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**CONTRIBUTIONS TO THE STUDY OF TIP LEAKAGE FLOW
IN A PLANAR CASCADE OF TURBINE BLADES**

by

George Danias

Thesis submitted in partial fulfillment of
the requirements for the degree of
Master of Engineering

DEPARTMENT OF MECHANICAL AND AERONAUTICAL ENGINEERING

CARLETON UNIVERSITY

OTTAWA, ONTARIO

CANADA

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The undersigned hereby recommend to the Faculty of Graduate Studies and Research acceptance of the thesis, "Contributions to the Study of Tip Leakage Flow in a Planar Cascade of Turbine Blades" submitted by George Danias in partial fulfillment of the requirements for the degree of Master of Engineering.

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ABSTRACT

Contributions to the study of tip leakage in a planar turbine cascade are made in two areas: (1) a moving belt rig was designed and manufactured in order to simulate the effects of rotation, and its use was demonstrated; (2) a seven-hole pressure probe was calibrated, over a wide range of pitch and yaw angles, and used to make preliminary measurements in the highly three-dimensional flow at the outlet of the cascade.

The moving belt rig was used for a preliminary experimental investigation of the effect of wall speed and Reynolds number on the behavior of the blade loading. The results revealed some unexpected, and rather marked changes in the flow behaviour near the tip at a blade chord Reynolds number between 0.62×10^5 and 1.0×10^5 .

The seven-hole probe was calibrated over a range of $\pm 50^\circ$ of flow misalignment in both pitch and yaw. A general purpose data reduction program was also developed. The use of the probe and software was demonstrated at the trailing edge plane of the cascade. The measurements showed that the flow angle varies by at least 70° through the tip leakage vortex.

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TABLE OF CONTENTS

ACCEPTANCE SHEET	ii
ABSTRACT	iii
ACKNOWLEDGEMENTS	iv
TABLE OF CONTENTS	v
LIST OF APPENDICES	vii
LIST OF FIGURES	viii
LIST OF PLATES	xi
LIST OF TABLES	xi
NOMENCLATURE	xii
 1.0 INTRODUCTION	 1
 Part I: The Moving Belt Rig	
2.0 BACKGROUND INFORMATION TO TIP WALL RELATIVE MOTION	4
2.1 Review of Previous Work	4
2.2 The Effect of Rotation on Tip Gap Mass Flow Rate	9
3.0 DESCRIPTION OF APPARATUS	20
3.1 Approach and Design Criteria	20
3.2 Cascade Test Section	29
3.3 Moving Belt Rig	31
3.4 Some Observations of the Rig in Operation	38
4.0 PRELIMINARY INVESTIGATION OF THE EFFECT OF TIP WALL RELATIVE MOTION ON BLADE LOADING	42
4.1 Description of Experiments	42
4.1.1 Blade Loading Experiments	42
4.1.2 Velocity Profiles at Leading Edge Plane	43
4.2 Experimental Method	43
4.2.1 Instrumentation	43
4.2.2 Data Acquisition Technique	44
4.3 Experimental Results and Discussion	46
4.3.1 Blade Loading Results	46
4.3.2 Velocity Profiles at Leading Edge Plane	57
4.3.3 Discussion of Results	66
4.3.4 Summary	71
 Part II: The Seven-Hole Probe	
5.0 THE CALIBRATION AND USE OF A SEVEN-HOLE NON-NULLING PRESSURE PROBE	72

5.1	Introduction	72
5.2	Incompressible Calibration Theory	73
5.2.1	Low Angle Regime	74
5.2.2	High Angle Regime	77
5.2.3	Flow Properties	77
5.2.4	Calibration Constants	80
5.2.5	Seven-Hole Probe Software	81
5.3	Apparatus and Procedure	83
5.3.1	Probe Geometry	83
5.3.2	Calibration Apparatus	83
5.3.3	Instrumentation	85
5.3.4	Test Conditions and Technique	86
5.4	Calibration Results and Discussion	88
5.4.1	Inner and Outer Sector Coefficients	88
5.4.2	Statistical Analysis	93
5.4.3	Reynolds Number Effects	98
5.4.4	Accuracy	99
5.5	Tip Leakage Investigation	100
5.5.1	Test Conditions	100
5.5.2	Discussion of Results	102
5.5.3	Summary	109
6.0	CONCLUSIONS AND RECOMMENDATIONS	110
6.1	The Moving Belt Rig	110
6.1.1	Conclusions	110
6.1.2	Recommendations	112
6.2	The Seven-Hole Probe	113
6.2.1	Conclusions	113
6.2.2	Recommendations	113
	REFERENCES	115
	APPENDIX A	119
	APPENDIX B	125
	APPENDIX C	133
	APPENDIX D	142
	APPENDIX E	148
	APPENDIX F	150

LIST OF APPENDICES

Appendix	Description	Page
APPENDIX A	Listings of the curve-fitting program, FIT.FOR, and the coefficient generating program, COEFF7HP.PAS	119
APPENDIX B	Documentations and listings of FLOWPROP.PGM and FLOWPROP.PSL (Data reduction software for the seven-hole probe)	125
APPENDIX C	Documentations and listings of programs used for the statistical analysis and data rejection of the seven-hole probe calibration data	133
APPENDIX D	Trigonometric relationships and listing of program to convert calibration high angle settings to equivalent low angles	142
APPENDIX E	Listings of data reduction programs for the FLOWPROP programs	148
APPENDIX F	Lists of calibration high angle conversions, and calibration pressure coefficients.	150

LIST OF FIGURES

Figure	Description	Page
2.1.1	Skewed inlet boundary layer (Dean, 1954)	7
2.1.2	Tangential force as a function of tip clearance and wall speed (Dean, 1954)	7
2.2.1	Tip gap flow	10
2.2.2	Tip gap velocity profiles (a) without rotation; (b) with rotation	12
2.2.3	Couette flow	13
2.2.4	Tip gap flow with rotation	16
3.1.1	Tip wall relative motion velocity flow vectors for (a) actual turbine and (b) simulation	21
3.1.2	Superimposed diagrams of velocity vectors through the boundary layer	22
3.1.3	Transverse boundary layer at cascade inlet for different belt widths	25
3.1.4	Axial velocity profiles due to transverse motion (Lohmann, 1976)	26
3.1.5	δ_T / δ vs x / δ correlation	28
3.2.1	Cascade test section and summary of cascade geometry (Sjolander & Amrud, 1986)	30
3.2.2	Test section belt guide	32
3.3.1	Assembly of moving belt rig	33
4.3.1	Blade pressure distribution repeatability tests for (a) $Re=6.2 \times 10^4$; (b) $Re=1.0 \times 10^5$ ($\tau/c=2.9\%$)	47
4.3.2	Variation of blade pressure distributions with wall speed at 2.9% clearance ($Re=6.2 \times 10^4$) at (a) $z/h=0.417$; (b) $z/h=0.021$	49
4.3.3	Variation of blade pressure distributions with Reynolds number at 2.9% clearance ($z/h=0.021$)	51

4.3.4	Variation of blade pressure distributions with and without trip wire near (a) midspan and (b) tip ($Re=5.2 \times 10^5$, $\tau/c=2.9\%$)	52
4.3.5	Variation of blade pressure distributions with wall speed at 2.9% clearance ($Re=1.0 \times 10^5$) at (a) $z/h=0.417$; (b) $z/h=0.021$	54
4.3.6	Variation of force coefficients with EES at (a) $z/h=0.417$ and at (b) $z/h=0.021$	56
4.3.7	Schematic of three-hole probe traverse location	58
4.3.8	Velocity profiles at blade leading edge with stationary wall for (a) $Re=1.0 \times 10^5$ and (b) $Re=3.0 \times 10^5$ ($\tau/c=2.9\%$)	59
4.3.9	Velocity profiles at blade leading edge at 100% EES ($Re=1.0 \times 10^5$) for the (a) axial and (b) tangential components	60
4.3.10	Flow angle distributions at L.E. ($\tau/c=2.9\%$)	61
4.3.11	Superimposed velocity vectors at blade leading edge (at EES, $Re=1.0 \times 10^5$, $\tau/c=2.9\%$) for (a) coplanar and (b) measured inlet boundary layer in actual machine	63
4.3.12	Typical inlet boundary layer configurations in actual machine	64
4.3.13	Tangential velocity profiles at blade L.E. at 100% EES ($Re=1.0 \times 10^5$)	65
4.3.14	Analogy of tip gap flow with moving wall to stationary tip gap flow with varying clearance	68
4.3.15	Shift of suction ridge with decreased vortex strength	69
5.2.1	(a) The tangential ($\alpha - \beta$) and polar ($\theta - \phi$) reference systems; (b) probe port nomenclature	75
5.2.2	Division of angular space (Gerner et al, 1984)	78
5.4.1(a)	Variation of angle of attack coefficient with angle of attack	89
5.4.1(b)	Variation of sideslip angle coefficient with sideslip angle	90
5.4.2	Variations of roll angle coefficient with roll	

	angle for (a) sector 1; (b) sector 3	91
5.4.2(c)	Variation of roll angle coefficient with roll angle for sector 5	92
5.4.3	Variations of pitch angle coefficient with pitch angle for (a) sector 2; (b) sector 4	94
5.4.3(c)	Variation of pitch angle coefficient with pitch angle for sector 6	95
5.5.1	Measurement grid location at trailing edge	101
5.5.2	Overturning angle at T.E. plane ($Re = 4.3 \times 10^5$, $\tau/c = 2.85\%$)	103
5.5.3	Velocity vectors at T.E. plane ($Re = 4.3 \times 10^5$, $\tau/c = 2.85\%$)	104
5.5.4	Total C_p distribution at T.E. plane ($Re = 4.3 \times 10^5$, $\tau/c = 2.85\%$)	105
5.5.5	Static C_p distribution at T.E. plane ($Re = 4.3 \times 10^5$, $\tau/c = 2.85\%$)	106
D.1	The tangential ($\alpha - \theta$) and polar ($\theta - \phi$) reference systems	144
D.2	Geometric relationship between probe and test section axes	146

LIST OF PLATES

Plate	Description	Page
3.3.1	The moving belt rig	34
3.3.2	Test section with tip wall relative motion apparatus	35
5.3.1	The calibration apparatus	84

LIST OF TABLES

Table	Description	Page
5.1	Standard deviations between measured and predicted values	96

NOMENCLATURE

English Symbols

A	- any of four flow properties: α, β (or θ, ϕ), C_o, C_q
A'	- Rains' viscous force parameter, $(\tau/t_{MAX})^2 Re (t_{MAX}/c)$
c	- nominal blade chord
C_D	- tip gap discharge coefficient
C_F	- resultant blade force coefficient, $F / \frac{1}{2} \rho V_{CL}^2 c$
C_o, C_q	- probe total, dynamic pressure coefficients
C_{P_t}	- total pressure coefficient, $(P_{oL} - P_o) / \frac{1}{2} \rho V_{CL}^2$
C_{P_s}	- static pressure coefficient, $(P - P_{WS}) / \frac{1}{2} \rho V_{CL}^2$
C_X, C_Y	- axial, tangential force coefficients
C_α, C_β	- angle of attack, sideslip angle coefficients for low angles
$C_{\alpha_1}, C_{\alpha_2}, C_{\alpha_3}$	- intermediate angle coefficients
C_θ, C_ϕ	- pitch, roll high angle coefficients
EES	- equivalent engine speed
F	- resultant blade force
F_X, F_Y	- axial, tangential blade forces
h	- blade span

k	-	correction factor
K	-	calibration constant for seven-hole probe
L.E.	-	leading edge of blade
m	-	mass flow rate
$m_{\text{gap}}, m_{\text{gap}0}$	-	gap mass flow rate with and without rotation
N	-	number of samples
P	-	static pressure
P_{ref}	-	reference static pressure (e.g. upstream wall static).
q	-	dynamic pressure, $\frac{1}{2}\rho v^2$
q_{ref}	-	reference pressure difference (e.g. wind tunnel contraction pressure difference)
Re	-	Reynolds number based on chord, $\rho v_{\text{CL}} c / \mu$
s	-	blade spacing
T.E.	-	trailing edge of blade
u, v, w	-	axial, tangential and spanwise velocity components
U	-	belt (wall) speed or blade tip speed
V	-	flow velocity
x, y, z	-	coordinates in the axial, tangential and spanwise directions
x'	-	coordinate in chordwise direction

Greek Symbols

α, β	-	angle of attack, sideslip angle for tangential reference system
δ, δ_T	-	axial, transverse boundary layer thickness
θ, ϕ	-	pitch, roll angles for polar reference system

- μ - viscosity
- γ - blade stagger angle
- ρ - density
- σ - unbiased standard deviation,
$$\sqrt{(\sum_{i=1}^N (X_i - X_{avg})^2 / (N-1))}$$
- τ - tip gap

Subscripts

- CL - undisturbed centre-line value
- i - i-th sample or data point
- L - local value at probe tip
- N - normal component
- n - probe port or sector number (1-7)
- n+, n- - adjacent probe ports clockwise and counter clockwise to port n
- o - total value
- r - relative value
- s - static value
- ws - upstream wall static in test section
- ∞ - dynamic value

Superscript

- quantity relative to probe axes for seven-hole probe
- denotes a flow vector in the boundary layer (e.g. $V''' = 0$ at wall; V = value at edge of layer)

1.0 INTRODUCTION

The full understanding of tip leakage flows are of prime importance to the turbine designer since they can account for as much as one third of the losses through a stage. Despite the progress which has been made in recent years, it is generally agreed that much still remains to be understood about these flows.

The work of Amrud (1985), using a planar cascade of turbine blades, provided much physical insight into this phenomenon. However, among other idealizations, there was no relative motion of the tip wall. Therefore, it seems appropriate to further pursue this investigation by looking at the effects of tip clearance on the cascade with tip wall relative motion. Consequently, a moving belt rig was designed and manufactured.

It is recognized that the use of a moving belt to simulate rotation is not perfect and does tend to cause some problems. Firstly, it is obvious that radial pressure gradient effects cannot be modelled through the use of a belt. Secondly, and probably more importantly, the moving belt does some work on the fluid and thus causes a total pressure rise at the wall. This is opposite to what happens

in the actual situation. Therefore any total pressure measurements that are made must be interpreted with caution. Finally, the tip wall statics together with surface oil flow visualization are no longer possible. On the other hand, the belt should simulate the effect of rotation on the mass flow through the tip gap, and the blade loading.

The thesis is divided into two parts since it is the result of research done in two distinct areas in the study of tip leakage flows. The first part describes the design of the moving belt rig and presents some preliminary measurements of the effect of the tip wall relative motion on the blade loading. In addition, the inlet velocity profile at the leading edge plane of the blade was measured in order to evaluate the simulation of the actual velocity triangles. The second part describes the calibration procedure for a seven-hole probe, originally designed by Amrud (1985), and the subsequent demonstration of the use of this probe, and the data reduction software written to analyze the probe data, in the complex flow at the trailing edge plane of the cascade.

Most of the present research comprised of the design and manufacture of the moving belt rig, and the "shaking-down" process of the apparatus which consisted of tests to determine the optimal operating belt speed and to correct any

mechanical problems. Chapter 3 contains the descriptions of the moving belt design, modifications to the existing cascade test section, and some observations of the rig in operation.

Tip leakage experiments consisted of a preliminary investigation of the effect of tip wall relative motion on blade loading, as well as measurements of the velocity profiles at the blade leading edge plane. A description of these experiments, including a discussion of their results, is found in Chapter 4.

Chapter 2 contains a review of past work on tip leakage and tip wall relative motion. A simple analysis is also presented which suggests a significant reduction to the tip gap mass flow rate due to tip wall relative motion.

Finally, the calibration procedure and use of the seven-hole probe are presented in Chapter 5. Conclusions and recommendations for future work, presented separately for Parts I and II, are contained in Chapter 6.

2.0 BACKGROUND INFORMATION TO TIP WALL RELATIVE MOTION

2.1 Review of Previous Work

A very comprehensive review of previous work in the area of tip leakage, especially with regards to past cascade work, is presented in Amrud (1985). Therefore only work relevant to the present study will be presented here. However, some basic theory on the phenomenon of tip leakage will be included for the sake of completeness.

The effects of tip clearance in a turbine largely parallel those of a compressor. A loss in efficiency with an associated loss in the loading coefficient is involved and the perturbed aerodynamics may reach over much of the blade height. In turbines, however, destabilization is not of interest, but the tip clearance problem is enhanced because of the gap sizes necessary to accommodate thermal expansion.

The mechanics of the tip leakage flow are not understood in detail. However, it may be assumed that the factors contributing to the basic flow mechanism are:

- (1) The pressure difference between suction and pressure surfaces of a blade.
- (2) The presence of the endwall boundary layer.

- (3) The relative motion between the blade and the casing.
- (4) The size of the clearance gap.

From the factors listed above, it is seen that leakage flow is influenced by both viscous and inertia forces. In addition, in an actual rotating machine the effect of relative motion, between the tip of the blades and the end wall, results in changes in the leakage flow rate at the gap due to convection of the viscous flow through the clearance gap. In a turbine, the boundary layer which is swept back over the tip opposes the leakage flow. The reverse holds true for a compressor. Also, in addition to the obvious similarities between compressors and turbines, some different aerodynamic effects exist because the flow through a turbine blade passage is accelerating, and therefore the wall boundary layer is not so prone to separation. Furthermore, the pressure distribution around the blade profile of a turbine is different, which may lead to an altered geometry of the flow.

Dean (1954) conducted a moving belt experiment, in a rectilinear compressor cascade. The belt covered an axial distance from 0.4 blade chords upstream of the cascade inlet to the cascade exit plane. In Dean's experiment the blades, inlet flow, and belt movement were in the correct relation-

ship. That is, the boundary layer was not convected simply in the direction of the stream flow, but had a component in the pitchwise direction of the blading. Furthermore, this pitchwise component being superimposed because of its viscous properties and being most evident at the belt surface, imparted a skew to the boundary layer as it would be seen by the rotor blade of the compressor (see Fig. 2.1.1).

Dean noted that up to large clearances the point of minimum pressure on the blade tip suction surface moved rearward, and the minimum pressure decreased with increased tip clearance. It was further observed that the tangential force on a blade was a function of tip clearance and relative wall speed (see Fig. 2.1.2). Dean's experiment showed that the convection effect of the viscous flow on the leakage flow rate due to tip wall relative motion is important.

Wadia and Booth (1982), using a water rig with idealized tip clearances and a cascade of turbine blades, noted that discharge coefficients were reduced due to wall motion. This is as one would expect since the relative motion of the wall was against the direction of the leakage flow. Their calculations showed roughly a 15% reduction in the discharge coefficients.

More recently, Graham (1985), using a planar turbine

Fig. 2.1.1 Skewed inlet boundary layer (Dean, 1954).

Fig. 2.1.2 Tangential force as a function of tip clearance and wall speed (Dean, 1954).

cascade in a water rig, also observed that leakage was reduced due to tip wall motion. Using flow visualization techniques, he found that by increasing the belt speed, at any given clearance, the leakage flow was reduced. Furthermore, for tight clearances, the leakage flow could be cut off altogether by increasing the belt speed. For example, at a clearance of 0.6% of blade span and at the correct speed for engine velocity triangle simulation (EES), the net leakage flow was reduced to zero (this was also observed at a clearance of about 0.9% span and 2 x EES). Therefore at tight clearances, increasing the belt speed has the same effect as reducing the tip clearance. His pressure measurements also showed that endwall motion modifies the leakage flow and leads to changes in the blade loading compared with the stationary case.

Research into tip leakage flows in turbines was begun at Carleton University by Amrud (1985) (see also Sjolander and Amrud, 1986). Amrud examined in detail the effects of tip clearance on blade loading in a stationary planar cascade of turbine blades. A new feature, found in this work, was the formation of multiple tip leakage vortices as the clearance increased. The blade loading measurements showed that the tip region pressure distributions differed considerably from the two-dimensional distribution. It was further observed that the blade and the endwall boundary layer is significant-

ly affected by the clearance gap. Amrud's study was continued by Yaras (1987) who performed a detailed study of the tip gap region.

From the examination of the available literature, it is evident that experimental data for cascades with tip wall relative motion is both sparse and lacking in detail. Thus the logical follow up to the stationary wall studies of Amrud and Yaras was to examine the effects of the relative wall motion. The present thesis describes the addition of this capability to the existing Carleton University cascade test section.

2.2 The Effect of Rotation on Tip Gap Mass Flow Rate

Cascade measurements with a stationary endwall have shown that the mass flow rate through the tip gap can be calculated reasonably well with a simple model (Yaras, 1987) as follows. Referring to Fig. 2.2.1, the mass flow rate is given by,

$$m = C_D \int \rho V_N dA$$

and

$$V_N = \sqrt{(2 \Delta P / \rho)}$$

where ΔP is the static pressure difference across the blade, away from the distorted flow region near the tip, and C_D is

Fig. 2.2.1 Tip gap flow.

the discharge coefficient for the gap.

For a turbine rotor blade, the relative wall motion is such that fluid is drawn back over the tip and the gap mass flow is reduced (Fig. 2.2.2). A simple analysis will be devised to estimate the relative importance of this effect.

A vaguely similar situation occurs in Couette flow between infinite parallel planes, as shown in Fig. 2.2.3 (for $U = 0$, the flow is known as Poiseuille flow). The flow is driven by a pressure gradient dP/dx along the channel.

The tip gap flow analysis will be based on an "equivalent" Couette flow. For the Couette flow, shown in Fig. 2.2.3, and assuming "fully-developed" flow, it can be shown that the momentum equation reduces to Eq. (2.2.1), and the resulting expression for the velocity is given by Eq. (2.2.2),

$$\frac{dP}{dx} = \mu \frac{d^2 u}{dx^2} \quad (2.2.1)$$

$$u = \frac{1}{2\mu} \frac{dP}{dx} (y^2 - h^2) + \frac{U}{2} \left(\frac{y}{h} + 1 \right) \quad (2.2.2)$$

The net mass flow rate between the planes is,

$$\dot{m} = \int \rho u \, dA \quad \text{where } dA = dy \text{ (assuming unit depth)}$$

Fig. 2.2.2 Tip gap velocity profile (a) without rotation; (b) with rotation.

Fig. 2.2.3 Couette flow.

Thus, for the flow defined by Eq. (2.2.2),

$$m = \frac{\rho}{2\mu} \frac{dP}{dx} \int_{-h}^{+h} (y^2 - h^2) dy + \frac{\rho U}{2} \int_{-h}^{+h} \left(\frac{y}{h} + 1\right) dy$$

carrying out the integration gives,

$$m = -\frac{2}{3} \frac{\rho h^3}{\mu} \frac{dP}{dx} + \rho U h \quad (2.2.3)$$

Now, from the simple model, for a stationary endwall,

$$m = C_D \int \rho v_N dA = C_D \int_{-h}^{+h} \sqrt{2\Delta P/\rho} dy$$

and assuming ΔP does not vary in the y direction,

$$m = C_D \sqrt{2\rho\Delta P} \int_{-h}^{+h} dy = C_D \sqrt{2\rho\Delta P} 2h \quad (2.2.4)$$

Equating Eqns. (2.2.3) and (2.2.4), with $U = 0$, gives,

$$C_D \sqrt{2\rho\Delta P} 2h = -\frac{2}{3} \frac{h^3}{\mu} \rho \frac{dP}{dx}$$

therefore,

$$-\frac{1}{\mu} \frac{dP}{dx} = \frac{3C_D}{h^2} \sqrt{2\Delta P/\rho} \quad (2.2.5)$$

Thus, the Couette flow which is "equivalent" to the tip-gap flow is the one which has $(1/\mu)dP/dx$ given by Eq. (2.2.5). Then, as a first approximation, assuming that C_D and ΔP are

unchanged by the effects of rotation, for the general case,

$$\begin{aligned} m_{\text{gap}} &= \frac{2}{3} \rho h^3 \left(\frac{3C_D}{h^2} \sqrt{(2\Delta P/\rho)} \right) + \rho U h \\ &= 2 \rho h C_D \sqrt{(2\Delta P/\rho)} + \rho U h \end{aligned}$$

Blade pressure coefficients have been defined (see Amrud, 1985) as,

$$C_P = \frac{P - P_{\text{ref}}}{\frac{1}{2} \rho V_{\text{CL}}^2}$$

where V_{CL} is the undisturbed upstream velocity. Therefore,

$$\Delta C_P = \frac{\Delta P}{\frac{1}{2} \rho V_{\text{CL}}^2}$$

and upon substitution of ΔP in the above expression of the gap mass flow rate gives,

$$m_{\text{gap}} = 2 \rho h C_D \sqrt{(\Delta C_P)} V_{\text{CL}} + \rho U h \quad (2.2.6)$$

For the tip gap flow, it would appear that U should be the component of the wall velocity which opposes the gap flow (denoted by U_N in Fig. 2.2.4). Then from Fig. 2.2.4, Eq. (2.2.6) may be written as,

$$m_{\text{gap}} = 2 \rho h C_D \sqrt{(\Delta C_P)} V_{\text{CL}} + \rho U_N \cos \gamma h$$

where γ is the stagger angle. The first term on the right-

Fig. 2.2.4 Tip gap flow with rotation.

hand side is due to the gap flow without rotation, and will be denoted as m_{gap0} . Therefore, in terms of the fractional change in mass flow rate due to the effects of rotation,

$$\frac{m_{gap}}{m_{gap0}} = 1 + \frac{\rho U_N h \cos \gamma}{2 \rho h C_D \sqrt{(\Delta C_P)} V_{CL}}$$

$$\frac{m_{gap}}{m_{gap0}} = 1 + \frac{\cos}{2 C_D \sqrt{(\Delta C_P)}} \left(\frac{U_N}{V_{CL}} \right) \quad (2.2.7)$$

where $\frac{U_N}{V_{CL}} < 0$ for turbines

$\frac{U_N}{V_{CL}} > 0$ for compressors

For reasonably typical values of $C_D = 0.7$, $\Delta C_P = 4$, $U_N/V_{CL} = -2$, and $\gamma = 40^\circ$, Eq. (2.2.7) gives a value of 0.45. Thus, the simple analysis suggests that the effects of rotation are considerable (a 55% decrease in gap mass flow in this case). Note that the expression developed applies to a particular chordwise location unless ΔC_P is interpreted as some sort of average value for the blade as a whole. An expression from which the total gap flow is obtained based on a chordwise distribution of ΔC_P follows.

A blade force coefficient has previously been defined as (see Amrud, 1985),

$$C_F = \frac{F}{\frac{1}{2} \rho V_{CL}^2 c} = \int_0^1 \Delta C_P d(x'/c) \quad (2.2.8)$$

An average value of ΔC_P can then be defined as the value which gives the correct force coefficient. That is,

$$C_F = \int_0^1 \Delta \overline{C_P} d(x'/c) = \Delta \overline{C_P} \quad (2.2.9)$$

Therefore, ΔC_P of Eq. (2.2.7) can be replaced by C_F to give an equation which defines the total (or net) mass flow rate through the gap. Sjolander and Amrud (1986) quoted a value of 1.77 for the midspan force coefficient. Using this value results in a predicted reduction of 82% of the net gap flow due to rotation. It is worth mentioning that although rotation may greatly reduce the net leakage flow rate, there will undoubtedly still be very significant tip clearance losses for the case shown.

At this time, there is no known available data to check the validity of the expression developed from this simple analysis. Nevertheless, even if this analysis overestimates the reduction in the mass flow rate by a factor of 2, it does serve to show that rotation has a significant effect on the mass flow rate through the gap, and is supported in a general way by Graham's observations.

The moving belt rig will be used to establish the actual effect of rotation. When that data is available, it could be used to define an empirical correction, perhaps along the same lines indicated, that is,

$$\frac{m_{\text{gap}}}{m_{\text{gap0}}} = 1 + \frac{k \cos \gamma}{2C_D C_F} \left(\frac{U_N}{V_{CL}} \right) \quad (2.2.10)$$

where k is a correction factor.

3.0 DESCRIPTION OF APPARATUS

As mentioned in Chapter 1, in order to investigate the effect of rotation on tip leakage in turbines, a moving belt rig was designed and manufactured for use with the existing cascade test section. This chapter describes the basic design approach used, and gives a detailed description of the rig design, as well as some observations of the rig in operation.

3.1 Design Approach

In an actual turbine, the rotor blades rotate while the tip wall or shroud is stationary. In the cascade simulation, the turbine blades are stationary while the tip wall is in motion. Thus in both cases, there is relative motion between the blade-tips and the tip wall. These situations together with the corresponding velocity triangles are shown in Figs. 3.1.1 and 3.1.2, respectively.

Consider first the actual case. From Fig. 3.1.1 (a) or Fig. 3.1.2, the inlet boundary layer is assumed to be coplanar in the absolute frame of reference. The relative velocity, however, is not coplanar but is skewed in the direction of negative incidence as the wall is approached.

Fig. 3.1.1 Tip wall relative motion; velocity flow vectors for (a) actual turbine and (b) simulation.

Fig. 3.1.2 Superimposed diagrams of velocity vectors through the boundary layer.

For our purposes the blade speed magnitude is considered constant through the boundary layer. Note that often in practice the inlet boundary layer is skewed in the absolute frame of reference. This is because a relatively moving row may precede the row in question. However, the coplanar inlet absolute flow represents the simplest case, and is therefore the one we have attempted to simulate.

Consider now the cascade simulation. The tip wall now moves (from suction to pressure side of the blade) rather than the blades, as shown in Fig. 3.1.1 (b). The result is that what were relative velocities in the actual machine will now be the absolute velocities in the cascade. Due to the no-slip condition at the moving wall surface, fluid is entrained in the direction of wall motion which gives rise to what can be thought of as a "transverse" (or tangential) boundary layer. Note that a necessary requirement for the simulation of an unskewed inlet boundary layer in the actual machine is that the locus of the tips of the resultant "relative" velocity vectors, through the boundary layer, be on a straight line when the velocity triangles are superimposed as shown in Fig. 3.1.2. Consequently, for a given axial boundary layer profile, there is a unique transverse boundary layer profile which is the equivalent of the unskewed inlet boundary layer in the actual machine. The axial and transverse boundary layers must clearly have the

same thickness. Since we cannot control the details of the transverse profile, the best that we can do is produce the required transverse boundary layer thickness, and hope that the resulting profile is close to the correct one.

The transverse boundary layer thickness at the cascade leading edge is a function of the length of the belt upstream, as shown in Fig. 3.1.3. The length required here was estimated based on experiments on the response of turbulent boundary layers to transverse surface motion, conducted by Bissonette and Mellor (1974), and Lohmann (1976). The configurations they used were similar and basically consisted of a long cylinder whose upstream section was stationary while its downstream section was rotated. Both studies were in agreement qualitatively. However, some differences were evident and some phenomena more apparent in Lohmann's experiment. For instance, Fig. 3.1.4 shows that strong coupling between the axial and transverse components of the flow do exist (note the nominal velocity profile for the undisturbed reference boundary layer is shown as a solid line), but the axial boundary layer thickness is essentially unaltered. From the above discussion for the simulation case, it was assumed that the axial boundary layer was unaffected by the transverse motion. Therefore, it would seem that the best we can hope for is an approximate simulation of the actual case.

Fig. 3.1.3 Transverse boundary layer at cascade inlet for different widths of belt.

Fig. 6 Axial velocity profiles in the boundary layer on the rotating surface

Fig. 3.1.4 Axial velocity profiles due to transverse motion (Lohmann, 1976).

From plots of the transverse velocity profiles on the rotating surface, by Bissonette & Mellor (1974) and Lohmann (1976), it was possible to obtain the local transverse boundary layer thickness as a function of the axial distance along the rotating part of the cylinder. This was then scaled on the local axial boundary layer thickness to produce the correlation of Fig. 3.1.5. The speed coefficient, Ω , is defined as the ratio of the belt speed to the undisturbed centre-line flow speed (U/V_{CL}), while the local axial boundary layer thickness is defined as the position, from the end wall, at which the axial velocity is 99% of the undisturbed freestream value.

The aerodynamic specifications of the cascade test section turbine blade were provided by Pratt & Whitney of Canada Inc. These blades have a speed coefficient of 2.164 at the specified design point. When this value is multiplied by the undisturbed centre-line velocity in the test section, this gives the belt speed required to simulate rotation at 100% equivalent engine speed (EES). Using Fig. 3.1.5 as the basis for selecting the required belt width, it is seen that for the transverse and axial boundary layers to be equal for a speed coefficient of about 2.164, the axial distance from the belt leading edge to the point of interest is equal to about 20 local axial boundary layer thicknesses. This corresponds to a distance of about 400 mm from the cascade

Fig. 3.1.5 δ_T / δ versus x / δ correlation.

leading edge to the upstream edge of the belt. This value was arrived at by using boundary layer measurements of Amrud (1985), made at 330 mm upstream of the cascade leading edge. However, due to mechanical considerations which are described in the next section, a shorter belt distance upstream of the cascade inlet was used.

3.2 Cascade Test Section

The cascade test section was used previously to study tip leakage under stationary conditions by Amrud (1985) and Yaras (1987), and is shown schematically in Fig: 3.2.1. The geometry of the cascade is also summarized in Fig. 3.2.1. The blades, which are of constant chord and are untwisted, have a profile which corresponds to the tip section of a recent Pratt & Whitney turbine blade design. However, a slightly higher solidity (c/s), and a lower incidence than in the actual application are used.

The moving belt replaces the plexiglass window of the test section, and covers about the same area. This was done in order to minimize mechanical modifications to the original test section. However, since inlet boundary layer bleed-off is possible with the test section, the required local axial boundary layer thickness, based on the aforementioned correlation, and the given axial distance from the edge of

Chord length, c : 250 mm
 Blade span, b : 200 mm
 Blade spacing, s : 150 mm
 Aspect ratio, b/c : 0.8
 Solidity, c/s : 1.667
 Stagger angle, γ : 37.6 deg
 Blade inlet angle, β_1 : 12.1 deg
 Blade outlet angle, β_2 : 50.7 deg

Fig. 3.2.1 Cascade test section and summary of cascade geometry (Sjolander & Amrud, 1986).

the belt guide, which is described below, to the cascade inlet is still possible. The trailing edge location of the belt extends about one blade chord downstream of the cascade outlet, which is the farthest distance that future measurements (e.g. mixing losses) are likely to be made. Therefore, the belt width was chosen to be two feet wide (about 610 mm).

Different clearance gaps are created by using shims at the two top and bottom belt rig attachment locations, as well as between the usual cascade tip wall and sidewalls. The tip-wall boundary layer bleed section of the cascade was replaced with a similar plexiglass section, which includes a belt guide, in order to locate the leading edge of the belt and to prevent any curling of the belt edge. Figure 3.2.2 shows a top view of the belt guide.

3.3 Moving Belt Rig

An assembly drawing of the moving belt rig is shown in Fig. 3.3.1. Plate 3.3.1 shows the actual rig, detached from the test section, while Plate 3.3.2 shows the rig attached to the test section.

The belt chosen for this application was a 24 inch wide, 108.8 inch long, endless SAB-8E Habasit belt. The SAB-8E synthetic rubber belt has a coefficient of friction of 0.15,

Fig. 3.2.2 Test section belt guide.

Fig. 3.3.1 Assembly of moving belt rig.

Plate 3.3.1 The moving belt rig.

Plate 3.3.2 Test section with tip wall relative motion apparatus.

and was "finger-spliced" which produced a smooth, almost unnoticeable, joint.

The main structural frame was manufactured using mostly C4 x 7.25 inch steel channels welded together with some L1.75 x 1.75 x 0.125 inch steel channels. The two drum pulleys were designed and manufactured using 8 inch O.D., 7 I.D., 26 inch long, cold drawn, seamless mechanical steel tubing. The shafts were manufactured from 1.5 inch drill rod. The upper of the two pulleys was crowned since this will tend to keep the belt from wandering sideways. Belt alignment and tensioning are accomplished by a simple bolt mechanism used on either side of the top drum pulley.

A suction box was designed in anticipation of a need to prevent the belt from flapping since constant tip clearance is essential for the investigation of tip leakage. In fact, flapping turned out not to be a problem. The suction box basically consists of a large (22.75 x 31 x 1/2 inch) aluminum plate with an 11 x 15, 1 inch diameter, grid of holes. To this plate is attached a sheet metal box with a nozzle for a vacuum hose, which provides the suction. A 1/16 inch thick teflon sheet, etched on one side for glueing to the aluminum plate, with its low coefficient of friction is used as the belt running surface on the suction box plate.

As mentioned earlier, Amrud used a maximum Reynolds number of 4.3×10^5 . However this would require a belt speed of about 65 m/s corresponding to 100% EES or a drum pulley RPM of about 6100. This high a speed was expected to lead to vibration problems although hoop stresses were checked and are acceptable upto 6200 RPM. Therefore, it was decided to reduce the maximum belt speed to about 18 m/s, corresponding to 1760 RPM. This would allow a maximum Reynolds number of about 1.4×10^5 with 100% EES.

The 3 hp a.c. motor, used to drive the belt, is attached behind the lower part of the rig (see Plate 3.3.2) on a base which is adjustable. The drive is 1:1 and is coupled to the lower drum pulley by a timing belt. A change of drive belt pulleys could accommodate for different speed ratios in the future. By varying both the amplitude and the frequency of the voltage applied to the motor, both its speed and torque can be controlled. This is accomplished by using an ACtech variable frequency speed control which is mounted on the laboratory wall with a remote speed control potentiometer mounted on the belt rig.

Finally, the moving wall parameters may be summarized as follows:

Moving wall surface	Smooth, endless SAB-8E Habasit belt
Moving wall motion	Vertical from pressure to suction, side of a blade passage (for turbine simulation)
Moving wall leading edge location	121 mm (about 0.48 c) upstream of the cascade leading edge
Moving wall trailing edge location	254 mm (about 1.0 c) downstream of the cascade trailing edge
Moving wall speed	0 to 18 m/s
AC speed control & induction motor	3 hp, 3 phase, 60 Hz, 460 Vac, 1760 RPM, 10/1 speed range

3.4 Some Observations of the Rig in Operation

The following observations are based on the rig's preliminary shakedown and subsequent use with the test section.

As expected, the starting torque is high and thus it is recommended to start the motor at a low potentiometer setting

of about 12% of the maximum, and to manually rotate the top pulley a few times. The speed can then be gradually increased while checking and adjusting the tension to keep the belt fairly centred on the drum pulley. During start up, the wind tunnel should be off otherwise the starting torque is considerably higher. When shutting down, the motor should be unloaded gradually.

Imbalance of the pulleys is not a serious problem for the present speed range, although dynamic balancing of the pulleys will undoubtedly be necessary for higher speeds. The RPM was monitored using a stroboscope which had an accuracy of ± 2.5 RPM in the 0-690 RPM range, and ± 10 in the 690-1760 range. There were marked increases of vibration in certain parts of the speed range notably at around 50% and 80% of the maximum speed, probably due to natural frequencies. Vibrations at these speeds were evident as well with the rig coupled to the test section. However the maximum speed was attainable, and even though it produced the highest noise, the test section backplate was not observed to vibrate (which would cause the clearance to vary), especially if the rig was secured on wooden blocks. Generally, the use of these blocks tended to damp out vibrations that otherwise would have been present.

Lateral stability of the belt was sufficient once the

belt was properly tensioned. This was accomplished by first tensioning both sides roughly, then by fixing the downstream pillow block bearing support, and then finally moving the upstream pillow block support by adjusting the tensioning bolt (while the belt is moving) up or down slightly, depending on whether the belt moved upstream or downstream, respectively. A change in speed usually required some fine adjustment. It is recommended that the belt be untensioned after use.

The belt itself remained cool when it was running, due to the air that it entrains on both sides of its surface, while the shafts around the bearings heated up, especially at the higher speeds. It is believed that the small air film between the teflon and the belt surface tends to increase slightly at higher speeds. The increased belt tension required at these higher speeds probably negates some of this effect, thus not altering the clearance by any significant amount, however this was not measured. Therefore this specific observation should be further investigated.

Since adequate belt tensioning was sufficient in keeping the belt flat against the flat plate, no suction was used (about a 0.010-0.015 inch maximum deflection was observed, using a gooseneck dial gauge, at any fixed speed, presumably due to the joint). At present there are no holes on the

teflon. Therefore if in the future suction or blowing (to aid with start-up) is required, the holes on the teflon should be drilled smaller than the 1 inch diameter holes of the suction plate, which were found to be oversized and resulted in a very large normal force.

Finally, the belt surface was kept a few millimetres away from the belt guide (see Fig. 3.2.2), since it tended to score the upstream edge of the moving belt. Electro-static charge build-up was also evident, if the belt rubbed closely against the belt guide, especially at high belt speeds. As a result of this gap between the belt and the belt guide, and the fact that the pressure inside the test section is higher than that of the laboratory, air leakage occurred. However, this did not seem to distort the inlet velocity profile significantly, as will be shown in the next chapter.

4.0 PRELIMINARY INVESTIGATION OF THE EFFECT OF TIP WALL RELATIVE MOTION ON BLADE LOADING

This chapter presents and discusses the results of the initial tip leakage experiments conducted with the moving belt rig.

4.1 Description of Experiments

As mentioned in Chapter 1, the largest part of the present work consisted of the design and manufacture of the moving belt rig. Therefore only a modest amount of actual tip leakage experiments were undertaken. They were performed in order to evaluate the belt rig design, and were also intended as a preliminary study in preparation for more detailed experiments on the effect of tip wall relative motion on the tip gap flow.

4.1.1 Blade Loading Experiments

A tip clearance of 2.9% of blade chord was used for all measurements. Static pressure distributions on the suction and pressure surfaces were collected for two of the fourteen static tap rows on the instrumented blade. One row is near the tip at about 2% of the blade span, and the other is near

midspan at about 42% of the blade span. The wall (belt) speed was varied to include several different speeds for Reynolds numbers of about 0.62×10^5 and 1.0×10^5 , corresponding to undisturbed upstream velocities of about 4 and 6 m/s, respectively. Typical wall speeds consisted of stationary, half EES, the EES (which was about 8 and 13 m/s for the low and high Reynolds numbers, respectively), and at a speed higher than the EES.

4.1.2 Velocity Profiles at Leading Edge Plane

A three-hole non-nulling probe was used to traverse the leading edge plane of the blades near mid-passage, from the tip wall to about midspan, at wall speeds of 0 and that for 100% EES at $Re = 1.0 \times 10^5$. A motorized traverse gear was used to move the probe away from the tip wall.

4.2 Experimental Method

4.2.1 Instrumentation

Pressures were measured using Rosemount model 831A capacitive-type differential pressure transducers. One (S/N 633) was used with a forty-eight port Scanivalve to measure the static tap pressures, and the upstream wall static pressure which was used as a reference pressure. The other

transducer (S/N 591) was used to continuously monitor the upstream dynamic pressure as indicated by the wind tunnel contraction pressure difference. They were calibrated through a wide range of pressures and their calibration curves may be found in Yaras (1987). Hysteresis effects were not found to be a problem even at very low pressures.

A Taurus KS100 multi-function data acquisition and control system, connected to an Eagle PC computer, was used to record the transducer output signals. The signals were also monitored visually using digital voltmeters (DVMs), and compared to computer on-screen values in order to detect instrumentation errors.

4.2.2 Data Acquisition Technique

After the moving belt was set to the required speed, with the wind off, the wind tunnel was started and then allowed to warm up for 10 to 15 minutes. Before each run, the required contraction pressure difference was calculated and set for the particular operating Reynolds number. This value is based on the blade chord, mean velocity at the centre of the test section 330 mm (1.32 blade chords) upstream of the blade leading edge, the settling chamber total temperature, and the barometric pressure. Changes in the settling chamber total temperature and the barometric

pressure were not accounted for during any particular run. However variations in these parameters were typically less than 1% of their absolute value even over extended runs (4 hours). For taking blade pressure measurements the blade surfaces were sealed with Ruban "highland" tape, leaving only the row of interest open to the flow.

The sampling times needed to obtain reliable mean values of the pressure signals were determined experimentally. A 5 sec waiting period, between the stepping of the Scanivalve and the collection of data, and a 40 sec sampling period were used.

Since the data acquisition system could only monitor one signal at a time, each cycle of data acquisition consisted of alternating between the monitoring of the Scanivalve port pressure signal and that of the contraction pressure difference. A data acquisition cycle consisted of the following three steps:

- (1) Collecting a sample of reference pressure (q_i);
- (2) Collecting a sample of the port pressure at the current port ($P_i - P_{ref}$);
- (3) Repeating (1) (q_{i+1}).

This procedure was repeated for the entire sampling period, with each sampling producing approximately 480 samples (12 samples per second) each for the port and flow pressures. The C_p value for the particular port was then computed by

averaging as follows,

$$C_p = \sum_{i=1}^N \frac{P_i - P_{ref}}{(q_i + q_{i+1}) / 2} \quad (4.2.1)$$

where subscripts i , ref , and N denote a particular sample, the reference value, and the total number of samples, respectively. This method of data acquisition accounts for any small amount of the drift in the operating point of the wind tunnel.

It should be mentioned that periodicity tests and calibration of the contraction were not carried out. Instead the flaps of the test section were set to the same positions used by Yaras (1987) for studying essentially the same clearance, and thus his contraction factor was used.

4.3 Experimental Results and Discussion

4.3.1 Blade Loading Results

As background information to what follows, Fig. 4.3.1 shows repeatability results at the tip for both Reynolds numbers at 100% EES. The higher Reynolds number produced less scatter in the data, with the maximum variation in pressure coefficient being about 0.1 and occurring near the suction peak. Generally agreement for most taps, at the

Fig. 4.3.1 Blade pressure distribution repeatability tests for
(a) $Re = 6.2 \times 10^4$; (b) $Re = 1.0 \times 10^5$ ($\tau/c = 2.9\%$).

higher Reynolds number, was considerably better.

The blade loading pressure distributions for the Reynolds number of 0.62×10^5 , near midspan ($z/h=0.417$) and near the tip ($z/h=0.021$) of the blade, are shown in Fig.

4.3.2. The effect of wall motion is negligible near midspan, as would be expected. However as a result of the low Reynolds number, a weak adverse pressure gradient on the suction surface causes a laminar separation bubble extending from about 20 to 40% of blade chord.

Near the tip, the effect of wall motion is quite dramatic. From Fig. 4.3.2 (b), there is minimal effect on the pressure surface for all speeds, the differences being within the range of repeatability shown in Fig. 4.3.1 (a). However, there are some very interesting changes occurring on the suction surface. The initial suction peak, located at about 20% of chord, moves forward by 10% of chord as wall speed is increased from 0. Note that the location as well as the pressure coefficient magnitude of the suction peak are consistent with those observed by Yaras (1987). At 50% EES unloading occurs along the entire surface, at 100% and 140% EES the loading increases rearward, especially after 30% of chord, compared to the stationary wall case. At 235% EES unloading occurs once again along the entire surface. Although this trend of unloading, loading and unloading again

Fig. 4.3.2 Variation of blade pressure distributions with wall speed at 2.9% clearance ($Re=6.2 \times 10^4$) at (a) $z/h=0.417$; (b) $z/h=0.021$.

with increasing wall speed was unexpected and remains to be explained, it appears to be genuine since the pressure variations are larger than the uncertainty in the measurements (Fig. 4.3.1 (a)). It should be noted that beyond 100% EES, the maximum suction peak gets chopped.

It was recognized that for the low Reynolds number that was used, in order to have a wider range of wall speeds, the flow might be sensitive to Reynolds number effects. Thus, it was decided to investigate the effect of Reynolds number with wall speed at 100% EES. Blade loading pressure distributions for three different Reynolds numbers were obtained. Figure 4.3.3 shows the results for the row of taps closest to the tip. As can be seen from the figure, there is a considerable change in the suction surface loading when the Reynolds number is decreased to 0.62×10^5 . In order to determine whether this was a local Reynolds number effect at the tip or a result of the laminar separation bubble away from the tip, it was decided to trigger early transition. To accomplish this a trip wire (0.053 inch diameter piano wire) was installed along the span, close to the leading edge of the suction surface of the blade (between taps 2 & 3). Figure 4.3.4 (a) shows that the trip wire was successful in removing the bubble. However, Fig. 4.3.4 (b) shows that the distribution near the tip is very similar to that obtained without the trip and not like that obtained at higher Reynolds

Fig. 4.3.3 Variation of blade pressure distributions with Reynolds number at 2.9% clearance ($z/h=0.021$).

Fig. 4.3.4 Variation of blade pressure distributions with and without trip wire near (a) midspan and (b) tip ($Re=6.2 \times 10^5$, $\tau/c=2.9\%$).

numbers (refer to Fig. 4.3.3). Therefore, it appears that there is a marked, Reynolds number dependent change in the tip gap flow which occurs somewhere between 0.62×10^5 and 1×10^5 .

As a result of the above findings, it was decided to repeat the blade loading measurements, as a function of EES, for a higher Reynolds number value of 1.0×10^5 . The results are shown in Fig. 4.3.5. The trends are somewhat similar to those obtained for the lower Reynolds number, but are less dramatic. For example, rearward loading on the suction surface occurs at 140%, but not at 100% EES (as was the case for $Re = 0.62 \times 10^5$). In addition, the maximum suction peak gets chopped at 140% EES. It was not possible to go to higher than 140% EES since this corresponds to the maximum available belt speed.

In order to quantify the blade loading results due to wall speed, the chordwise pressure distributions were integrated to obtain axial, tangential and resultant force coefficients. The pressures were assumed to vary linearly from tap to tap and to act on a flat panel defined by the two tap coordinates. Since no attempt was made to interpolate a stagnation point or to extrapolate pressure distributions to the trailing edge, the results are approximate. According to Sjolander & Amrud (1986), who used a higher operating

Fig. 4.3.5 Variation of blade pressure distributions with wall speed at 2.9% clearance ($Re=1.0 \times 10^5$) at (a) $z/h=0.417$; (b) $z/h=0.021$.

Reynolds number of 4.3×10^5 , when the uncertainty in the pressures themselves is combined with the integration scheme, the absolute force coefficients are probably accurate to no better than ± 0.05 . Since the present Reynolds numbers used here are lower, the uncertainties are probably higher, especially for 0.62×10^5 .

The variation of the force coefficients with wall speed, near midspan and near the tip of the blade, are shown in Fig. 4.3.6. Near midspan, the change in the force coefficients is negligible for the higher Reynolds number. The value of the resultant force coefficient is also consistent with the quoted midspan zero clearance value ($C_F=1.77$) of Sjolander & Amrud (1986). For the lower Reynolds number there is a noticeable increase and then decrease in the force coefficients. Near the tip, for the lower Reynolds number, there is first a decrease, then an increase and then a decrease again in the resultant force coefficient as noted earlier. Interestingly, the tangential component is affected more than the axial component. Near the tip, for the higher Reynolds number, there appears to be a small increase in all the force coefficients, especially beyond 100% EES. Although the uncertainty of these coefficients is probably greater than 0.05, it should be recalled that there was an increase in rearward blade loading for 140% EES (see Fig. 4.3.5). The axial component of the force coefficient increases slightly

Fig. 4.3.6 Variation of force coefficients with EES at (a) $z/h=0.417$ and at (b) $z/h=0.021$.

more than the tangential component therefore causing the force vector to rotate toward the axial direction. Consequently, the increase in axial thrust (or pressure drag) would be proportionally higher than the increase in the torque developed by the rotor.

4.3.2 Velocity Profiles at Leading Edge Plane

A schematic of the three-hole probe location at the leading edge plane of the cascade is shown in Fig. 4.3.7. The probe was rotated 40 degrees from the axial. The resultant velocity profiles with stationary wall at Reynolds numbers of 1.0×10^5 and 3.0×10^5 are shown in Fig. 4.3.8. There is considerable scatter in the data for the lower Reynolds number. This is believed to be a result of the low analog input voltages relative to the resolution of the A/D converter of the data acquisition system. If this is indeed the case, amplification of the input signal should rectify the problem. It should be noted that this problem is not thought to be caused by the pressure transducers (see Section 4.2.1). The smooth profile of Fig. 4.3.8 (b) suggests that the air leakage that occurs at the gap between the belt guide and the belt, mentioned in the previous chapter, does not significantly distort the boundary layer to the inlet of the cascade. Figure 4.3.9 contains the axial and tangential (transverse) velocity components, while the flow angle

distribution for both Reynolds numbers is given in Fig.

4.3.10.

By extracting smoothed data from the measured values of Figs. 4.3.9 (a) and (b), it was possible to construct the

Fig. 4.3.7 Schematic of three-hole probe traverse location.

Fig. 4.3.8 Velocity profiles at blade leading edge with stationary wall for (a) $Re=1.0 \times 10^5$ and (b) $Re=3.0 \times 10^5$ ($\tau/c=2.9\%$).

Fig. 4.3.9 Velocity profiles at blade L.E. at 100% EES ($Re=1.0 \times 10^5$) for the (a) axial and (b) tangential components.

Fig. 4.3.10 Flow angle distributions at blade L.E ($\tau/c=2.9\%$).

resultant velocity flow vectors through the boundary layer. The velocity triangles were then superimposed and are shown in Fig. 4.3.11. Figure 4.3.11 (a) shows the tangential components of velocity which together with the measured axial components through the layer, simulate a coplanar inlet boundary layer in an actual machine. It will be recalled (see Section 3.2) that in order to simulate a coplanar inlet boundary layer in the actual machine, a requirement was that the locus of the tips of the resultant velocity vectors must lie on a straight line, on this type of diagram. As seen from Fig. 4.3.11 (b), the measured tangential components are lower than those needed to simulate the coplanar inlet boundary layer. In fact, we are simulating a skewed inlet boundary layer of the type shown in the lower part of Fig. 4.3.12.

The two tangential velocity distributions: the measured one and that required to simulate the coplanar inlet boundary layer are shown in Fig. 4.3.13. The required tangential boundary layer thickness to simulate the coplanar inlet boundary layer is about 14% of the total passage height (or about 30 mm), while the measured tangential boundary layer thickness is less than 10% of the total passage height (less than 20 mm).

It will be recalled that the correlation of Chapter 3

Fig. 4.3.11 Superimposed velocity vectors at blade L.E. (at EES, $Re=1.0 \times 10^5$, $\tau/c=2.9\%$) for (a) coplanar and (b) measured inlet boundary layer in actual machine.

Fig. 4.3.12 Typical inlet boundary layer configurations in actual machine.

Fig. 4.3.13 Tangential velocity profiles at blade L.E. at 100% EES ($Re=1.0 \times 10^5$).

(Fig. 3.1.5) predicted that the axial boundary layer thickness should be about $X/20$, where X is the belt distance from the cascade leading edge to the belt guide. Since X is 121 mm, the axial boundary layer thickness was at the cascade leading edge should be about 6 mm. The measured axial boundary layer thickness was about 30 mm. The measurements suggest that the axial boundary layer thickness should be reduced but not as much as implied by the correlation. This reduction in the inlet boundary layer thickness can be achieved by bleeding air through the existing slots of the test section.

4.3.3 Discussion of Results

As mentioned earlier, some of the blade loading results are unexpected and remain to be fully explained. However, some of their aspects do appear to be consistent with our present understanding of the physics of the leakage flow.

In the first place, there appears to be an analogy between increasing wall speed and decreasing tip gap. As the gap is decreased, the net mass flow through the gap is also decreased. Therefore, there is less available mass flow for the tip leakage vortex. Consequently, the strength of the vortex is reduced. This causes its separation line to move closer to the suction side of the blade passage, and its

suction peak to decrease in magnitude, which was observed by Amrud (1985). For a fixed gap, if the wall is in motion, the mass flow rate through the gap is reduced as the speed increases, as shown schematically in Fig. 4.3.14. (The leakage vortex separation line was denoted by S_1 in Sjolander & Amrud (1986); the same nomenclature is used in Fig. 4.3.14). One would therefore expect a reduction in the strength of the tip leakage vortex with increasing wall speed, and therefore, a reduction in the suction peak. Such a reduction in the suction peak near the tip, with increasing wall speed, was in fact observed for both Reynolds numbers (see Figs. 4.3.2 (b) & 4.3.5 (b)).

The reduced size of the vortex, as a result of the increasing wall speed, might also explain the increase in the loading with increased wall speed towards the trailing edge. The locus of pressure minima lie on a line as shown in Fig. 4.3.15, and is believed to be in line with the centre of the vortex core. Furthermore it is inclined at an angle to the blade-tip, in proportion to the strength of the leakage vortex. For example, Sjolander & Amrud (1986) found that for a clearance of 2.86% of chord, the line or "suction ridge" as they referred to it, was inclined at about 15° to the blade-tip. One would expect that the angle of inclination would decrease with a reduction in the strength of the vortex (as shown in Fig. 4.3.15), locating itself closer to the suction

Fig. 4.3.14 Analogy of tip gap flow with moving wall to stationary tip gap flow with varying clearance.

Fig. 4.3.15 Shift of suction ridge with decreased vortex strength.

tip. Therefore, the net effect on the static pressure taps might in fact be to reduce the pressure there. That is, the pressure minima might move closer to the taps nearest the tip, and therefore show an increase in the suction surface loading.

The variation in pressure distribution with Reynolds number may be related to the behavior of the separation bubble at the tip gap. We know (e.g. Sjolander & Amrud (1986)) that at high Reynolds numbers, the separation bubble does reattach on the blade-tip. It is conceivable that at very low Reynolds numbers (wall speeds may be a determining factor as well) the separation bubble does not reattach. Then as Reynolds number is increased, a point is reached where it will reattach and one will expect a fairly abrupt change in the flow (i.e. a sudden step change). If this phenomenon is present here, this may help to account for the significant differences seen in the pressures at the row of taps nearest to the tip for the low Reynolds number (see Fig. 4.3.3), and the rather different behaviours of the force coefficients of Fig. 4.3.6.

Finally, Rains' constant, $A' = (\tau/t_{MAX})^2 Re(t_{MAX}/c)$, is 73 for $Re=0.62 \times 10^5$, and 118 for $Re=1.0 \times 10^5$. Rains (1954) suggested that for $A' > 125$ inertia effects would dominate over viscous effects in the tip-gap, while for $A' < 12$

viscous effects would dominate. Therefore, it would seem that inertia and pressure forces are slightly more dominant for both cases, and more so at the higher Reynolds number. Assuming that the analogy between wall speed and decreasing gap size holds, the value of Rains' constant will decrease with increasing wall speed, thus possibly making viscous forces more important. For instance, if the effective clearance decreases by half, the resulting Rains' constants are reduced by a factor of four.

4.3.4 Summary

The preliminary measurements made with the moving belt rig showed an unexpected and rather marked change in the flow behaviour at a blade chord Reynolds number between 0.62×10^5 and 1.0×10^5 . This was reflected in changes in the pressure distributions and force coefficients, with wall speed, which depend on the Reynolds number. With regard to the boundary layer measurements at the leading edge plane, the present measurements suggest that the axial boundary layer thickness should be reduced, but not as much as implied by the correlation (Fig. 3.1.5), in order to obtain a closer simulation of a coplanar inlet boundary layer in an actual machine.

5.0 THE CALIBRATION AND USE OF A SEVEN-HOLE NON-NULLING PRESSURE PROBE

5.1 Introduction

An important aspect of aerodynamic studies such as the study of tip leakage flows, is the quantitative measurement of the properties in these highly complex flows. For example, strong induced vortices in tip leakage experiments may have local flow angles exceeding 40 degrees relative to the average flow direction. Five-hole pressure probes and tri-axial hot wire probes are not accurate when the local flow angles are greater than 40 degrees. Therefore, obtaining accurate data at higher flow angles requires elaborate, and consequently, expensive methods such as nulling probes or laser Doppler velocimetry. Everett et al (1983) suggested that accurate data can be obtained for high angles of misalignment by using a seven-hole probe. Such a probe was manufactured by Amrud (1985) but was never calibrated or used.

This chapter describes the basic theory and procedure used in the calibration (based on Gerner et al (1984) and Everett et al (1983)) of the seven-hole non-nulling pressure probe designed and manufactured by Amrud (1985). In addi-

tion, the use of this probe is explained and demonstrated in a planar cascade which is used to investigate tip leakage in turbines.

The calibration theory is described in Section 5.2. Section 5.3 describes the apparatus and procedure used for the calibration process, while Section 5.4 contains a discussion of the results. The tip leakage cascade investigation using this probe is contained in Section 5.5 which includes the description of the experiment and the results obtained.

5.2 Incompressible Calibration Theory

The total pressure, static pressure, and flow angles relative to the probe are obtained from the measured probe pressures of the seven-hole probe. The data are treated differently depending on whether the flow misalignment is small or large. At low relative flow angles all seven port pressures are used. However, at high relative flow angles the flow tends to separate over the leeward side of the probe. As will be shown later, this seems to make the probe sensitive to Reynolds number effects. Therefore, only four pressures on the windward side of the probe are used to determine the flow quantities.

The incompressible calibration theory defines functions such as,

$$\text{Ang}_1, \text{Ang}_2, C_o, C_q = f(C_{\text{ang1}}, C_{\text{ang2}}) \quad (5.2.1)$$

which explicitly determine the relative flow angles, denoted as Ang_1 and Ang_2 , and the total and dynamic pressure coefficients, C_o and C_q , respectively, both of which are defined later on in the chapter. The functions defined by the general Eq. (5.2.1) are polynomial expressions of two variables to account for the two angular degrees of freedom, which specify the orientation of the oncoming flow vector. The two independent variables denoted by C_{ang1} and C_{ang2} , respectively, are non-dimensional pressure coefficients defined from the measured probe port pressures. These two coefficients henceforth will be referred to as the angle coefficients and will be defined explicitly later on.

The present calibration method is valid only for incompressible flows. Extension to compressible flows requires the inclusion of an additional independent pressure coefficient which takes into account compressibility (Mach number) effects (see Everett et al (1983) or Gerner et al (1984)).

5.2.1 Low Angle Regime

The tangential (α - β) system shown in Fig. 5.2.1 (a) is

Fig. 5.2.1 (a) The tangential (α - β) and polar (θ - ϕ) reference systems; (b) probe port nomenclature.

used for low relative flow angles (typically less than 25°). Using the port nomenclature defined in Fig. 5.2.1 (b), a set of pressure coefficients are defined as follows,

$$C_{\alpha_1} = \frac{P_4 - P_1}{P_7 - P_{1-6}} ; \quad C_{\alpha_2} = \frac{P_3 - P_6}{P_7 - P_{1-6}} ; \quad C_{\alpha_3} = \frac{P_2 - P_5}{P_7 - P_{1-6}} \quad (5.2.2)$$

where the numerator measures changes in flow angularity based on the differences between opposite port pressures, and the denominator non-dimensionalizes the term with the what may be termed the probe "dynamic pressure". The probe "dynamic pressure" is obtained from the difference between the central port pressure, P_7 , which approximates the total pressure, and the average of the six surrounding pressures, P_{1-6} , which approximates the static pressure.

Of the three coefficients, only two are required (since there are two degrees of freedom) to uniquely define the direction of the oncoming velocity flow vector. The following angle coefficients are therefore defined,

$$C_\alpha = (2C_{\alpha_1} + C_{\alpha_2} - C_{\alpha_3}) / 3 ;$$

$$C_\beta = (C_{\alpha_2} + C_{\alpha_3}) / \sqrt{3} \quad (5.2.3)$$

which are obtained by equally weighing the contribution of each coefficient of Eqs. (5.2.2) along the two tangential coordinate axes.

5.2.2 High Angle Regime

Figure 5.2.1 (a) also shows the polar (θ - ϕ) system used for high relative flow angle measurements. Angle coefficients are defined for each of the six circumferential sectors shown in Fig. 5.2.2, as follows,

$$C_{\theta_n} = \frac{P_n - P_7}{P_n - (P_{n-} + P_{n+}) / 2} ; \quad C_{\phi_n} = \frac{P_{n-} - P_7}{P_n - (P_{n-} + P_{n+}) / 2} \quad (5.2.4)$$

where these are sensitive to pitch and roll angles, respectively, and where n , $n+$ and $n-$ are the probe pressure port number, and the adjacent ports clockwise and counterclockwise to n , respectively. Each set of coefficients applies to a nominal 60° sector centred on one of the six peripheral pressure ports.

5.2.3 Flow Properties

Figure 5.2.2 shows the division of angular space for each of the seven sectors. The port with the highest pressure indicates the general direction of the approaching velocity flow vector. A given data point is therefore allocated to the sector with the highest port pressure. The appropriate set of coefficients is then applied to evaluate the flow properties.

Fig. 5.2.2 Division of angular space (Germer et al, 1984).

Local flow angles are determined explicitly from their respective polynomial functions which have the functional form of Eq. (5.2.1). For low angles, these are represented by the angle of attack, α , and sideslip angle, β . For high angles, the pitch angle, θ , and the roll angle, ϕ , are used instead. The local total and dynamic pressures are obtained from the non-dimensional total and dynamic pressure coefficients which are also determined from polynomial functions. These two coefficients correct, respectively, for the differences between the probe "total pressure" and the actual total pressure, and for the probe "dynamic pressure" and the actual dynamic pressure. For low angles, these coefficients are defined as follows,

$$C_o = \frac{P_7 - P_{oL}}{P_7 - P_{1-6}} ; \quad C_q = \frac{P_7 - P_{1-6}}{P_{oL} - P_{\infty L}} \quad (5.2.5)$$

For high angles, these coefficients are defined by the following general equations,

$$C_{o_n} = \frac{P_n - P_{oL}}{P_{n-} - (P_{n-} + P_{n+}) / 2} ;$$

$$C_{q_n} = \frac{P_n - (P_{n-} + P_{n+}) / 2}{P_{oL} - P_{\infty L}} \quad (5.2.6)$$

The local total and dynamic pressures, P_{oL} and $P_{\infty L}$, respectively, can then be calculated for the low and high angle regimes from Eqs. (5.2.5) and (5.2.6), respectively.

5.2.4 Calibration Constants

During the calibration process, probe pressure data are collected for a range of relative flow angles, and will be specified in section 5.3.4. Once all the measured data points are allocated to their respective sectors, and the corresponding angle coefficients formed, the flow properties (viz. α and β (or θ and ϕ), C_α , C_β) are curve-fitted to fourth-order polynomial expansions in two variables. This is done using the FIT.FOR FORTRAN computer program listed in Appendix A and written by Sjolander (1986). The program fits the polynomials to the calibration data using the method of least squares. For the inner (low angle) sector the general expression for one of the four properties, denoted by A_i , would be,

$$\begin{aligned}
 A_i = & (K_1 + K_2 C_\alpha + K_3 C_\beta + K_4 C_\alpha^2 + K_5 C_\alpha C_\beta \\
 & + K_6 C_\beta^2 + K_7 C_\alpha^3 + K_8 C_\alpha^2 C_\beta + K_9 C_\alpha C_\beta^2 + \\
 & + K_{10} C_\beta^3 + K_{11} C_\alpha^4 + K_{12} C_\alpha^3 C_\beta + K_{13} C_\alpha^2 C_\beta^2 \\
 & + K_{14} C_\alpha C_\beta^3 + K_{15} C_\beta^4)_i
 \end{aligned} \tag{5.2.7}$$

where the subscripted K corresponds to one of the 15 calibration constants for the i-th flow property. For the outer (high angle) sectors, C_α and C_β in Eq. (5.2.7) would be replaced by C_θ and C_ϕ , respectively.

It should be noted that Everett et al (1982) used a third order polynomial expansion to determine the flow properties of compressible flows. The choice of using a fourth order polynomial for the present calibration was a direct result of having compared the results of curve fitting the calibration data to both a third and a fourth order polynomial. In addition, both polynomials were checked for oscillations between data points. The fourth order was observed to give a more accurate curve fit.

5.2.5 Seven-Hole Probe Software

A general-purpose data reduction subprogram was developed for the seven-hole probe. The complete Turbo Pascal listings and documentations for the FLOWPROP.PGM main program and the FLOWPROP.PSL subprogram used to compute the desired flow properties, given only the dimensionless probe port pressures, are contained in Appendix B. The subprogram is based on the calibration theory outlined above. It accepts the seven measured port pressures in the form,

$$C_{p_n} = \frac{P_n - P_{ref}}{q_{ref}}, \quad n = 1 \text{ to } 7 \quad (5.2.8)$$

where P_{ref} is the reference static pressure and q_{ref} is the reference pressure difference (such as the wind tunnel contraction pressure difference) used in the particular

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experiment. The program identifies the sector to which the data belongs and then uses the calibration constants discussed in the previous section to extract all the flow parameters, in the form:

$$\alpha, \beta, C_{Po}, C_{Pq}, u/V, v/V, w/V$$

where the last three terms are the non-dimensional velocity components along the probe axes (refer to Fig. 5.2.1 (a)). C_{Po} and C_{Pq} are non-dimensional forms of the local total and dynamic pressures, which are defined by Eqns. (5.2.9),

$$C_{Po} = \frac{P_{oL} - P_{ref}}{q_{ref}}; \quad C_{Pq} = \frac{q_L}{q_{ref}} \quad (5.2.9)$$

where P_{ref} and q_{ref} were defined previously, and P_{oL} and q_L are the local total and dynamic pressures, respectively.

The subprogram could be modified for use with future calibrations (or other seven-hole probes) by simply replacing the present calibration constants, which are contained in a Pascal constant declaration statement, with the new ones. Appendix F contains a table of port pressures, in coefficient form, which can be used as a reference in order to check whether the probe has to be recalibrated. For example, the probe might be placed in a known flow, the port pressures measured and compared to the corresponding C_p values of

Appendix F. Note that trigonometric relationships of the probe are contained in Appendix D, while the program (COEFF-7HP) used to calculate the calibration coefficients (i.e. C_{ang1} , C_{ang2} , C_o , C_q) as input to the FIT.FOR program is included in Appendix A.

5.3 Apparatus and Procedure

5.3.1 Probe Geometry

As mentioned in the introduction, the seven-hole probe was designed by Amrud (1985). It was constructed by packing seven stainless steel tubes inside a larger, 2.4 mm outside diameter, stainless steel tube whose inside diameter was exactly three times the inner tubes outside diameter. Once in place, the tubes were soldered together and the tip machined to form a cone with a 30 degree half-angle.

5.3.2 Calibration Apparatus

The apparatus used for the seven-hole probe calibration consisted of a blower connected to a settling chamber which had a 38 mm inside diameter nozzle fixed at one end. The jet flow that was produced was controlled by varying the voltage on the blower through the use of a variac. A two degree of freedom dial mechanism, shown in Plate 5.3.1, allowed for the

Plate 5.3.1 The calibration apparatus.

setting of the tangential system relative flow angle ($\alpha-\beta$) orientation, to an accuracy of 0.1° .

In order to minimize flow disturbances arising from the probe's stem, a 2-D potential flow analysis was performed in order to determine the upstream distance of the probe tip from the stem. It was found that at a pitch angle of 50° , and at a radial distance of five stem diameters from the centre of the stem diameter, a flow deviation of 0.6° (i.e. actual pitch angle is 50.6°) or an error of roughly 1% of the assumed flow direction results.

5.3.3 Instrumentation

Pressures were measured using Rosemount model 831A capacitive-type differential pressure transducers. One was used with a forty-eight port Scanivalve to measure the seven port pressures and the plenum pressure, which was approximately the total pressure. The other transducer was used to continuously monitor the operating flow rate as indicated by the pressure difference between the plenum and atmosphere pressure, which was approximately the dynamic pressure. The reference pressures for the two transducers were the plenum and atmospheric pressures, respectively.

A Taurus KS100 multi-function data acquisition and

control system connected to an Eagle PC computer, was used to record the transducer output signals. In addition, the signals were monitored visually using digital voltmeters (DVMs).

5.3.4 Test Conditions and Technique

The calibration was performed at a freestream velocity of about 26 m/sec. The corresponding Reynolds number was about 1.6×10^6 /m. Limited data for twice and half the flow rate were collected to verify that Reynolds number effects are of no significance as indicated by Everett et al, 1983.

The sampling times needed to obtain reliable mean values of the pressure signals were determined experimentally. For a waiting period of 15 sec, between the stepping of the Scanivalve and the collection of data, a 15 sec sampling period was found to yield mean values which were inside the error band of the very long time averages.

The data acquisition technique was the same as that described in Section 4.2.2 and therefore will not be repeated here. Each sampling produced approximately 210 samples (14 samples per second) each for the port and flow pressures. The C_p value for the particular port was then computed by averaging the sample C_p 's as indicated in Eq. (4.2.1). As

mentioned in Chapter 4, this method of data acquisition accounts for any small changes in the flow, therefore, the drift in the flow operating point is of little significance.

For the low angle regime, α and β were each varied from 0 to 25°, in 5° increments. For the high angle regime, θ and ϕ were both varied in 5° increments from 20 to 50°, and from 0 to 355°, respectively. This ensured about a 5° overlap in pitch angle between the low and high angle regime boundaries. With six circumferential sectors, each sector should span 60°. However, the calibration coefficients were fitted to data from within 35° of the nominal centre of a given sector.

Throughout the calibration, the probe was reset periodically to $\alpha = 25^\circ$, and $\beta = 25^\circ$ and the readings checked for consistency. This was done randomly before, during or after data acquisition of actual calibration data to ensure that no instrumentation (such as probe contamination) and/or data acquisition system errors arose. From these readings it was observed that the maximum variation in C_p for any particular port was ± 0.02 (the average being ± 0.01). From a plot of C_p versus α (with $\beta = 0$) for sector 1 and 4, the magnitudes of the slopes were both 0.026 which translated to a $\pm 0.8^\circ$ variation in α for a C_p variation of ± 0.02 .

5.4 Calibration Results and Discussion

5.4.1 Inner and Outer Sector Coefficients

All the angle coefficients, for each sector, were plotted against the angles which were expected to have the strongest influence on them. This was done to examine their relationships, and to check the scatter in the data. Figure 5.4.1 (a) shows the variation of the angle of attack coefficient, C_α , with the angle of attack, α , for sector 7. It is seen that the curves are well behaved (there are no abrupt changes in the slopes), and nearly linear, especially towards the inner part of the sector. This is true throughout the range of α , and for all sideslip angles, β . Some spreading out of the curves is observed near the overlapping regions with the outer sectors. Similar results were obtained for C_β when plotted against β for different values of α , as shown in Fig. 5.4.1 (b).

Figures 5.4.2 (a) to 5.4.2 (c) show typical outer sector variations of the roll angle coefficient, C_ϕ , with roll angle, ϕ , for different pitch angles, θ . The curves are well behaved with increased curvatures at the outer edges, where overlapping of adjacent sectors occurs. C_ϕ is also quite sensitive to θ as evidenced by the spreading out of the curves. The occurrence of this spreading out effect depends

Fig. 5.4.1 (a) Variation of angle of attack coefficient with angle of attack

Fig. 5.4.1 (b) Variation of sideslip angle coefficient with sideslip angle.

Fig. 5.4.2 Variations of roll angle coefficient with roll angle for (a) sector 1; (b) sector 3.

Fig. 5.4.2 (c) Variation of roll angle coefficient with roll angle for sector 5.

on the particular sector, indicating that the probe is not completely symmetrical. Subsequently, it was observed that sectors 1 and 4, 2 and 5, and 3 and 6, respectively, behaved in a similar fashion.

Figures 5.4.3 (a) to 5.4.3 (c) show typical outer sector variations of C_θ with θ for different ϕ . Again the curves are seen to be quite sensitive to changes in ϕ in addition to changes in θ .

5.4.2 Statistical Analysis

As mentioned earlier, the calibration constants for the polynomial expansions were computed using the FIT.FOR FORTRAN computer program. In addition, this program computed the differences between the measured calibration data and the curve-fitted predicted values. A statistical analysis based on these differences was carried out in order to assess the accuracy of the curve fit. Table 5.1 shows the unbiased standard deviations for the differences between the measured calibration data and the curve-fitted predicted values. Assuming a normal (Gaussian) error distribution, the flow angles are predicted to within 1.1° of the measured values with 95% (within 2σ) confidence, for the outer sectors. For the inner sector this reduces to 0.4° . From the definition

Fig. 5.4.3 Variations of pitch angle coefficient with pitch angle for (a) sector 2; (b) sector 4.

Fig. 5.4.3 (c) Variation of pitch angle coefficient with pitch angle for sector 6.

Table 5.1. Standard deviations between measured and predicted values.

Sector	σ_a, σ_θ	$\sigma_\beta, \sigma_\phi$	σ_{C_0}	σ_{C_q}
1	0.4932	0.5178	0.0136	0.0220
2	0.4320	0.7250	0.0078	0.0218
3	0.3515	0.5195	0.0074	0.0195
4	0.4486	0.4544	0.0133	0.0189
5	0.3224	0.5236	0.0084	0.0160
6	0.4041	0.5843	0.0107	0.0161
Avg 1-6	0.4086	0.5541	0.0102	0.0190
7	0.2096	0.2089	0.0098	0.0045

of C_o , the difference between the total pressure approximated by the probe and the actual total pressure is predicted to within approximately 2% (with 95% confidence) of the probe "dynamic pressure" (defined in Section 5.2.1) for all sectors. Furthermore, from the definition of C_q , the probe "dynamic pressure" is predicted to within 2% and 1% (95% confidence) of the local dynamic, respectively, for the outer and inner sectors. Therefore, the difference between the total pressure approximated by the probe and the actual total pressure is predicted to within approximately 4% and 2% (with 95% confidence) of the local dynamic pressure, respectively, for the outer and inner sectors.

Two methods of removing dubious data points were considered. Firstly, the original data was plotted and the bad data points identified by inspection. These were then removed from the data set. Secondly, data points were removed by applying Chauvenet's criterion for data rejection on the original data set. This method was also used by Everett et al (1983) and specifies that for N samples of a given measurement, an experimental reading may be rejected if the probability of obtaining a particular deviation from the mean is less than $1/2N$ (see Holman, 1984). The criterion is usually applied in terms of a ratio of maximum acceptable deviation to standard deviation for a particular number of readings. Since Chauvenet's criterion is a more systematic

method of data smoothing and since the standard deviations between the measured and curve-fitted predicted values were found to be slightly less, it was decided to use it over simple hand-smoothing for the final results.

Listings together with documentations of computer programs, written in Turbo Pascal, used for the statistical analysis, and for identifying points that should be rejected using Chauvenet's criterion are contained in Appendix C.

5.4.3 Reynolds Number Effects

In order to investigate Reynolds number effects, selected data at twice and at half the nominal operating flow rate were collected. Data were collected within an outer sector (4) at a constant roll angle of 0° , and at a nominal outer sector boundary (between sectors 4 and 3) at a constant roll angle of 30° . The data indicated no changes to the port pressure coefficients for the low angle regime. However, the leeward port pressure coefficients, were nominally lower and higher for the lower and higher flow rates, respectively. Thus, there are apparently some Reynolds number effects but they appear to be confined to the leeward side pressures which were, as mentioned earlier, not used in the calibration coefficients.

5.4.4 Accuracy

An estimate of the overall accuracy of the calibration will now be attempted. The main sources of error were identified as:

- (1) Angle setting dial mechanism.
- (2) Uncertainty in flow direction.
- (3) Uncertainty in pressure measurements.
- (4) Accuracy of curve-fit.

The accuracy of (1) was mentioned previously to be 0.1° . From the potential flow analysis, the uncertainty in (2) was found to be about 0.6° at the maximum pitch angle setting. From the repeatability tests, the maximum scatter in the pressures was mentioned to be equivalent to an angle setting error of about 0.8° . From the statistical analysis, the curve-fit was estimated to give flow angles to within 1.1° for the outer sectors, and to within 0.4° for the inner sector, with 95% confidence. These various uncertainties cannot be combined in any simple way to obtain an overall uncertainty. However, in the light of the observed magnitudes, it would seem fairly reasonable to expect measured flow angles to be within about 2° of the true values.

5.5 Tip Leakage Investigation

The use of the seven-hole probe was demonstrated in a planar cascade of turbine blades which is used to investigate tip leakage in turbomachines. The intention was to show that the probe and data reduction software produce plausible values of the flow properties in a complex, unknown flow. Therefore the flow quantities were measured on a coarse grid of points in the trailing edge plane of the cascade over the outer 35% of the blade span and 55% of the passage width as shown in Fig. 5.5.1. A constant step-size of 10mm was used in both directions which corresponded to an 8 x 9 grid of measurement points.

In addition to demonstrating the use of the probe, the measurements were also intended as a preliminary study in preparation for a more detailed investigation of the outlet plane flow. Since this will be one of the areas in which this probe will find considerable use, a knowledge of the vortex spatial dimensions as well as the step-size necessary for adequate flow field resolution is needed for future investigations.

5.5.1 Test Conditions

A tip clearance of 2.85% of blade chord and an operating

Fig. 5.5.1 Measurement grid location at trailing edge plane.

Reynolds number of $4.3 \times 10^5 \pm 2\%$ were used for this experiment. The probe was rotated 50 degrees from the axial direction to align it roughly with the average outlet flow direction. All data were collected using the Hewlett-Packard model 3054A Automatic Data Acquisition and Control System and the technique outlined in Section 5.3.4.

5.5.2 Discussion of Results

Figure 5.5.2 shows a plot of the pitchwise flow angle relative to the probe axis (referred to as overturning angle) versus the distance from the end wall (non-dimensionalized on the passage height, i.e. blade span plus clearance gap) for several pitchwise locations. Figure 5.5.3 shows a velocity vector plot at the passage exit plane. This plot was obtained by transforming the dimensionless components of the relative velocities (relative to the probe axes) into absolute components (relative to the test section axes), and then by vectorially summing the two trailing edge plane components. The relationships between test section and probe axes are contained in Appendix D. Figures 5.5.4 and 5.5.5 show contour plots of the total and static pressure coefficients, respectively, with the measurement grid points indicated with small circles. Computer programs used for reducing output data from FLOWPROP.PGM are contained in Appendix E.

Fig. 5.5.2 Overturning angle at T.E. plane ($Re = 4.3 \times 10^5$, $\tau/c = 2.85\%$).

Fig. 5.5.3 Velocity vectors at T.E. plane ($Re = 4.3 \times 10^5$, $\tau/c = 2.85\%$).

Fig. 5.5.4 Total Cp distribution at T.E. plane ($Re = 4.3 \times 10^5$, $\tau/c = 2.85\%$).

Fig. 5.5.5 Static C_p distribution at T.E. plane ($Re = 4.3 \times 10^5$, $\tau/c = 2.85\%$).

Figure 5.5.2 includes the spanwise traverse, at 27% of the blade spacing, at which the largest variation in flow angle was measured. As seen from the figure, the flow angle varied from 20° of overturning to nearly 50° of underturning (incidentally, the other flow angle varied from 20° , in the spanwise direction towards the tip wall, to 40° in the opposite direction). This clearly shows that this flow would be difficult to measure using conventional four or five-hole pressure probes in the non-nulling mode. Even with the seven-hole probe, care will have to be used to remain within the 50° of misalignment for which it was calibrated. The measurements indicate that the core of the main tip leakage vortex lies at about 27% of the blade spacing. At 53% spacing there are still some signs of cross-flow but it appears that we are close to the edge of the vortex. The measurements are thus consistent with Amrud's (1985) smoke flow visualization observations that for this clearance, the tip leakage flow extends to half the passage width at the trailing edge plane.

The location and extent of the tip leakage vortex is also clear from the velocity vector plot, Fig. 5.5.3, and the total and static pressure contours, Figs. 5.5.4 and 5.5.5, respectively. Figures 5.5.4 and 5.5.5, at first glance seem to indicate two inner cores within a larger one. This is certainly not evident in the vector plot. From the contour

plots and the superimposed grid points, it is evident that the measurement grid is too coarse to allow detailed features, such as the existence of multiple vortices, to be resolved.

From the data, the static C_p varied from -2.7, in the inner core, to -1.6. At the tip wall, it is observed that the static C_p varies from about -1.5 to a minimum value of about -2 beneath the vortex core (see Fig. 5.5.5). These wall static values cannot be considered very reliable since the probe was nearly touching the wall and there must therefore have been considerable interference.

End wall static pressure measurements made by Yaras (1987) gave a pressure coefficient of about -1.6 in the trailing edge plane with the minimum of about -1.8 also being observed at about 25% of the spacing. The static pressures extracted from the probe measurements thus appear quite reasonable.

Langston et al (1977) studied the three-dimensional flow inside a large scale planar turbine cascade. They measured the minimum total C_p of the secondary vortex to be about -1.0. From Figure 5.5.4, the minimum total C_p is about -2.8, which is almost three times their value. It should be noted that Langston et al used an aspect ratio of about 1.0 rather

than 0.8, in addition, their cascade had more turning (about 7° more) which would tend to increase secondary losses. Thus even these preliminary measurements have illustrated that the tip leakage flow is a very significant source of losses.

5.5.3 Summary

The very limited measurements made with the seven-hole probe have shown that it produces very plausible and reasonable data in the sort of highly complex, three-dimensional flow for which it was intended. With regard to this particular flow it is evident that a finer grid of measurement points is needed to resolve the detailed structure of the tip leakage flow. For future measurements a step-size of 2 or 3 mm is suggested.

6.0 CONCLUSIONS AND RECOMMENDATIONS

In keeping with the basic organization of this thesis, the main conclusions and recommendations for future work will be presented separately for each part of the thesis.

6.1 The Moving Belt Rig

6.1.1 Conclusions

The design and subsequent preliminary tip leakage experiments with tip wall relative motion were presented. Based on observations of the rig in operation and the results of the experiments, the performance of the belt rig was found to be satisfactory for the present speed range. The belt runs at a maximum speed of about 18 m/s with a drum pulley speed of 1760 RPM. This is not as high as we would like since it forces us to work with lower blade chord Reynolds numbers than were used in previous stationary tip leakage studies. However, from our preliminary investigation of Reynolds number effects on blade pressure distribution, we believe that we can achieve sufficiently high Reynolds numbers that behave like those in the higher range. For our particular blade row which has a speed coefficient (U/V_{CL}) of 2.164, we can simulate the velocity triangles for a speed

range of 0% to 140% EES at a Reynolds number of 1.0×10^5 . For a blade row which has a lower speed coefficient, the EES speed range will increase for the same Reynolds number.

The maximum belt speed can easily be increased by changing the drive pulleys. However, from preliminary experience with the belt rig, the drum pulleys will have to be dynamically balanced which is unnecessary at the present speed range. It is worth mentioning that other aspects such as heating and flapping of the belt, as well as static charge build-up on the belt were not found to be a problem for the present speed range either.

The preliminary experiments with the belt rig not only demonstrated the performance of the rig, but also resulted in some rather interesting findings which we believe to be genuine. The results showed an unexpected and rather marked change in the flow behaviour for blade chord Reynolds numbers between 0.62×10^5 and 1.0×10^5 . This was reflected in changes to the pressure distributions and the force coefficients, with increasing wall speed, depending on whether we were operating in the low or high end of the range. We are not aware that this phenomenon has been previously identified.

6.1.2 Recommendations

In view of the results and the fact that we were operating in the range of low pressures, where it is more difficult to get accurate data, this preliminary set of blade loading experiments should be repeated. Furthermore, the effect of tip wall speed on blade loading for different clearances should be thoroughly investigated. However, before this is done, it would be of interest to identify the boundary Reynolds number between low and high Reynolds number behavior, in the range between 0.62×10^5 and 1.0×10^5 , and to identify if the changes in this range occur gradually or abruptly. This would be desirable since it is advantageous to use the lowest Reynolds number, which behaves like a high one, in order to obtain a wider EES speed range.

In order to better simulate a coplanar inlet boundary layer in an actual machine, the measurements suggest that the axial boundary layer thickness should be reduced, but not as much as is implied by the correlation of Fig. 3.1.5.

Detailed measurements in the gap with wall motion should allow for a check on the validity of the tip gap mass flow rate expression of Chapter 2 (viz. Eq.(2.2.7)), or a correction factor to be found along the lines of Eq. (2.2.10). In addition, further physical insight into the interaction

between the leakage, secondary and scraping flows may explain some of the seemingly peculiar blade loading results.

6.2 The Seven-Hole Probe

6.2.1 Conclusions

The calibration procedure and use of a seven-hole probe were presented. Local flow properties such as relative flow angles, velocities, total and static pressures were easily extracted using a fourth-order polynomial expansion of a set of defined pressure coefficients based on maximum port pressures.

The very limited measurements made with the seven-hole probe have shown that it produces very plausible and reasonable data in the sort of highly complex, three-dimensional flow for which it was intended. The preliminary measurements made at the outlet of the cascade showed that the flow angle varies by at least 70° through the tip leakage vortex.

6.2.2 Recommendations

For the detailed flow field measurements at the outlet plane of the cascade, it is recommended that a finer grid of measurement points be used in order to resolve the detailed

structure of the tip leakage flow. In addition, since the flow angles are larger than anticipated, care will have to be used when aligning the probe in order to remain within the 50 degrees of misalignment for which it was calibrated. For future calibrations of the probe a wider range of misalignment in pitch and yaw should be considered.

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APPENDIX A

This appendix contains listings of the FIT.FOR, and COEFF7HP.PAS computer programs. FIT.FOR was used to curve-fit the calibration coefficients to fourth-order polynomials. COEFF7HP.PAS was used to calculate the calibration coefficients, which are used as input to FIT.FOR, from the measured probe port pressures.


```
22      INTCH=INTCH+1  
        CONTINUE  
        III=(INTCH/2)+2  
        IF (III.NE.INTCH) DETER=-DETER  
C  
C      RETURN WITH RESULTS  
C  
      SIMUL=DETER  
      CONTINUE  
      RETURN  
      END
```



```

CLOSE(OUTFILE3)
CLOSE(OUTFILE4)
CLOSE(OUTFILE5)
CLOSE(OUTFILE6)
GOTO 2)
( Calculate Sector 7 Coefficients for Low Angle Region )
1) WRITE( ENTER FILE NAME FOR SECTOR7 COEFFICIENTS )
READLN(FILE7)
ASSIGN(OUTFILE7,FILE7)
REWRITE(OUTFILE7)
WRITELN(OUTFILE7, SECTOR 7 ANG1 ANG2 X1 X2 CQ
CQ )
WRITELN(OUTFILE7)
FOR I = 1 TO N DO
BEGIN
HIGHSECTORCOEFF( Procedure )
WRITELN(OUTFILE7,ANG1(1),ANG2(1),X1,
X2(1),CQ(1),X2(1),CQ(1),X1,X2
END)
CLOSE(OUTFILE7)
2) END. ( COEFF7HP )

```

```

ISECT := 1)
HIGHSECTORCOEFF( Procedure )
WRITELN(OUTFILE1,ANG1(1),X1,ANG2(1),X2,
X1(1),X2(1),CQ(1),X1,X2,CQ(1),X1,X2)
END
( Sector 2 )
FOR I = 1 TO N DO
BEGIN
IF ( ANG2(1) >= 85 ) AND ( ANG2(1) <= 135 ) THEN
BEGIN
ISECT := 2)
HIGHSECTORCOEFF( Procedure )
WRITELN(OUTFILE2,ANG1(1),X1,ANG2(1),X2,
X1(1),X2(1),CQ(1),X1,X2,CQ(1),X1,X2)
END
END)
( Sector 3 )
FOR I = 1 TO N DO
BEGIN
IF ( ANG2(1) >= 25 ) AND ( ANG2(1) <= 95 ) THEN
BEGIN
ISECT := 3)
HIGHSECTORCOEFF( Procedure )
WRITELN(OUTFILE3,ANG1(1),X1,ANG2(1),X2,
X1(1),X2(1),CQ(1),X1,X2,CQ(1),X1,X2)
END
END)
( Sector 4 )
FOR I = 1 TO N DO
BEGIN
IF ( ANG2(1) >= 325 ) OR ( ANG2(1) <= 35 ) THEN
BEGIN
ISECT := 4)
HIGHSECTORCOEFF( Procedure )
WRITELN(OUTFILE4,ANG1(1),X1,ANG2(1),X2,
X1(1),X2(1),CQ(1),X1,X2,CQ(1),X1,X2)
END
END)
( Convert High Angles in Sector 4 to Equivalent Negative Values )
IF ( ANG2(1) > 180 ) THEN
ANG2(1) := ANG2(1) - 360
WRITELN(OUTFILE4,ANG1(1),X1,ANG2(1),X2,
X1(1),X2(1),CQ(1),X1,X2,CQ(1),X1,X2)
END
END)
( Sector 5 )
FOR I = 1 TO N DO
BEGIN
IF ( ANG2(1) >= 265 ) AND ( ANG2(1) <= 335 ) THEN
BEGIN
ISECT := 5)
HIGHSECTORCOEFF( Procedure )
WRITELN(OUTFILE5,ANG1(1),X1,ANG2(1),X2,
X1(1),X2(1),CQ(1),X1,X2,CQ(1),X1,X2)
END
END)
( Sector 6 )
FOR I = 1 TO N DO
BEGIN
IF ( ANG2(1) >= 205 ) AND ( ANG2(1) <= 275 ) THEN
BEGIN
ISECT := 6)
HIGHSECTORCOEFF( Procedure )
WRITELN(OUTFILE6,ANG1(1),X1,ANG2(1),X2,
X1(1),X2(1),CQ(1),X1,X2,CQ(1),X1,X2)
END
END)
CLOSE(OUTFILE1)
CLOSE(OUTFILE2)

```

APPENDIX B

This appendix contains the documentation and listing of the software (FLOWPROP.PGM and FLOWPROP.PSL) used to data reduce the seven-hole probe measured data.

$C_{dyn} = q / gref$

- Flow velocity components along the 3 tangential probe axes non-dimensionalized on the resultant velocity.

$U = u/v_i$ $V = v/v_i$ $W = w/v_i$

- Flagged sets of data that are found to lie outside the 7-hole probe calibration region.

VARIABLES

C_p 1-D array storing the probe $C_p = (P - P_{ref}) / gref$

I, J Looping indices

M Number of data lines (7 port pressures on each line)

$Flag$ Used to flag points outside calibration range

A 1-D array storing the flow properties α ALPHA, β BETA, C_0 , C_0 , array index values of 1, 2, 3, 4, respectively

U, V, W Non-dimensional velocity components with respect to probe axes

C_{total} Non-dimensional total pressure, $C_{total} = (P - P_{ref}) / gref$

C_{dyn} Non-dimensional dynamic pressure, $C_{dyn} = q / gref$

$High$ Used to store "Maximum" C_p value when FlowProp.PS is called the first time. A value of 0 after the second time that that procedure is called, indicates that no other high reading port was found for the particular measurement

$Files, Files2$ Strings used for input and output file names

$InFile, OutFile$ Test files used for input and output

MODIFICATIONS

If different formats are used for the input files, the input sections (including any dummy variables) must be modified accordingly.

When changing any part of the code, particular attention should be paid to the variables "High" and "Flag"

PROGRAM LISTING

program FlowProp

! Main program

label

!!

True

RealArray1 = array(1 : 7) of Real,

RealArray2 = array(1 : 4) of Real,

```

=====
PROGRAM FLOWPROP.PS
=====
Written by George Denies
for the 7-hole Probe
CARLETON UNIVERSITY
Ottawa, Feb. 1987
=====

```

```

=====
PROGRAM FLOWPROP.PS
=====
PURPOSE: To calculate the flow properties using the 7-hole Probe
pressure data

NOTE: This program is written specifically for use with the 7-HOLE PRES-
SURE PROBE. It uses calibration constants, obtained by curve-fitting,
the calibration data to 4th-order polynomials using least squares, as
the constants of a 4th-order polynomial expansion of the pressure coef-
ficients, derived from measured experimental data, to represent the flow
properties.
=====

```

USAGE

This program utilizes the included subprogram FlowProp.PS, in order to calculate the flow properties in the leakage experiments at Carleton U. by using the non-dimensionalized port pressures of the 7-hole Probe.

EXPECTED INPUT: Filename of input data file containing the non-dimensional pressure readings, i.e. $C_{p1} = (P_1 - P_{ref}) / gref$. MAKE SURE THAT THE FIRST LINE OF THIS FILE CONTAINS THE NUMBER (N) OF LINES OF DATA CONTAINED IN THE FILE. Each subsequent line must contain the 7 port C_p values.

SUBPROGRAM CALLED: FlowProp.PS Include file FlowProp.PS

Calling Sequence: FlowPropFlag, C_p , A , J , M , C_{total} , C_{dyn} , $High$

RESULTANT OUTPUT C_{total} and C_{dyn} , ALPHA, BETA, flow angles, total and dynamic pressure, non-dimensional forces,

$C_{total} = P_0 - P_{ref} / gref$

U = U/V1 V = V/V1 W = W/V1
 - Flagged sets of data that are found to lie outside the 7-Hole Probe Calibration region.

Subprograms Called: (Note: No variables are passed to these either by value or by reference, and all subprograms make use of local as well as global variables)

Procedure: Properties

- performs most of the flow property calculations
- calls:

Procedure: CheckRanges

- Flags data set which lies outside calibration region

Procedure: VelocityComponents

- Computes the velocity components with respect to the probe axis

Input

Co 1-D array Contains the 7 port Cp values, where $Cp_i = (P_i - P_{ref}) / \rho V^2$, $i = \text{Port } i$

The following global type declarations must be specified in the calling program:

```
type
  RealArray = array(1..7);
  RealArray2 = array(1..4);
```

Output

A 1-D array

Stores the following 4 flow properties: Alpha, Beta, Co, Cd, which correspond to array subscripts 1, 2, 3, 4, respectively

Cototal real

Total pressure in the non-dimensional form, $Cototal = (P_{total} - P_{ref}) / \rho V^2$

Codyn real

Dynamic pressure in the non-dimensional form, $Codyn = (P_{dyn} - P_{ref}) / \rho V^2$

U, V, W real

Flow velocity components along the 3 tangential probe axes non-dimensionalized on the resultant velocity,

Flag integer

Flags sets of data that are found to lie outside the 7-Hole Probe Calibration region

Max real

Stores maximum C value of particular set of data

FLOWPROB.F90

Written by George Danias

for the 7-Hole Probe

CARLETON UNIVERSITY

Ottawa, Feb. 1997

Name: Flowprob

Type: Procedure

Purpose: To calculate the flow properties of an unknown flow given the port pressures of the 7-Hole pressure probe

Calling Sequence: Flowprob(Flag, Co, A, U, V, W, Cototal, Codyn, High)

NOTE:

This procedure is written specifically for use with the 7-HOLE PROBE. It uses calibration constants, obtained by curve-fitting the calibration data to algebraic polynomials using least squares, as the contents of a four-order polynomial expansion of the pressure coefficients, derived from measured experimental data, to represent the flow properties.

Description

You only need to provide the 1-D array which stores the 7 non-dimensional probe port pressures or Cp values. Flowprob.F90 then does just what its name says, it computes the FLOW PROPERTIES for the particular data set. Specifically, it returns the following values to the calling program:

- Pitch and yaw (Alpha, Beta) flow angles;
- Total and dynamic pressures in non-dimensional form.

Cototal = (P0 - Pref) / rho * V^2

Codyn = (P2 - Pref) / rho * V^2

- Flow velocity components along the 3 tangential probe axes non-dimensionalized on the resultant velocity.


```

Theta := A[1]
end
else if (Cos(Radians(A[1])) = 0) or (Cos(Radians(A[2])) = 0) then
  writeln( 'ERROR: LOW ANGLE NEBINE ANGLE = 90 DEGREES; Press - C ')
else Phi := Degrees(ArcTan(Tan(Radians(A[2])) / Tan(Radians(A[1]))))
  if Cos(Radians(Phi)) < 0 then
    Theta := Degrees(ArcTan(Tan(Radians(A[2])) / Sin(Radians(Phi))))
  else
    Theta := Degrees(ArcTan(Tan(Radians(A[2])) / Cos(Radians(Phi))))
  end
VelocityComponents ( Procedure )
1: end; ( Properties )

begin ( FlowProp )
  ( Calculate pressure coefficients )
  ( First locate the sector reading highest pressure, then compute )
  ( the probe pressure coefficients by sector considering both Low and )
  ( High Flow Angle Angles. )
  ( For Low Angles (Sector 7) : Alpha, Beta, Co, Cp = (Calpha, Cbeta) )
  ( For High Angles (Sectors 1-6) : Theta, Phi, Co, Cp = (Ctheta, Cphi) )

  if High < 0 then goto 1;
  Isect := 1;
  High := Cp[1];
  for J := 1 to 6 do
    begin
      if Cp[J] > High then
        begin
          High := Cp[J];
          Isect := J;
        end
      end;
    end;
  end;
  Properties ( Procedure )
  if Flag = 1 then goto 3 ( Abort calculations )
  else goto 2; ( Return to Main )

  ( Check if another port reads high at same angle setting )

  1: HighLow := 0; ( Initialize HighLow )
  for J := 1 to 7 do
    begin
      if Abs(Cp[J] - High) < Tolerance and (Cp[J] < High) then
        begin
          if Abs(Cp[J]) > HighLow then
            begin
              HighLow := Cp[J];
              Isect := J;
            end
          end;
        end;
      end;
    end;
  end;
  if HighLow = 0 then ( No other port reads high )
  begin
    High := 0;
    goto 3;
  end
  else Properties ( Procedure )

  Convert Polar System angles to Tangential System angles for sectors 1-6
  2: if Isect < 4 then
    begin
      Alpha := Degrees(ArcTan(Radians(A[1])) / Cos(Radians(A[2])));
      Beta := Degrees(ArcTan(Radians(A[1])) / Sin(Radians(A[2])));
      A[1] := Alpha;
      A[2] := Beta;
    end
  end
end

```

APPENDIX C

This appendix contains documentations and listings of computer programs used for the seven-hole probe statistical analysis and for rejecting data based on Chauvenet's criterion.

2-D array used to store the random variables, that is, the Co values in Part 1, and to store the difference between measured and predicted values from the curve for Part 2. The first subscript references the particular data set, while the second references the random number, Part 1, and predicted predicted difference, Part 2. 1, 2, 3, and 4 refer to Alpha/Theta, Beta/Phi, Co, Ca, respectively.

1-D array used to pass the λ values for a particular part (Part 1) or property (Part 2)

ENTER 10 ON READER SERVICE

Standard deviation of the mean

The mean value of $\bar{X}$ value

Number of people of next title

Character (Y/N) answer of on-screen prompts

Questions used to read in values contained in input file, which are not used except in Part 1 for printing the repeated angle setting

9427 put but does

sector of probe, used in part 2 of program

strings used for input and output, all names

1 and 2, no one but them will see.

NOI SCUS I OH

The procedure Sista is used to save the necessary statistical calculations. For the calculation of standard deviation estimator the square of the sum of the deviations is expended out which tends to reduce round-off error of the mean value, also $M-1$ is used instead of M if of samples in the standard deviation estimator, which makes the estimator "unbiased" and is, therefore, considered a better estimator than the first (which uses M), that is,

11-11-65 10:00 AM 11-11-65 10:00 AM

1-4 BURN AND DISJUNCTIONS

(NOTE: For a sample size of 20 or more and can be used; Both estimators are considered efficient and consistent.)

DECLASSIFICATION

to support industry, but also to support the
petroleum and diamond industry and
the steel industry.

1571166

924257100

STAT374P.PAS
Written by George Denies
For the 7-Hole Probe Calibration
CARLETON UNIVERSITY
Ottawa, Feb. 1987

PURPOSE: To calculate statistics for the 7-HOLE PHONE CALIBRATION

PAGE

This program calculates the standard deviation uncertainty and the standard error in the SEV-HP-30 model calculations. The first part of the program, the CALCULATIONS are performed for each part at a constant angle setting of 10 mrad , which was continuously monitored throughout the entire data acquisition period for both Low and High Angle Beams. In the second part of the program, the calculation is performed for the entire data set. The calculated and measured values for the 4 independent parameters (ALPHA , BETA , GAMMA , DELTA) are listed. In addition, Part 1 and 2 may be omitted.

The program begins by prompting you for an output file name, then it asks whether you want to do a statistical analysis on the repeated angle setting (see Part 1). If you answer "N", Part 2 is automatically assumed and the output file name is asked for. This file should be the output file name from the FILEX program. If you answer "Y", an input file must contain the 2 repeating programs. If you answer "N", an input file should contain the angle settings and the CD values of the repeated angle setting which was used throughout the calibration process. Then you are asked whether or not you want to continue with Part 2. Finally, the LAST line of both input files MUST have a first value greater than 00 (end of file).

100

The Standard Deviation, Standard Deviation of the Sample Mean or Standard Error, and the Sample Mean are tabulated independently for each of the 1000 replications. The number of samples are 1 and 2, 1 and 3, 1 and 4, 1 and 5, 1 and 6, 1 and 7, 1 and 8, 1 and 9, 1 and 10, 2 and 2, 2 and 3, 2 and 4, 2 and 5, 2 and 6, 2 and 7, 2 and 8, 2 and 9, 2 and 10, 3 and 3, 3 and 4, 3 and 5, 3 and 6, 3 and 7, 3 and 8, 3 and 9, 3 and 10, 4 and 4, 4 and 5, 4 and 6, 4 and 7, 4 and 8, 4 and 9, 4 and 10, 5 and 5, 5 and 6, 5 and 7, 5 and 8, 5 and 9, 5 and 10, 6 and 6, 6 and 7, 6 and 8, 6 and 9, 6 and 10, 7 and 7, 7 and 8, 7 and 9, 7 and 10, 8 and 8, 8 and 9, 8 and 10, 9 and 9, 9 and 10, 10 and 10.

536165


```

writeIn(OutFile,
-----
);
writeIn(OutFile,
D(Prop) Std Dev   D(Prop) Std Error
writeIn(OutFile,
-----
);
for J = 1 to 4 do
begin
  for I = 1 to N do (Convert 2-D array to 1-D array for procedure )
    Value(I) := X(I,J);
  Statist(StandardDeviation,StandardError,Mean,Value);
  writeIn(OutFile,
    'J,      StandardDeviation:1214,
    StandardError:1214,      Mean:1214,
    writeIn(OutFile,
-----
);
end;
writeIn(
writeIn(OutFile,
readIn(Mean);
if (Ans = Y) or (Ans = V) then goto 3;
3: close(OutFile);
END. ( Stats74p )

```

```

=====
STATS.PBL
=====
Written by George Denies
CARLETON UNIVERSITY
Ottawa, Feb. 1987
=====

```

Name: State
Type: Procedure
Purpose: To calculate statistics for a set of random variables
Calling Sequence: Stats(N,StandardDeviation,StandardError,Mean,I)

Description

You provide the data for the 1-D array I. Stats then computes the sample mean, standard deviation, and the standard error (standard deviation of the sample mean).

Input

I 1-D Array Stores the random variables
N Integer Number of samples of input file
The following type declaration must be specified in your calling program.
type
 RealArray = array[1..N] of real;
where N is a positive integer.
Output

```

StandardDeviation  real    Standard deviation of s
StandardError      real    Standard deviation of the sample mean
Mean              real    Sample mean value of s

```

Variables

```

SumOfS            real    Sum of s values
SumOfSQuared      real    Sum of s squared
LoopingIndex      integer Looping index

```

Discussion

For the calculation of standard deviation estimator the square of the sum of the deviations is expanded out which tends to reduce round-off error of the mean value, also, $N-1$ is used instead of N (is of samples) in the standard deviation estimator, which makes the estimator "unbiased" and is, therefore, considered a better estimator than the RMS (which uses N), that is,

$$Expectation[Std Dev using N (RMS)] = (Actual Std Dev) \cdot \sqrt{(N-1) / N}$$

$$Expectation[Std Dev using N-1] = (Actual Std Dev)$$

(NOTE: For a sample size of 20 or more RMS can be used: Both estimators are considered efficient and consistent.)

Subprogram Listing

```

procedure Stats(N: integer;
var StandardDeviation, StandardError, Mean: real;
i: RealArray);
( Calculate the standard deviation, standard error, and mean )
var SumOfS, SumOfSQuared: real;
i: integer;
begin
  SumOfS := 0;
  for i := 1 to N do
    SumOfS := i[i] + SumOfS;
  Mean := SumOfS / N;
  SumOfSQuared := 0;
  for i := 1 to N do
    SumOfSQuared := Sqr(i[i]) + SumOfSQuared;
  StandardDeviation := Sqrt((SumOfSQuared - Sqr(SumOfS) * N) / (N-1));
  StandardError := StandardDeviation / Sqrt(N);
end; ( Errors )

```

TESTDATA.PAS

Written by George Danias
For the 7-hole Probe Calibration
CARLETON UNIVERSITY
Ottawa, Feb 1987

```

(-----)
( PURPOSE: To calculate statistics for the 7-HOLE PROBE CALIBRATION )
(-----)

```

USAGE

This program uses Chauvenet's criterion of data rejection to flag questionable experimental data of the 7-HOLE PROBE calibration. The first part of the program does this for a constant angle setting of (ALPHA,BETA) which was continuously monitored throughout the entire data acquisition process for both Low and High Angle Regions. Each probe part is tested. In the second part, the differences between curve-fitted and measured values for each of the 4 flow properties (ALPHA/THETA, BETA/PHI, Co, Ca) are checked. In addition, one has the option of doing only one or both calculations.

The program begins by prompting you for an output file name, then it asks whether you want to do data testing of the repeated angle setting results (Part 1). If you answer 'N', Part 2 is automatically assumed and an input file name is asked for. This file should be the output file name from the FIT.EXE curve-fitting program. If you answer 'Y', an input file should contain the 2 angle settings and the 7 Co values of the repeated angle setting which was monitored throughout the calibration process. Then you are asked whether or not you want to continue with Part 2. Finally, the LAST line of both input files MUST have a first value greater than 100 (End of File).

OUTPUT

The Rejected points based on Chauvenet's criterion are listed by row and column α , and angle settings. In addition, the dubious value is given. If no points are rejected, a message mentions this.

VARIABLES

2-D array used to store the random variables, that is, the Co values in Part 1, and to store the differences between measured and predicted values from the curve fit for Part 2. The first subscript references the particular data set, while the second references the port number, for Part 1, and the particular property differences between measured and curve-fit predicted values, for Part 2 (1, 2, 3, 4 refer to ALPHA/THETA, BETA/PHI, Co, Co, respectively)

1-D array used to pass the I values for a particular port (Part 1) or property (Part 2)

StandardDeviation
Standard error of I value used in Stats Procedure)

Standard error of I value used in Stats Procedure)

The mean value of I value

N
Number of input lines (samples)

Ans
Character (Y/N) answer of on-screen prompts

Ang1, Ang2
Flow angles ALPHA/THETA, BETA/PHI

I, J
Looping indices

Flag
Flag whose value determines printed output message

Counter
Counter to check if none of data points of a particular sample were rejected

Sector
Sector of probe, used in Part 2 of program

File1, File2
Strings used for input and output file names

InFile, OutFile
Text files used for input and output

DISCUSSION

Merely is it that an experimenter does not find that some of the data points look bad and out of place with the bulk of the data. He must then decide whether these "bad" points represent an experimental error, and therefore may be ignored, or a new physical phenomenon. A consistent basis for elimination is therefore necessary. If N samples of a given measurement is large enough that the results would be expected to follow the Gaussian error distribution, then this distribution may be used to calculate the probability that a given reading will deviate more than 1-N because this would be unlikely to occur in the set of N measurements. Therefore, a point whose deviation probability is less than 1-N would be prime candidate for elimination. A more restrictive test for data rejection is Chauvenet's criterion.

The procedure Reject, which is used, uses Chauvenet's criterion of data rejection and lists the dubious data points. This criterion specifies that an experimental reading may be rejected if the probability of obtaining a deviation from the mean is less than 1-N. See Holman, Experimental Methods for Engineers, 4th ed. 1981.

Since for the "single probe calibration" pressure coefficients are constant and from a combination of several pressures, a bad data point would tend to

influence several, if not all, coefficients, therefore the whole data set for a particular angle setting which contains a "bad" point should be eliminated.

Procedure State is used to calculate the standard deviation and mean which are required by Reject

MODIFICATIONS

If different formats for the input files are used, the input sections of the program should be modified

PROGRAM LISTING

program TestData1

label
0, 1, 2, 3;

type
RealArray = array[1..200] of Real;
RealArray2 = array[1..200,1..7] of Real;

var
Ans: Char;
Ang1, Ang2, xValue: RealArray;
I: RealArray2;
StandardDeviation, StandardError, IMean: Real;
N, J: Integer; Flag, Counter: Integer;
File1, File2: string[20];
InFile, OutFile: text;

(1st Stats.PBL)
(2nd Reject.PBL)

BEGIN (Main)

clear;
write('ENTER OUTPUT FILE NAME FOR LIST OF DUBIOUS EXPERIMENTAL DATA POINTS'

); readln(File2);

assign(OutFile, File2);

rewrite(OutFile);

write(OutFile, 'LIST OF DUBIOUS EXPERIMENTAL DATA POINTS BASED ON

CHAUVENET'S CRITERION FOR DATA REJECTION

); write(OutFile, 'Part 1)

); write(OutFile, 'DO YOU WANT TO TEST THE REPEATED VALUES DONE AT A CONSTANT

ANGLE SETTING, DURING THE CALIBRATION

); write(OutFile, 'Y/N or Ans = 0 then goto 1;

); write(OutFile, 'ENTER THE INPUT FILE NAME FOR THE REPEATED PORT CO VALUES

); readln(InFile);

assign(InFile, File1);

reset(InFile);

```

- Data File Name : ,File1;

writeln(OutFile);
writeln(OutFile);
M := 0;
for J := 1 to 200 do
begin
  readln(InFile, Ang1(1), Ang2(1), x(1,1), x(1,2), x(1,3), x(1,4), x(1,5),
    x(1,6), x(1,7));
  if (Ang1(1) > 100) then goto 1;
  M := M + 1;
end;
1: close(InFile);
for J := 1 to 7 do
begin
  Counter := 0;
  for I := 1 to M do
  value[I] := x(1,J); (Convert 2-D array to 1-D for procedure)
  StatistM, StandardDeviation, StandardError, Mean, Value);
  for I := 1 to M do
  begin
    Rejection, StandardDeviation, Mean, Value, Flag;
    if Flag = 1 then
      begin
        writeln(OutFile, REMOVE POINT AT I = ,I/3, J = ,J/3,
          WHERE x(1,J) = ,x(1,J)/100);
        writeln(OutFile, WHERE ANG1(1) = ,Ang1(1)/10);
        end
      else Counter := Counter + 1 (Point passed test)
      end;
    if Counter = M then
      begin
        writeln(OutFile, NO POINTS HAVE TO BE REMOVED FOR J = ,J);
        end;
      writeln;
      write( DO YOU WANT TO CONTINUE WITH ANOTHER SECTOR ? );
      readln(Ans);
      if (Ans = Y) or (Ans = V) then goto 0;
      3: close(OutFile);
      END. (TestData)

```

```

type
  RealArray = array(1..N) of real;

where N is greater or equal to N, the sample size.

Output
-----

Flag      integer      Flag any points which fall under
                        Chauvenet's criterion of data rejection.
                        Flag = 1 indicates a rejected point.
                        Flag = 2 indicates no rejected points in
                        data sample

```

```

Variables
-----

Deviation  real        Deviation of 1 from mean
Ratio      real        Ratio of deviation of 1 to standard
                        deviation of total samples
RatioMax   real        Maximum allowable ratio of deviation
                        to standard deviation according to
                        Chauvenet's criterion

```

Discussion

Rarely is it that an experimenter does not find that some of the data points look bad and out of place with the bulk of the data. He must then decide whether these "bad" points represent an experimental error, and therefore may be ignored, or a new physical phenomenon. A consistent basis for elimination is therefore necessary. If N samples of a given measurement is large enough that the results would be expected to follow the Gaussian error distribution, then this distribution may be used to compute the probability that a given reading will deviate a certain amount from the mean. One would not expect a probability much smaller than $1/N$ because this would be unlikely to occur in the set of N measurements. Therefore, a point whose deviation probability is less than $1/N$ would be prime candidate for elimination. A more restrictive test for data rejection is Chauvenet's criterion. This criterion specifies that an experimental reading may be rejected if the probability of obtaining a deviation from the mean is less than $1/2N$. (See Holman, Experimental Methods for Engineers, 4th ed., 1984).

Subprogram Listing

```

procedure Reject(M: integer);
  StandardDeviation, Mean: real;
  RealArray;
  var Flag: integer;

  { Chauvenet's Criterion for data rejection }

  var Deviation, Ratio, RatioMax: real;

begin
  Flag = 0; { Initialization }
  Deviation = Abs 1(1) - Mean;

```

PROCEDURE REJECT PSL

Written by George Denias
CARLETON UNIVERSITY
Ottawa, Feb. 1987

```

10 Name: Reject
11
12 Type: Procedure
13
14 Purpose: To flag dubious data points using Chauvenet's
15          criterion of data rejection
16
17 Calling Sequence: Reject(M, StandardDeviation, Mean, Flag)
18
19

```

Description

You provide the data for the 1-D array and the number of samples, N , and the standard deviation. Reject then computes the individual deviations from the mean, forms the ratio of deviation of each point to that of the sample standard deviation. Then Chauvenet's criterion of data rejection is applied.

Input

```

1 1-D array Stores the random variables
N  integer Number of samples of input file
StandardDeviation real Standard deviation of 1
Mean real Sample mean value of 1

```

The following global type declaration must be specified in your main program:

```

Ratio := Deviation / StandardsDeviation;
( Check number of samples )
if N = 3 then
  RatioMax := 1.38
else if N = 4 then
  RatioMax := 1.54
else if N = 5 then
  RatioMax := 1.63
else if N = 6 then
  RatioMax := 1.73
else if (N >= 7) and (N < 10) then
  RatioMax := 0.0333 * (N - 7) + 1.80
else if (N >= 10) and (N < 15) THEN
  RatioMax := 0.034 * (N - 10) + 1.96
else if (N >= 15) and (N < 25) THEN
  RatioMax := 0.02 * (N - 15) + 2.13
else if (N >= 25) and (N < 50) THEN
  RatioMax := 0.0096 * (N - 25) + 2.33
else if (N >= 50) and (N < 100) THEN
  RatioMax := 0.0048 * (N - 50) + 2.57
else if (N >= 100) and (N < 300) THEN
  RatioMax := 0.0016 * (N - 100) + 2.81
else if (N >= 300) and (N < 500) THEN
  RatioMax := 0.00075 * (N - 300) + 3.14
else if (N >= 500) and (N < 1000) THEN
  RatioMax := 0.00038 * (N - 500) + 3.29;
( Apply criterion and flag )
if Ratio > RatioMax then ( Reject data point )
  Flag := 1
end; ( Reject )

```

APPENDIX D

The trigonometric relationships of the seven-hole probe are presented.

(a) The trigonometric relationships between tangential and polar system angles are shown in Fig. 5.2.1 (a) which has been reproduced below as Fig. D.1. for easy reference.

From Fig. D.1 it can readily be observed that,

$$V \cos \theta \tan \beta = V \sin \theta \sin \phi \quad \text{and}$$

$$V \cos \theta \tan \alpha = V \sin \theta \cos \phi$$

The two equations above can be rewritten, respectively, as,

$$\tan \beta = \tan \theta \sin \phi$$

$$\tan \alpha = \tan \theta \cos \phi$$

Solving for α and β gives the following two expressions,

$$\alpha = \tan^{-1}(\tan \theta \cos \phi) \quad (\text{D.1})$$

$$\beta = \tan^{-1}(\tan \theta \sin \phi) \quad (\text{D.2})$$

The velocity components (from Fig. D.1), in terms of polar and tangential angles, respectively, are:

polar:

$$u = V \cos \theta$$

$$v = V \sin \theta \sin \phi \quad (D.3)$$

$$w = V \sin \theta \cos \phi \quad (D.4)$$

tangential:

$$u = V \cos \alpha \cos \beta$$

$$v = -V \sin \beta$$

$$w = V \sin \alpha \cos \beta$$

Expressions such as Eqs. (D.1) and (D.2) in terms of θ and ϕ can be derived as follows. Referring to Fig. D.1 again, it is seen that,

$$\text{Eq. (F.3)} = V \cos \theta \tan \beta \quad (D.5)$$

$$\text{Eq. (F.4)} = V \cos \theta \tan \alpha \quad (D.6)$$

therefore, dividing Eq. (D.5) by (D.6) gives Eq. (D.7), while Eqs. (D.5) and (D.6) give Eqs. (D.8 a & b), respectively.

$$\phi = \tan^{-1} [\tan \beta / \tan \alpha] \quad (D.7)$$

$$\theta = \tan^{-1} [\tan \beta / \sin \phi] \quad (D.8.a)$$

$$\theta = \tan^{-1} [\tan \alpha / \cos \phi] \quad (D.8.b)$$

Fig. D.1 The tangential (α - β) and polar (θ - ϕ) reference systems.

(b) Trigonometric relationships between probe and test section axes are listed below. Referring to Fig. D.2, the velocity components relative to test-section axes, can be written in terms of quantities relative to probe axes (primed). The transformations are as follows, where primes refer to quantities relative to probe axes:

$$u = u' \cos \gamma - w' \sin \gamma$$

$$v = u \tan \alpha$$

$$w = v'$$

$$\alpha = \alpha' + \gamma$$

$$\beta = \tan^{-1} \left(\frac{w}{u} \right)$$

(c) The computer program (ANGLES.PAS) used to convert the calibration θ - ϕ high angle settings to the equivalent α - β settings, which are required for the calibration apparatus, is listed below together with the angles themselves.

```

      ***** ANGLES.PAS *****
      (
      ( Written by: George Denies, Carleton University, Ottawa, Oct. 23, 1986,
      ( for the 7-Hole Probe Calibration Apparatus. This program calculates
      ( the corresponding tangential coordinate system angles, alpha and beta,
      ( from the polar coordinate system angles, theta and phi. Theta and phi
      ( varied from 20 to 50 and from 0 to 355 degrees, respectively, at 5 deg-
      ( ree increments.
      )
      )

PROGRAM ANGLES;
VAR
  THETA, PHI, ALPHA, BETA, A, B : REAL;
  I, J, COUNTER : INTEGER;
  FILE : STRING(20);
  OUTFILE : TEXT;

FUNCTION RADIANS( ANGLE : REAL ) : REAL;
  ( Convert Degrees to Radians )
BEGIN
  RADIANS := ANGLE*PI/180;
END;

FUNCTION DEGREES( ANGLE : REAL ) : REAL;
  ( Convert Radians to Degrees )
BEGIN
  DEGREES := ANGLE*180/PI;
END;

BEGIN ( Main )
  WRITE( 'ENTER OUTPUT FILE NAME : ' );
  READLN( FILE );
  ASSIGN( OUTFILE, FILE );
  REWRITE( OUTFILE );

  ( Headings )
  Writeln( OUTFILE, '  ' THETA      PHI      ALPHA      BETA      (Degrees
  ) );
  Writeln( OUTFILE );
  COUNTER := 0;
  FOR I := 20 TO 50 DO ( Theta Range )
  BEGIN
    IF ( I MOD 5 = 0 ) THEN ( Check for 5 Degree Increments )
    BEGIN
      THETA := I;
      FOR J := 0 TO 355 DO ( Phi Range )
      BEGIN
        IF ( J MOD 5 = 0 ) THEN ( Check for 5 Degree Increments )
        BEGIN
          PHI := J;
          COUNTER := COUNTER+1;

          ( Convert Polar System Angles to Tangential System Angles )
          ALPHA := DEGREES( ARCTAN( SIN( RADIANS( THETA ) ) / COS( RADIANS( THETA ) ),
                                COS( RADIANS( PHI ) ) ) );
          BETA := DEGREES( ARCTAN( SIN( RADIANS( THETA ) ) / COS( RADIANS( THETA ) ),
                                SIN( RADIANS( PHI ) ) ) );

          ( Output Angles )
          Writeln( OUTFILE, COUNTER:3, THETA:10:1, PHI:10:1, ALPHA:13:1, BETA:11:1
          ) );
        END;
      END;
    END;
  END;
  CLOSE( OUTFILE );
END.

```

APPENDIX B

•

1

```

(                                LOSS7HP.PAS                                )
(                                                                           )
( Written by: George Danias, Carleton U., Ottawa, Apr. 2, 1987          )
( This program computes the total and static pressure losses, in non-di- )
( mensional form for Seven-Hole Probe tip leakage traverses.           )
(                                                                           )

program Loss7HP;

var
  Alpha, Beta, Cdtotal, Cdpvn, U, V, W : real;
  TotalPressureLoss, StaticPressureLoss : real;
  I, NumLines : integer;
  File1, File2 : string[20];
  InFile, OutFile : text;

begin
  ClrScr;
  write( 'Enter the input file name of 7-Hole Probe reduced data: ');
  readln(File1);
  write( 'Enter the output file name for Total & Static Co. ef: ');
  readln(File2);
  assign(InFile, File1);
  reset(InFile);
  assign(OutFile, File2);
  rewrite(OutFile);

  ( Headings )
  write(OutFile, '7-Hole Probe Pressure Losses ');
  write(OutFile, '----- ');
  write(OutFile, 'Alpha      Beta      (Pc1-Pc2)/      (P-Pw)/ ');
  write(OutFile, ' (deg)      (deg)      qin      qin ');
  write(OutFile, '----- ');

  ( Input )
  readln(InFile, NumLines);
  for I := 1 to NumLines do
  begin
    readln(InFile, Alpha, beta, Cdtotal, Cdpvn, U, V, W);
    TotalPressureLoss := 1 - Cdtotal;
    StaticPressureLoss := Cdtotal - Cdpvn;
    write(OutFile, Alpha:10:1, Beta:10:1, TotalPressureLoss:11:4,
          StaticPressureLoss:11:4);

    end;
  close(InFile);
  close(OutFile);
end.

```

APPENDIX F

A listing of the high angle setting conversions (from polar to tangential system), as well as the calibration probe port pressure coefficients.

	THETA	PMI	ALPHA	BETA	(Degrees)					
1	20.0	0.0	20.0	0.0		64	20.0	315.0	19.4	-14.4
2	20.0	5.0	19.9	1.8		65	20.0	320.0	19.4	-13.2
3	20.0	10.0	19.7	3.4		66	20.0	325.0	19.4	-11.8
4	20.0	15.0	19.4	5.0		67	20.0	330.0	19.4	-10.3
5	20.0	20.0	18.9	6.7		68	20.0	335.0	18.9	-8.7
6	20.0	25.0	18.3	8.3		69	20.0	340.0	18.3	-7.1
7	20.0	30.0	17.5	10.0		70	20.0	345.0	17.5	-5.4
8	20.0	35.0	16.4	11.8		71	20.0	350.0	16.4	-3.4
9	20.0	40.0	15.2	13.2		72	20.0	355.0	15.2	-1.8
10	20.0	45.0	14.4	14.4		73	25.0	0.0	25.0	0.0
11	20.0	50.0	13.2	15.2		74	25.0	5.0	24.9	2.3
12	20.0	55.0	11.8	16.4		75	25.0	10.0	24.7	4.4
13	20.0	60.0	10.3	17.5		76	25.0	15.0	24.2	6.9
14	20.0	65.0	8.7	18.3		77	25.0	20.0	23.7	9.1
15	20.0	70.0	7.1	18.9		78	25.0	25.0	22.9	11.1
16	20.0	75.0	5.4	19.4		79	25.0	30.0	22.0	13.1
17	20.0	80.0	3.4	19.7		80	25.0	35.0	20.9	15.0
18	20.0	85.0	1.8	19.9		81	25.0	40.0	19.7	16.7
19	20.0	90.0	0.0	20.0		82	25.0	45.0	18.2	18.2
20	20.0	95.0	-1.8	19.9		83	25.0	50.0	16.7	19.7
21	20.0	100.0	-3.4	19.7		84	25.0	55.0	15.0	20.9
22	20.0	105.0	-5.4	19.4		85	25.0	60.0	13.1	22.0
23	20.0	110.0	-7.1	18.9		86	25.0	65.0	11.1	22.9
24	20.0	115.0	-8.7	18.3		87	25.0	70.0	9.1	23.7
25	20.0	120.0	-10.3	17.5		88	25.0	75.0	6.9	24.2
26	20.0	125.0	-11.8	16.4		89	25.0	80.0	4.4	24.7
27	20.0	130.0	-13.2	15.2		90	25.0	85.0	2.3	24.9
28	20.0	135.0	-14.4	14.4		91	25.0	90.0	0.0	25.0
29	20.0	140.0	-15.2	13.2		92	25.0	95.0	-2.3	24.9
30	20.0	145.0	-16.4	11.8		93	25.0	100.0	-4.4	24.7
31	20.0	150.0	-17.5	10.3		94	25.0	105.0	-6.9	24.2
32	20.0	155.0	-18.3	8.7		95	25.0	110.0	-9.1	23.7
33	20.0	160.0	-18.9	7.1		96	25.0	115.0	-11.1	22.9
34	20.0	165.0	-19.4	5.4		97	25.0	120.0	-13.1	22.0
35	20.0	170.0	-19.7	3.4		98	25.0	125.0	-15.0	20.9
36	20.0	175.0	-19.9	1.8		99	25.0	130.0	-16.7	19.7
37	20.0	180.0	-20.0	0.0		100	25.0	135.0	-18.2	18.2
38	20.0	185.0	-19.9	-1.8		101	25.0	140.0	-19.7	16.7
39	20.0	190.0	-19.7	-3.4		102	25.0	145.0	-20.9	15.0
40	20.0	195.0	-19.4	-5.4		103	25.0	150.0	-22.0	13.1
41	20.0	200.0	-18.9	-7.1		104	25.0	155.0	-22.9	11.1
42	20.0	205.0	-18.3	-8.7		105	25.0	160.0	-23.7	9.1
43	20.0	210.0	-17.5	-10.3		106	25.0	165.0	-24.7	6.9
44	20.0	215.0	-16.4	-11.8		107	25.0	170.0	-24.9	2.3
45	20.0	220.0	-15.2	-13.2		108	25.0	175.0	-25.0	0.0
46	20.0	225.0	-14.4	-14.4		109	25.0	180.0	-25.0	-2.3
47	20.0	230.0	-13.2	-15.2		110	25.0	185.0	-24.9	-4.4
48	20.0	235.0	-11.8	-16.4		111	25.0	190.0	-24.7	-6.9
49	20.0	240.0	-10.3	-17.5		112	25.0	195.0	-24.2	-9.1
50	20.0	245.0	-8.7	-18.3		113	25.0	200.0	-23.7	-11.1
51	20.0	250.0	-7.1	-18.9		114	25.0	205.0	-22.9	-13.1
52	20.0	255.0	-5.4	-19.4		115	25.0	210.0	-22.0	-15.0
53	20.0	260.0	-3.4	-19.7		116	25.0	215.0	-20.9	-16.7
54	20.0	265.0	-1.8	-19.9		117	25.0	220.0	-19.7	-18.2
55	20.0	270.0	-0.0	-20.0		118	25.0	225.0	-18.2	-19.7
56	20.0	275.0	1.8	-19.9		119	25.0	230.0	-16.7	-19.7
57	20.0	280.0	3.4	-19.7		120	25.0	235.0	-15.0	-20.9
58	20.0	285.0	5.4	-19.4		121	25.0	240.0	-13.1	-22.0
59	20.0	290.0	7.1	-18.9		122	25.0	245.0	-11.1	-22.9
60	20.0	295.0	8.7	-18.3		123	25.0	250.0	-9.1	-23.7
61	20.0	300.0	10.3	-17.5		124	25.0	255.0	-6.9	-24.2
62	20.0	305.0	11.8	-16.4		125	25.0	260.0	-4.4	-24.7
63	20.0	310.0	13.2	-15.2		126	25.0	265.0	-2.3	-24.9
						127	25.0	270.0	0.0	-24.9
						128	25.0	275.0	2.3	-24.7
						129	25.0	280.0	4.4	-24.2

130	25.0	285.0	6.9	-24.2	196	30.0	235.0	-8.5	-29.1
131	25.0	290.0	9.1	-23.7	197	30.0	240.0	-5.7	-29.6
132	25.0	295.0	11.1	-22.9	198	30.0	245.0	-2.9	-29.9
133	25.0	300.0	13.1	-22.0	199	30.0	270.0	-0.0	-30.0
134	25.0	305.0	15.0	-20.9	200	30.0	275.0	2.9	-29.9
135	25.0	310.0	16.7	-19.7	201	30.0	280.0	5.7	-29.6
136	25.0	315.0	18.2	-18.2	202	30.0	285.0	8.5	-29.1
137	25.0	320.0	19.7	-16.7	203	30.0	290.0	11.2	-28.5
138	25.0	325.0	20.9	-15.0	204	30.0	295.0	13.7	-27.6
139	25.0	330.0	22.0	-13.1	205	30.0	300.0	16.1	-26.6
140	25.0	335.0	22.9	-11.1	206	30.0	305.0	18.3	-25.3
141	25.0	340.0	23.7	-9.1	207	30.0	310.0	20.4	-23.9
142	25.0	345.0	24.2	-6.9	208	30.0	315.0	22.2	-22.2
143	25.0	350.0	24.7	-4.6	209	30.0	320.0	23.9	-20.4
144	30.0	355.0	24.9	-2.3	210	30.0	325.0	25.3	-18.3
145	30.0	360.0	24.9	0.0	211	30.0	330.0	26.6	-16.1
146	30.0	365.0	24.6	2.9	212	30.0	335.0	27.6	-13.7
147	30.0	370.0	24.1	5.7	213	30.0	340.0	28.5	-11.2
148	30.0	375.0	23.5	8.5	214	30.0	345.0	29.1	-8.5
149	30.0	380.0	22.9	11.2	215	30.0	350.0	29.6	-5.7
150	30.0	385.0	22.0	13.7	216	30.0	355.0	29.9	-2.9
151	30.0	390.0	20.9	16.1	217	30.0	360.0	30.0	0.0
152	30.0	395.0	19.7	18.3	218	30.0	365.0	30.0	3.0
153	30.0	400.0	18.2	20.4	219	30.0	370.0	30.0	6.9
154	30.0	405.0	16.7	22.2	220	30.0	375.0	30.0	10.3
155	30.0	410.0	15.0	23.9	221	30.0	380.0	30.0	13.7
156	30.0	415.0	13.1	25.3	222	30.0	385.0	30.0	16.5
157	30.0	420.0	11.2	26.6	223	30.0	390.0	30.0	19.3
158	30.0	425.0	9.1	27.6	224	30.0	395.0	30.0	21.9
159	30.0	430.0	6.9	28.5	225	30.0	400.0	30.0	24.2
160	30.0	435.0	4.6	29.1	226	30.0	405.0	30.0	26.3
161	30.0	440.0	2.3	29.6	227	30.0	410.0	30.0	28.2
162	30.0	445.0	0.0	30.0	228	30.0	415.0	30.0	29.6
163	30.0	450.0	-2.3	29.9	229	30.0	420.0	30.0	30.0
164	30.0	455.0	-4.6	29.6	230	30.0	425.0	30.0	30.0
165	30.0	460.0	-6.9	29.1	231	30.0	430.0	30.0	30.0
166	30.0	465.0	-9.1	28.5	232	30.0	435.0	30.0	30.0
167	30.0	470.0	-11.2	27.6	233	30.0	440.0	30.0	30.0
168	30.0	475.0	-13.7	26.6	234	30.0	445.0	30.0	30.0
169	30.0	480.0	-16.1	25.3	235	30.0	450.0	30.0	30.0
170	30.0	485.0	-18.3	23.9	236	30.0	455.0	30.0	30.0
171	30.0	490.0	-20.4	22.2	237	30.0	460.0	30.0	30.0
172	30.0	495.0	-22.2	20.4	238	30.0	465.0	30.0	30.0
173	30.0	500.0	-23.9	18.3	239	30.0	470.0	30.0	30.0
174	30.0	505.0	-25.3	16.1	240	30.0	475.0	30.0	30.0
175	30.0	510.0	-26.6	13.7	241	30.0	480.0	30.0	30.0
176	30.0	515.0	-27.6	11.2	242	30.0	485.0	30.0	30.0
177	30.0	520.0	-28.5	8.5	243	30.0	490.0	30.0	30.0
178	30.0	525.0	-29.1	5.7	244	30.0	495.0	30.0	30.0
179	30.0	530.0	-29.6	2.9	245	30.0	500.0	30.0	30.0
180	30.0	535.0	-29.9	0.0	246	30.0	505.0	30.0	30.0
181	30.0	540.0	-29.9	-2.3	247	30.0	510.0	30.0	30.0
182	30.0	545.0	-29.6	-4.6	248	30.0	515.0	30.0	30.0
183	30.0	550.0	-29.1	-6.9	249	30.0	520.0	30.0	30.0
184	30.0	555.0	-28.5	-9.1	250	30.0	525.0	30.0	30.0
185	30.0	560.0	-27.6	-11.2	251	30.0	530.0	30.0	30.0
186	30.0	565.0	-26.6	-13.7	252	30.0	535.0	30.0	30.0
187	30.0	570.0	-25.3	-16.1	253	30.0	540.0	30.0	30.0
188	30.0	575.0	-23.9	-18.3	254	30.0	545.0	30.0	30.0
189	30.0	580.0	-22.2	-20.4	255	30.0	550.0	30.0	30.0
190	30.0	585.0	-20.4	-22.2	256	30.0	555.0	30.0	30.0
191	30.0	590.0	-18.3	-23.9	257	30.0	560.0	30.0	30.0
192	30.0	595.0	-16.1	-25.3	258	30.0	565.0	30.0	30.0
193	30.0	600.0	-13.7	-26.6	259	30.0	570.0	30.0	30.0
194	30.0	605.0	-11.2	-27.6	260	30.0	575.0	30.0	30.0
195	30.0	610.0	-9.1	-28.5	261	30.0	580.0	30.0	30.0

262	35.0	225.0	-26.3	-26.3	328	40.0	195.0	39.0	12.3
263	35.0	230.0	-24.2	-28.2	329	40.0	200.0	38.3	16.0
264	35.0	235.0	-21.9	-29.8	330	40.0	205.0	37.3	19.5
265	35.0	240.0	-19.3	-31.2	331	40.0	210.0	-36.0	27.8
266	35.0	245.0	-16.5	-32.4	332	40.0	215.0	-34.5	-25.7
267	35.0	250.0	-13.5	-33.3	333	40.0	220.0	-32.7	-28.3
268	35.0	255.0	-10.3	-34.1	334	40.0	225.0	-30.7	-30.7
269	35.0	260.0	-6.9	-34.6	335	40.0	230.0	-28.3	-32.7
270	35.0	265.0	-3.5	-34.9	336	40.0	235.0	-25.7	-34.5
271	35.0	270.0	-0.0	-35.0	337	40.0	240.0	-22.8	-36.0
272	35.0	275.0	3.5	-34.9	338	40.0	245.0	-19.5	-37.3
273	35.0	280.0	6.9	-34.6	339	40.0	250.0	-16.0	-38.3
274	35.0	285.0	10.3	-34.1	340	40.0	255.0	-12.3	-39.0
275	35.0	290.0	13.5	-33.3	341	40.0	260.0	-8.3	-39.6
276	35.0	295.0	16.5	-32.4	342	40.0	265.0	-4.2	-39.9
277	35.0	300.0	19.3	-31.2	343	40.0	270.0	-0.0	-40.0
278	35.0	305.0	21.9	-29.8	344	40.0	275.0	4.2	-39.9
279	35.0	310.0	24.2	-28.2	345	40.0	280.0	8.3	-39.6
280	35.0	315.0	26.3	-26.3	346	40.0	285.0	12.3	-39.0
281	35.0	320.0	28.2	-24.2	347	40.0	290.0	16.0	-38.3
282	35.0	325.0	29.8	-21.9	348	40.0	295.0	19.5	-37.3
283	35.0	330.0	31.2	-19.3	349	40.0	300.0	22.8	-36.0
284	35.0	335.0	32.4	-16.5	350	40.0	305.0	25.7	-34.5
285	35.0	340.0	33.3	-13.5	351	40.0	310.0	28.3	-32.7
286	35.0	345.0	34.1	-10.3	352	40.0	315.0	30.7	-30.7
287	35.0	350.0	34.6	-6.9	353	40.0	320.0	32.7	-28.3
288	35.0	355.0	34.9	-3.5	354	40.0	325.0	34.5	-25.7
289	40.0	0.0	40.0	0.0	355	40.0	330.0	36.0	-22.8
290	40.0	5.0	39.9	4.2	356	40.0	335.0	37.3	-19.5
291	40.0	10.0	39.6	8.3	357	40.0	340.0	38.3	-16.0
292	40.0	15.0	39.0	12.3	358	40.0	345.0	39.0	-12.3
293	40.0	20.0	38.3	16.0	359	40.0	350.0	39.6	-8.3
294	40.0	25.0	37.3	19.5	360	40.0	355.0	39.9	-4.2
295	40.0	30.0	36.0	22.8	361	45.0	0.0	45.0	0.0
296	40.0	35.0	34.5	25.7	362	45.0	5.0	44.9	5.0
297	40.0	40.0	32.7	28.3	363	45.0	10.0	44.6	9.9
298	40.0	45.0	30.7	30.7	364	45.0	15.0	44.0	14.5
299	40.0	50.0	28.3	32.7	365	45.0	20.0	43.2	18.9
300	40.0	55.0	25.7	34.5	366	45.0	25.0	42.2	22.9
301	40.0	60.0	22.8	36.0	367	45.0	30.0	40.9	26.6
302	40.0	65.0	19.5	37.3	368	45.0	35.0	39.3	29.8
303	40.0	70.0	16.0	38.3	369	45.0	40.0	37.3	32.7
304	40.0	75.0	12.3	39.0	370	45.0	45.0	35.3	35.3
305	40.0	80.0	8.3	39.6	371	45.0	50.0	32.7	37.3
306	40.0	85.0	4.2	39.9	372	45.0	55.0	29.8	39.5
307	40.0	90.0	0.0	40.0	373	45.0	60.0	26.6	40.9
308	40.0	95.0	-4.2	39.9	374	45.0	65.0	22.9	42.2
309	40.0	100.0	-8.3	39.6	375	45.0	70.0	18.9	43.2
310	40.0	105.0	-12.3	39.0	376	45.0	75.0	14.5	44.0
311	40.0	110.0	-16.0	38.3	377	45.0	80.0	9.9	44.6
312	40.0	115.0	-19.5	37.3	378	45.0	85.0	5.0	44.9
313	40.0	120.0	-22.8	36.0	379	45.0	90.0	0.0	45.0
314	40.0	125.0	-25.7	34.5	380	45.0	95.0	5.0	44.9
315	40.0	130.0	-28.3	32.7	381	45.0	100.0	9.9	44.6
316	40.0	135.0	-30.7	30.7	382	45.0	105.0	14.5	44.0
317	40.0	140.0	-32.7	28.3	383	45.0	110.0	18.9	43.2
318	40.0	145.0	-34.5	25.7	384	45.0	115.0	22.9	42.2
319	40.0	150.0	-36.0	22.8	385	45.0	120.0	26.6	40.9
320	40.0	155.0	-37.3	19.5	386	45.0	125.0	29.8	39.5
321	40.0	160.0	-38.3	16.0	387	45.0	130.0	32.7	37.3
322	40.0	165.0	-39.0	12.3	388	45.0	135.0	35.3	35.3
323	40.0	170.0	-39.6	8.3	389	45.0	140.0	37.3	32.7
324	40.0	175.0	-39.9	4.2	390	45.0	145.0	39.5	29.8
325	40.0	180.0	-40.0	0.0	391	45.0	150.0	40.9	26.6
326	40.0	185.0	-39.9	-4.2	392	45.0	155.0	42.2	22.9
327	40.0	190.0	-39.6	-8.3	393	45.0	160.0	43.2	18.9

394	45.0	165.0	-44.0	14.5	460	50.0	135.0	-40.1	40.1
395	45.0	170.0	-44.6	9.9	461	50.0	140.0	-42.4	37.5
396	45.0	175.0	-44.9	5.0	462	50.0	145.0	-44.3	34.4
397	45.0	180.0	-45.0	0.0	463	50.0	150.0	-45.9	30.8
398	45.0	185.0	-44.9	-5.0	464	50.0	155.0	-47.2	26.7
399	45.0	190.0	-44.6	-9.9	465	50.0	160.0	-48.2	22.2
400	45.0	195.0	-44.0	-14.5	466	50.0	165.0	-49.0	17.1
401	45.0	200.0	-43.2	-18.9	467	50.0	170.0	-49.6	11.7
402	45.0	205.0	-42.2	-22.9	468	50.0	175.0	-49.9	5.9
403	45.0	210.0	-40.9	-26.6	469	50.0	180.0	-50.0	0.0
404	45.0	215.0	-39.3	-29.8	470	50.0	185.0	-49.9	-3.9
405	45.0	220.0	-37.5	-32.7	471	50.0	190.0	-49.6	-11.7
406	45.0	225.0	-35.3	-35.3	472	50.0	195.0	-49.0	-17.1
407	45.0	230.0	-32.7	-37.5	473	50.0	200.0	-48.2	-22.2
408	45.0	235.0	-29.8	-39.3	474	50.0	205.0	-47.2	-26.7
409	45.0	240.0	-26.6	-40.9	475	50.0	210.0	-45.9	-30.8
410	45.0	245.0	-22.9	-42.2	476	50.0	215.0	-44.3	-34.4
411	45.0	250.0	-18.9	-43.2	477	50.0	220.0	-42.4	-37.5
412	45.0	255.0	-14.5	-44.0	478	50.0	225.0	-40.1	-40.1
413	45.0	260.0	-9.9	-44.6	479	50.0	230.0	-37.5	-42.4
414	45.0	265.0	-5.0	-44.9	480	50.0	235.0	-34.4	-44.3
415	45.0	270.0	0.0	-45.0	481	50.0	240.0	-30.8	-45.9
416	45.0	275.0	5.0	-44.9	482	50.0	245.0	-26.7	-47.2
417	45.0	280.0	9.9	-44.6	483	50.0	250.0	-22.2	-48.2
418	45.0	285.0	14.5	-44.0	484	50.0	255.0	-17.1	-49.0
419	45.0	290.0	18.9	-43.2	485	50.0	260.0	-11.7	-49.6
420	45.0	295.0	22.9	-42.2	486	50.0	265.0	-9.9	-49.9
421	45.0	300.0	26.6	-40.9	487	50.0	270.0	-0.0	-50.0
422	45.0	305.0	29.8	-39.3	488	50.0	275.0	5.9	-49.9
423	45.0	310.0	32.7	-37.5	489	50.0	280.0	11.7	-49.6
424	45.0	315.0	35.3	-35.3	490	50.0	285.0	17.1	-49.0
425	45.0	320.0	37.5	-32.7	491	50.0	290.0	22.2	-48.2
426	45.0	325.0	39.3	-29.8	492	50.0	295.0	26.7	-47.2
427	45.0	330.0	40.9	-26.6	493	50.0	300.0	30.8	-45.9
428	45.0	335.0	42.2	-22.9	494	50.0	305.0	34.4	-44.3
429	45.0	340.0	43.2	-18.9	495	50.0	310.0	37.5	-42.4
430	45.0	345.0	44.0	-14.5	496	50.0	315.0	40.1	-40.1
431	45.0	350.0	44.6	-9.9	497	50.0	320.0	42.4	-37.5
432	45.0	355.0	44.9	-5.0	498	50.0	325.0	44.3	-34.4
433	50.0	0.0	50.0	0.0	499	50.0	330.0	45.9	-30.8
434	50.0	5.0	49.9	5.9	500	50.0	335.0	47.2	-26.7
435	50.0	10.0	49.6	11.7	501	50.0	340.0	48.2	-22.2
436	50.0	15.0	49.0	17.1	502	50.0	345.0	49.0	-17.1
437	50.0	20.0	48.2	22.2	503	50.0	350.0	49.6	-11.7
438	50.0	25.0	47.2	26.7	504	50.0	355.0	49.9	-5.9
439	50.0	30.0	45.9	30.8					
440	50.0	35.0	44.3	34.4					
441	50.0	40.0	42.4	37.5					
442	50.0	45.0	40.1	40.1					
443	50.0	50.0	37.5	42.4					
444	50.0	55.0	34.4	44.3					
445	50.0	60.0	30.8	45.9					
446	50.0	65.0	26.7	47.2					
447	50.0	70.0	22.2	48.2					
448	50.0	75.0	17.1	49.0					
449	50.0	80.0	11.7	49.6					
450	50.0	85.0	5.9	49.9					
451	50.0	90.0	0.0	50.0					
452	50.0	95.0	-5.9	49.9					
453	50.0	100.0	-11.7	49.6					
454	50.0	105.0	-17.1	49.0					
455	50.0	110.0	-22.2	48.2					
456	50.0	115.0	-26.7	47.2					
457	50.0	120.0	-30.8	45.9					
458	50.0	125.0	-34.4	44.3					
459	50.0	130.0	-37.5	42.4					

SEVEN-HOLE PROBE

LOW ANGLE REGIME CALIBRATION PRESSURE COEFFICIENTS (Oct 84)

ALPHA	BETA	CP1	CP2	CP3	CP4	CP5	CP6	CP7
23.0	23.0	-1.722	-1.177	-0.038	-0.626	-1.517	-1.678	-0.642
23.0	20.0	-1.603	-1.204	-0.089	-0.432	-1.419	-1.584	-0.539
23.0	15.0	-1.506	-1.238	-0.143	-0.292	-1.210	-1.520	-0.424
23.0	10.0	-1.433	-1.273	-0.289	-0.196	-1.007	-1.463	-0.352
23.0	5.0	-1.419	-1.308	-0.431	-0.143	-0.823	-1.423	-0.297
23.0	0.0	-1.412	-1.337	-0.412	-0.126	-0.634	-1.343	-0.271
23.0	-5.0	-1.415	-1.410	-0.798	-0.134	-0.471	-1.313	-0.273
23.0	-10.0	-1.443	-1.439	-0.986	-0.170	-0.334	-1.244	-0.305
23.0	-15.0	-1.516	-1.528	-1.201	-0.216	-0.200	-1.177	-0.373
23.0	-20.0	-1.610	-1.623	-1.429	-0.309	-0.110	-1.117	-0.446
23.0	-25.0	-1.734	-1.702	-1.638	-0.440	-0.058	-1.120	-0.577
20.0	23.0	-1.602	-0.947	-0.053	-0.708	-1.340	-1.575	-0.534
20.0	20.0	-1.470	-0.987	-0.093	-0.519	-1.134	-1.440	-0.414
20.0	15.0	-1.372	-1.033	-0.174	-0.377	-1.137	-1.374	-0.301
20.0	10.0	-1.302	-1.047	-0.279	-0.284	-0.940	-1.303	-0.226
20.0	5.0	-1.261	-1.103	-0.400	-0.228	-0.746	-1.231	-0.170
20.0	0.0	-1.246	-1.144	-0.543	-0.213	-0.606	-1.148	-0.143
20.0	-5.0	-1.261	-1.231	-0.734	-0.220	-0.434	-1.112	-0.151
20.0	-10.0	-1.341	-1.379	-0.970	-0.259	-0.319	-1.032	-0.182
20.0	-15.0	-1.461	-1.475	-1.330	-0.385	-0.113	-0.937	-0.341
20.0	-20.0	-1.583	-1.568	-1.542	-0.523	-0.071	-0.893	-0.456
15.0	23.0	-1.441	-0.738	-0.079	-0.793	-1.442	-1.474	-0.435
15.0	20.0	-1.337	-0.786	-0.113	-0.618	-1.267	-1.340	-0.324
15.0	15.0	-1.222	-0.823	-0.190	-0.482	-1.079	-1.250	-0.200
15.0	10.0	-1.136	-0.880	-0.283	-0.387	-0.914	-1.149	-0.127
15.0	5.0	-1.109	-0.971	-0.401	-0.342	-0.742	-1.077	-0.085
15.0	0.0	-1.108	-1.002	-0.549	-0.311	-0.605	-1.011	-0.072
15.0	-5.0	-1.112	-1.077	-0.703	-0.311	-0.442	-0.934	-0.073
15.0	-10.0	-1.139	-1.140	-0.877	-0.338	-0.314	-0.847	-0.090
15.0	-15.0	-1.193	-1.239	-1.054	-0.384	-0.219	-0.803	-0.133
15.0	-20.0	-1.308	-1.374	-1.248	-0.493	-0.139	-0.744	-0.239
15.0	-25.0	-1.437	-1.491	-1.444	-0.627	-0.094	-0.691	-0.337
10.0	23.0	-1.332	-0.536	-0.109	-0.903	-1.411	-1.425	-0.390
10.0	20.0	-1.208	-0.611	-0.163	-0.724	-1.209	-1.288	-0.251
10.0	15.0	-1.096	-0.630	-0.228	-0.594	-1.040	-1.170	-0.148
10.0	10.0	-1.032	-0.724	-0.330	-0.501	-0.874	-1.078	-0.081
10.0	5.0	-0.993	-0.808	-0.441	-0.443	-0.745	-0.983	-0.039
10.0	0.0	-0.975	-0.887	-0.567	-0.412	-0.612	-0.893	-0.019
10.0	-5.0	-0.978	-0.947	-0.710	-0.416	-0.478	-0.810	-0.022
10.0	-10.0	-1.000	-1.071	-0.872	-0.440	-0.342	-0.719	-0.033
10.0	-15.0	-1.067	-1.173	-1.015	-0.501	-0.243	-0.640	-0.063
10.0	-20.0	-1.132	-1.288	-1.194	-0.596	-0.178	-0.548	-0.117
10.0	-25.0	-1.244	-1.432	-1.407	-0.734	-0.123	-0.471	-0.194
5.0	23.0	-1.238	-0.411	-0.174	-1.014	-1.371	-1.378	-0.344
5.0	20.0	-1.080	-0.440	-0.221	-0.840	-1.186	-1.254	-0.212
5.0	15.0	-0.948	-0.509	-0.343	-0.714	-1.039	-1.104	-0.117
5.0	10.0	-0.903	-0.593	-0.381	-0.638	-0.903	-0.989	-0.044
5.0	5.0	-0.858	-0.649	-0.489	-0.573	-0.746	-0.893	-0.013
5.0	0.0	-0.836	-0.772	-0.611	-0.545	-0.642	-0.792	-0.007
5.0	-5.0	-0.839	-0.879	-0.733	-0.543	-0.515	-0.693	-0.002
5.0	-10.0	-0.881	-0.994	-0.940	-0.571	-0.404	-0.608	-0.020
5.0	-15.0	-0.916	-1.101	-1.018	-0.627	-0.318	-0.507	-0.042
5.0	-20.0	-1.015	-1.222	-1.173	-0.713	-0.218	-0.434	-0.121
5.0	-25.0	-1.141	-1.372	-1.370	-0.871	-0.134	-0.348	-0.250
0.0	23.0	-1.101	-0.245	-0.170	-0.940	-1.481	-1.497	-0.333
0.0	20.0	-0.948	-0.325	-0.118	-0.846	-1.357	-1.345	-0.251
0.0	15.0	-0.834	-0.385	-0.111	-0.646	-1.157	-1.245	-0.161
0.0	10.0	-0.712	-0.439	-0.123	-0.463	-1.043	-1.045	-0.096
0.0	5.0	-0.608	-0.475	-0.163	-0.343	-0.915	-0.929	-0.014
0.0	0.0	-0.490	-0.796	-0.789	-0.474	-0.592	-0.610	-0.004
0.0	-5.0	-0.727	-0.911	-0.913	-0.705	-0.494	-0.501	-0.017
0.0	-10.0	-0.883	-1.045	-1.044	-0.748	-0.399	-0.400	-0.044
0.0	-15.0	-0.983	-1.181	-1.188	-0.844	-0.325	-0.327	-0.114
0.0	-20.0	-1.011	-1.332	-1.335	-0.985	-0.264	-0.264	-0.233
0.0	-25.0	-1.003	-1.492	-1.375	-1.244	-0.190	-0.174	-0.347
-5.0	23.0	-0.839	-0.240	-0.413	-1.084	-1.229	-1.200	-0.221
-5.0	20.0	-0.723	-0.311	-0.490	-0.932	-1.092	-1.043	-0.109
-5.0	15.0	-0.642	-0.392	-0.566	-0.892	-0.987	-0.914	-0.054
-5.0	10.0	-0.596	-0.502	-0.647	-0.833	-0.882	-0.794	-0.030
-5.0	5.0	-0.572	-0.625	-0.748	-0.801	-0.748	-0.644	-0.007
-5.0	0.0	-0.572	-0.743	-0.854	-0.803	-0.643	-0.544	-0.004
-5.0	-5.0	-0.608	-0.891	-0.979	-0.833	-0.574	-0.430	-0.079
-5.0	-10.0	-0.641	-1.031	-1.092	-0.892	-0.489	-0.337	-0.074
-5.0	-15.0	-0.749	-1.177	-1.218	-0.960	-0.419	-0.248	-0.135
-5.0	-20.0	-0.890	-1.335	-1.372	-1.123	-0.367	-0.180	-0.251
-10.0	23.0	-0.892	-0.113	-0.324	-1.375	-1.448	-1.428	-0.403
-10.0	20.0	-0.721	-0.171	-0.361	-1.205	-1.292	-1.234	-0.271
-10.0	15.0	-0.597	-0.238	-0.415	-1.081	-1.154	-1.044	-0.160
-10.0	10.0	-0.511	-0.310	-0.479	-1.004	-1.061	-0.917	-0.094
-10.0	5.0	-0.444	-0.438	-0.748	-0.959	-0.932	-0.774	-0.056
-10.0	0.0	-0.438	-0.370	-0.854	-0.933	-0.844	-0.635	-0.035
-10.0	-5.0	-0.435	-0.704	-0.935	-0.928	-0.749	-0.495	-0.033
-10.0	-10.0	-0.469	-0.869	-1.044	-0.944	-0.686	-0.375	-0.047
-10.0	-15.0	-0.634	-1.003	-1.144	-1.009	-0.617	-0.278	-0.101
-10.0	-20.0	-0.823	-1.184	-1.274	-1.127	-0.547	-0.193	-0.181
-10.0	-25.0	-0.733	-1.378	-1.419	-1.267	-0.514	-0.129	-0.302
-15.0	23.0	-0.619	-0.084	-0.491	-1.301	-1.531	-1.497	-0.481
-15.0	20.0	-0.419	-0.137	-0.732	-1.340	-1.371	-1.298	-0.345
-15.0	15.0	-0.491	-0.199	-0.772	-1.205	-1.234	-1.103	-0.229
-15.0	10.0	-0.393	-0.276	-0.823	-1.118	-1.128	-0.928	-0.149
-15.0	5.0	-0.347	-0.411	-0.894	-1.078	-1.042	-0.774	-0.109
-15.0	0.0	-0.326	-0.555	-0.977	-1.071	-0.972	-0.634	-0.100
-15.0	-5.0	-0.327	-0.700	-1.056	-1.044	-0.897	-0.481	-0.099
-15.0	-10.0	-0.362	-0.874	-1.140	-1.094	-0.821	-0.339	-0.117
-15.0	-15.0	-0.407	-1.053	-1.233	-1.182	-0.754	-0.239	-0.172
-15.0	-20.0	-0.508	-1.243	-1.340	-1.271	-0.708	-0.156	-0.260
-15.0	-25.0	-0.642	-1.438	-1.479	-1.427	-0.660	-0.097	-0.411
-20.0	23.0	-0.485	-0.060	-0.897	-1.424	-1.618	-1.544	-0.395
-20.0	20.0	-0.315	-0.104	-0.925	-1.447	-1.445	-1.393	-0.437
-20.0	15.0	-0.382	-0.173	-0.969	-1.349	-1.344	-1.191	-0.347
-20.0	10.0	-0.300	-0.281	-1.001	-1.242	-1.241	-1.001	-0.263
-20.0	5.0	-0.242	-0.402	-1.057	-1.213	-1.171	-0.824	-0.205
-20.0	0.0	-0.220	-0.562	-1.113	-1.194	-1.100	-0.645	-0.190
-20.0	-5.0	-0.213	-0.737	-1.186	-1.191	-1.031	-0.494	-0.181
-20.0	-10.0	-0.245	-0.915	-1.252	-1.232	-0.982	-0.359	-0.217
-20.0	-15.0	-0.304	-1.127	-1.344	-1.307	-0.925	-0.233	-0.278
-20.0	-20.0	-0.386	-1.310	-1.442	-1.412	-0.884	-0.134	-0.359
-20.0	-25.0	-0.528	-1.517	-1.566	-1.535	-0.841	-0.084	-0.449
-25.0	23.0	-0.433	-0.038	-1.103	-1.747	-1.720	-1.719	-0.702
-25.0	20.0	-0.444	-0.139	-1.139	-1.610	-1.592	-1.512	-0.568
-25.0	15.0	-0.310	-0.177	-1.171	-1.482	-1.443	-1.304	-0.472
-25.0	10.0	-0.218	-0.249	-1.194	-1.402	-1.378	-1.093	-0.392
-25.0	5.0	-0.148	-0.438	-1.234	-1.350	-1.324	-0.902	-0.342
-25.0	0.0	-0.133	-0.602	-1.274	-1.335	-1.263	-0.715	-0.308
-25.0	-5.0	-0.140	-0.794	-1.334	-1.344	-1.204	-0.515	-0.315
-25.0	-10.0	-0.149	-0.994	-1.398	-1.374	-1.171	-0.383	-0.352
-25.0	-15.0	-0.212	-1.187	-1.432	-1.444	-1.128	-0.248	-0.388
-25.0	-20.0	-0.359	-1.413	-1.535	-1.535	-1.088	-0.134	-0.497
-25.0	-25.0	-0.439	-1.623	-1.643	-1.645	-1.045	-0.061	-0.596

BEV-HOLE PRESS

HIGH ANGLE RESINE CALIBRATION PRESSURE COEFFICIENTS (Dec 64)

THETA	Phi	Cp1	Cp2	Cp3	Cp4	Cp5	Cp6	Cp7
20.00	0.00	-1.1905	-1.1111	-0.5472	-0.2057	-0.3790	-1.1131	-0.1278
20.00	3.00	-1.1881	-1.0826	-0.4840	-0.2128	-0.4213	-1.1284	-0.1271
20.00	6.00	-1.1847	-1.0545	-0.4594	-0.2237	-0.4718	-1.1429	-0.1273
20.00	9.00	-1.1812	-1.0318	-0.4491	-0.2418	-0.5243	-1.1537	-0.1272
20.00	12.00	-1.1777	-1.0140	-0.4478	-0.2617	-0.5785	-1.1629	-0.1274
20.00	15.00	-1.1744	-0.9994	-0.4460	-0.2834	-0.6337	-1.1717	-0.1274
20.00	18.00	-1.1704	-0.9864	-0.4437	-0.3070	-0.6893	-1.1800	-0.1273
20.00	21.00	-1.1657	-0.9742	-0.4404	-0.3310	-0.7452	-1.1880	-0.1271
20.00	24.00	-1.1604	-0.9624	-0.4362	-0.3562	-0.8013	-1.1946	-0.1268
20.00	27.00	-1.1545	-0.9504	-0.4310	-0.3824	-0.8575	-1.2000	-0.1264
20.00	30.00	-1.1481	-0.9384	-0.4248	-0.4094	-0.9137	-1.2042	-0.1259
20.00	33.00	-1.1412	-0.9264	-0.4176	-0.4370	-0.9699	-1.2072	-0.1253
20.00	36.00	-1.1338	-0.9144	-0.4094	-0.4650	-1.0261	-1.2090	-0.1246
20.00	39.00	-1.1259	-0.9024	-0.4004	-0.4930	-1.0823	-1.2096	-0.1238
20.00	42.00	-1.1175	-0.8904	-0.3910	-0.5210	-1.1385	-1.2090	-0.1229
20.00	45.00	-1.1087	-0.8784	-0.3810	-0.5490	-1.1947	-1.2072	-0.1219
20.00	48.00	-1.1004	-0.8664	-0.3704	-0.5770	-1.2509	-1.2042	-0.1208
20.00	51.00	-1.0916	-0.8544	-0.3594	-0.6050	-1.3071	-1.2000	-0.1196
20.00	54.00	-1.0823	-0.8424	-0.3484	-0.6330	-1.3633	-1.1946	-0.1184
20.00	57.00	-1.0725	-0.8304	-0.3374	-0.6610	-1.4195	-1.1880	-0.1171
20.00	60.00	-1.0622	-0.8184	-0.3264	-0.6890	-1.4757	-1.1800	-0.1158
20.00	63.00	-1.0514	-0.8064	-0.3154	-0.7170	-1.5319	-1.1717	-0.1144
20.00	66.00	-1.0401	-0.7944	-0.3044	-0.7450	-1.5881	-1.1629	-0.1129
20.00	69.00	-1.0283	-0.7824	-0.2934	-0.7730	-1.6443	-1.1537	-0.1114
20.00	72.00	-1.0160	-0.7704	-0.2824	-0.8010	-1.7005	-1.1429	-0.1099
20.00	75.00	-1.0032	-0.7584	-0.2714	-0.8290	-1.7567	-1.1317	-0.1084
20.00	78.00	-0.9904	-0.7464	-0.2604	-0.8570	-1.8129	-1.1196	-0.1069
20.00	81.00	-0.9776	-0.7344	-0.2494	-0.8850	-1.8691	-1.1072	-0.1054
20.00	84.00	-0.9648	-0.7224	-0.2384	-0.9130	-1.9253	-1.0946	-0.1039
20.00	87.00	-0.9519	-0.7104	-0.2274	-0.9410	-1.9815	-1.0823	-0.1024
20.00	90.00	-0.9391	-0.6984	-0.2164	-0.9690	-2.0377	-1.0699	-0.1009
20.00	93.00	-0.9263	-0.6864	-0.2054	-0.9970	-2.0939	-1.0575	-0.0994
20.00	96.00	-0.9135	-0.6744	-0.1944	-1.0250	-2.1499	-1.0451	-0.0979
20.00	99.00	-0.9007	-0.6624	-0.1834	-1.0530	-2.2059	-1.0327	-0.0964
20.00	102.00	-0.8879	-0.6504	-0.1724	-1.0810	-2.2619	-1.0203	-0.0949
20.00	105.00	-0.8751	-0.6384	-0.1614	-1.1090	-2.3179	-1.0079	-0.0934
20.00	108.00	-0.8623	-0.6264	-0.1504	-1.1370	-2.3739	-0.9955	-0.0919
20.00	111.00	-0.8495	-0.6144	-0.1394	-1.1650	-2.4299	-0.9831	-0.0904
20.00	114.00	-0.8367	-0.6024	-0.1284	-1.1930	-2.4859	-0.9707	-0.0889
20.00	117.00	-0.8239	-0.5904	-0.1174	-1.2210	-2.5419	-0.9583	-0.0874
20.00	120.00	-0.8111	-0.5784	-0.1064	-1.2490	-2.5979	-0.9459	-0.0859
20.00	123.00	-0.7983	-0.5664	-0.0954	-1.2770	-2.6539	-0.9335	-0.0844
20.00	126.00	-0.7855	-0.5544	-0.0844	-1.3050	-2.7099	-0.9211	-0.0829
20.00	129.00	-0.7727	-0.5424	-0.0734	-1.3330	-2.7659	-0.9087	-0.0814
20.00	132.00	-0.7599	-0.5304	-0.0624	-1.3610	-2.8219	-0.8963	-0.0799
20.00	135.00	-0.7471	-0.5184	-0.0514	-1.3890	-2.8779	-0.8839	-0.0784
20.00	138.00	-0.7343	-0.5064	-0.0404	-1.4170	-2.9339	-0.8715	-0.0769
20.00	141.00	-0.7215	-0.4944	-0.0294	-1.4450	-2.9899	-0.8591	-0.0754
20.00	144.00	-0.7087	-0.4824	-0.0184	-1.4730	-3.0459	-0.8467	-0.0739
20.00	147.00	-0.6959	-0.4704	-0.0074	-1.5010	-3.1019	-0.8343	-0.0724
20.00	150.00	-0.6831	-0.4584	0.0036	-1.5290	-3.1579	-0.8219	-0.0709
20.00	153.00	-0.6703	-0.4464	0.0146	-1.5570	-3.2139	-0.8095	-0.0694
20.00	156.00	-0.6575	-0.4344	0.0256	-1.5850	-3.2699	-0.7971	-0.0679
20.00	159.00	-0.6447	-0.4224	0.0366	-1.6130	-3.3259	-0.7847	-0.0664
20.00	162.00	-0.6319	-0.4104	0.0476	-1.6410	-3.3819	-0.7723	-0.0649
20.00	165.00	-0.6191	-0.3984	0.0586	-1.6690	-3.4379	-0.7599	-0.0634
20.00	168.00	-0.6063	-0.3864	0.0696	-1.6970	-3.4939	-0.7475	-0.0619
20.00	171.00	-0.5935	-0.3744	0.0806	-1.7250	-3.5499	-0.7351	-0.0604
20.00	174.00	-0.5807	-0.3624	0.0916	-1.7530	-3.6059	-0.7227	-0.0589
20.00	177.00	-0.5679	-0.3504	0.1026	-1.7810	-3.6619	-0.7103	-0.0574
20.00	180.00	-0.5551	-0.3384	0.1136	-1.8090	-3.7179	-0.6979	-0.0559
20.00	183.00	-0.5423	-0.3264	0.1246	-1.8370	-3.7739	-0.6855	-0.0544
20.00	186.00	-0.5295	-0.3144	0.1356	-1.8650	-3.8299	-0.6731	-0.0529
20.00	189.00	-0.5167	-0.3024	0.1466	-1.8930	-3.8859	-0.6607	-0.0514
20.00	192.00	-0.5039	-0.2904	0.1576	-1.9210	-3.9419	-0.6483	-0.0499
20.00	195.00	-0.4911	-0.2784	0.1686	-1.9490	-3.9979	-0.6359	-0.0484
20.00	198.00	-0.4783	-0.2664	0.1796	-1.9770	-4.0539	-0.6235	-0.0469
20.00	201.00	-0.4655	-0.2544	0.1906	-2.0050	-4.1099	-0.6111	-0.0454
20.00	204.00	-0.4527	-0.2424	0.2016	-2.0330	-4.1659	-0.5987	-0.0439
20.00	207.00	-0.4399	-0.2304	0.2126	-2.0610	-4.2219	-0.5863	-0.0424
20.00	210.00	-0.4271	-0.2184	0.2236	-2.0890	-4.2779	-0.5739	-0.0409
20.00	213.00	-0.4143	-0.2064	0.2346	-2.1170	-4.3339	-0.5615	-0.0394
20.00	216.00	-0.4015	-0.1944	0.2456	-2.1450	-4.3899	-0.5491	-0.0379
20.00	219.00	-0.3887	-0.1824	0.2566	-2.1730	-4.4459	-0.5367	-0.0364
20.00	222.00	-0.3759	-0.1704	0.2676	-2.2010	-4.5019	-0.5243	-0.0349
20.00	225.00	-0.3631	-0.1584	0.2786	-2.2290	-4.5579	-0.5119	-0.0334
20.00	228.00	-0.3503	-0.1464	0.2896	-2.2570	-4.6139	-0.4995	-0.0319
20.00	231.00	-0.3375	-0.1344	0.2996	-2.2850	-4.6699	-0.4871	-0.0304
20.00	234.00	-0.3247	-0.1224	0.3096	-2.3130	-4.7259	-0.4747	-0.0289
20.00	237.00	-0.3119	-0.1104	0.3196	-2.3410	-4.7819	-0.4623	-0.0274
20.00	240.00	-0.2991	-0.0984	0.3296	-2.3690	-4.8379	-0.4499	-0.0259
20.00	243.00	-0.2863	-0.0864	0.3396	-2.3970	-4.8939	-0.4375	-0.0244
20.00	246.00	-0.2735	-0.0744	0.3496	-2.4250	-4.9499	-0.4251	-0.0229
20.00	249.00	-0.2607	-0.0624	0.3596	-2.4530	-5.0059	-0.4127	-0.0214
20.00	252.00	-0.2479	-0.0504	0.3696	-2.4810	-5.0619	-0.4003	-0.0199
20.00	255.00	-0.2351	-0.0384	0.3796	-2.5090	-5.1179	-0.3879	-0.0184
20.00	258.00	-0.2223	-0.0264	0.3896	-2.5370	-5.1739	-0.3755	-0.0169
20.00	261.00	-0.2095	-0.0144	0.3996	-2.5650	-5.2299	-0.3631	-0.0154
20.00	264.00	-0.1967	0.0024	0.4096	-2.5930	-5.2859	-0.3507	-0.0139
20.00	267.00	-0.1839	0.0144	0.4196	-2.6210	-5.3419	-0.3383	-0.0124
20.00	270.00	-0.1711	0.0264	0.4296	-2.6490	-5.3979	-0.3259	-0.0109
20.00	273.00	-0.1583	0.0384	0.4396	-2.6770	-5.4539	-0.3135	-0.0094
20.00	276.00	-0.1455	0.0504	0.4496	-2.7050	-5.5099	-0.3011	-0.0079
20.00	279.00	-0.1327	0.0624	0.4596	-2.7330	-5.5659	-0.2887	-0.0064
20.00	282.00	-0.1199	0.0744	0.4696	-2.7610	-5.6219	-0.2763	-0.0049
20.00	285.00	-0.1071	0.0864	0.4796	-2.7890	-5.6779	-0.2639	-0.0034

25.00	-0.8393	-1.2872	-1.3149	-1.3149	-1.0438	-0.3345	-0.1694	-0.2594	30.00	230.00	-0.4722	-1.4378	-1.4942	-1.5010	-0.8624	-0.0943	-0.4534
25.00	-0.8934	-1.2962	-1.3115	-1.0774	-1.0276	-0.3031	-0.2074	-0.2233	30.00	235.00	-0.5475	-1.4357	-1.4911	-1.4779	-0.7451	-0.0844	-0.4272
25.00	-0.9678	-1.2874	-1.3012	-0.9614	-0.9043	-0.2619	-0.2483	-0.2192	30.00	240.00	-0.6237	-1.4315	-1.4913	-1.4518	-0.6818	-0.0899	-0.3948
25.00	-1.0303	-1.3074	-1.3001	-0.9003	-0.8448	-0.2192	-0.2923	-0.2183	30.00	245.00	-0.7148	-1.4812	-1.4880	-1.4298	-0.5949	-0.0799	-0.3925
25.00	-1.0839	-1.3080	-1.3022	-0.8448	-0.7778	-0.1892	-0.3500	-0.2180	30.00	250.00	-0.8015	-1.4890	-1.4959	-1.3877	-0.5080	-0.0683	-0.3903
25.00	-1.1227	-1.3232	-1.2993	-0.7778	-0.7046	-0.1676	-0.4108	-0.2184	30.00	255.00	-0.8809	-1.4902	-1.4872	-1.3484	-0.4423	-0.1021	-0.3808
25.00	-1.1740	-1.3302	-1.3007	-0.7140	-0.6410	-0.1449	-0.4723	-0.2274	30.00	260.00	-0.9618	-1.4493	-1.4456	-1.2767	-0.3414	-0.1151	-0.3617
25.00	-1.1986	-1.3240	-1.2811	-0.6210	-0.5306	-0.1306	-0.5337	-0.2284	30.00	265.00	-1.0344	-1.4492	-1.4767	-1.2067	-0.2848	-0.1375	-0.3444
25.00	-1.2390	-1.3245	-1.2617	-0.5735	-0.4734	-0.1195	-0.5914	-0.2172	30.00	270.00	-1.1203	-1.4705	-1.4794	-1.1314	-0.2230	-0.2005	-0.3355
25.00	-1.2488	-1.3419	-1.2319	-0.4849	-0.4174	-0.1093	-0.6494	-0.2287	30.00	275.00	-1.2038	-1.4414	-1.4895	-1.0621	-0.1730	-0.2692	-0.3345
25.00	-1.2801	-1.3439	-1.2156	-0.4341	-0.3613	-0.1005	-0.7054	-0.2294	30.00	280.00	-1.2644	-1.4741	-1.4964	-0.9703	-0.1340	-0.3346	-0.3435
25.00	-1.3011	-1.3386	-1.1794	-0.3784	-0.3247	-0.1005	-0.7621	-0.2327	30.00	285.00	-1.3308	-1.4807	-1.4994	-0.8879	-0.1091	-0.4042	-0.3444
25.00	-1.3190	-1.3314	-1.1413	-0.3247	-0.2849	-0.1005	-0.8206	-0.2344	30.00	290.00	-1.3707	-1.4843	-1.4951	-0.8397	-0.0907	-0.4540	-0.3448
25.00	-1.3349	-1.3333	-1.0934	-0.2849	-0.2436	-0.1005	-0.8793	-0.2391	30.00	295.00	-1.4177	-1.4907	-1.4959	-0.7247	-0.0818	-0.5041	-0.3754
25.00	-1.3319	-1.3486	-1.0304	-0.2236	-0.2036	-0.1005	-0.9382	-0.2349	30.00	300.00	-1.4510	-1.4945	-1.4819	-0.6346	-0.0747	-0.5545	-0.3778
25.00	-1.3317	-1.3374	-0.9388	-0.1978	-0.1637	-0.1005	-0.9974	-0.2349	30.00	305.00	-1.4734	-1.5039	-1.4625	-0.5521	-0.0747	-0.6045	-0.3778
25.00	-1.3348	-1.3348	-0.8967	-0.1637	-0.1375	-0.1005	-1.0568	-0.2349	30.00	310.00	-1.4938	-1.5035	-1.4237	-0.4715	-0.0827	-0.6545	-0.3778
25.00	-1.3345	-1.3345	-0.8327	-0.1375	-0.1125	-0.1005	-1.1161	-0.2349	30.00	315.00	-1.5091	-1.5035	-1.4010	-0.3857	-0.0845	-0.7045	-0.3778
25.00	-1.3302	-1.3386	-0.7573	-0.1375	-0.1005	-0.1005	-1.1794	-0.2349	30.00	320.00	-1.5242	-1.5212	-1.3718	-0.3344	-0.1051	-0.7545	-0.3778
25.00	-1.3349	-1.3302	-0.6618	-0.1275	-0.0877	-0.1005	-1.2425	-0.2349	30.00	325.00	-1.5242	-1.5183	-1.3048	-0.2836	-0.1376	-0.8045	-0.3778
25.00	-1.3098	-1.3030	-0.6423	-0.0772	-0.0609	-0.1005	-1.3077	-0.2349	30.00	330.00	-1.5147	-1.5112	-1.2348	-0.1901	-0.1796	-0.8545	-0.3778
25.00	-1.3192	-1.4980	-0.5460	-0.0877	-0.0787	-0.1005	-1.3726	-0.2349	30.00	335.00	-1.5147	-1.5112	-1.1625	-0.1349	-0.2454	-0.9045	-0.3778
25.00	-1.3102	-1.4434	-0.4390	-0.0992	-0.0739	-0.1005	-1.4375	-0.2349	30.00	340.00	-1.4991	-1.5034	-1.0377	-0.1136	-0.3125	-0.9545	-0.3778
25.00	-1.3168	-1.4344	-0.3546	-0.1283	-0.0937	-0.1005	-1.5024	-0.2349	30.00	345.00	-1.5087	-1.5035	-0.9784	-0.0936	-0.3747	-1.0045	-0.3778
25.00	-1.3117	-1.3845	-0.2734	-0.1739	-0.1005	-0.1005	-1.5673	-0.2349	30.00	350.00	-1.5141	-1.5209	-0.8460	-0.0831	-0.4729	-1.0545	-0.3778
25.00	-1.3028	-1.3777	-0.2012	-0.2213	-0.1005	-0.1005	-1.6322	-0.2349	30.00	355.00	-1.5042	-1.5209	-0.7548	-0.0744	-0.5746	-1.1045	-0.3778
25.00	-1.3158	-1.3727	-0.1399	-0.2946	-0.1005	-0.1005	-1.6971	-0.2349	30.00	360.00	-1.4648	-1.5124	-0.7349	-0.0299	-0.7437	-1.1545	-0.3778
25.00	-1.3247	-1.3730	-0.1161	-0.3795	-0.1005	-0.1005	-1.7620	-0.2349	30.00	365.00	-1.4742	-1.5124	-0.6001	-0.0388	-0.8089	-1.2045	-0.3778
25.00	-1.3178	-1.4210	-0.0819	-0.4649	-0.1005	-0.1005	-1.8269	-0.2349	30.00	370.00	-1.4696	-1.5004	-0.4874	-0.0463	-0.8738	-1.2545	-0.3778
25.00	-1.3150	-1.4231	-0.0709	-0.5474	-0.1005	-0.1005	-1.8918	-0.2349	30.00	375.00	-1.4701	-1.5004	-0.3600	-0.0544	-0.9387	-1.3045	-0.3778
25.00	-1.3200	-1.4284	-0.0431	-0.6309	-0.1005	-0.1005	-1.9567	-0.2349	30.00	380.00	-1.4701	-1.5004	-0.2325	-0.0625	-1.0036	-1.3545	-0.3778
25.00	-1.3200	-1.4284	-0.0431	-0.7134	-0.1005	-0.1005	-2.0216	-0.2349	30.00	385.00	-1.4701	-1.5004	-0.1050	-0.0706	-1.0685	-1.4045	-0.3778
25.00	-1.3116	-0.8211	-0.0437	-0.7960	-0.1005	-0.1005	-2.0865	-0.2349	30.00	390.00	-1.4701	-1.5004	0.0225	-0.0787	-1.1234	-1.4545	-0.3778
25.00	-1.4441	-0.7671	-0.0490	-0.8789	-0.1005	-0.1005	-2.1514	-0.2349	30.00	395.00	-1.4701	-1.5004	0.1500	-0.0868	-1.1823	-1.5045	-0.3778
25.00	-1.4441	-0.7671	-0.0490	-0.9614	-0.1005	-0.1005	-2.2163	-0.2349	30.00	400.00	-1.4701	-1.5004	0.2775	-0.0949	-1.2412	-1.5545	-0.3778
25.00	-1.4441	-0.7671	-0.0490	-1.0444	-0.1005	-0.1005	-2.2812	-0.2349	30.00	405.00	-1.4701	-1.5004	0.4050	-0.1030	-1.3001	-1.6045	-0.3778
25.00	-1.4441	-0.7671	-0.0490	-1.1269	-0.1005	-0.1005	-2.3461	-0.2349	30.00	410.00	-1.4701	-1.5004	0.5325	-0.1111	-1.3590	-1.6545	-0.3778
25.00	-1.4441	-0.7671	-0.0490	-1.2094	-0.1005	-0.1005	-2.4110	-0.2349	30.00	415.00	-1.4701	-1.5004	0.6600	-0.1192	-1.4179	-1.7045	-0.3778
25.00	-1.4441	-0.7671	-0.0490	-1.2919	-0.1005	-0.1005	-2.4759	-0.2349	30.00	420.00	-1.4701	-1.5004	0.7875	-0.1273	-1.4768	-1.7545	-0.3778
25.00	-1.4441	-0.7671	-0.0490	-1.3744	-0.1005	-0.1005	-2.5408	-0.2349	30.00	425.00	-1.4701	-1.5004	0.9150	-0.1354	-1.5357	-1.8045	-0.3778
25.00	-1.4441	-0.7671	-0.0490	-1.4569	-0.1005	-0.1005	-2.6057	-0.2349	30.00	430.00	-1.4701	-1.5004	1.0425	-0.1435	-1.5946	-1.8545	-0.3778
25.00	-1.4441	-0.7671	-0.0490	-1.5394	-0.1005	-0.1005	-2.6706	-0.2349	30.00	435.00	-1.4701	-1.5004	1.1700	-0.1516	-1.6535	-1.9045	-0.3778
25.00	-1.4441	-0.7671	-0.0490	-1.6219	-0.1005	-0.1005	-2.7355	-0.2349	30.00	440.00	-1.4701	-1.5004	1.2975	-0.1597	-1.7124	-1.9545	-0.3778
25.00	-1.4441	-0.7671	-0.0490	-1.7044	-0.1005	-0.1005	-2.8004	-0.2349	30.00	445.00	-1.4701	-1.5004	1.4250	-0.1678	-1.7713	-2.0045	-0.3778
25.00	-1.4441	-0.7671	-0.0490	-1.7869	-0.1005	-0.1005	-2.8653	-0.2349	30.00	450.00	-1.4701	-1.5004	1.5525	-0.1759	-1.8302	-2.0545	-0.3778
25.00	-1.4441	-0.7671	-0.0490	-1.8694	-0.1005	-0.1005	-2.9302	-0.2349	30.00	455.00	-1.4701	-1.5004	1.6800	-0.1840	-1.8891	-2.1045	-0.3778
25.00	-1.4441	-0.7671	-0.0490	-1.9519	-0.1005	-0.1005	-2.9951	-0.2349	30.00	460.00	-1.4701	-1.5004	1.8075	-0.1921	-1.9480	-2.1545	-0.3778
25.00	-1.4441	-0.7671	-0.0490	-2.0344	-0.1005	-0.1005	-3.0600	-0.2349	30.00	465.00	-1.4701	-1.5004	1.9350	-0.2002	-2.0069	-2.2045	-0.3778
25.00	-1.4441	-0.7671	-0.0490	-2.1169	-0.1005	-0.1005	-3.1249	-0.2349	30.00	470.00	-1.4701	-1.5004	2.0625	-0.2083	-2.0658	-2.2545	-0.3778
25.00	-1.4441	-0.7671	-0.0490	-2.1994	-0.1005	-0.1005	-3.1898	-0.2349	30.00	475.00	-1.4701	-1.5004	2.1900	-0.2164	-2.1247	-2.3045	-0.3778
25.00	-1.4441	-0.7671	-0.0490	-2.2819	-0.1005	-0.1005	-3.2547	-0.2349	30.00	480.00	-1.4701	-1.5004	2.3175	-0.2245	-2.1836	-2.3545	-0.3778
25.00	-1.4441	-0.7671	-0.0490	-2.3644	-0.1005	-0.1005	-3.3196	-0.2349	30.00	485.00	-1.4701	-1.5004	2.4450	-0.2326	-2.2425	-2.4045	-0.3778
25.00	-1.4441	-0.7671	-0.0490	-2.4469	-0.1005	-0.1005	-3.3845	-0.2349	30.00	490.00	-1.4701	-1.5004	2.5725	-0.2407	-2.3014	-2.4545	-0.3778
25.00	-1.4441	-0.7671	-0.0490	-2.5294	-0.1005	-0.1005	-3.4494	-0.2349	30.00	495.00	-1.4701	-1.5004	2.7000	-0.2488	-2.3603	-2.5045	-0.3778
25.00	-1.4441	-0.7671	-0.0490	-2.6119	-0.1005	-0.1005	-3.5143	-0.2349	30.00	500.00	-1.4701	-1.5004	2.8275	-0.2569	-2.4192	-2.5545	-0.3778
25.00	-1.4441	-0.7671	-0.0490	-2.6944	-0.1005	-0.1005	-3.5792	-0.2349	30.00	505.00	-1.4701	-1.5004	2.9550	-0.2650	-2.4781	-2.6045	-0.3778
25.00	-1.4441	-0.7671	-0.0490	-2.7769	-0.1005	-0.1005	-3.6441	-0.2349	30.00	510.00	-1.4701	-1.5004	3.0825	-0.2731	-2.5370	-2.6545	-0.3778
25.00	-1.4441	-0.7671	-0.0490	-2.8594	-0.1005	-0.1005	-3.7090	-0.2349	30.00	515.00	-1.4701	-1.5004	3.2100	-0.2812	-2.5959	-2.7045	-0.3778
25.00	-1.4441	-0.7671	-0.0490	-2.9419	-0.1005	-0.1005	-3.7739	-0.2349	30.00	520.00	-1.4701	-1.5004	3.3375	-0.2893	-2.6548	-2.7545	-0.3778
25.00	-1.4441	-0.7671	-0.0490	-3.0244	-0.1005	-0.1005	-3.8388	-0.2349	30.00	525.00	-1.4701	-1.5004	3.4650	-0.2974	-2.7137	-2.8045	-0.3778
25.00	-1.4441	-0.7671	-0.0490	-3.1069	-0.1005	-0.1005	-3.9037	-0.2349	30.00	530.00	-1.4701	-1.5004	3.5925	-0.3055	-2.7726	-2.8545	-0.3778
25.00	-1.4441	-0.7671	-0.0490	-3.1894	-0												

35.00	208.00	-0.0967	-1.2932	-1.6358	-1.6181	-1.4578	-0.3730	-0.6344	40.00	170.00	-0.0549	-0.3255	-1.8128	-1.7539	-1.8133	-1.3786	-0.8442
35.00	209.00	-0.1364	-1.4093	-1.6356	-1.6316	-1.4075	-0.2927	-0.6413	40.00	175.00	-0.0234	-0.6808	-1.8361	-1.7472	-1.8195	-1.2375	-0.8433
35.00	210.00	-0.1971	-1.4852	-1.6406	-1.6540	-1.3050	-0.1982	-0.6307	40.00	180.00	-0.0172	-0.8627	-1.8366	-1.7135	-1.7930	-1.0413	-0.8561
35.00	215.00	-0.2697	-1.5668	-1.6504	-1.6990	-1.2375	-0.1301	-0.6418	40.00	185.00	-0.0113	-1.0378	-1.8372	-1.7465	-1.7781	-0.8467	-0.8501
35.00	220.00	-0.3558	-1.6399	-1.6515	-1.7042	-1.1577	-0.1003	-0.6384	40.00	190.00	-0.0149	-1.2136	-1.8282	-1.7504	-1.7471	-0.6732	-0.8407
35.00	225.00	-0.4470	-1.6433	-1.6509	-1.7125	-1.0907	-0.0728	-0.6297	40.00	195.00	-0.0491	-1.3944	-1.8241	-1.7828	-1.6903	-0.5149	-0.8409
35.00	230.00	-0.5503	-1.6981	-1.6598	-1.7261	-1.0502	-0.0437	-0.6237	40.00	200.00	-0.0869	-1.5814	-1.8266	-1.8031	-1.6274	-0.3631	-0.8326
35.00	235.00	-0.6721	-1.6947	-1.6694	-1.7047	-0.9934	-0.0379	-0.6073	40.00	205.00	-0.1499	-1.8489	-1.8261	-1.8370	-1.5671	-0.2663	-0.8430
35.00	240.00	-0.8284	-1.6927	-1.6371	-1.6812	-0.7533	-0.0338	-0.6013	40.00	210.00	-0.2424	-2.1714	-1.8271	-1.8621	-1.4903	-0.1822	-0.8424
35.00	245.00	-0.9382	-1.6921	-1.6359	-1.6539	-0.6421	-0.0338	-0.5813	40.00	215.00	-0.3304	-2.5436	-1.8273	-1.8928	-1.3803	-0.1049	-0.8496
35.00	250.00	-0.9738	-1.6779	-1.6187	-1.6119	-0.5474	-0.0397	-0.5739	40.00	220.00	-0.4342	-2.9695	-1.8273	-1.9134	-1.2737	-0.0472	-0.8374
35.00	255.00	-1.0413	-1.6760	-1.6235	-1.5730	-0.4613	-0.0351	-0.5742	40.00	225.00	-0.5196	-3.4542	-1.8142	-1.9183	-1.1816	-0.0310	-0.8484
35.00	260.00	-1.1082	-1.6465	-1.6162	-1.4900	-0.3618	-0.0817	-0.5310	40.00	230.00	-0.6314	-3.9376	-1.8194	-1.9498	-1.0430	-0.0108	-0.8311
35.00	265.00	-1.2278	-1.6300	-1.6271	-1.4042	-0.2482	-0.1104	-0.5430	40.00	235.00	-0.7632	-4.4552	-1.8211	-1.9316	-0.9442	-0.0103	-0.8317
35.00	270.00	-1.3984	-1.6258	-1.6336	-1.3173	-0.2026	-0.1743	-0.5344	40.00	240.00	-0.8636	-4.9368	-1.8079	-1.9434	-0.8347	-0.0103	-0.8317
35.00	275.00	-1.5293	-1.6223	-1.6359	-1.2417	-0.1400	-0.2413	-0.5433	40.00	245.00	-0.9792	-5.4168	-1.8033	-1.9077	-0.7232	-0.0075	-0.8232
35.00	280.00	-1.6777	-1.6243	-1.6822	-1.1436	-0.1037	-0.3378	-0.5734	40.00	250.00	-1.0924	-5.8942	-1.7948	-1.8592	-0.6236	-0.0143	-0.8075
35.00	285.00	-1.8244	-1.6227	-1.6760	-1.0379	-0.0722	-0.4292	-0.5542	40.00	255.00	-1.2009	-6.3676	-1.7897	-1.8020	-0.4866	-0.0774	-0.7793
35.00	290.00	-1.9843	-1.6328	-1.6966	-0.9313	-0.0436	-0.5292	-0.5653	40.00	260.00	-1.3104	-6.8459	-1.7833	-1.7189	-0.3903	-0.0479	-0.7634
35.00	295.00	-2.1660	-1.6437	-1.7077	-0.8487	-0.0418	-0.6396	-0.5855	40.00	265.00	-1.4119	-7.3226	-1.8000	-1.6361	-0.2914	-0.1034	-0.7444
35.00	300.00	-2.3575	-1.6466	-1.6994	-0.7437	-0.0336	-0.7642	-0.5900	40.00	270.00	-1.5094	-7.7932	-1.8062	-1.5378	-0.1994	-0.1537	-0.7548
35.00	305.00	-2.5579	-1.6598	-1.6961	-0.6350	-0.0207	-0.8781	-0.5913	40.00	275.00	-1.5934	-8.2532	-1.8340	-1.4484	-0.1347	-0.2518	-0.7662
35.00	310.00	-2.7114	-1.6803	-1.6849	-0.5428	-0.0312	-1.0072	-0.6123	40.00	280.00	-1.6812	-8.7143	-1.8535	-1.3402	-0.0804	-0.3523	-0.7781
35.00	315.00	-2.8289	-1.6747	-1.6421	-0.4413	-0.0363	-1.1312	-0.6121	40.00	285.00	-1.7458	-9.1740	-1.8744	-1.2222	-0.0235	-0.3940	-0.7941
35.00	320.00	-2.9148	-1.6775	-1.6005	-0.3508	-0.0672	-1.2512	-0.6079	40.00	290.00	-1.8088	-9.6337	-1.8903	-1.1124	-0.0235	-0.3940	-0.8119
35.00	325.00	-2.9794	-1.7046	-1.4777	-0.1948	-0.0391	-1.3711	-0.6079	40.00	295.00	-1.8622	-10.0932	-1.9131	-0.9969	-0.0167	-0.7179	-0.8119
35.00	330.00	-3.0374	-1.7091	-1.3902	-0.1380	-0.0364	-1.4911	-0.6153	40.00	300.00	-1.9081	-10.5529	-1.9316	-0.8867	-0.0091	-0.8543	-0.8247
35.00	335.00	-3.0891	-1.7258	-1.2611	-0.0958	-0.2036	-1.6103	-0.6025	40.00	305.00	-1.9796	-11.0125	-1.9228	-0.6335	-0.0123	-1.1310	-0.8426
35.00	340.00	-3.1451	-1.7268	-1.1470	-0.0844	-0.3789	-1.7349	-0.5877	40.00	310.00	-1.9361	-11.4704	-1.9080	-0.5434	-0.0172	-1.2931	-0.8328
35.00	345.00	-3.1963	-1.7268	-1.0470	-0.0844	-0.5789	-1.8641	-0.5877	40.00	315.00	-1.9136	-11.9270	-1.8591	-0.4220	-0.0308	-1.4110	-0.8471
35.00	350.00	-3.2430	-1.7333	-0.9215	-0.0396	-0.8791	-1.7011	-0.5846	40.00	320.00	-1.9003	-12.3821	-1.7964	-0.3344	-0.0433	-1.5132	-0.8534
35.00	355.00	-3.2850	-1.7321	-0.8826	-0.0383	-0.6144	-1.7251	-0.5808	40.00	325.00	-1.8919	-12.8370	-1.7540	-0.2382	-0.1107	-1.6275	-0.8435
40.00	0.00	-1.8272	-1.7381	-0.8561	-0.0162	-0.8441	-1.9489	-0.7717	40.00	330.00	-1.8843	-13.2919	-1.6370	-0.1316	-0.1847	-1.7132	-0.8197
40.00	5.00	-1.8323	-1.7440	-0.6783	-0.0299	-1.0240	-1.9658	-0.7926	40.00	335.00	-1.8637	-13.7464	-1.4576	-0.0966	-0.2746	-1.7828	-0.8131
40.00	10.00	-1.8422	-1.7311	-0.5315	-0.0474	-1.1613	-1.9500	-0.8131	40.00	340.00	-1.8428	-14.2014	-1.2476	-0.0578	-0.3775	-1.8586	-0.7998
40.00	15.00	-1.8790	-1.6641	-0.2692	-0.1782	-1.4711	-1.9144	-0.8601	40.00	345.00	-1.8371	-14.6564	-1.0790	-0.0171	-0.5201	-1.9049	-0.7840
40.00	20.00	-1.8737	-1.7946	-0.1222	-0.2757	-1.5936	-1.9039	-0.8940	40.00	350.00	-1.8392	-15.1114	-0.9297	-0.0162	-0.6724	-1.9443	-0.7744
40.00	25.00	-1.8748	-1.6644	-0.0982	-0.4206	-1.6830	-1.8810	-0.8934	45.00	0.00	-1.9476	-15.5664	-0.7537	-0.0087	-0.8280	-2.1287	-0.9984
40.00	30.00	-1.8999	-1.5001	-0.0362	-0.5684	-1.8343	-1.8542	-0.9344	45.00	5.00	-1.9488	-16.0214	-0.5537	-0.0112	-1.1422	-2.1038	-0.9984
40.00	35.00	-1.9203	-1.3884	-0.0095	-0.8047	-1.8882	-1.8548	-0.9312	45.00	10.00	-1.9673	-16.4764	-0.3784	-0.0401	-1.3425	-2.0493	-1.0315
40.00	40.00	-1.9472	-1.2534	-0.0040	-0.9991	-1.8943	-1.8295	-0.9423	45.00	15.00	-1.9849	-16.9314	-0.2807	-0.0274	-1.5112	-2.0299	-1.0594
40.00	45.00	-1.9702	-1.2534	-0.0040	-0.9991	-1.8943	-1.8295	-0.9423	45.00	20.00	-1.9849	-17.3864	-0.2807	-0.0274	-1.5112	-2.0299	-1.0594
40.00	50.00	-1.9702	-1.2534	-0.0040	-0.9991	-1.8943	-1.8295	-0.9423	45.00	25.00	-1.9849	-17.8414	-0.2807	-0.0274	-1.5112	-2.0299	-1.0594
40.00	55.00	-1.9702	-1.2534	-0.0040	-0.9991	-1.8943	-1.8295	-0.9423	45.00	30.00	-1.9849	-18.2964	-0.2807	-0.0274	-1.5112	-2.0299	-1.0594
40.00	60.00	-1.9702	-1.2534	-0.0040	-0.9991	-1.8943	-1.8295	-0.9423	45.00	35.00	-1.9849	-18.7514	-0.2807	-0.0274	-1.5112	-2.0299	-1.0594
40.00	65.00	-1.9702	-1.2534	-0.0040	-0.9991	-1.8943	-1.8295	-0.9423	45.00	40.00	-1.9849	-19.2064	-0.2807	-0.0274	-1.5112	-2.0299	-1.0594
40.00	70.00	-1.9702	-1.2534	-0.0040	-0.9991	-1.8943	-1.8295	-0.9423	45.00	45.00	-1.9849	-19.6614	-0.2807	-0.0274	-1.5112	-2.0299	-1.0594
40.00	75.00	-1.9702	-1.2534	-0.0040	-0.9991	-1.8943	-1.8295	-0.9423	45.00	50.00	-1.9849	-20.1164	-0.2807	-0.0274	-1.5112	-2.0299	-1.0594
40.00	80.00	-1.9702	-1.2534	-0.0040	-0.9991	-1.8943	-1.8295	-0.9423	45.00	55.00	-1.9849	-20.5714	-0.2807	-0.0274	-1.5112	-2.0299	-1.0594
40.00	85.00	-1.9702	-1.2534	-0.0040	-0.9991	-1.8943	-1.8295	-0.9423	45.00	60.00	-1.9849	-21.0264	-0.2807	-0.0274	-1.5112	-2.0299	-1.0594
40.00	90.00	-1.9702	-1.2534	-0.0040	-0.9991	-1.8943	-1.8295	-0.9423	45.00	65.00	-1.9849	-21.4814	-0.2807	-0.0274	-1.5112	-2.0299	-1.0594
40.00	95.00	-1.9702	-1.2534	-0.0040	-0.9991	-1.8943	-1.8295	-0.9423	45.00	70.00	-1.9849	-21.9364	-0.2807	-0.0274	-1.5112	-2.0299	-1.0594
40.00	100.00	-1.9702	-1.2534	-0.0040	-0.9991	-1.8943	-1.8295	-0.9423	45.00	75.00	-1.9849	-22.3914	-0.2807	-0.0274	-1.5112	-2.0299	-1.0594
40.00	105.00	-1.9702	-1.2534	-0.0040	-0.9991	-1.8943	-1.8295	-0.9423	45.00	80.00	-1.9849	-22.8464	-0.2807	-0.0274	-1.5112	-2.0299	-1.0594
40.00	110.00	-1.9702	-1.2534	-0.0040	-0.9991	-1.8943	-1.8295	-0.9423	45.00	85.00	-1.9849	-23.3014	-0.2807	-0.0274	-1.5112	-2.0299	-1.0594
40.00	115.00	-1.9702	-1.2534	-0.0040	-0.9991	-1.8943	-1.8295	-0.9423	45.00	90.00	-1.9849	-23.7564	-0.2807	-0.0274	-1.5112	-2.0299	-1.0594
40.00	120.00	-1.9702	-1.2534	-0.0040	-0.9991	-1.8943	-1.8295	-0.9423	45.00	95.00	-1.9849	-24.2114	-0.2807	-0.0274	-1.5112	-2.0299	-1.0594
40.00	125.00	-1.9702	-1.2534	-0.0040	-0.9991	-1.8943	-1.8295	-0.9423	45.00	100.00	-1.9849	-24.6664	-0.2807	-0.0274	-1.5112	-2.0299	-1.0594
40.00	130.00	-1.9702	-1.2534	-0.0040	-0.9991	-1.8943	-1.8295	-0.9423	45.00	105.00	-1.9849	-25.1214	-0.2807	-0.0274	-1.5112	-2.0299	-1.0594
40.00	135.00	-1.9702	-1.2534	-0.0040	-0.9991	-1.8943	-1.8295	-0.9423	45.00	110.00	-1.9849	-25.5764	-0.2807	-0.0274	-1.5112	-2.0299	-1.0594
40.00	140.00	-1.9702	-1.2534	-0.0040	-0.9991	-1.8943	-1.8295	-0.9423	45.00	115.00	-1.9849	-26.0314	-0.2807	-0.0274	-1.5112	-2.0299	-1.0594
40.00	145.00	-1.9702	-1.2534	-0.0040	-0.9991												

50.00	110.00	-1.7105	-0.0443	-0.9345	-2.4152	-2.1044	-2.1243	-1.4423
50.00	115.00	-1.4058	-0.0425	-1.1152	-2.4081	-2.1244	-2.1770	-1.5045
50.00	120.00	-1.4920	-0.0295	-1.2541	-2.3796	-2.1209	-2.1757	-1.5108
50.00	125.00	-1.5616	-0.0221	-1.3744	-2.3237	-2.1230	-2.2395	-1.5076
50.00	130.00	-1.7255	-0.0262	-1.5460	-2.2608	-2.1334	-2.3044	-1.5491
50.00	135.00	-1.1288	-0.0406	-1.6564	-2.2268	-2.1406	-2.3709	-1.5564
50.00	140.00	-1.0087	-0.0438	-1.7430	-2.2030	-2.1217	-2.4083	-1.5905
50.00	145.00	-0.8601	-0.0728	-1.8775	-2.1831	-2.1281	-2.4339	-1.5947
50.00	150.00	-0.6868	-0.1131	-2.0217	-2.1714	-2.1248	-2.3934	-1.5280
50.00	155.00	-0.4875	-0.1728	-2.1132	-2.1370	-2.1051	-2.2914	-1.4825
50.00	160.00	-0.3449	-0.3013	-2.1708	-2.0916	-2.1134	-2.1710	-1.4612
50.00	165.00	-0.1947	-0.4714	-2.2277	-2.0441	-2.1049	-2.0108	-1.4264
50.00	170.00	-0.0948	-0.6379	-2.2473	-2.0038	-2.0843	-1.7988	-1.3972
50.00	175.00	-0.0349	-0.8801	-2.2111	-1.9899	-2.1127	-1.6008	-1.3550
50.00	180.00	-0.0107	-1.1288	-2.1597	-1.9747	-2.1338	-1.3503	-1.3353
50.00	185.00	-0.0148	-1.3931	-2.1116	-1.9801	-2.1779	-1.0966	-1.3398
50.00	190.00	-0.0395	-1.6598	-2.0911	-2.0119	-2.1566	-0.8442	-1.3494
50.00	195.00	-0.0934	-1.8849	-2.0987	-2.0438	-2.1148	-0.6196	-1.3421
50.00	200.00	-0.1975	-2.0898	-2.1059	-2.0899	-2.0204	-0.4222	-1.3804
50.00	205.00	-0.3282	-2.2378	-2.1131	-2.1055	-1.9177	-0.2921	-1.4301
50.00	210.00	-0.4844	-2.3714	-2.1114	-2.1172	-1.8034	-0.1748	-1.4903
50.00	215.00	-0.6031	-2.4045	-2.1039	-2.1220	-1.6646	-0.1139	-1.5694
50.00	220.00	-0.7451	-2.4509	-2.1107	-2.1478	-1.5493	-0.0844	-1.6328
50.00	225.00	-0.8491	-2.4308	-2.1042	-2.1402	-1.4544	-0.0527	-1.6485
50.00	230.00	-1.0105	-2.3949	-2.0948	-2.2070	-1.3277	-0.0331	-1.6127
50.00	235.00	-1.1154	-2.3503	-2.0942	-2.3126	-1.2079	-0.0259	-1.6106
50.00	240.00	-1.1948	-2.2973	-2.0756	-2.3340	-1.0949	-0.0128	-1.5841
50.00	245.00	-1.2748	-2.2444	-2.0677	-2.3449	-0.9753	-0.0199	-1.5335
50.00	250.00	-1.4127	-2.1824	-2.0418	-2.3205	-0.7884	-0.0161	-1.2994
50.00	255.00	-1.5567	-2.1619	-2.0421	-2.2810	-0.6437	-0.0391	-1.2680
50.00	260.00	-1.6845	-2.1323	-2.0430	-2.2103	-0.5262	-0.0873	-1.2585
50.00	265.00	-1.7925	-2.1014	-2.0317	-2.1049	-0.4446	-0.1215	-1.2449
50.00	270.00	-2.0248	-2.0712	-2.0742	-1.9743	-0.3374	-0.2209	-1.2249
50.00	275.00	-2.0284	-2.0410	-2.0891	-1.8839	-0.1792	-0.3343	-1.2613
50.00	280.00	-2.1345	-2.0404	-2.1198	-1.7588	-0.1090	-0.4708	-1.2942
50.00	285.00	-2.2040	-2.0422	-2.1341	-1.6103	-0.0720	-0.4234	-1.3014
50.00	290.00	-2.2432	-2.0497	-2.1344	-1.5074	-0.0438	-0.7734	-1.3320
50.00	295.00	-2.2834	-2.0541	-2.1845	-1.3774	-0.0438	-0.9240	-1.3438
50.00	300.00	-2.3035	-2.0439	-2.1992	-1.2424	-0.0247	-1.1120	-1.3841
50.00	305.00	-2.2440	-2.0444	-2.2694	-1.1344	-0.0227	-1.2620	-1.4003
50.00	310.00	-2.2297	-2.0794	-2.3199	-1.0129	-0.0223	-1.3926	-1.4069
50.00	315.00	-2.1616	-2.0821	-2.3908	-0.9222	-0.0376	-1.5204	-1.4150
50.00	320.00	-2.1449	-2.0911	-2.3448	-0.8018	-0.0357	-1.6342	-1.4152
50.00	325.00	-2.1226	-2.0775	-2.3414	-0.6437	-0.0478	-1.7503	-1.4024
50.00	330.00	-2.1240	-2.1048	-2.2904	-0.4828	-0.1047	-1.9084	-1.3895
50.00	335.00	-2.1272	-2.1182	-2.1348	-0.3325	-0.1714	-2.0522	-1.3514
50.00	340.00	-2.1249	-2.1201	-1.9909	-0.1939	-0.2901	-2.1748	-1.3114
50.00	345.00	-2.1231	-2.1249	-1.7931	-0.0960	-0.4534	-2.3133	-1.2794
50.00	350.00	-2.0778	-2.1334	-1.5498	-0.0371	-0.8181	-2.4420	-1.2420
50.00	355.00	-2.0714	-2.1783	-1.3502	-0.0140	-0.8560	-2.5444	-1.2211

45.00	140.00	-0.7915	-0.0273	-1.6171	-2.1054	-2.0140	-2.2289	-1.2348
45.00	145.00	-0.6319	-0.0397	-1.7032	-2.0715	-2.0087	-2.2034	-1.2348
45.00	150.00	-0.5208	-0.1005	-1.8109	-2.0347	-2.0095	-2.1726	-1.2530
45.00	155.00	-0.3453	-0.1849	-1.8843	-2.0246	-2.0039	-2.0824	-1.2534
45.00	160.00	-0.2347	-0.2873	-1.9838	-1.9736	-1.9973	-1.9739	-1.1844
45.00	165.00	-0.1224	-0.4180	-2.0144	-1.9285	-1.9779	-1.7541	-1.1734
45.00	170.00	-0.0413	-0.5884	-2.0283	-1.9004	-1.9473	-1.5976	-1.1353
45.00	175.00	-0.0708	-0.7850	-2.0381	-1.8745	-1.9778	-1.3831	-1.0718
45.00	180.00	-0.0046	-0.9972	-2.0087	-1.8614	-1.9450	-1.1393	-1.0171
45.00	185.00	-0.0075	-1.2345	-1.9935	-1.8718	-1.9481	-0.9311	-0.9790
45.00	190.00	-0.0212	-1.4577	-1.9737	-1.8934	-1.9153	-0.7139	-1.0804
45.00	195.00	-0.0348	-1.6344	-1.9725	-1.9175	-1.9073	-0.5432	-1.1043
45.00	200.00	-0.1193	-1.8295	-1.9839	-1.9791	-1.8528	-0.4015	-1.1202
45.00	205.00	-0.2203	-1.9744	-1.9880	-2.0234	-1.7407	-0.2422	-1.1229
45.00	210.00	-0.3244	-2.0752	-1.9824	-2.0422	-1.6491	-0.1743	-1.1329
45.00	215.00	-0.4313	-2.1450	-1.9995	-2.0714	-1.5445	-0.0965	-1.1325
45.00	220.00	-0.5760	-2.1919	-1.9921	-2.1130	-1.4364	-0.0435	-1.1476
45.00	225.00	-0.6921	-2.2213	-1.9844	-2.1429	-1.3373	-0.0338	-1.1457
45.00	230.00	-0.8161	-2.2327	-1.9844	-2.1721	-1.2280	-0.0148	-1.1437
45.00	235.00	-0.9402	-2.1804	-1.9491	-2.1909	-1.1002	-0.0030	-1.1129
45.00	240.00	-1.0411	-2.1364	-1.8748	-2.1821	-0.9719	-0.0035	-1.1070
45.00	245.00	-1.1140	-2.1207	-1.7500	-2.1522	-0.8442	-0.0032	-1.0357
45.00	250.00	-1.1253	-2.0939	-1.6405	-2.1245	-0.7305	-0.0144	-1.0418
45.00	255.00	-1.3411	-2.0359	-1.9254	-2.0580	-0.5790	-0.0259	-1.0104
45.00	260.00	-1.4781	-2.0004	-1.9148	-1.9727	-0.4570	-0.0350	-0.9837
45.00	265.00	-1.6049	-1.9494	-1.9321	-1.8749	-0.3377	-0.0987	-0.9837
45.00	270.00	-1.6998	-1.9264	-1.9320	-1.7553	-0.2177	-0.1782	-0.9719
45.00	275.00	-1.7978	-1.9243	-1.9808	-1.6338	-0.1407	-0.2794	-0.9937
45.00	280.00	-1.8974	-1.9148	-1.9993	-1.5385	-0.0905	-0.4039	-0.9937
45.00	285.00	-1.9771	-1.9145	-2.0458	-1.4012	-0.0437	-0.5283	-1.0303
45.00	290.00	-2.0284	-1.9244	-2.0707	-1.3031	-0.0144	-0.6812	-1.0541
45.00	295.00	-2.0712	-1.9381	-2.0875	-1.1735	-0.0135	-0.8440	-1.0728
45.00	300.00	-2.1182	-1.9318	-2.1393	-1.0423	-0.0094	-0.9976	-1.1139
45.00	305.00	-2.1229	-1.9410	-2.1524	-0.9433	-0.0042	-1.1375	-1.1236
45.00	310.00	-2.1211	-1.9734	-2.1592	-0.8409	-0.0031	-1.2915	-1.1531
45.00	315.00	-2.1117	-1.9835	-2.1599	-0.7122	-0.0084	-1.4158	-1.1354
45.00	320.00	-2.0917	-1.9879	-2.1154	-0.5777	-0.0340	-1.5721	-1.1240
45.00	325.00	-2.0408	-1.9859	-2.0492	-0.4457	-0.0435	-1.6941	-1.1111
45.00	330.00	-2.0446	-2.0134	-1.9274	-0.3245	-0.1357	-1.8944	-1.1072
45.00	335.00	-2.0057	-2.0189	-1.7536	-0.1159	-0.2741	-2.1038	-1.0374
45.00	340.00	-1.9401	-2.0348	-1.5817	-0.0947	-0.5050	-2.1507	-1.0244
45.00	345.00	-1.8448	-2.0476	-1.3842	-0.0705	-0.7439	-2.1374	-0.9844
45.00	350.00	-1.7473	-2.0596	-1.1870	-0.0168	-0.9719	-2.1495	-1.0041
45.00	355.00	-1.6473	-2.0796	-0.9749	-0.0083	-1.0215	-2.4532	-1.0124
45.00	360.00	-1.5417	-2.1109	-0.8537	-0.0283	-1.2828	-2.4532	-1.0124
45.00	365.00	-1.4448	-2.1580	-0.8222	-0.0903	-1.5078	-2.3734	-1.0734
45.00	370.00	-1.3442	-2.1278	-0.6424	-0.1840	-1.7125	-2.3734	-1.0734
45.00	375.00	-1.2494	-2.1279	-0.2879	-0.3435	-1.8992	-2.1002	-1.4638
45.00	380.00	-1.1547	-2.1761	-0.1838	-0.5149	-2.0550	-2.0927	-1.4637
45.00	385.00	-1.0547	-2.0800	-0.1104	-0.7233	-2.1908	-2.0945	-1.4351
45.00	390.00	-0.9448	-1.9791	-0.0706	-0.9243	-2.2812	-2.0935	-1.4798
45.00	395.00	-0.8243	-1.7733	-0.0419	-1.0944	-2.3174	-2.0604	-1.4910
45.00	400.00	-0.6949	-1.6430	-0.0345	-1.2594	-2.3277	-2.0551	-1.4910
45.00	405.00	-0.5604	-1.5338	-0.0303	-1.3884	-2.3042	-2.0525	-1.4944
45.00	410.00	-0.4248	-1.4434	-0.0289	-1.4942	-2.2111	-2.0338	-1.4878
45.00	415.00	-0.2873	-1.3634	-0.0331	-1.5988	-2.0485	-2.0443	-1.4752
45.00	420.00	-0.1499	-1.2838	-0.0372	-1.6970	-1.8485	-2.0443	-1.4552
45.00	425.00	-0.0149	-1.2043	-0.0471	-1.7920	-1.5748	-2.0249	-1.4243
45.00	430.00	0.1248	-1.1248	-0.0573	-1.8837	-1.2548	-2.0249	-1.4130
45.00	435.00	0.2602	-1.0454	-0.1612	-1.9731	-0.9051	-2.0451	-1.3641
45.00	440.00	0.3954	-0.9664	-0.2452	-2.0512	-0.5481	-2.0451	-1.3541
45.00	445.00	0.5304	-0.8874	-0.3283	-2.1248	-0.1935	-2.0451	-1.3541
45.00	450.00	0.6654	-0.8084	-0.4114	-2.1934	0.1554	-2.0451	-1.3541
45.00	455.00	0.8004	-0.7294	-0.4945	-2.2574	0.5004	-2.0451	-1.3541
45.00	460.00	0.9354	-0.6504	-0.5775	-2.3174	0.8454	-2.0451	-1.3541
45.00	465.00	1.0704	-0.5714	-0.6606	-2.3724	1.1904	-2.0451	-1.3541
45.00	470.00	1.2054	-0.4924	-0.7437	-2.4224	1.5354	-2.0451	-1.3541
45.00	475.00	1.3404	-0.4134	-0.8268	-2.4674	1.8804	-2.0451	-1.3541
45.00	480.00	1.4754	-0.3344	-0.9099	-2.5074	2.2254	-2.0451	-1.3541
45.00	485.00	1.6104	-0.2554	-0.9930	-2.5424	2.5704	-2.0451	-1.3541
45.00	490.00	1.7454	-0.1764	-1.0761	-2.5774	2.9154	-2.0451	-1.3541
45.00	495.00	1.8804	-0.0974	-1.1592	-2.6124	3.2604	-2.0451	-1.3541
45.00	500.00	2.0154	-0.0184	-1.2423	-2.6474	3.6054	-2.0451	-1.3541
45.00	505.00	2.1504	0.0606	-1.3254	-2.6824	3.9504	-2.0451	-1.3541
45.00	510.00	2.2854	0.1396	-1.4085	-2.7174	4.2954	-2.0451	-1.3541
45.00	515.00	2.4204	0.2188	-1.4916	-2.7524	4.6404	-2.0451	-1.3541
45.00	520.00	2.5554	0.2979	-1.5747	-2.7874	4.9854	-2.0451	-1.3541
45.00	525.00	2.6904	0.3771	-1.6578	-2.8224	5.3304	-2.0451	-1.3541
45.00	530.00	2.8254	0.4563	-1.7409	-2.8574	5.6754	-2.0451	-1.3541
45.00	535.00	2.9604	0.5355	-1.8240	-2.8924	6.0204	-2.0451	-1.3541
45.00	540.00	3.0954	0.6147	-1.9071	-2.9274	6.3654	-2.0451	-1.3541
45.00	545.00	3.2304	0.6939	-1.9902	-2.9624	6.7104	-2.0451	-1.3541
45.00	550.00	3.3654	0.7731	-2.0733	-3.0000	7.0554	-2.0451	-1.3541
45.00	555.00	3.5004	0.8523	-2.1564	-3.0350	7.4004	-2.0451	-1.3541
45.00	560.00	3.6354	0.9315	-2.2395	-3.0700	7.7454	-2.0451	-1.3541
45.00	565.00	3.7704	1.0107	-2.3226	-3.1050	8.0904	-2.0451	-1.3541
45.00	570.00	3.9054	1.0899	-2.4057	-3.1400	8.4354	-2.0451	-1.3541
45.00	575.00	4.0404	1.1691	-2.4888	-3.1750	8.7804	-2.0451	-1.3541
45.00	580.00	4.1754	1.2483	-2.5719	-3.2100	9.1254	-2.0451	-1.3541
45.00	585.00	4.3104	1.3275	-2.6550	-3.2450	9.4704	-2.0451	-1.3541
45.00	590.00	4.4454	1.4067	-2.7381	-3.2800	9.8154	-2.0451	-1.3541
45.00	595.00	4.5804	1.4859	-2.8212	-3.3150	10.1604	-2.0451	-1.3541
45.00	600.00	4.7154	1.5651	-2.9043	-3.3500	10.5054	-2.0451	-1.3541
45.00	605.00	4.8504	1.6443	-2.9874	-3.3850	10.8504	-2.0451	-1.3541
45.00	610.00	4.9854	1.7235	-3.0705	-3.4200	11.1954	-2.0451	-1.3541
45.00	615.00	5.1204	1.8027	-3.1536	-3.4550	11.5404	-2.0451	-1.3541
45.00	620.00	5.2554	1.8819	-3.2367	-3.4900	11.8854	-2.0451	-1.3541
45.00	625.00	5.3904	1.9611	-3.3198	-3.5250	12.2304	-2.0451	-1.3541
45.00	630.00	5.5254	2.0403	-3.4029	-3.5600	12.5754	-2.0451	-1.3541
45.00	635.00	5.6604	2.1195	-3.4860	-3.5950	12.9204	-2.0451	-1.3541
45.00	640.00	5.7954	2.1987	-3.5691	-3.6300	13.2654	-2.0451	-1.3541
45.00	645.00	5.9304	2.2779	-3.6522	-3.6650	13.6104	-2.0451	-1.3541
45.00	650.00	6.0654	2.3571	-3.7353	-3.7000	13.9554	-2.0451	-1.3541
45.00	655.00	6.2004	2.4363	-3.8184	-3.7350	14.3004	-2.0451	-1.3541
45.00	660.00	6.3354	2.5155	-3.9015	-3.7700	14.6454	-2.0451	-1.3541
45.00	665.00	6.4704	2.5947	-3.9846	-3.8050	14.9904	-2.0451	-1.3541
45.00	670.00	6.6054	2.6739	-4.0677	-3.8400	15.3354	-2.0451	-1.3541
45.00	675.00	6.7404	2.7531	-4.1508	-3.8750	15.6804	-2.0451	-1.3541
45.00	680.00	6.8754	2.8323	-4.2339	-3.9100	16.0254	-2.0451	-1.3541
45.00	685.00	7.0104	2.9115	-4.3170	-3.9450	16.3704	-2.0451	-1.3541
45.00	690.00	7.1454	2.9907	-4.4001	-3.9800	16.7154	-2.0451	-1.3541
45.00	695.00	7.2804	3.0699	-4.4832	-4.0150	17.0604	-2.0451	-1.3541
45.00	700.00	7.4154	3.1491	-4.5663	-4.0500	17.4054	-2.0451	-1.3541
45.00	705.00	7.5504	3.2283	-4.6494	-4.0850	17.7504	-2.0451	-1.3541
45.00	710.00	7.6854	3.3075	-4.7325	-4.1200	18.0954	-2.0451	-1.3541
45.00	715.00	7.8204	3.3867	-4.8156	-4.1550	18.4404	-2.0451	-1.3541
45.00	720.00	7.9554	3.4659	-4.8987	-4.1900	18.7854	-2.0451	-1.3541
45.00	725.00	8.0904	3.5451	-4.9818	-4.2250	19.1304	-2.0451	-1.3541
45.00	730.00	8.2254	3.6243	-5.0649	-4.2600	19.4754	-2.0451	-1.3541
45.00	735.00	8.3604	3.7035	-5.1480	-4.2950	19.8204	-2.0451	-1.3541
45.00	740.00	8.4954	3.7827	-5.2311	-4.3300	20.1654	-2.0451	-1.3541
45.00</								

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