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The Aerodynamic Effects of Roughness on the Performance of a Turbine Cascade.

By

**Michael William Paul Abbott
B.Eng. (Mechanical Engineering)**

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

MASTER OF ENGINEERING

**OTTAWA-CARLETON INSTITUTE FOR MECHANICAL
AND AEROSPACE ENGINEERING**

**DEPARTMENT OF MECHANICAL AND AEROSPACE ENGINEERING
CARLETON UNIVERSITY
OTTAWA, CANADA
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**"The Aerodynamic Effects of Roughness on the
Performance of a Turbine Cascade."**

submitted by Michael William Paul Abbott, B.Eng.
in partial fulfilment of the requirements for
the degree of Master of Engineering

Thesis Supervisor, R.J. Kind

Chair, Department of Mechanical and Aerospace Engineering

Carleton University

September 1993

Abstract

A review of the literature has shown that the majority of experimental research on the effects of surface roughness on turbine blades, has been conducted using profiles which were completely covered with roughness. The objective of the present study is to establish a database of profile loss and flow deflection data, for a current turbine profile design which is partially covered with surface roughness. Measurements were made of the flow at mid-span in a two-dimensional cascade of blades. A randomly distributed sand grain roughness was applied to the blades in spanwise strips. Examination of the flow was made for design and off-design conditions, with varying configurations of the surface roughness.

Different roughness configurations were investigated by varying the roughness height, the location of the roughness strip, and the width of the roughness strip. All three of these parameters were found to have a substantial effect on the losses. In general, increasing the roughness height and the width of the roughness strip caused a significant increase in the total-pressure-loss, but only a small decrease in the outlet flow angle. Roughness was applied both upstream and downstream of mid-chord on the suction surface. Roughness strips at or upstream of mid-chord had a significant effect on the flow, while the flow was relatively insensitive to roughness near the trailing edge. Measurements at off-design incidence showed that the overall shape of the total-pressure-loss and flow deviation curves was preserved for the roughened blades with both curves being uniformly shifted.

Dedication

For my grandparents and my parents, without whose sacrifice and hard work, my efforts could not be possible.

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Nomenclature

A_f	Frontal area of roughness element
A_p	Plan area of roughness element
A_T	Total plan area of surface
AVR	Axial velocity ratio
b	Grid bar width
C	Blade chord
C_f	Skin friction coefficient, $C_f = 2 \tau_w / \rho U^2$
Cp_0	Total-pressure-loss coefficient normalized by reference dynamic pressure. $Cp_0 = (P_{0ref} - P_{02}) / q_{ref}$
Cx	Blade axial chord
D	Pipe diameter
f	Resistance factor
G	Clauser's (1954) pressure gradient parameter (see Equation 2.26)
H	Blade span, also shape factor
Δh	Change in enthalpy
i	Angle of incidence, $i = \alpha_1 - \alpha_{ides}$
k	Roughness height
k_s	Equivalent sand roughness height
K_1, K_{12}, K_{13} $K_{\phi 2}, K_{\phi 3}, K_{23}$	Probe calibration coefficients
l	Mixing length (see Equation 2.13)
$\dot{m}$	Mass flow rate
M	Mesh interval size
P	Pressure measure by probe port
P_s	Static pressure
P_0	Total pressure
q	Dynamic pressure

r	Pipe radius
Re	Reynolds number
s	Blade coordinate for roughness location, measured in chordwise direction
Δs	Blade coordinate for roughness strip width, measured along blade profile
S	Blade pitch or spacing
Tu	Turbulence intensity (see Equation 4.10)
u	Flow velocity in streamwise direction
u'	Fluctuating component of streamwise velocity
U	Freestream flow velocity, or maximum velocity for pipe flow
u*	Friction velocity, $u^* = (\tau_w / \rho)^{1/2}$
V	Velocity in streamwise direction
V_x	Velocity in axial direction
x	Coordinate in axial direction, also coordinate in direction of flow
X	Downstream distance of measuring plane from turbulence grid
y	Coordinate perpendicular to axial direction, also coordinate perpendicular to flow direction
Δy	Effective wall location according to Schlichting (1936)
Y	Total-pressure-loss coefficient normalized by outlet dynamic pressure (see Equation 2.3 and Equation 4.16)
Δz	Effective wall location according to Coleman, et. al. (1984)
α	Flow angle measured from axial direction
β	Blade metal angle measured from axial direction
γ	Blade stagger angle
δ	Flow deviation angle, $\delta = \alpha_2 - \beta_2$, also boundary layer thickness
δ^*	Boundary layer displacement thickness $\delta^* = \int_0^{\delta} \left(1 - \frac{u}{U} \right) dy$
η	Efficiency (see Equation 2.27)
θ	Blade camber angle
λ	Simpson's (1973) roughness spacing parameter, $\lambda = A_1 / A_t$

λ_D	Dvorak's (1969) roughness spacing parameter. $\lambda_D = A_1 / A_r$
λ_s	Schlichting's (1936) roughness density parameter. $\lambda_s = A_r / A_1$
μ	Fluid dynamic viscosity
ν	Fluid kinematic viscosity
ρ	Fluid density
σ	Blade passage throat opening
τ_w	Shear stress at the wall
ϕ^2	Kinetic energy loss (see Equation 2.4)

Subscripts:

des	design
l.e.	blade leading edge
m	fully mixed-out losses
ref	test-section reference plane
t.e.	blade trailing edge
1	inlet measuring plane
2	outlet measuring plane
-	(overbar) mass-averaged quantity

Chapter 1: Introduction

This thesis reports on an experimental investigation into the effects of surface roughness on the performance of gas-turbine blades. During the course of operation, the turbine blades of a gas turbine engine can experience damage in a variety of forms. One form of damage is a roughening of the otherwise smooth surface of the blades. Gas turbine blades are manufactured with great care and to very stringent tolerances, to minimize the deviation from the required profile. However, once in operation, there are several factors which can cause surface roughness to develop on the blades.

The blades are subject to erosion, corrosion and deposit contamination because of their operating environment. Erosion can be caused by impurities entrained in the air and fuel, which impinge upon the blade. Industrial gas turbines which use non-refined fuel, are particularly prone to build up of combustion products and impurities. Both of these phenomena lead to roughening of the blade surface.

Erosion tends to occur near the leading edge of the blades and particularly on blades in the early stages of the turbine. Deposition occurs all over the blade, particularly on the rear portion of the profile, and is more common in the latter stages of a turbine. Erosion of the profile can cause thinning of the leading edge. Deposition generally causes thickening of the profile, but the deposit can sometimes split off removing some of the base metal and resulting in thinning of the blade.

Surface roughening can cause several unfavourable phenomena such as:

- 1) Changes of the blade aerodynamic characteristics.
- 2) Changes of the strength and dynamic characteristics of the blade due to altering of the mass distribution. Deposition generally increases the centrifugal forces experienced by the blade.
- 3) Acceleration of fatigue because of changes in material properties from corrosion or due to notching effects caused by erosion.

These phenomena generally lead to a decrease in the turbine efficiency. However, severe deterioration of the blades can result in a failure of the blade which can have serious consequences. Study of the effects of surface roughness can lead to a method of determining how the presence of surface roughness on turbine blades will affect their performance. This would allow those involved in engine health monitoring to determine when it would be profitable to replace the blades, or when it would be hazardous to not replace them.

The present study will focus on the changes in the blade aerodynamics. The principal effect of surface roughness is to alter the boundary layer on the blade surface. This alteration may take several forms:

- 1) Change in the friction losses.
- 2) Change in location of the laminar-to-turbulent transition.
- 3) Change in boundary layer separation position.

The present work was undertaken to experimentally measure the two-dimensional aerodynamic effects which spanwise strips of roughness have on the performance of a gas turbine blade. A review of the literature revealed that most experimental work had examined blade profiles which had been completely covered with surface roughness. Measurements for this study were made in a two-dimensional turbine cascade, using sand grain roughness applied to portions of the blades.

Roughness characteristics can be classified in various ways. The elements used for the roughness simulation can be two-dimensional (such as rectangular bars or strips, placed transverse to the flow) or three-dimensional (such as sand grains or glass beads). The roughness elements can be discrete or distributed, and their geometry can be described as regular or random. One major difficulty of examining surface roughness is in defining the roughness. Several parameters are required to adequately describe the roughness geometry and its effect on the boundary layer. For random roughness, a statistical approach is used to determine if two surfaces are statistically equivalent. In the present study, a randomly distributed roughness was used, and a statistical measurement was employed to assist in describing the roughness.

The goal of the present work is to establish a database of profile loss and flow deflection information, for randomly distributed roughness. This experimental database will ultimately be used in the development of a computational method to predict the effects of surface roughness on the profile-loss and flow-deflection performance of turbine blade profiles.

This thesis includes an overview of the theory of rough surface boundary layer flows. In addition, the literature review surveys the experimental results of previous researchers from the early work in pipe and channel flows, up to measurements in cascades and turbines. A full description is given of the experimental apparatus and equipment used during this study. There is a detailed discussion of the measurement procedures undertaken during this experimental program. This includes the calibration of the three-hole probes, the application of the sand-grain roughness, the data measurement procedure, and data reduction. Then the results of the measurements are examined. There is a discussion of the effect of a turbulence generating grid on two-dimensional flow in the test section, and a review of the effect of each of the roughness parameters which were varied during this study. Finally, there is a summary of the results of this experimental program, and recommendations for future work.

Chapter 2: Literature Review

The detrimental effects of surface roughness have long been studied in both turbomachinery and general fluid flow applications. The majority of the early research on the effects of surface roughness, was conducted using pipe flow and flat plates. Later research was conducted using cascade blades and actual turbines. In this chapter, a review of the pertinent literature will be presented.

When designing a turbine, the ultimate goal is to achieve the best performance of the final full scale machine. Assessing the performance involves examining the losses developed in the machine. These losses will be viewed as the combined overall effect of several different loss mechanisms. It is useful to the designer to analyze the physical aspects of each loss mechanism individually, to improve the design of the turbine as a whole. The overall loss of a turbomachine blade row can be divided into the following loss components:

- 1) Profile Loss - Loss associated with the boundary layer growth on the blade

surfaces in a uniform two-dimensional flow.

- 2) Trailing Edge Loss - Loss associated with the finite thickness of the blade trailing edge. This loss is often grouped with the profile loss, for simplified comparison.
- 3) Annulus Loss - Loss due to the skin friction at the hub and the casing.
- 4) Tip Clearance Loss - Loss due to the leakage of fluid around the blade ends.
- 5) Secondary Loss - Loss due to cross flows near the endwall within the blade row.

When designing a turbine, each of these loss components are generally predicted for the blade row using empirical correlations. Three of the more prominent correlations are those of Ainley and Mathieson (1951) and the refined version by Kacker and Okapuu (1982), as well as Moustapha et. al. (1990). However, none of these correlations attempt to predict the effect of surface roughness on the loss.

There are other sources of loss such as disc windage loss, wetness loss in steam turbines, and partial admission loss. These are not correlated in terms of the total pressure loss but are accounted for as a net decrease in stage efficiency. Another important loss are mixing losses which are mechanical energy losses which arise because of mixing in a non-uniform flow. Much of the trailing edge loss is actually generated during the mixing process as the flows from the suction side and pressure side mix together downstream of the blade trailing edge. This study is mainly concerned with the effect of surface roughness on the profile loss. Therefore, the review of the literature will concentrate on the first and second types of losses, namely profile loss and trailing edge loss, which shall be considered together.

2.1 Terminology

2.1.1 Cascade Geometry

The notation commonly used for cascade geometry is illustrated in Figure 2.1. The true chord C is measured directly from leading edge to trailing edge, while the axial chord C_x is the chord measured in the axial direction. The blade stagger angle, γ , is defined as the angle between the blade chord direction and the axial direction. The inlet and exit metal angles of the blade are β_1 and β_2 . The inlet metal angle is selected by the designer to give the lowest profile losses at design conditions. For the present work, the off-design incidence i is defined as the difference between the actual inlet flow angle, α_1 , and the design inlet flow angle, α_{1des} (for the blade profile used, $\alpha_{1des} = \beta_1 + 3.00^\circ$, as indicated in Table A.1).

$$i = \alpha_1 - \alpha_{1des} \quad (2.1)$$

Some other blade geometry parameters include the blade spacing or pitch, S . The camber angle, θ , is the difference between the inlet and outlet metal angles. The throat width, σ , is the perpendicular distance between the trailing edge and the suction surface of the adjacent blade. Surface roughness can cause changes in the throat width due to deposition or erosion. The flow deviation angle, δ , is the difference between the outlet flow angle and blade exit metal angle.

$$\delta = \alpha_2 - \beta_2 \quad (2.2)$$

Figure 2.1: Cascade geometry and nomenclature - reproduced from Whitehouse (1993).

2.1.2 Losses

The two most important results of cascade testing are outlet flow angle α_2 and total-pressure-loss coefficient, Y . The results discussed in this study are losses and flow angles measured at mid-span, in a region of two-dimensional flow. The total-pressure-loss coefficient is the loss of total pressure through the blade row, normalized by the outlet dynamic pressure. For incompressible flow, Y is defined as:

$$Y = \frac{P_{01} - P_{02}}{\frac{1}{2} \rho V_2^2} \quad (2.3)$$

Another loss coefficient commonly used in the literature, is the kinetic energy loss coefficient, ϕ^2 . This is defined as the difference between the outlet isentropic velocity squared and the actual outlet velocity squared, normalized by the isentropic velocity squared:

$$\phi^2 = 1 - \frac{V_2^2}{V_{2\text{isen}}^2} \quad (2.4)$$

For incompressible flow, the kinetic energy loss coefficient can be related to the total-pressure-loss coefficient as:

$$Y = \frac{1}{1 - \phi^2} - 1 \quad (2.5)$$

2.2 Roughness Effects in Zero Pressure Gradient Flows

Most of the early work done on the effects of surface roughness was conducted on flat plates or in pipe flows, and therefore, in a flow of nominally zero pressure gradient. Some of these experiments used detailed analysis of the boundary layer to reveal information about the losses.

The turbulent boundary layer can be broken down into 3 regions of flow. Adjacent to the wall is the viscous sub-layer, where turbulent fluctuations are damped out and viscous shear stress dominates the layer. The thickness of this layer is approximately one hundredth of the boundary layer thickness. Above the viscous sub-layer is the log-law region of the boundary layer, in which the boundary layer velocity distribution can be represented as a logarithmic function. This occupies the region from 2% to 15% of the boundary layer. Flow in the viscous sub-layer and in the log-law region is controlled by the wall shear stress and is not directly dependent upon flow behaviour in the outer regions of the boundary layer (although the latter does influence the wall shear stress and thus has an indirect influence). The viscous sub-layer and log-law region together are known as the "law-of-the-wall" or inner region of the boundary layer. Outside of the log-law region, occupying the remainder of the boundary layer, is the outer region. This region is dominated by large turbulent eddies, and it is believed that viscosity plays no direct part in the velocity distribution. The velocity profile in the outer region of zero-pressure-gradient boundary layers follows the so-called "velocity defect law". The defect law also applies in the outer portion of the law-of-the-wall region (the "overlap region") and here the defect

law is also logarithmic in form. The logarithmic portion of the law-of-the-wall, for smooth walls, is:

$$\frac{u}{u^*} = \frac{1}{k} \ln\left(\frac{yu^*}{\nu}\right) + B \quad \text{Smooth Wall Log-Law} \quad (2.6)$$

The logarithmic portion of the defect law is:

$$\frac{U-u}{u^*} = -\frac{1}{k} \ln\left(\frac{y}{\delta}\right) + A \quad \begin{array}{l} \text{Velocity Defect Law} \\ \text{in overlap region} \end{array} \quad (2.7)$$

where: u^* = Friction Velocity

$$= \sqrt{\frac{\tau_w}{\rho}}$$

The applicability of these equations for smooth surfaces was shown in some of the earliest experimental flows.

Numerous papers have been written since the early 1900's, examining the effects of surface roughness. One of the earliest and most detailed papers was written by Nikuradse (1933). Nikuradse performed a very extensive series of experiments to measure the effects of fine and coarse roughnesses in pipe flow, for a wide range of Reynolds numbers. **Re**

Nikuradse used sand grains, adhered to the inside of pipes, at maximum density. Measurements were made of: loss of head, velocity distribution, flow rate, and water temperature. The data collected from these tests became the baseline of roughness data and this work was referred to in the majority of subsequent research.

Nikuradse determined a resistance factor f , for various values of Re and relative roughness (r/k). where:

$$Re = \frac{\bar{u} D}{\nu}$$

$$f = \frac{D}{\bar{q}} \frac{dP}{dx}$$

$\bar{u}$ = Average flow velocity

$\bar{q}$ = Dynamic pressure of average flow velocity

D = Pipe diameter

$$r = \frac{D}{2}$$

k = Average height of roughness elements

The relationship $f = f(Re, r/k)$ is illustrated in Figure 2.2. Three distinct régimes of flow were observed. First for low Re (laminar flow region, $Re < 2000$) the variation in relative roughness has no effect on the resistance factor. In this flow régime, the viscous sub-layer is thick enough that it covers all of the roughness projections, and they create no more additional loss than the smooth surface. The resistance factor in this region, is independent of roughness size and according to Schlichting (1936), is given by:

$$f = 0.0032 + \frac{0.221}{Re^{0.237}} \quad (2.8)$$

The skin friction stress on a roughened surface is composed of the effect of two forces: form drag on the roughness elements and viscous shear force. Form drag arises because of a difference in the pressure distribution around a roughness element exposed to

Figure 2.2: Relation between $\log(100 f)$ and $\log Re$ - from Nikuradse (1933).
(where $\lambda = f$)

the flow. Viscous shear force is the integrated fluid shear stresses exerted on the surface.

In the laminar flow régime, the skin friction is solely due to viscous shearing stress.

In the transition régime ($2000 < \text{Re} < 10^5$), both the relative roughness and Re have an effect on the resistance factor. In this region, the viscous sub-layer thickness is of the same order as the roughness size. Some of the roughness projections extend through the viscous sub-layer, causing them to shed vortices and produce mechanical energy loss. Also, as the Re increases, more of the roughness projections extend through the viscous sub-layer, further increasing the energy loss. Both viscous shearing stress and form drag contribute to the skin friction in this flow régime. For this range of flow, the resistance factor is given by:

$$f = \frac{1}{\left(a + b \log \left(\frac{u^* k}{\nu} \right) + 2 \log \frac{r}{k} \right)^2} \quad (2.9)$$

where a and b vary with the value of $\frac{u^* k}{\nu}$.

In the third régime ($\text{Re} > 10^5$), the flow is fully turbulent; many practical flows fall in this régime. The viscous sub-layer has become so thin that all of the roughness projections extend through it. In this region the skin friction is dominated by form drag. The energy loss due to the vortices associated with the form drag on the roughness projections, is constant and independent of Re , so it only varies with relative roughness. However, in actual gas turbines, the Reynolds number is not generally in the fully turbulent region, and so the resistance is not independent of Reynolds number. The resistance factor for fully turbulent pipe flow can be expressed by:

$$f = \frac{1}{\left(1.74 + 2 \log \frac{r}{k}\right)^2} \quad (2.10)$$

Rearranging the expression for resistance, and graphing it as a function of the friction velocity u^* :

$$\frac{1}{\sqrt{f}} - 2 \log \frac{r}{k} = f \left(\log \frac{u^* k}{v} \right) \quad (2.11)$$

In Figure 2.3, it is obvious that for the turbulent region

$$f \left(\log \frac{u^* k}{v} \right) = 1.74 \quad (2.12)$$

as required by Equation 2.10.

Measurements of the velocity distribution showed that near a rough wall, the velocity gradient is less steep and the overall distribution becomes more pointed (see Figure 2.4). Nikuradse also determined that the mixing length distribution was the same for both smooth and rough surfaces (see Figure 2.5) for large values of Re . Mixing length is given by:

Figure 2.3: Relation between resistance factor and roughness function - from Nikuradse (1933). (where: $\lambda = f \cdot \frac{v_*}{u_*^2}$)

Figure 2.4: Velocity distribution in fully rough flow - from Nikuradse (1933).

Figure 2.5: Mixing length distribution - from Nikuradse (1933)

$$l = \sqrt{\frac{\frac{\tau}{\rho}}{\left(\frac{du}{dy}\right)^2}} \quad (2.13)$$

where τ is the local shear stress in the flow. This suggests that the mechanics of turbulence are independent of the wall surface finish except very near the wall. The logarithmic law for velocity distribution remains valid for rough surfaces, with different constants of integration. According to Nikuradse, for fully rough flow over standard sand roughness, the logarithmic wall law is:

$$\begin{aligned} \frac{u}{u^*} &= A \log \frac{y}{k} + B' \\ &= 5.75 \log \frac{y}{k} + 8.5 \end{aligned} \quad (2.14)$$

This equation is graphed in Figure 2.6, and it is obvious that all of the experimental data for Nikuradse's sand roughness, for various relative roughness heights, collapses to correspond with the equation.

In the above equation, B is known as the roughness function. Nikuradse plotted the roughness function in Figure 2.7. It is seen to depend on the value of $\frac{u^*k}{\nu}$. From this, Nikuradse determined the flow régime to be given by:

hydraulically smooth:	$0 \leq \log \frac{u^*k}{\nu} < 0.55$
transitionally rough:	$0.55 \leq \log \frac{u^*k}{\nu} \leq 1.83$
fully rough:	$\log \frac{u^*k}{\nu} > 1.83$

Figure 2.6: Velocity distribution through boundary layer - from Nikuradse (1933)
(where: $v_* = u_*'$)

Figure 2.7: Relation between roughness function and roughness Reynolds number - from Nikuradse (1933) (where: $\lambda = f$, $v_* = u_*^*$)

When Nikuradse's results are plotted in law of the wall coordinates (Figure 2.8), it is found that the data can be represented by:

$$\frac{u}{u^*} = A \log \frac{yu^*}{\nu} + B - \frac{\Delta u}{u^*} \quad (2.15)$$

This is the familiar log-law of Equation 2.6, with the additional term $\frac{\Delta u}{u^*}$ which represents the shift in the intercept of the logarithmic velocity profile relation due to roughness. For the smooth case $\frac{\Delta u}{u^*} = 0$. Equation 2.15 reduces to Equation 2.14 if $\frac{\Delta u}{u^*} = A \log \frac{ku^*}{\nu} - 3.0$. The constants **A** and **B** have varied slightly from one author to another. Nikuradse determined them to be **A** = 5.75 and **B** = 5.5. Nikuradse also plotted the velocity distribution in defect form in Figure 2.9 and found that his data were well represented by:

$$\frac{U-u}{u^*} = A \log \left(\frac{r}{y} \right) \quad (2.16)$$

Schlichting (1936) performed similar roughness experiments using flow in a channel of rectangular cross section. The roughness was applied to one wall of the channel. Sand grains were either adhered to a flat plate, or roughness shapes were stamped in galvanized sheet iron. Schlichting used several shapes of roughness: spheres, spherical segments, cones, short and long angles.

Schlichting introduced a second parameter, roughness density, λ_s to describe the roughness. Nikuradse had only used the relative roughness r/k , with the sand grains

Figure 2.8: Relation between velocity and roughness Reynolds number - from Nikuradse (1933) (where: $\eta = u_*^2 k / \nu$, $v_* = u_*^*$)

Figure 2.9: Velocity defect distribution through boundary layer - from Nikuradse (1933). (where: $u_{max} = U$, $v_* = u_*^*$)

attached at a maximum density. Schlichting did not perform experiments with the roughness at a maximum density. Schlichting defined his density parameter as:

$$\lambda_s = \frac{A_F}{A_T} \quad (2.17)$$

where A_F is the total frontal area of all the roughness elements, and A_T is the total plan area of the plate. Thus a smooth plate would have a roughness density of $\lambda_s = 0$. Schlichting also used Nikuradse's data as a "standard sand roughness", and pointed out that a new roughness was fully known if one could identify the "equivalent sand roughness", k_s , or the size of roughness in Nikuradse's data which gave the same resistance. This was done through analysis of the measured velocity profiles.

The results obtained using sand grains, differed from those of Nikuradse by only 1 to 2 percent, which is partially attributed to the difference in ratio of roughness height to channel height, of the two set-ups. Schlichting's results confirmed the applicability of the universal velocity distribution equation, Equation 2.14 (see Figure 2.10).

Upon examining the effect of roughness density, it was found that as the density, λ_s , increases, the flow resistance, $\frac{u^*}{u}$ (proportional to wall shear) generally increases to a maximum and then decreases again. Schlichting examined roughness densities varying from $\lambda_s = 0.00785$ to $\lambda_s = 0.907$. For spherical roughness elements, the maximum flow resistance occurs at $\lambda_s = 0.4$. This behaviour occurs because for an isolated roughness element, the entire frontal area of the roughness is effective in creating resistance, but when

Figure 2.10: Velocity distribution for all rough plates referred to equivalent sand roughness - from Schlichting (1936) (where: $v_* = u^*$)

the elements are closely packed, there is some sheltering of downstream roughness elements by the upstream ones.

Schlichting also defined a resistance coefficient based on the resistance due to the roughness elements alone, and not the resistance of the space between them. It was found that for low values of roughness density, the resistance coefficient is constant; each roughness element contributes the same resistance and is unaffected by neighbouring elements. However, at higher values of roughness density, the resistance coefficient decreases sharply, as some roughness elements are sheltered from the flow by the elements upstream.

Hama (1954) performed a series of experiments on roughened flat plates mounted in a wind tunnel. His results confirmed that the velocity defect distribution is universal for both smooth and rough surfaces. However, since the boundary layer thickness is often difficult to define, Hama suggests that a better form of the velocity defect law is that proposed by Clauser (1954):

$$\frac{U-u}{u^*} = - \left(A \log \left(\frac{yu^*}{\delta^* U} \right) + B \right) \quad (2.18)$$

where: $A = 5.6$

$B = 0.6$

Hama showed that both the wall law and the velocity defect law apply for smooth and rough surfaces, in zero pressure gradient. However, Hama also determined that the

wall log law intercept is shifted by an amount $\frac{\Delta u}{u^*}$. for rough surfaces (this was also observed by Nikuradse for pipe flow, see Equation 2.15). The amount of shift $\frac{\Delta u}{u^*}$. was shown by Hama to be a function of the roughness parameter $\frac{u^* k}{\nu}$ (Figure 2.11). This parameter varies gradually with boundary layer growth along a flat plate (due to variation of u^*), whereas it is constant for pipe flow.

Since the shift $\frac{\Delta u}{u^*}$ depends primarily on $\frac{u^* k}{\nu}$, the roughness effect should be independent of outside flow conditions. This means that the results of experiments in pipes or two dimensional channels can be extended to boundary layer theory for zero pressure gradient. This is advantageous since pipe and channel experiments are often easier to perform and more accurate.

From the rough wall log law and the velocity defect law, Hama derived a relation for the skin friction coefficient for rough surfaces in zero pressure gradient:

$$\frac{2}{\sqrt{C_f}} = A \log \frac{U^* \delta^*}{\nu} + B - \frac{\Delta u}{u^*} \quad (2.19)$$

This is consistent with the smooth wall relation, with $\frac{\Delta u}{u^*} = 0$ for the smooth wall.

Coleman et. al. (1984) reanalysed Schlichting's (1936) original experiments and showed that some of his original assumptions caused significant errors in the determination of the skin friction coefficient $\left(C_f = \frac{2\tau_w}{\rho U^2} \right)$ and equivalent sand roughness (k_s). Schlichting made measurements of the velocity profile at the outlet of the test section, in a mid-span plane. Only one wall of the rectangular test section was roughened, and the other three

walls remained smooth. Schlichting assumed that the shear on the two smooth side walls of his test section could be neglected. Coleman et. al. determined that this was an inaccurate assumption based on the work of Leutheusser (1963), who determined that the wall shear stress in the mid-span plane is larger than the average shear stress for this type of channel. Therefore, Coleman et. al. suggested that a correction factor of 10% should be applied to the wall shear. Recalculating the skin friction coefficient showed that Schlichting's original values were too large by 0.5 to 73 percent (depending on the Reynolds number and roughness configuration).

Schlichting (1936) determined an equivalent sand roughness by comparing the rough wall log law data to the data measured by Nikuradse (1933). Schlichting calculated an effective wall location as the distance from a smooth wall which would give the same fluid volume as does the presence of the roughened wall (see Δy in Figure 2.12). Coleman et. al. suggest that while Schlichting's wall location parameter made logical sense, it is unrelated to any characteristics of the velocity profile. Coleman et. al. proposed that a more appropriate effective wall location would be a wall shift which would give a velocity profile slope of 5.75 (in accordance with Equation 2.14), when plotted in log law coordinates (see Δz in Figure 2.12). Coleman et. al. then recalculated the equivalent sand roughness in the same manner as did Schlichting. Schlichting's values of $\frac{k}{k_s}$ were found to be too large by 26 to 555 percent. Using the revised k_s to calculate the roughness Reynolds number, it was found that some of the tests which Schlichting had assumed to be fully rough, were in fact transitionally rough.

Figure 2.11: Shift in log law intercept for wire screens - from Hama (1954)
(where: $U = u$, $v^* = u^*$)

Figure 2.12: Rough wall coordinates and effective wall location - reproduced from Coleman et. al. (1984)

2.3 Roughness Effects With Pressure Gradient

Clauser (1954) measured the effects of pressure gradient on velocity distribution in a boundary layer in a flexible test-section wind tunnel. He verified that the wall law was valid for smooth and rough walls, with and without pressure gradient. Clauser wrote the wall law in the following form, with a vertical shift $\left(\frac{\Delta u}{u^*}\right)$ to account for the roughness effect:

$$\frac{u}{u^*} = 5.6 \log \left(\frac{yu^*}{\nu} \right) + 4.9 - \frac{\Delta u}{u^*} \quad (2.20)$$

Clauser also determined that the velocity defect relation was a universal function of $\left(\frac{yu^*}{\delta^* U}\right)$, which is independent of viscosity and roughness height as indicated in Equation 2.18. However, it is also a function of the pressure gradient, so that Clauser writes the velocity defect relation as:

$$\frac{U - u}{u^*} = -5.6 \log \left(\frac{yu^*}{\delta^* U} \right) - 0.6 + \frac{\Delta u_2}{u^*} \quad (2.21)$$

where $\frac{\Delta u_2}{u^*}$ is the shift of the straight line portion of the curves in Figure 2.13. The shift is measured from the line of the constant-pressure profile, and $\frac{\Delta u_2}{u^*} = f \left(\frac{\delta^*}{\tau_w} \frac{dP}{dx} \right)$. The term $\left(\frac{\delta^*}{\tau_w} \frac{dP}{dx} \right)$ is Clauser's non-dimensional pressure-gradient parameter. In non-zero pressure gradients, the velocity profiles collapse onto the same curve in defect-law coordinates only if this parameter is constant, that is the boundary layer is in equilibrium.

Perry and Joubert (1963) performed roughness experiments on flat plates mounted in a wind tunnel, which were subjected to adverse pressure gradients. They found that in the fully rough régime, the adverse pressure gradient had a negligible effect on the value of the roughness function $\frac{\Delta u}{u^*}$ (see Figure 2.14). As well measurements of the velocity profiles indicate that the logarithmic law of the wall is valid, and its form is unaffected by the size of the wake region of the velocity profile (Figures 2.15 and 2.16).

Dvorak (1969) expands on Equation 2.19 by further splitting the velocity shift term as follows:

$$\frac{\Delta u}{u^*} = A \log \frac{u^* k}{\nu} + C' \quad (2.22)$$

where C' is a function of the roughness geometry and density. Dvorak cites the work of Bettermann (1965) who measured the effect of spacing of two-dimensional roughness elements on $\frac{\Delta u}{u^*}$. Bettermann found that for a particular spacing of the roughness, $\frac{\Delta u}{u^*}$ was a maximum, and as the spacing was increased or decreased, there was a decrease in $\frac{\Delta u}{u^*}$ (see Figure 2.17). This was also observed by Schlichting (1936).

Dvorak defined the spacing parameter ($\lambda_D = A_T / A_P$) as the ratio of the total surface area to total planar roughness area. Bettermann found that for $1 \leq \lambda_D \leq 5$, the variation of $\frac{\Delta u}{u^*}$ was given by:

$$\begin{aligned} \frac{\Delta u}{u^*} &= A \log \frac{u^* k}{\nu} + C' \\ &= 5.6 \log \frac{u^* k}{\nu} + 17.35 (1.625 \log \lambda_D - 1) \end{aligned} \quad (2.23)$$

Figure 2.13: Logarithmic plot of turbulent equilibrium velocity profiles - from Clauser (1954)

Figure 2.14: Shift in log law intercept versus roughness Reynolds number - from Perry and Joubert (1963) (where: $h = k$, $U = u$, $U_\tau = u^*$)

Figure 2.15: Velocity profiles for adverse pressure gradient series II - from Perry and Joubert (1963) (where: $U = u$, $U_\tau = u_\tau^*$)

Figure 2.16: Velocity profiles for adverse pressure gradient series III - from Perry and Joubert (1963) (where: $U = u$, $U_\tau = u_\tau^*$)

For $\lambda_D > 5$, the variation of $\frac{\Delta u}{u^*}$ is based on the data of Schlichting, and is given by:

$$\begin{aligned}\frac{\Delta u}{u^*} &= A \log \frac{u^* k}{\nu} + C' \\ &= 5.6 \log \frac{u^* k}{\nu} - 5.95 (1.103 \log \lambda_D - 1)\end{aligned}\quad (2.24)$$

The variation of the value of C with spacing parameter is illustrated in Figure 2.18.

Dvorak also cites the work of Arndt and Ippen (1967), who have expanded Equation 2.19 by including a second shift term. This shift represents the effect of adverse pressure gradients. The expanded skin friction law now appears as:

$$\frac{2}{\sqrt{C_f}} = A \log \frac{U \delta^*}{\nu} + B - \frac{\Delta u_1}{u^*} + \frac{\Delta u_2}{u^*} \quad (2.25)$$

where the value of $\frac{\Delta u_2}{u^*}$ is determined as:

$$\frac{\Delta u_2}{u^*} = 1.253 (G - 6.7) \quad \text{for: } G \geq 6.7$$

$$\frac{\Delta u_2}{u^*} = 0.404 (G - 6.7) \quad \text{for: } G < 6.7$$

where:

$$G = \int_0^{\delta^*} \left(\frac{U - u}{u^*} \right)^2 d \left(\frac{y u^*}{\delta^* U} \right) \quad (2.26)$$

is a parameter introduced by Clauser (1954). Clauser developed this parameter to identify a family of equilibrium, or self-preserving boundary layers. He demonstrated that in an

equilibrium boundary layer. G is a unique function of $\left(\frac{\delta^+}{\tau_w} \frac{dP}{dx}\right)$. An equilibrium boundary layer (constant value of G) is one which has the same velocity defect distribution for all x , and is said to have a constant history.

Simpson (1973) suggests the use of a spacing parameter similar to Dvorak's but based on the frontal area of the roughness instead of the planar area of the roughness ($\lambda = A_T / A_F$). This is similar to the density parameter previously suggested by Schlichting (1936). For square-bar, spherical, and cubical type roughness elements, Simpson's and Dvorak's spacing parameters would be equal. Simpson's spacing parameter would appear to be more logical since the form drag should be roughly proportional to the frontal area.

The triangular shape of Figure 2.18 can be explained in the manner proposed by Schlichting where for very low values of spacing parameter, λ , the roughness elements tend to shelter each other. When the elements are sheltered, only a portion of their diameter is effective in producing resistance. At some larger value of λ , the full diameter of the roughness becomes effective, and the resistance is at a maximum. Then as λ becomes even larger, the resistance becomes smaller as the number of elements decreases.

Bettermann's and Dvorak's work featured rough wall flows with values of $\frac{k}{\delta} \ll 1$. Simpson suggests that for larger values of $\frac{k}{\delta}$ (for larger roughness) larger vortices can be generated which affect the flow throughout the entire shear layer, instead of just the wall region. The effect of this increased $\frac{k}{\delta}$ is to increase the value of C in Figure 2.18.

2.4 Roughness Effects On Cascade Performance

Speidel (1954) measured the influence of sandpaper roughness on flow losses in a planar turbine cascade. Speidel determined that surface roughness has little effect on the static pressure distribution around the profile. Examining the mixed-out total pressure loss coefficient at various inlet flow angles, it was seen that for the smallest roughnesses, there was virtually no change in loss (see Figure 2.19). However, as the roughness size increased, the total pressure loss became progressively larger. The effect of roughness size is also illustrated in Figure 2.20. The smaller roughness causes no significant increase in loss. This category of roughness is known as hydraulically smooth. For larger roughness, the total pressure loss jumps to a much higher value where the loss then rises at constant slope; this is the fully rough region. In this region, the effect of roughness size on the loss is similar for each value of the inlet flow angle.

Speidel found that the roughness caused a change in the deviation angle by as much as 5° (Figure 2.21). The inlet flow angle did not have as significant an effect on the loss as did the size of roughness. The maximum loss value for each of the inlet flow angles, was found to correspond to the roughness size in which the flow enters the fully rough region, shown in Figure 2.20. Speidel also determined that most of the loss occurs on the suction surface due to the higher velocity there.

Bammert and Milsch (1972) examined the effect of surface roughness on a cascade of compressor blades. The loss is determined most by the development of the boundary

layer, while the turning angle is affected primarily by the pressure distribution. As previously indicated by Speidel (1954), the pressure distribution around a turbomachine profile, is not greatly affected by the presence of roughness. Therefore, one would expect roughness not to have a drastic effect on the flow angle. Bammert and Milsch found that increasing roughness caused decreases in the flow turning angle; this became more pronounced for higher cambered blades (Figure 2.22).

Measurements of the boundary layer velocity profile showed that the roughness increases the momentum thickness in the laminar and turbulent regions of flow on both the pressure and suction surfaces. The most dramatic increase was found to be in the turbulent region of the suction surface. It was also seen that the roughness causes the transition point to move further forward. Examining the velocity distribution itself shows that increasing the roughness causes a decrease in the velocity gradient, resulting in a very flattened velocity distribution curve (Figure 2.23). For flows that were subject to separation, it was observed that increasing the roughness size will move the separation point further forward (Figure 2.24). The losses resulting from these changes in the boundary layer are shown in Figure 2.25. These figures show that for very low values of roughness, there is little increase in loss. As the roughness size moves further from the hydraulically smooth region, the increase in loss becomes much more significant. It was also observed that the loss coefficient decreased for increasing pitch/chord ratio.

Stabe and Liebert (1975) measured the aerodynamic effects of roughness caused by ceramic coatings on a two-dimensional cascade of turbine vanes. Tests were done with the

Figure 2.19: Total pressure loss versus inlet flow angle for various roughness heights - from Speidel (1954)

Figure 2.20: Total pressure loss versus roughness height for various inlet flow angles - from Speidel (1954) (where: $\beta_1 = \alpha_1$)

Figure 2.21: Outlet flow angle versus roughness height for various inlet flow angles - from Speidel (1954) (where: $\beta_1 = \alpha_1$)

Figure 2.22: Air turning angle versus roughness height for various airfoil profiles - from Bammert and Milsch (1972) (where: $\beta = \alpha$)

a: $k/l < 0.23 \times 10^{-3}$ (smooth)

b: $k/l = 1.56 \times 10^{-3}$

c: $k/l = 5.56 \times 10^{-3}$

Figure 2.23: Velocity distribution in boundary layer - from Bammert and Milsch (1972)

Figure 2.24: Cascade pressure distribution and momentum thickness - from Hammert and Milsch (1972)

a: NACA 65-6 10

- $\alpha_1 = 139.4^\circ$
- ▽ $\alpha_1 = 138.0^\circ$
- ◇ $\alpha_1 = 137.3^\circ$

b: NACA 65-(12)10

- $\alpha_1 = 144.6^\circ$
- ▽ $\alpha_1 = 142.5^\circ$
- ◇ $\alpha_1 = 141.4^\circ$

c:

- $\alpha_1 = 146.9^\circ$. NACA 65-(18)10
- ◇ $\alpha_1 = 142.5^\circ$. NACA 65-(12)06

- Hollow markers are from wake survey.
- Filled markers are from boundary layer measurements.

Figure 2.25: Total pressure loss coefficient versus roughness height for various inlet flow angles - from Bammert and Milsch (1972) (where: $\zeta = \phi^2$)

blades in one of three conditions: 1) smooth, 2) rough sprayed coating, or 3) polished sprayed coating. The total pressure wakes (Figure 2.26) for the rough coating were found to be significantly larger than those for the polished coating, consequently giving a higher total pressure loss. For the design condition, the rough coating gave a loss that was more than twice that for the smooth condition. This increased loss also resulted in a lower mass flow rate (see Figure 2.27).

Measurements of the outlet flow angle indicate that the roughness had very little effect except for operating speeds above the design condition. In this range, the roughness caused a slight increase (overturning) of the outlet flow angle. Stabe and Liebert attributed much of the increased loss to the larger trailing edge thickness due to the applied ceramic coating. They suggested that in the case of the polished sprayed coating, the loss was equivalent to that which would be measured on a smooth blade with the same trailing edge thickness.

Bammert and Sandstede (1980) continued their cascade roughness experiments using a turbine profile, completely roughened with emery grains. Examination of the effect on static pressure distribution around the profile, confirmed their previous findings for compressor blades - the static pressure is affected very little. Figure 2.28 shows that near the trailing edge on the suction side, the pressure coefficient becomes lower, indicating a decrease in the velocity in this region. On the pressure side, the opposite effect is observed.

Figure 2.26: Variation in exit total pressure versus pitch - from Stabe and Liebert (1975).

Figure 2.27: Flow angle, flow rate, and kinetic energy loss coefficient versus Mach number, for smooth and rough vanes - from Stabe and Liebert (1975)

Figure 2.28: Static pressure distribution for various roughness heights - from Bammert and Sandstede (1980)

- smooth
- △ $k_s/l = 0.57 \times 10^{-3}$
- ▽ $k_s/l = 1.02 \times 10^{-3}$
- ◇ $k_s/l = 3.31 \times 10^{-3}$

Calculation of the momentum thickness also agreed with the compressor cascade data presented earlier in Figure 2.24. On the pressure side, the momentum thickness increases to a maximum near mid-chord and then decreases again towards the trailing edge (Figures 2.29 and 2.30). On the suction side, the momentum thickness increases suddenly near mid-chord and continues increasing toward the trailing edge. For the largest roughness examined, the momentum thickness at the trailing edge was approximately 2.5 and 3.5 times greater, for the pressure surface and suction surface respectively, than it was for the smooth surface. Since the boundary layer on the suction surface is much thicker, it will affect the profile loss to a greater extent than will the pressure surface.

Examination of the shape factor (Figures 2.31 and 2.32) shows that as the roughness size increases, the location of transition (point where H drops below 2) moves further forward. For the largest roughness, on the suction surface, the flow is turbulent almost immediately, and separates (point where H emerges above 2) near the trailing edge.

Kryzanowski and Szprengiel (1986) performed cascade experiments on tip profiles from an actual steam turbine, with damaged leading edges. A comparison of the loss coefficient showed a slight decreasing trend for increasing Mach number and Reynolds number (see Figure 2.35). The increase in loss for the eroded blades remained the same. The influence of the inlet flow angle on the loss, was very small except at low Mach numbers. The change in outlet flow angle for the eroded profiles was less than 2° (underturning). The effect of the inlet flow angle was negligible.

Figure 2.29: Momentum thickness at pressure side - from Bammert and Sandstede (1980)

- smooth
- △ $k_s/l = 0.57 \times 10^{-3}$
- ▽ $k_s/l = 1.02 \times 10^{-3}$
- ◇ $k_s/l = 3.31 \times 10^{-3}$

Figure 2.30: Momentum thickness at suction side - from Bammert and Sandstede (1980)

Figure 2.31: Shape factor at pressure side - from Bammert and Sandstede (1980)

Figure 2.32: Shape factor at suction side - from Bammert and Sandstede (1980)

Figure 2.33: Total pressure loss coefficient (ζ_p) and outlet flow angle versus Reynolds number - from Kryzanowski and Szprengiel (1986) (where: $\beta = \alpha$)

Watt et. al. (1988) measured the effects of a sprayed thermal barrier coating on the boundary layer of gas turbine cascade airfoils. These experiments were similar to the work of Stabe and Liebert (1975). Watt et. al. used a turbulence generating grid to make measurements at two values of turbulence intensity. Watt et. al. examined a rough sprayed coating and a polished sprayed coating, as well as the smooth blades. The rough sprayed coating caused a wider and deeper wake (Figure 2.34), and the profile loss has more than doubled (Figure 2.35). Watt et. al. confirmed the findings of Stabe and Liebert (1975), that polishing of the coating reduces the loss to very near that of the smooth case. Watt et. al. suggested that the increased loss is caused by advancement of the transition point.

It is apparent in Figure 2.35 that as the Reynolds number increases, so does the loss. The amount of increase in loss is obviously affected by the level of free stream turbulence intensity. For the higher turbulence intensity, the losses increase significantly with Reynolds number. For low turbulence intensity the effect is much smaller; in fact for the rough sprayed condition, the loss is virtually independent of Reynolds number. For very low Reynolds numbers, the loss appears to be independent of the roughness.

Boles and Sari (1988) did an experimental study on a roughened gas turbine cascade operating in the transonic region. Their study examined a roughness which was mostly applied to the pressure surface, as that was the most common deposit site for the industrial gas turbine being studied. Roughness was also applied to the forward 40 percent of the suction surface. In the transonic region, the flow through the roughened cascade was most dramatically altered through the location and shape of the shock, which arises as a result of

Figure 2.34: Outlet total pressure ratio for smooth and roughened blades - from Watt et. al. (1988)

Figure 2.35: Profile loss coefficient ($1-\eta$) for smooth and rough blades - from Watt et. al. (1988)

change in the blade shape. The deposit changes the shape and thickness of the trailing edge, and the inter-blade passage is reduced by approximately 5 percent at the throat. The change in geometry by the applied deposit had very little effect on the Mach number distribution, except very near the sonic point and the trailing edge. On the suction side, the roughness caused the sonic point to move slightly forward. This gave a larger expansion around the trailing edge, and a higher Mach number upstream of the shock.

Bolcs and Sari found that the roughness caused the boundary layer on the suction side to become turbulent and thicker almost immediately downstream of the leading edge. This naturally increases the size of the wake with larger recirculation zones, and gives higher losses. There was no noticeable increase in the thickness of the pressure surface boundary layer.

Kind and Lawrysyn (1992) measured the aerodynamic effects of frost roughness. Wind tunnel measurements of frost on flat plates determined appropriate values of roughness height and spacing. These values were then incorporated into a computational model to predict how such a frost roughness would affect the performance of an airfoil. The most important result of this prediction was that the frost roughness only had significant effect if it extended very near the leading edge of the airfoil - the region of the suction peak. Roughness at a distance away from the leading edge was predicted to have a negligible effect. This is attributed to two reasons: 1) well beyond the suction peak, the severity of the adverse pressure gradient is reduced, and 2) the ratio of roughness height to boundary layer thickness is smaller and so the skin friction increment is lower.

2.5 Roughness Effects On Turbine Performance

Forster (1966) examined the loss of efficiency in actual steam turbines and in plane cascade tests with emery paper surface roughness. Forster tested cascade blades completely covered with emery paper for a variety of roughness sizes. The largest roughness size produced the lowest efficiency correction factor which was 93% (see Figure 2.36).

Forster also determined the efficiency loss when only a portion of the surface was covered. Regions of either surface were covered with emery paper, starting at the leading edge or the trailing edge (see Figure 2.37). These tests found:

- 1) Roughness over the entire suction surface is 3 times as detrimental as over the entire pressure surface.
- 2) Roughness over the first 30 percent of the suction surface and 60 percent of the pressure surface, causes virtually no loss at all.
- 3) The region most susceptible to roughness is from throat to trailing edge along the suction surface.

Forster also developed a simple theoretical model to calculate the efficiency drop of the cascade based on the geometric parameters of the free stream, and a Prandtl-Schlichting (1934) skin friction coefficient for rough surfaces. Most importantly this model predicts that the maximum allowable roughness for the high pressure end of the turbine is much smaller than the maximum allowable roughness for the low pressure end.

Figure 2.36: Efficiency correction factor for blades completely covered with roughness - from Forster (1966)

Figure 2.37: Efficiency correction factor for blades partially covered with roughness - from Forster (1966)

Bammert and Sandstede (1972) used a four-stage air turbine with thinned and thickened blades to examine the effects of erosion and deposition on turbine blades. Bammert and Sandstede suggested that the first stages of a gas turbine are more prone to thinning due to erosion and corrosion, while the latter stages are more likely to be thickened by deposits. Measurements were made on the turbine using various combinations of the thinned and thickened blades, with and without roughness applied.

The efficiency of the turbine is measured as a function of enthalpy drop:

$$\eta = \frac{\Delta h_{effective}}{\Delta h_{isentropic}} \quad (2.27)$$

For increasing roughness, the turbine loading curves were found to steepen, so that the loading is higher for a greater roughness than a low one. The efficiency curves were also seen to steepen, giving lower efficiency for the larger roughness (Figure 2.38).

The use of the thinned and thickened blades also caused a reduction in the turbine efficiency (Figure 2.39). Off-design speed operation causes a small decrease in the efficiency (Figure 2.40). However, it is apparent in these two figures that neither of these effects is as detrimental as the application of surface roughness.

Iarada and Suzuki (1993) presented the measurements of roughness on new and used turbomachinery blades. The blades were taken from industrial, marine, and aero-engines. The centre-line-average (c.l.a.) roughness heights versus service time are presented in Figure 2.41. The data are presented for measurements on the pressure surface, suction surface, and the leading edge. The largest roughness appears to form on the pressure

surface. Tarada and Suzuki determined that the roughness level for military aero-engines was typically 161 μm c.l.a. and for civilian aero-engines it was 80 μm c.l.a. For industrial and marine aero-engines, the roughness levels were typically 50 μm c.l.a. The unused aero-engines had a roughness level of 2 μm c.l.a., which is well below the axis of Figure 2.41.

Figure 2.38: Turbine loading coefficient versus mass flow for various roughness heights and operating speeds - from Bammert and Sandstede (1972).

Figure 2.39: Effective turbine efficiency versus velocity ratio for normal as well as thinned and thickened blades - from Bammert and Sandstede (1972)

Figure 2.40: Effective turbine efficiency for normal blading with different roughness grades and speeds - from Bammert and Sandstede (1972)

Chapter 3: Description Of Apparatus

3.1 Wind Tunnel

The wind tunnel used in this research is an open circuit wind tunnel. It is a recent design, which has aimed at delivering a uniform flow of low turbulence intensity. The air forcing equipment is comprised of a centrifugal blower with a bell mouth inlet, which is powered by an AC motor (see Figure 3.1). The blower forces the air through a diffuser, which contains a honeycomb section to remove swirl, and 5 screens which improve the flow quality and prevent separation of the flow from the diffuser walls. From the diffuser, the air passes into a rectangular settling chamber. The settling chamber contains several screens to help remove the large turbulent structures and other non-uniformities. After the settling chamber, the flow passes through a square to rectangular transition section which has a contraction ratio of 14:1. At the exit of the contraction a turbulence generating grid can be inserted.

Figure 3.1: Schematic of wind tunnel - from Rodger (1992).

The turbulence generating grid was designed according to the method of Baines et. al. (1951), to raise the turbulence intensity level of the test section inlet from 0.3% to 2.0%. The grid is a square arrangement of aluminum rods, soldered at their intersections and mounted in an aluminum frame (see Figure 3.2). The frame slides into an aluminum holder which is bolted between the contraction outlet and the test section inlet. The grid can be easily removed from the frame to perform tests at both high and low turbulence intensity measurements.

The speed of the fan motor is controlled by using a variable-frequency electrical supply: the frequency is selected by a remote control keypad. The fan can deliver a mass flow rate of 5 kg/s at a total pressure of 12 cm of water (gauge). At the outlet of the contraction, the maximum exit velocity is approximately 30 m/s which corresponds to a Mach number of 0.09.

3.2 Turbulence Generating Grid

The turbulence generating grid was designed to raise the turbulence intensity of the flow in the test section inlet to approximately 2.0%. Measurements were made by Whitehouse (1993) with the turbulence generating grid in place to allow comparison with the results of earlier research by Tremblay (1989), which had been conducted using a different wind tunnel having a turbulence intensity of 1.5%. The design of this grid was

Figure 3.2: Turbulence generating grid.

based on the work of Baines and Peterson (1951). The turbulence generating grid is positioned downstream of the contraction to ensure that the turbulence is isotropic.

To generate a turbulence intensity of 2.0%, Figure 3.3 indicates that the ratio of the downstream distance, X , to grid bar width, b , should be approximately $X/b = 275$. For a distance of $X = 915$ mm from the location of the turbulence generating grid to the measuring plane, the grid bar width would be $b = 3.33$ mm $\approx 1/8"$. Baines and Peterson (1951) recommend that at least 5 to 10 mesh lengths is required to ensure good flow establishment. Positioning the grid at $12 M$ (where M = mesh interval size) upstream of the measuring plane, the grid mesh is determined to be $M = X/12 = 76.25$ mm $\approx 3"$. Initial use of the turbulence generating grid revealed binding of the aluminum frame when sliding it into the aluminum holder. This was rectified with the use of a graphite based grease and by not over-tightening the fastener of the frame.

3.3 Cascade Apparatus

3.3.1 Cascade Test Section

The test section used in this research was designed by Goobie (1989), and is illustrated in Figure 3.4. The test section inlet and the turbulence generating grid are bolted to the contraction outlet flange. The cross section of the test section is rectangular, with an aluminum back wall and a removable plexiglass window (not shown in Figure 3.4) for the

Figure 3.3: Variation in intensity of turbulence produced by lattice-type screens, referred to bar size - from Baines and Peterson (1951) (where $v'_x = u'$, $V = U$)

Figure 3.4: Variable incidence cascade test section with turbulence generating grid - drawn in part by S.A. Sjolander.

front wall. The plexiglass window permits flow visualization. Near the test section inlet are two vertical boundary layer bleed slots which help reduce the thickness of boundary layers.

The five cascade blades are bolted, at a fixed stagger angle, to a removable mounting plate which in turn attaches to the rotating turntable. Rotation of the turntable causes a change in the inlet flow angle and allows examination of off-design incidence conditions. The sliding endplates are positioned on the blades at a certain distance from the front and back walls. The endplates reduce the boundary layer thickness in the blade passage, and help establish two-dimensional flow conditions. Open-cell foam weather stripping, adhered to the endplates, is used to seal the gap between the blades and the endplate cut-outs. This prevents a spanwise flow developing from the outside to the inside of the passage. These endplates are described in more detail by Rodger (1992).

In addition to the endplates, there are seven other control surfaces which can be adjusted to modify the flow entering and leaving the cascade. It is desirable to have a uniform inlet flow and a periodic outlet flow from the cascade. When the flow satisfies these requirements, the five blades will behave aerodynamically, in a manner similar to behaviour in a real turbine. Measurements of the flow conditions can be made through the instrumentation slots located upstream and downstream of the cascade.

3.3.2 Cascade Blades

The blade profile being studied is a modified large scale model of a mid-span section of a power turbine blade from a Pratt and Whitney Canada engine. The original blade profile was studied by Goobie (1989), Tremblay (1989) and Rodger (1992). The modified profile has an increased leading edge radius and a reduced wedge angle, and was first examined by Whitehouse (1993). The latter blade profile was used in the present study, and its geometric parameters are illustrated in Figure 3.5 and are also given in Table A.1. The blades have a 162.3 mm chord, a span of 200 mm, and a blade spacing of 111 mm. The coordinates used to describe the profile for manufacturing of the blades are contained in Table A.2. Figure 3.5 also shows both the inlet and outlet measuring planes. The inlet plane is approximately 60% axial chord length upstream of the blade leading edge. The five cascade blades are bolted to a common aluminum plate, such that all five blades can be installed and removed from the test section at once without altering the cascade geometry. Foam is applied to the end of the blades to provide a tight seal against the plexiglass window.

Two sets of these blades were used during this study. The first set were manufactured from aluminum using a numerically controlled milling machine. The performance of these blades was first examined in the wind tunnel by Whitehouse (1993). The second set of blades was manufactured by a mold casting process, using Devcon Plastic Steel casting compound. The mold was created to the same profile, using one of the aluminum blades as a master. Use of the mold casting process produced a set of blades

Figure 3.5: Cascade geometry and measuring plane nomenclature - reproduced from Whitehouse (1993)

that were much less expensive to manufacture than the aluminum blades. A more detailed description of this casting process is given by Klein (1993). A full cascade of five epoxy blades was manufactured, and attached to a second mounting plate. Having two completely separate sets of blades allowed rapid changeover of roughness configurations. This also permitted the previous roughness pattern to be preserved until analysis of the data verified that further testing would not be required.

3.4 Roughness Application Equipment

An apparatus was designed to allow the attachment of roughness to the blades, in various configurations. It was desired that various sizes of sand roughness be applied at different densities or spacing. To facilitate this, the apparatus illustrated in Figure 3.6 was constructed. This apparatus consists of a wheeled cart which carries the blade on a wooden track, underneath a sand hopper that distributes the sand over the surface of the blades. The cart is pulled along the track by a string, which is wound on a pulley attached to a small AC electric motor. The rotation of the pulley, and hence the speed of the cart, is controlled by varying the voltage supplied to the electric motor using a Superior Electric Variac. The wooden track is 2.3 metres long, and the sand hopper is located approximately one length of the cart from the end. The velocity of the cart, at this location, was measured for various voltage settings on the variac. The velocity was measured using the set-up illustrated in Figure 3.7. Two Tandy Infra-Red Detectors were used in conjunction with a

Figure 3.6: Schematic of roughness application apparatus.

Figure 3.7: Cart velocity calibration set-up.

2

MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS
STANDARD REFERENCE MATERIAL 1010a
(ANSI and ISO TEST CHART No. 2)

Dynascan Storage Oscilloscope (Model 2520). Both detectors sent a continuous signal to the oscilloscope. When the cart passed between a detector and its corresponding reflector (positioned on the opposite side of the track), the signal to the oscilloscope was interrupted. The time required for the cart to travel between the two detectors is shown on the oscilloscope trace. The velocity of the cart is determined by dividing the distance between the two detectors, by the time indicated on the oscilloscope trace. The cart velocity was calibrated in this manner for both the mass of the aluminum blade and the mass of the epoxy blade.

The sand hopper consists of a wooden frame, two adjustable, sliding, aluminum plates, and a container of sand. The sliding aluminum plates are attached to the wooden frame with C-clamps, and have a specific gap between them. The size of the gap is determined by the size of the sand grains being used. The container of sand sits immediately on top of the aluminum plates. A rectangular hole in the bottom of the container allows the sand to flow through the gap in the aluminum plates, and onto the surface of the blade. Underneath the track is a catch tray to retrieve the falling sand which is not deposited on the blades' surface, thus allowing the sand to be reused. To prevent the sand from falling onto the wooden track, two chutes project over the track, catching the falling sand and redirecting it away to the sand catch tray. When the cart is pulled into position underneath the hopper, the leading edge of the cart pushes these chutes out of the way.

The sand is adhered to the surface of the blade using a Crown Vinyl Strippable Coating (product #68040). The spray is applied to the blade before the cart begins

traversing. The sand which falls onto the coated portion of the blade surface remains attached until the vinyl dries. The approximate drying time is 3 minutes. The vinyl coating is strippable so that when a new roughness pattern is required, the vinyl is easily removed from the aluminum blades. An additional agent is required to make the vinyl easy to remove from the epoxy blades. Crown Mold Release For Nylon (product #63065) had to be applied to the blade before the vinyl coating, to make the latter readily strippable.

3.5 Instrumentation and Data Acquisition Apparatus

3.5.1 Pressure Measuring Instruments

The instrument used to measure the flow parameters of velocity, angle and total pressure in this research has been a three-hole probe, as shown in Figure 3.8. Two probes were used: one had been specifically designed for measuring at the inlet, while the other three-hole probe was used exclusively at the outlet. The outlet probe was designed by Amrad (1985) and was first utilized by Yaras (1987). The inlet probe was designed by Rodger (1992). The inlet probe is shorter and is used to make measurements at the inlet plane which is only 60% chord upstream of the leading edges of the blades, where the longer probe would interfere with the blades.

Both probes are comprised of a square metal bar with three metal tubes running the length of the probe. The probe head is 2.0 mm wide and 0.7 mm thick. The probe is

Figure 3.8: Three-hole pressure probe configuration and nomenclature.

mounted in a holder socket such that the probe tip is at least five diameters of the holder upstream. The angle of the probe is set with a protractor having an alignment accuracy of $\pm 0.5^\circ$. The holder attaches to a traverse rod which passes through the instrumentation slot of the cascade test section, to the traversing motors attached to the rear of the turntable (see Figure 3.9). The instrumentation slot has a slider which moves with the rod, to maintain a seal and prevent leakage of the passage flow. The combination of traversing gears allows the outlet probe to be moved in both the pitchwise and spanwise directions within the test section.

The two probes used in this study were calibrated according to the method established by Lewis (1966). The probes were calibrated in an open jet flow using the apparatus illustrated in Figure 3.10. Two blower boxes force air into the settling chamber of the calibration discharge box. The air then exhausts as an axisymmetric jet onto the probe. A motor driven turntable steps the probe through a range of yaw angles from -10° to $+10^\circ$ in increments of 0.5° . The pressures are sampled at each angle and from this data, several coefficients are calculated which are then used to create a calibration data set.

3.5.2 Turbulence Intensity Measuring Equipment

Turbulence intensity of the flow in the test section was measured to determine the effect of the turbulence generating grid. Measurements were made using a DISA 55p11 hot-wire probe with wire of 0.007 mm diameter and span of 0.7 mm, oriented at 90° to the

Figure 3.9: Probe positioning apparatus and configuration.

Figure 3.10: Three-hole probe calibration apparatus.

flow. The probe was located at 220% of axial chord upstream of the leading edge of the cascade. The hot-wire probe was controlled by a Thermo-Systems Inc. (TSI) 1053-B constant temperature anemometer. The anemometer outputs a voltage signal related to the velocity measured by the probe. The hot-wire anemometer was calibrated in the test section for flow velocity ranging from 0 to 40 m/s. For each flow velocity, the voltage output of the anemometer was recorded, and the data was curve fit using a third-order polynomial. The polynomial coefficients were used as the settings on a TSI-1052 signal linearizer. The linearizer converts the voltage output from the anemometer, and relates it to a DC voltage on a linear scale from 0 to 10 V. 0 V would indicate a flow velocity of 0 m/s, and 10 V would indicate a flow velocity of 40 m/s.

The DC component of this voltage was measured using a time-averaging DISA 55D31 voltmeter. The RMS AC component of the voltage signal was measured with a Fluke 8050A digital multimeter. The spectral content of the signal was examined using a HP3582A Spectrum Analyzer and an HP7044A x-y recorder. A detailed description of the measurement procedure is given in Whitehouse (1993).

3.5.3 Data Acquisition Equipment

The pressures sensed by the three-hole probes are converted to electrical signals by pressure transducers. The data are stored by the computer. The arrangement of the equipment which does this is shown in Figures 3.11 and 3.12. Two set-ups are illustrated

because additional pressure transducers became available approximately halfway through the experimental program.

As shown in Figure 3.11, each tube of the three hole probe is connected using TYGON tubing to the inputs of a scani-valve system. The scani-valve is a multi-port pneumatic switching device with 48 inputs and one output. The output is connected with TYGON tubing, to one of two Rosemount variable capacitance pressure transducers (serial #s 591 and 633). The inputs are read individually as the scani-valve sequentially switches each input port to connect with the output port. The second transducer is connected to a pitot tube and a static tap, located upstream in the reference plane, at the test section inlet. This instrumentation measures the reference dynamic pressure.

Use of the scani-valve, to assist in measuring the pressures sensed by the probe, impedes the efficiency of the data acquisition system. When the scani-valve switches from one input to the next, the pressure measurement system experiences a large fluctuation in pressure. A waiting period of approximately 15 seconds is necessary before the pressure has begun to stabilize. After the waiting period, the data is briefly sampled for 10 seconds to determine the range of the data. Then both the dynamic pressure in the reference plane, and the pressure output from the scani-valve, are sampled simultaneously for 30 seconds. The waiting periods, required to allow the pressure signal to stabilize, make acquiring data at a single station quite time consuming.

Figure 3.12 shows the arrangement of data acquisition equipment after the installation of two additional transducers - a Baratron (serial #79508-1) and a Rosemount (serial # 367). The two additional transducers allowed each outlet of the three-hole probe

Figure 3.11: Data acquisition system - two pressure transducers.

Figure 3.12: Data acquisition system - four pressure transducers.

to be directly connected to a transducer. This eliminated the need to use the scan-valve. Consequently there were no large fluctuations in pressure as each port of the probe was sampled, and the waiting times could be eliminated. Measurements by Isaacs (1993) showed that a 2 second check of the range of data, followed by a 15 second sample of the data, was adequate to ensure a stable pressure reading. This second arrangement allowed the time to acquire data at a single station, to be reduced to one third of the time required with the original set-up.

The pressures measured by the transducers are converted to voltage signals, which are then sent to a Sciometric Instruments Analog Digital converter (Model 81 902, serial # 9023J19006). The transducer voltages are simultaneously monitored by a DISA 55D31 time-averaging voltmeter. The converter sends a digital signal to the computer via the serial port. The computer subtracts the zero value of the transducer and converts the voltage to pressure using the calibration coefficients of the transducers. The pressure data measured at the probe is then normalized by the reference dynamic pressure at the test section inlet, to create a pressure coefficient. Both the voltages and pressure coefficients are stored in a data file by the computer.

The movement of the probes is accomplished using an arrangement of three traversing gears: one vertical traverse gear for the inlet probe, and one vertical and one horizontal traverse gear for the outlet probe. These motors are also controlled by a voltage signal from the computer via the parallel port. The signal from the computer passes through an amplifier to a motor controller which powers the stepper motor. The motor drives a traversing gear which moves the probe rod in the desired direction.

The data acquisition system, including sampling and recording of pressure data, movement of the probes, and control of the scani-valve are all controlled by the computer using the Pascal program THP. This program is described by Whitehouse (1993). Some changes to this program were required to facilitate the addition of two more transducers, and for other procedures that became necessary. The units of the program which have been changed are included in Appendix E, and the changes have been documented in the code.

Chapter 4: Calibration And Measurement Procedures

4.1 Three-Hole Probe

4.1.1 Calibration And Measurements

Recall that one three-hole probe was used to traverse the inlet flow, upstream of the cascade and another used to traverse the exit flow. These three-hole probes were the instruments used to acquire most of the data in this research. Therefore, it was important to ensure that the probe measurements were accurate and consistent over the duration of the study. Great care was taken to protect the probes from accidental damage. Whenever a probe was not in use, the tip was covered with a piece of TYGON tubing, since small changes in probe tip geometry can have dramatic effects on its calibration.

The probes had last been calibrated by Rodger (1992) in July 1991. They were re-calibrated by the author in October 1992 and May 1993. Each probe is calibrated using the

apparatus shown in Figure 3.10, by measuring the pressures of each probe port, over a range of yaw angles from -10° to $+10^\circ$ in increments of 0.5° . This calibration procedure is given in more detail in Rodger (1992). The measured pressures are used to calculate six coefficients according to the method of Lewis (1966). The calibration coefficients are defined as follows:

$$K_1 = \frac{P_1 - P_s}{q} \quad (4.1)$$

$$K_{12} = \frac{P_1 - P_2}{q} \quad (4.2)$$

$$K_{13} = \frac{P_1 - P_3}{q} \quad (4.3)$$

$$K_{23} = \frac{P_2 - P_3}{q} \quad (4.4)$$

$$K_{\phi 2} = \frac{P_1 - P_2}{P_1 - P_3} \quad (4.5)$$

$$K_{\phi 3} = \frac{P_1 - P_3}{P_1 - P_2} \quad (4.6)$$

where :

P_1 = Pressure at port #1.	}	See Figure 3.8 for port arrangement.
P_2 = Pressure at port #2.		
P_3 = Pressure at port #3.		
P_s = Static pressure at probe.		
q = Dynamic pressure at probe.		

The calibration coefficient values and the corresponding probe angles are written in a two

column data file. Two such calibration data files are created, one for each of the three-hole probes. The calibration coefficients obtained in October 1992 and May 1993 are presented graphically in Figures 4.1 to 4.12, for both the inlet and outlet probes. It can be seen that the calibration of the probes has been very stable over this period. However, Figures 4.3 and 4.11 show that the calibration for the inlet probe had changed quite significantly since it had been calibrated by Rodger in July 1991. There is an obvious bend in the probe tip, which probably occurred between July 1991 and October 1992, and this has caused the previous calibration to become inaccurate.

The above calibration data, can be used to determine the parameters of an unknown flow, provided that the flow angle and the dynamic pressure are within the correct range. When the probe is placed in the test section, it is aligned with the expected nominal flow angle. When the pressures of all three ports are measured, the sign of the flow angle can be determined by evaluating the coefficient K_{23} . Then the magnitude of the flow angle is determined by calculating $K_{\theta 2}$ or $K_{\theta 3}$, and using a linear interpolation of the calibration data (Figures 4.9 to 4.12) to extract the flow angle. Both K_{θ} coefficients are calculated because both curves have asymptotes at larger flow angles, when one port is in a region of separated flow. To determine the flow angle, the K_{θ} coefficient which does not have the asymptote in the appropriate range of data, is used. For the range of $\pm 10^\circ$ yaw, neither of the curves is in the range of the asymptote and either of the K_{θ} coefficients could be used.

Once the flow angle (with respect to the probe) is determined, the coefficients K_{12} or K_{13} can be determined from the calibration data (Figures 4.3 to 4.6). Then using the known pressures at the probe, the dynamic pressure can be calculated as follows (for positive yaw):

Figure 4.1: Inlet probe calibration data.

Figure 4.2: Outlet probe calibration data.

Figure 4.3: Inlet probe calibration data.

Figure 4.4: Outlet probe calibration data.

Figure 4.5: Inlet probe calibration data.

Figure 4.6: Outlet probe calibration data.

Figure 4.7: Inlet probe calibration data.

Figure 4.8: Outlet probe calibration data.

Figure 4.9: Inlet probe calibration data.

Figure 4.10: Outlet probe calibration data.

Figure 4.11: Inlet probe calibration data.

Figure 4.12: Outlet probe calibration data.

$$q_{probe} = \frac{(P_1 - P_2)_{probe}}{K_{12_{calibration}}} \quad (4.7)$$

Similarly, the static pressure at the probe can be calculated by first determining the value of K_1 , and using the dynamic pressure just calculated:

$$P_{s_{probe}} = P_{1_{probe}} - K_{1_{calibration}} \cdot q_{probe} \quad (4.8)$$

The total pressure at the probe is simply the sum of the dynamic and static pressures. For a more detailed description of the data extraction process for the three-hole probes, see Yaras (1987).

4.1.2 Accuracy of the Three-Hole Probe Measurements

The three-hole probe is calibrated for yaw angles from -10° to $+10^\circ$, with a pitch angle of 0° , and a single fixed dynamic pressure. Placing the probe in a flow other than these conditions can cause inaccuracy in the results. The ability of the three-hole probe to determine accurate values of flow angle, dynamic pressure, and total pressure was examined by Tremblay (1989). Tremblay found that in a uniform flow, for pitch angles within $\pm 10^\circ$, there was a systematic shift in the flow angle, of a maximum of 0.5° . The error in dynamic pressure for the same range of pitch angles was 1% in the worst case. Yaras (1987) also investigated the effect of dynamic pressure on the accuracy of the three-hole probe using the outlet probe shown in Figure 3.8. He tested the probe in a jet flow at dynamic

pressures of 500 Pa and 1760 Pa . He determined that there was noticeable difference only at very high angles of attack, well outside the range of flow angles in the present study.

Tremblay (1989) determined that there was an additional error introduced in the flow angle when measuring in a non-uniform flow, such as in the wake of a blade, because of a finite pressure difference across the probe tip. This effect is illustrated in Figure 4.13. The error in flow angle in the wake was estimated by Tremblay to be within $\pm 1^\circ$. Measurements during the present study indicate that the error in the measured flow angle in the wake can be as much as 30%, however, this equates to an error of only 0.6%. As shown in Figures 4.1 and 4.2, the error in total pressure is a maximum of 2.5% at -10° and $+10^\circ$, while for yaw angles between -5° and $+5^\circ$, the error is negligible. Tremblay used a pitot tube to confirm that the error in dynamic pressure due to the shear flow in the wake is less than 3%. Therefore, the combined error in the mass averaged total-pressure-loss coefficient is within $\pm 5\%$. The errors introduced by the shear flow in the wake are considered acceptably small and can be neglected. Therefore, no attempt was made to correct for any of the above errors.

4.2 Flow Quality

4.2.1 Operating Point

The operating point of the wind tunnel, used to obtain the results presented in this

Note: Scale exaggerated for clarity

Figure 4.13: Flow angle error in wakes - from Rodger (1992).

work, is at Reynolds number of 300,000. The Reynolds number is calculated using a characteristic length of blade chord as follows:

$$Re = \frac{\rho V_{ref} C}{\mu} \quad (4.9)$$

where : ρ = Density of air.

V_{ref} = Test section inlet velocity.

C = Blade chord length.

μ = Viscosity of air.

The density and viscosity were calculated from atmospheric conditions in the laboratory at the time of the test. The test section reference velocity is measured using the pitot-static instruments described in section 3.5.3. The Reynolds number of 300,000 is the same operating point used by previous investigators Whitehouse (1993), Rodger (1992), Tremblay (1989) and Goobie (1989). To obtain a Reynolds number of 300,000 in the wind tunnel, the fan speed controller is adjusted until the dynamic pressure measured at the inlet corresponds to the necessary velocity, which is about 30 m/s.

4.2.2 Inlet Flow Uniformity

It is important to ensure that the inlet flow impinging on each blade be the same. This more correctly simulates the flow in an actual turbine. The flow at the inlet to the cascade is measured using the inlet three-hole probe, positioned in a plane 60% of axial

chord upstream of the leading edge. This probe is traversed in the pitchwise direction at mid-span to measure the flow approaching the middle three blades (the other two blades are beyond the range of the traversing gear). Several control surfaces (shown in Figure 4.14) can be used to adjust the flow. The primary control surfaces affecting the inlet flow are the top and bottom flaps.

Initially a very coarse traverse of the inlet flow is carried out to get an overall impression of the inlet flow. Then the control surfaces at the top and bottom are adjusted, and the flow is retested. This process is repeated until the flow angle throughout the inlet is uniform within $\pm 0.5^\circ$. A typical, final sampling of the inlet is shown in Figure 4.15 and Figure 4.16.

For high angles of incidence onto the blade ($+10^\circ$ and $+20^\circ$), uniform inlet flow could not be achieved without the addition of a perforated plate across the outlet. The perforated plate has a solidity ratio of 0.28 and is installed approximately 175% axial chord downstream of the trailing edge of the cascade. This perforated plate served to raise the back pressure and make the control surfaces in the test section more effective. As well, a periodic variation in the inlet flow angle was observed. This appeared to be caused by the upstream influence of the cascade blades. This effect was strong enough that for some cases, the inlet probe was positioned 26% of axial chord further upstream, with the use of an extension rod. At this location, the measured flow was uniform.

Figure 4.14: Test section control surfaces - from Rodger (1992)

Figure 4.15: Typical inlet flow angle distribution.

Figure 4.16: Typical inlet flow velocity distribution.

4.2.3 Outlet Flow Periodicity

The flow past a blade is influenced by the neighbouring blades. The outlet flow from a blade row in a real turbine, should be periodic because the large number of blades are arranged in a circle. In this way, the flow past each blade should be affected in a similar way by its neighbours. In a planar cascade, only a finite number of blades can be used, and the blades on the ends will each have only one neighbouring blade. To properly simulate the conditions in a real turbine, it is necessary to achieve periodicity in the outlet flow of the planar cascade. In the test section being used, two tailboards, positioned at the end blades (see Figure 4.14), are used to guide the flow. They can be adjusted until periodicity exists.

To check for periodicity, the three-hole probe is used to traverse the outlet at mid-span, at a location of 40% axial chord downstream of the trailing edge of the cascade. The probe is roughly aligned with the flow, since the probe is only calibrated for a yaw range of $\pm 10^\circ$. The flow angle is not known at this point but it is assumed to be slightly less than the blade exit metal angle. Two flow parameters are measured and used as criteria for the existence of periodicity: flow angle and total-pressure-loss. If the values of these parameters are not the same for each blade, the tailboard positions can be adjusted to attain periodicity with an accuracy outlined below.

Typical results of an outlet flow traverse can be seen in Figures 4.17 and 4.18. The total-pressure-loss is examined to verify that the depth and width of the outboard wakes are within $\pm 4\%$ of the middle wake. The flow angle is also compared and is considered

Figure 4.17: Typical outlet flow angle distribution.

Figure 4.18: Typical outlet total-pressure-loss coefficient distribution.

acceptable if it is periodic within a tolerance of $\pm 1.0^\circ$. The large variation in measured flow angle in the wake of each blade is partially due to an apparent overturning or underturning sensed by the probe due to the strong dynamic and total pressure gradients within the blade wakes. This was discussed in section 4.1.2 and is illustrated in Figure 4.13. The finite width of the probe tip in the wake, causes ports #2 and #3 to experience different magnitudes of pressure. The probe erroneously perceives this as the presence of a flow angle. This effect is observed in opposite directions on the suction and pressure surfaces. Since this distortion is nearly symmetrical, the effect on the pressure side tends to cancel the effect on the suction side so that the effect on average flow angle is small. The flow angle is mass averaged across one entire blade-to-blade passage. The mass flow in the wake region is smaller, and so the distortion of the flow angle in the wake will be weighted less, helping to minimize its overall effect. Therefore, no corrections for this effect were applied

4.2.4 Effect of Turbulence Generating Grid

Measurements of longitudinal turbulence intensity (Tu), with and without the turbulence generating grid, were reported by Whitehouse (1993). The results are shown in Figures 4.19 and 4.20. The velocity measurements were made at mid-span, in a plane approximately 220% of axial chord upstream of the cascade leading edges. The turbulence intensity is calculated as:

Figure 4.19: Pitchwise distribution of turbulence intensity level, grid not installed - reproduced from Whitehouse (1993)

Figure 4.20: Pitchwise distribution of turbulence intensity level, with grid installed - reproduced from Whitehouse (1993)

$$Tu = \frac{\sqrt{\overline{u'^2}}}{U} \times 100\% \quad (4.10)$$

where : u = Fluctuating component of velocity in x-direction.

U = Mean velocity in x-direction.

The results given by Whitehouse (1993) showed an increase of Tu from 0.3% to 3.0% with the addition of the turbulence generating grid. Figure 4.20 indicates that the Tu is not as uniform with the grid in place. Whitehouse (1993) suggests that this is because the effect of the grid on the flow has not been entirely uniform. The author's early tests also confirmed this hypothesis. This will be discussed further in section 5.1.

4.3 Roughness Selection and Application

4.3.1 Roughness Application Procedure

It was believed that the phenomena of interest in the present study, could be most easily simulated using sand grain roughness. Review of the literature revealed that many of the previous experiments using sand grain roughness, were performed using a roughness of maximum density distribution. It was desired that the roughness used in this study be of a density somewhat less than the maximum. For this reason, the apparatus described in section 3.4 was constructed.

The roughness was applied to the blades by first outlining the area of the blade to be covered with masking tape. The blade was secured to the cart and placed at the far end of the track. The container of sand was placed on top of the hopper with a sheet of paper covering the aluminum gap, to prevent the sand from flowing. With the power switch in the off position, the variac was set to give the desired speed, as determined by the previous calibration procedure (described in section 3.4). A cardboard template was placed over the blade to prevent adhesive from falling onto the undesired areas of the blade. The vinyl spray was applied to the blade, and the cardboard template was removed. The sheet of paper was withdrawn from beneath the sand container to start the sand flowing, and then the electric motor was started. The electric motor began winding the string pulling the cart down the track. When the cart passed beneath the hopper, sand fell onto the adhesive and remained attached. When the cart reached the end of the track, the power to the electric motor was switched off and the cart was arrested. The masking tape was then removed from the blade before the adhesive began to dry. The vinyl begins to dry within 1 minute of application, and is completely dry within 5 minutes. A typical application of roughness is shown in Figure 4.21.

The distribution of sand on the blade can be varied by adjusting the variac setting (and hence the velocity of the cart), the gap setting of the hopper, or the sand grain size. For the present tests, the cart velocity was kept at 2 m/s. The sand grain size was varied to determine its effect on the aerodynamics. As the grain size increased, the gap size was correspondingly increased to maintain a uniform flow. If the gap size is not increased, the flow will not be uniform and may cease altogether. The appropriate gap size was selected

Figure 4.21: Typical roughness strip on blade.

Figure 4.22: Typical photograph of roughness strip with grid.

as the minimum value which gave a constant uniform flow. This value was determined by trial and error. In general, the gap size was approximately 3 times the nominal diameter of the sand grains.

After the roughness had been applied to all of the blades, an examination of the roughness distribution was necessary. Immediately after the roughness was applied, the blades were visually inspected. If the roughness on a blade was obviously not uniform, or clearly did not match the distribution on the other blades, the roughness was removed, and the application process was repeated. A more thorough examination of the roughness was also performed. A square grid was drawn on a transparency film. This was laid across the roughness on the blade, and photographs were taken with slide film. A typical photograph is illustrated in Figure 4.22. The photographs were later projected onto a wall, and the sand grains inside of random squares were counted. This was used to calculate an average density. The average densities for the various roughness applications are listed in Appendix D.

As well, a qualitative analysis of the sand grains was desired. It was important to determine if the adhesive changed the apparent shape of the sand grains (particularly when the sand grains were clustered). Also, it was relevant to examine the relative thickness of the adhesive in comparison to the sand grains. To accomplish this, several roughness samples were observed using a JSM-6400 Digital Scanning Electron Microscope at the Facility for Cryo Scanning Electron Microscopy and Microanalysis at Carleton University. Figures 4.23 and 4.24 clearly show that the adhesive does not significantly change the

Figure 4.23: Electron microscope photograph of beach sand adhered to surface.

Figure 4.24: Electron microscope photograph of silica sand adhered to surface.

Figure 4.25: Electron microscope photograph of distributed silica sand adhered to surface.

Figure 4.26: Electron microscope photograph of silica sand showing relative thickness of adhesive layer.

apparent shape of the sand grains. Figure 4.26 shows that the thickness of the adhesive is negligible in comparison with the sand grain diameter.

4.3.2 Roughness Selection Procedure

In this study, effort was made to use a quantifiable roughness by selecting sand that was as uniform in size as possible. To obtain a uniform sample, the sand was sifted using screens and a vibrating platform. To obtain a desired size of sand, the screens were stacked on top of the vibrating platform. At the top was a screen with mesh openings slightly larger than the desired nominal size; this caught all of the grains which were too large. Second in the stack was a screen which had mesh openings slightly less than the desired nominal size. Beneath this screen was a tray which caught all of the undersized grains. When the screens were stacked, a small sample of unsorted sand was added to the top layer, and the stack was covered and clamped to the vibrating platform. The vibration machine was activated for approximately two minutes. When the cover was removed, the sand was sorted in the screens, according to its size.

Three different sizes of sand were obtained in this manner. Approximately 2 litres were collected of each size of sand. Two different types of sand were used in this study silica sand and ordinary "beach sand". There is a noticeable difference in the shape of the grains for these two types of sand, as can be seen from Figures 4.23 and 4.24. The beach sand grains appear to be rather rounded, whereas the silica sand grains tend to be more

angular. The silica sand was purchased as pre-sifted, industrial grade silica. However, it was found that the silica sand still contained a wide range of sizes of sand particles, and it had to be re-sifted using the apparatus described above. The types of sand collected and the approximate grain sizes are listed in Table 4.1. The nominal grain size of the sand is taken as the average of the mesh opening size of the screen on which the sand has been caught and that of the last screen through which the sand has passed.

Table 4.1: Sand Grain Sizes

Grade # of Catching Screen	Mesh Size of Passed Screen (μm)	Mesh Size of Catching Screen (μm)	Nominal Sand Grain Size, k (μm)	Non-Dimensional Sand Grain Size k/C
20 (Silica)	1190	850	1020	0.00628
30 (Silica)	850	594	722	0.00445
60 (Beach)	425	250	337.5	0.00208

4.4 Cascade Set-up and Measurement Procedure

The set-up of the test section begins with installing the roughened blades in the cascade test section. Each of the 5 blades was roughened, with every effort made to obtain statistically the same roughness configuration on each blade. The endplates were designed to be slid on over the blades, however with the roughness attached to the blades this could not be done. To avoid disturbing the roughness, the inner endplate was installed first, then the blades were bolted to the mounting plate, and finally the outer endplate was slid into place. This had to be done carefully to ensure that the foam weather stripping maintained a good seal.

Once the blades are in place, the 9 control surfaces are set. As a starting point, the control surfaces are adjusted to the settings previously used for a given incidence (although this does not automatically ensure uniform flow). Then a check of the inlet flow must be performed to verify the presence of uniform inlet flow. As outlined earlier this entails an examination of the inlet flow angle, static pressure and velocity. The probe is installed on a traverse rod and levelled with respect to the horizontal, so that it should be roughly in line with the flow. The TYGON tubing connected to the inlet probe is passed through the traverse rod slot between the inner endplate and the turntable wall, to prevent it from rubbing against the sand on the blades. The probe is traversed at mid-span, in a plane approximately 60% axial chord upstream of the leading edges. If the control surfaces were set using previous settings, only minor fine tuning was needed to achieve uniformity. Once uniform flow is established, a fine traverse of the inlet flow is performed including at least

one complete blade spacing at the middle blade. The traversing gear only has the ability to examine the 3 middle blades and cannot traverse the outer passages.

Once the inlet traverse is complete, the flow at the outlet is examined. The inlet probe is removed, and its traverse slot is taped over to prevent disruption of the flow through the passage. The outlet probe is installed on the traverse rod, and its angle is set to approximately -52° with respect to the axial direction, which should be roughly aligned with the flow. The probe is traversed at mid-span in a plane 40% of the axial chord downstream of the trailing edge of the cascade. A traverse is made of the middle three blades, for uniformity of the flow angle and periodicity of the total-pressure-loss. If these conditions do not exist, then the control surfaces may have to be fine tuned and the flow is rechecked. When a periodic flow is present, a fine traverse is performed of at least one blade spacing at the middle blade.

A reduction calculation is performed on the raw data collected for both the inlet and outlet flow. From this reduction calculation the mass-averaged flow angle, total-pressure-loss, and axial-velocity at both the inlet and the outlet, are determined. The ratio of the axial velocities at the leading edge and trailing edge is calculated. If the ratio is within $\pm 1.0\%$ of 1.00, then this satisfies a necessary requirement for two-dimensional flow. If the ratio is not within the acceptable range, then the endplates must be adjusted to either raise or lower the outlet velocity. Then the entire testing procedure must be repeated, beginning with the check for uniform flow at the inlet.

4.5 Data Reduction

The data measured by the three-hole probe during a traverse is initially stored as pressure coefficients. A pressure coefficient is calculated at each traverse station, for each port of the three-hole probe, as follows (for hole #1):

$$Cp_1 = \frac{P_1 - P_{sref}}{q_{ref}} \quad (4.11)$$

To make use of the data measured during a traverse, it must be processed. Processing the initial pressure coefficient data gives more revealing information such as flow angle, dynamic pressure, static pressure, and total pressure at each of the traverse stations. The method by which these quantities are derived from the raw data, is described in section 4.1.1. A total-pressure-loss coefficient can also be calculated at each traversing station. This is defined as the drop in total pressure across the blade row normalized by the inlet dynamic pressure:

$$Cp_0 = \frac{P_{0ref} - P_{02}}{q_{ref}} \quad (4.12)$$

In this equation, the reference pressure is not the total pressure at the cascade inlet, but the total pressure in the reference plane, located approximately 565% of true chord upstream of the blade leading edge. This assumes that the total pressure measured at the reference plane is equivalent to the total pressure at the cascade inlet. This equivalence is illustrated in Figure 5.3 which shows that the total-pressure-loss from the reference plane to the

cascade inlet is negligible. The inlet dynamic and total pressures are measured using a pitot-static system shown in Figures 3.11 and 3.12. This assumes that the pressure distribution is uniform throughout the reference plane, a good assumption as shown by Figure 5.3. Example graphs of the distributions of total-pressure-loss coefficient and flow angle at the cascade outlet, are presented in Figures 4.17 and 4.18.

It is useful to evaluate the aerodynamic performance of the blade row, by referring to a single average quantity of these parameters. Since the outlet flow is not uniform throughout the passage, a weighted average is used. The average is determined across one blade spacing, and the value of the parameter at each measurement point is weighted by the mass flow in the corresponding streamtube. The program THP, written by Whitehouse (1993), is used to process the data, and it calculates mass averaged values of flow angle, velocity, axial velocity, and total-pressure-loss coefficient. However, it was determined that the calculation being performed by this program was not a true mass flow weighted average. Therefore, modifications to the program were made for the present work. The revised calculations are shown below. The parameters are averaged between the values at two consecutive measurement points, and then weighted by the mass flow through the two points. Note that for incompressible, two-dimensional flow, the density and passage width fall out of the calculations.

The mass-averaged flow angle is:

$$\begin{aligned}\bar{\alpha} &= \frac{1}{\dot{m}} \int_0^s \alpha \, dm \\ &= \frac{\sum_{i=1}^{n-1} \left[\left(\frac{\alpha_i + \alpha_{i+1}}{2} \right) \left(\frac{V_i \cos \alpha_i + V_{i+1} \cos \alpha_{i+1}}{2} \right) (y_{i+1} - y_i) \right]}{\sum_{i=1}^{n-1} \left[\left(\frac{V_i \cos \alpha_i + V_{i+1} \cos \alpha_{i+1}}{2} \right) (y_{i+1} - y_i) \right]}\end{aligned}\quad (4.13)$$

The mass-averaged velocity is:

$$\begin{aligned}\bar{V} &= \frac{1}{\dot{m}} \int_0^s V \, dm \\ &= \frac{\sum_{i=1}^{n-1} \left[\left(\frac{V_i + V_{i+1}}{2} \right) \left(\frac{V_i \cos \alpha_i + V_{i+1} \cos \alpha_{i+1}}{2} \right) (y_{i+1} - y_i) \right]}{\sum_{i=1}^{n-1} \left[\left(\frac{V_i \cos \alpha_i + V_{i+1} \cos \alpha_{i+1}}{2} \right) (y_{i+1} - y_i) \right]}\end{aligned}\quad (4.14)$$

The mass-averaged axial velocity is :

$$\begin{aligned}\bar{V}_a &= \frac{1}{\dot{m}} \int_0^s V_a \, dm \\ &= \frac{\sum_{i=1}^{n-1} \left[\left(\frac{V_i \cos \alpha_i + V_{i+1} \cos \alpha_{i+1}}{2} \right)^2 (y_{i+1} - y_i) \right]}{\sum_{i=1}^{n-1} \left[\left(\frac{V_i \cos \alpha_i + V_{i+1} \cos \alpha_{i+1}}{2} \right) (y_{i+1} - y_i) \right]}\end{aligned}\quad (4.15)$$

The mass-averaged total-pressure-loss is the average loss in total pressure across a single blade. This is calculated by integrating the area under the pressure loss coefficient curve (C_{p_0}), with respect to the free stream data as reference. Mass-averaged total-

pressure-loss is:

$$\begin{aligned}\bar{Y} &= \left(\frac{1}{\dot{m}} \int_0^S C p_0 dm \right) \times \left(\frac{q_{ref}}{q_{out}} \right) \\ &= \frac{\sum_{i=1}^{n-1} \left[\left(\frac{C p_{0_i} + C p_{0_{i+1}}}{2} \right) \left(\frac{V_i \cos \alpha_i + V_{i+1} \cos \alpha_{i+1}}{2} \right) (y_{i+1} - y_i) \right] \times \left(\frac{V_{ref}}{V_2} \right)^2}{\sum_{i=1}^{n-1} \left[\left(\frac{V_i \cos \alpha_i + V_{i+1} \cos \alpha_{i+1}}{2} \right) (y_{i+1} - y_i) \right]} \quad (4.16)\end{aligned}$$

The mass averaged total-pressure-loss is measured at the plane of the probe. Further loss occurs as the wakes mix out to a uniform flow at some distance downstream. This additional loss is known as mixing loss and is added to the mass-averaged total-pressure-loss to get a total loss given by:

$$\bar{Y}_m = \bar{Y} + \left\{ 1 - 2 \frac{\int_0^1 V_2^2 d(y/s)}{\left(\int_0^1 V_2 d(y/s) \right)^2} + \frac{\int_0^1 V_2^3 d(y/s)}{\left(\int_0^1 V_2 d(y/s) \right)^3} \right\} \quad (4.17)$$

In this expression, the first term is the mass-averaged total-pressure-loss coefficient previously calculated in Equation 4.16. The remainder of the expression is the mixing loss which is calculated using the equations of continuity, momentum, and energy, assuming incompressible flow and constant area mixing. The derivation of this component of loss is given in Goobie (1989).

The final step in evaluating the data was to verify that the mid-span flow was two-dimensional. A general indicator of two-dimensionality is the axial velocity ratio (AVR) which is calculated as follows:

$$AVR = \frac{\bar{V}_{ate}}{\bar{V}_{ale}} \quad (4.18)$$

These velocities are not known at the leading and trailing edges of the blades; they are only known at the upstream and downstream measuring planes. To determine the values at the leading and trailing edges, a linear interpolation is used. This calculation is illustrated in Figure 4.27. Although the axial velocity does not vary linearly in this region, it is felt that the magnitude of the velocities are close enough that the linear interpolation is an adequate approximation.

$$V_{l.e.} = V_1 + \frac{(V_2 - V_1) X_1}{T}$$

$$V_{l.e.} = V_1 + \frac{(V_2 - V_1) (X_1 + Cx)}{T}$$

Figure 4.27: Schematic top view of cascade and endplates presented with interpolation scheme used to determine the leading and trailing edge, mass-averaged, axial velocities - reproduced from Whitehouse (1993)

Chapter 5: Results And Discussion

5.1 Establishing Two Dimensional Flow

The work of Rodger (1992) proposed that one could infer the existence of two-dimensional flow in the test section, if all of three conditions are met. These conditions are:

- 1) There exists a spanwise region of uniform total pressure in the middle of the passage, at the cascade outlet.
- 2) There exists a spanwise region of uniform mass-averaged velocity and flow angle, at the outlet of the cascade.
- 3) The axial velocity ratio is equal to 1.0.

The author's early tests with the wind tunnel attempted to delineate the region of uniform total pressure which had been previously shown by Rodger (1992) and Whitehouse (1993). These tests were done with the turbulence generating grid installed, measuring the mixed-

out total-pressure-loss, downstream of the cascade blade row. As illustrated in Figure 5.1, the results clearly lacked the symmetry exhibited by the results of both Rodger (1992) and Whitehouse (1993). After extensive testing to determine the cause of the poor results, a survey of the inlet flow, across the entire inlet plane, was performed with a three-hole probe. The measurements were made in a plane 170% axial chord upstream of the cascade inlet. The distribution of total-pressure-loss in the inlet plane, with the turbulence generating grid in place, is shown in Figure 5.2. Surprisingly, the flow was not at all uniform, even at a distance of 275 grid-rod diameters downstream of the turbulence generating grid.

The total-pressure-loss distribution in the inlet plane was again measured with the turbulence generating grid removed. These results are shown in Figure 5.3, and reveal a much more uniform pressure distribution. The spanwise distribution of total-pressure-loss was also measured at the outlet of the cascade blades. Figure 5.4 displays a much more symmetrical distribution of losses, than existed with the turbulence generating grid in place. The low-loss region is slightly narrower than that demonstrated by Whitehouse, but is still quite acceptable. The difference in width may be attributable to an effect of the turbulence generating grid holder. Even though the grid is removed, the frame and holder remain in place in the wind tunnel. This apparatus was not present when the spanwise loss measurements of Whitehouse (1993) were performed. Another item which may contribute to the difference in width of the low-loss region, is the material used to seal the gaps in the endplates. Whitehouse used a silicone caulking compound as a sealant, which may present less blockage to the flow, than the foam weather-stripping used in the present study.

Figure 5.1: Spanwise distribution of outlet total-pressure-loss coefficient, for smooth blades at high turbulence intensity.

Figure 5.2: Spanwise distribution of total-pressure-loss coefficient throughout the inlet measuring plane for high turbulence intensity (where: $Cp_0 = (P_{01} - P_{0ref}) / q_{ref}$).

Figure 5.3: Spanwise distribution of total-pressure-loss coefficient throughout the inlet measuring plane for low turbulence intensity (where: $Cp_0 = (P_{01} - P_{0rd}) / q_{rd}$).

Figure 5.4: Spanwise distribution of outlet total-pressure-loss coefficient, for smooth blades at low turbulence intensity.

Figures 5.5 and 5.6 illustrate the spanwise distribution of the outlet flow velocity and angle respectively, for the same flow presented in Figure 5.4. Both figures show a mid-span region of uniform flow conditions, thereby satisfying the second requirement for two-dimensional flow.

Two sets of data from the present study are shown in Figure 5.4, for the same conditions. The second partial set of data illustrates a uniform low-loss region, with the magnitude of the loss smaller and more in line with the data of Whitehouse. This data was obtained in May 1993, during the latter portion of the testing. The magnitude of the low-loss region for the first curve is significantly larger. This data was acquired early in the course of testing in August 1992, before the probes had been re-calibrated. The inaccuracy of the calibration data performed by Rodger (1992), for the present probe configuration, was presented in section 4.1.1. This inaccuracy in the calibration data caused the inlet flow angle to be in error by as much as 1.5° . Examination of Figure 5.10 shows that the lowest value of total-pressure-loss is at the design inlet flow angle. Neighbouring values of incidence show slightly larger magnitudes of total-pressure-loss. It appears that the magnitude of the loss is sensitive to inlet flow angle, near the design angle. Therefore, the error in the flow angle, because of the inaccurate calibration data, probably caused the losses of the first curve to be larger than they should. It is felt that the latter data is the more accurate.

Figure 5.7 shows the same pressure loss distribution curve, with a second curve for the results of the epoxy blades, under the same conditions. The data for the epoxy blades compares very well with that of the aluminum blades. This confirms that the two sets of

Figure 5.5: Spanwise distribution of outlet flow velocity.

Figure 5.6: Spanwise distribution of outlet flow angle.

Figure 5.7: Spanwise distribution of total-pressure-loss coefficient for smooth aluminum and epoxy blades.

blades can be used interchangeably.

Figure 5.8 illustrates the effects of incidence on the low-loss region. Negative incidence tends to widen the low-loss region. Positive incidence tends to make the low-loss region narrower. The results shown for $+10^\circ$ suggest that incidence much higher than this value would eliminate the existence of two dimensional flow. The tests of Rodger (1992) show that even at $+20^\circ$, there should be a significant region of two dimensional flow.

In Figure 5.9, the spanwise low-loss regions are examined for blades that have been roughened. For design incidence, the low-loss region of the roughened blades is higher and narrower. This might be expected because the presence of the roughness would tend to enhance the corner vortices which exist between the mid-passage and the endplates. For the roughened case at $+10^\circ$, there does not appear to be a region of uniform low loss. The curve appears parabolic in shape, without a region of constant loss which would indicate a possible region of two dimensional flow. However, the absence of two dimensional flow should produce significantly higher losses. Since the $+10^\circ$ curve has only slightly higher losses than the 0° curve, this suggests it is possible that a small region of two dimensional flow is present in the mid-span vicinity for $+10^\circ$ incidence.

5.2 Off-Design Losses

The initial tests by the author attempted to reproduce the off-design loss data obtained by Whitehouse (1993). Figures 5.10 and 5.11 show the comparisons of this data.

Figure 5.8: Spanwise distribution of total-pressure-loss coefficient for varying incidence - smooth blades.

Figure 5.9: Spanwise distribution of total-pressure-loss coefficient for varying incidence - rough blades ($k/C=0.00208$, $s/C=0.250$, $\Delta s/C=0.470$, $\lambda=8.8$).

The total-pressure-loss, $\overline{Y}_m$ compares very well except at high incidence of $+20^\circ$. The loss at this incidence is dominated by separated flow. The difference in the loss at $+20^\circ$ may be due to the effect of flow separating at a different location, or due to the difference in AVR of the two data points (Whitehouse: AVR=0.985, present study: AVR=1.031). Whitehouse (1993) showed that increasing the AVR caused a decrease in the total-pressure-loss.

Examination of the deviation angle, δ , in Figure 5.11 shows that the trend is very similar for the present data and that of Whitehouse. However, the minimum value for Whitehouse is located at the design incidence, 0° . The results of the current study indicate that the minimum deviation occurs near $+10^\circ$ incidence. Subsequent data, obtained for roughened blades, also showed the minimum deviation to occur at $+10^\circ$.

5.3 Effect of Roughness

The data collected during this study was obtained with different roughness parameters being varied simultaneously. For this reason, it is impossible to present all of the data on a single graph. Therefore, the following sections will attempt to describe the effect that each individual roughness parameter had on the flow. The two parameters which will be used to analyze the flow will be the mass-averaged total-pressure-loss, $\overline{Y}_m$, and deviation angle, δ . A summary of the roughness configurations and the measured data is given in Table 5.1. The curves presented in the figures to follow will be identified by the

Figure 5.10: Total-pressure-loss coefficient versus incidence for smooth blades - comparison with Whitehouse (1993).

Figure 5.11: Flow deviation angle versus incidence for smooth blades - comparison with Whitehouse (1993).

Table 5.1: Roughness configurations and measured data.

Trial #	Roughness Position s/C	Sand Grain Size k/C	Roughness Strip Width $\Delta s/C$	Incidence Angle i	Spacing Parameter λ	Total Pressure Loss $\bar{Y}_m$	Flow Deviation δ
1 a	----	----	----	0°	----	0.0337	-4.19°
1 b	----	----	----	+10°	----	0.0355	-4.46°
1 c	----	----	----	-10°	----	0.0299	-3.98°
1 d	----	----	----	+20°	----	0.2370	-9.82°
1 e	----	----	----	-20°	----	0.0304	-3.94°
2 a	0.645	0.00208	0.235	0°	7.4	0.0316	-4.29°
2 b	0.645	0.00208	0.235	+10°	7.4	0.0372	-4.32°
2 c	0.645	0.00208	0.235	-10°	7.4	0.0302	-4.35°
2 d	0.645	0.00208	0.235	+20°	7.4	0.1763	-9.24°
2 e	0.645	0.00208	0.235	-20°	7.4	0.0319	-4.61°
3 a	0.645	0.00445	0.235	0°	10.0	0.0310	-4.47°
3 b	0.645	0.00445	0.235	+10°	10.0	0.0358	-3.86°
3 c	0.645	0.00445	0.235	-10°	10.0	0.0317	-4.05°
4 a	0.534	0.00445	0.470	0°	9.0	0.0367	-4.38°
4 b	0.534	0.00445	0.470	+10°	9.0	0.0363	-3.89°
5 a	0.250	0.00445	0.470	0°	13.7	0.0543	-4.78°
5 b	0.250	0.00445	0.470	+10°	13.7	0.0573	-4.51°
5 c	0.250	0.00445	0.470	-10°	13.7	0.0572	-5.76°
5 d	0.250	0.00445	0.470	-20°	13.7	0.2247	-9.56°
5 e	0.250	0.00445	0.470	-20°	13.7	0.0567	-4.64°

Table 5.1: (cont.) Roughness configurations and measured data.

Trial #	Roughness Position s/C	Sand Grain Size k/C	Roughness Strip Width $\Delta s/C$	Incidence Angle i	Spacing Parameter λ	Total Pressure Loss $\bar{Y}_m$	Flow Deviation δ
6 a	0.250	0.00445	0.235	0°	13.7	0.0477	-4.93°
6 b	0.250	0.00445	0.235	+10°	13.7	0.0491	-4.47°
6 c	0.250	0.00445	0.235	-10°	13.7	0.0468	-5.47°
7 a	0.250	0.00208	0.470	0°	8.8	0.0464	-4.81°
7 b	0.250	0.00208	0.470	+10°	8.8	0.0494	-4.46°
7 c	0.250	0.00208	0.470	-10°	8.8	0.0481	-5.19°
8 a	0.250	0.00208	0.235	0°	8.8	0.0405	-4.35°
8 b	0.250	0.00208	0.235	+10°	8.8	0.0438	-4.08°
8 c	0.250	0.00208	0.235	-10°	8.8	0.0413	-4.45°
9 a	0.250	0.00628	0.470	0°	15.9	0.0605	-4.01°
10 a	0.250	0.00628	0.235	0°	15.9	0.0551	-4.72°
11 a	0.250	0.00208	0.470	0°	10.0	0.0458	-4.50°
12 a	----	----	----	0°	----	0.0275	-3.99°
12 b	----	----	----	+10°	----	0.0327	-3.41°
12 c	----	----	----	-10°	----	0.0279	-4.15°

Figure 5.12: Location of roughness strips on blade profile.

Trial # listed in Table 5.1 (e.g. curve T6 will indicate the data measured for Trial 6). In some of the figures to follow, the data measured for the smooth blades at $+20^\circ$ and -20° (Trials 1d and 1e) are presented with the data for Trial 12 since these two incidences were not repeated. Figure 5.12 illustrates the locations of the roughness strips on the blade profile.

5.3.1 Effect of Roughness at Design Operating Point

Figure 5.13 shows the variation of total-pressure-loss with roughness height for various roughness configurations. Each curve in Figure 5.13 represents constant roughness strip location and width. There is a rapid change in loss from the smooth blade to the first roughness. Above this, the loss appears to increase more gradually. From Figure 2.25a, it would appear that the loss increase should be linear when plotted on a log scale with the equivalent sand roughness height. However, the data in Figure 5.13 is not graphed as equivalent sand roughness height, but is direct roughness height. Also, the data from Figure 2.25a is for blades that were entirely coated with roughness. The effect of isolated regions of roughness may not follow the same linear trend. As well, the magnitude of the spacing parameter is not constant for each curve, so the loss will vary slightly as does the roughness function shown in Figure 2.18.

The effect of the roughness on the wake can be seen in Figure 5.14, which shows the pitchwise distribution of the total-pressure-loss, for various roughness heights and

Figure 5.13: Total-pressure-loss coefficient versus roughness height, for design incidence.

Figure 5.14: Pitchwise total-pressure-loss distribution for various roughness heights and roughness strip widths, at design incidence ($s/C = 0.250$).

roughness strip widths. The figure clearly illustrates that for increasing roughness height and roughness strip width, the wake becomes wider and deeper. This effect is only observed on the suction surface side ($y/S < 0$) of the wake which is reasonable since that is the only surface to which the roughness was applied. On the pressure surface side ($y/S > 0$), the wake appears to be unaffected by the roughness, and the initiation point of the wake remains the same.

Figure 5.15 shows the outlet flow deviation corresponding to the loss values presented in Figure 5.13. One might intuitively expect the deviation to increase with roughness height, due to the growth of a thicker boundary layer which may be inclined to separate earlier. At least two data points shown in Figure 5.15, do not fit this hypothesis. The deviation for the roughness at $k/C = 0.00628$, is actually less than that for the previous roughness height on the same two curves. These two data points were obtained from the same roughness sample, the rear half of the roughness having been removed for the $\Delta s/C = 0.235$ tests. While most of the roughness parameters are constant for each curve of Figure 5.15, the spacing parameter, λ , is not. The roughness configuration for $k/C = 0.00628$, has the largest value of λ , and so would be expected to have a smaller effect on the flow. Therefore, the different magnitude of spacing parameter may have caused the deviation, for the roughness $k/C = 0.00628$, to be lower than expected. Recall however, that the loss coefficient was highest for $k/C = 0.00628$, as seen in Figure 5.13. The deviation angles given in Figure 5.15 are all within 1° of each other. As stated previously, the accuracy to which the three-hole probe can be aligned is $\pm 0.5^\circ$. Therefore, the anomalous points may be due to the misalignment error of the probe.

Figure 5.15: Flow deviation angle versus roughness height, for design incidence.

5.3.2 Off-Design Losses

Figures 5.16 and 5.17 show the losses for various roughness sizes at varying angles of incidence. The losses show that the effect of incidence is the same for the different roughness sizes, since the curves are of the same shape. The effect of increasing the roughness size is to cause a uniform upward shift of the loss curve.

Figures 5.18 and 5.19 show the effect of the roughness on the deviation, at off-design. There is an overall trend to which most of the data points subscribe with just a few exceptions. As discussed in section 5.3.1, the deviation for $k/C = 0.00628$ (Trial 9) is lower than expected. The remainder of the data follows the same general pattern with any anomalies falling within the alignment uncertainty of the probe. For the majority of the data, the deviation for the roughened blades is higher than for the smooth blades.

As reported previously, the minimum deviation occurs at an incidence of $+10^\circ$. However, the minimum total-pressure-loss does not occur at $+10^\circ$ incidence but at 0° incidence. This would appear contradictory since one might expect that the lowest value of deviation would indicate a smaller boundary layer thickness, a smaller blade wake, and therefore a lower total-pressure-loss coefficient. Examination of Figure 5.20 reveals that the smallest wake occurs for the $+10^\circ$ incidence. This would support the lower value of measured deviation angle for $+10^\circ$, and this is verified by the outlet flow surveys in Figure 5.21. This also suggests that the total-pressure-loss coefficient should be lower for $+10^\circ$ incidence than it is for 0° incidence, which is not the case. To calculate the total pressure loss, $\bar{Y}_m$, the integral of C_{p_0} is normalized by the outlet velocity as shown in Equation 4.16.

Figure 5.16: Total-pressure-loss coefficient versus incidence for various roughness heights (with $s/C = 0.250$, $\Delta s/C = 0.470$).

Figure 5.17: Total-pressure-loss coefficient versus incidence for various roughness heights (with $s/C = 0.645$, $\Delta s/C = 0.235$).

Figure 5.18: Flow deviation angle versus incidence for various roughness heights (with $s/C = 0.250$, $\Delta s/C = 0.470$).

Figure 5.19: Flow deviation angle versus incidence for various roughness heights (with $s/C = 0.645$, $\Delta s/C = 0.235$).

Figure 5.20: Pitchwise distribution of outlet total-pressure-loss coefficient for various incidence (smooth blades).

Figure 5.21: Pitchwise distribution of outlet flow angle for various incidence (smooth blades).

The outlet velocity for 0° incidence is greater than the outlet velocity for $+10^\circ$ incidence. When $\bar{Y}_m$ is calculated for both these cases, the lower value of total-pressure-loss coefficient occurs for 0° incidence.

5.3.3 Effect of Location of Roughness Strip

Figures 5.22 and 5.23 illustrate the effect of the location of the roughness on the loss. The roughness data illustrated in these figures are for the same roughness size and width of roughness strip. In the current study, roughness was applied at three different locations, $s/C = 0.250$, 0.534 and 0.645 (see Figure 5.12). Two widths of roughness strip, $\Delta s/C = 0.235$ and 0.470 were used at the $s/C = 0.250$ position. From Figures 5.22 and 5.23, it is clear that the roughness positioned at $s/C = 0.645$ caused only a small increase in the losses.

Figure 5.24 shows the static pressure distribution, as determined by Whitehouse, for the smooth case of the blade profile being investigated. According to the work of Speidel (1954), the static pressure distribution is not greatly affected by the presence of roughness. The roughness positioned at $s/C = 0.534$ and $s/C = 0.645$ places most of the roughness in a region of mildly adverse pressure gradient. The presence of roughness in a relatively strong adverse pressure gradient would be expected to trigger early separation and increase the losses quite significantly. However, the absence of a significant increase in measured loss for $s/C = 0.534$ and 0.645 indicates that earlier separation did not occur. Also, since these

Figure 5.22: Total-pressure-loss coefficient versus incidence for various roughness locations (with $k/C = 0.00445$, $\Delta s/C = 0.235$)

Figure 5.23: Total-pressure-loss coefficient versus incidence for various roughness locations (with $k/C = 0.00208$, $\Delta s/C = 0.235$)

Figure 5.24: Mid-span blade static pressure distribution, at design incidence - reproduced from Whitehouse (1993) (where $C_{p_b} = (P_b - P_2) / (\frac{1}{2} \rho V_2^2)$)

locations are far downstream of the leading edge, the boundary layer has probably grown to be thick enough that the ratio of roughness height to boundary layer thickness is relatively small so it is understandable that losses did not increase substantially.

In contrast, the roughness located at $s/C = 0.250$, is in a region of high velocity and favourable pressure gradient. The high velocity and relatively thin boundary layer imply a high drag force on the roughness elements; higher losses might thus be expected. In fact, Speidel's (1954) experiments found the largest loss to occur near the region of greatest velocity. In Figure 5.22, the data for roughness located at $s/C = 0.250$ do indeed show a significant increase in the loss. This is in contrast with the results of Forster (1966) who found that the region from the throat to the trailing edge was most susceptible to the roughness. However, it is consistent with the results of Kind and Lawrystyn (1992) who predicted that roughness nearer the leading edge would have a more detrimental effect.

The effect of roughness location on deviation is shown in Figures 5.25 and 5.26. One might expect the presence of roughness to increase the deviation of the flow. This is the case for Figure 5.26 and at the design incidence in Figure 5.25. The greatest increase in deviation occurred for roughness located at $s/C = 0.250$. In Figure 5.25 the deviation angles for $+10^\circ$ incidence are actually lower than for the smooth blade case. It is possible that the presence of roughness on the suction surface has caused a reduction of the adverse pressure gradient, such as is shown in Figure 2.28. The reduced adverse pressure gradient might allow the boundary layer to remain attached slightly longer, causing the deviation to be reduced. This effect is even more pronounced for roughness located at mid-chord. This is so because the roughness near the trailing edge has greater opportunity to influence the flow as it leaves the blade.

Figure 5.25: Flow deviation angle versus incidence for various roughness locations (with $k/C = 0.00445$, $\Delta s/C = 0.235$)

Figure 5.26: Flow deviation angle versus incidence for various roughness locations (with $k/C = 0.00208$, $\Delta s/C = 0.235$)

5.3.4 Effect of Percentage of Surface Covered with Roughness

Figure 5.27 shows the change in loss $\overline{Y_m}$, when the width of the roughness strip is changed, for several roughness heights. The current study made measurements using two widths of roughness strip: $\Delta s/C = 0.235$ and $\Delta s/C = 0.470$. For the roughness located at $s/C = 0.250$, the roughness strip width $\Delta s/C = 0.235$ was obtained by removing the rear half of the roughness strip of width $\Delta s/C = 0.470$. The curves in Figures 5.27 are presented in pairs. The curves for Trials 5 and 6 are for the same roughness sample, with half the strip removed for Trial T6. The same relation occurs between curves T8 and T7 as well as curves T10 and T9. The curves show that increasing the width of the roughness strip, causes a uniform increase in the loss. The shift is not only uniform for each point in the curve, but the magnitude of the shift appears to be very similar from one set of curves to the next.

One interesting result in Figure 5.27 is that the losses for curve T7 are approximately equal to the losses for the curve having the next larger roughness size, and half the width of roughness strip (i.e. curve T6). The same effect is also observed for curves T5 and T10. This effect can also be seen by examining a survey of the wakes shown in Figure 5.14. The wakes for trials 7a and 6a are approximately the same size, although curve 16a is slightly deeper and narrower than T7a. Likewise, wakes T5a and T10a are very similar in size.

Figure 5.28 presents the deviation angle for two widths of roughness strip for the smallest roughness ($k/C = 0.00208$), with other roughness parameters being the same. This

Figure 5.27: Total-pressure-loss coefficient versus incidence for various roughness heights and strip widths (with $s/C = 0.250$).

Figure 5.28: Flow deviation angle versus incidence for varying roughness strip width ($s/C = 0.250$, $k/C = 0.00208$).

Figure 5.29: Flow deviation angle versus incidence for varying roughness strip width ($s/C = 0.250$, $k/C = 0.00445$).

graph shows that there is a significant effect of width of the roughness strip. The deviation curve is shifted upwards for increasing width of the roughness strip, while maintaining the same trend with incidence as for the smooth case. The largest width of roughness has caused the deviation to increase by approximately 1° .

Figure 5.29 presents the deviation angle for the same roughness configuration (k/C 0.00445). The average increase in deviation for curve T5 of Figure 5.29, is also approximately 1° . For both widths of roughness strip, the roughness has caused an increase in the boundary layer thickness, as is evident from the increased total-pressure-loss coefficient shown in Figure 5.27. While the two roughness configurations of Figure 5.29 have caused different degrees of boundary layer growth, the difference in boundary layer thickness has not been great enough to cause an appreciable difference in the outlet flow angle. For these roughness configurations, the roughness height appears to be the dominating factor, and the forward portion of the roughness produces the main effects on the deviation.

5.3.5 Repeatability of Data

An effort was made to determine if the loss data could be repeated for a given roughness configuration. To do this, new roughness was applied to the smooth blades using the same roughness parameters as were used for Trial 7. Examination of the spacing parameter showed that λ differed by 12% between the two trials.

The total-pressure-loss, for the design incidence, was determined and is shown in Figure 5.30 (curve T11). Time constraints prevented the acquisition of loss data for any other incidence or configurations. The data shown in Figure 5.30 indicates that the most recent and the earlier loss measurements were very consistent: this gives promising evidence that the roughness application method and measurement methodology give repeatable loss data.

Figure 5.31 shows that the deviation for Trial 11 was slightly lower than for Trial 7. This may possibly be attributable to the 12% higher value of the spacing parameter for Trial 11. Also, the difference in deviation angle is within the alignment accuracy of the probe, as previously noted. In general, this suggests that small differences in spacing parameter may have a noticeable effect on the deviation, but an insignificant effect on the total-pressure-loss.

Figure 5.30: Total-pressure-loss coefficient versus incidence for repeated test with same roughness configuration.

Figure 5.31: Flow deviation angle versus incidence for repeated test with same roughness configuration.

Chapter 6: Conclusions And Recommendations

The following conclusions have been drawn from the results and discussions presented in Chapter 5:

- 1) The turbulence generating grid raised the turbulence intensity to the desired level, but it altered the inlet flow such that it became non-uniform. In this condition, the inlet flow was not acceptable.
- 2) The presence of the roughness on the blades caused a narrowing of the region of two-dimensional flow in the test section.
- 3) The total-pressure-loss increases nearly linearly for increasing roughness height. Such a trend was not apparent from the data for deviation angle.

- 4) The location of the roughness strip was shown to be important in determining the magnitude of the losses. The roughness located in the $3/4$ chord region, on the suction surface, had only a small, insignificant, effect on losses. Roughness located at $1/4$ chord had an obvious effect on the losses. There was no consistent trend for the deviation angle.
- 5) The effect on the losses of halving the percentage of surface covered with roughness, was approximately equivalent to using the next smallest roughness height. The effect of increasing roughness strip width on the deviation, is to cause an upward shift in the deviation angle.
- 6) There was usually an increase in the flow deviation angle when roughness was present on the blades' surface. However, the deviation was insensitive to the actual configuration of the roughness. There was very little difference in the deviation for any of the roughness configurations in the present work.
- 7) A repeat run of a single test point gives a promising indication that the roughness distribution process, and the measurement methods give repeatable data.

During this work, several areas requiring additional work or improvement became apparent. For any future work on this topic, the following recommendations are made:

- 1) All of the roughness configurations that had been originally planned, could not be performed. Therefore, the current database should be expanded, particularly with more roughness sizes and roughness locations. The effect of roughness located on the pressure surface would be an interesting comparison with the suction surface data.
- 2) The spacing parameter for each of the current roughness configurations is unique. Some of these roughness configurations should be repeated with different values of spacing parameter. This would further determine the effect of varying the spacing parameter on the aerodynamic parameters.
- 3) A computational model should be developed to determine if the experimental data can be predicted with satisfactory accuracy.
- 4) Time constraints prevented any further analysis of the effects of the turbulence generating grid. It would be of interest to determine why the grid was so detrimental to uniformity of the inlet flow.
- 5) An improved method of determining the spacing parameter should be developed. The current method has a lag time of several days between

application of the roughness, and calculation of the spacing parameter. This makes it impractical to replace the roughness if it is determined that the value of the spacing parameter is not adequate. A digital image processing system is currently employed by the Department of Mechanical and Aerospace Engineering to determine similar geometric parameters for metallurgical micro-structures. If this system could be utilized, it would permit immediate analysis of the roughness, allowing the roughness to be replaced if required.

- 6) The personal computer currently used for data acquisition in the laboratory is becoming aged and is prone to crashing because of hardware problems. This makes the potential for losing data very serious, and requires frequent backups. It would be desirable to replace this computer at the earliest possible opportunity.

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MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS
TANDEM REFERENCE MATERIAL FROM
ANALYTICAL TEST CHART NO. 2

Appendix A

Blade and Cascade Geometry

Table A.1: Blade geometric parameters.

Table A.2: Blade profile coordinates

Table A.1: Blade geometric parameters.

Inlet flow angle, α_{1des}	28.35°
Exit flow angle, α_{2des}	57.65°
Inlet metal angle, β_1	25.35°
Exit metal angle, β_2	57.51°
Design incidence, i_{des}	3.00°
Design deviation, η , δ_{des}	-0.145°
Stagger angle, γ	21.6°
Camber angle, θ	82.86°
Chord length, C	162.3 mm
Axial chord length, Cx	149.4 mm
Pitch length (spacing), S	110.71 mm
Blade Span, H	200 mm
Pitch to chord ratio, S/C	0.68
Aspect ratio (AR), H/C	1.23
Leading edge diameter, d	16.7 mm
Leading edge wedge angle	43.0°
Trailing edge thickness	4.2 mm
Maximum thickness, t_{max}	31.8 mm
t_{max}/C	0.196
Throat opening, σ	63.6 mm

Table A.2: Blade profile coordinates.

Suction Surface		Pressure Surface	
x/C	y/C	x/C	y/C
0.0050	0.3578	0.0050	0.3578
0.0015	0.3674	0.0102	0.3490
0.0001	0.3776	0.0171	0.3415
0.0006	0.3878	0.0254	0.3355
0.0032	0.3977	0.0347	0.3312
0.0077	0.4069	0.0447	0.3288
0.0139	0.4150	0.0549	0.3285
0.0162	0.4174	0.0570	0.3286
0.0207	0.4220	0.0612	0.3289
0.0275	0.4286	0.0675	0.3293
0.0365	0.4367	0.0759	0.3298
0.0456	0.4442	0.0844	0.3303
0.0591	0.4544	0.0970	0.3310
0.0772	0.4665	0.1138	0.3319
0.0953	0.4771	0.1306	0.3326
0.1134	0.4863	0.1475	0.3332
0.1315	0.4945	0.1643	0.3337
0.1496	0.5016	0.1812	0.3340

Table A.2: Blade profile coordinates.

Suction Surface		Pressure Surface	
x/C	y/C	x/C	y/C
0.1677	0.5077	0.1980	0.3342
0.1858	0.5130	0.2148	0.3343
0.2129	0.5192	0.2401	0.3340
0.2400	0.5237	0.2653	0.3334
0.2762	0.5270	0.2990	0.3317
0.3124	0.5273	0.3327	0.3290
0.3486	0.5245	0.3663	0.3251
0.3847	0.5188	0.4000	0.3199
0.4209	0.5099	0.4337	0.3133
0.4571	0.4977	0.4674	0.3052
0.4933	0.4822	0.5010	0.2955
0.5294	0.4631	0.5347	0.2840
0.5656	0.4402	0.5684	0.2707
0.6018	0.4134	0.6020	0.2555
0.6380	0.3825	0.6357	0.2381
0.6742	0.3473	0.6694	0.2184
0.7103	0.3078	0.7031	0.1961
0.7465	0.2637	0.7367	0.1709

Table A.2: Blade profile coordinates.

Suction Surface		Pressure Surface	
x/C	y/C	x/C	y/C
0.7827	0.2153	0.7704	0.1424
0.8098	0.1764	0.7957	0.1186
0.8370	0.1356	0.8209	0.0922
0.8550	0.1076	0.8377	0.0731
0.8731	0.0791	0.8546	0.0525
0.8912	0.0502	0.8714	0.0303
0.9048	0.0285	0.8840	0.0125
0.9116	0.0177	0.8904	0.0032
0.9161	0.0104	0.8946	-0.0031
0.9184	0.0068	0.8967	-0.0070
0.9197	0.0038	0.8988	-0.0095
0.9203	0.0005	0.9016	-0.0114
0.9200	-0.0028	0.9047	-0.0126
0.9188	-0.0060	0.9080	-0.0128
0.9169	-0.0087	0.9113	-0.0123
0.9144	-0.0108	0.9144	-0.0108

Appendix B

Tables of Data

- Table B.1:** Turbulence intensity measurements.
- Table B.2:** Spanwise total-pressure-loss coefficient at cascade outlet for high Tu.
- Table B.3:** Inlet spanwise distribution of total-pressure-loss coefficient for high Tu.
- Table B.4:** Inlet spanwise distribution of total-pressure-loss coefficient, for low Tu.
- Table B.5:** Spanwise total-pressure-loss coefficient, flow velocity and angle at cascade outlet for low Tu.
- Table B.6:** Spanwise total-pressure-loss coefficient at cascade outlet for low Tu.
- Table B.7:** Spanwise distribution of total-pressure-loss coefficient at cascade outlet for epoxy blades.
- Table B.8:** Spanwise distribution of total-pressure-loss coefficient at off-design incidence, for smooth and rough blades.

Table B.1: Turbulence intensity measurements (Figures 4.19 and 4.20)

Grid not installed		Grid installed	
y/S	Tu	y/S	Tu
-1.4865	0.34	-1.4865	3.1
-1.3514	0.39	-1.3514	3.3
-1.1261	0.39	-1.1261	3.0
-0.9009	0.34	-0.9009	2.7
-0.6757	0.32	-0.6757	2.9
-0.4505	0.36	-0.4505	3.2
-0.2252	0.35	-0.2252	2.7
0.0	0.35	0.0	3.0
0.2252	0.36	0.2252	3.4
0.4505	0.33	0.3153	3.2
0.6757	0.33	0.4054	2.7
0.9009	0.35	0.4505	2.2
1.1261	0.34	0.4955	2.1
1.3514	0.35	0.5405	2.4
1.5766	0.36	0.5856	3.0
		0.6757	3.2
		0.9009	3.2
		1.1261	3.1
		1.3514	3.2
		1.5766	2.9

Table B.2: Spanwise total-pressure-loss coefficient at cascade outlet for high Tu (Figure 5.1).

z/H	C_{p_0}
0.3103	0.0564
0.3448	0.0431
0.3793	0.0281
0.4138	0.0240
0.4828	0.0240
0.4966	0.0269
0.5172	0.0292
0.5517	0.0340
0.5862	0.0410
0.6207	0.0430
0.6552	0.0530

Table B.3: Inlet spanwise distribution of total-pressure-loss coefficient for high $1u$ (Figure 5.2).

Spanwise Position z/H	Total-Pressure-Loss Coefficient, $C_{p_0} = (P_{01} - P_{0ref}) / q_{ref}$						
	$y/S = -0.451$	$y/S = -0.225$	$y/S = -0.108$	$y/S = 0.0$	$y/S = 0.108$	$y/S = 0.225$	$y/S = 0.451$
0.0936	-0.0956	-0.0284	-0.0258	-0.0632	-0.1049	-0.1360	0.0043
0.1034	-0.0709	-0.0234	-0.0243	-0.0616	-0.0950	-0.1269	0.0097
0.1133	-0.0420	-0.0213	-0.0234	-0.0555	-0.0875	-0.1036	0.0130
0.1231	-0.0237	-0.0221	-0.0234	-0.0554	-0.0739	-0.0885	0.0180
0.1330	-0.0175	-0.0174	-0.0232	-0.0502	-0.0669	-0.0769	0.0205
0.1428	-0.0057	-0.0149	-0.0194	-0.0437	-0.0563	-0.0608	0.0193
0.1674	0.0118	-0.0173	-0.0129	-0.0299	-0.0322	-0.0353	0.0112
0.1920	0.0294	-0.0179	-0.0082	-0.0142	-0.0207	-0.0124	0.0041
0.2166	0.0543	-0.0152	0.0021	-0.0015	0.0062	0.0076	0.0000
0.2412	0.0768	-0.0101	0.0179	0.0245	0.0291	0.0354	0.0095
0.2904	0.0799	-0.0083	0.0429	0.0755	0.0911	0.0952	0.0525
0.3397	0.0594	-0.0060	0.0703	0.1192	0.1383	0.1432	0.1001
0.3894	0.0564	-0.0051	0.0774	0.1291	0.1449	0.1437	0.1294
0.4386	0.0567	-0.0064	0.0658	0.1047	0.0931	0.0777	0.1201
0.4878	0.0352	-0.0118	0.0415	0.0548	0.0241	0.0052	0.0698
0.5370	0.0205	-0.0078	0.0255	0.0287	0.0048	-0.0196	0.0275
0.5863	0.0586	0.0139	0.0430	0.0481	0.0228	-0.0117	0.0516
0.6355	0.1064	0.0159	0.0549	0.0841	0.0694	0.0379	0.0975

Table B.3: Inlet spanwise distribution of total-pressure-loss coefficient for high Tu (Figure 5.2).

Spanwise Position z/H	Total-Pressure-Loss Coefficient, $C_{p_0} = (P_{01} - P_{0ref}) / q_{ref}$						
	$y/S = -0.451$	$y/S = -0.225$	$y/S = -0.108$	$y/S = 0.0$	$y/S = 0.108$	$y/S = 0.225$	$y/S = 0.451$
0.6847	0.1327	0.0009	0.0402	0.1048	0.1293	0.1181	0.1257
0.7339	0.1287	-0.0068	0.0316	0.0991	0.1489	0.1508	0.1321
0.7585	0.1260	-0.0031	0.0405	0.1004	0.1441	0.1411	0.1340
0.7831	0.1167	0.0039	0.0387	0.0966	0.1310	0.1129	0.1228
0.8077	0.0979	0.0012	0.0357	0.0877	0.1063	0.0719	0.0987
0.8323	0.0735	-0.0023	0.0279	0.0692	0.0755	0.0325	0.0718
0.8569	0.0497	-0.0044	0.0182	0.0451	0.0472	0.0033	0.0478
0.8815	0.0251	-0.0056	0.0037	0.0180	0.0236	-0.0198	0.0255
0.8914	0.0182	-0.0155	0.0024	0.0110	0.0148	-0.0207	0.0213
0.9012	0.0120	-0.0282	-0.0016	0.0051	0.0029	-0.0249	0.0174
0.9111	0.0059	-0.0550	-0.0105	-0.0020	-0.0024	-0.0284	0.0135
0.9214	-0.0030	-0.0932	-0.0189	-0.0052	-0.0083	-0.0321	0.0084
0.9313	-0.0234	-0.1432	-0.0384	-0.0157	-0.0139	-0.0377	0.0000
0.9411	-0.0620	-0.1964	-0.0746	-0.0304	-0.0323	-0.0498	-0.0201
0.9510	-0.1154	-0.2561	-0.1242	-0.0718	-0.0684	-0.0825	-0.0648
0.9608	-0.1844	-0.3160	-0.1889	-0.1439	-0.1380	-0.1443	-0.1344
0.9707	-0.2670	-0.3813	-0.2683	-0.2321	-0.2267	-0.2247	-0.2209
0.9805	-0.2694	-0.3921	-0.2920	-0.2572	-0.2471	-0.2441	-0.2420

Table B.4: Inlet spanwise distribution of total-pressure-loss coefficient, for low Tu (Figure 5.3)

Spanwise Position z/H	Total-Pressure-Loss Coefficient, $C_{p_0} = (P_{01} - P_{0,ref}) / q_{0,ref}$				
	$y/S = -0.451$	$y/S = -0.225$	$y/S = 0.0$	$y/S = 0.225$	$y/S = 0.451$
0.0936	-0.0712	-0.0414	-0.0517	-0.0822	-0.0604
0.1034	-0.0558	-0.0385	-0.0325	-0.0670	-0.0345
0.1133	-0.0409	-0.0250	-0.0240	-0.0528	-0.0205
0.1231	-0.0310	-0.0215	-0.0176	-0.0420	-0.0122
0.1330	-0.0245	-0.0174	-0.0124	-0.0351	-0.0068
0.1428	-0.0148	-0.0118	-0.0061	-0.0240	-0.0079
0.1674	-0.0064	-0.0039	-0.0017	-0.0137	-0.0015
0.1920	-0.0043	-0.0006	-0.0010	-0.0085	-0.0001
0.2166	0.0009	0.0006	-0.0013	-0.0048	0.0001
0.2412	0.0021	0.0047	0.0023	-0.0010	0.0027
0.2904	0.0046	0.0062	0.0024	0.0000	0.0001
0.3397	0.0056	0.0064	0.0004	0.0013	0.0011
0.3894	0.0056	0.0075	0.0030	0.0007	0.0024
0.4386	0.0054	0.0085	0.0044	0.0038	0.0023
0.4878	0.0044	0.0094	0.0059	0.0038	0.0057
0.5370	0.0043	0.0068	0.0060	0.0068	0.0033
0.5863	0.0045	0.0099	0.0049	0.0041	0.0049
0.6355	0.0045	0.0077	0.0076	0.0037	0.0029

Table B.4: Inlet spanwise distribution of total-pressure-loss coefficient, for low Tu (Figure 5.3)

Spanwise Position z/H	Total-Pressure-Loss Coefficient, $Cp_0 = (P_{01} - P_{0ref}) / q_{ref}$				
	$y/S = -0.451$	$y/S = -0.225$	$y/S = 0.0$	$y/S = 0.225$	$y/S = 0.451$
0.6847	0.0058	0.0130	0.0036	0.0040	0.0027
0.7339	0.0056	0.0080	0.0054	0.0024	0.0025
0.7585	0.0038	0.0090	0.0036	0.0031	0.0050
0.7831	0.0044	0.0101	0.0041	0.0030	0.0029
0.8077	0.0054	0.0082	0.0049	0.0034	0.0018
0.8323	0.0049	0.0112	0.0054	0.0034	0.0034
0.8569	0.0047	0.0089	0.0065	0.0038	0.0026
0.8815	0.0029	0.0095	0.0045	0.0024	0.0037
0.8914	0.0013	0.0064	0.0059	0.0023	0.0007
0.9012	0.0034	0.0086	0.0028	0.0003	-0.0005
0.9111	-0.0006	0.0066	0.0024	0.0001	-0.0038
0.9214	-0.0080	0.005	-0.0031	-0.0031	-0.0114
0.9313	-0.0309	-0.0136	-0.0178	-0.0126	-0.0326
0.9411	-0.0740	-0.0535	-0.0521	-0.0432	-0.0786
0.9510	-0.1415	-0.1228	-0.1205	-0.0979	-0.1402
0.9608	-0.2239	-0.2097	-0.1936	-0.1766	-0.2228
0.9707	-0.3115	-0.3029	-0.3032	-0.2692	-0.3112
0.9805	-0.3281	-0.3351	-0.4053	-0.2927	-0.3453

Table B.5: Spanwise total-pressure-loss coefficient, flow velocity and angle at cascade outlet for low Tu (Figures 5.4 - 5.6).

z/H	C_{p_0}	V_2/V_{ref}	α_2
0.1897	0.0785	1.4339	52.8560
0.2931	0.0895	1.4214	52.7863
0.3276	0.0592	1.4455	53.3631
0.3621	0.0382	1.4625	53.6275
0.3966	0.0336	1.4662	53.7179
0.4310	0.0334	1.4678	53.7474
0.4655	0.0326	1.4662	53.7847
0.5000	0.0322	1.4682	53.6605
0.5345	0.0333	1.4658	53.6829
0.5690	0.0314	1.4696	53.6198
0.6034	0.0309	1.4689	53.5499
0.6379	0.0396	1.4615	53.3660
0.6724	0.0673	1.4389	52.9651
0.7069	0.0968	1.4172	52.2298
0.8103	0.0841	1.4297	52.7285

Table B.6: Spanwise total-pressure-loss coefficient at cascade outlet for low Tu (Figure 5.4).

z/H	C_{p_0}
0.3929	0.0280
0.4821	0.0275
0.5179	0.0273
0.5995	0.0287

Table B.7 Spanwise distribution of total-pressure-loss coefficient at cascade outlet for epoxy blades (Figure 5.7).

z/H	C_{p_0}
0.3966	0.0346
0.4310	0.0339
0.4655	0.0337
0.5000	0.0318
0.5345	0.0317
0.5690	0.0311
0.6034	0.0309

Table B.8. Spanwise distribution of total-pressure-loss coefficient at off-design incidence. for smooth and rough blades (Figures 5.8 and 5.9).

Smooth Blades				Rough Blades			
$i = -10^\circ$		$i = +10^\circ$		$i = 0^\circ$		$i = +10^\circ$	
z/H	C_{p_0}	z/H	C_{p_0}	z/H	C_{p_0}	z/H	C_{p_0}
0.2797	0.0468	0.4161	0.0450	0.3415	0.0554	0.3819	0.0688
0.3147	0.0330	0.4510	0.0360	0.3768	0.0508	0.4167	0.0579
0.3497	0.0298	0.5210	0.0362	0.4120	0.0488	0.4514	0.0526
0.4895	0.0279	0.5559	0.0358	0.4472	0.0463	0.4861	0.0512
0.6294	0.0293	0.6084	0.0381	0.4824	0.0464	0.5556	0.0494
0.6573	0.0284	0.6434	0.0477	0.5176	0.0456	0.5903	0.0510
0.6993	0.0336			0.5528	0.0452	0.6250	0.0546
0.7343	0.0552			0.5880	0.0450	0.6597	0.0632
				0.6232	0.0476		
				0.6585	0.0500		
				0.6937	0.0575		

Appendix C

Control Surface Nomenclature and Settings

Figure C.1: Control surface locations and labelling.

Figure C.2: Endplate nomenclature and settings.

Table C.1: Control surface settings to establish uniform flow

Figure C.1: Control surface locations and labelling - reproduced from Rodger (1992).

Figure C.2: Endplate nomenclature and settings - reproduced from Whitehouse (1993).

The following are the average settings used to establish uniform, two dimensional flow in the test-section for each of the angles of incidence, i , as indicated. The geometry and measurement of the control surfaces and the endplates are shown in Figures C.1 and C.2.

Table C.1: Control surface settings to establish uniform flow.

Incidence i (°)	Endplate Settings				Control Surface Settings							
	X1	X2	X3	X4	TF	BF	TTB	BTB	FW	BP1	BP2	Screen
	(mm)	(mm)	(mm)	(mm)	(°)	(°)	(°)	(°)	(°)	(mm)	(mm)	Used
-20	33.5	135.5	30.0	143.0	10.0	15.0	62.0	60.0	-2.5	Max*	0.0	No
-10	33.5	135.5	30.0	143.0	22.5	19.0	68.0	70.0	-2.0	Max*	0.0	No
0	33.5	137.5	31.5	142.0	44.0	24.5	82.5	80.5	2.5	35.0	28.0	No
+10	33.0	138.0	30.0	144.0	50.5	45.5	97.0	92.0	0.0	50.0	40.0	Yes
+20	34.0	135.0	32.0	139.0	75.0	50.0	102.0	95.0	0.5	72.0	83.0	Yes

* Max = Maximum opening possible (BP1)

Appendix D

Spacing Parameter Calculation

Table D.1: Spacing parameter calculation.

Figure D.1: Effect of roughness spacing on law of the wall intercept.
showing spacing parameters from present study.

Table D.1 shows the calculation of the spacing parameter, λ , for each of the roughness configurations. The measurements were made by counting the number of sand grains inside a square block of a grid overlaying the roughness. Up to 8 different blocks were counted for each blade. The average number of grains was calculated for each blade and then for the cascade. Only the three middle blades of the cascade were examined for this calculation. The frontal area was calculated by assuming that the sand grains were of spherical shape, and having a nominal diameter as determined by the mesh sizes of the sifting apparatus (see section 4.3.2).

Table D.1: Spacing parameter calculation.

Trial #	Blade #	Measurement								Blade Average	Average of Cascade	Grid Block Area (cm ²)	Grain Size (μm)	Spacing Parameter λ
		1	2	3	4	5	6	7	8					
2	2	140	16	16	11	155	130	176		148	152	1	337.5	7.4
	3	168	14	15	11	136	156	136		145				
	4	165	18	15	15	183	142	145		162				
3	2	121	88	97	85	121	88	83		97.6	97.6	4	722	10.0
	3	73	11	10	11	103	81	94		97.1				
	4	117	10	10	92	110	72	85		98				
4	2	147	14	11	11	109	124	104	111	122	109	4	722	9.0
	3	90	10	10	10	107	106	86	103	101				
	4	114	10	10	96	116	89	95	101	103				
5.6	2	55	62	67	56	64	76	56	74	63.8	71.5	4	722	13.7
	3	100	85	74	74	60	66	83	71	76.6				
	4	71	87	67	64	80	78	91	55	74.1				

Table D.1: Spacing parameter calculation.

Trial #	Blade #	Measurement								Blade average	Average of Cascade	Grid Block Area (cm ²)	Grid Size (μ m)	Spacing Parameter λ
		1	2	3	4	5	6	7	8					
7.8	2	135	11	12	14	125	128	131	151	131	127	1	337.5	8.8
	3	118	13	10	12	141	120	127	133	125				
	4	119	11	11	10	134	132	148	124	124				
9.10	2	69	58	73	51	83	76			68.3	69.2	9	1020	15.9
	3	80	61	71	68	57	54			65.2				
	4	92	62	59	90	83	59			74.2				
11	2	119	11	11	11	127	119	104	108	116	111	1	337.5	10.0
	3	104	12	11	11	117	103	106	113	112				
	4	101	10	10	10	113	112	113	108	107

Figure D.1: Effect of roughness spacing on law of the wall intercept, showing spacing parameters from present study - reproduced from Dvorak (1969).

Appendix E

Program Listings

THP Code Modified from Whitehouse (1993)

- E.1: THP_TRV.PAS**
- E.2: THPMENU.PAS**
- E.3: TRAVERSE.PAS**
- E.4: SAMPLING.PAS**
- E.5: REDUCT.PAS**
- E.6: GLOBALS3.PAS**

```

$M $4000.0,$4000.0
Program ThreeHoleProbe.

! Written by M.I. Yaros - November 1980 }
! Version 2.0 by David Whitehouse - May 1991 }
! Version 2.1 - Modified by Michael Abbott - August 1992 }
!   - Horizontal Traverse }
! Version 2.2 - Modified by Michael Abbott - October 1992 }
!   - Beta calculation changed }
! Version 2.3 - Modified by D. Isaacs and M. Abbott - March 1993 }
!   - Sampling method modified for 4 transducers }
!   - Extrapolation beyond range of arrays added }
! Version 2.31 - Added DOS Shell option to Main Menu }
!   - new procedure Shell in THPMI.NI.PAS }
!   - added compiler directive "$M $4000.0,$4000.0" }
!   to THP_TRV.PAS This may have adverse }
!   effects on the graphing routines }
!   - March 1993 }
! Version 2.32 - Corrected PLOC Calc to calculate the true mass }
!   average of the losses, angles, and velocities }
!   Similar changes were also done to MixLoss }
!   - April 8th, 1993 }

uses ThpMenu.

Begin
! sets to 2400 Baud, no parity, one stop bit, 8 data bits }
! 0 - serial port 1 }

InitMenu.
MainMenu.

end

```

```

unit THPMENU;

interface

uses (Crt,Dos,Mouse,Sampling, Traverse, Global3, Reduct, utility);

procedure InitMenu;
{ initializes all parameters for display in menu }

procedure SystemMenu;

procedure ProbeMenu;

procedure MainMenu;

implementation

var code          integer;
    fieldin       string;
    DefaultFile   PathStr;
    DefaultFileHeader string;

procedure LoadDefaults(InDefaultFile PathStr);
var i integer;
    DefaultFile text;
begin
    Assign(DefaultFile, InDefaultFile);
    Reset(DefaultFile);
    Readln(DefaultFile, DefaultFileHeader);
    Readln(DefaultFile, Probe_Angle, Not_Ninit);
    Readln(DefaultFile, Waiting_Time, Sampling_Time);
    Readln(DefaultFile, Outfill);
    Readln(DefaultFile, RedFile);
    Readln(DefaultFile, CalFile);
    CalArrayReady := false; { This was not present before and caused problems }
    Readln(DefaultFile, InDataFile);
    Readln(DefaultFile, InletAngle);
    for i = 1 to 9 do
        Readln(DefaultFile, TraverseStepSize[i], TraverseStations[i], TraverseStep[i] to 2);
    end;
    Close(DefaultFile);

var code integer;
    fieldin string;
    DefaultFile PathStr;
    DefaultFileHeader string;

procedure SaveDefaults(OutDefaultFile PathStr);
var i integer;
    DefaultFile text;
begin
    Assign(OutDefaultFile, OutDefaultFile);
    Rewrite(OutDefaultFile);
    WriteLn(OutDefaultFile, DefaultFileHeader);
    WriteLn(OutDefaultFile, Probe_Angle, 10, 1, Not_Ninit to 2);
    WriteLn(OutDefaultFile, Waiting_Time, 10, Sampling_Time, 10);
    WriteLn(OutDefaultFile, Outfill);
    WriteLn(OutDefaultFile, RedFile);
    WriteLn(OutDefaultFile, CalFile);
    WriteLn(OutDefaultFile, InDataFile);
    WriteLn(OutDefaultFile, InletAngle);
    for i = 1 to 9 do
        WriteLn(OutDefaultFile, TraverseStepSize[i], 2, TraverseStations[i], 10, TraverseStep[i] to 2);
    end;
    Close(OutDefaultFile);

function DefaultMenuLabel(i integer) PathStr;
var out PathStr;
begin
    out := '';
    case i of
        1: out := 'Default File Header';
        2: out := 'Load Default File';
        3: out := 'Save Default File';
        4: out := 'Save Standard Default File { STD.DFT }';
    end; { case }
    DefaultMenuLabel := out;
end;

function DefaultMenuDefault(i integer) PathStr;
var out PathStr;
begin
    out := '';
    case i of
        1: out := DefaultFileHeader;
    end; { case }
    DefaultMenuDefault := out;
end;

procedure DefaultMenuAction(i integer);

```

```

    DefaultMenuActive(i),
until (pCase(Choice) = 'Q');
end;

procedure InitMenu;
begin
    InitTraverse;
    InitReduct;
    InitMotor;
    InitOperatingPoint;
    InitSampling;
    Port = 1; Hand_Rate = 2400; Par = '0'; SBits = 1; DBits = 8;
    OutFile = 'DAVIDDRWFILS\3\PTTSTDRAW';
    TipClr = 0; Contraction = 10; { these are not set in current version }

    GetDateYearMonthDay, DayOfWeek; Enter_Init = 1001;
    CalCoef0 = 1.382; CalCoef2 = 1.352; { pressure transducer calibration coefficients }
    CalCoef3 = 0.686; CalCoef4 = 1.389; { added for 3 transducer use }
    ScanValveUse = false; { added for 3 transducer use }
    Slot = 3; Probe_Angle = 86;
    XInit = 100; YInit = 0.0; ZInit = 100.0; { axial distance from leading edge }
    DefaultFileHeader = '';
    DefaultFile = 'STD.DFT';
    if FileExists(DefaultFile) then
        LoadDefaults(DefaultFile);
    end;

    { following are System Menu routines }

function SystemLabel(i: integer): MenuLabel;
var out: MenuLabel;
begin
    out := '';
    Case i of
        1 out = 'Port Number';
        2 out = 'Hand Rate';
        3 out = 'Parity';
        4 out = 'Stop Bits';
        5 out = 'Data Bits';
        8 out = 'Zero reading entering period';
    end;
end;

begin
case i of
1 StrMenu(DefaultFileHeader);
2 begin
    WriteLn(DefaultFile);
    InitMenu(DefaultFile);
    LoadDefaults(DefaultFile);
end;
3 begin
    WriteLn(DefaultFile);
    OutFileMenu(DefaultFile);
    SaveDefaults(DefaultFile);
end;
4 SaveDefaults('STD.DFT');
end; { case }
end;

procedure DisplayDefaultMenu;
var i: integer;
begin
    WriteLn('File menu');
    WriteLn;
    for i = 1 to 4 do
        begin
            WriteLn(' ', DefaultMenuLabel(i));
            Tab(50);
            WriteLn(DefaultMenuLabel(i));
            WriteLn;
        end;
    end;
    QuitLine;
    WriteLn;
end;

procedure DefaultMenu;
var Choice: char;
    i: integer;
begin
    repeat
        ClrScr;
        DisplayDefaultMenu;
        repeat
            Choice = ReadKey;
            until (Choice in ['1', '4', 'Q', 'q']);
        until Choice.code = 13;
        WriteLn(DefaultMenuLabel(i));
    end;
end;

```

```

    9 out = 'Quit';
end; { Case }
SystemLabel ~out;
end; { SystemLabel }

function SystemDefault(i integer) PathStr;
var out PathStr;
begin
    out := '';
    case i of
        1 : str(Port,out);
        2 : str(Baud Rate,out);
        3 : out ~Par;
        4 : str(SBits,out);
        5 : str(DBits,out);
        8 : begin
            str (Enter Init,out);
            out ~every ' + out + ' measurements';
        end;
    end; { Case }
    SystemDefault ~out;
end; { SystemDefault }

procedure SystemInput(i integer);
begin
    case i of
        1 : System(Port);
        2 : Input(Baud Rate);
        3 : CharMenu(Par);
        4 : ByteMenu(SBits);
        5 : ByteMenu(DBits);
        8 : InitMenu(Enter Init);
    end;
end; { SystemInput }

procedure DisplaySystemMenu;
var i integer;
begin
    gotoXY(1,1);
    WriteLn 'Serial Port Settings Menu';
    WriteLn .....;
    WriteLn * Port Number 1..2 *
    WriteLn * Baud Rate bits 300'600'2400'4800'9600 *
    WriteLn .....;
    WriteLn * (0) None, (1) Even, (2) Odd *
    WriteLn * 1..2 *
    WriteLn * Data Bits 7..8 (if parity is enabled, *);
    WriteLn * n should be set to 8 *);
    WriteLn .....;
    WriteLn '');
    for i := 1 to 8 do
        begin
            WriteLn(Colon, SystemLabel(i));
            Tab(50);
            WriteLn(SystemDefault(i));
        end;
    end;
    QuitLine;
    WriteLn;
    DelLine;
end; { Display System Menu }

procedure SystemMenu;
var i integer;
    Choice char;
begin
    ClrScr;
    repeat
        DisplaySystemMenu;
    repeat
        Choice := UpCase(ReadKey);
    until (Choice in ['1'..'9','Q'])
    Val(Choice,i,code);
    Write(SystemLabel(i));
    Tab(50);
    SystemInput(i);
    until Choice = 'Q';
end; { SystemMenu }

; following are File Data Menu Routines ;

; following are Probe information menu procedures ;

function ProbeMenu(m integer) MenuLabel;
var out MenuLabel;
begin
    case m of

```



```

1 out Text Date
2 out Current probe vertical location.
3 out Current distance of stem head from endwall.
4 out Probe angle Negative when probe looks down
5 out Probe traverse slot (far downstream slot = 5)
6 out
7 out
8 out Number of Holes in Probe
9 out Out
end
ProbeMenuLine out
end. {Probe Menu Line}

procedure ProbeMenuLabel(i integer).
begin
  GetAbsolute(Int,YInt)
  Write(ProbeMenuLabel(i),Tab(60)).
  ( case i of
    1 Datedisplay.
    2 Write (YInt/31.7 mm ).
    3 Write (ZInt/31.7 mm ).
    4 Write (ProbeAngle/31.7 ).
    5 Write (Slot.').
    6 Write (Probe_Holes.').
  end. { Case }
  Ctrlol. { clears to the end of line.. eliminates overlap with previous entry }
end. {Menu labels}

procedure ProbeMenuInput(i integer).
begin
  ( case i of
    1 DateMenu (Month,Day,Year).
    4 RealMenu(Probe_Angle).
    5 IntMenu(Slot).
    8 IntMenu(Probe_Holes).
  end.
  if Probe_Holes > 10 then Probe_Holes = 10.
end. { ProbeMenuInput }

procedure DisplayProbeMenu.
var i integer
begin
  WriteInt Probe Information Menu ).
  WriteLn.
  for i = 1 to 8 do
    begin
      Write(Colon).
      ProbeMenuLabel(i).
      WriteLn
    end
    OutLn.
    WriteLn.
    DelLn.
    DelLn.
  end. {Display ProbeMenu}

procedure ProbeMenu.
var i integer.
    Choice char.
begin
  ( isSet.
  repeat
    DisplayProbeMenu.
  repeat
    Choice = UpCase(ReadKey).
  until ((Choice in '1'..'8'..'Q'))
  if Choice < 'Q' then
    begin
      Val(Choice,i).
      ProbeMenuLabel(i).
      ProbeMenuInput(i).
    end.
  until Choice='Q'.
end. {ProbeMenu}

{ following are Inlet traverse setting menus }

{ following are Sampling Menu procedures }

{ Following are the TraverseType Menu procedures }

function TraverseType(i integer) MenuLabel.
var out MenuLabel.
begin

```

```

out ...
case 1 of
  1 out - 'Static Tap Test (Cartelon Cascade 3 Only)';
  2 out - 'Single Point Probe Sample';
  3 out - 'Quick Traverse';
  4 out - 'Horizontal Traverse';      { Modified for Horizontal Traverse }
  5 out - 'Traverse Settings';
  6 out - 'Vertical Traverse';
  7 out - 'Output File Name';
  8 out - 'Reduced Data File Name';
  9 out - 'Quit';
end; { case }
TraverseType := out;
end; { TraverseType }

procedure TraverseTypeMenuLabel(i integer);
begin
  Tab(40);
  case 1 of
    1 6 Write('');
    7 Write(outfill);
    8 Write(redfill);
  end; { Case }
end; { TraverseTypeMenuLabel }

procedure SetUpTraverseTypeMenu(i integer);
begin
  case 1 of
    1 StaticTapTest;
    2 SinglePointProbeSample;
    3 QuickMenu;      { found in Traverse unit }
    4 MikeTraverse;   { Modified for Horizontal Traverse }
    5 TraverseMenu;
    6 PhilTraverse;
    7 FileMenu(outfill); { checking occurs when traverse is run }
    8 OutFileMenu(redfill); { must be entered for automatic saving }
  end;

end; { SetUpTraverseTypeMenu }

procedure DisplayTraverseTypeMenu;
var i integer;
begin
  ClrScr;
  GotoXY(1,1);
  WriteLn('Traverse Menu ');
  WriteLn;
  for i = 1 to 8 do
    begin
      Write(i,Colon,TraverseType(i));
      TraverseTypeMenuLabel(i);
      WriteLn;
    end;
  QuitLn;

end; { Display TraverseTypeMenu }

procedure TraverseTypeMenu;
var i integer;
    Choice char;
begin
  ClrScr;
  repeat
    DisplayTraverseTypeMenu;
  repeat
    Choice := UpCase(ReadKey);
  until (Choice in ['1'..'9','Q'])
  and (Choice.i < 0);
  WriteLn;
  Write(TraverseType(i));
  SetUpTraverseTypeMenu(i);
  until Choice = 'Q';

end; { TraverseTypeMenu }

{ following are the Main Menu procedures }
function MainMenu(mel(integer) MenuLabel;
var out MenuLabel;
begin
  out ...;
  case 1 of
    1 out = 'Serial port settings';
    2 out = 'SamplingMenu';
    3 out = 'Probe Options';
    4 out = 'Defaults';
    5 out = 'Tunnel Information';
    6 out = 'Motor Control';
    7 out = 'Traverse';
    8 out = 'Data Reduction Menu';
    9 out = 'DOS Shell';

```

```

end. { case }
MainMenuLine := out;
end. { MainMenuLine }

procedure Shell;
var
  path string;
begin
  WriteLn('THP V2.3 MS-DOS Shell');
  WriteLn('Implemented Saturday, March 13th by Dave Isaacs');
  WriteLn('Type Exit to return to THP');
  path := GetEnv('COMSPEC');
  SwapVectors;
  Exec(GetEnv('COMSPEC'), '');
  SwapVectors;
  WriteLn;
  WriteLn('returning to THP');
  If DosError <> 0 Then
  Begin
    WriteLn;
    WriteLn('ERROR: Could Not Run COMMAND.COM');
    WriteLn('Dos Error Code is ' + DosError);
    WriteLn('Mem Avail. bytes available');
    WriteLn('Largest free block is ' + MaxAvail + ' bytes');
    WriteLn('Hit any key to return to THP');
    While not KeyPressed do;
  End; {if}
End; {procedure Shell}

procedure SetUpMainMenu(integer);
{ the actions list }

var Ch char;
begin
  Case i of
    1: SystemMenu;
    2: SamplingMenu;
    3: ProbeMenu;
    4: DefaultMenu;
    5: TunnelMenu;
    6: MotorMenu;
    7: TraverseTypeMenu;
    8: ReduceMenu;
    9: Shell;
  end; { of unit thpmenu }
end; { of unit thpmenu }
end; { MainMenu } { the program should now be terminated }
{ all cleanup must be done here }

```



```

WriteLn (outfile1, ' Horizontal step size (mm) ', Ver_Step_Size ^ 4);
WriteLn (outfile1, ' Turning direction ', V(CW));
WriteLn (outfile1, ' Number of measurement stations ', VN[3]);
WriteLn (outfile1, ' ');
WriteLn (outfile1, ' First line (111) V# H# InQentr InP Q1entr P1 Q2entr P2 Q3entr
P3 ');
WriteLn (outfile1, ' Second line (222) V# H# Patm 10 Cp1 Cp2 Cp3 ');
WriteLn (outfile1, '.....');
WriteLn (outfile1, ' ');

end. { procedure fileheader }

procedure DataFileOutput(var Outfile text; VII,HII integer; P,Q,Cp Probe_Array);
var i integer;
begin
  RunScreen('Writing to data file');
  Write (outfile, '111 ' VII 3, ' HII 3, ' InitQ 9 3, ' InitP 9 3);
  for i = 1 to Probe_Holes do
    Write(outfile, ' Q1[C.contraction 9 6, ' P[i] 9 6);
  WriteLn(outfile);

  Write (outfile, '222 ' VII 3, ' HII 3, ' Patm 5 2, ' F0% 5 2);
  for i = 1 to Probe_Holes do
    Write(outfile, ' Cp[i] 10 7);
  WriteLn(outfile);

end.

procedure StepChangeV(var Outfile text; Message string; NewStep real);
var /Abs, YAbs real;

{ Name StepChangeV changed from StepChange for Horizontal Traverse }
begin
  GetAbsolute(/Abs, YAbs);
  WriteLn(Outfile, '333 ' Message, ' YInit StepSize ');
  WriteLn(Outfile, '444 ' YAbs 10 2, ' NewStep 10 2);

end.

procedure StepChangeH(var Outfile text; Message string; NewStep real);
var /Abs, YAbs real;

{ Procedure StepChangeH Added for Horizontal Traverse }
{ Note: Data is outputted to file such that it can be read as Y traverse }
{ data It can be viewed although this is not entirely correct }

```

```

if KeyPressed then
begin
  KeyCheck;
  C1Pscr
  WriteLn 'Waiting resumed Press O key to reevaluate operating point );
end

Reset f1
GetTime(hour minute sec2 sec200);
if sec2 >= sec1 then
begin
  total := total+1; { Routine cycles until the number of seconds }
  sec1 := sec2; { passed equals the wait time }
  GotoXY(1 3);
  GetTime(hour minute second sec1 00);
  WriteLn('Current Time ' Hour 2, ' Minute 2, ' Second 2)(tr ol);
end.
until (total > seconds); { ending on the conservative side of the wait }
RunScreen('Waiting finished');
End.

{ ..... }
{ -- }
{ -- Data File Output Procedures }
{ -- }
{ ..... }

procedure DataFileHeader(var outfile text);
begin
  GetDate (Year, Month, Day, DayOfWeek);
  GetAbsolute(ZInit, YInit);
  WriteLn (outfile1, ' Test Date = ' Month, ' Day, ' Year);
  WriteLn (outfile1, ' Clearance size (U/c) ', TipChr 10 5);
  WriteLn (outfile1, ' Tunnel contraction factor ', Contraction 10 5);
  WriteLn (outfile1, ' Transducer calibration coef for Psc2-Psc1 ' (CalcoR) 5 3);
  WriteLn (outfile1, ' Transducer calibration coef for P-Prf ' (CalcoP) 5 3);
  WriteLn (outfile1, ' Waiting period (sec) ', Waiting_Time 3);
  WriteLn (outfile1, ' Sampling period (sec) ', Sampling_Time 3);
  WriteLn (outfile1, ' Traverse slot # ', Slot 3);
  WriteLn (outfile1, ' Probe angle (deg) ', Probe_Angle 5 2);
  WriteLn (outfile1, ' Initial location of the probe stem head ');
  WriteLn (outfile1, ' Horz Distance from endwall (mm) ' YInit 10 4);
  WriteLn (outfile1, ' Vert Distance from A2 (above A2 is positive) (mm) ' Yinit 10 4);
  WriteLn (outfile1, ' ');
  WriteLn (outfile1, ' Patm in mmHg, T0 in Kelvin and the other Dimensional ');
  WriteLn (outfile1, ' parameters in volts ');

```

```

begin
  GetAbsolute(ZAbs.YAbs);
  WriteLn(Outfile, 333 'Message: ZInit StepSize');
  WriteLn(Outfile, 444 ' /Abs 10 2.' 'NewStep 10 2);
end;

{-----}
{-- Sampling Procedures --}
{-----}

procedure Sample(seconds integer; Gain1, Gain2 cha;
  var i integer;
  Hole string;
begin
  Get ScanValve_Port(0);
  Str(i, Hole);
  RunScreen('ScanValve Hole ' + Hole + ' Gain1 ' + Gain1 + ' Gain2 ' + Gain2);
  Channel := Channel2;
  StartSample(Gain1, Gain2);
  Pause(seconds); { lets system sample for time of seconds }
  StopSample;
end;

procedure HoleSample(var P_Pref, Psc2_Psc1 Array 1 var 1 integer);
var Gain1, Gain2 char;
begin
  RunScreen('PreSampling Waiting');
  Pause(Waiting_Time); { pause function displays clock }
  Gain1 := 0; Gain2 := 0; { starts with lowest gain }
  Sample(Gain1_Time, Gain1, Gain2); { checking and adjusting gain }
  DumpTo (Psc2_Psc1, P_Pref, 1); { dumps serial port data to string arrays }
  Gain1 := GainChange(Psc2_Psc1, 1);
  Gain2 := GainChange(P_Pref, 1);
  Sample(Sampling_Time, Gain1, Gain2); { data sampling }
  DumpTo(Psc2_Psc1, P_Pref, 1);
end;

procedure HoleStep(var Hole integer); { Procedure Added for 3 Transducer Use }
begin
  if ScanValveUse then
    begin
      Channel2 := Channel;
      CalCoP := CalCoP2;
      InitP := InitP2;
    end;
  if Hole = 1 then { Following 4 lines have been modified }
    Home_ScanValve { and moved from ProbeSample for }
  else { Transducer Use }
    StepToScanValvePort(Hole);
  end; {if ScanValveUse}
  if not(ScanValveUse) then
    begin
      Case Hole of
        1 begin
          Channel2 := Channel;
          CalCoP := CalCoP2;
          InitP := InitP2;
        end;
        2 begin
          Channel2 := Channel3;
          CalCoP := CalCoP3;
          InitP := InitP3;
        end;
        3 begin
          Channel2 := Channel4;
          CalCoP := CalCoP4;
          InitP := InitP4;
        end;
      end;
    end; {Case}
  end; {if not ScanValveUse}
end; {Procedure HoleStep}

procedure ProbeSample(var P_Q, Cp Probe_Array); {uses HoleSample on
each probe hole}
var Hole integer;
P_Pref, Psc2_Psc1 array 1;
i integer;
begin
  for Hole = 1 to Probe_Holes do { Three Hole Probe loop }
    begin
      HoleStep(Hole); { Added for 3 Transducer Use }
      HoleSample(P_Pref, Psc2_Psc1);
      AverageData(P_Pref, Psc2_Psc1, P[Hole], Q[Hole], Cp[Hole]);
    end; { Port Loop }
  end;
end;

```

```

end. {ProbeSample Procedure}

{-----}
{-- Traverse Procedures --}
{-----}

procedure SetUpTraverse(var ExitCode: char);
{ performs functions common to all traverses }
var Y/N: boolean;

begin
  Y/N := false;
  ClrScr;
  if Outfill = '' then
    OutFileMenu(outfill);
  if FileExists(outfill) then
    begin
      WriteLn(outfill, ' already exists ');
      WriteLn('Over write file (Y/N) ');
      boolMenu(Y/N);
      if not(Y/N) then OutFileMenu(outfill);
    end;
  Assign(outfile, outfill);
  ReWrite(outfile);
  Home; Scanvalve;
  OperatingPoint;
  WriteLn('Make certain Scanvalve is plugged in '); WriteLn;
  WriteLn('Press the G key to begin sampling ');
  WriteLn('Otherwise control returns to the menu ');
  WriteLn; WaitForKey(ExitCode); ExitCode := UpCase(ExitCode);
  if ExitCode = 'G' then
    begin
      InitGTime;
      RunScreen('Setting Up Serial Port');
      SetUpSerialPort(Port,Baud_Rate,Par,DBits,SBits);
    end;
  end;

procedure SinglePointProbeSample;
var Cp,P,Q: integer;
    AvQ,Rho,Vel,V: real;
begin
  {-----}
  {-- Main Traverse Procedure - PhilTraverse --}
  {-----}
  { uses Phil's method for doing a traverse using different step sizes }

```

```

OperatingPoint;
RunScreen('Setting Up Serial Port');
SetUpSerialPort(Port,Baud_Rate,Par,DBits,SBits);
Home; Scanvalve;
SetRunScreenHeader('Single Hole Sample');
RunScreen('This data is not being saved to a file ');
InitGTime; { initializes time }
ProbeSample(P,Q,Cp);
WriteLn('Reference Dynamic Pressure in Pa');
{ 123456789012345678901234567890 }
for i = 1 to 3 do
  begin
    Q[i] = (Q[i]-InitQ)*CalCoef*1000; { because readings are in volts }
    WriteLn(i:10,Q[i]:10:3); { CalCoef is in Pa/mV }
  end;
  AvQ = (Q[1]+Q[2]+Q[3])/3;
  WriteLn('Average reference Q = ',AvQ:10:3,' Pa');
  GetRho(Rho);
  WriteLn('Density is ',Rho:10:3,' kg/m^3');
  if AvQ=0 then
    begin
      AvQ := 0.0;
      WriteLn('Average Q corrected to 0.0 to avoid Sqrt(ave)');
    end;
  V = Sqrt(2*Rho*AvQ);
  WriteLn('Reference velocity is ',V:10:3,' m/s');
  WriteLn('Press Shift + G to continue');
  Repeat Until ReadKey = 'G';
  GetAbsolute(ZAbs,YAbs);
  SetCpValues(Cp[1],Cp[2],Cp[3],YAbs);
  PointIn(Vel);
  WriteLn('Probe Velocity reading is ',Vel*V:10:3,' m/s');
  WriteLn; WriteLn('Press Shift + G to continue');
  Repeat Until ReadKey = 'G';
  ResetCrt;
end.

```

```

{ all data is saved to one file where format lines 333 and 444 are used }
{ 333 signals a change in step size , 444 gives new initial Y and stepsize }

```

```

var I,J,K,Hole,Time,Stat : integer;
    Y,S,Z,S,X,C : real;
    Psc2_Psc1,P_Pref : Array1;
    Cp,P,Q : Probe_Array;

```

```

begin
  if Probe_Angle = 0.0 then
    CheckCalArray;

```

```

    k = 1; VN1 = 0; Ver_Step_Size = TraverseStepSize[1];
    repeat
      VN1 = VN1 + TraverseStations[k];
      inc(k);
    until TraverseStep[k-1] = 0.0;

```

```

    i = 1; Station = 0;
    RunScreenHeader = 'Vertical Traverse';
    SetTraverse(Ch);
    if Chr = 'G' then
      Exit; { returns to menu }
    { performs common traverse functions }

```

```

    DataFileHeader(Outfile1); { otherwise write to file }
    InitTime; { initializes time }
    OpenRange;
    repeat

```

```

      Ver_Step_Size = TraverseStepSize[i];
      StepChangeY(Outfile1,Step_Size,Ver_Step_Size); { marks the following step size }
      for Stat = 1 to TraverseStations[i] do { begin station loop }
        begin

```

```

          inc(Station);
          ProbeSample(P,Q,Cp);
          DataFileOutput(Outfile1,Stat,1,P,Q,Cp); { write data output line }
          GetAbsolute(Z,Abs,Y,Abs);
          SetPVvalues(Cp[1],Cp[2],Cp[3],Y,Abs);
          if Stats ~ TraverseStations[i] then { if this is not the last station move to next

```

```

            VMove(TraverseStepSize[i]);
            end; { Station Loop }
            VMove(TraverseStep[i]);
            inc(i);
            until TraverseStep[i-1] = 0.0; { repeat the loop until end of last traverse }
            Close(Outfile1);
            CloseRange; { sets the range boundaries on the reduce list }

```

```

ColdCPUBoot; { cold boots the CPU module }
CleanUp; { tidy up the A/D equipment and software }
RunScreenTest Finished Prepare to enter new file name and move probe';
WaitForKey(Ch);
ResetTr; { return to full screen size }
end;

```

```

{-----}
{--}
{-- Horizontal Traverse Procedure - MikeTraverse --}
{--}
{-----}

```

procedure MikeTraverse;

```

{ This entire procedure was added to do Horizontal Traverses
{ Note: Data is outputted to file such that it can be read as Y traverse }
{ data It can be viewed although this is not entirely correct }
{ Phil Rodger's method adapted by Mike Abbott to do spanwise traverses }
{ All data is saved to one file where format lines 333 and 444 are used }
{ 333 signals a change in step size , 444 gives new initial Z and stepsize }

```

```

var I,J,K,Hole,Time,Stat : integer;
    Y,S,Z,S,X,C : real;
    Psc2_Psc1,P_Pref : Array1;
    Cp,P,Q : Probe_Array;

```

```

begin
  if Probe_Angle = 0.0 then
    CheckCalArray;

```

```

    k = 1; VN1 = 0; Ver_Step_Size = TraverseStepSize[1];
    repeat
      VN1 = VN1 + TraverseStations[k];
      inc(k);
    until TraverseStep[k-1] = 0.0;

```

```

    i = 1; Station = 0;
    RunScreenHeader = 'Horizontal Traverse';
    SetTraverse(Ch);
    if Chr = 'G' then
      Exit; { returns to menu }
    { performs common traverse functions }

```

```

    DataFileHeader(Outfile1); { otherwise write to file }
    InitTime; { initializes time }

```



```

OpenRange.
repeat
  Ver_Step_Size := TraverseStepSize[i].
  StepChangeH(Outfile1, Step_Size, Ver_Step_Size); { marks the following step size }
  for Stat = 1 to TraverseStations[i] do
    { begin station loop }
    begin
      inc(Station);
      ProbeSample(P,Q,Cp);
      DataFileOutput(Outfile1, Stat, P, Q, Cp); { write data output line }
      GetAbsolute(ZAbs, YAbs);
      Set(pValues[Cp][1], Cp[2], Cp[3], YAbs);
      if Stat < TraverseStations[i] then
        { if this is not the last station move to next }
        HMove(TraverseStepSize[i]);
      end; { Station Loop }
      HMove(TraverseStep[i]);
      inc(i);
    until TraverseStep[i-1] = 0.0; { repeat the loop until end of last traverse }
  Close(Outfile1);
  CloseRange; { sets the range boundaries on the reduce list }
  ColdStartBoot; { cold boots the CPT module }
  CleanUp; { tidy up the A/D equipment and software }
  RunScreenTest Finished Prepare to enter new file name and move probe);
  WaitforKey(Ch);
  ResetCrt; { return to full screen size }
end;

{ ----- }
{ -- }
{ -- Quick Traverse and File Procedures }
{ -- }
{ ----- }

procedure QuickFileHeader( var outfile1 text);
begin
  GetAbsolute(ZAbs, YAbs);
  Write(outfile1, 'VER2.0');
  Write(outfile1, 'QCR(T)');
  GetDate (Year, Month, Day, DayofWeek);
  Write(outfile1, 'Test Date = ', Month, '-', Day, '-', Year);
  Write(outfile1, 'Z = ', ZAbs, '10 2);
  Write(outfile1, '-----');
  Write(outfile1, 'Y P Q Cp');
  Write(outfile1, '1012345678901234567890123456789012345689);
end; {Quick File Header}

```

```

procedure QuickFileOutput( var outfile1 text, Y, P, Q, Cp real);
begin
  Write(outfile1, 'Y 10 1 P 10 4 Q 10 4 Cp 10 4);
end;

```

```

procedure QuickTraverse;

```

```

var L_Hole integer;
Psc2_Psc1_P_Pref Array1;
Cp,P,Q real;
ZAbs,YAbs real;
VStep real;
Stop boolean;
H1,V11 integer;

```

```

begin
  { Data obtained with this procedure is written directly to a file }
  { to make proper use of it it should be examined with an editor or }
  { spreadsheet program }
  ChScr:= InitGTime;
  VNI = trunc(Q_Start-Q_Stop)+1;
  Station=1, V11 =1;
  RunScreenHeader := 'Quick Outlet Traverse';
  SetUpTraverse(Ch);
  if UpCase(Ch) <> 'G' then
    Exit;
  QuickFileHeader(Outfile1);
  OpenRange;
  repeat
    { begin main sampling loop }
    Hole = 1;
    HoleStep(Hole);
    RunScreen('Sampling for five seconds');
    Sample(Q_Time, '1', '1'); { sample for 5 seconds with Gain of 1 for each channel }
    DumpTo (Psc2_Psc1, P_Pref, 1);
    AverageData(P_Pref, Psc2_Psc1, P, Q, Cp);
    GetAbsolute(ZAbs, YAbs);
    QuickFileOutput(Outfile1, YAbs, P, Q, Cp);
    SetCp1(Cp, YAbs); { Sets Cp on reduced list. Other values set to 0. }
    { Does not call reduce procedure }
    if YAbs > Q_Stop then
      begin
        RunScreen('Moving probe down 1 mm');
        inc(V11);
        inc(Station);
      end;
    end;
  until Traverse(Ch) = 0;
end;

```

```

VMove(Q_Step);
end;
until YAbs = Q_Step.
CloseRange;
RunScreen 'Test Finished';
Close(Outfile);
Close(Boot, CleanUp);
WaitforKey(Ch);
CloseCase(Ch);
ResetIt;
end;

Procedure SetRunScreenHeader(Header string);
begin
  RunScreenHeader = Header;
end;

Procedure RunScreen(WindowMessage string);
var Hour, Minute, Second: sec100 word;

begin
  ResetIt;
  GotoXY(1,1);
  GetAbsolute(Abs.YAbs);
  GetTime(Hour, Minute, Second, Sec100); ClrEol;
  Write(RunScreenHeader); ClrEol;
  Write('Start Time: ', Hour, 2, 'Minute 2, ', Second, 2); ClrEol;
  Write('Current Time: ', Hour, 2, 'Minute 2, ', Second, 2); ClrEol;
  Write('Initial Y: ', colon, YInit, 3, 'mm', ' Initial Z: ', colon, ZInit, 3, 'mm', '); ClrEol;
  Write('Current Y: ', colon, YAbs, 3, 'mm', ' Current Z: ', colon, ZAbs, 3, 'mm', '); ClrEol;
  Write('Step Size: ', colon, VerStep, 3, 'mm', '); ClrEol;
  Write('Number of stations: ', colon, VN, 1); ClrEol;
  Write('Current station: ', colon, Station); ClrEol;
  Write;
  Write('Output file: ', colon, Outfile); ClrEol;
  Write;
  HLine(80);
  Write(WindowMessage); ClrEol;
  Write;
  HLine(80);
  Window(WhereY, 80, 25);
  ClrScr;
end;

end;
{ -- }
{ -- Quick Traverse Setup Menu Procedures -- }
{ -- }
{ -- }

function QuickLabel(i: integer) MenuLabel;
var out: MenuLabel;
begin
  out := '';
  Case i of
    1 out = 'Current Probe Position';
    2 out = 'End';
    3 out = 'Step size';
    4 out = 'Wait Time';
    8 out = 'Begin Sampling';
    9 out = 'Quit';
  end; { Case }
  QuickLabel = out;
end; { QuickLabel }

function QuickDefault(i: integer) PathStr;
var out: PathStr;
begin
  GetAbsolute(Abs.Q_Start);
  out := '';
  Case i of
    1 str(Q_Start, 5, out);
    2 str(Q_Stop, 5, out);
    3 str(Q_Step, 5, out);
    4 str(Q_Time, 5, out);
  else
    out := '';
  end; { Case }
  QuickDefault = out;
end; { QuickMenuLabel }

procedure QuickInput(i: integer);
begin

```

```

( case i of
  1 RealMenu(Q_Start);
  2 RealMenu(Q_Stop);
  3 RealMenu(Q_Stop);
  4 InitMenu(Q_Time);
  8 QuickTraverse
end ( case )
end ; SetUpMenu )

procedure DisplayQuickMenu;
var i integer;
begin
  clrscr;
  WriteLn('Quick Settings Menu ');
  WriteLn(' ');
  for i := 1 to 8 do
    begin
      WriteLn('olom,QuickIabel(i));
      Tab(50);
      WriteLn(QuickDefault(i));
    end;
  QuitLine;
end; {Display Quick Menu}

procedure QuickMenu;
var i integer;
    choice char;
begin
  clrscr;
  repeat
    DisplayQuickMenu;
  repeat
    ( choice := UpCase(ReadKey);
    until (choice in ['1'..'8','Q']);
    Val(choice,i);
    Write(QuickIabel(i));
    Tab(50);
    QuickInput(i);
    until choice = 'Q';
  until choice = 'Q';
  clrscr;
end; {QuickMenu}

( case i of
  1 RealMenu(Q_Start);
  2 RealMenu(Q_Stop);
  3 RealMenu(Q_Stop);
  4 InitMenu(Q_Time);
  8 QuickTraverse
end ( case )
end ; SetUpMenu )

procedure StaticTestProcedures;
begin
  YOrN := false;
  clrscr;
  if Outfile = '' then
    OutfileMenu(outfill);
  if FileExists(outfill) then
    begin
      WriteLn(outfill, ' already exists ');
      WriteLn('Over write file (Y/N) ');
      YOrN := YOrN;
      if not YOrN then OutfileMenu(outfill);
    end;
  Assign(Outfile1,outfill);
  ReWrite(outfile1);
  Home; Scanivalve;
  OperatingPoint;
  WriteLn('Make certain Scanivalve is plugged in '); WriteLn;
  WriteLn('Press the G key to begin sampling ');
  WriteLn('Otherwise control returns to the menu ');
  WriteLn; WaitForKey(FixCode); ExitCode := UpCase(FixCode);
  if ExitCode = 'G' then
    begin
      InitGTime;
      RunScreen('Setting Up Serial Port');
      SetUpSerialPort(Port, baud_Rate, Par, (Misc, SBits));
    end;
  end;

  procedure StaticTapLeadertvar Outfile text;
  begin
    WriteLn(outfile, 'The diffusion angle is zero ');
    WriteLn(outfile, 'Tap : ' (p) );
  end;

  procedure StaticTapInquitvar Outfile text; HoleNumber integer; Cp real);
  begin
    WriteLn(outfile, HoleNumber:5 (p 10 5));
  end;

```

```

end.

InitTime: { initializes time }

StepNoScannalvePort(42).
StaticSample(Cp42).
StaticTapOutput(Outfile1, 42, (p42).
SwitchLygonMessage.
StepNoScannalvePort(43).
StaticSample(Cp43).
StaticTapOutput(Outfile1, 43, (p43).
TestIndMessage.
WriteLn('Hole 42 has Cp =',(p42).
WriteLn('Hole 43 has Cp =',(p43).
WriteLn('Press B to continue').
Repeat until ReadKey = 'B'.
Close(Outfile1)
end.

procedure StaticTapTest.
var Cp array[1..50] of real.
    i,j integer.
    Ntap integer.
begin
    Set(p5)Traverse(h). { performs common traverse functions }
    if (h = 'G') then
        Exit. { returns to menu }
    begin
        DataFileHeader(Outfile1).
        StaticTapHeader(Outfile1).
        InitTime. { initializes time }
        StaticHoles = 43.
        Ntap = 25. { start at base pressure tap }
        for i = 1 to 50 do
            (p[i]) := 0.0.
        ; begin sampling ;
        RunScreen Stepping Scannalve'.
        StepNoScannalvePort(23)
        StaticSample(p[23]). { because 23,24 are shared and tube is attached to 23 }
        StepNoScannalvePort(24)
        StaticSample(p[24]). { because 24,26 are shared and tube is attached to 24 }
        StepNoScannalvePort(25)
    end.

procedure StaticSample(var Cp of real).
var P Pref, Psc2 Psc1 array[1..
    i integer.
    Pq real.
{ uses the standard hole sample procedure }
begin
    Cp = 1.001.
    HoleSample(P Pref,Psc2 Psc1).
    AverageData(P Pref,Psc2 Psc1,P,Q,Cp).
end.

procedure SwitchLygonMessage.
begin
    ClrScr.
    WriteLn('The first 41 holes have been sampled').
    WriteLn('Uncover the holes 23 and 24 - Tape over holes 26 and 27').
    WriteLn.
    WriteLn('There is a leakage path between the channels for holes 42 and 43').
    WriteLn('Tape hole 43 and Tape over hole 42').
    WriteLn.
    WriteLn('To continue testing press Shift - B').
    Repeat until ReadKey = 'B'.
end.

procedure TestIndMessage.
begin
    ClrScr.
    WriteLn('Test is completed Press B to return to menu').
    Repeat until (p42(ReadKey) = 'B').
end.

procedure Test4243.
var Cp42 Cp43 real.
begin
    Set(p5)Traverse(h). { performs common traverse functions }
    if (h = 'G') then
        Exit. { returns to menu }
    begin
        DataFileHeader(Outfile1)
        StaticTapHeader(Outfile1).

```

```

StaticSample(p[50]); { first base pressure measurement }

for i = 28 to StaticHoles do
  begin
    StepInScannivalvePort(i);
    StaticSample(p[i]);
  end;
WriteLn(bufFile, 'False hole 43 reading is ', C(p[43]));
for i = 1 to (Ntap) do
  begin
    if i = 23 then
      SwitchTsgonMessage;
    StepInScannivalvePort(i);
    StaticSample(p[i]);
  end;
RunScreen('Stepping Scannivalve');
StepInScannivalvePort(42);
StaticSample(p[48]);
StepInScannivalvePort(43);
C(p[49]) := C(p[43]);
StaticSample(p[43]);
for i = 1 to 43 do
  begin
    StaticTapOutput(bufFile, i, C(p[i]));
  end;
WriteLn(bufFile, 'Final base pressure measurement');
StaticTapOutput(bufFile, 25, C(p[50]));
WriteLn(bufFile, 'Sealed hole 43 reading ');
StaticTapOutput(bufFile, 43, C(p[49]));
WriteLn(bufFile, 'Sealed hole 42 reading ');
StaticTapOutput(bufFile, 42, C(p[48]));

TextLn(Message);

Close(bufFile);
Close(PULPort);
CleanUp;
WaitForKey(Ch);
Ch := UpCase(Ch);
Reset(r);
end;

{
  ..
  ..
  .. General Traverse Setup Menu Procedures
  ..
  ..
}

```

```

procedure TraverseSettings(i: integer);
begin
  WriteLn('For traverse number ', i, ' please enter the following ');
  WriteLn('Step Size (', TraverseStepSize[i], ')', RealMenu(TraverseStepSize[i]));
  WriteLn('Number of Stations (', TraverseStations[i], ')', IntMenu(TraverseStations[i]));
  WriteLn('After Traverse Step Size (', TraverseStep[i], ')');
  WriteLn('Enter a zero if this is the last traverse ', RealMenu(TraverseStep[i]));
end;

function TraverseDefault(i: integer; (choice char) PathStr:
var out: PathStr;
    i, k: integer;
    a, b, c, d, e, f: string[15];
    Y1, Y2: real;
    LastIn: boolean;
    Init: real;
begin
  LastIn := false;
  out := '';
  a := 'b'; c := 'd'; e := 'f';
  str(i, a);
  for k = 1 to (i-1) do
    if TraverseStep[k] = 0 then
      LastIn := true;
  end;
  GetAbsolut(ZAbs, YAbs); { the calculation needs the probe to be in the correct
  position }
  if Choice = 'Z' then
    Init := ZAbs;
  if Choice = 'Y' then
    Init := YAbs;
  Y1 := Init;
  if i > 1 then
    begin
      for j = 1 to (i-1) do
        Y1 := Y1 - (TraverseStations[j] - 1) * TraverseStepSize[j] - TraverseStep[j];
      end;
      Y2 := Y1 - (TraverseStations[i] - 1) * TraverseStepSize[i];
      if (LastIn) and (i > 1) then
        TraverseDefault := a + colon;
      else
        begin
          str(TraverseStepSize[i], b);
          str(TraverseStations[i], c);

```

```

begin
  ClrScr;
  repeat
    Display TransducerMenu2;
  repeat
    Choice := UpCase(ReadKey);
  until (Choice in ['1'..'4','Q'])
  Val(Choice,code);
  Writeln;
  Write(TransducerMenu1.in2(n),Lab40);
  TransducerMenuInput2(n);
  until Choice = 'Q';
end. { TransducerMenu2 }

function TransducerMenu1.in3(i:integer) Menu1.abel;
{ This function added for 3 transducer use }
var out Menu1.abel;
begin
  out := '';
  case i of
    1: out := 'Initial Reading for Psc2-Psc1'; { Moved from TunnelMenu1.in2 }
    2: out := 'Initial Reading for P-Prcl'; { Moved from TunnelMenu1.in2 }
    3: out := 'Initial Reading for P-Prcl2';
    4: out := 'Initial Reading for P-Prcl3';
    5: out := '';
    6: out := '';
    7: out := '';
    8: out := '';
    9: out := 'Quit';
  end; { case }
  TransducerMenu1.in3 := out;
end. { TransducerMenu1.in3 }

procedure TransducerMenu1.abel3(i:integer);
{ This procedure added for 3 transducer use }
begin
  Write(TransducerMenu1.in3(n),
  Lab40);
  case i of
    1: Write (InitQ $ 3,' Volts '); { Moved from TunnelMenu1.abel }
    2: Write (InitP2 $ 3,' Volts '); { Moved from TunnelMenu1.abel }
    3: Write (InitP3 $ 3,' Volts ');
    4: Write (InitP4 $ 3,' Volts ');
  end;
end.

```

```

5: Write (' ');
6: Write (' ');
7: Write (' ');
8: Write (' ');
end. { Case }
ClrScr;
end.

procedure TransducerMenuInput3(i:integer);
{ This procedure added for 3 transducer use }
begin
  case i of
    1: RealMenu(InitQ); { Moved from SetUpTunnelMenu }
    2: RealMenu(InitP2); { Moved from SetUpTunnelMenu }
    3: RealMenu(InitP3);
    4: RealMenu(InitP4);
  end;
end. { TransducerMenuInput3 }

procedure DisplayTransducerMenu3;
{ This procedure added for 3 transducer use }
var i:integer;
begin
  GotoXY(1,1);
  ClrScr;
  Write(Init Transducer Initial Readings ');
  Writeln;
  for i := 1 to 8 do
    begin
      Write(Colon);
      TransducerMenu1.abel3(i);
      Writeln;
    end; { loop }
  Until i.n;
end. { Display TransducerMenu3 }

procedure TransducerMenu3;
{ This procedure added for 3 transducer use }
var i:integer; Choice:char;
begin
  ClrScr;
  repeat
    Display TransducerMenu3;
  repeat

```

```

unit Sampling
; Nothing in this unit should depend on the MATH or unit ;
; This unit is reserved for procedures that require serial port io ;

interface

uses Dos, AsyncDio, SysUtility, Globals3 module

type array1 = array [1..300] of real

var Kps, Registers,
    CP1, Option, integer,
    Ch, channel1, channel2, char,
    channel3, channel4, char, {added for 3 transducer use}
    channel, char, {added for 3 transducer use}
    Waiting Time, Sampling Time, integer,
    Gain, Time, integer,
    Answer, string;

procedure InitSampling;

procedure Send Command (command string);

procedure Communicate(command string, var response string);

function Get Answer String;

procedure SetUpSerialPort(Port, Baud, integer, Parity, char, Dbits, Sbits, integer);

procedure StartSample (Gain1, Gain2, char);

procedure StopSample;

procedure DumpTo (var Data1, Data2, array1, var I, integer);

procedure AverageData(P, Pref, Psc2, Psc1, array1, I, integer, var
    AverageP, AverageQ, AverageI, p, real);

function GainChange(Data, array1, I, integer) char;

procedure BootM;

procedure Cleanup;

procedure SamplingMenu;

```

```

; Added for 3 transducer use ;
; Added for 3 transducer use ;
; Added for 3 transducer use ;

procedure TransducerMenu1;
procedure TransducerMenu2;
procedure TransducerMenu3;

procedure Cold Pt Host
implementation

var Error byte;

procedure InitSampling;
begin
    Waiting Time := 15;
    Sampling Time := 30;
    Gain := 10;
    Channel1 := 2; Channel2 := 4;
    Channel3 := 5; Channel4 := 6; {added for 3 transducer use}
end;

procedure Send Command (command string);
begin
    Async Send String(command+#13+#10);
end;

procedure Communicate(command string, var response string);
begin
    Send Command(command);
    Response := Get Answer;
end;

function Get Answer string;
var
    Answer string;
begin
    Ch := '';
    Answer := '';
    repeat
        if (Async Buffer Check(Ch)) and (Ch <> CR) and (Ch <> LF) then
            Answer := Answer+ch;
    until ch = LF;

```

```

Get Answer := Answer;
{ The A/D controller sends messages in the form of a string followed by }
{ a carriage return and an end of line control characters (#14 and #10) }
End;

procedure SetUpSerialPort(Baud: integer; Parity: char; DBits, SBits: integer)
begin
  { the following set up procedure taken from Varas HTP 1RV }
  Ch := Answer;
  Ch := Answer;
  Async Init;
  if Async (OpenPort(Baud, Parity, DBits, SBits)) then
    Writeln('Make sure the green light is on on the A/D controller');
  WaitForKey(Ch);
  Ch := Answer;
  Communicate('VTR', Answer);
  Writeln('The Software Version in the CPU module is ', Answer);
  if (Answer[1] = 'Y') then
    CPU_Option := 902
  else
    CPU_Option := 901;
  Delay (250);
  Communicate('ACTRISET', Answer);
  Writeln('M', CPU_Option, ' memory is cleared of commands, response ', Answer);
  Delay (250);
  Communicate('ACTRDATA', Answer);
  Writeln('M', CPU_Option, ' memory is cleared of data, response ', Answer);
  Delay (250);
  Communicate('SE1AZ', 0.1, Answer);
  Writeln('Auto-Zero is enabled, response ', Answer);
  Delay (250);
  Communicate('SETDATE', 0.1, 1.0, Answer);
  Writeln('Date is set to SUN-1-JAN-190, response ', Answer);
  WaitForKey(Ch);
  Ch := Answer;
  end; {Set Up SerialPort}

procedure StartSample (Gain1, Gain2: char)
var Command1, Command2: string
    i: integer
begin
  Communicate('ACTRISET', Answer);
  Writeln('M', CPU_Option, ' memory is cleared of commands, response ', Answer);
  Delay (250);
  Command1 := 'A DCV', Channel1, 'Gain1';
  Command2 := 'A DCV', Channel2, 'Gain2';
  Delay (250);
  Communicate(Command1, Answer);
  Writeln('First command is loaded to M', CPU_Option, ' memory, response ', Answer);
  Delay (250);
  Communicate(Command2, Answer);
  Writeln('Second command is loaded to M', CPU_Option, ' memory, response ', Answer);
  Delay (250);
  Communicate('SCAN', -1.0, 0.01, Answer); {starts autoscan}
  Writeln('Scanning is started, response ', Answer);
  end;

procedure StopSample;
begin
  Communicate('AUTOSC', 0, Answer); {stops autoscan}
  Writeln('Scanning is stopped, response ', Answer);
  end; {sample procedure}

procedure DumpTo (var Data: Data2 Array); var I: integer;
var J: real;
    K: integer;
    Data_Error: boolean;
    Saves: string;
begin
  if (CPU_Option = 901) then
    Communicate('DUMP', 0, Answer)
  else
    Communicate('DUMP', 0.0, 10000, Answer);
  repeat {might not be necessary now}
    Answer := Get Answer
  until (Answer = #10);
  ExtractReal(I, Answer, J, Data_Error); {determines the number of}
  I := Trunc(I); {saves performed}
  StrI(Saves);
  if Data_Error then Writeln('Error');

```



```

For K = 1 to L do
begin
  Answer := Get_Answer
  Writeln(Answer);
  ExtractReal1(Answer, Data1[K], Data_Error);
  ExtractReal2(Answer, Data2[K], Data_Error);
end;
end; {procedure dump to}

function GainChange(Data_Array1: integer) char;
var K: integer;
    Data_Max, Data_Min: real;
begin
  Data_Max := Abs(Data1[]);
  For K = 1 to L do
  begin
    If Abs(Data[K]) > Data_Max then
      Data_Max := Abs(Data[K]);
  end;
  { Since the gain band width is symmetric about zero we only }
  { need to look at Data_Max in absolute terms. }
  if (Data_Max < 0.005) then
    GainChange := '3';
  else if (Data_Max < 0.030) then
    GainChange := '2';
  else if (Data_Max < 0.400) then
    GainChange := '1';
  else
    { any other case must be >= 0.400 }
    GainChange := '0'; { especially if error is returned }
  end; { procedure GainChange }

procedure AverageData(P_Pref, Psc: array[1..integer] of real;
  AverageP, AverageQ, AverageCp: real);
var Sum_P_Pref, Sum_Q, Sum_Cp: real;
    I: integer;
begin
  Writeln('Channel is: '+Channel2); {three writelns added for 3 transducer use}
  Writeln('Initial Reading: 'InitP 5.3, 'Volts');
  Writeln('Calibration: 'CalOff 5.3, 'Pd/mV');

  Sum_P_Pref := 0.0; Sum_Q := 0.0; Sum_Cp := 0.0;
  For I = 1 to L do
  begin
    Sum_P_Pref := Sum_P_Pref + P_Pref[I];
    Sum_Q := Sum_Q + Psc2_Psc[I];
    Sum_Cp := Sum_Cp + (P_Pref[I] - InitP)*CalOff;
    ((Psc2_Psc[I] - InitQ)*CalOff*Contraction);
  end;
  AverageP := Sum_P_Pref/L; { remember this is a voltage }
  AverageQ := Sum_Q*Contraction/L; { remember this is a voltage }
  AverageCp := Sum_Cp/L; { non - dimensional }
end; { Average Values }

procedure BootM;
var Answer: string;
begin
  Answer := 'C';
  Writeln(' Do you want to perform warm or cold boot to M '(CPU_Option 3);
  Writeln(' W = warm ');
  Writeln(' C = cold ');
  Writeln(' N = none ');
  StrMenu(Answer);
  if UpCase(Answer[1]) = 'N' then
    exit;
  if UpCase(Answer[1]) = 'C' then
    Send_Command('CPURESET 1');
  else
    Send_Command('CPURESET 0');
  if (CPU_Option = 901) then
    Answer := Get_Answer;
  Write(' In 30 seconds the M '(CPU_Option 3) ' will reboot');
  if (CPU_Option = 901) then
    Writeln(' response: ', Answer);
  WaitForKey(Ch);
  'IsScr';
end;

procedure ColdCPUBoot;
begin
  Send_Command('CPURESET 1');
  if (CPU_Option = 901) then

```



```

    out:=out+' Pa.mV';
end;
4 begin
  str (CalCoffP4:5:3,out);
  out:=out+' Pa.mV';
end;
end; { case }
TransducerDefault:=out;
end; { TransducerDefault }

procedure TransducerMenuInput2(i:integer);
{ This procedure added for 3 transducer use }
begin
  case i of
    1 RealMenu(CalCoff); { Moved from SystemInput }
    2 RealMenu(CalCoffP2); { Moved from SystemInput }
    3 RealMenu(CalCoffP3);
    4 RealMenu(CalCoffP4);
  end;
end; { TransducerMenuInput2 }

procedure DisplayTransducerMenu2;
{ This procedure added for 3 transducer use }
var i:integer;
begin
  GotoXY(1,1);
  ClrScr;
  WriteLn('Transducer Calibration Coefficients ');
  WriteLn;
  for i:=1 to 8 do
    begin
      Write(i,Colon,TransducerMenuLine2(i));
      Tab(50);
      WriteLn(TransducerDefault(i));
    end; { loop }
  WriteLn;
  end; {Display TransducerMenu2}

procedure TransducerMenu2;
{ This procedure added for 3 transducer use }
var i:integer, Choice:char;
until (Choice in ['1'..'4','0'])
  Val(Choice,code);
  WriteLn
  Write(TransducerMenuLine1(n),Tab(40));
  TransducerMenuInput1(n)
until (Choice = '0')
end {TransducerMenu1}

function TransducerMenuLine2(i:integer)MenuLabel;
{ This function added for 3 transducer use }
var out:MenuLabel;
begin
  out := '';
  case i of
    1 out := 'Calibration Coefficient for Psc2-Psc1'; {Moved from SystemLabel};
    2 out := 'Calibration Coefficient for P-Pref1'; {Moved from SystemLabel};
    3 out := 'Calibration Coefficient for P-Pref2';
    4 out := 'Calibration Coefficient for P-Pref3';
    5 out := '';
    6 out := '';
    7 out := '';
    8 out := '';
    9 out := 'Out';
  end; { case }
  TransducerMenuLine2:=out;
end; { TransducerMenuLine2 }

function TransducerDefault(i:integer)Pathstr;
{ This function added for 3 transducer use, based on SystemDefault }
var out:Pathstr;
begin
  out := '';
  case i of
    1 begin
      str (CalCoffQ:5:3,out);
      out:=out+' Pa/mV';
    end;
    2 begin
      str (CalCoffP2:5:3,out);
      out:=out+' Pa/mV';
    end;
    3 begin
      str (CalCoffP3:5:3,out);

```

```

begin
  ClrScr.
repeat
  Display TransducerMenu2.
repeat
  Choice := UpKey(ReadKey).
until (Choice = ['1','4','Q'])
Val(choice,code).
WriteLn.
Write(TransducerMenuLine2(n),Tab(40).
TransducerMenuInput2(n).
until Choice = 'Q'.
end. {TransducerMenu2}

function TransducerMenuLine3(i:integer) MenuLabel.
{ This function added for 3 transducer use }
var out MenuLabel.
begin
  out :=
case i of
  1: out := 'Initial Reading for Psc2-Psc1'. {Moved from TunnelMenuLine}
  2: out := 'Initial Reading for P-Pref1'. {Moved from TunnelMenuLine}
  3: out := 'Initial Reading for P-Pref2'.
  4: out := 'Initial Reading for P-Pref3'.
  5: out := ' '.
  6: out := ' '.
  7: out := ' '.
  8: out := ' '.
  9: out := 'Quit'.
end. { case }
TransducerMenuLine3 := out.
end. { TransducerMenuLine3 }

procedure TransducerMenuLabel3(i:integer).
{ This procedure added for 3 transducer use }
begin
  Write(TransducerMenuLabel3(i)).
Tab(40)
Case i of
  1: Write (InitQ 5.3, Volts ). { Moved from TunnelMenuLabel }
  2: Write (InitP2 5.3, Volts ). { Moved from TunnelMenuLabel }
  3: Write (InitP3 5.3, Volts ).
  4: Write (InitP4 5.3, Volts ).
end. { TransducerMenuLabel3 }

5: Write (' ').
6: Write (' ').
7: Write (' ').
8: Write (' ').
end. { Case }
ClrEol.
end.

procedure TransducerMenuInput3(i:integer).
{ This procedure added for 3 transducer use }
begin
Case i of
  1: RealMenu(InitQ). { Moved from SetUpTunnelMenu }
  2: RealMenu(InitP2). { Moved from SetUpTunnelMenu }
  3: RealMenu(InitP3).
  4: RealMenu(InitP4).
end.
end. { TransducerMenuInput3 }

procedure DisplayTransducerMenu3.
{ This procedure added for 3 transducer use }
var i:integer.
begin
  GotoXY(1,1).
  ClrScr.
  WriteLn(Transducer Initial Readings ).
  WriteLn.
  for i = 1 to 8 do
    begin
      Write(i,Colon).
      TransducerMenuLabel3(i).
      WriteLn.
    end. { loop }
  Until i = 9.
end. { Display TransducerMenu3 }

procedure TransducerMenu3.
{ This procedure added for 3 transducer use }
var i:integer. Choice:char.
begin
  ClrScr.
  repeat
    Display TransducerMenu3
  until i = 9.
end.

```

```

Choice := Up(asetReadKey);
until (Choice in ['1'..'4','Q'])
  Vail(Choice:code)
  WriteLn
  Write(TransducerMenu.inc3(i)).Tab(40);
  TransducerMenuInput3(i);
until (Choice = 'Q');
end; {TransducerMenu3}

function SamplingMenu.inc(i:integer) MenuLabel;
var out MenuLabel;
begin
  out := '';
  case i of
    1: out := 'Transducer/Data acquisition channels'; { modified for 3 transducer use }
    2: out := 'Transducer Calibration Coefficients'; { modified for 3 transducer use }
    3: out := 'Transducer Initial Readings'; { modified for 3 transducer use }
    4: out := ''; { modified for 3 transducer use }
    5: out := 'Waiting period ( max = 60)';
    6: out := 'Sampling period ( max = 240)';
    7: out := 'Gain Check period (max = 60)';
    8: out := 'ScanValve in use'; { modified for 3 transducer use }
    9: out := 'Quit';
  end; { case }
  SamplingMenu.inc := out;
end; { SamplingMenu.inc }

procedure SamplingMenuLabel(i:integer);
begin
  Write(SamplingMenu.inc(i)).
  Tab(40);
  case i of
    1: Write(' '); { modified for 3 transducer use }
    2: Write(' '); { modified for 3 transducer use }
    3: Write(' '); { modified for 3 transducer use }
    4: Write(' '); { modified for 3 transducer use }
    5: Write('Waiting Time: ' s);
    6: Write('Sampling Time: ' s);
    7: Write('Gain Time: ' s);
    8: begin
        {added 3 transducer use}
        if ScanValveUse then Write('Yes'); {added 3 transducer use}
        if not(ScanValveUse) then Write('No'); {added 3 transducer use}
      end;
    end; { Case }
  end; { Case }
end; { Case }

ClrScr;
end; { SamplingMenuInput }

procedure DisplaySamplingMenu;
var i:integer;
begin
  GotoXY(1,1);
  ClrScr;
  WriteLn('Sampling Parameters Menu ');
  WriteLn;
  for i = 1 to 8 do
    begin
      Write(i:Colon);
      SamplingMenuLabel(i);
      WriteLn;
    end; { loop }
  end; { loop }
  QuitLn;
end; {Display SamplingMenu}

procedure SamplingMenu;
var i:integer; Choice:char;

```

```

  ClrScr;
end;

```

```

procedure SamplingMenuInput(i:integer);
var YOrN: boolean; {added for 3 transducer use}
begin
  case i of
    1: TransducerMenu1; { modified for 3 transducer use }
    2: TransducerMenu2; { modified for 3 transducer use }
    3: TransducerMenu3; { modified for 3 transducer use }
    5: IntMenuWaitingTime;
    6: IntMenuSamplingTime;
    7: IntMenuGainTime; {added for 3 transducer use}
    8: IntMenuScanValveUse;
  end;

```

```

  if WaitingTime < 60 then
    WaitingTime := 60;
  if SamplingTime < 240 then
    SamplingTime := 240;
  if GainTime < 60 then
    GainTime := 60;

```

```

end; { SamplingMenuInput }

procedure DisplaySamplingMenu;

```

```

var i:integer;
begin
  GotoXY(1,1);
  ClrScr;
  WriteLn('Sampling Parameters Menu ');
  WriteLn;
  for i = 1 to 8 do
    begin
      Write(i:Colon);
      SamplingMenuLabel(i);
      WriteLn;
    end; { loop }
  end; { loop }
  QuitLn;
end; {Display SamplingMenu}

procedure SamplingMenu;
var i:integer; Choice:char;

```

```

begin
  ClScr;
  repeat
    DisplaySamplingMenu;
  repeat
    Choice := UpCase(ReadKey);
  until (Choice in ['1'..'8','Q','D']);
  Val(Choice,i.code);
  WriteLn;
  Write(SamplingMenu1 inc(i)).Tab(40);
  SamplingMenuInput(i);
  until (Choice = 'Q');
end. {SamplingMenu}
{.....}
End. {CH Sampling Unit}

```

```

unit reduct;
interface
uses Dos, Crt, Globals, 3.utility, Graph, GraphExt;

procedure InitReduct;
procedure ReSetCpPointer;
procedure SetCp(C1,YAbs:real);
procedure SetCpValues(C1,C2,C3,YAbs:real);
procedure OpenRange;
procedure CloseRange;
procedure ReduceFileOut(var OutData:PathStr);
procedure PointInfo(var V:real);
procedure ReduceMenu;
procedure PlotCurve(k:char);
procedure PlottingMenu;
procedure PlCSettings;
procedure PlCMenu;
procedure CheckCalArray;
procedure PlCCalc;
procedure PlCReport;
implementation
const CalArraySize = 246;
PressAKey = ' ( Press a Key to Continue )';
type
CalibrationArray = Array[1..246] of real;
ReducedData      = Array[1..300] of real;
FileList         = Array[1..10] of PathStr;
Array10          = Array[1..10] of word;
{ available to all reduce procedures }

const LineStyle  Array10 = (0,0,0,0,1,2,3,0,1);
BlockStyle      Array10 = (2,3,4,1,2,3,4,1,2,3);

var CpPointer      integer;
Wake_Step_Size, Passage_Step_Size real;
CalArray          CalibrationArray;
Ch               char;
Y,Cpl,Cp2,Cp3,Beta,Vel,q,ps,ptloss ReducedData;
Y,S,X,C,Z,S      Real;
GraphList        Array[1..10] of FileList;
RangeStart,RangeEnd Array[1..10] of integer;
Range            integer;
PlCSymbolsOn,SymbolSetOn boolean;
ResetList        boolean;

{ for PlC calculations }
Ybar            real;
PlCSitation      array[1..4] of integer;
Blank           array[1..9] of Boolean;
pitch           real;
SCoeff,RCoeff   real;
CPAVG,BetaAvg   real;
VAVG1,VAAVG     real;
VAVG1,VAVG2,VAVG3 real;
MINLOS,TOTLOS   real;

procedure InitReduct;
var i:integer;
begin
InitHardware; { sets graphics hardware to internal default of hercules hi }
RedFile = 'C:\DAVID\RED\FILES\RED';
RedFile = 'C:\RED';
CalFile = 'ARRAY10A.DAT';
{ InDataFile = 'C:\DAVID\DRWF\FILES\3HPJL08A.DRW'; }
InDataFile = 'C:\3HPJL08A.DRW';
ResetCpPointer; CalArrayReady:=false;
Range = 1; { set range pointer to one }
for i = 1 to 4 do

```

```

PI('Station'[i] = 0;
Blank[5] = false;
Blank[6] = false;
Blank[7] = false;
InletAngle = 28.35;
Ybar = 0.0;
Pitch = 111.0; SCoeff = 0.0; BCoeff = 0.0;
CPAvg = 0.0; BetAvg = 0.0; MINLOS = 0.0; TOTLOS = 0.0;
VAVG2 = 0.0; VAVG3 = 0.0;
DriverNumber = 2;
end.

{ ..... }
{ 1st management functions and procedures }
{ ..... }

procedure ReSetCpPointer;
begin
  CpPointer = 1;
  Range = 1;
  RangeStart[Range] = 1;
  RangeEnd[Range] = 1; { will automatically be incremented }
  { as data points are added to list }
  RangeStart[Range+1] = 1;
end.

procedure SetCpPointer(i: integer);
begin
  CpPointer = i;
end.

procedure OpenRange;
begin
  RangeStart[Range] = CpPointer;
end.

procedure CloseRange;
begin
  RangeEnd[Range] = CpPointer+1;
  inc(Range);
  RangeStart[Range] = CpPointer;
end.

{ ..... }
{ reduction functions and procedures }
{ ..... }

procedure InitCalArray(InArray: string);
var i: integer;
    InFile: text;
begin
  Assign(InFile, InArray);
  Reset(InFile);
  for i = 1 to 246 do
    Readln(InFile, CalArray[1,i], CalArray[2,i]);
  end;
  Close(InFile);
  CalArrayReady = True;
end.

procedure interpolate(L: integer; A: real; var B: real);
{ This procedure has been modified to allow extrapolation beyond the range }
{ of the arrays. Warning is printed to screen when this has occurred }
var J1, pos1, pos2, I: integer;
    per: real;
begin
  I := 999;
  J := 4 * (L - 1) + 1;
  pos1 = J;
  pos2 = J + 1;
  for I = J to J + 39 do
    if (A < CalArray[1,J+40]) and (CalArray[1,J+40] < CalArray[1,J+39]) then
      begin
        pos1 = J + 39;
        pos2 = J + 40;
        { If loop added for extrapolation }
      end;
    if (A < CalArray[1,J+40]) and (CalArray[1,J+40] < CalArray[1,J+39]) then
      begin
        pos1 = J + 39;
        pos2 = J + 40;
        { If loop added for extrapolation }
      end;
    if (A < CalArray[1,1]) and (A < CalArray[1,1+1]) or ((A < CalArray[1,1]) and
      (A < CalArray[1,1+1])) then
      begin
        pos1 = 1;
        pos2 = 1 + 1;
        { Added for extrapolation }
        I := 0;
        { Added for extrapolation }
      end;
    B := (A - CalArray[1, pos1]) * (CalArray[1, pos2] - CalArray[1, pos1]) +
      CalArray[1, pos1] * (CalArray[2, pos2] - CalArray[2, pos1]) +
      CalArray[2, pos1];
    { Modified }
  end;

```



```

end. ; procedure DataReduce ;

procedure ReducelileHeader(var Outfile text);
begin
  Writeln(outfile, ' X Y and Z location of three-hole probe');
  Writeln(outfile);
  Writeln(outfile, ' # XC YS ZH');
  Writeln(outfile, '.....');
end.

procedure ReducelileHeader2(var Outfile text);
begin
  Writeln(outfile, 'Beta Flow direction relative to the');
  Writeln(outfile, ' horizontal axis Positive air');
  Writeln(outfile, ' flows upward');
  Writeln(outfile, ' Q Dynamic pressure at the data point');
  Writeln(outfile, ' nondimensionalised by Qin');
  Writeln(outfile, ' V Velocity at the data point');
  Writeln(outfile, ' nondimensionalised by centerline Vin');
  Writeln(outfile, ' Ps Static pressure at the data point');
  Writeln(outfile, ' (Ps - Pcin)/Qin');
  Writeln(outfile, ' PLoss Total pressure loss coef at the');
  Writeln(outfile, ' data point (Ptot - Ptotin)/Qin');
  Writeln(outfile, ' # Q V Ps Beta PLoss');
  Writeln(outfile, '.....');
end.

procedure (Mdl)ileInfo var Infile text; var (Mdl)date string; var
Angle/Init YInit VStep real; var
NumStep integer);

var InString string;
i integer;
OutReal real;
Data_Err boolean;
begin
  for i = 1 to 22 do
    begin
      Readln(Infile, InString);
      ExtractReal2(InString, OutReal, Data_Err);
      case i of
        1 (Mdl)date = InString;
        9 Angle = OutReal;
        11 /Init = OutReal;
      end
    end
  end;

  if i < 22 then
    { Modified for extrapolation ;
    Writeln 'Out of range at array I = ', i;
    end

  procedure DataRedt(p1, p2, p3 real; var q vel; p, beta, ploss real)

  var k23, kps2, kps3 real;
  k12, k13 real;
  i integer;
  angle real;

  begin
    k23 = (p2 - p3) / (p1 - p3);
    kps2 = (p1 - p2) / (p1 - p3);
    kps3 = 1 / kps2;

    if not (CalArrayReady) then
      begin
        Writeln;
        Writeln 'Initializing the calibration array (Call file)';
        InitCalArray(CallFile);
      end;

    if CalArrayReady then
      begin
        if k23 <= 0 then { for negative angles use KPS3 and K13 curves }
          begin
            Interpolate(kps3, angle);
            Interpolate3(angle, K13);
            q = (p1 - p3) / K13;
          end
        else if k23 > 0 then { for positive angles use KPS2 and K12 curves }
          begin
            Interpolate(kps2, angle);
            Interpolate2(angle, K12);
            q = (p1 - p2) / K12;
          end
        end;

        Interpolate1(angle, k1);

        beta = (0 - Probe_Angle) + angle; { Modified to account for change in }
        ps = Cp1 * q * k1; { calibration array was "-angle" ;
        ploss = q + ps - 1;
        if q > 0.0 then
          vel = SQR(1/q)
        else
          Writeln 'Negative Q == err';
        end.

```

```

12 YInit := OutReal;
16 VStep := OutReal;
18 NumStep := trunc(OutReal);
end; { case }
Passage Step Size := VStep;
Probe Angle Angle;
end;
end;

procedure (Hdf:fileData) var Infile:Text; YInit,VStep:real; NumStep:integer)
var V,H,P,I      real;
    Cp1,Cp2,Cp3  real;
    some         string;
    InString      real;
    i,k          integer;
    YS           real;
    InW akc:StepChange boolean;

begin
    i := 1; k := 1;
    { Reads in all the data lines in the output file }
    if Range < 0 then
        OpenRange;
    repeat
        Readln(Infile,InString,some);
        if InString = 333 then
            begin
                Readln(Infile,InString,YInit,VStep);
                i := 1; { reset the data counter }
                StepChange := True;
            end
        else if InString = 111 then
            begin
                Readln(Infile,InString,V,H,P,I,Cp1,Cp2,Cp3);
                YS := (YInit-VStep*(i-1));
                incl(i); { another line of data has been retrieved };
                SetPValues(Cp1,Cp2,Cp3,YS);
                if (k < 4) and StepChange then
                    begin
                        PL(Station[k]) := CpPointer-1;
                        incl(k);
                        StepChange := False;
                    end
                end
            until eof(Infile);

```

```

if k = 4 then
    PL(Station[k]) := CpPointer-1;
if Range < 0 then
    CloseRange;
end; { (Hdf:fileData) }

procedure AddFile( Indata PathStr );

var
    (Hdf:file      string;
    Angle          real;
    ZInit,YInit    real;
    VStep          real;
    NumStep        integer;
    Infile         text;

begin
    Assign(Infile,Indata);
    Reset(Infile);
    (Hdf:file) := (Infile,(Hdf:file),Angle,ZInit,YInit,VStep,NumStep);
    (Hdf:fileData) := (Infile,YInit,VStep,NumStep);
    Close(Infile);
end;

procedure ReduceFile(hdf:var (Hdf:file PathStr);

{ Save the reduced data in the list to the reduced file specified }

var (huf:file      text;
    i)             integer;

begin
    WriteLn('Saving reduced data file ',(Outdata));
    Assign(huf,ile(Outdata));
    ReWrite(huf,ile);
    (huf:file) := (Year,Month,Day,(DayofWeek),
    WriteLn('outfile',TestDate := Month,Day,Year);
    WriteLn(huf,ile);
    ReduceFileHeader(huf,ile);

    ZS := ZInit/200;
    VC := VInit/62.8;

    for i := 1 to (CpPointer-1) do
        begin
            i := (CpPointer-1) + (i-1)

```

```

Y_S := Y[i]Pnch;
WriteLn(Outfile,14,X,(83,Y_583,Z_583);
end

WriteLn(Outfile);

ReduceFileHeader2(Outfile);

for i := 1 to (CpPointer-1) do
begin
  i := (CpPointer-1)4-(i-1);
  WriteLn(Outfile,j4,q[i]104,cell[i]94,xy[i]94,Retal[i]94,Ptloss[i]94);
end;

Close(Outfile);
WaitOnKey(Ch);
Close;
end;

procedure Reduce(pValue(i integer);
begin
  DataRed(Cp1[i],Cp2[i],Cp3[i],q[i],cell[i],ps[i],betal[i],ptloss[i]);
end;

procedure Zero(Pointer integer); { sets everything at pointer to zero }
begin
  Cp1[Pointer] = 0;
  Cp2[Pointer] = 0;
  Cp3[Pointer] = 0;
  Y[Pointer] = 0;
  Retal[Pointer] = 0; q[Pointer] = 0;
  cell[Pointer] = 0; ps[Pointer] = 0;
  ptloss[Pointer] = 0;
end;

procedure SetCp(C1,YAbs real); { Sets Cp on reduced list (Yter values set to 0) }
begin
  { Does not call reduce procedure }
end;

begin
  if CpPointer = 301 then
  begin
    WriteLn('Cp arrays are full');
    exit;
  end
  else
  begin
    Cp1[CpPointer] = 0;
    Cp2[CpPointer] = 0;
    Cp3[CpPointer] = 0;
    Y[CpPointer] := YAbs;
    ReduceCpValue(CpPointer);
    inc(CpPointer);
    inc(RangeInd[Ranger]);
    Zero(CpPointer);
  end;
end;

procedure ReduceAllVar (Outdata PathStr);
var i integer;
begin
  for i := 1 to (CpPointer-1) do
  begin
    DataRed(Cp1[i],Cp2[i],Cp3[i],q[i],cell[i],ps[i],betal[i],ptloss[i]);
  end;
end;

procedure PointInfin(var V real);
var i integer;
begin
  WriteLn('p1 := ',Cp1[CpPointer-1]103);
  WriteLn('p2 := ',Cp2[CpPointer-1]103);
end;

```



```

        WriteLn('Unable to find emacs.')
        WaitForKey(t h)
    end
end
end;

6 begin
    if (pPointer = 1) then
        PlottingMenu
    else
        begin
            WriteLn
            WriteLn('No data has been loaded.')
            WaitForKey(t h)
        end
    end
7 ReadMenu(NInt);
8 begin
    if Range = 2 then
        begin
            WriteLn
            WriteLn('Are you sure (Y/N)?')
            ReadMenu(Resell);
        end
    else
        Resell := true;
    if Resell then
        Reset pPointer;
    end
end;

end; { save }

end; { ReduceMenuInput }

procedure DisplayReduceMenu;
var i: integer;
begin
    begin
        CtrScr;
        WriteLn('Data Reduction Menu');
        WriteLn
        for i := 1 to 8 do
            begin
                WriteLn('  Reduce(a,b)(i)');
                Tab(40);
                WriteLn('  Reduce(Default)(i)');
                CtrOf;
                WriteLn
            end
        end
    end
end; { DisplayReduceMenu }

procedure ReduceMenu;
var i: integer;
    Choice: char;
begin
    CtrScr;
    repeat
        DisplayReduceMenu
    repeat
        Choice := ReadKey;
    until (Choice in ['1'..'9','Q'])
        Val(t h,Choice);
        CtrOf;
        WriteLn('Reduce(a,b)(i) Reduce(Default)(i)');
        ReduceMenuInput(i);
    until Choice = 'Q';
end; { ReduceMenu }

{ ..... }
{ ..... Graphics menus and procedures follow ..... }
{ ..... }

function MaximumOf(RSeries ReducedData) real;
var i: integer;
    Max: real;
begin
    Max := Series[1];
    for i := 1 to C(pPointer)-1 do
        if Series[i] > Max then
            Max := Series[i];
        MaximumOf := Max;
    end;

function MinimumOf(RSeries ReducedData) real;
var i: integer;
    Min: real;

```

```

begin
  Min := Series[1];
  for i := 1 to CpPointer-1 do
    if Series[i] < Min then
      Min := Series[i];
  MinimumOf Min;
end;

procedure PlotRange(var XSeries, YSeries: ReducedData; Start, Stop: integer);
var i: integer;
begin
  WMoveTo(XSeries[Start], YSeries[Start]); { move to start of range }
  for i := Start to Stop do { loop to plot range r }
    WLineTo(XSeries[i], YSeries[i]);
  end;

procedure PlotSymbolRange(var XSeries, YSeries: ReducedData; Start, Stop, WhichSymbol: integer);
var i: integer;
begin
  for i := Start to Stop do { loop to plot range r }
    begin
      if SymbolOf i then
        Symbol(XSeries[i], YSeries[i], WhichSymbol)
      else if PlotSymbolsOf i then
        begin
          for i := 1 to 4 do
            begin
              if PlotStationOf i then
                Symbol(XSeries[i], YSeries[i], 3, 1);
            end;
          end;
        end;
    end;
end;

procedure PlotReducedData(var XSeries, YSeries: ReducedData; MinY, MaxY: real);
var r: integer;
begin
  r := 1; { start with first range }
  InitNewPort;
  SetWindowPort(0, GetMaxX, GetMaxY, CpPointer);
  SetWindowPort(200, YMax, 200, YMin);
  SetTicks(10, 10);
  SetHeaderOn;
  SetBorderOn;
  AxisLabels;
  AxesOn;

  while RangeStart[r] < CpPointer do
    begin
      SetLineStyle(LineStyle[r], 0, 1); { changes line style between ranges }
      PlotRange(XSeries, YSeries, RangeStart[r], RangeEnd[r]);
      if SymbolOf r or PlotSymbolsOf r then
        PlotSymbolRange(XSeries, YSeries, RangeStart[r], RangeEnd[r], BlockStyle[r]);
      inc(r);
    end;
  end;

procedure FindMaxMin(var Series: ReducedData; var MinY, MaxY: real);
var SerMaxY, SerMinY: real;
begin
  SerMaxY := MaximumOf(Series); SerMinY := MinimumOf(Series);
  if (MinY < SerMinY) or (MaxY > SerMaxY) then
    MinY := SerMinY * 0.9; { is MinY small enough for series ? }
  if (MaxY > SerMaxY) or (MaxY < SerMinY) then
    MaxY := SerMaxY * 1.1; { is MaxY large enough for series ? }
  end;

procedure PlotCurve(k: char);
var Ch: char;
    MinY, MaxY: real;
begin
  Ch := k;
  MinY := -1.0; MaxY := 1.2;
  DefineHeader('Beta vs S1 - Press A Key');
  PlotReducedData(YBeta, MinY, MaxY);
end;

1' begin
  MaxY := (Int(Abs(ProbeAngle * 10) * 7); MinY := MaxY - 14;
  FindMaxMin(Beta, MinY, MaxY);
  DefineHeader('Beta vs S1 - Press A Key');
  PlotReducedData(YBeta, MinY, MaxY);
end;

2' begin
  MinY := -1.0; MaxY := 1.2;
  DefineHeader('Quick Traverse Output - Press A Key');
  PlotReducedData(YCp, MinY, MaxY);
end;

```

```

3' begin
  MinY := -10, MaxY := 11;
  DefineHeader 'Pressure Coefficient (p) *PressAKey);
  PlotReducedData(Y.Ploss, MinY, MaxY);
end;

4' begin
  MinY := 0.5, MaxY := 2;
  DefineHeader 'Air Flow Velocity *PressAKey);
  PlotReducedData(Y.Vel, MinY, MaxY);
end;

5' begin
  MinY := -2, MaxY := 2;
  DefineHeader 'Air Flow Pressure *PressAKey);
  PlotReducedData(Y.Ps, MinY, MaxY);
end;

6' begin
  PlC.SymbolsOn := not(PlC.SymbolsOn);
  if PlC.SymbolsOn then
    SymbolsOn := false;
  end;

7' GridOn := not(GridOn);
8' SymbolsOn := not(SymbolsOn);
9' Drivers;
10' Drivers;
end; { case }

11' 5' begin { cleans up any graphs that had been done }
  Ch := ReadKey;
  GraphCleanup;
end;

end; { case }
end;

function Plotting(i integer) MenuLabel;
var out MenuLabel;
begin
  out := '';
  case i of
    1: out := 'Beta - Flow Angle';
    2: out := 'Cpl - Quick Traverse Output';
    3: out := 'Cp - Total Pressure Loss';
    4: out := 'Velocity';
    5: out := 'Pressure';
    6: out := 'Show PLC Stations';
    7: out := 'Show Grid';
    8: out := 'Show Data Points';
  end;

```

```

9 out := 'Graph Drivers';
end; { case }
Plotting := out;
end; { Traverse Type }

procedure PlottingMenuLabel(i integer);
begin
  Tab(40);
  case i of
    1: 5' Write('');
    6' Write(YesNot(PlC.SymbolsOn));
    7' Write(YesNot(GridOn));
    8' Write(YesNot(SymbolsOn));
  end; { Case }
end; { Traverse Type menu Label }

procedure DisplayPlottingMenu;
var i integer;
begin
  clrScr;
  gotoXY(1,1);
  Write('Available Graphs ');
  WriteLn;
  for i := 1 to 9 do
    begin
      Write(i, Colon, Plotting(i));
      PlottingMenuLabel(i);
      WriteLn;
    end;
  end;

QuitLine;

end; {Display PlottingMenu}

procedure PlottingMenu;
var i integer;
  Choice char;
begin
  clrScr;
  repeat
    DisplayPlottingMenu;
  repeat
    Choice := UpCase(ReadKey);
  until (Choice in ['1'..'9', 'D', 'Q']);

```

```

Valid(choice:code);
WriteLn;
Write(Plotting(i));
Tab(60);
if Choice <= 'Q' then
  PlotCurve(choice)
until Choice = 'Q';
end; {PlottingMenu}

procedure CheckCalArray;
var YorN: boolean;

begin
  YorN := True;
  ClrScr;
  if Probe_Angle = 0.0 then
    begin
      WriteLn('Probe angle is set to 0.0 °');
      WriteLn('Calibration Array is 'CalFile);
      WriteLn('Write' Is this correct (Y/N) '); Boomenu(YorN);
      if not(YorN) then FileMenu(CalFile);
    end;
  end;

  {----- }
  { following are Pressure Loss Menu Procedures }
  {----- }

  procedure HighlightInet(inet: integer);
  begin
    HighVideo;
    WriteLn('Y[i] 10 1,Pl loss[i] 9 4);
    NormVideo;
  end;

  procedure PlClk(header: string; Station: StartColumn integer);
  var i: Station1..Station2: integer;

  begin
    if StartColumn < 40 then
      StartColumn := 40;
    Window(0+StartColumn,1 40+StartColumn,25);
    ClrScr;
  end;

  WriteLn(header);
  If inet(1,40); WriteLn;
  WriteLn('Station Y Cp');
  If inet(1,40);
  Window(0+StartColumn,5,40+StartColumn,25);
  if Station < 11 then
    Station1 := 1
  else
    Station1 := Station-10;
    if Station1+20 < CpPointer-1 then
      Station2 := CpPointer-1
    else
      Station2 := Station1+18;
    for i := Station1 to Station2 do
      begin
        if i = Station then
          HighlightInet(i)
        else if (i = PlC[Station][1]) or (i = PlC[Station][4]) then
          HighlightInet(i)
        else
          WriteLn('Y[i] 10 1,Pl loss[i] 9 4);
        end;
      end;
    procedure DisplayWakeBoundary; { lets user look at pressure loss data }
    var Ch: char;
    begin
      ClrScr;
      WriteLn('Press any key to return to menu ');
      PlClk('Wake Start 'PlC[Station][2],1);
      PlClk('Wake End 'PlC[Station][3],40);
      Ch := ReadKey;
      Window(1 1,80,25);
    end;
  end;

  function WakeWidth: real;
  begin
    WakeWidth := Y[PlC[Station][4]]-Y[PlC[Station][1]];
  end;

  procedure PLCSettings;
  begin
    WriteLn('Nothing Yet');
  end;

  function PlClabel(i: integer; MenuLabel:

```



```

var out MenuLabel;
begin
  out :=
  case i of
    1 out = 'Passage Start';
    2 out = 'Wake Start';
    3 out = 'Wake End';
    4 out = 'Passage End';
    5 out = 'Link at data';
    6 out = 'Inlet Angle';
    7 out = 'Pitch';
    8 out = 'Report';
    9 out = 'Plot Data';
  end; { Case }
  PLCTLabel := out;
end; { QuickLabel }

function PLCTDefault(i: integer) PathStr;
var out PathStr;
    i integer;
    a,b,c,d,e,f string[15];
    Y1,Y2 real;
    LastOn boolean;
begin
  LastOn := false;
  out :=
  a := 'b'; c := 'c'; d := 'd'; e := 'e'; f := 'f';
  str(i,a);
  for k := 1 to 4 do
    { set to blank if no entry }
    begin
      if PLCTStation[k] = 0 then
        Blank[k] := true;
      else
        Blank[k] := false;
      if PLCTStation[k] > CpPointer-1 then
        PLCTStation[k] := CpPointer-1;
      end;
    end;
  if Blank[i] then
    out := '' { does not show any value if the blank flag is set }
  else if i in [1..4] then
    begin
      str(PLCTStation[i],b);
      str(Y[PLCTStation[i]],c);
      str(PLoss[PLCTStation[i]],d);
    end;
  else if i = 6 then
    begin
      out = concat(b,c,d,e,f);
    end;
  else if i = 7 then
    begin
      str(InletAngle,10.2,out);
      out = out + ' mm';
    end;
  else if i = 8 then
    begin
      str(Pitch,10.2,out);
      out = out + ' mm';
    end;
  else if i = 9 then
    begin
      PLCTDefault := out;
      end; { MenuLabel }
    end;

procedure PLCTInput(i: integer);
begin
  case i of
    1..4 InitMenu(PLCTStation[i]);
    5 DisplayWakeBoundary;
    6 RealMenu(InletAngle);
    7 RealMenu(Pitch);
    8 PLCTReport;
    9 begin
      GridOn := false;
      PLCTSymbolsOn := true;
      SymbolsOn := false;
      PlottingMenu;
    end;
  end; { case }
end; { SetUpMenu }

procedure DisplayPLCTMenu;
var i: integer;
begin
  CLS;
  WriteLn('Pressure Loss Calculation Menu');
  WriteLn('');
  Tab(40); WriteLn('Station Y Cp');
  for i := 1 to 9 do
    begin
      WriteLn('-----');
      WriteLn('Station Y Cp');
    end;
end;

```

```

Label40);
WriteLn(PLCDefault(i));
end;
QuitLine;
end; {Display PLC Menu}

procedure PLCMenu;
var i: integer;
    Choice: char;
begin
    ClrScr;
    repeat
        DisplayPLCMenu;
    repeat
        Choice := UpCase(ReadKey);
    until (Choice in ['1'..'9', 'Q']);
    Val(Choice, i, code);
    Write(PLCLabel(i));
    Write(PLCDefault(i));
    PLCInput(i);
    until Choice = 'Q';
    ClrScr;
end; {PLCMenu}

var k: integer;
    Slope[k]: real;
    Ploss[k]: real;
    LineFitSCoeff, BCoeff: real;
    for k := PLCStation[1]+1 to PLCStation[4] do
        Slope[k] := (Ploss[k]-Ploss[k-1])/(Y[k]-Y[k-1]);
        LineFitSCoeff, BCoeff := find zero loss line;
    for k := PLCStation[1] to PLCStation[4] do
        Ploss[k] := Ploss[k]-4*SCoeff*Y[k]+BCoeff; { scales Ploss to this line }
    ; for k := PLCStation[1] to PLCStation[4]-1 do
        begin
            Angle1 := (Beta[k]-InletAngle)*PI/180;
            VA[k] := Vell[k]*Cos(Angle1);
            Angle2 := (Beta[k+1]-InletAngle)*PI/180;
            VA[k+1] := Vell[k+1]*Cos(Angle2);
            Count1 := (VA[k+1]-VA[k])*(Y[k]-Y[k+1])/2*Pitch;
            VAAVG := Count1 + VAAVG;
            Count2 := (Vell[k+1]-Vell[k])*(Y[k]-Y[k+1])/2*Pitch;
            VAVG := Count2 + VAVG;
        end; {loop commented out by Dave Isaacs, 18-Mar-93}

```

```

begin
  Count1 = 0.0, Count2 = 0.0, Count3 = 0.0;
  VAVG1 = 0.0, VAVG2 = 0.0, VAVG3 = 0.0;
  for i = PLCStation[1] to PLCStation[4]-1 do
    begin
      VA1 = Vel[i+1], VA2 = SQR(VA1), VA3 = VA2*VA1,
      V1 = Vel[i], V2 = SQR(V1), V3 = V2*V1,
      Count1 = (VA1+V1)*(Y[i]-Y[i+1])*Pitch/2.0,
      Count2 = (VA2+V2)*(Y[i]-Y[i+1])*Pitch/2.0,
      Count3 = (VA3+V3)*(Y[i]-Y[i+1])*Pitch/2.0,
      VAVG1 = Count1 + VAVG1,
      VAVG2 = Count2 + VAVG2,
      VAVG3 = Count3 + VAVG3,
      MIXLOSS = -1-2*VAVG2/SQR(VAVG1)+VAVG3/(VAVG1*SQR(VAVG1))
    } - sign to make this loss conform to other loss }
  end;
end.

procedure PLCreport;
var Ch: char;
    D: DirStr;
    N: NameStr;
    F: FstStr;
begin
  ClrScr;
  F:=FindDataFile.D(N,F);
  Writeln('Pressure Loss Calculation Report file ',N+E);
  Writeln;
  Writeln('Inlet Angle ',InletAngle:10:3,' °');
  Writeln('Passage Width ',Abs(Y[PLCStation[4]]-Y[PLCStation[1]])/10:2,' mm');
  Writeln('Pitch ',Pitch:10:2,' mm');
  Writeln;
  PLCCalc;
  MixLoss;
  TotLoss = MixLoss + CpAVG;
  Writeln('Zero loss line ');
  Writeln('Slope ',SCoeff:10:4);
  Writeln('Y intercept ',IKCoff:10:4);
  Writeln;
  Writeln('Mass average loss ',CPAVG:10:4);
  Writeln;
  Writeln('Mass average axial velocity ',VAAVG:10:4);

```

```

{new loop added 18-Mar-93 will only calculate the axial velocities}
for k = PLCStation[1] to PLCStation[4]-1 do
begin
  Angle1 = (Beta[k]-InletAngle)*PI/180.0;
  Valk = Vel[k]*Cos(Angle1)
end; {for}

{ CPAVG = 0.0, BetAVg = 0.0, }
{ for k = PLCStation[1] to PLCStation[4]-1 do }
{ begin { note use scaled Piloss for these calculations }
{ Count3 =
{ (Piloss2[k+1]+Piloss2[k])*Y[k]-Y[k+1])*Pitch/2*(VA[k+1]-VA[k])/VAAVG/2.0, }
{ CPAVG = CPAVG + Count3/SQR(VAVG), }
{ Count4 = (Beta[k+1] + Beta[k])*Y[k]-Y[k+1])/PITCH/2.0, }
{ BetAVG = BetAVg + Count4, }
{ end. } {loop commented out by Dave Isaacs, 18-Mar-93}

{new loop added 18-Mar-93 will calculate the mass averaged values for }
{ Cp, Beta, V, and Va. Note the pitch has dropped out of the calculation }
{ This implies that the summation region spans on pitch }
Count1 = 0, Count2 = 0, Count3 = 0, Count4 = 0,
CpAVg = 0, BetAVg = 0, VAVg = 0, VaAVg = 0,
for k = PLCStation[1] to PLCStation[4]-1 do
begin
  Count1 = Y[k] - Y[k+1],
  Count2 = Count1*0.5*(VA[k]+Valk+1),
  Count3 = Count3 + Count2,
  CpAVg = CpAVg + 0.5*(Piloss2[k]+Piloss2[k+1])*Count2,
  BetAVg = BetAVg + 0.5*(Beta[k]+Beta[k+1])*Count2,
  VAVg = VAVg + 0.5*(Vel[k]+Vel[k+1])*Count2,
  VaAVg = VaAVg + 0.5*(Valk+Valk+1)*Count2;
end; {for}
VAVg = VaAVg/Count3; {divide all summed values by mass flow}
VAVg = VAVg/Count3;
BetAVg = BetAVg/Count3;
CpAVg = CpAVg/Count3;
CpAVg = CpAVg/(VAVg*VAVg); {reference to qout, on separate line for clarity,
end. { PLC Calculate }

procedure MixLoss;
var i: integer;
    Count1, Count2, Count3: real;
    VA1, VA2, VA3: real;
    V1, V2, V3: real;

```

```

WriteLn(' Mass average angle      ',BE*AVG,10:4,' °').
WriteLn.
WriteLn('Mixed out loss      ',MIX1*OS,10:4).
WriteLn.
WriteLn(' Average Velocity      ',VAVG1,10:4).
WriteLn(' Average Velocity Squared ',VAVG2,10:4).
WriteLn(' Average Velocity Cubed   ',VAVG3,10:4).
WriteLn.
WriteLn('Total Loss      ',TOTL*OS,10:4).
WaitForKey('h').

end.

end { unit Reduce }

```

```

unit Globals3
interface
uses Dos,Crt,utility,Graph;

type MenuLabel = string[80];
  TraverseType = array[1..9] of real;
  array3 = array[1..3] of real;
  { used by reduct unit since it only }
  { works on three hole probe data }

var
{ not used on newer wind tunnel sampling }
  TipLr, Contraction Real;
{ System menu -- TIPMENU }

PortSBits,DBits Byte;
Baud_Rate Integer;
Par char;
CalcOffP, CalcOffQ Real;
CalcOffP3, CalcOffP4, CalcOffP2 Real; {added for 3 transducer use}
Inter_Init Integer;

{ Operating point -- see below }
Palm, TOF, TOC, Tok Real;
InitP, InitQ, Re Real;
InitP3, InitP4, InitP2 Real; {added for 3 transducer use}
Ch2(Cb4f real;

Outfill PathStr; { output file path and name }
Outfile1 text; { output file }

Shut Integer;
Probe Angle real;
Zinit, Yinit, Xinit Real;
Year,Month,Day,DayofWeek word;

{ Reduct Unit }

CalcFile,InDataFile,RedFile PathStr;
CalcArrayReady boolean;
InletAngle real;

{ Traverse Unit }
TraverseStepSize,TraverseStep TraverseType;
TraverseStations array[1..9] of integer;
ScanValueUse boolean; {added 3 transducer use}

procedure TunnelMenu;
procedure InitOperatingPoint;
procedure OperatingPoint;
procedure GetRho(var Density real);
implementation

var rho real;
  rhoCalculated boolean;

procedure InitOperatingPoint;
begin
  Palm:=755.0; Tok:=0; TOF:=82;
  Re:=300000;
  InitQ:=0.011; InitP2:=-0.014; { operating point reynolds number }
  InitP3:=-0.024; InitP4:=-0.003; { initial channel 2 and 4 readings }
  rhoCalculated:=false; { added for 3 transducer use }
end;

function TunnelMenuLine(i:integer) MenuLabel;
var out MenuLabel;
begin
  out:= '';
  case i of
    1 out:= 'Reynolds Number';
    2 out:= 'Tip clearance size [Uc]';
    3 out:= 'Tunnel contraction factor';
    4 out:= 'Atmospheric Pressure, Palm [mmHg]';
    5 out:= 'Ambient Temperature, TOF';
    6 out:= '';
    7 out:= '';
  end;
end;

```

```

      8 out = 'Operating point'.
      9 out = 'Quit'.
    end. { case }
    TunnelMenu inc = out.
  end. { TunnelMenu inc }

procedure TunnelMenuLabel(i integer).
begin
  Write(TunnelMenuInc(i).Tab(48)).
  Case i of
    1 Write (Re 50.' '),
    2 Write (TipC 31.' '),
    3 Write (Contraction 31.' '),
    4 Write (Palm 31.' mmHg '),
    5 Write (TOF 31.' °F ').
    { most convenient to enter in °F }
    { Celsius and kelvin conversions done in
      OperatingPoint procedure }
  end. { Case }
  CtrlOl. { clears to the end of line.. eliminates overlap }
end. {MenuLabel}

procedure SetUpTunnelMenu(i integer).
begin
  Case i of
    1 RealMenu(Re).
    2 RealMenu(TipC).
    3 RealMenu(Contraction).
    4 RealMenu(Palm).
    5 RealMenu(TOF).
    { Modified for 3 transducer use }
    8 OperatingPoint.
  end.
end. { SetUpTunnelMenu }

procedure DisplayTunnelMenu.
var i integer.
begin
  ClrScr.
  Write(Tunnel Information Menu ').
  WriteLn.
  for i = 1 to 8 do
    begin
      Write(' :').
      TunnelMenuLabel(i).
    end.
  end.
end. {Display TunnelMenu}

WriteLn(' ').
end.
QuitInc.

end. {Display TunnelMenu}

procedure TunnelMenu.
var i integer.
  Choice char.
begin
  ClrScr.
  repeat
    DisplayTunnelMenu.
  repeat
    Choice = UpCase(ReadKey).
    until (Choice in ['1'..'8'..'Q']).
    Val(Choice, i, code).
    TunnelMenuLabel(i).
    SetUpTunnelMenu(i).
    until Choice = 'Q'.
  end. {TunnelMenu}

procedure OperatingPoint.
const T1 = 0.0, T2 = 50.0, RHO1 = 1.29, RHO2 = 1.09,
      MU1 = 0.000171, MU2 = 0.000195.

var density, viscosity real.
    CalcCh2 real.
    C char.
begin
  { procedure automatically determines whether Reynolds number
    or channel reading is desired }
  ClrScr.
  TOC = (TOF - 32) * 5/9.
  TOK = TOC + 273.3.
  density = (TOC - T1) / (T2 - T1) * (RHO2 - RHO1) + RHO1 * Palm * 760.
  rhoCalculated = true. rho = density { kg m-3 }.
  viscosity = (TOK - T1) / (T2 - T1) * (MU2 - MU1).
  WriteLn('Operating Point Determination').
  WriteLn.
  if Re < 2300 then
    begin
      WriteLn('Channel 2 initial reading is ' IntQ 5 3).

```

```

WriteLn('Channel 4 initial reading is ',InitP2:5:3);
WriteLn('Channel 5 initial reading is ',InitP3:5:3); {added for 3 transducer use;}
WriteLn('Channel 6 initial reading is ',InitP4:5:3); {added for 3 transducer use;}
WriteLn('Atmospheric pressure is ',Palm:5:1);
WriteLn('Ambient temperature is ',Tof:5:1,'F');
WriteLn('Air density is ',Density:10:3,' kg/m^3');
WriteLn('Determining channel 2 final reading for Reynolds number ',Re:5:0);
WriteLn;
CaK:=CaKofQ;
Ch2F:=0.5*Density*SQR(Re*Viscosity/(Density*0.16281))/CaK+(InitQ*1000);
Ch2F:=Ch2F/1000;
WriteLn('Channel 2 reading at operating point is ',Ch2F:5:3,' Volts');
WriteLn;
WriteLn('Adjust tunnel speed accordingly ');
end
else
begin
WriteLn('Determining Reynolds number from channel 2 reading ');
WriteLn;
WriteLn('Enter channel2 final reading in Volts ');
ReadMenu(Ch2f);
Ch2:=(Ch2f-InitQ)*1000;
Re:=Density*SQR(12.0*Ch2*CaK/Density)*0.16281/Viscosity;
WriteLn('The Reynolds number is ',Re:5:0);
end;
WriteLn;

WaitForKey(C);
ClrScr;
end. { Operating Point }

procedure GetRho(var Density real);
begin
if not rhoCalculated then OperatingPoint;
Density:=rho;
end;

end {unit Globals3}

```

END

0 9-1 1-9 4

FIN