing, Lockheed/Georgia and McDonnell-Douglas are available from NASA Langley under a continuing program for the development of a future transport aircraft incorporating suction boundary layer control. It should be mentioned that joints and access panels must not only remain flush to within a few thousandths of an inch but must also be sealed so that air cannot bleed out into the boundary layer.

(L) Care and Maintenance of Laminar Surfaces

As mentioned previously, surface roughness from insects and/or mud must be removed between flights if any has accumulated. Some method of contamination prevention must almost certainly be employed in the operating environment of any partially laminar commuter aircraft. A completely successful system would obviate the need for time-consuming and costly between-flight cleaning.

Erosion and corrosion are two additional sources of trouble. Boeing has proposed using a thin titanium outer skin at the leading edge as the most resistant material. They further propose that this thin outer layer at the leading edge be replaceable in case of hail damage.

Corrosion of aluminum skins may be prevented by a suitable coating. Recently, Boeing and Avco conducted an extensive study of both liquid coatings and bonded films with respect to resistance to deterioration in service[40]. The purpose of these coatings was to reduce the drag of turbulent boundary layers over the typical surface imperfections of existing aircraft. The data should be applicable to the aluminum corrosion problem of laminar surfaces. Elastomeric polyurethane liquid coatings demonstrated excellent resistance to rain erosion but were susceptible to deterioration after extensive exposure to hydraulic fluid. Films such as Tradlon and Kapton bonded with polysulfide PR1422 were found excellent in all respects. Concern was expressed over the cost of bonding large areas on already existing aircraft. This should not be a concern for a new laminar commuter aircraft constructed in female molds. Additional service tests of liquid coatings, and adhesively bonded films vs. plain metal surfaces are probably required to establish which approach will lead to the lowest maintenance problem in airline operation.

Dust accumulation has not been found to be a problem in laminar flight experiments to date.

(M) Experience With Existing Natural Partially Laminar Production Man Carrying Aircraft

In spite of a time passage of more than three decades since the outstanding success of the King Cobra experiments, there do not yet exist powered production man-carrying aircraft with extensive laminar flow. To date, the only experimental aircraft properly instrumented to monitor extensive laminar flow was the X-21 which incorporated distributed suction rather than natural laminar flow. There is in existence one experimental single engine propeller driven aircraft (the Bellanca Skyrocket) which has a smooth sandwich constructed moderate 64 series laminar wing. It is hoped that extensive, properly instrumented flight tests will be conducted with this aircraft under the new NASA Langley investigation of natural laminar flow.

There are approximately two decades of experience with production man-carrying sailplanes incorporating extensive natural laminar flow. These superbly refined aircraft employing foam fiberglass sandwich construction, operate at wing chord Reynolds numbers of about 0.5×10^6 to 4×10^6. They obtain low profile drag coefficients over a range of lift coefficients from less than 0.1 at high speed to 1.4 in circling flight with the aid of cruise flaps. Well instrumented flight tests have been carried out by

Raspet and Bikle in the U. S. and Eppler in Germany where boundary layer transition and profile drag have been monitored as well as the overall performance. These tests have revealed extent of laminar flow and profile drag coefficients consistent with design values and in some cases, slightly superior to values found in low turbulence wind tunnels. Competition sail-plane pilots clean insects from the leading edge when necessary between flights. They also monitor the surface waviness as their sailplanes age. The experience on surface waviness deterioration on fiberglass -foam production sailplane wings with time is mixed. Dr. Eppler who minotors boundary layer transition location and profile drag claims he has had no deterioration in seven years on his Phoenix sailplane. Other pilots who only check the surface waviness claim they do some smoothing each year to keep their wings in the same condition as when delivered from the factory.

Sailplanes cruise at Reynolds number per foot of 1/4 to 1/2 that which are typical of commuter aircraft and chord length Reynolds numbers which are even smaller relative to commuter aircraft. Still they have served as the path finder in showing the promise of extensive natural laminar flow on production man-carrying aircraft.

(N) Prevention of Insect Contamination With Elastic Surface

In 1963, Dr. F. X. Wortmann of Stuttgart presented a fundamentally different solution to the insect contamination problem (Reference 39). Previous successful methods had been limited to inconvenient jetisonable covers or continuous water sprays. Wortmann's solution was to use an elastic surface which continuously prevents insect contamination from occurring.

He reasoned that the high kinetic energy of the insect caused the body shell to burst and distribution of shell particles adhering to the surface in the viscous body fluids. The problem then was to prevent this action. Wortmann's solution was to find a surface which would constitute an elastic spring to store the impact energy for a short time and then push the insect away from the surface. The characteristics he believed important were: (1) a small spring mass so that the spring can be tensioned, (2) a small oscillation time to prevent excessive distortion of the viscous droplet (insect), (3) small spring damping even at high frequencies to retain sufficient energy to separate the drop from the surface, and (4) poorly wetted surface to facilitate separation.

The first experiments entailed high speed photographic study of liquid drop impingement on a flat surface. A water drop at low velocity was so invicid that it disintegrated before reflecting from the surface. An oil drop at low velocity demonstrated an oscillation in shape but the impact energy was insufficient to separate the drop from the surface. A water drop impacting a silicon solid rubber surface at 150 m/sec exhibited the desired results of separation as a unit from the surface with only a very small amount of liquid remaining on the surface.

The experiments were continued in the summer of 1961 and 1962 with real insects and various elastic surfaces. Both solid and foam rubber from 1 to 3 mm in thickness and shore hardness of 10 to 35 were employed.

The wind tunnel tests were limited to fruit flies while automobile and training aircraft experiments included many types of insects. The best surfaces were completely free of insect remains sufficiently large to trip the laminar boundary layer. A very thin liquid residue gave assurance that insect impingement had occurred. It was found that a 1 mm thickness was only effective to 100 km/hr but that a 3 mm thickness with a specific wt of 0.6 was effective over the entire test range of 40 to 200 km/hr. Silicone foam rubber with a powdered foam layer and having a large air content gave the cleanest results. This is known as Silikonschaumgummi from the firm of Rehau-Plastics, Rehau Bayern.

Dr. Wortmann claims that surface distortion due to pressure distribution is not a problem. Rain erosion is seen as the most serious practical problem. The light silicone rubber is limited to a Mach number of 0.35 while solid silicone rubber is adequate up to M = 0.6.

The writer visited Dr. Wortmann at Stuttgart in 1978 and asked whether additional work had been done on elastic coatings. He said he had not carried the work further since his 1963 paper but still felt the method should be practical for many applications. He said the silicon feature was probably not necessary if the other properties found optimum in the initial tests were met.

Further Development Plan

Both the continuous water spray from the leading edge and the resilient leading edge solution to the insect contamination problem are sufficiently promising to encourage further development. In the case of water spray, it still remains to be proven whether a flush slot or hole dispersion scheme can be properly located to keep both upper and lower surface clean without causing premature transition when not in use. There is also the question of whether the scheme will be effective at the greater distances aft of the leading edge required on the lower surface during take-off and climb.

The resilient leading edge has even further to go in development and due to its promise of being a simpler system with less weight penalty and the only one capable of being effective for long continuous operation in an insect environment, it should probably receive attention first unless proven impractical for the commuter aircraft application.

Initial experiments should probably employ the foam rubber 3 mm coatings found effective in the Wortmann experiments of the early 1960's. Even in those early tests, there appeared to be a problem with rain erosion of the light foam rubber found to be most effective against insects.

The development should consist of three parts. The first effort entails locating materials and combinations of materials with the proper combination of mass, spring constant, damping, and oscillation time similar to those found in Wortmann's experiments. Secondly, these must be subject to rain erosion tests simulating the operating range of the commuter aircraft. Those which pass the erosion test must then be studied to determine their effectiveness as insect repellers. Actually, the second and third steps probably should be approached together. Exhaustive study of an effective repeller which is impractical because of erosion is pointless but so is a study of a coating having good erosion resistance if it will not repell insects. It is hoped that a superior insect repelling coating such as the light high air content foam with a powdered layer can be coated on its outer surface to improve erosion resistance without modifying its elastic properties too drastically. An important team member on such a development program will be a Materials Engineer specializing in foam rubber, and plastic and liquid films. Some help can probably be expected from rubber, plastic, and paint manufacturers.

A survey of experimental facilities for erosion tests should be conducted. The Air Force Materials Lab rotating arm apparatus at AVCO Wilmington, Massachusetts [40] appears to be a convenient facility for initial sorting, unless a similar facility is available at Ames or can rapidly be made available from existing equipment. Injection of water spray in a wind tunnel may impose unacceptable maintenance problems to the facility. Final evaluation should be conducted on an aircraft. These type of experiments can often be done "piggy back" on flights devoted to other purposes whether on an Ames research aircraft or on a working commuter aircraft. It is possible that concern over effects on safety may dictate against trial installation on an airliner.

Initial sorting of coatings with respect to insect contamination could be done in still air by expelling insects at high velocity from an air gun. Use of shop air supply together with a simple tube and pressure regulator should suffice. Impact velocity could be controlled by a combination of chamber pressure and distance from muzzle to the leading edge of the test airfoil and measured by a rapid acting pressure gage monitoring the stagnation pressure at the leading edge. Location of impact can be controlled by the vertical location of the air gun relative to the airfoil.

More realistic tests could be conducted in the wind tunnel providing an additional screen downstream of the airfoil is used to prevent contamination of the fine turbulence reduction screens located further down the tunnel. With either of these methods, it will be necessary to obtain a supply of insects. Fruit flies seem to be the most readily obtainable and can probably be purchased from existing suppliers to other scientific and medical experimenters.

Use of automobiles while useful in the initial Wortmann experiments is perhaps not advisable at this stage of the game due to the lower impact velocity inherent in such testing. An aircraft with a speed potential and lift coefficient similar to the climb speed of a modern commuter aircraft would constitute the most realistic test bed. Several types of coatings can be investigated simultaneously together with sections of untreated leading edge.

Serious consideration of drag reduction through extensive natural laminar flow on a commuter aircraft is dependent upon elimination of the insect contamination problem. Should the development program not lead to a successful resilient leading edge which is also practical from the service standpoint, the effort should then be directed torward completing the development of the water spray method.

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