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**An INVESTIGATION into the AERODYNAMIC
EFFECTS of WING PATCHES**

by

Cameron Lindsay Carnegie, B.Eng.

**A thesis submitted to
the Faculty of Graduate Studies and Research
in partial fulfilment of
the requirements for the degree of
Master of Engineering**

**Department of Mechanical and Aerospace Engineering
Ottawa-Carleton Institute for Mechanical and Aerospace Engineering**

Carleton University

Ottawa, Ontario

5 October 1992

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ISBN 0-315-84121-4

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The undersigned hereby recommend to
the Faculty of Graduate Studies and Research
acceptance of the thesis,

**An Investigation into the Aerodynamic
Effects of Wing Patches**

submitted by

Cameron Lindsay Carnegie, B.Eng.

in partial fulfilment of the requirements
for the degree of Master of Engineering

Chair, Department of Mechanical and Aerospace Engineering

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5 October 1992

ABSTRACT

During combat conditions, aircraft such as the McDonnell Douglas CF-18 will acquire damage that must be repaired quickly to allow the aircraft to complete at least one more mission. Aircraft Battle Damage Repair (ABDR) is a predetermined set of guidelines that applies methods of rapid repair with the goal of returning the aircraft to operational status within 24 hours. Many of the ABDR methods involve the application of a patch, that can be as thick as 12.7 mm ($\frac{1}{2}$ inch), over the damaged area to compensate for loss of structural and skin strength. The intention of this report is to investigate the effect of the patches on the aerodynamics of the CF-18 wing.

Boundary layer information was obtained by a series of wind tunnel tests on chamfered and unchamfered plates, of various thicknesses ($Re_h = 2100$ to 33650), laid on the test section floor of the Carleton University wind tunnel. The results were expressed as polynomial curves fits with ΔH and $\frac{\Delta \theta}{\theta_1}$ as functions of $\frac{h}{\theta_1}$. These plate correlation curves were then encoded into the Stalled Airfoil Modelling Package (STAMP); a software package capable of performing viscous, attached or separated flow analyses on 2-dimensional airfoils using a combination of potential flow and boundary layer theory. The STAMP software package was used to analyse the effect of the patches on the flow over the CF-18 wing profile. The results revealed that even for the thickest patch (12.7 mm), the influence on lift is limited at low angles of attack ($\alpha \leq 1^\circ$ to 3°) but increases for higher angles of attack ($\alpha > 3^\circ$). The influence of the patches on drag is generally much greater and can double C_D with the thickest patches. Further investigation is required to evaluate the influence of patches on the fuselage of the CF-18.

ACKNOWLEDGEMENTS

The author wishes to express his gratitude to Professor R.J. Kind for his guidance and support during the preparation of this thesis report. Also, special thanks is extended to Major Tremblay, Captain D. Poirel and Captain T. Appels for their assistance in the literature search and to F. Barrett for his assistance in preparing the lab equipment.

*This thesis is dedicated to
my wife, Carolyn.
and our families
for their support and encouragement.*

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LIST of SYMBOLS

A, B	Law of the wall constants
c	Chord length
C_D	Coefficient of drag
C_f	Skin friction coefficient
C_L	Coefficient of lift
C_p	Pressure coefficient
h	Step height or patch thickness
h^+	Roughness Reynolds number
H	Shape factor, $\frac{\delta^*}{\theta}$
$H_{s-\delta^*}$	Head's Shape parameter $\frac{h-\delta^*}{\theta}$
L	Patch length
$P_{min\ max}$	Minimum and maximum static pressures over a step
$P(x)$	Static pressure distribution
P_{DYN}	Dynamic boundary layer pressure, $P_{T1} - P_{S2}$
P_{T1}, P_{S1}	Total and static air pressure
P_{REF}	Dynamic reference pressure, $P_{R1} - P_{R2}$
Re_c	Chord Reynolds number, $\frac{U_\infty c}{\nu}$
Re_h	Step height or patch thickness Reynolds number, $\frac{U_\infty h}{\nu}$
Re_θ	Momentum thickness Reynolds number, $\frac{U_\infty \theta_c}{\nu}$
s	Boundary layer length
u	Boundary layer velocity
u_τ	Friction velocity ($\frac{\tau_w}{\rho}$) ^{1/2}
U	Non-Viscous freestream flow over the CF-18 wing
$U_{BL\ REF}$	Boundary layer and upstream Reference velocities
U_∞	Free stream flow velocity

W	Test section width
x	Axis parallel to the chord length or the wall
x_p	Chord position of the patch leading edge
x_{r2}	Distance to the second boundary layer reattachment point downstream from a forward facing step
x_{r3}	Distance to the boundary layer reattachment point downstream from a backward facing step
x^*	The distance from the backward facing step to the position where the pressure rise is $\frac{1}{2}(C_{Pmax} - C_{Pmin})$
y	Axis perpendicular to chord length or the wall
y_{r1}	Height of the first boundary layer reattachment point on the face of a forward facing step
α	Angle of attack
δ^*	Displacement thickness
ΔC_L	Difference between the lift coefficient on a wing profile with and without patches, $C_L = (C_L)_{patch} + \Delta C_L$
ΔH	Difference in shape factor across the patch leading or trailing edge
θ	Momentum thickness
$\Delta \theta$	Difference in momentum thickness across the patch leading or trailing edge
ν	Kinematic viscosity
ρ	Density
ϕ	Fillet angle from the horizontal

Subscripts

i	Initial value, 10 step heights upstream from the patch leading edge
$clean$	Value without patches on the CF-18 wing profile
$patched$	Value with one patch located on the upper surface of the CF-18 wing profile
r	Reference value in absence of a step or patch
$R1, R2$	Reference values at the inlet and outlet of the wind tunnel nozzle, respectively
s	Reference value at separation
∞	Freestream value

1.0 INTRODUCTION

During combat conditions, aircraft may acquire damage that must be quickly assessed and repaired to allow the aircraft to complete at least one more mission. The Canadian Forces have developed a method called Aircraft Battle Damage Repair (ABDR) that categorizes the severity of the damage and establishes an appropriate response. Since time is critical, ABDR must be performed within 24 hours or else the aircraft is deemed unrepairable and its components are scavenged for use on other aircraft. Repairs completed within the time-frame can be crude, involving quick repair or replacement of damaged components and, if necessary, the fastening of a plate over the damaged skin area.

It is the addition of these plates to the airframe that is of primary concern in this report. Many of the skins on modern fighters are load bearing and can require a plate as thick as 12.7 mm (0.5 in) to compensate for loss of skin strength and internal structural strength, as well. Depending on the positioning of the plates, the aircraft could suffer severe aerodynamic consequences resulting in loss of lift, increased drag, and early stall.

1.1 DAMAGE CLASSIFICATIONS

The following is a list of the ABDR classifications of damage that is based on a process of triage. Note that many of the classes may require the attachment of a plate over the damaged areas.

Class A Damage Aircraft damage is severe and cannot be repaired by ABDR techniques within the 24 hour time constraint. Depending on battle conditions, the aircraft may be prepared for movement to a facility capable of rendering repairs. Otherwise, it is set aside for removal of undamaged parts to service other aircraft.

Class B Damage Aircraft damage is severe and cannot be repaired but servicing is possible by replacement of the affected parts, equipment, or assemblies. Also, repairs are not justified for critical components that cannot be returned to full performance or for components that can be replaced faster than repaired.

Class C Damage The addition of supplementary material, such as plates, is necessary to repair major damage to the aircraft. The ABDR methods by which this is done are detailed in Section 1.2.

Class D Damage When the damage is minor during intense battle conditions, this class is utilized to allow the aircraft to return to limited operation without repairs. This requires that the aircraft be flown so as not to over stress the damaged area by restriction of the acceleration ('gravities') to which the aircraft can be subjected.

Class E Damage Due to the light nature of this damage class, the aircraft can continue operation without repair. If the skin has been ruptured, a thin patch will be required to maintain aerodynamic integrity.

1.2 ABDR SKIN TECHNIQUES

After the internal repairs have been completed, the damaged skin is cleaned and covered with a plate held in place by fasteners. Depending on the diameter of the damage and the skin thickness, the patch can consist of multiple layers of metal laid over top of each other. Table (1.1) displays the patch thicknesses, based on the diameter of the damage and the wing skin thickness, and shows that patches can range from 0.032 inches (0.8 mm) to 0.375 inches (10 mm) thick. Arrangement of the patch and fasteners is displayed in Figure (1.1). The patch shape is rectangular and oversized enough to provide ample strength and protect against delamination of

GRAPHITE/EPOXY THICKNESS (INCHES)	DAMAGE DIAMETER (CLEANED) (INCHES)							
	1	2	3	4	5	6	7	8
0.1	0.032	0.063	0.063	0.063	0.063	0.063	0.063	0.063
0.2	0.063	0.063 + 0.032	0.063 + 0.032	0.125	0.125	0.125	0.125	0.125
0.3	-	0.125	0.125 + 0.032	0.125 + 0.063	0.125 + 0.063	0.125 + 0.063	0.125 + 0.063	0.125 + 0.063
0.4	-	0.125 + 0.032	0.125 + 0.063	0.125 + 0.125	0.125 + 0.125	0.125 + 0.125	0.125 + 0.125	0.125 + 0.125 + 0.032
0.5	-	0.125 + 0.063	0.125 + 0.125	0.125 + 0.125 + 0.032	0.125 + 0.125 + 0.063	0.125 + 0.125 + 0.063	0.125 + 0.125 + 0.063	0.125 + 0.125 + 0.125
0.6	-	0.125 + 0.125	0.125 + 0.125 + 0.032	0.125 + 0.125 + 0.063	0.125 + 0.125 + 0.125	0.125 + 0.125 + 0.125	0.125 + 0.125 + 0.125	-
0.7	-	0.125 + 0.125 + 0.032	0.125 + 0.125 + 0.125	0.125 + 0.125 + 0.125	-	-	-	-

NOTES

1. In stacked patches, put thinner sheet on top.
2. For 3g limit, on WING PATCHES ONLY, patch thickness may be reduced. For double-stack patch or triple-stack patch, eliminate thinnest sheet.
3. To meet aerodynamic limits on upper forward wing box, titanium patch is required. Use two sheets of 0.125 inch titanium instead of aluminum. Use standard titanium pre-drilled sheets when available. Use same number of fasteners.

Table 1.1 Aluminum Patch Thickness for Graphite / Epoxy Repair

Figure 1.1 CF-18 Patch Configurations for Composite / Metal Skins

Figure 1.2 Delamination Damage of Graphite / Epoxy Skins

composite skins. Figure (1.2) shows that delamination damage can extend substantial distances beyond the edge of the puncture or through damage.

In recent years, composite materials have come to play a more important role on the structure of aircraft because of its high strength and light weight. The Canadian Forces, McDonnell Douglas CF-18 incorporates Graphite/Epoxy composite skins on the wings, stabilizers, and various access doors, accounting for approximately 40% of its surface area. A permanent repair with composites must cure for at least a day with high pressure and temperature. This requires more time and equipment than ABDR techniques have to offer. Other techniques, better suited for ABDR, have been experimented with by the Canadian Air Force. One method involves filling the hole with fibreglass paste or adhesives and covering with an aluminum plate which is riveted or bonded into place. This can be accomplished in one or two hours and provides temporary strength for several missions. Another more permanent method involves filling the hole with resin and a matrix of carbon fibres. However, special equipment which may not be available is needed to apply the high temperature and pressure. Therefore, future research will concentrate on creating laminate materials at low pressures (15 psi) using equipment that is more commonly available such as a heat blanket, capable of generating the necessary high temperatures, and a vacuum pump, capable of producing moderate pressures.

1.3 THESIS OBJECTIVE and OUTLINE

Despite the possible advances in repair techniques mentioned above, the metal patch will remain an integral part of ABDR. Unfortunately, the patches are bulky, and can alter the aerodynamics of the aircraft. It is the goal of this thesis to study the effects of the patches on a boundary layer and on the aerodynamics of a CF-18 wing (Fig. 1.3). Wind tunnel testing is utilized to develop a set of correlation curves for describing the

Figure 1.3 CF-18 WING PROFILE
 $c = 2.77$ m.

main effects of the plates on boundary layers. These curves are incorporated into the Stalled Airfoil Modelling Program (STAMP). This is an existing package of computer programs for the analysis of 2-dimensional viscous, incompressible flow, including stall effects, over airfoils. Although flow over the CF-18 wing is certainly 3-dimensional, it is believed that a 2-dimensional study is sufficiently realistic to provide useful results regarding the effects of the patches. This is supported by Young et al. (1981) who demonstrate that a two dimensional forward facing step generates approximately the same amount of drag per unit width as a circular or rectangular plate.

The longitudinal patch length is usually much greater than its thickness and can be represented as independent forward and backward facing steps. Thus, the literature search of Section 2 focuses on previous work on flow over forward and backward facing steps. Even though this is a subsonic study, some attention is given to supersonic flow, due to the high speed capabilities of the CF-18. Section 3 provides a complete description of the apparatus and experimental procedure used to obtain the boundary layer data for a series of plates. It also contains a description of the methods of calibration and of the data reduction equations and theory. Section 4 presents the results of the wind tunnel testing of the plates along with a verification of results. Section 5 provides a short description of the STAMP program package and presents the computed wing lift performance curves with and without plates. Finally, the conclusions and recommendations are outlined in Sections 6 and 7, respectively.

2.0 LITERATURE SEARCH

In the past twenty years, much work has been devoted to studying flow over forward and backward facing steps. Unfortunately, most of the efforts do not directly apply to this study because of variations in the tunnel configurations. For example, much of the literature is devoted to supersonic and transonic flows and / or large step heights. Supersonic and transonic flow fields are very different from the subsonic case due to the presence of shock and expansion waves. Large step heights within a closed test section accelerate / decelerate the flow creating pressure distributions not present in an infinite flow field over a step. Thus, the available information is limited to a few relevant sources that deal exclusively with a forward facing step or a backward facing step. Since the effects of a forward facing step can extend thirty step heights downstream, the forward and backward facing step configurations can continue to be handled separately if the plate extends beyond this distance. Information on steps with fillets is even more scarce. Some sources exist with large step heights but only two references (Tani et al, 1961 and Young et al, 1981) were found with the desired configuration.

2.1 FORWARD FACING STEP

In order to adjust to a positive surface discontinuity or forward facing step, the flow field typically develops two regions or bubbles of separated, reverse flow (Fig. 2.1). These are located in the corner just upstream of the step and on top of the step. The circulation in the latter bubble is found to be much stronger due to its position under the high velocity region of the flow. All sources reviewed on this configuration generally agree on the static pressure distribution along the wall but there is some discrepancy over how far upstream the flow field is affected by the presence of the step. The first sign of an approaching step is a slight increase in the wall static pressure.

Figure 2.1 The Forward Facing Step

Elfstrom (1984) reports a pressure increase starting at $x = -30h$ for step heights of 0.69*h*, and 1.0*h*. Taulbee and Robertson (1969, 1971) claim that the increase starts at $x = -15h$ for a range of heights ($\frac{h}{\delta_r} = 0.2$ to 1.13). This was supported by Moss and Baker (1980) who report a positive pressure gradient extending at least $x = -12h$ upstream for ($\frac{h}{\delta_r} \approx 1.13$). Approaching the step, the static pressure quickly increases to a plateau value at the step base (point A of Fig. 2.1). The static pressure quickly increases again up the step face until it reaches a maximum at about $y = 0.55$ to $0.75h$, at which point it drops sharply to the edge of the protruding corner (point B). This results in a strong adverse pressure gradient along the upper surface until partial pressure recovery is achieved one or two step heights downstream. A mild favourable pressure gradient extends further downstream from this point.

AUTHOR	h	Re_h	$\frac{L_s}{h}$	$\frac{y_{sep}}{h}$	$\frac{L_{rec}}{h}$
Bradshaw and Galea (1965)	1.75 δ_r	34992	1.2		
Taulbee and Robertson (1969)	1.25 δ_r	16663	0.96	0.56	3.33
	2.12 δ_r	55372	0.92	0.62	3.8
	2.5 δ_r	33326	1.2	0.7	4.3
	5.0 δ_r	66652	1.4	0.73	4.6
Taulbee and Robertson (1971)	0.56 δ_r	16148	0.84	0.56	
	1.25 δ_r	16148	0.96	0.56	
Moss and Baker (1980)	1.43 δ_r	50000	1 ~ 1.5	0.65	4.7
Elfstrom (1984)	1.3 δ_r	218675	1.2		
	1.0 δ_r	168211	1.2		
	0.8 δ_r	134569	1.2		
Farabee and Casarella (1984)	0.42 δ_r	21000			3.0 ~ 4.0
	0.625 δ_r	34000			3.0 ~ 4.0
Baron (1987) -see Fig 2.2 & 2.3		29500			

Table 2.1 Typical Forward Facing Step Flow Parameters

Except at very low Reynolds numbers, the first adverse pressure gradient results in separation of the boundary layer producing the lower separation bubble at the base of the step. Referring to Table (2.1), a summary of separation bubble parameters observed by various researchers, the position of the first separation depends on the

step height and ranges from $0.8h$ to $1.5h$ upstream of the step. Moss and Baker (1980) display the separation process with a series of velocity profile plots that slowly deteriorate to reversed flow. In the presence of the strong favourable pressure gradient on the upper half of the step face, reattachment is eventually achieved so that separation is confined to a bubble in the notch of the step. Table (2.1) lists the position of reattachment on the step face; this is between $y_{r1} = 0.55h$ to $0.75h$ which corresponds with the range of the maximum pressure position. At the top of the step, the flow separates again due to the strong adverse pressure gradient found there. The profile plots indicate strong reverse flow with velocity of the order of $0.2U_\infty$. Reattachment occurs 3 to 5 step heights downstream from the step where the second negative pressure gradient exists.

Baron (1987) has done an extensive study of the growth and decay of the upper and lower separation bubbles in response to various flow configurations. At low Reynolds number ($Re_h < 600$), he has found that the sizes of the separation bubbles are strongly dependent on the boundary layer thickness and the Reynolds number. First, consider the effect of the boundary layer thickness on laminar flow at very low Reynolds number ($Re_h \approx 100$). If the boundary layer thickness is very small, the upstream separation bubble is virtually nonexistent because of the high energy state of the fluid adjacent to the wall that is capable of overcoming the weak adverse pressure gradient. Increasing the boundary layer thickness moves the high energy fluid away from the lower surface resulting in the formation and growth of an upstream separation bubble. However, the rate of pressure recovery along the surface after the step, is reduced along with the strength of the second adverse pressure gradient, delaying separation, and shrinking the upper separation bubble. As the boundary layer thickness is further increased, the upper separation bubble will eventually vanish leaving the lower separation bubble to peak in size and eventually level off.

Increasing Re , within the range stated above, simply increases the size and response of the separation bubbles. Above $Re_h = 600$, Baron found that the separation bubbles become insensitive to Re_h . Robertson and Taulbee (1969) suggest a dependency of the lower separation point, x_s , on Re , but admit the trend might be a result of the unsteady nature of the lower bubble. The consensus of the sources covered agree with Baron but with the reservation that there is the possibility of a very weak dependency on Re . In fact, Elfstrom discovered such a trend by plotting the pressure rise to separation, corrected for near-step effects, versus Re .

Baron expanded his study, by increasing the Reynolds number of the flow well into the turbulent range ($Re_h = 29500$). This served to increase the size of the upper and lower separation bubbles and alter their responses to changes in the boundary layer thickness. At near-zero thickness, the lower separation bubble is nonexistent and the upper bubble is very elongated, extending approximately 9 step heights. Increasing the boundary layer thickness results in the rapid growth of the lower separation bubble and a relatively faster shrinkage of the upper bubble. The growth of the lower bubble peaks at $\frac{h}{\lambda_s} = 2.8$, followed by some shrinkage and an eventual levelling off, relatively, at $\frac{h}{\lambda_s} = 1.25$. The decrease in size of the upper bubble begins to level off over the same range. Figures (2.2) and (2.3) display the plots of Baron's separation and secondary reattachment distributions along with the data in Table (2.1). The unstable nature of the separation and reattachment points and the variation in tunnel configurations account for the scatter in the data of the other researchers. Taking this into account, Baron's data seems to be in good agreement with Table (2.1).

In supersonic flow, the pressure rise and gradients toward the step are much larger than in the subsonic case due to the greater availability of flow energy and the presence of shock waves. Chapman et al. (1957) found that the pressure distribution over the step in supersonic flow is dependent on Re or on the position of boundary layer

Figure 2.2 FORWARD FACING STEP LOWER
SEPARATION POINTS

Figure 2.3 FORWARD FACING STEP UPPER
REATTACHMENT POINTS

transition to turbulence. If the supersonic flow is laminar, a strong adverse pressure gradient begins about one step height upstream from separation and continues well into the separation bubble where it gradually levels off to a value 30% greater than the initial pressure. If transition is located near the step within the separation bubble, two distinct adverse pressure gradients exist. The first rise in pressure is aligned with separation followed by a region of relatively constant pressure (plateau pressure), extending over most of the separation bubble. The second pressure rise occurs through transition and is subdued as transition moves upstream toward the separation point. If the flow is turbulent, a single strong adverse pressure gradient exists across the considerably smaller separation bubble, tripling the static wall pressure at the base of the step. In all three cases, a shock wave originates from the outer edge of the boundary layer above the separation point. Chapman found that the separation point could extend as far upstream as $16h$ for laminar flow. Zukoski (1967) reports a separation distance of $4.2h$ for fully turbulent flow that is roughly independent of Mach number, Re , and step height if $\frac{h}{\delta_r} > 1.2$. The plateau pressure is dependent on step height (if $h < \delta_r$) and on the Mach number.

Young et al. (1981) performed a study on drag generated by various surface discontinuities such as rounded and chamfered forward facing steps, backward facing steps, and discs. Accumulating data from other authors for a forward facing step ($\phi = 90^\circ$), Young plotted the ratio of the drag and surface friction coefficients $\frac{C_D}{C_f}$ versus a roughness Reynolds number $h^+ = \frac{u_* h}{\nu}$ based on the step height, h , where u_* is the friction velocity. The drag increases logarithmically with step height but the dependence on Mach number is not so simple. The drag increase from Mach 0.2 to 0.8 is much less than the increase through the transonic range to Mach 1.4 where it begins to level off again with respect to Mach number. Rounding the edge of the protruding corner or inserting a fillet can decrease the drag significantly. Young found that an 80% reduction is possible for subsonic flow if the corner is rounded to a radius of h .

An equivalent reduction can be achieved with a fillet angle of 20° to the horizontal. Supersonic flow experiences much lesser reductions because of the dominant effect of the shock waves.

A narrow test section seems to limit the three dimensional nature of the flow and the size of the separation bubbles. Since complex lateral flows exist within the separation bubbles, the walls of the tunnel must inhibit this movement which can have far reaching effects in a narrow test section. For low Re , Baron indicates that anything less than a width of 100 step height affects the results but is not serious until $\frac{W}{h} < 20$. This did not present a problem during the present study since the ratio for the largest step is $\frac{W}{h} \geq 60$.

2.2 BACKWARD FACING STEP

In comparison to the forward facing step, the flow over the backward facing step is easier to comprehend. Unable to follow the contour of the step, the boundary layer separates off the step edge becoming suspended as a free shear layer above a highly turbulent separation bubble, known as the recirculation zone (Fig. 2.1), where the reverse flow velocities can reach as high as $0.2U_\infty$. Turbulent mixing occurs and the shear layer enlarges as it entrains fluid from the recirculation zone. Initially, the shear layer remains parallel with the wall but further downstream, it approaches the wall with increasing curvature. This establishes a reattachment point and terminates the recirculation zone, creating a separation bubble. Due to the unsteady nature of the shear layer, the reattachment point fluctuates back and forth, forming a reattachment zone. Downstream of the reattachment zone, a new wall boundary layer develops that interacts with turbulent structures from the shear layer, creating unsteady flow patterns. The smaller eddies near the wall quickly dissipate but larger eddies further out can endure much longer, resulting in a velocity deficiency in the middle layer of

Figure 2.4 The Backward Facing Step

the velocity profile far downstream from reattachment. Bradshaw and Wong (1971) report that the interference can persist as far as 52 step heights and beyond. That is, the boundary layer is not completely similar to an undisturbed two-dimensional boundary layer for a distance of over 50 step heights downstream of a backward facing step.

Subsonic flow begins to adjust to the presence of the backward facing step with a gentle decrease in the static wall pressure. Moss and Baker (1980) found this to begin $6h$ upstream from the step. This favourable pressure gradient rapidly increases upon approach to the step edge, resulting in a relatively constant low static pressure down the step face. A gentle pressure decrease continues along the lower surface to a pressure minimum approximately 3.5 step heights downstream. This is followed by a strong adverse pressure gradient that extends through the reattachment zone and reaches a maximum shortly downstream where the near-wall velocity and turbulent energy are low. This strong adverse pressure gradient forces much of the fluid from the reattaching shear layer back upstream into the recirculation zone, compensating it for the fluid entrained into the free shear layer. Narayanan et al. (1974) found that the pressure distribution could be influenced by tunnel configuration or blockage. By plotting $\frac{P_{min}-P(x)}{P_{min}-P_{max}}$ versus $\frac{x-x^*}{h}$, where x^* is the distance from the step to the position where the pressure rise is $\frac{1}{2}(C_{pmax} - C_{pmin})$, they were able to demonstrate similarity through the separation bubble to the middle of the reattachment region. It is reported that similarity is maintained for very small steps where the maximum pressure is low.

At high Reynolds ($Re_\theta \geq 2600$), all authors agree that the reattachment point x_r is insensitive to $\frac{h}{\lambda_\tau}$ or to Re if the separating boundary layer is turbulent or becomes turbulent shortly after separation. Tani et al. (1961) argue that the flow within the separation bubble is maintained by turbulent shear stresses in the shear layer. Since these stresses are not greatly affected by $\frac{h}{\lambda_\tau}$ or Re , neither is the separation bubble or

reattachment length. The position of the reattachment point is very unsteady which accounts for the scatter in the data of most researchers. Kim et al. (1978) define reattachment as a range or fluctuating band of two step heights ($7h \pm 1h$) which is supported by a consensus of authors who agree that the mean value for fully turbulent flow lies at $\frac{x_{r3}}{h} \approx 6.5$.

If the free shear layer is laminar and does not undergo transition to turbulence shortly after separation, then x_{r3} is highly dependent on $\frac{h}{\delta^*}$ and on Re . Eaton and Johnston found that x_{r3} increased with momentum thickness Reynolds number, Re_θ , until reaching a peak value of $8.2h$ in transitional flow ($Re_\theta = 442$). The reattachment length decreases and levels off to approximately $7.6h$ as the shear layer becomes fully turbulent ($Re_\theta > 2600$). The shorter reattachment distances ($6.3h \leq x_{r3} \leq 7.0h$) associated with a laminar shear layer is a result of a greater entrainment rate. Eaton and Johnston believe that the existence of a very organized, spanwise vortex structure, which is not present in the turbulent case, causes early rapid growth of the laminar shear layer and possible pairing of spanwise vortices.

The shear layer growth and curvature are considered to be the strongest factors in establishing the point of reattachment. The growth of the shear layer is rapid when the entrainment rate is high which leads to a short reattachment distance. This can also be connected to a strong longitudinal adverse pressure gradient ($\frac{\partial p}{\partial x}$) that reroutes much of the shear layer flow into the separation bubble to supply a high entrainment rate. The curvature of the shear layer is mainly a result of the positive pressure gradient in the vertical (cross-stream) direction ($\frac{\partial p}{\partial y}$). Eaton and Johnston believe that the first factor is more important since the reattachment point can be closely estimated with the assumption of no shear layer curvature. Also, they point out that momentum plays an important role and must be accounted for in computer modelling.

As mentioned above, the shear layer is unsteady and, in fact, exhibits a flapping motion that is responsible for the fluctuation of the reattachment point. Eaton and Johnston attribute this to the instantaneous imbalance of the backflow into the recirculation zone and the entrainment rate into the shear layer. For example, an occasional large entrainment structure, such as pairing of spanwise vortices, may cause a decrease in the recirculation zone. The shortened length of the shear layer would reduce the entrainment rate below the backflow rate, allowing the recirculation zone to expand again.

In order to obtain more insight into the dependence of the separation bubble on the state of the boundary layer, Tani et al. (1961) inserted a triangular fillet (angled 8° with the horizontal) into the step notch. They found that the fillet had virtually no effect on the pressure distribution if the fillet height didn't exceed one half of the step height. Beyond this limit, the redirection of flow into the separation bubble is inhibited and a pressure increase across most of the separation region results. The same effect can be created by placing a fence two step heights downstream from the step.

Similar to the forward facing step, the pressure distribution and gradients are much greater in supersonic flow over a backward facing step than for the subsonic case. Also important is the dependence on the state of the boundary layer. In turbulent, supersonic flow, Chapman et al. (1957) found that the pressure drops severely and without warning at the step edge. A constant pressure from the base of the step is maintained until a severe adverse pressure gradient is encountered at $x \approx 1.8h$ that continues through reattachment. When transition is located within the separation bubble, the pressure drop is reduced by 40% from the turbulent flow case and pressure recovery takes place within the region of transition. For the purely laminar case, the adverse pressure gradient is reduced along with the pressure drop, 50% down from

the turbulent configuration. Chapman indicates that the reattachment distance is dependent on Mach number and Reynolds number.

The drag on a backward facing step can be much less than that on a forward facing step but still exhibit the same increasing logarithmic response to roughness Reynolds number or step height. Young et al. (1981) found that the drag ratio $\frac{C_D}{C_{D0}}$ for subsonic flow over a backward facing step can be 50% less than that for the forward facing step. The drag response to step height for supersonic flow is in closer agreement for both step configurations but tends to be less for the backward facing step. The drag response to Mach number is also similar to the forward facing step, displaying a leap in magnitude through the transonic range, but untypically decreases slowly after supersonic flow is established. Rounding the step's edge has little effect on drag and from Young's results, tends to cause an increase. The addition of fillets can also increase the drag by as much as 20% for fillet angles of 40° to 65° for subsonic flow and angles from 7° to 45° for supersonic flow (Mach 1.2 to 1.7).

Previous work focused mainly on discovering the nature of the flow field, and not on establishing the changes in the overall boundary layer parameters such as θ , δ^* , and H across the step and the resulting zone of disturbance. This kind of output / input information is needed for the present work, so that correlations representing the effect of upstream and downstream facing steps can be formulated. Such correlations are needed to represent the effects of the steps associated with repair patches or plates in the computations of boundary layer development in the STAMP package.

3.0 EXPERIMENTAL PROCEDURE and EQUIPMENT

The purpose of the wind tunnel testing of the plates was not to provide a complete description of the flow configuration, but to define the effect of the leading and trailing edges of the plates on the boundary layer parameters, momentum thickness θ and the shape factor H , of the CF-18 wing. The profile of the CF-18 wing (Fig. 1.3) is essentially a NACA 65A-004 airfoil with a 0.005c nose droop, starting at 0.18c. The tasks of defining the flow configuration over a clean (no patch) CF-18 wing profile and calculating the lift were performed by the STAMP package, mentioned in Section 1.3. Unfortunately, it couldn't account for surface discontinuities typical of wing patches. To overcome this shortfall, the plate correlation curves (Appendix 1) developed during the wind tunnel testing were incorporated into the boundary layer subprogram (BLAP2) to enable it to deal with patches. The boundary layer computational algorithm, marching from the leading edge stagnation point and computing the boundary layer parameters, simply referenced the correlation curves, when a patch was encountered, and obtained the relation between the variables across the discontinuities.

To simulate the flow over the CF-18 wing patches, Aluminum plates were laid on the floor of the Carleton wind tunnel test section and subjected to boundary layer analyses with little or no pressure gradient using Pitot tube / traversing gear apparatus (Fig. 3.4). The thicknesses of the plates were varied and 45° fillets were added to the plate edges in order to study the influence of these alterations on the momentum thickness and shape factor increments ($\frac{\Delta\theta}{h}$, ΔH) over leading and trailing edges. To cover a range of boundary layers, the increments were plotted against $\frac{x}{h}$, where the subscript '1' indicates an initial point $10h$ upstream from the leading edge. The equations were then inserted into the coding of the STAMP package. Before proceeding with

the specifics of the tunnel testing and data reduction, a description of the equipment utilized in this study is offered.

3.1 EQUIPMENT

A schematic of the wind tunnel equipment is displayed in Figure (3.1). Pressure signals were transmitted from the Pitot tube and static pressure taps in the wind tunnel through Tygon tubing to the boundary layer and reference pressure transducers. The transducers were connected to the computer through a Sciometrics Labmate Data Acquisition box. Two manometers were connected in parallel to the transducers for daily calibrations and confirmation of velocity profiles. The traversing gear stepper motor was connected to the computer through an interpreter unit and coordinated with the transducers to move the boundary layer Pitot tube vertically between pressure measurements.

3.1.1 Wind Tunnel

The plate correlation curves were developed from the boundary layer analyses of the plates within the 0.5×0.7 metre test section of a closed circuit wind tunnel at Carleton University (Figs. 3.2 and 3.3). Powered by a 44.76 kW induction motor, wind speeds up to 90 m/s (200 mph) were possible. The tunnel fan rotational velocity was controlled by a magnetic clutch with 3% slip. A breather vent located at the end of the test section maintained atmospheric pressure within the tunnel. The test section floor was constructed of Aluminum, providing a smooth surface suitable for boundary layer analyses. The plates spanned the tunnel floor and were fixed in place with floor tape and two screws, offset 27 cm from the centreline. Since increasing degrees of damage to the aircraft can require thicker patches, six plates of thicknesses 12.7 mm ($\frac{1}{2}$ in), 9.525 mm ($\frac{3}{8}$ in), 6.35 mm ($\frac{1}{4}$ in), 3.175 mm ($\frac{1}{8}$ in), 1.5875 mm ($\frac{1}{16}$ in), and

Figure 3.1 Wind Tunnel Apparatus Schematic

Figure 3.2 Carleton University Circuit Wind Tunnel

Figure 3.3 Wind Tunnel Test Section

0.79375 mm ($\frac{1}{32}$ in) were tested. Each plate was tested twice; once with 45° plasticine fillets at the leading and trailing edges and once without the fillets. The longitudinal dimensions of the plates were of sufficient length to allow the boundary layer to make an approximate recovery from the effects of the plate leading edge before reaching the trailing edge. It was determined from the literature search that the distance should be at least 36 plate thicknesses or step heights. This coordinated well with the test section since data could be taken 20 step heights upstream and downstream of the largest plate without influence from the nozzle or the breathing vent.

3.1.2 Pitot Tube and Traversing Gear

Data were obtained with a Pitot tube supported by a traversing gear capable of providing longitudinal and vertical motion (Fig. 3.4). The vertical motion was computer controlled by means of a stepper motor. The motor was connected to the printer port of a microcomputer and drove a Brass worm screw (20 threads/inch) threaded through a platform upon which the Pitot tube was clamped. Two aluminum, 12.7 mm diameter rods provided guidance and strong support to counter any oscillations that the Pitot tube and platform might have experienced. An interpreter unit, connected between the computer and the stepper motor, integrated binary signals from the computer and directed the motor accordingly. Calibration of the stepper motor was accomplished with a depth dial meter accurate to 0.01 mm. It was found that an accuracy of 0.1 mm could be achieved over a traverse distance of 70 mm by the Pitot tube.

Since the accuracy of the longitudinal positioning of the Pitot tube was not as critical as the vertical positioning, longitudinal movement was done manually. Mounted on top of the test section, a sled and rail system supported the Pitot tube / traversing gear assembly (Figs. 3.4 and 3.5). The rails were approximately 1.2 metres long and

Figure 3.4 Traversing Gear Assembly

Figure 3.5 Traversing Gear Track

were held to the test section roof by wood screws. Four arms, each extending from a corner of the sled and around a rail, formed clasps that guided the sled, traversing gear, and Pitot tube assembly along the longitudinal axis. Once longitudinal positioning was achieved, set screws at the ends of the clasps clamped the sled and traversing gear to the rails and the test section. Centred between the rails, a 6.35 mm wide slot extending approximately 1 metre was cut into the test section ceiling to allow longitudinal passage of the Pitot tube. To minimize any test section flow disturbances that may have resulted from the slot, a 26 mm wide Lexan strip was inserted into the test section ceiling to seal off the portion of the slot unoccupied by the Pitot tube. The strip was free to slide with the Pitot tube and was guided upward over obstacles at both ends of the test section by ramps.

In order to reach the plates, the Pitot tube had to extend the height of the test section and be strong enough to resist drag related flexure. Most of its length consisted of 6.35 mm outer diameter steel tubing reinforced with a 12.7 mm (Fig. 3.6) wide steel spine. Pressure-fitted into the end of the steel tube, 2.5 mm outer diameter brass tubing extended 100 mm vertically and 7 mm longitudinally, tapering to a flattened opening. The opening measured 0.51 mm high by 1.2 mm wide and was sanded and polished to minimize the frontal area of the Pitot tube mouth.

During testing, the reinforced steel rod limited the longitudinal deflection of the tube opening to approximately 1 mm. Unfortunately, the cross sectional shape generated enough lateral lift to oscillate the Pitot tube and flex the ceiling of test section. This problem was corrected with the addition of a stabilizer, capable of providing aerodynamic lateral dampening. Also, plasticine was moulded around the steel spine to streamline the cross-section and reduce drag.

Figure 3.6 Pitot Tube

Figure 3.7 Pressure Transducers and Manometer

3.1.3 Data Acquisition

Boundary layer velocities were determined from dynamic pressure values, taken as the difference between the reading of the Pitot tube (P_{T1}), described above, and the static pressure measured at taps in the test section ceiling. The static taps (Fig. 3.5) were longitudinally spaced 150 mm apart to ensure that two taps would be in close proximity to the Pitot tube position throughout the test section. Boundary layer velocity profiles taken between the taps required pneumatic averaging whereby two taps spanning the Pitot tube position were linked at a T-intersection to produce a single averaged pressure signal (P_{S2}). In order to account for the wind tunnel velocity drift, a reference velocity was incorporated into the data reduction routine. This was determined from the difference of two static pressure taps located in the wall of the tunnel contraction; one at the inlet (P_{R1}) and the other at the outlet (P_{R2}).

Two Setra pressure transducers with a range of ± 690 Pascals (± 0.1 psid) and an accuracy of $\pm 0.1\%$ full scale were used to measure the boundary layer and reference velocities. Prior to testing, the transducers were refurbished by the manufacturer so that the nonlinearity of the calibration curves was no greater than $\pm 0.1\%$ full scale. The maximum output voltage was ± 2.5 volts but typical output ranged from 0 to 0.8 volts during testing. To permit daily calibration, two vertical manometers containing fluid with a specific gravity of 1.0 were connected in parallel to the transducers (Fig. 3.7). The drift of the transducer calibration lines were found to be very small and could be attributed to human error in reading the manometers (± 0.5 mm).

The pressure transducer outputs were connected to a Sciometrics Labmate Data Acquisition box for 12 bit A/D conversion (Fig 3.8). Channels 1 and 2 were set up to accept a full range of ± 5 volts with unity gain, an accuracy of 12 millivolts, and a sampling period of about 1 second. Channel 4 was short-circuited for purposes of auto-zeroing. Its voltage was automatically measured and subtracted from the other

Figure 3.8 Electronic Apparatus

Figure 3.9 Data Acquisition Software Schematic

channels to account for any drift. Also, the channel voltages were periodically checked with a voltmeter.

3.2 WIND TUNNEL TESTING

To cover a full range of patch configurations and conditions to which they might be subjected, a test matrix was created consisting of five variables: patch thickness, fillet angle, air flow velocity or Reynolds number, initial ($10h$ upstream of plate leading edge) boundary layer thickness or momentum thickness, and sampling position on the patch. Testing was performed on six different patches with thicknesses commonly used on the CF 18 wing (See Section 3.1.1). Each plate was configured with two fillet angles of 90° and 45° with the reasoning that this would be sufficient to establish any trends associated with the fillet angle. To increase the range of $\frac{\theta}{h}$ experienced by the plates, they were subjected to two boundary layers with different thicknesses. The first boundary layer was unaltered and ‘naturally’ generated by the test section with an initial (no plate) momentum thickness of $\theta_r = 1.25$ mm, a shape factor of $H_r = 1.28$, and $Re_\theta = 3311$. The second boundary layer was thickened by a 23 cm wide strip of coarse, 50 grit, sandpaper taped to the floor at the nozzle exit. This served to increase the momentum thickness to 2.15 mm ($Re_\theta = 5563$) without an appreciable change to the shape factor ($H_r = 1.27$). Finally, four Pitot tube / traversing gear positions, located upstream and downstream of the plate leading and trailing edges, were chosen for data collection (Appendix 1). The upstream positions had to be located beyond the influence of the step formed by the edges of the plate. From the literature search, this was determined to be $10h$ for the leading edge and $6h$ for the trailing edge. The downstream positions had to be sufficiently far from the step that the boundary layer had approximately returned to equilibrium. Again, the literature search revealed that $30h$ was appropriate for the leading edge and $18h$ for the trailing edge. An alternative method involved measuring the boundary layer

parameters at several stations upstream and downstream from the edges of the plate and then extrapolating the data to determine the effect of the plate on the boundary layer directly at its edges. Unfortunately, the extra Pitot tube traverses would have exceeded the time constraint for the project.

The data requirements called for a total of 96 boundary layer traverses. To ensure that the accumulation of data did not become overwhelming, a hierarchy of programs (Fig. 3.9) was created to control the experiment, reduce the data into a useful form, and keep track of the data files. The three main units of software were the Traversing program, the Calibration program, and the Profile program. The listings of these programs appear in Appendix 2. The programs are described here by outlining the data flow.

3.2.1 The Traversing Program

The Traversing program controlled the movement of the Pitot tube and the input of raw voltage (pressure) data from the boundary layer and reference transducers. The sequence of control basically involved reading pressure voltages from two channels in the Sciometrics A/D unit into an array and stepping the Pitot tube to the next position in the boundary layer. The programming language, Basic, allowed easy control of the stepper motor with single statements that sent binary signals to the motor via the parallel port and the D/A control unit. One signal or step rotated the motor and worm screw 1.69° and moved the Pitot tube vertically about 0.006 mm. Thus, a vertical traverse of 1 mm required 168 steps and a motor rotation of 283.3° . Due to the high curvature of the boundary layer velocity profile near the wall, the initial Pitot tube step distance was very small (0.1 mm) and increased by a factor of 1.2 every step or measurement. After a traverse distance of about 68 mm, the Pitot

tube was well into the freestream flow where the velocity gradient was close to zero and the step size had increased to 11.4 mm.

It should be noted that the Pitot tube was resting on the wind tunnel floor when located at the initial traverse position. This was considered to be $y = 0.254$ mm (the position of the stagnation point at the Pitot tube inlet) where velocities approximately equal to $U_{\infty}^2 = 0.6$ were obtained. The displacement effect of the streamlines and movement of the stagnation point on the Pitot tube within the vicinity of the wall was not accounted for in the data reduction calculations due to the small size of the Pitot tube opening and the fact that most of the influence of this effect cancels out with the calculation of $\Delta\theta$ and ΔH .

Each measured voltage represents the average of eight samples or 1 second sample time. It was found from repeatability tests that this sampling time window sufficiently reduced the influence of random fluctuating patterns and provided consistent results. To minimize the error introduced by transducer zero drift, the initial, zero pressure, voltages were recorded before each traverse and subtracted off of the subsequent average values during the traverse. Once the traverse was completed, the pressure voltages were stored into files in the data reduction directory. It was decided to separate the data reduction routine from the Traversing program to preserve the raw tunnel data should any errors in the data analysis become obvious at a later time. Also stored within the files are the atmospheric conditions, initial transducer voltages and a short description of the test run configuration (See Appendix 2 for sample output).

The Traversing program was also used to gather transducer calibration data. During this mode of operation, the Pitot tube was positioned in the freestream flow and the wind tunnel velocity was varied. For each speed setting, the pressure voltages from the transducers were accepted and the user was prompted to enter the fluid heights from

the manometers connected in parallel with the transducers. Once the pressure range of 0 to 2000 Pascals was covered, the data were stored in the Calibration directory for curve fitting. A calibration run was performed at the beginning of each day of testing to monitor any transducer drift and eliminate its effects on the results.

3.2.2 The Calibration Program

The Calibration program accepted the transducer / manometer data from the Traversing program, calculated a polynomial curve fit, and sent the polynomial coefficients to a file in the data reduction directory for reference by the Profile program. The polynomial curve fit coefficients were calculated using the method of least squares (Hornbeck, 1985). The resulting matrix was solved for the polynomial coefficients using Gauss-Jordan elimination. It was found that a linear curve fit served quite well for both the boundary layer and reference transducers (Fig. 3.10). To provide visual confirmation of an accurate fit, the manometer calibration data was automatically plotted with the calibration curves. Calibration curves from previous days' work could be included on this plot, as well, for quick confirmation of any transducer drift. Despite the efforts to guard against transducer drift throughout the tunnel testing, no appreciable amount of drift was ever detected and the calibration curves did not vary beyond $\pm 1.2\%$ of the values presented in Figure (3.10).

3.2.3 The Profile Program

The Profile program was responsible for the calculation of the non-dimensional velocity profiles and the boundary layer parameters. Upon accepting the pressure voltage data from the Traverse program and the polynomial calibration curve coefficients from the Calibration program, the voltages were converted to Pitot tube pressures in a routine utilizing the polynomial coefficients. A simple reduction of the Bernoulli

Figure 3.10 PRESSURE TRANSDUCER
CALIBRATION CURVES

equation provided the relation (Eq. 3.1) between the boundary layer velocity and the dynamic pressure, where $P_{DYN} = P_{T1} - P_{S2}$. The free stream velocity, U_∞ , is also determined from this equation.

$$U_{BL}^2 = \frac{2P_{DYN}}{\rho} \quad (3.1)$$

The wind tunnel calibration relation can be written as

$$U_{REF}^2 = \frac{2P_{REF}}{0.91\rho} \quad (3.2)$$

where $P_{REF} = P_{R1} - P_{R2}$. As mentioned earlier, in order to eliminate the effects of tunnel velocity and transducer sensitivity drift, each boundary layer and free stream measurement was divided by the simultaneously measured reference velocity according to Equation (3.3).

$$\frac{u}{U_\infty} = \frac{\left(\frac{U_{BL}}{U_{REF}}\right)}{\left(\frac{U_\infty}{(U_{REF})_\infty}\right)} \quad (3.3)$$

Determination of the boundary layer velocity profile and the boundary layer profile parameters was a process involving several cycles. Starting from the floor position, the velocity profile is initially calculated using a free stream velocity, U_∞ , measured as far away from the tunnel floor as the traversing apparatus could contract. A running average of the past three velocity points is maintained until the change in averages is less than 0.15 m/s at the edge of the boundary layer. The last calculated average is then used as the free stream velocity in a secondary velocity profile calculation. Since the boundary layer thickness is defined as the vertical position where $u = 0.995U_\infty$ (Young, 1989), a least-squares curve fit interpolation was applied to five velocity points below the position where the freestream velocity was determined. The vertical distance to the position of $0.995U_\infty$ was defined as δ . The calculation of δ^* and θ was

performed using trapezoidal integration on Equations (3.4) and (3.5).

$$\delta^* = \int_0^{\delta} \left(1 - \frac{u}{U_{\infty}}\right) dy \quad (3.4)$$

$$\theta = \int_0^{\delta} \frac{u}{U_{\infty}} \left(1 - \frac{u}{U_{\infty}}\right) dy \quad (3.5)$$

Head's shape parameter (Head, 1958) and the shape factor were simply calculated from $H(\delta^*) = \frac{\delta - \delta^*}{\delta^*}$ and $H = \frac{\delta^*}{\theta}$, respectively.

Trapezoidal integration gave satisfactory accuracy because the number of data points for each velocity profile was large: typically about 23 points. Since the traverse position nearest the wind tunnel floor ($y = 0.254$ mm) provided velocities around $\frac{u}{U_{\infty}} = 0.6$, a straight line from $y = 0$ mm and $\frac{u}{U_{\infty}} = 0$ (no slip condition), associated with trapezoidal integration, was assumed. Fortunately, due to the small vertical distance between the two points relative to δ , the resulting error in calculating δ^* , θ , and H was only about 3.5%, 2.3%, and 6%, respectively.

The most challenging part in the development this computer package was coding the routine that determined where the edge of the boundary layer was located. Despite this, the software provided satisfactory nondimensional velocity profiles that were accurately comparable with profiles measured simultaneously with a manometer (See Fig. 4.1 in Section 4.1). Each velocity profile was automatically plotted to provide visual confirmation of a satisfactory result. The results were then stored in plotting and text files for later reference.

4.0 EXPERIMENTAL ANALYSIS

The boundary layer momentum thickness increase ($\Delta\theta$) was nondimensionalized by the plate thickness and plotted as $\frac{\Delta\theta}{h}$ versus $\frac{h}{x_1}$. The shape factor increase (ΔH) was also plotted versus $\frac{h}{x_1}$. The plots, displayed in Figures (4.5) to (4.8), were intended to relate the boundary layer parameters to their values upstream of the plate step. All the plots exhibited some scatter from which three patterns have been identified.

- 1) At low values of $\frac{h}{x_1}$, the scatter had a tendency to increase. The small scale of the plate thickness and resulting flow patterns created a sensitizing effect in the data reduction calculations that amplified any errors associated with random flow effects and measurement inaccuracies.
- 2) The non-chamfered plate data had more scatter than the chamfered plate data. This is probably due to an extra degree of unsteadiness of flow patterns generated by the protruding upper corner of this plate configuration.
- 3) The scatter was greater for the trailing edge data than for the leading edge data. The literature search revealed that most researchers experienced a backward facing step separation bubble that fluctuated in size and created a certain amount of scatter in their data.

Despite the scattered nature of the data, it was found from repeatability tests that the curves are consistent to within $\Delta H = \pm 0.01$ and $\frac{\Delta\theta}{h} = \pm 0.03$. The boundary layer data received from the wind tunnel testing of the plates and used to create Figures (4.5) to (4.8) is listed in Appendix 1 along with the curve fit polynomials. Much effort was expended on verifying that the boundary layer information received from the tunnel testing was legitimate. An account of these efforts is made here.

4.1 VERIFICATION of EXPERIMENTAL RESULTS

During the development of the Profile program, the calculated transducer velocity profiles were frequently plotted against profiles, measured simultaneously, with a manometer. The initial success of the software and the tunnel equipment was ascertained by the agreement between the two profiles. Figure (4.1), a plot of one of the final comparisons, shows that the transducer / computer profile traces the manometer profile with an accuracy of $\pm 1.6\%$. The error associated with the straight line assumption between $\frac{y}{\delta} = 0$, $\frac{u}{U_\infty} = 0$ and the first profile point is discussed in Section 3.2.3. Several velocity profiles were taken along the test section floor to determine the distribution of the boundary layer parameters and local skin friction coefficient (Fig. 4.2). As expected for a smooth surface, the skin friction coefficients were near 0.0034 and had a tendency to decrease as the boundary layer thickness increased from 15 to 30 mm.

Utilizing the Law of the Wall

$$\frac{u}{u_\tau} = A \log\left(\frac{u_\tau}{U_\infty} \frac{U_\infty y}{\nu}\right) + B \quad (4.1)$$

one can create a Clauser chart to check the accuracy of measured velocity profiles against a well established standard. Substituting, $A = 4.9$, $B = 5.6$, (Clauser, 1954) and $\frac{u_\tau}{U_\infty} = \sqrt{\frac{C_f}{2}}$ into Equation (4.1) gives the general formula for the chart.

$$\frac{u}{U_\infty} = 4.9 \log\left(\sqrt{\frac{C_f}{2}} \frac{U_\infty y}{\nu}\right) + 5.6 \quad (4.2)$$

When the test section velocity profiles, mentioned above, were plotted on a Clauser chart (Fig. 4.3), a slight deviation from Clauser's results was observed very close to the tunnel floor. Despite this, the profiles were found to correlate accurately with the lines of Equation (4.2) within the typical range $0.7 \leq \frac{u}{U_\infty} \leq 0.9$.

During the wind tunnel testing of the plates, data for both the shape factor, H , and Head's shape factor, H_{Head} , were gathered for use in the STAMP program. According

Figure 4.1 PRESSURE TRANSDUCER/
MANOMETER VELOCITY
PROFILES

Figure 4.2 TEST SECTION FLOOR SKIN
FRICTION DISTRIBUTION

Figure 4.3 Clauser Chart

Figure 4.4 HEAD'S SMOOTH SURFACE SHAPE
PARAMETER, $H_{\delta-\delta'}$, vs. SHAPE
FACTOR, H

to Head (1958), the relation between the two shape factors for smooth surfaces is described by $H(\infty) \sim G(H)$ where the function $G(H)$ is displayed in Figure (4.10). The data gathered during the wind tunnel testing fell on the plot near the upper limit of $H(\infty)$ and were found to agree with the function G . Thus, Dvorak's relation could continue to be used in the STAMP package.

4.2 DISCUSSION of EXPERIMENTAL RESULTS

The leading edge of the plate produced a positive momentum thickness increment, $\Delta \theta^+$ (Fig. 4.5). For thin plates, the increment was small and increased rapidly with $\frac{h}{x_1}$ as the upper surface of the step protruded further into regions of greater velocity within the boundary layer, enhancing the upper separation bubble. When the upper step surface reached the outer region of the boundary layer ($\frac{h}{x_1} \sim 10$) where the velocity gradient $\frac{\partial u}{\partial y}$ was not as large, the upper separation bubble began to stabilize in size and $\Delta \theta^+$ levelled off. The addition of a fillet to the leading edge lessened the severity of the pressure gradients resulting in a smaller upper separation bubble. Thus, the chamfered plates generally experienced smaller momentum thickness increments at their leading edge.

For the trailing edge of the plate, the momentum thickness increment response was quite different (Fig. 4.7). Starting at a high value near the low end of $\frac{h}{x_1}$, the increment demonstrated a weak inverse dependency on $\frac{h}{x_1}$. Unlike the leading edge, the size of the separation bubble most likely maintained pace with the step size. Thus, the non-dimensional momentum thickness increment was approximately constant throughout the range of step heights. The slightly negative slope of the function could possibly be a result of history effects in the boundary layer left over from the leading edge. Although the plates were of sufficient length to isolate most of the effects of the leading edge from the trailing edge, it is known from the literature search that turbulent eddies

Figure 4.5 $\Delta\theta/h$ versus h/θ_1
Leading Edge

Figure 4.6 ΔH versus h/θ_1
Leading Edge

Figure 4.7 $\Delta\theta/h$ versus h/θ_1
Trailing Edge

$\Delta\theta$

Figure 4.8 ΔH versus h/θ_1
Trailing Edge

ΔH

can persist far downstream. Therefore, it is possible that the leading edge of a thick plate, generating larger scale turbulence and a larger value of $\frac{\Delta x}{h}$ than a thin plate, could leave the boundary layer in a state such that the momentum thickness would be less susceptible to the effects of the trailing edge, relative to h . Interaction effects may also have played a role for plates with fillets which streamlined the leading edge and reduced its impact on $\frac{\Delta x}{h}$, allowing the trailing edge to have a greater effect. Hence, $\frac{\Delta x}{h}$ at the trailing edge was greater for plates with fillets. It should be noted that this was a minor tendency relative to the influence of the separation bubble.

The plates had little effect on the shape factor (Figs. 4.6 and 4.8), and produced increments within $\Delta H = \pm 0.07$. For the leading edge of a thin plate, the shape factor increment increased to reach a maximum near the same position ($\frac{h}{x_1} \simeq 1.0$) as that where the size of the separation bubble stabilized and $\frac{\Delta x}{h}$ began to level out. Larger values of $\frac{h}{x_1}$ saw a drop in the shape factor increment to negative values. The negative values were double checked and retested but were still found to be within $\Delta H = \pm 0.01$. It is possible that as the disturbed boundary layer developed over the upper surface of a thick plate, it contained larger scale turbulence than normal, giving rise to a thicker, fuller velocity profile and reduced shape factor. The addition of a fillet produced a similar curve with smaller increments for the thinner plates and larger increments for the thicker plates. The reduction of the increment for thin plates can be attributed to the smaller size of the upper separation bubble but the larger increment for the thick plates may be a result of suppressed turbulence and reduced entrainment of high velocity flow into the boundary layer.

The response of the shape parameter at the trailing edge (Fig. 4.8) was again one that was inversely linked to $\frac{h}{x_1}$, with the chamfered plates having a greater effect. Although it is not fully understood why the shape parameter would decrease with increased $\frac{h}{x_1}$, it is possible that the large turbulent eddies created by a thick plate

increased the entrainment rate of high velocity freestream fluid into the boundary layer. This would have supplied the inner region of the boundary layer with sufficient energy to produce a fuller velocity profile with a smaller shape factor. This effect may be reduced by the fillets.

5.0 COMPUTER ANALYSIS

As mentioned in Section 3.0, the STAMP package was modified to accept the plate correlation curves, giving it the ability to analyse a wing profile with patches. The CF 18 wing profile was analysed with the leading edge of the patches positioned on the upper surface at $x_p = 0.03c$ and $0.5c$ where $c = 2.7746$ metres (at span station XW ≈ 3.69 metres) and $Re_c = 3 \times 10^7$. Several plate parameters, such as the chamfer angle ($\phi = 0^\circ, 45^\circ$) and the thickness ($h = 12.7, 6.35, \& 1.59$ mm), were varied but the longitudinal length of the patches was held at $0.1c$. The resulting lift coefficient data, C_L , were plotted against the wing angle of attack, α , along with a clean airfoil lift curve for comparison. Before proceeding with the discussion of results, a description of the STAMP software, along with the alterations made to accompany the plate correlation curves, is provided.

5.1 THE STAMP SOFTWARE

The STAMP package used source and vortex distributions from potential flow theory to model the flow around an airfoil profile. The contour of the airfoil was defined by a set of control points or panels. Initially, each panel had only a vortex strength that introduced a disturbance velocity into the flow field, establishing a relation for each panel. Since fluid could not pass through the wing surface, each plate was subjected to the local boundary condition that the normal flow velocity was zero. Another condition, that established the last equation, was the Kutta condition which required equal flow velocities off the upper and lower trailing edge surfaces. This set of equations was solved simultaneously for the vortex strengths. Based on the velocity distribution determined from these calculations, the airfoil boundary layer parameters were calculated along with the position of the separation points.

The Boundary Layer Analysis Program II (BLAP2), mentioned in Section 3.0, utilized momentum integral methods. Thwaites' method (Thwaite, 1949) was used to determine the laminar boundary layer parameters and provided the condition for laminar separation: when the momentum thickness variable, λ , equalled -0.09 . The turbulent boundary layer was modelled by Dvorak's method (Dvorak, 1969) which integrated the momentum integral equation simultaneously with Head's entrainment rate equation (Head, 1958) and the relation $H_{\delta^*}/\delta^* = G(H)$ (See Fig. 4.4) to obtain the boundary layer parameters. Turbulent separation was predicted when the shape factor exceeded 3.0. Transition to a turbulent boundary layer on the upper surface of the airfoil was predicted by the H-Rx (Wazzan et al, 1981) method or was forced at the suction peak. The distance to transition on the lower surface from the stagnation point was entered by the user. These calculations established a distribution of sources at the control points to displace the free stream flow away from the airfoil surface and model the boundary layer displacement effects.

A second set of airfoil calculations, using the source distribution from the boundary layer computations and the vortex strength distribution from the initial airfoil calculations, accounted for the boundary layer and the wake to obtain a new, more accurate, vortex strength distribution. Based on the new potential flow parameters, the airfoil lift performance curve could be calculated. The separation wake was modelled by a set of vortex panels that were aligned along the wake streamline. The vortex strengths were equal to the separation point vortex strength and the wake panels were subjected to a zero normal velocity condition. The airfoil and wake vortex strengths were solved for simultaneously during the second set of calculations.

The alterations to the STAMP package involved modifying (BLAP2) to accept the plate correlation curves (Appendix 1) and information concerning the configuration

of the plate or patch on the wing profile. Inserted into the data initialization subroutine of BLAP2 is coding (See Appendix 2) that prompted the user for 45° fillets, the patch thickness, and the chord position of the patch leading and trailing edges. This information was referenced by the boundary layer calculation algorithm so that it initiated the appropriate plate correlation curves at the proper chord position and determined the influence of the plate on the boundary layer. The algorithm could access four sets of plate correlation curves that modelled the chamfered and unchamfered leading and trailing edges of the patch. The added airfoil thickness or 'bump' due to the presence of the patch was not taken into account; other than its effect on the boundary layer parameters. The resulting sudden pressure perturbation would have created difficulties in the functioning of the BLAP2 program.

The STAMP package is essentially a collection of batch programs capable of analysing the following multiple flow types over two dimensional airfoils: inviscid attached flow, inviscid separated flow, viscous attached flow, and viscous separated flow. The type of flow dictates the sequence of batch programs used in the analysis. Since the CF-18 wing profile demonstrated leading edge stall, according to the STAMP software, the viscous attached flow type was used mostly throughout this study. The order of the programs required to complete an analysis of an airfoil with this flow type is listed below.

INIT1: The user is prompted for the flow configuration parameters such as the airfoil control points, angle of attack, and flow type. Various flags and data files are initialized based on this input.

STAMPLOT: An inviscid analysis on the airfoil determines the vortex strength distribution and creates a data file (BLAPIN.DAT) containing the velocity distribution for the boundary layer analysis.

BLAP2: Taking into account the possibility of turbulent transition and separation, the Boundary Layer Analysis Program starts with a laminar boundary layer at the leading edge stagnation point and calculates the boundary layer parameters using Thwaites' method and Dvorak's method. This program was modified to use the plate correlation curves and calculate the effect of the patches on the boundary layer. Based on the boundary layer displacement effects, a source distribution is calculated and stored in a file (BLAPOUT.DAT) for use in the second viscous pass of STAMPLOT.

CHANGE: Various flags are reset to re-initiate STAMPLOT for a viscous analysis.

COMMUNE: If separation occurs, as determined by BLAP2, the upper and/or lower surface separation points are aligned with the nearest control points and stored in the airfoil data file.

IWMP: If separation occurs, a set of vortex panels are used to model the wake streamlines from the points of separation. The coordinates of the wake streamlines are stored in a file for reference during the second analysis by STAMPLOT.

STAMPLOT (2nd pass): Accepting the source distribution from BLAP2, another potential flow analysis determines a new vortex strength distribution. This distribution is more accurate since it represents the viscous effects of the boundary layer and, if separation occurs, a separation region.

It was suggested that airfoils analysed by the STAMP software have a thickness to chord ratio greater than 0.15 to ensure that the sources and vortices on the upper and lower panels didn't give rise to numerical difficulty due to interference with each other. Despite this and the CF-18 airfoil thickness to chord ratio of only 0.025, no oscillations in the source and vortex distributions, typical of interference effects, was evident.

5.2 DISCUSSION of COMPUTATIONAL RESULTS

The lift performance curves for the CF-18 wing profile are displayed in Figures (5.1) to (5.4) and represent the results of a viscous analysis by the STAMP software. They are plotted from $\alpha = 1^\circ$ to 3.9° . The boundary layer remains attached throughout this range of angles until $\alpha = 4^\circ$, at which point leading edge turbulent separation occurs. The viscous, separated analysis ($\alpha \geq 4^\circ$) by STAMP produced unrealistic results (negative C_L) and are not shown but it is assumed that severe loss of lift occurs. Despite this, the viscous, attached results of the STAMP package was found to be within reasonably good agreement with results from VSAERO, another airflow analysis program capable of 3 - dimensional analysis of aircraft. Figure (5.5) displays the pressure distributions created by STAMP and VSAERO for the CF-18 wing at $C_L = 0.21$. The VSAERO pressure distribution, believed to be for a wing section close to the fuselage, is influenced by higher velocities because of the flow displacement effects around the fuselage. Since VSAERO can account for these effects, its pressure distribution has a negative pressure displacement from the STAMP pressure distribution.

The upper surface distributions of momentum thickness, shape factor, and the skin friction coefficient are plotted against the boundary layer distance, $\frac{x}{c}$, for $\alpha = 1^\circ$, 3° , and 3.9° (Figs. 5.6 to 5.8) and a 12.7 mm ($\frac{1}{2}$ inch) thick patch. From the leading edge stagnation point, the momentum thickness increased and experienced abrupt positive deviations from the clean airfoil θ curve when a patch surface discontinuity was encountered. Every increase in θ produced a corresponding decrease in the skin friction, C_f . An increase in θ , and the shear layer thickness, reduced the near - wall velocity gradient and the skin friction coefficient. Chamfering the edges of the patch reduced its impact on θ and C_f . As discovered during the development of the plate correlation curves (Chapter 4), the response of the shape factor could be positive or negative, depending on the condition of the boundary layer approaching the patch

Figure 5.1 C_L vs. ANGLE OF ATTACK, $\alpha = 90^\circ$
 $x_p = 0.03c$, $L = 0.1c$

Figure 5.2 C_L vs. ANGLE OF ATTACK, $\alpha = 45^\circ$
 $x_p = 0.03c$, $L = 0.1c$

Figure 5.3 C_L vs. ANGLE OF ATTACK, $\alpha = 90^\circ$
 $x_p = 0.5c$, $L = 0.1c$

Figure 5.4 C_L vs. ANGLE OF ATTACK, $\alpha = 45^\circ$
 $x_p = 0.5c$, $L = 0.1c$

Figure 5.5 VSAERO and STAMP Pressure Distributions for $C_L = 0.21$

Figure 5.7
MOMENTUM THICKNESS DISTRIBUTION
 $\alpha = 3^\circ$

SHAPE FACTOR DISTRIBUTION
 $\alpha = 3^\circ$

SURFACE FRICTION DISTRIBUTION
 $\alpha = 3^\circ$

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Figure 5.8
MOMENTUM THICKNESS DISTRIBUTION
 $\alpha = 3.9^\circ$

SHAPE FACTOR DISTRIBUTION
 $\alpha = 3.9^\circ$

SURFACE FRICTION DISTRIBUTION
 $\alpha = 3.9^\circ$

..... $\delta^+ = 10$
 - - - - - $\delta^+ = 5$
 $\delta^+ = 2$
 - - - - - $\delta^+ = 1$

..... $H = 10$
 - - - - - $H = 5$
 $H = 2$
 - - - - - $H = 1$

..... $C_f = 1.0$
 - - - - - $C_f = 0.5$
 $C_f = 0.2$
 - - - - - $C_f = 0.1$

leading edge. Sometimes the plate correlation curves produced a response that was counteracted or enhanced by the boundary layer calculation algorithm in BLAP2. For example at $\alpha = 3^\circ$, the H curve ($x_L = 0.03c$) experienced a negative response down to $H = 1.37$ by the plate correlation curve at the leading edge but the calculation algorithm accentuated this response down to $H = 1.29$. Further along the boundary layer, the patch leading edge at $x_p = 0.5c$ produced a positive response in H that was quickly reduced by the calculation algorithm, producing a spike in the distribution. In both cases, the chamfered plates induced greater reductions in H . As mentioned in Chapter 4, it is believed that the influence of the plates increased the rate of entrainment of high energy mainstream flow, creating a fuller boundary layer profile. Based on this argument, the entrainment rate of the chamfered patches must be greater than the unchamfered patches, resulting in a smaller shape factor.

The solid line of the lift performance curves (Figs. 5.1 to 5.4) represents the clean airfoil without any patches. The dashed lines are the lift curves for the airfoil with patches of various thicknesses positioned on the upper surface at $x_L = 0.03c$ and $0.5c$. These curves display a loss of lift,

$$\Delta C_L = C_{L, clean} - C_{L, patch}$$

from the clean airfoil curve that increases with plate thickness. This is to be expected since the leading edge of a thicker patch created a thicker boundary layer at the trailing edge that had a tendency to de-camber the airfoil. Below $\alpha = 2^\circ$, ΔC_L did not change significantly when the patch position was moved. The maximum loss of lift resulting from the 12.7 mm unchamfered patches was 0.031 and 0.046 at $x_p = 0.03c$ and $0.5c$, respectively. One might expect a greater loss of lift with a patch at $0.03c$, but the sharp leading edge of the CF-18 airfoil created a sharp suction peak at $0.00015c$ with an adverse pressure gradient that diminished almost to zero near $0.03c$ (Fig. 5.9). Also, at the lower angles of attack when the boundary layer thickness was not as

large, placing a patch as thick as 12.7 mm so close to the leading edge might have created more camber and reduced the C_L decrement. At higher angles this effect quickly disappeared as the boundary layer thickness increased relative to the patch thickness. At $\alpha = 3^\circ$, ΔC_L increased to 0.041 when the 12.7 mm. patch was at $x_p = 0.03c$ and decreased to 0.038 when the patch was at $x_p = 0.5c$.

The 45° fillets, added to the leading and trailing edges of the plates, didn't seem to have a large effect on the lift below $\alpha = 3^\circ$, despite their potential to reduce the boundary layer thickness. For the chamfered 12.7 mm plate at low α , ΔC_L was reduced to 0.026 and 0.041 for $x_p = 0.03$ and 0.5. At $\alpha = 3^\circ$, the $x_p = 0.03c$ loss of lift increased to 0.034 while the $x_p = 0.5c$ value decreased to 0.03. Again, this is probably due to the effect, discussed above, where the thicker plate at the leading edge increased the airfoil camber at the lower angles of attack.

One of the more prominent features of the lift performance curves was the deviation from linearity for $\alpha > 3^\circ$. During the first non-viscous analysis by the STAMPLOT program, a velocity distribution was created for the boundary layer analysis. Figure (5.10) displays the velocity distribution over the upper airfoil surface. As the angle of attack increased from 3.0° to 3.9° , the velocity at the lower trailing edge increased. Since the Kutta condition required that the flow velocities separating off the upper and lower trailing edges must be equal, the upper surface velocity experienced an increase near the trailing edge at $\alpha = 3.9^\circ$ (Fig. 5.10). After the viscous analysis, this velocity increase translated into an increase in the skin friction and a decrease in the momentum thickness and shape factor near the trailing edge (Fig. 5.8). These factors added up to a decrease in pressure on the upper surface (Fig 5.9) and a significant loss of lift despite the thinner trailing edge boundary layer. The unchamfered patch at $x_p = 0.03c$ displayed the most severe loss that decreased as the patch was moved

Figure 5.9
PRESSURE DISTRIBUTION
 $\alpha = 3^\circ$

PRESSURE DISTRIBUTION
 $\alpha = 3.9^\circ$

Figure 5.10 NON-VISCOUS VELOCITY
DISTRIBUTIONS
(Upper Surface)

$\frac{x_p}{c}$	h (mm)	ϕ (deg)	DRAG RATIO $C_{D_{patched}}/C_{D_{clean}}$			
			$\alpha = 1^\circ$	$\alpha = 2^\circ$	$\alpha = 3^\circ$	$\alpha = 3.9^\circ$
0.03	12.7	90	1.70	1.80	1.95	2.00
0.50	12.7	90	1.70	1.75	1.75	1.70
0.03	6.35	90	1.30	1.40	1.45	1.50
0.50	6.35	90	1.30	1.30	1.30	1.30
0.03	.063	90	1.08	1.10	1.10	1.13
0.50	.063	90	1.06	1.07	1.07	1.07
0.03	12.7	45	1.55	1.65	1.75	1.80
0.50	12.7	45	1.55	1.60	1.60	1.55
0.03	6.35	45	1.25	1.30	1.35	1.40
0.50	6.35	45	1.25	1.25	1.25	1.25
0.03	.063	45	1.07	1.08	1.10	1.10
0.50	.063	45	1.06	1.06	1.07	1.06

Table 5.1 Ratio of Drag With the Patch to Drag Without the Patch

CF-18 profile : $c = 2.77$ metres ; $L = 0.1c$

further aft to $x_p = 0.5c$. The addition of fillets to the patches at either position served to reduce ΔC_L .

If the flow remains attached and the static pressure is close to the freestream static pressure at the trailing edge, Squire and Young (Abbott and Van Doenhoff, 1959) state that the profile drag coefficient, C_D , is directly proportional to the total momentum thickness ($\theta_{upper} + \theta_{lower}$) at the trailing edge. Table 5.1 lists the ratios of drag with patches to drag without patches, $C_{D_{patched}}/C_{D_{clean}}$, which are based on an evaluation of $\theta_{upper} + \theta_{lower}$. The 12.7 mm patch generated the largest trailing edge values of momentum thickness and represented the worst case scenario in terms of drag production. For $\alpha = 2^\circ$ to 3.9° , unchamfered patches located closer to the leading edge increased the momentum thickness and C_D . This trend is weak at lower angles of attack ($\alpha = 1^\circ$) where patches located further aft near the maximum airfoil thickness were more exposed to the freestream and produced more drag. Chamfering the patches reduces the drag significantly for $\alpha > 1^\circ$ and less so at $\alpha = 1^\circ$.

In summary, the patches do not have an extreme effect on the lift performance curve at angles of attack $\alpha \leq 3^\circ$. Plate thicknesses up to $\frac{1}{2}$ inch produced losses of lift up to about $\Delta C_L = 0.01$. Due to the quick pressure recovery from the suction peak, movement of the patches aftward had a lesser effect on ΔC_L over the same range of α . The addition of fillets to the patch leading and trailing edges had little effect on ΔC_L as well. The influence of the patches on the airfoil drag was much greater, doubling the clean airfoil C_D in the worst cases. Movement of the patches further aft and / or chamfering also had a greater effect on decreasing the drag for $\alpha > 1^\circ$. Aftward patch movement had lesser effect for smaller angles of attack. For $\alpha > 3^\circ$, the influence of the Kutta condition increased the upper surface flow velocity near the trailing edge, decreasing the boundary layer thickness and increasing pressure. This resulted in a large loss of lift that was enhanced by movement of the patch upstream and/or unchamfered patches.

6.0 CONCLUSIONS

The wind tunnel testing of the plates revealed that the momentum thickness increased over the plates. The leading edge of the plates produced a positive momentum thickness increment, $\frac{\Delta\theta}{h}$, that increased rapidly for low $\frac{h}{\sigma_1}$ and levelled off at $\frac{h}{\sigma_1} \sim 1.0$ as the protruding corner penetrated the outer region of the boundary layer. The addition of a fillet streamlined the leading edge and lessened the momentum thickness increment. For the trailing edge of the plate, $\frac{\Delta\theta}{h}$ demonstrated a weak inverse dependency on $\frac{h}{\sigma_1}$. Chamfering the plate generally increased $\frac{\Delta\theta}{h}$ at the trailing edge. This was possibly a result of the streamlining effects at the leading edge that allowed the trailing edge to have a greater effect.

The plates had little effect on the shape factor and produced increments within $\Delta H \pm 0.07$. Larger values of $\frac{h}{\sigma_1}$ saw a drop in the shape factor increment to negative values which was probably due to a larger entrainment rate of high energy freestream flow creating a fuller boundary layer profile. Chamfering produced a similar curve with smaller increments for the thinner plates and larger increments for the thicker plates. The response of the shape parameter at the trailing edge was inversely proportional to $\frac{h}{\sigma_1}$, with the chamfered plates having a greater effect. Again, it is believed that the decrease in H with plate thickness and removal of fillets is linked to a higher entrainment rate of freestream flow due to larger turbulent eddies.

The STAMP package computational analysis of the CF-18 wing with patches revealed that the boundary layer remains attached until $\alpha > 3.9^\circ$, at which point turbulent separation occurs very near to the leading edge. For α values below separation, the patches increased the momentum thickness which tended to de-camber the airfoil resulting in a loss of lift. The patch thickness was the most influential parameter on the aerodynamics of the CF-18 airfoil. For $\alpha \leq 3^\circ$ and 12.7 mm thick plates, the

decrease in lift was moderate with maximum values of $\Delta C_L = 0.04$. For $\alpha > 3^\circ$, the loss of lift can be as large as 0.21.

The sharp leading edge of the CF-18 airfoil creates a sharp suction peak at $0.00015c$ with an adverse pressure gradient that diminishes almost to zero near $0.03c$. Due to the quick pressure recovery from the suction peak, the addition of the patches at chord positions $0.03c$ and $0.5c$ did not affect the angle of attack at which the boundary layer separated. For $\alpha = 1^\circ$ to 3° , movement of the patches between these positions had little effect on ΔC_L but for $\alpha > 3^\circ$, movement of the plate from $0.03c$ to $0.5c$ produced significant reductions in ΔC_L . Similarly, the addition of fillets to the patch leading and trailing edges had little effect on ΔC_L for $\alpha = 1^\circ$ to 3° and reduced ΔC_L significantly for $\alpha > 3^\circ$.

Based on an evaluation of the momentum thickness at the trailing edge, the drag coefficient can double with the addition of a 12.7 mm plate to a clean airfoil. Aftward movement of the patch and/or chamfering produced significant decreases in ΔC_D for $\alpha = 3^\circ$. As α decreased to 1° the effect of chamfering on ΔC_D is reduced. Decreasing α also reduced, and reversed, the influence of moving the patch aftward from the leading edge.

7.0 RECOMMENDATIONS

Further 3-dimensional study of wing patches is required to fully investigate their influence on the aerodynamics of the CF-18. Also, further study is needed to determine the influence of the patches on the fuselage and stabilizers. Since the cost of wind tunnel testing a model is tremendous, it is recommended that a 3-dimensional computer analysis program provide the basis for the study. If the results warrant more analysis, then wind tunnel testing would be the final option.

8.0 REFERENCES

- Baton, A. (1987) *Flow Field and Heat Transfer Associated With a Forward Facing Step*. Drexel University Ph.D. Thesis.
- Bradshaw, P. (1966) *Step-Induced Separation of a Turbulent Boundary Layer in Incompressible Flow*. Journal of Fluid Mechanics, Vol. 27, Part 1, pp. 111-130.
- Galwe, P.V. (1972) *The Reattachment and Relaxation of a Turbulent Shear Layer*. Journal of Fluid Mechanics, Vol. 52, Part 1, pp. 113 - 135.
- Bradshaw, P. (1957) *Investigation of Separated Flows in Supersonic and Subsonic Streams With Emphasis on the Effect of Transition*. NACA Technical Note 3869.
- Kuehn, D.M. (1969) *Calculation of Turbulent Boundary Layers on Rough Surfaces in Pressure Gradient*. AIAA Journal, Vol.7, No.9., pp. 1752 - 1759.
- Larson, H.K. (1990) *Canadian Forces Technical Order C - 12 - 188 - 000/MV - 000 DND Headquarters, Ottawa*. pp. 2-1 to 3-118.
- Chapman, D.R. (1984) *An Experimental Investigation of Subsonic Turbulent Boundary Layer Flow Over a Wide Reynolds Number Range*. NRC Report LTR-HA-5x5/0146.

- Eaton, J.K. (1980) *Turbulent Flow Reattachment: An Experimental Study of the Flow and Structure Behind a Backward Facing Step*. National Science Foundation, Stanford University, Report MD-39.
- Farabee, T.M. (1984) *Effects of Surface Irregularity on Turbulent Boundary Layer Wall Pressure Fluctuations*. Journal of Vibration, Acoustics, Stress, and Reliability in Design, Vol. 106, pp. 343 - 350.
- Head, M.R. (1958) *Entrainment in the Turbulent Boundary Layer*. Aeronautical Research Council, R. & M. 3152.
- Hornbeck, W.R. (1975) *Numerical Methods*. Prentice Hall.
- Hughs, D. (1990) *Canadians Develop Composite Techniques for CF-18 Battle Damage Repair Program*. Aviation Week and Space Technology, May 21/90, pp 106 - 109.
- Kim, J. (1978) *Investigation of Separation and Reattachment of a Turbulent Shear Layer: Flow Over a Backward Facing Step*. U.S. Air Force Office of Scientific Research, Stanford University, Mechanics Division, Report MD-37.
- Kline, S.J.
- Johnston, J.P.
- Lawrysyn, M.A. (1989) *Aerodynamic Characteristics of Frost Roughness*. M.Eng. Thesis, Department of Mechanical and Aerospace Engineering, Carleton U.

- Moss, W.D. (1980) *Re - Circulating Flows Associated With Two - Dimensional Steps*. Aeronautical Quarterly, No. 31, pp. 151 - 172.
- Baker, S.
- Narayanan, M.A. (1971) *Similarities in Pressure Distribution in Separated Flow Behind Backward-Facing Steps*. Aeronautical Quarterly, No. 25, pp. 305 - 312.
- Khadgi, V.N.
- Viswanath, P.R.
- O'Malley, K. (1991) *Models for High-Reynolds Number Flow Down a Step*. Journal of Fluid Mechanics, Vol. 222, pp. 139 - 155.
- Fitt, A.D.
- Jones, I.V.
- Ockendon, J.R.
- Rae, H.R.Jr. (1984) *Low-Speed Wind Tunnel Testing*. John Wiley and Sons.
- Pope, A.
- Schlichting, H. (1968) *Boundary Layer Theory*. McGraw-Hill Book Co.
- Iani, I. (1961) *Experimental Investigation of Flow Separation Associated With a Step or a Groove*. Aeronautical Research Institute, University of Tokyo, Report No. 364.
- Inchi, M.
- Komoda, H.
- Laulbee, D.B. (1969) *Turbulent Boundary Layer Separation Flow Ahead of a Step*. Developments in Mechanics, Vol. 5. Proceedings of the 11th Midwestern Mechanics Conference:10, pp. 1 -7.
- Robertson, J.M.
- Laulbee, D.B. (1971) *Turbulent Separation Analysis Ahead of a Step*. ASME Paper No. 71-WA FE-32.
- Robertson, J.M.

- Thwaite, B. (1949) *Approximate Calculation of the Laminar Boundary Layer*. Aeronautical Quarterly, Vol. 1, pp. 245 – 280.
- Wazzan, A.R. (1981) *H-Rx Method for Predicting Transition*. AIAA Journal (81-1140), Vol. 19, No. 6, pp. 810 – 812.
- Gazley, C.Jr. (1981-1140), Vol. 19, No. 6, pp. 810 – 812.
- Smith, A.M.O.
- White, F.M. (1974) *Viscous Fluid Flow*. McGraw-Hill Book Co.
- White, F.M. (1986) *Fluid Mechanics*, 2nd ed. McGraw-Hill Book Co.
- Young, A.D. (1981) *Aircraft Excrescence Drag*. AGARDograph 264.
- Paterson, J.H.
- Young, A.D. (1989) *Boundary Layers*. BSP Professional Books.
- Zukoski, E.E. (1967) *Turbulent Boundary Layer Separation in Front of a Forward Facing Step*. AIAA Journal, Vol. 5, No. 10, pp. 1746 – 1753.

APPENDIX 1

Plate Wind Tunnel Data

Polynomial Curve Fits of the Plate Wind Tunnel Results

Plate Wind Tunnel Data

h	ϕ	δ (mm)						θ (mm)						H					
		LE			TE			LE			TE			LE			TE		
		-10h	+30h	-6h	+18h	-10h	+30h	-6h	+18h	10h	+30h	-6h	+18h	-10h	+30h	-6h	+18h	-10h	+18h
1/2	90	15.0	38.9	38.9	41.7	1.75	4.81	4.81	6.12	1.29	3.69	3.69	4.69	1.34	1.30	1.30	1.31	1.30	1.31
5/8	90	15.3	32.4	32.4	45.4	1.83	4.56	4.56	6.12	1.35	3.37	3.37	4.55	1.36	1.35	1.35	1.34	1.35	1.34
1/4	90	15.1	25.1	25.1	31.8	1.86	3.76	3.76	4.74	1.37	2.64	2.64	5.49	1.36	1.33	1.33	1.40	1.33	1.40
1/8	90	15.6	18.2	21.3	22.3	1.93	2.54	2.72	3.67	1.42	1.80	1.95	2.37	1.36	1.31	1.30	1.12	1.30	1.12
1/16	90	17.7	17.8	21.1	21.8	2.01	2.22	2.61	2.99	1.49	1.76	1.89	2.13	1.37	1.32	1.30	1.41	1.38	1.41
1/32	90	17.7	17.8	21.2	21.4	2.08	2.12	2.53	2.68	1.50	1.51	1.84	1.94	1.38	1.31	1.30	1.40	1.38	1.40
1/2	45	14.6	30.7	30.7	38.5	1.57	3.77	3.77	5.64	1.15	2.80	2.80	4.18	1.36	1.35	1.35	1.35	1.35	1.35
5/8	45	15.1	25.5	25.5	32.2	1.80	3.48	3.48	5.05	1.32	2.51	2.51	3.63	1.36	1.39	1.39	1.39	1.39	1.39
1/4	45	15.3	21.2	21.2	25.9	1.85	3.00	3.00	4.06	1.36	2.11	2.11	2.81	1.36	1.33	1.33	1.41	1.33	1.41
1/8	45	15.2	18.1	21.2	22.1	1.87	2.33	2.64	3.19	1.38	1.68	1.90	2.26	1.36	1.38	1.38	1.39	1.38	1.41
1/16	45	17.5	17.8	21.0	21.6	2.05	2.07	2.54	2.87	1.49	1.50	1.83	2.06	1.38	1.38	1.38	1.40	1.38	1.40
1/32	45	17.8	17.4	21.1	21.6	2.02	2.06	2.45	2.64	1.48	1.48	1.81	1.90	1.37	1.39	1.38	1.39	1.38	1.39

Table 1 PLATE BOUNDARY LAYER DATA

Natural Test Section Boundary Layer

$$\delta_x = 14.67 \text{ mm} \quad \delta_y = 16 \text{ mm} \quad \theta_x = 125 \text{ mm} \quad H_x = 128 \quad Re_x = 5311$$

Note: The position of measurement relative to the plates leading edge (LE) and trailing edge (TE) is

expressed in terms of plate thickness h where the positive direction is downstream

h	ϕ	δ (mm)						δ^* (mm)						θ (mm)						H					
		IE			IE			IE			IE			IE			IE			IE			IE		
		10h	+30h	-6h	+18h	-10h	+10h	-6h	+18h	-10h	+10h	-6h	+18h	-10h	+30h	-6h	+18h	-10h	+30h	-6h	+18h	-10h	+30h	-6h	+18h
1/2	90	25.9	39.8	39.8	49.3	2.84	5.72	5.72	7.45	2.16	4.27	4.27	5.60	1.31	4.27	4.27	5.60	1.31	4.27	4.27	5.60	1.31	4.27	4.27	5.60
3/8	90	25.9	37.3	37.3	46.4	2.89	5.31	5.31	6.78	2.20	3.86	3.86	4.97	1.31	3.86	3.86	4.97	1.31	3.86	3.86	4.97	1.31	3.86	3.86	4.97
1/4	90	26.6	31.5	31.5	37.7	3.01	4.75	4.75	5.69	2.33	3.39	3.39	4.02	1.30	3.39	3.39	4.02	1.30	3.39	3.39	4.02	1.30	3.39	3.39	4.02
1/8	90	26.6	30.5	31.2	32.5	3.06	3.63	3.63	4.40	2.34	2.67	2.67	3.20	1.31	2.67	2.67	3.20	1.31	2.67	2.67	3.20	1.31	2.67	2.67	3.20
1/16	90	26.9	30.1	31.9	32.0	3.11	3.44	3.80	4.00	2.38	2.55	2.55	2.97	1.31	2.55	2.55	2.97	1.31	2.55	2.55	2.97	1.31	2.55	2.55	2.97
1/32	90	26.7	27.0	31.4	31.6	3.20	3.30	3.62	3.85	2.42	2.47	2.47	2.87	1.32	2.47	2.47	2.87	1.32	2.47	2.47	2.87	1.32	2.47	2.47	2.87
1/2	45	25.7	36.7	36.7	45.7	2.82	4.73	4.73	6.64	2.15	3.51	3.51	4.90	1.31	3.51	3.51	4.90	1.31	3.51	3.51	4.90	1.31	3.51	3.51	4.90
3/8	45	25.9	31.6	31.6	39.0	2.89	4.39	4.39	6.00	2.20	3.24	3.24	4.33	1.31	3.24	3.24	4.33	1.31	3.24	3.24	4.33	1.31	3.24	3.24	4.33
1/4	45	26.3	31.3	31.3	37.1	3.04	4.04	4.04	5.11	2.30	2.97	2.97	3.66	1.32	2.97	2.97	3.66	1.32	2.97	2.97	3.66	1.32	2.97	2.97	3.66
1/8	45	26.5	30.5	31.2	32.3	3.11	3.47	3.73	4.24	2.37	2.59	2.59	3.11	1.31	2.59	2.59	3.11	1.31	2.59	2.59	3.11	1.31	2.59	2.59	3.11
1/16	45	26.8	27.1	31.5	32.2	3.20	3.21	3.68	3.98	2.43	2.46	2.46	2.97	1.31	2.46	2.46	2.97	1.31	2.46	2.46	2.97	1.31	2.46	2.46	2.97
1/32	45	29.7	27.1	31.8	32.0	3.15	3.26	3.63	3.86	2.39	2.45	2.45	2.89	1.32	2.45	2.45	2.89	1.32	2.45	2.45	2.89	1.32	2.45	2.45	2.89

Table 2 PLATE BOUNDARY LAYER DATA

Thickened Test Section Boundary Layer

 $\delta_y = 25.1 \text{ mm}$, $\delta^* = 2.72 \text{ mm}$, $\theta_r = 2.15 \text{ mm}$, $H_r = 1.27$, $Re_\theta = 5563$

Polynomial Curve Fits of the Plate Wind Tunnel Results

Plate Leading edge

Fillet angle = 90°

$$\frac{\Delta\theta}{h} = 2.65 \times 10^{-2} + 5.63 \times 10^{-2} \left(\frac{h}{\theta_1} \right) - 4.39 \times 10^{-3} \left(\frac{h}{\theta_1} \right)^2 - 1.86 \times 10^{-4} \left(\frac{h}{\theta_1} \right)^3 + 2.27 \times 10^{-5} \left(\frac{h}{\theta_1} \right)^4 \quad (Fig. 4.5)$$

$$\Delta H = 4.22 \times 10^{-2} + 1.67 \times 10^{-2} \left(\frac{h}{\theta_1} \right) - 2.69 \times 10^{-3} \left(\frac{h}{\theta_1} \right)^2 \quad (Fig. 4.6)$$

Fillet angle = 45°

$$\frac{\Delta\theta}{h} = 6.84 \times 10^{-3} + 4.52 \times 10^{-2} \left(\frac{h}{\theta_1} \right) - 6.09 \times 10^{-3} \left(\frac{h}{\theta_1} \right)^2 + 2.84 \times 10^{-4} \left(\frac{h}{\theta_1} \right)^3 \quad (Fig. 4.5)$$

$$\Delta H = 5.04 \times 10^{-4} + 2.40 \times 10^{-2} \left(\frac{h}{\theta_1} \right) - 2.52 \times 10^{-3} \left(\frac{h}{\theta_1} \right)^2 + 2.31 \times 10^{-5} \left(\frac{h}{\theta_1} \right)^3 \quad (Fig. 4.6)$$

Plate Trailing edge

Fillet angle = 90°

$$\frac{\Delta\theta}{h} = 1.21 \times 10^{-1} - 2.73 \times 10^{-3} \left(\frac{h}{\theta_1} \right) \quad (Fig. 4.7)$$

$$\Delta H = 1.71 \times 10^{-2} - 3.26 \times 10^{-3} \left(\frac{h}{\theta_1} \right) \quad (Fig. 4.8)$$

Fillet angle = 45°

$$\frac{\Delta\theta}{h} = 1.35 \times 10^{-1} - 3.62 \times 10^{-3} \left(\frac{h}{\theta_1} \right) \quad (Fig. 4.7)$$

$$\Delta H = 1.96 \times 10^{-2} - 1.48 \times 10^{-3} \left(\frac{h}{\theta_1} \right) \quad (Fig. 4.8)$$

APPENDIX 2

Computer Codes and Sample Output

The Traversing Program

```

*****
' BOUNDARY LAYER TRAVERSING CONTROL PROGRAM
*****
' THIS PROGRAM CONTROLS THE BOUNDARY LAYER PILOT TUBE,
' TRAVERSING GEAR AND THE PRESSURE TRANSDUCERS TO OBTAIN RAW
' VOLTAGE/PRESSURE DATA. A BUILT IN OPTION ALLOWS SIMULTANEOUS
' RECORDING OF THE PRESSURE TRANSDUCER VOLTAGES AND MANOMETER
' HEIGHTS FOR PURPOSES OF CALIBRATION
*****
' INITIALIZE SCHEMETRIC'S LABLINE SUBROUTINES
*****
' $INCLUDE 'common.bas'
DECLARE SUB Calib (AA(), nt%, volt%, density%, velocity%)
DECLARE SUB Volts (badd%, model AS MODELTYPE, chan%, range%, func%, azmode%, result%, er%)
DECLARE SUB ViaRegisterTest (badd%, er%)
DECLARE SUB InitModel (badd%, model AS ANY, intent&(), azmode%)
DECLARE SUB SetupModel (badd%, model AS ANY, azmode%)
DECLARE SUB PressAnyKey (a$)
DECLARE SUB GetInt (prompt$, x%)
DECLARE SUB PrintError (er%)
DECLARE SUB MainMenu (badd%, model AS MODELTYPE, intent&(), azmode%)
DECLARE SUB ViaInitialize (badd%)
DECLARE SUB AtoDI (badd%, model AS MODELTYPE, chan%, range%, func%, azmode%, result%, er%)
DECLARE SUB DAC (badd%, model AS MODELTYPE, chan%, count%, er%)
DECLARE SUB DigitalOutput (badd%, model AS MODELTYPE, chan%, state%, er%)
DECLARE SUB Relay (badd%, model AS MODELTYPE, chan%, state%, er%)
DECLARE SUB ResetCounter (badd%, model AS MODELTYPE, chan%, intent&(), er%)
DECLARE SUB DOWN (stan%)
DECLARE SUB UP (stan%)
' LABLINE
' LEVEL 1 QUICKBASIC SOFTWARE
' VERSION 4.0
' SCHEMETRIC INSTRUMENTS
' START UP ROUTINES
' July 1989
DIM model AS MODELTYPE
DIM intent&(4)
refres(1) = 100      'QuickBasic does not allow arrays to be included
refres(2) = 10000    'in records. Thus the reference resistances and
refres(3) = 100000    'and gains have been set as constants
gains(0) = 1
gains(1) = 10
gains(2) = 100
gains(3) = 500
CALL SetupModel(badd%, model, azmode%)
CALL InitModel(badd%, model, intent&(), azmode%)
CALL MainMenu(badd%, model, intent&(), azmode%)
func% = 0
CALL Volts(badd%, model, chan%, range%, func%, azmode%, result%, er%)
CLS
*****
' VARIABLE DESCRIPTIONS
*****
'atmosphere= initial room pressure
'blres = B L transducer voltage reading
'blsum = sum of all B L transducer measurements
'blvel = average of all B L samples, representing the flow velocity
'blvolt = initial voltage of boundary layer pressure transducer
'chan = channel to read voltage from in Schemetric equipment
' channel 1 = B L press trans, channel 2 = reference press trans

```

diff = difference between successive B.L. velocity measurements
 er = Sciemetrics error code
 filename = name of data storage file
 fineness = measurement step multiplication factor, intended to increase the distance between measurements toward the outer edge of B.L.
 freedbl = free stream velocity
 freedist = distance from last B.L. measurement to freestream measurement
 freedvel = corresponding reference vel at time of freestream measurement
 funct = units of channel (0 = 10 Volt) function called by Sciemetrics software during scan of analog channel
 I = sample measurement counter
 info = relevant information on wind tunnel run
 initbl = B.L. pressure transducer voltage at zero velocity
 initref = reference pressure transducer voltage at zero velocity
 j = B.L. measurement/position counter
 jmax = maximum value of variable 'j'
 model = Model number of Sciemetrics Data Acquisition unit
 ok = response to yes or no question
 pausetime = time allotted for movement of pitot tube to new measurement position
 position = distance from tunnel floor
 range = range of voltage on channel
 refvel = reference transducer voltage reading
 refsum = sum of all reference transducer measurements
 refvel = average of all reference samples, representing the flow velocity
 refvoltage = initial voltage of reference pressure transducer
 roomtemp = initial temperature of the room
 samplenum = number of samples taken for each measurement
 start = number of times stepper motor must cycle to traverse distance
 stepdist = distance between measurement during B.L. traverse
 sum = cumulative distance traversed over multi-samples
 tolerance = difference in successive velocity measurements at edge of B.L.
 travdist = total distance of B.L. traverse
 U = non-dimensional velocity
 vel = freestream velocity (used to set tunnel velocity)
 velres = transducer voltage (used to set tunnel velocity)
 wormratio = number of times stepper motor must cycle to traverse 1 mm.
 determine how far in real world 1 represents.

```

*****
DIM blvel(100), refvel(100), position(100), U(100), AA(10), Aref(10)

```

```

R = 287!
freedist = 2!
stepdist = 1!
travdist = 65!
wormratio = 157.8
samplenum% = 8
fineness = 1.2
tolerance = .001
range% = 0
on$ = "yes"

```

```

*****
DETERMINE INITIAL PRESSURE TRANSDUCER VOLTAGES AT ZERO TUNNEL SPEED
*****

```

```

INPUT "REMEMBER TO REPOSITION B.L. STATIC PROBE!!!! ", crt$
10 PRINT "Measuring transducer voltages at 0 m/s"
refinitsum = 0!
blinitsum = 0!
FOR i% = 1 TO samplenum%
  chan% = 1
  CALL Vols(badd%, model, chan%, range%, func%, azmode%, res1, er%)
  blinitsum = res1 + blinitsum

  chan% = 2
  CALL Vols(badd%, model, chan%, range%, func%, azmode%, res2, er%)
  refinitsum = res2 + refinitsum
PRINT res1, res2

```

```

NEXT i%
imtbl = blinitsum / (samplenun% * 1')
mitref = refinitsum / (samplenun% * 1')
*****
* DETERMINE IF THIS IS A B.L. TRAVERSE OR A TRANSDUCER
* CALIBRATION RUN
*****
INPUT "Is this a transducer calibration run? (Y or N) ",
on$
IF on$ = "Y" THEN
4 INPUT "Enter calibration data source file number: ",
calfile$
PRINT "Source data file name = " + calfile$
INPUT "Is this satisfactory (y or n) ? ", ok$
IF ok$ = "n" THEN
GOTO 4
END IF
*****
* OPEN A TRANSDUCER CALIBRATION CURVE DATA FILE, AS THE
* VOLTAGES ARE INPUT FROM THE TRANSDUCERS, PROMPT THE USER
* FOR MANOMETER FLUID HEIGHTS AND NEW TUNNEL VELOCITY
* SETTING.
*****
OPEN "c:\trav\calib\test" + calfile$ + ".cal" FOR OUTPUT AS #1
5 INPUT "Set tunnel speed and hit return", cr%
bres = 0!
refres = 0!
FOR i% = 1 TO samplenun%
chan% = 1
CALL Vols(badd%, model, chan%, range%, func%, azmode%, res1, cr%)
bres = res1 + bres

chan% = 2
CALL Vols(badd%, model, chan%, range%, func%, azmode%, res2, cr%)
refres = res2 + refres

PRINT res1, res2
NEXT i%
ref = (refres / (samplenun% * 1')) - mitref
bl = (bres / (samplenun% * 1')) - imtbl
PRINT " *****"
INPUT "Enter B.L. manometer height (mm): ", BLhgt
PRINT " *****"
INPUT "Enter REFERENCE manometer height (mm) ", REFhgt
PRINT "Reference voltage = ", ref
PRINT "B.L. voltage = ", bl
PRINT "B.L. Manometer height = ", BLhgt
PRINT "REF Manometer height = ", REFhgt
PRINT "More measurements (Y or N)? "
INPUT "(A = abort last data set) ", query$
SELECT CASE query$
CASE "n"
WRITE #1, BLhgt, bl, REFhgt, ref
CLOSE #1
GOTO 999
CASE "a"
PRINT "Last data set scrapped"
GOTO 5
CASE ELSE
WRITE #1, BLhgt, bl, REFhgt, ref
GOTO 5
END SELECT
END IF
*****
* FOR A B.L. TRAVERSE, PROMPT FOR OPERATIONAL CONDITIONS
*****
PRINT "Enter the date, plate thickness, and pitot tube position

```

```

INPUT "Enter file name = ", info$
INPUT "Enter input file number = ", filename$
INPUT "Enter room pressure (mm Hg) = ", atmosphere
INPUT "Enter temperature of the room (Celsius) = ", roomtemp

density = (atmosphere * 133.3224) / (R * (roomtemp + 273.15))
H = density * 9.81/EHLN
density = 1.2
END H

*****
' 133.3224 is the conversion factor from mm Hg to Pascals
*****

PRINT "Note = ", info$
PRINT "Output file name = TEST" & filename$
PRINT "Traverse distance = ", traydist, " mm "
PRINT "Initial distance between measurements = ", stepdist, " mm "
PRINT "Number of samples = ", samplenum%
PRINT ""
PRINT "Air temperature = ", roomtemp, " Celsius"
PRINT "Atmospheric pressure = ", atmosphere, " mm Hg"
PRINT "Air density = ", density, " Kg/c metre"
PRINT "Initial B.L. press trans voltage = ", initbl, " volts"
PRINT "Initial reference press trans voltage = ", initref, " volts"
PRINT ""

INPUT "Are these values satisfactory (y or n) ? ", ok$
IF ok$ = "n" THEN
    GOTO H0
END IF
PRINT ""
INPUT "SET TUNNEL VELOCITY AND HIT RETURN", crt$
PRINT

*****
' PROMPT USER TO SET TUNNEL WIND VELOCITY THEN RECALL
' PRESSURE TRANSDUCER CURVE FIT COEFFICIENTS
*****

m% = 1
OPEN "tray\data\refpoly.dat" FOR INPUT AS #1
DO UNTIL EOF(1)
    INPUT #1, Aref(m%)
    m% = m% + 1
LOOP
nref% = m% - 1
CLOSE #1
*****

chan% = 2
20 velsum = 0
vel = 0
temp1 = 0
temp2 = 0
FOR i% = 1 TO samplenum%
    CALL Vols(badd%, model, chan%, range%, func%, azmode%, velres, er%)
    velsum = velsum + velres
    PRINT velres
NEXT i%
*****
' SET THE WIND TUNNEL FLOW VELOCITY USING A 2nd ORDER
' POLYNOMIAL CURVE FIT TO THE REFERENCE TRANSDUCER
' CALIBRATION CURVE
*****

voltvel = (velsum / (samplenum% * 1)) - initref
CALL Calib(Aref(), nref%, voltvel, density, vel)

PRINT "The free stream velocity is ", vel, " m/s"
INPUT "Is this satisfactory (y or n) ? ", ok$
IF ok$ = "y" THEN

```

```

        GOTO 21
    ELSE
        GOTO 20
    END IF
=====
* DUE TO THE UNAVOIDABLE FLEXURE OF THE PITOT TUBE, IT IS
* NECESSARY TO ALIGN THE PITOT TUBE WITH THE TUNNEL FLOOR
* WHILE THE TUNNEL IS RUNNING.
=====
21 PRINT "INITIALIZE PITOT TUBE HEIGHT "
22 INPUT "Enter direction of traverse (u,d or q) ", direct$
    IF direct$ = "q" THEN
        GOTO 22
    END IF
    INPUT "Enter traverse distance (mm) ", dist
    stair% = CINT(dist * wormratio)
    IF direct$ = "u" THEN
        CALL UP(stair%)
        GOTO 25
    END IF
    IF direct$ = "d" THEN
        CALL DOWN(stair%)
        GOTO 25
    END IF
=====
* WHILE THE B.L. PITOT TUBE IS WITHIN PRESET MARGIN, STEP
* AND MEASURE THE VELOCITY/VOLTAGE, STEP AND MEASURE, ETC.
* FOR EACH MEASUREMENT POINT, TAKE THE AVERAGE OF MANY
* SAMPLES.
=====
22 sum = 255
j% = 0
WHILE sum <= travdist
    j% = j% + 1
    position(j%) = sum
    PRINT "Reading reference pressure and BL pressure at " sum " mm "
    blsum = 0!
    refsum = 0!
    FOR i% = 1 TO samplenum%
        chan% = 1
        CALL Volts(badd%, model, chan%, range%, func%, azmode%, bires, cr%)
        blsum = blsum + bires

        chan% = 2
        CALL Volts(badd%, model, chan%, range%, func%, azmode%, refres, cr%)
        refsum = refsum + refres
        PRINT bires, refres
    NEXT i%
    blvel(j%) = (blsum / (samplenum% * 1!)) - initbl
    refvel(j%) = (refsum / (samplenum% * 1!)) - initref

    PRINT "The bl voltage is ", blvel(j%)
    PRINT "The reference voltage is " refvel(j%)

    jmax% = j%
    PRINT "Stepping BL pitot tube "
    stair% = CINT(stepdist * wormratio)
    CALL UP(stair%)
=====
    INCREASE STEP SIZE AND LOOP AGAIN.
=====
    sum = sum + stepdist
    stepdist = stepdist * fineness
WEND
=====
* NOW MOVE OUT OF THE B.L. AND MEASURE THE FREESTREAM VELOCITY
=====
30 PRINT

```



```

      star% = CINT((freedist + traydist - position(jmax%)) * wormratio)
      star% = CINT(wormratio * freedist)
      CALL CPT(star%)
      blsum = 0
      relsum = 0
      PRINT "Taking free stream measurements at " sum, " mm."
      FOR i% = 1 TO samplenum%
        chan% = 1
        CALL Volts(badd%, model, chan%, range%, func%, azmode%, bires, ei%)
        blsum = blsum + bires

        chan% = 2
        CALL Volts(badd%, model, chan%, range%, func%, azmode%, refres, ei%)
        relsum = relsum + refres
        PRINT bires, refres
      NEXT i%
      freebl = (blsum / (samplenum% * 1)) - initbl
      freeref = (relsum / (samplenum% * 1)) - mitref

      PRINT "The freestream voltage is ", blvel(j%)
      PRINT "The freestream ref voltage is ", refvel(j%)
*****
' STORE DATA INTO AN OUTPUT FILE FOR LATER ANALYSIS
*****
      OPEN "c:\tray\data\test" + filename$ + ".dat" FOR OUTPUT AS #1
      WRITE #1, info$
      WRITE #1, atmosphere, roomtemp, density
      WRITE #1, initbl, mitref
      WRITE #1, freebl, freeref
      PRINT info$
      PRINT atmosphere, roomtemp, density
      PRINT initbl, mitref
      PRINT freebl, freeref
      FOR j% = 1 TO jmax%
        WRITE #1, blvel(j%), refvel(j%), position(j%)
        PRINT blvel(j%), refvel(j%), position(j%)
      NEXT j%
      CLOSE #1
    END
  SUB Calib (AA(), n1%, volt, density, velocity)
*****
' A LEAST SQUARES POLYNOMIAL CURVE FIT OF THE 0.1 psi B.L.
' PRESSURE TRANSDUCER CALIBRATION CURVE IS UTILIZED TO
' CONVERT THE TRANSDUCER VOLTAGE TO VELOCITY.
*****
      FOR k% = 1 TO n1%
        press = press + AA(k%) * volt - (k% - 1)
      NEXT k%
      velocity = SQR(ABS((2 * press) / density))
    END SUB
  SUB DOWN (star%)
*****
' SENDS BINARY SIGNALS TO THE TRAVERSING GEAR INTERPRETER
' D/A BOX TO MOVE THE PITOT TUBE VERTICALLY DOWN. "956" IS
' THE ADDRESS OF THE PARALLEL PORT
*****
      CLS
      OUT 956, 0
      FOR B% = 1 TO star%
        OUT 956, 12
        OUT 956, 4
        PRINT B%
      NEXT B%
      OUT 956, 0
      CLS

```

```

END SUB
SUB UP (star%)
-----
' SENDS BINARY SIGNALS TO THE TRAVERSING GEAR INTERPRETER
' D/A BOX TO MOVE THE PILOT TUBE VERTICALLY UP 0.95CM IS
' THE ADDRESS OF THE PARALLEL PORT.
-----
CLS
PRINT "Stepping to next measurement"
OUT 956, 0
FOR B% = 1 TO star%
    OUT 956, 6
    OUT 956, 4
    PRINT B%
NEXT B%
OUT 956, 0
CLS
END SUB

```

2 OF/DE 2

PM-1 3 1/2"x4" PHOTOGRAPHIC MICROCOPY TARGET
NBS 1010a ANSI/ISO #2 EQUIVALENT

The Calibration Program

```

=====
PRESSURE TRANSDUCER CALIBRATION PROGRAM
=====
THIS PROGRAM CREATES A LEAST SQUARES POLYNOMIAL CURVE
FIT TO THE CALIBRATION MANOMETER/VOLTAGE DATA SENT FROM
THE TRAVERSING PROGRAM.
=====

DECLARE SUB CURVE (A%(), n%, jmax%, voltage%(), pressure%())
DECLARE SUB GaussJ (n% C%(), R%(), A%())
DECLARE SUB LeastSq (jmax%, x%(), fx%(), n%, C%(), R%())
DIM BLvolt(50), BLhgt, Aref(10), Abt(10), C(10, 10), R(10)
DIM voltage(50), pressure(50), REFvolt(50), REFhgt
DIM REFpress(50), BLpress(50), PRESS(50)
DIM oldvolt1(50), oldvolt2(50), oldpres1(50), oldpres2(50)
CLS
=====
CHOOSE CALIBRATION RUN FILE NUMBER FROM "TRAVERSE" SOFTWARE
=====
INPUT "Enter calibration file number: ", filename$
44 PRINT "Enter calibration choice: "
PRINT "=¿ B.L. transducer (1)"
PRINT "=¿ Ref transducer (2) "
PRINT "=¿ Both transducers (ENTER)"
INPUT "          =====¿ ", choice%
OPEN "test" + filename$ + ".cal" FOR INPUT AS #1
j% = 1
DO UNTIL EOF(1)
    INPUT #1, BLhgt, BLvolt(j%), REFhgt, REFvolt(j%)
    =====
    CONVERT MANOMETER HEIGHT TO PRESSURE
    PRESSURE = MANO FLUID DENSITY * GRAVITY * MANO HEIGHT (mm.)
    (1000 Kg/cu. metre) * (9.81) * (hgt*1metre/1000 mm.)
    =====
    BLpress(j%) = 9.81 * BLhgt
    REFpress(j%) = 9.81 * REFhgt
    j% = j% + 1
LOOP
jmax% = j% - 1
CLOSE #1
=====
READ IN PREVIOUS CALIBRATION CURVE FIT TO ASCERTAIN AMOUNT
OF TRANSDUCER DRIFT, IF ANY.
=====
OPEN "curv1fit.dat" FOR INPUT AS #1
OPEN "curv2fit.dat" FOR INPUT AS #2
j% = 1
DO UNTIL EOF(1)
    INPUT #1, oldvolt1(j%), oldpres1(j%)
    j% = j% + 1
LOOP
oldjmax1% = j% - 1
j% = 1
DO UNTIL EOF(2)
    INPUT #2, oldvolt2(j%), oldpres2(j%)
    j% = j% + 1
LOOP
oldjmax2% = j% - 1
CLOSE #1, #2
SELECT CASE choice%
CASE 1

```

=====

DETERMINE THE B.L. TRANSDUCER CALIBRATION CURVE COEFFICIENTS

=====

```

INPUT "Enter the B.L. polynomial order required: ", BLn%
PRINT "***** CALCULATING B.L. COEFFICIENTS *****"
CALL LeastSq(jmax%, BLvolt(), BLpress(), BLn%, C(), R())
CALL GaussJ(BLn%, C(), R(), Abl())
INPUT "Enter (Y) to save the coefficients. ", ans$
IF ans$ = "y" THEN
    OPEN "c:\trav\data\blpoly.dat" FOR OUTPUT AS #1
    FOR k% = 1 TO BLn%
        PRINT #1, Abl(k%)
    NEXT k%
    CLOSE #1
    PRINT "B.L. coefficients saved in file BLPOLY.DAT"
ELSE
    PRINT "B.L. Coefficients are not saved."
END IF

```

=====

GENERATE PRESSURE/VOLTAGE CALIBRATION CURVE DATA AND SEND TO STORAGE FILE FOR GRAPHIC DISPLAY.

=====

```

CALL CURVE(Abl(), BLn%, jmax%, voltage(), pressure())
OPEN "calcurv1.dat" FOR OUTPUT AS #1
OPEN "curvfit.dat" FOR OUTPUT AS #2
FOR j% = 1 TO jmax%
    PRINT #1, Pl.volt(j%), BLpress(j%)
NEXT j%
FOR j% = 1 TO jmax%
    PRINT #2, voltage(j%), pressure(j%)
NEXT j%
CLOSE #1, #2
PRINT "Enter (Y) if you want a comparison with the "
INPUT "old calibration curve. =c ", ans$
IF ans$ = "y" THEN
    OPEN "old1.dat" FOR OUTPUT AS #1
    FOR j% = 1 TO oldjmax1%
        PRINT #1, oldvolt1(j%), oldpres1(j%)
    NEXT j%
    CLOSE #1
ELSE
    OPEN "old1.dat" FOR OUTPUT AS #1
    PRINT #1, nothing
    CLOSE #1
END IF

```

CASE 2

=====

DETERMINE THE REFERENCE TRANSDUCER CALIBRATION CURVE COEFFICIENTS

=====

```

INPUT "Enter the REF polynomial order required: ", REFn%
PRINT "***** CALCULATING REFERENCE COEFFICIENTS *****"
CALL LeastSq(jmax%, REFvolt(), REFpress(), REFn%, C(), R())
CALL GaussJ(REFn%, C(), R(), Aref())
INPUT "Enter (Y) to save the coefficients. ", ans$
IF ans$ = "y" THEN
    OPEN "c:\trav\data\refpoly.dat" FOR OUTPUT AS #1
    FOR k% = 1 TO REFn%
        PRINT #1, Aref(k%)
    NEXT k%
    CLOSE #1
    PRINT "Ref coefficients saved in file REF POLY.DAT"
ELSE
    PRINT "REFERENCE Coefficients are not saved."
END IF
CALL CURVE(Aref(), REFn%, jmax%, voltage(), pressure())

```

```

OPEN "calcurv2.dat" FOR OUTPUT AS #1
OPEN "curv2ht.dat" FOR OUTPUT AS #2
FOR j% = 1 TO jmax%
    PRINT #1, REFvolt(j%), REFpress(j%)
NEXT j%
FOR j% = 1 TO jmax%
    PRINT #2, voltage(j%), pressure(j%)
NEXT j%
CLOSE #1, #2
PRINT "Enter (Y) if you want a comparison with the "
INPUT "old calibration curve.  =; ", ans$
IF ans$ = "y" THEN
    OPEN "old2.dat" FOR OUTPUT AS #2
    FOR j% = 1 TO oldjmax2%
        PRINT #2, oldvolt1(j%), oldpress1(j%)
    NEXT j%
    CLOSE #2
ELSE
    OPEN "old2.dat" FOR OUTPUT AS #2
    PRINT #2, nothing
    CLOSE #2
END IF

```

CASE 0

.....
DETERMINE THE REFERENCE AND B.L. TRANSDUCER CALIBRATION
CURVE COEFFICIENTS
.....

```

INPUT "Enter the B.L. polynomial order required: ", BLn%
INPUT "Enter the REF polynomial order required: ", REFn%
PRINT "***** CALCULATING B.L. COEFFICIENTS *****"
CALL LeastSq(jmax%, BLvolt(), BLpress(), BLn%, C(), R())
CALL GaussJ(BLn%, C(), R(), Abl())
PRINT "***** CALCULATING REFERENCE COEFFICIENTS *****"
CALL LeastSq(jmax%, REFvolt(), REFpress(), REFn%, C(), R())
CALL GaussJ(REFn%, C(), R(), Aref())
INPUT "Enter (Y) to save the coefficients. ", ans$
IF ans$ = "y" THEN
    OPEN "c:\trav\data\blpoly.dat" FOR OUTPUT AS #1
    OPEN "c:\trav\data\refpoly.dat" FOR OUTPUT AS #2
    FOR k% = 1 TO BLn%
        PRINT #1, Abl(k%)
    NEXT k%
    FOR k% = 1 TO REFn%
        PRINT #2, Aref(k%)
    NEXT k%
    CLOSE #1, #2
    PRINT "B.L. coefficients saved in file BLPOLY.DAT"
    PRINT "Ref coefficients saved in file REFPOLY.DAT"
ELSE
    PRINT "B.L. and REF Coefficients are not saved."
END IF
CALL CURVE(Abl(), BLn%, jmax%, voltage(), pressure())
OPEN "calcurv1.dat" FOR OUTPUT AS #1
OPEN "curv1fit.dat" FOR OUTPUT AS #2
FOR j% = 1 TO jmax%
    PRINT #1, BLvolt(j%), BLpress(j%)
NEXT j%
FOR j% = 1 TO jmax%
    PRINT #2, voltage(j%), pressure(j%)
    pressure(j%) = 0

```

```

NEXT j%
CLOSE #1, #2
CALL CURVE(Aref(), REF n%, jmax%, voltage(), pressure())
OPEN "calurv2.dat" FOR OUTPUT AS #1
OPEN "curv2ht.dat" FOR OUTPUT AS #2
FOR j% = 1 TO jmax%
    PRINT #1, REF volt(j%), REF press(j%)
NEXT j%
FOR j% = 1 TO jmax%
    PRINT #2, voltage(j%), pressure(j%)
NEXT j%
CLOSE #1, #2

PRINT "Enter (Y) if you want a comparison with the "
INPUT "old calibration curves.   =_ ", ans$
IF ans$ = "y" THEN
    OPEN "old1.dat" FOR OUTPUT AS #1
    OPEN "old2.dat" FOR OUTPUT AS #2
    FOR j% = 1 TO oldjmax1%
        PRINT #1, oldvolt1(j%), oldpress1(j%)
    NEXT j%
    FOR j% = 1 TO oldjmax2%
        PRINT #2, oldvolt1(j%), oldpress1(j%)
    NEXT j%
    CLOSE #1, #2
ELSE
    OPEN "old1.dat" FOR OUTPUT AS #1
    OPEN "old2.dat" FOR OUTPUT AS #2
    PRINT #1, nothing
    PRINT #2, nothing
    CLOSE #1, #2
END IF

CASE ELSE
    GOTO 44
END SELECT
SUB CURVE (A(), n%, jmax%, voltage(), pressure())
.....
' THIS SUBROUTINE GENERATES THE TRANSDUCER CALIBRATION CURVE
' FOR GRAPHICAL DISPLAY
.....
FOR j% = 1 TO jmax%
    voltage(j%) = j% * 4.3 / (jmax% * 1!)
    FOR k% = 1 TO n%
        pressure(j%) = pressure(j%) + A(k%) * voltage(j%) ^ (k% - 1)
    NEXT k%
    PRINT voltage(j%), pressure(j%)
    INPUT "hit return", crt$
NEXT j%
END SUB
SUB GaussJ (n%, C(), R(), A())
.....
' THIS SUBROUTINE SOLVES THE LEAST SQUARES MATRIX
' USING GAUSS JORDAN ELIMINATION AND OBTAINS THE
' COEFFICIENTS A(i,j) OF THE POLYNOMIAL CURVE FIT
' TO THE TRANSDUCER CALIBRATION CURVE.
.....
    k% = 1
30    temp = 1 / C(k%, k%)
    start% = k%
    FOR j% = start% TO n%
        C(k%, j%) = C(k%, j%) * temp
    NEXT j%
    R(k%) = R(k%) * temp
    j% = 1

```

```

20  IF k% = j% THEN
    GOTO 10
END IF
temp = C(j%, k%)
start% = k%
FOR i% = start% TO n%
    C(j%, i%) = C(j%, i%) - C(k%, i%) * temp
NEXT i%
R(j%) = R(j%) - R(k%) * temp
10  IF j% < n% THEN
    j% = j% + 1
    GOTO 20
END IF
IF k% < n% THEN
    k% = k% + 1
    GOTO 30
END IF
FOR k% = 1 TO n%
    A(k%) = R(k%)
NEXT k%
END SUB
SUB LeastSq (jmax%, x(), fx(), n%, C(), R())
.....
' THIS SUBROUTINE SETS UP THE SET OF EQUATIONS OR MATRIX
' UTILIZED IN THE METHOD OF LEAST SQUARES CURVE FITTING.
.....
FOR k% = 1 TO n%
    FOR i% = 1 TO n%
        FOR j% = 1 TO jmax%
            C(k%, i%) = C(k%, i%) + x(j%) * (i% + k% - 2)
        NEXT j%
    NEXT i%
NEXT k%
FOR k% = 1 TO n%
    FOR j% = 1 TO jmax%
        R(k%) = R(k%) + (fx(j%) * x(j%) * (k% - 1))
    NEXT j%
NEXT k%
END SUB

```


The Profile Program

```

.....
*      DATA REDUCTION PROGRAM
*.....
*  THIS PROGRAM CALCULATES THE NON-DIMENSIONAL VELOCITY
*  PROFILE ALONG WITH THE BOUNDARY LAYER PARAMETERS:
*  MOMENTUM DISPLACEMENT, & B.L. THICKNESS AND SHAPE
*  FACTOR
*.....
  DECLARE SUB CURVE (A!(), n%, newjmax%, U!(), del!, velstar)
  DECLARE SUB GaussJ (n%, C!(), R!(), A!())
  DECLARE SUB LeastSq (newjmax%, x!(), fx!(), n%, C!(), R!())
  DECLARE SUB Calib (AA!(), n!%, volt!, density!, velocity!)
  DECLARE SUB Refcal (volt!, density!, velocity!)
  DECLARE SUB Blcal (volt!, density!, velocity!)
  DIM blvel(100), refvel(100), position(100), U(100), starpos(100)
  DIM Ublvel(100), Urefvel(100), veldata(100), posdata(100)
  DIM A(3), AA(10), Abl(10), Aref(10), C(3, 3), R(3)
*.....
*  ENTER THE FILE # CREATED BY AND SENT FROM THE TRAVERSING
*  SOFTWARE
*.....
  CLS
  INPUT "Enter file test number to be profiled: ", filename$
  OPEN "test" + filename$ + ".dat" FOR INPUT AS #1
  INPUT #1, info$
  PRINT , info$
  INPUT #1, atmosphere, roomtemp, density
  PRINT , atmosphere, roomtemp, density
  INPUT #1, initbl, initref
  PRINT , initbl, initref
  INPUT #1, freebl, freeref
  PRINT , freebl, freeref
*.....
*  READ IN THE PRESSURE TRANSDUCER CALIBRATION POLYNOMIAL
*  CURVE FIT (COEFFICIENTS SENT FROM THE CALIBRATION SOFTWARE)
*.....
  OPEN "blpoly.dat" FOR INPUT AS #2
  I% = 1
  DO UNTIL EOF(2)
    INPUT #2, Abl(I%)
    I% = I% + 1
  LOOP
  nbl% = I% - 1
  m% = 1
  OPEN "refpoly.dat" FOR INPUT AS #3
  DO UNTIL EOF(3)
    INPUT #3, Aref(m%)
    m% = m% + 1
  LOOP
  nref% = m% - 1
*.....
*  READ IN THE B.L. TRAVERSE DATA FROM THE TRAVERSE SOFTWARE.
*  SUBROUTINE CALIB CONVERTS THE TRANSDUCER VOLTAGES INTO
*  VELOCITIES
*.....
  Ublvel(1) = 0!
  Urefvel(1) = 1!
  position(1) = 0!
  j% = 2
  DO UNTIL EOF(1)
    INPUT #1, blvel(j%), refvel(j%), position(j%)
    PRINT , blvel(j%), refvel(j%), position(j%)
  
```

```

CALL Calib(Abl(), nbl%, blvel(j%), density, Ublvel(j%))
CALL Calib(Aref(), nref%, refvel(j%), density, Urefvel(j%))
j% = j% + 1
LOOP
jmax% = j% - 1
CLOSE #1, #2, #3

```

 CONVERT FREE STREAM VOLTAGE MEASUREMENTS INTO VELOCITIES

```

CALL Calib(Abl(), nbl%, freebl, density, Ufreebl)
CALL Calib(Aref(), nref%, freeref, density, Ufreeref)
PRINT Ufreebl, Ufreeref

```

 STARTING FROM THE TUNNEL FLOOR, THE B.L. VELOCITY MEASUREMENTS
 ARE NON-DIMENSIONALIZED BY DIVISION BY THE FREE STREAM VALUE
 ALSO, TO ACCOUNT FOR TUNNEL VELOCITY DRIFT, THE B.L. AND FREE
 STREAM MEASUREMENTS ARE DIVIDED BY THEIR REFERENCE COUNTERPARTS
 A RUNNING AVERAGE OF THE LAST THREE MEASUREMENTS IS MAINTAINED
 IN ORDER TO DETERMINE THE EDGE OF THE B.L. A MORE ACCURATE
 POSITION OF THE B.L. EDGE IS DETERMINED WHEN THE CHANGE IN
 THE AVERAGE IS LESS THAN OR EQUAL TO THE TOLERANCE VALUE (toler).

```

denom = Ufreebl / Ufreeref
toler = .15
5 oldavg = 0!
FOR j% = 1 TO jmax%
  U(j%) = (Ublvel(j%) / Urefvel(j%)) / denom
  newjmax% = j%
  IF (j% + 1) <= jmax% OR (j% - 1) <= 1 THEN
    newavg = (Ublvel(j% - 1) + Ublvel(j%) + Ublvel(j% + 1)) / 3!
    refavg = (Urefvel(j% - 1) + Urefvel(j%) + Urefvel(j% + 1)) / 3!
  END IF
  IF (j% + 1) <= jmax% THEN
    newavg = (Ublvel(j% - 1) + Ublvel(j%)) / 2!
    refavg = (Urefvel(j% - 1) + Urefvel(j%)) / 2!
  END IF

```

 WHEN THE TOLERANCE CONDITION IS MET, THE NON-DIMENSIONAL
 VELOCITY PROFILE IS RECALCULATED WITH THE MORE ACCURATE
 FREESTREAM VELOCITY.

```

diff = ABS(newavg - oldavg)
IF (diff <= toler) AND ((newjmax%) <= 9) THEN
  n% = 3
  denom = newavg / refavg
  FOR i% = 1 TO newjmax%
    U(i%) = (Ublvel(i%) / Urefvel(i%)) / denom
  NEXT i%

```

 FOR PURPOSES OF CALCULATING THE MOMENTUM THICKNESS,
 DISPLACEMENT THICKNESS AND SHAPE FACTOR, A POLYNOMIAL CURVE
 FIT IS APPLIED TO THE SIX B.L. MEASUREMENTS IN THE VICINITY
 OF THE B.L. EDGE TO ACCURATELY DETERMINE THE POSITION OF
 99.5% B.L. THICKNESS

```

CALL LeastSq(newjmax%, U(), position(), n%, C(), R())
CALL GaussJ(n%, C(), R(), A())
CALL CURVE(A(), n%, newjmax%, U(), del, velstar)
FOR m% = (newjmax% - 5) TO newjmax%
  IF velstar <= U(m%) THEN
    newjmax% = m%
    position(newjmax%) = del
    U(newjmax%) = velstar
  GOTO 9

```

```

        END IF
      NEXT m%
    END IF
    oldavg = newavg
  NEXT j%
  *****
  IF THE TOLERANCE CONDITION IS NEVER MET, PROMPT USER FOR
  A NEW TOLERANCE AND RESTART THE CALCULATION.
  *****
  PRINT "TOLERANCE FAILURE! Enter new tolerance."
  INPUT " = ", toler
  GOTO 5
  *****
  BASED ON THE NEW FOUND POSITION OF .995 B.L. THICKNESS,
  CALCULATE THE SHAPE FACTOR, MOMENTUM THICKNESS, AND
  DISPLACEMENT THICKNESS USING TRAPEZOIDAL INTEGRATION.
  *****
  0 dispthick = 0!
  momthick = 0!
  FOR j% = 2 TO (newjmax% - 1)
    stair = position(j%) - position(j% - 1)

    delstar = (stair / 2!) * (2! - (U(j% - 1) + U(j%)))
    dispthick = dispthick + delstar

    temp = U(j% - 1) * (1! - U(j% - 1)) + U(j%) * (1! - U(j%))
    phi = (stair / 2!) * temp
    momthick = momthick + phi
  NEXT j%
  shapefact = dispthick / momthick
  *****
  DATA OUTPUT
  *****
  OPEN "c:\trav\table\table" + filename$ + ".dat" FOR OUTPUT AS #1
  PRINT #1, "Note = "; info$
  PRINT #1, "===== "
  PRINT #1, "Atmospheric pressure      = "; atmosphere; " mm Hg"
  PRINT #1, "Tunnel room temperature    = "; roomtemp; " Celsius"
  PRINT #1, "Air density                    = "; density; " Kg/cubic metre"
  PRINT #1, "Initial B.L. transducer voltage = "; initbl
  PRINT #1, "Initial REF transducer voltage = "; initref
  PRINT #1, "===== "
  PRINT #1, "Freestream velocity      = "; Ufreebl; " m/s"
  PRINT #1, "Boundary layer thickness = "; del; " mm"
  PRINT #1, "Displacement thickness   = "; dispthick; " mm"
  PRINT #1, "Momentum thickness      = "; momthick; " mm"
  PRINT #1, "Shape factor              = "; shapefact
  PRINT #1, "===== "
  PRINT #1, TAB(28); " VELOCITY      HEIGHT"
  PRINT #1, TAB(26); "      .      .      "
  FOR j% = 1 TO newjmax%
    starpos(j%) = position(j%) / del
    PRINT #1, TAB(26); U(j%), starpos(j%)
  NEXT j%
  CLOSE #1
  CLS
  PRINT "Note = "; info$
  PRINT "===== "
  PRINT "Atmospheric pressure      = "; atmosphere; " mm Hg"
  PRINT "Tunnel room temperature    = "; roomtemp; " Celsius "
  PRINT "Air density                    = "; density; " Kg/cubic metre "
  PRINT "Initial B.L. transducer voltage = "; initbl
  PRINT "Initial REF transducer voltage = "; initref
  PRINT "===== "

```

```

PRINT "Freestream velocity      = ", U freebl, " m/s"
PRINT "Boundary layer thickness = ", del, " mm"
PRINT "Displacement thickness   = ", displthick, " mm"
PRINT "Momentum thickness       = ", momenthick, " mm"
PRINT "Shape factor             = ", shapefact
PRINT "=====
INPUT "Hit return when ready", crt$
OPEN "test.dat" FOR OUTPUT AS #2
OPEN ":", "trav"graph"graph" + filename$ + ".dat" FOR OUTPUT AS #3
PRINT TAB(28); " VELOCITY      HEIGHT"
PRINT TAB(26); " - - - - -"
FOR j% = 1 TO newjmax%
  PRINT #2, U(j%), starpos(j%)
  PRINT #3, U(j%), starpos(j%)
  PRINT TAB(30); USING " #.### #.### "; U(j%), starpos(j%)
NEXT j%
CLOSE #2, #3
SUB Calib (AA(), n1%, volt, density, velocity)
*****
' AN LEAST SQUARES POLYNOMIAL CURVE FIT OF THE 0.1 psi B.L.
' PRESSURE TRANSDUCER CALIBRATION CURVE IS UTILIZED TO
' CONVERT THE TRANSDUCER VOLTAGE TO VELOCITY.
*****
FOR k% = 1 TO n1%
  press = press + AA(k%) * volt ^ (k% - 1)
NEXT k%
velocity = SQR(ABS((2! * press) / density))
END SUB
SUB CURVE (A(), n%, newjmax%, U(), del, velstar)
*****
' THIS SUBROUTINE UTILIZES THE CURVE FIT POLYNOMIAL OF
' SIX POINTS IN THE VICINITY OF THE B.L. EDGE TO
' ACCURATELY FIND THE POSITION OF 99.5% OF THE B.L.
' THICKNESS.
*****
DIM UU(120), ypos(120)
temp = U(newjmax%) - U(newjmax% - 5)
FOR i% = 1 TO 100
  UU(i%) = U(newjmax% - 5) + (i% * temp) / 100!
  FOR k% = 1 TO n%
    ypos(i%) = ypos(i%) + A(k%) * UU(i%) ^ (k% - 1)
  NEXT k%
  IF UU(i%) <= .995 THEN
    del = ypos(i%)
    velstar = UU(i%)
    GOTO 77
  END IF
NEXT i%
77 END SUB
SUB GaussJ (n%, C(), R(), A())
*****
' THIS SUBROUTINE UTILIZES GAUSS JORDAN ELIMINATION TO
' SOLVE THE MATRIX CREATED BY THE LEAST SQUARES CURVE
' FITTING ROUTINE.
*****
k% = 1
30 temp = 1! / C(k%, k%)
start% = k%
FOR j% = start% TO n%
  C(k%, j%) = C(k%, j%) * temp
NEXT j%
R(k%) = R(k%) * temp
j% = 1
20 IF k% = j% THEN

```

```

      C(j%, i%) = C(j%, i%) - C(k%, i%) * temp
    NEXT i%
    R(j%) = R(j%) - R(k%) * temp
10  IF j% < n% THEN
      j% = j% + 1
      GO TO 20
    END IF
    IF k% < n% THEN
      k% = k% + 1
      GO TO 30
    END IF
    FOR k% = 1 TO n%
      A(k%) = R(k%)
    NEXT k%
END SUB
SUB LeastSq (newjmax%, x(), fx(), n%, C(), R())
.....
' THIS SUBROUTINE CREATES A LEAST SQUARES POLYNOMIAL CURVE
' FIT TO SIX VELOCITY MEASUREMENTS IN THE VICINITY OF THE
' EDGE OF THE B.L.
.....
    FOR k% = 1 TO n%
      FOR i% = 1 TO n%
        FOR j% = (newjmax% - 5) TO (newjmax% + 1)
          C(k%, i%) = C(k%, i%) + x(j%) ^ (i% + k% - 2)
        NEXT j%
      NEXT i%
    NEXT k%
    FOR k% = 1 TO n%
      FOR j% = (newjmax% - 5) TO (newjmax% + 1)
        R(k%) = R(k%) + (fx(j%) * x(j%) ^ (k% - 1))
      NEXT j%
    NEXT k%
END SUB

```

Sample Output

Note = 05/30/92 1/2m IE +30h IE -6h

=====

Atmospheric pressure = 769.6 mm Hg

Tunnel room temperature = 21 Celsius

Air density = 1.215395 Kg/cubic metre

Initial B.E. transducer voltage = - .004

Initial REF transducer voltage = .027

=====

Freestream velocity = 39.94014 m/s

Boundary layer thickness = 39.83970 mm

Displacement thickness = 5.719642 mm

Momentum thickness = 4.270761 mm

Shape factor = 1.339256

=====

VELOCITY HEIGHT

u/U_∞ y/δ

=====

0.0	0.0
.5338553	6.400635E-03
.5482289	8.910689E-03
.5625544	1.192275E-02
.5815979	1.553723E-02
.5970691	.0198746
.6104716	2.507945E-02
.6231338	3.132526E-02
.6370925	3.882026E-02
.6531229	4.781423E-02
.6649693	5.860701E-02
.678201	7.155833E-02
.6913522	8.709992E-02
.7027971	.1057498
.7167308	.1281297
.7298539	.1549856
.7433668	.1872126
.7575384	.2258851
.7753456	.272292
.8013282	.3279804
.8276903	.3948065
.8613045	.4749977
.9049314	.5712271
.9481699	.6867026
.9815847	.8252732
.9959798	1

Modified BLAP2 Computer Code

```

CSNOCHECK
----- B-1 -----
*
*          B.L.A.P.
*
*          BOUNDARY LAYER ANALYSIS PROGRAM
*
-----
*
* *****
*   MAIN PROGRAM
* *****
*   IMPLICIT INTEGER(I-N),REAL(A-H,O-Z)
C$INCLUDE BLAP2.CMN
*   INTEGER FLAG
*   REAL NAM1,NAM2,NAM3,LAMBDA,L,LENODE
*   INTEGER IND,TYPE,THICK,PHI,BESIG,FFSIG
*   OPEN (7,FILE='CON')
*   WRITE(7, '(A)') ' Unit 6 is the primary output FILE'
*   WRITE(7, '(A)') ' File CHECK is for output of additional '
*   WRITE(7, '(A)') ' information such as the coefficient matrix'
*   WRITE(7, '(A)') ' or the polynomial fit of FN2'
*   WRITE(7, '(A)') ' Unit 4 is for the data FILE used by STAMP'
*   WRITE(7, '(A)') ' with junction point strength distribution'
*   WRITE(7, '(A)') ' Unit 5 is for the data FILE to be input'
*   WRITE(7, '(A)') ' '
*   OPEN(2,FILE='CON')
*   OPEN(10,FILE='IND.DAT')
*   READ(10,*) IND,TYPE
*   CLOSE(10)
*   IF(TYPE.EQ.3)THEN
*       OPEN(6,FILE='C:\STAMPLOT\TYPE3-BLAPOUT,ERR=170,STATUS='NEW')
*       GOTO 175
170  OPEN(6,FILE='C:\STAMPLOT\TYPE3-BLAPOUT,STATUS='OLD')
175  WRITE(7,*)
*   ELSEIF(TYPE.EQ.4)THEN
*       OPEN(6,FILE='C:\STAMPLOT\TYPE4-BLAPOUT,ERR=180,STATUS='NEW')
*       GOTO 185
180  OPEN(6,FILE='C:\STAMPLOT\TYPE4-BLAPOUT,STATUS='OLD')
185  WRITE(7,*)
*   ELSE
*       OPEN(6,FILE='C:\STAMPLOT\TYPE5-BLAPOUT,ERR=190,STATUS='NEW')
*       GOTO 195
190  OPEN(6,FILE='C:\STAMPLOT\TYPE5-BLAPOUT,STATUS='OLD')
195  WRITE(7,*)
*   ENDIF
*   OPEN(3,FILE='CHECK',ERR=200,STATUS='NEW')
*   GOTO 205
200  OPEN(3,FILE='CHECK',STATUS='OLD')
205  OPEN(4,FILE='BLAPOUT.DAT',ERR=210,STATUS='NEW')
*   GOTO 215
210  OPEN(4,FILE='BLAPOUT.DAT',STATUS='OLD')
215  OPEN(5,FILE='BLAPIN.DAT',ERR=220,STATUS='NEW')
*   GOTO 225
220  OPEN(5,FILE='BLAPIN.DAT',STATUS='OLD')
225  OPEN(UNIT=20,FILE='SEPPT',ERR=230,STATUS='NEW')
*   GOTO 235
230  OPEN(UNIT=20,FILE='SEPPT',STATUS='OLD')
*
*   INITIALIZE ALL THE OPTION INDICATORS
*
235  DO 11=1,12

```

```

      FLAG(1)=0.0
1 CONTINUE
-
- CALL THE SUBROUTINE "INPUT" WHICH READS IN
- ALL THE REQUIRED DATA TO RUN THE PROGRAM
-
- CALL INPUT
-
- CALL THE SUBROUTINE "INTERX" WHICH DIVIDES
- UP THE UPPER AND LOWER SURFACE INTO
- SMALL INCREMENTS
-
- CALL INTERX
-
- CALL THE SUBROUTINE "INTERVAL" WHICH CALCULATES
- THE FINELY INCREMENTED VALUES OF VELOCITY AND
- DERIVATIVE OF VELOCITY AT EACH STEP
-
- CALL INTERV
-
- UNTIL CHANGED, THE UPPER AND LOWER SURFACE
- SEPARATION POINTS ARE SET TO THE AIRFOIL
- TRAILING EDGE
-
- ISEP1=NPTU
- ISEP1=NPT
- SSEP(1)=XC(NPT)
- SSEP(2)=XC(NTOT)
- XSEP(1)=XCART(NPT)
- XSEP(2)=XCART(NTOT)
-
- DEFINITION OF VARIOUS CONSTANTS
- (Pi & Kinematic viscosity)
-
- VIS=1/REYNO
- PI=3.141592654
-
- CALL THE SUBROUTINE "OUT1" WHICH OUTPUTS VARIOUS
- PARAMETERS OF THE BOUNDARY LAYER ANALYSIS
-
- CALL OUT1
- WRITE(6,15)
- WRITE(6,16)
15 FORMAT(//,32X,'BOUNDARY LAYER PARAMETERS UPPER AIRFOIL SURFACE,')
16 FORMAT(32X,' - - - - - ')
- IF (FLAG(4).EQ.0) FLAG(1)=0
- IF (FLAG(4).EQ.1) FLAG(1)=1
- IF (FLAG(4).EQ.2) FLAG(1)=0
-
- AN OVERALL DO LOOP IS SET UP WHICH CALCULATES
- THE DEVELOPMENT OF BOTH THE LAMINAR AND
- TURBULENT BOUNDARY LAYER.
- THE UPPER AIRFOIL SURFACE IS FIRST CONSIDERED
- AND THEN "NS" AND "NF" (the initial and limit
- value) ARE CHANGED SO THAT THE CALCULATIONS
- ARE PERFORMED ON THE LOWER AIRFOIL SURFACE.
- IF DESIRED
-
- NS=1
- NF=NPTU
3 DO 2 I=NS,NF
-
- *****
- FIRST MODIFICATION - JULY 1992: EQUATIONS,
- DEVELOPED FROM WIND TUNNEL TESTING, THAT
- MODEL THE PATCH INFLUENCE ON THE BOUNDARY LAYER
- *****
- FIRST CHECK TO SEE IF THE PLATE'S LE OR TE
- HAS BEEN REACHED AND TAKE APPROPRIATE

```


ACTIONS IF THIS IS TRUE

```

.....
BLDIST = (I-1)*STEPX
IF((BLDIST.GT.LENGDLE).AND.(BFSIG.EQ.1))THEN
  XX = PLATE(THICK)/THEIA(I)
  IF(XX.GT.10)XX = 10
  WRITE(7,*)'=, PLATE LEADING EDGE HAS BEEN ENCOUNTERED ;==
  WRITE(6,*)'=, PLATE LEADING EDGE HAS BEEN ENCOUNTERED ;==
  IF((PHLEQ.1)THEN
    WRITE(7,*)'=, WITH A FILLET ANGLE OF 90 DEGREES ;==
    WRITE(7,*)' AND h/phi = ,XX
    WRITE(6,*)'=, WITH A FILLET ANGLE OF 90 DEGREES ;==
    TEMP = 2.65298E-2 + 5.62617E-2*XX - 1.39414E-3*XX**2
    - 1.86339E-4*XX**3 + 2.27339E-5*XX**4
    THEIAO = THEIAO + TEMP * PLATE(THICK)
    TEMP = 4.22389E-2 + 1.67399E-2 * XX - 2.69005E-3*XX**2
    IF(TEMP.LT.0.0)TEMP = 0.0
    HCONVO = HCONVO + TEMP
    HDELSO = 10.61 - 0.925*XX + 0.0805*XX**2
  ELSE
    WRITE(7,*)'=, WITH A FILLET ANGLE OF 45 DEGREES ;==
    WRITE(7,*)' AND h/phi = ,XX
    WRITE(6,*)'=, WITH A FILLET ANGLE OF 45 DEGREES ;==
    TEMP = 6.838E-3 + 4.52164E-2*XX - 6.09026E-3*XX**2
    + 2.80637E-4*XX**3
    THEIAO = THEIAO + TEMP * PLATE(THICK)
    TEMP = 5.04484E-4 + 2.10234E-2*XX - 2.52079E-3*XX**2
    + 2.31132E-5*XX**3
    IF(TEMP.LT.0.0)TEMP = 0.0
    HCONVO = HCONVO + TEMP
    HDELSO = 10.51 - 0.609*XX + 0.05243*XX**2
  ENDIF
  DSTAR(I) = THEIAO * HCONVO
  HCONV(I) = HCONVO
  THEIA(I) = THEIAO
  HDELS(I) = HDELSO
  DELS(I) = HDELS(I) * THEIA(I)
  DELSO = DELS(I)
  RETH(I) = (U(I)*DSTAR(I)*THEIA(I))/VIS
  Q(I) = (U(I)*DSTAR(I)-U(I-1)*DSTAR(I-1))/STEPX
  FFSIG = 0
ENDIF
IF((BLDIST.GT.TENODE).AND.(BFSIG.EQ.1))THEN
  XX = PLATE(THICK)/THEIA(I)
  IF(XX.GT.10.0)XX = 10.0
  WRITE(7,*)'=, PLATE TRAILING EDGE HAS BEEN ENCOUNTERED ;==
  WRITE(6,*)'=, PLATE TRAILING EDGE HAS BEEN ENCOUNTERED ;==
  IF((PHLEQ.1)THEN
    WRITE(7,*)'=, WITH A FILLET ANGLE OF 90 DEGREES ;==
    WRITE(7,*)' AND h/phi = ,XX
    WRITE(6,*)'=, WITH A FILLET ANGLE OF 90 DEGREES ;==
    TEMP = 0.121442 - 2.73892E-3*XX
    THEIAO = THEIAO + TEMP * PLATE(THICK)
    TEMP = 1.70535E-2 - 3.26111E-3*XX
    HCONVO = HCONVO + TEMP
    HDELSO = 9.626 - 0.568*XX + 0.0408*XX**2
  ELSE
    WRITE(6,*)'=, WITH A FILLET ANGLE OF 45 DEGREES ;==
    WRITE(7,*)'=, WITH A FILLET ANGLE OF 45 DEGREES ;==
    WRITE(7,*)' AND h/phi = ,XX
    TEMP = 1345.27 - 3.62108E-3*XX
    THEIAO = THEIAO + TEMP * PLATE(THICK)

```

```

      TEMP = 1.95675E-2 - 1.48458E-3*XX
      HCONVO = HCONVO + TEMP
      HDELSO = 0.807 - 0.664*XX + 0.0483*XX**2
    ENDIF
    DSTAR(I) = THEIAO * HCONVO
    HCONV(I) = HCONVO
    THETA(I) = THETAO
    HDELS(I) = HDELSO
    DELS(I) = HDELS(I) * THETA(I)
    DELSO = DELS(I)
    RETH(I) = (U(I)*THETA(I))/VIS
    Q(I) = (U(I)*DSTAR(I)-U(I-1)*DSTAR(I-1))/STFPX
    BFSIG = 0
  ENDIF
  ++++++
  RHT=RH(I)
  RDEN=RDE(I)
  IF(RDEN.LT.2.0.OR.RDEN.GT.140.)RDEN=140.
  RHMIN=1./REYNO
  IF(RHT.LT.RHMIN) RHT=RHMIN
  II=I+1
  IF(FLAG(4).EQ.1)GO TO 6
  IF(FLAG(1).EQ.0) THEN
    -----
    *          LAMINAR FLOW REGION
    *          (Thwaites' Method)
    -----
    IF(I.EQ.1.OR.IEQ.NLS)THEN
      WRITE(6,17)
      WRITE(6,18)
    17 FORMAT(//,'LAMINAR FLOW REGION')
    18 FORMAT(' - - - - - ')
      WRITE(6,19)
      WRITE(6,20)
      WRITE(6,19)
    19 FORMAT(/,'
1-----')
    20 FORMAT(/,' 1   S/C   U/Uref   DU/DS   DELSTAR/C   THEIA/
1C  H   Rex   Reth   Cf   SOR ')
    END IF
    IF(I.EQ.1) THEN
      IF(FLAG(10).EQ.0)THETA(1)=0.0
      IF(FLAG(10).EQ.1)THETA(1)=SQRT(0.075/(REYNO*DU(1)))
    END IF
    IF(I.EQ.NLS)THEN
      IF(FLAG(10).EQ.0)THETA(NLS)=0.0
      IF(FLAG(10).EQ.1)THETA(NLS)=SQRT(0.075/(REYNO*DU(NLS)))
    END IF
    LAMBDA=THETA(I)**2.0*DU(I)*REYNO
    *
    *
    *          CHECK FOR LAMINAR SEPARATION
    *
    IF(LAMBDA.LT.-0.0842)THEN
      BFSIG = 0
      BFSIG = 0
      CALL LAMSEP
      GO TO 100
    END IF
    *
    *
    *          CALL SUBROUTINE "THWAITS" WHICH DETERMINES
    *          THE VALUES OF THWAITS PARAMETERS
    *
    CALL THWAITS
    RETH(I)=U(I)*THETA(I)*REYNO

```

```

DSIAR(I)=HCONV(I)*THEIA(I)
IF (I EQ 1 OR I EQ NLS) THEN
  CFI(I)=(2.0*Lj)/(REYNO*THEIA(I))
  REX(I)=0.0
  Q(I)=DSIAR(I)*DU(I)
  GO TO 91
END IF
90 CONTINUE
  CFI(I)=(2.0*Lj)/(REYNO*THEIA(I)*U(I))
  REX(I)=U(I)*X(I)*REYNO
  Q(I)=(U(I)*DSIAR(I)-U(I-1)*DSIAR(I-1))/STEPX
91 CONTINUE
  ***CRITERION FOR ROUGHNESS-INDUCED TRANSITION
  TCRIT=SQRT(CFI(I)/2.)*RETH(I)*U(I)*REYNO
  WRITE(6,23)IX(I),U(I),DU(I),DSIAR(I),THEIA(I),HCONV(I),
  1      REX(I),RETH(I),CFI(I),Q(I)
23 FORMAT(I3.5X,F4.3,4X,F6.4,5X,F8.4,4X,F8.7,2X,F8.7,2X,F5.3,2X,
  1      E10.5,2X,E10.5,2X,E10.5,2X,F9.7)
  IF(FLAG(2).EQ.0.AND.I.LGT.NPT) THEN
    WRITE(6,19)
    GO TO 100
  END IF
  IF(FLAG(2).EQ.1.AND.I.LGT.NPT) THEN
    WRITE(6,19)
    GO TO 100
  END IF
  *
  * THE TRAPEZOIDAL RULE IS NOW USED TO INTEGRATE
  * THE DIFFERENTIAL EQUATION FROM "I" TO "I+1"
  *
  SUM=0.225*(U(I)**5+U(I+1)**5)*(X(I+1)-X(I))/REYNO
  THEIA(I+1)=SQRT(((THEIA(I)**2)*(U(I)**6)+SUM)/(U(I+1)**6))
  IF (I EQ 2) THEIA(2)=THEIA(1)
  IF (I EQ NLSS) THEIA(NLSS)=THEIA(NLS)
  *****
  * TEST FOR TRANSITION - SUCCTION PEAK OR ROUGHNESS-INDUCED
  *****
  IF(FLAG(3).EQ.1.AND.FLAG(2).EQ.0.AND.IEQ.ITRANS.OR.TCRIT.GT.20.)
  * THEN
    WRITE(7,*) 'The point of forced transition (based on max peak vel'
    WRITE(7,*) 'or roughness on the upper airfoil surface has been'
    *reached'
    WRITE(7,*) ' '
    WRITE(7,*) 'Turbulent calculations have begun.'
    WRITE(7,*) ' '
    WRITE(6,19)
    WRITE(6,24)
24 FORMAT(/, 'THE POINT OF FORCED TRANSITION (UPPER SURFACE) HAS',/,
  1      'BEEN REACHED. TURBULENT CALCULATIONS HAVE BEGUN.')
    ITRANS=1
    FLAG(1)=1.0
    GO TO 6
  END IF
  *****
  * TEST FOR TRANSITION
  * (Using H-Rex Method)
  *****
  IF(FLAG(4).EQ.1.AND.FLAG(2).EQ.1.AND.X(I).GE.XTP(1)) THEN
    WRITE(7,*) 'The point of forced transition has been reached on the'
    WRITE(7,*) 'lower airfoil surface.'
    WRITE(7,*) ' '
    WRITE(7,*) 'Turbulent calculations have begun.'
    WRITE(7,*) ' '

```

```

WRITE(6,19)
WRITE(6,25)
25 FORMAT(/, 'THE POINT OF FORCED TRANSITION (LOWER SURFACE) HAS',
1 ' BEEN REACHED. TURBULENT CALCULATIONS HAVE BEGUN')
ITRANS=1
FLAG(1)=1.0
GO TO 6
END IF
IF(FLAG(3).EQ.0)THEN
IF(HCONV(1).GT.2.1.AND.HCONV(1).LE.3.1)THEN
RLOG= -40.4557+(64.8066*HCONV(1))-(26.7538*(HCONV(1)**2.0))
+ (3.3819*(HCONV(1)**3.0))
RE9=10.0**RLOG
END IF
IF(HCONV(1) GE.1.9.AND.HCONV(1).LE.2.1)THEN
RLOG= -40.4557+(64.8066*2.1)-(26.7538*(2.1**2.0))
+ (3.3819*(2.1**3.0))
RE9=10.0**RLOG
END IF
IF(HCONV(1).LE.1.9.OR.HCONV(1).GT.3.1)THEN
WRITE(7,*) 'The shape factor H is outside the applicable range of'
WRITE(7,*) 'the H-Rex method for predicting the point of transition'
*
WRITE(6,19)
WRITE(6,28)
28 FORMAT(/, 'SHAPE FACTOR H IS OUTSIDE THE APPLICABLE RANGE OF',
* ' H-Rex METHOD--STOP')
GO TO 100
END IF
IF(REX(1).GE.RE9)THEN
IF(FLAG(2).EQ.0)THEN
WRITE(7,*) '
WRITE(7,*) 'The H-Rex method has predicted transition on the upper'
WRITE(7,*) 'airfoil surface. The turbulent calculations have begun'
WRITE(7,*) '
WRITE(6,19)
WRITE(6,26)
26 FORMAT(/, 'THE H-Rex METHOD HAS PREDICTED TRANSITION ON THE',
1 ' UPPER AIRFOIL SURFACE')
END IF
IF(FLAG(2).EQ.1)THEN
WRITE(7,*) '
WRITE(7,*) 'The H-Rex method has predicted transition on the lower'
WRITE(7,*) 'airfoil surface. The turbulent calculations have begun'
WRITE(7,*) '
WRITE(6,19)
WRITE(6,27)
27 FORMAT(/, 'THE H-Rex METHOD HAS PREDICTED TRANSITION ON THE',
1 ' LOWER AIRFOIL SURFACE')
END IF
IF(FLAG(4).EQ.0)GO TO 100
ITRANS=1
FLAG(1)=1.0
GO TO 6
END IF
END IF
END IF
6 CONTINUE
=====
* ROUGH WALL TURBULENT FLOW REGION
* [Dvoraks' Method (1969)]
=====
IF(FLAG(4).EQ.0)GO TO 5

```

```

      IF (FLAG(1).EQ.1) THEN
      IF (I.EQ.1 TRANS OR I.EQ.NS) THEN
      WRITE(6,29)
      WRITE(6,30)
29 FORMAT(/,' TURBULENT FLOW REGION')
30 FORMAT(' ')
      WRITE(6,31)
      WRITE(6,32)
31 FORMAT(/,
      *
      *
      *
32 FORMAT(/, ' U S/C U/Uref DU/DS DESTAR/C THETA/C H
      * Rex Reth CF Utau*K/NU HDELS DELS SOR')
      WRITE(6,31)
      END IF
      *
      * CALCULATE THE INITIAL VALUE (for turbulent calculations)
      * OF H DELTA-DELTA STAR, EQUAL TO G(Hconv)
      *
      IF (I.EQ.1 TRANS OR I.EQ.NS) THEN
      IF (AHCONV.GT.1.6) GO TO 33
      HDELS(I)=3.3+EXP(0.4667-2.722*LOG(AHCONV-0.6798))
      GO TO 34
33 HDELS(I)=3.3+EXP(0.4385-3.064*LOG(AHCONV-0.6798))
34 CONTINUE
      U1=U(I)
      * INITIALISE THETA FOR TURBULENT B.L. CALCS
      IF ((FLAG(4)).EQ.1) THEN
      THETA(I)=ATHETA
      END IF
      IF (FLAG(4).EQ.2) THEN
      IF (RDE(I).LE.0.0) RDE(I)=140.
      THETRGH=10.0*RH(I)/RDE(I)
      IF (THETRGH.GT.THETA(I)) THETA(I)=THETRGH
      END IF
      HCONV(I)=AHCONV
      DELS(I)=HDELS(I)*THETA(I)
      IJJ=0
      CFOI=CFO
      *
      * INITIAL CF IS CALCULATED USING INPUT H, ESTIMATED CF AND LOCAL
      * THETA, UNLESS LOCAL THETA (UPPER SURFACE) IS LESS THAN INPUT
      * THETA, IN WHICH CASE THE LATTER IS USED ON UPPER SURFACE
      *
      THETINI=THETA(I)
      IF (THETINI.LT.ATHETA AND I.LT.NPTU) THETINI=ATHETA
      CFINIL=CFOO(CFOI,AHCONV,THETINI,VIS,U1,RHT,RDEN,JJJ)
      CFI(I)=CFINIL
      UKONU(I)=SQRT(CFI(I)/2.0)*RHT*U(I)*REYNO
      REX(I)=U(I)*X(I)*REYNO
      RETH(I)=U(I)*THETA(I)*REYNO
      DSTAR(I)=HCONV(I)*THETA(I)
      IF (FLAG(4).EQ.2) THEN
      Q(I)=(U(I)*DSTAR(I)-U(I-1)*DSTAR(I-1))/STEPX
      END IF
      IF (FLAG(4).EQ.1) THEN
      Q(I)=ABS(DSTAR(I)*DU(I))
      END IF
      END IF
      WRITE(6,35) I,X(I),U(I),DU(I),DSTAR(I),THETA(I),HCONV(I),
      * REX(I),RETH(I),CFI(I),UKONU(I),HDELS(I),DELS(I),Q(I)
35 FORMAT(I3,2X,F5.3,2X,F6.4,2X,F7.3,2X,F8.7,2X,F8.7,2X,F5.3,2X,

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```

      E10.5,1X,F7.0,1X,E10.5,1X,E10.5,2X,F6.3,2X,F8.7,2X,F8.0)
      IF (L.EQ.NFT) THEN
        WRITE(6,*)'NO FLOW SEPARATION'
      C      HCONV(I)=0.1
        GO TO 314
      END IF

      THE "OLD" OR INITIAL VALUES TO BE USED TO FIND THE VALUES
      AT THE NEXT STATION ARE TAKEN AS THE VALUES AT THE PRESENT

      CFO1=CFI(I)
      HCONVO=HCONV(I)
      THETA0=THETA(I)
      U1=U(I)
      U2=U(I+1)
      HDEL0=HDELS(I)
      DEL0=DELS(I)
      DUP=DU(I)
      DXP=DX(I)

      NUMERICAL CHECK TO DETERMINE IF THE TURBULENT BOUNDARY
      LAYER HAS SEPARATED FROM EITHER AIRFOIL SURFACE

314 IF(HCONV(I).GT.3.0)THEN
      CALL TURBSEP
      BFSIG = 0
      FFSIG = 0
      GO TO 100
      END IF

      CALL SUBROUTINE RUNGEK TO INTEGRATE THE DIFFERENTIAL
      EQUATIONS IN ORDER TO FIND VALUES FOR HCONV, THETA,
      DELTA-DELTASTAR, H DELTA-DELTASTAR, CF AND SOURCE
      STRENGTH AT THE NEXT STATION

      CALL RUNGEK(CFO1,HCONVO,THETA0,VIS,U1,U2,RHT,RDEN,U,HDEL0,
      DEL0,DUP,HCONVN,THETAN,DELSN,HDELSN,CFN,DXP)

      UPDATING THE INITIAL VALUES

      HCONVO=HCONVN
      THETA0=THETAN
      HDEL0=HDELSN
      DEL0=DELSN
      HCONV(I+1)=HCONVN
      THETA(I+1)=THETAN
      DELS(I+1)=DELSN
      HDELS(I+1)=HDELSN
      CFI(I+1)=CFN
      UKONU(I+1)=SQRT(CFI(I+1)/2.0)*RHT*REYNO*U(I+1)
      DSTAR(I+1)=HCONV(I+1)*THETA(I+1)
      REX(I+1)=(U(I+1)*X(I+1))/VIS
      RETH(I+1)=(U(I+1)*THETA(I+1))/VIS
      Q(I+1)=(U(I+1)*DSTAR(I+1)-U(I)*DSTAR(I))/STEPX
      END IF
5 CONTINUE
      IF(L.EQ.NF)GO TO 99
2 CONTINUE
99 CONTINUE
      WRITE(6,31)
100 CONTINUE

      CALL THE SUBROUTINE "XPOSEP" WHICH DETERMINES
      THE CARTESIAN "X" POSITION OF THE UPPER AND
      LOWER SURFACE SEPARATION POINTS

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```

      CALL XPOSEP
      IF ONLY ONE SURFACE OR ONE TEST RUN IS TO BE
      PERFORMED, TRANSFER CONTROL
      IF (FLAG(8).EQ.0) GO TO 11
      CHANGE THE OBJECT OF DO LOOP 2 IN ORDER FOR THE
      PROGRAM TO CALCULATE THE DEVELOPMENT OF THE
      LOWER SURFACE BOUNDARY LAYER
      IF (NF.EQ.NPT) GO TO 14
      IF (NS.EQ.1.AND.NF.EQ.NPTU) THEN
        NS=NLS
        NF=NPT
        CFO1=CFO
        IF (FLAG(4).EQ.0) FLAG(1)=0
        IF (FLAG(4).EQ.1) FLAG(1)=1
        IF (FLAG(4).EQ.2) FLAG(1)=0
        FLAG(2)=1.0
        WRITE(6,38)
        WRITE(6,39)
38 FORMAT(//,40X,'BOUNDARY LAYER PARAMETERS LOWER AIRFOIL SURFACE')
39 FORMAT(40X,'-----')
        GO TO 3
      ELSE
        GO TO 14
      END IF
14 CONTINUE

      CALL THE SUBROUTINE "DISPLACE" IN ORDER TO
      GENERATE A FILE OF THE SOURCE STRENGTHS AT
      THE AIRFOIL JUNCTION POINTS
      IF (FLAG(5).EQ.1) THEN
        CALL DISPLACE
      END IF
      IF (THICK.NE.0) THEN
        TEMP = PLATE(THICK)*109.2362
        WRITE(7,*) 'THE PLATE THICKNESS = ' .TEMP
      ELSE
        WRITE(7,*) 'NO PLATE'
      ENDIF
      STOP
      END

      SUBROUTINE INPUT
      *****
      ***** B-14 *****
      *****
      This subroutine controls the reading in all of the
      required data necessary to run the boundary layer program
      *****
      IMPLICIT INTEGER(I-N),REAL(A-H,O-Z)
      *INCLUDE HLA2.CMN
      INTEGER FLAG,FFSIG,BFSIG,THICK,PHI
      REAL NAM1,NAM2,NAM3,LAMBDA,LLEPOS,LENODE
      READ(5,1) NAM1,NAM2,NAM3
1 FORMAT(3A4)
      READ(5,2) ALPHA,FLAG(4)
2 FORMAT(F6.2,X,I1)
      READ(5,3) CHORD,UREF,STEPX
3 FORMAT(F6.4,X,F9.4,X,F7.4)
      READ(5,4) ATHE1A,AHCONV,CRO
4 FORMAT(4X,F8.7,2X,F8.5,2X,F8.7)

```

```

      READ(5,5)RDEN,RHT,REYNO
      5 FORMAT(F12.6,2X,F8.6,3X,F9.0)
      READ(5,6)NTOT,NUPNLOW
      6 FORMAT(I3,2X,I2,2X,I2)
      ++++++
      * SECOND MODIFICATION - JULY 1990 : DATA ENTRY
      *****
      * THE PLATE LEADING AND TRAILING EDGE POSITIONS AND
      * CORRESPONDING FLAGS ARE SET HERE.
      *****
      WRITE(7,99)
      READ(2,*)THICK
      IF(THICK.EQ.0)THEN
        FFSIG = 0
        BFSIG = 0
        DO 577 I = 1,NTOT
          READ(5,7)XCART(I),XC(I),UC(I),RDENS(I),RHTT(I)
577   CONTINUE
          GOTO 579
        ENDIF
        WRITE(7,*)'Enter the chord position (x/c) of the plate LE.'
        READ(2,*)LEPOS
        WRITE(7,*)'Enter the chord position (x/c) of the plate TE.'
        READ(2,*)TEPOS
        FFSIG = 1
        BFSIG = 1
99   FORMAT(2X,'Enter the plate thickness:'./,
        *'NO PLATE' =_ 0'./,
        *'1/2 in. =_ 1'./,
        *'3/8 in. =_ 2'./,
        *'1/4 in. =_ 3'./,
        *'1/8 in. =_ 4'./,
        *'1/16 in. =_ 5'./,
        *'1/32 in. =_ 6')
        * The plate thickness is in units of (mm/chord) where chord = 2774.6mm
        PLATE(1)=.00457722
        PLATE(2)=.0034329
        PLATE(3)=.00225257
        PLATE(4)=.0011443
        PLATE(5)=.00057215
        PLATE(6)=.00028608
        WRITE(7,*)'Enter the fillet angle:'
        WRITE(7,*)'90 deg =_ 1'
        WRITE(7,*)'45 deg =_ 2'
        READ(2,*)PHI
        DO 578 I=1,NTOT
          READ(5,7) XCART(I),XC(I),UC(I),RDENS(I),RHTT(I)
          IF(I.GE.2)THEN
            IF(XCART(I).GT.XCART(I-1))THEN
              IF((XCART(I).GT.LEPOS).AND.(FFSIG.EQ.1))THEN
                FFSIG = 0
                LENODE = XC(I)
              ENDIF
              IF((XCART(I).GT.TEPOS).AND.(BFSIG.EQ.1))THEN
                BFSIG = 0
                TENODE = XC(I)
              ENDIF
            ENDIF
          ENDIF
578   CONTINUE
          FFSIG = 1
          BFSIG = 1
579   CONTINUE
      ++++++

```



```

7 FORMAT(3(F8.5),(F9.5),(F9.6))
WRITE(7,*) 'The current type of boundary-layer analysis is.'
WRITE(7,*) ' '
IF(FLAG(4).EQ.0)WRITE(7,*) 'Laminar flow analysis only.'
IF(FLAG(4).EQ.1)WRITE(7,*) 'Turbulent flow analysis only.'
IF(FLAG(4).EQ.2)WRITE(7,*) 'Full Laminar-Turbulent flow analysis.'
WRITE(7,*) ' '
WRITE(7,*) 'Do you want to change the type of analysis?'
WRITE(7,*) 'ENTER 0-NO, 1-YES: ANS = 1-YES'
C 10 READ(2,*)FLAG(9)
FLAG(9) = 0
C 13 FORMAT(1G)
IF(FLAG(9).EQ.1)THEN
WRITE(7,*) ' '
WRITE(7,*) 'Enter the number corresponding to the type of'
WRITE(7,*) 'boundary-layer analysis desired.'
WRITE(7,*) ' '
WRITE(7,*) 'Enter 0 Laminar analysis only.'
WRITE(7,*) 'Enter 1 Turbulent analysis only.'
WRITE(7,*) 'Enter 2 Full Laminar-Turbulent analysis.'
READ(2,*)FLAG(4)
C 14 FORMAT(1G)
END IF
IF(FLAG(4).EQ.0.OR.FLAG(4).EQ.2)THEN
WRITE(7,*) ' '
WRITE(7,*) 'Enter the number code corresponding to the type of'
WRITE(7,*) 'initial condition for the laminar flow calculations.'
WRITE(7,*) '+++++; ANS: 1'
WRITE(7,*) 'ENTER 1 Analysis begins at a stagnation point.'
WRITE(7,*) 'ENTER 0 Flat plate analysis'
WRITE(7,*) ' (i.e. initial cond. zero thick. bound. layer)'
C 10 READ(2,*)FLAG(10)
FLAG(10)=1
C 15 FORMAT(1G)
END IF
WRITE(7,*) ' '
WRITE(7,*) 'Do you want the program to perform the boundary layer'
WRITE(7,*) 'analysis on both the upper and lower airfoil surfaces?'
WRITE(7,*) 'ENTER 0-NO, 1-YES +++++; ANS = 1-YES'
WRITE(7,*) 'Entering 0 will not create an output file for stampplot'
C 10 READ(2,*)FLAG(8)
FLAG(8) = 1
C 12 FORMAT(1G)
IF(FLAG(4).EQ.2.OR.FLAG(4).EQ.0)THEN
WRITE(7,*) 'Select the transition criterion.'
WRITE(7,*) ' '
WRITE(7,*) ' '
WRITE(7,*) 'Two options are available for implementation.'
WRITE(7,*) 'ENTER 0 Use the H-Rex method of predicting transition'
WRITE(7,*) ' '
WRITE(7,*) 'ENTER 1 Fix the upper surface transition point'
WRITE(7,*) ' at the peak velocity position.'
WRITE(7,*) '+++++; ANS: = 1'
FLAG(3) = 1
C 10 READ(2,8)FLAG(3)
C 8 FORMAT(1I)
END IF
IF(FLAG(3).EQ.1.AND.FLAG(8).EQ.1)THEN
WRITE(7,*) 'Enter the surface linear distance length'

```

```

      WRITE(7,*)'(for the transition point) on the lower airfoil surface
      "+++++; ANS: = 0.15"
C     READ(2,*)XTP(1)
      XTP(1) = 0.15
C     9 FORMAT(1G)
      END IF
-
-   IF A SOURCE DISTRIBUTION IS DESIRED FOR USE WITH
-   "CAMP" THEN THE NEXT STATEMENT SETS THE FLAG
-
      IF(FLAG(8).EQ.1) THEN
-
-       WRITE(7,*)'Do you want a source strength distribution (at the'
-       WRITE(7,*)'airfoil junction points) for use in the STAMP program'
-       WRITE(7,*)'ENTER 0-NO, 1-YES'
-       READ(2,11)FLAG(5)
-
-   11 FORMAT(I1)
      FLAG(5)=1
      END IF
      RETURN
      END

```

END

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FIN