To the Graduate Council:

I am submitting herewith a thesis written by Ho-Pen Chang entitled "Droplet Trajectory Model for Icing Collection Efficiencies." I have examined the final copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Aerospace Engineering.

Walter Frost, Major Professor

We have read this thesis and recommend its acceptance:

John E. Caruthers

Roy J. Schulz

Accepted for the Council:

Vice Chancellor
Graduate Studies and Research

DROPLET TRAJECTORY MODEL FOR ICING
COLLECTION EFFICIENCIES

A Thesis
Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville

Ho-Pen Chang

June 1982

ACKNOWLEDGMENTS

The work reported herein was partially supported by the National Aeronautics and Space Administration, Lewis Research Center, Cleveland, Ohio, under Contract NAS3-22448. The author wishes to express his appreciation to all the members of The University of Tennessee Space Institute who have assisted during completing this study.

Special thanks should go to Dr. Walter Frost, the project supervisor, for his suggestion of the topic of this study and for his help in completing the study. Sincere appreciation is given to Dr. Kenneth R. Kimble and Dr. Chih-Fang Shieh for their guidance during the accomplishment of the present study. The author would like to thank his committee, Dr. John Caruthers and Dr. Roy Schulz, for their helpful comments.

Furthermore, the author wishes to extend appreciation to his family, especially to his father, Mr. Rung-Guay Chang, his mother, Jung-Man Chang, and his girlfriend, Shi-Min Sau for their constant encouragement.

The author would also like to thank Mrs. Barbara Smith for typing this thesis and Mr. Robert (Mutt) Suttles for preparing the illustrations presented in this study.

ABSTRACT

A numerical model has been developed to calculate ice accretion characteristics of two-dimensional bodies in a potential flow field. Particle trajectories are calculated in a potential flow field computed for the bodies of interest. The potential flow computation technique employs a distribution of sources, sinks, and/or vortices along the body surface.

The governing equations of motion of droplets in the flow field are integrated by Adams-Moulton predictor-corrector method with a variable time step to yield the particle trajectories. With the trajectories known, the location of droplets impinging on the body are determined, and then the local and total collection efficiency are determined.

A computer program is developed for calculating the particle trajectories, the impingement limits, the local collection efficiency, and the total collection efficiency. The program utilizes the existing potential flow programs to provide numerical solutions for airfoils (with tunnel walls or without walls) and two-dimensional inlet with single-sized or multi-sized droplet distribution.

TABLE OF CONTENTS

CHAPTER PAGE

LIST OF TABLES

LIST OF FIGURES

FIGURE PAGE

LIST OF SYMBOLS

SYMBOL	DEFINITION
A	Reference area of particle
Be	Best number ($Be = C_d Re^2$)
C_d	Drag coefficient
C_{do}	Steady-state drag coefficient
$C_{d\alpha}$	Drag coefficient due to the angle α (Figure 2.1)
C_ℓ	Lift coefficient
$C_{\ell o}$	Steady-state lift coefficient
$C_{\ell\alpha}$	Lift coefficient due to the angle α (Figure 2.1)
C_m	Moment coefficient
C_{mo}	Steady-state moment coefficient
$C_{m\alpha}$	Moment coefficient due to the angle α (Figure 2.1)
D	Particle diameter
$\tilde{D}$	Aerodynamic drag force
E	Total collection efficiency
PRL	Particle reference line in the x-y plane
g	Acceleration of gravity (9.8 m/s^2)
h	Projected height of the body along the vertical coordinate line
I_{zz}	Moment of inertia of mass relative to the z axis
$\tilde{L}$	Aerodynamic lift force
LWC	Liquid water content
ℓ_c	Reference length of body; chord length of wing or mouth diameter of inlet

SYMBOL	DEFINITION
M	Moment of aerodynamic forces acting on the particle
m	Mass of water droplet (kg)
$\dot{m}$	Mass flow rate
n_i	Number of particles of size i per unit volume
Re	Reynolds number based on the diameter of the particle
s	Surface distance measured from the leading edge of each body; positive along the lower surface and negative along the upper surface
S_L	Lower surface impingement limit
S_U	Upper surface impingement limit
t	Time
$\vec{V}$	Velocity of particle
$\vec{V}_a$	Velocity of particle relative to flow field
$\vec{W}$	Velocity of flow field
W_x	x-component velocity of flow field
W_y	y-component velocity of flow field
W_∞	Free-stream velocity
x	x-coordinate of particle
$\dot{x}$	x-component velocity of particle
$\ddot{x}$	x-component acceleration of particle
x_o	Initial value of the horizontal coordinate of particle
y	y-coordinate of particle
$\dot{y}$	y-component velocity of particle
$\ddot{y}$	y-component acceleration of particle
y_o	Initial value of the vertical coordinate of particle

SYMBOL	DEFINITION
y_{ou}	Initial vertical coordinate of the particle which hits the body at surface distance S_U
$y_{o\ell}$	Initial vertical coordinate of the particle which hits the body at surface distance S_L

Greek Symbols

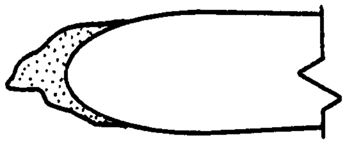
α	Angle between the PRL and the velocity vector $\vec{V}_a$ (Figure 2.1)
β	Local collection efficiency
γ	Particle path angle $\left(\gamma = \tan^{-1} \dfrac{\dot{y} - W_y}{\dot{x} - W_x}\right)$
δ	Angle between $\vec{V}$ and $\vec{V}_a$
η_i	Percentage liquid water contained in particles of size D_i
θ	Pitch angle of particle
$\dot{\theta}$	Angular velocity of particle
$\ddot{\theta}$	Angular acceleration of particle

CHAPTER I

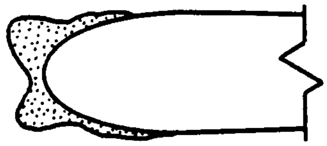
INTRODUCTION

In the past, before 1950, both the National Advisory Committee for Aeronautics (NACA) and the Federal Aviation Administration (FAA) have conducted comprehensive icing research in the areas of meteorology, theoretical droplet trajectory calculations, experimental ice accretion and iced aircraft performance. Much of this effort, however, was terminated in the late 1950's and little research has been conducted in the interim. There is no question that this prior work has served the industry well, but new aircraft technology has generated requirements for increased understanding of icing phenomena. This re-examination of the icing problem, this time with the aid of the high-speed computer facilities, promises improvements in icing technology necessary to increase the utilization of general aviation aircraft and helicopters in adverse weather. In an icing environment, aircraft can accumulate ice resulting in a sharp increase in drag and reduction of maximum lift.

Ice may form on the unheated forward-facing surfaces of an aircraft flying through clouds of supercooled water droplets. At low temperature, the water droplets freeze immediately on impact with airfoil leading edges, forming rime ice (Figure 1.1a). At higher temperature, the water droplets may flow over the surface for a short distance before freezing, resulting in glaze ice (Figure 1.1b). The size, shape, and extent of ice formation depends on the cloud liquid water content, the droplet size and temperature, the flight speed and angle of attack, airfoil or body geometry, and duration of the icing encounter.



(a) Rime ice.



(b) Glaze ice.

Figure 1.1 Ice formations on the unheated forward-facing surfaces.

This study, as part of the re-examination of icing problem, focuses upon numerical solutions of the impingement characteristics for droplet trajectory about two-dimensional bodies. The method used in this study is limited to the rime ice or dry accretion case in which the super-cooled water droplets freeze on the airfoil at the point of impact. The method developed in this study calculates water droplet trajectories in known airfoil flow fields computed with existing two-dimensional potential flow computer programs. Equations describing the motion of particles in the flow field are derived in Chapter II. The impingement limits, the local collection efficiency and the total collection efficiency are also defined in Chapter II.

The Douglas two-dimensional potential flow programs developed by Hess and Smith are used in the present study for calculating air velocities about a two-dimensional body (see NASA TM-78930 [1]* and NASA

*Numbers in brackets represent similarly numbered references in the List of References.

TM-79144 [2]). The related input and output of these programs are briefly described in Chapter III.

A computer program (see Appendix C) was developed to calculate numerical solutions for impingement characteristics of particle trajectories. The code is programmed to include all of the following cases.

1. Airfoil with walls (to simulate wind tunnel walls) or without walls and with single-sized or multi-sized particle distribution.

2. Inlet of an aircraft engine with hub or without hub and with single-sized or multi-sized particle distribution.

User's instructions as well as program capabilities and functions are described in Appendices A and B.

In Chapter IV, computed impingement characteristics are presented for a number of test cases (see page 29). For most of the numerical results, the agreement with experiment is good. On the other hand, for a thin airfoil (i.e., NACA 65_A-004) at large angle of attack (i.e., 8°) the computed results do not agree well with experiment. This disagreement is due to the effects of flow separation.

Conclusions along with interpretation of the results and program limitation is given in Chapter V. The potential flow computer program used in this study has a relatively large discretization error very close to the body. The correction for the discretization error near the body and the utilization of Cunningham correction factor for small-sized particle (<10 μ) distribution is also discussed in Chapter V.

CHAPTER II

METHODOLOGY

The procedure for computing the particle trajectory around a two-dimensional body has been divided into the following steps:

1. Compute the potential field around a body of arbitrary shape assuming the particles do not influence the flow field.

2. Determine the velocity flow field around the body with or without angle of attack for a given free-stream airspeed.

3. Calculate the trajectories of droplets in the flow field determined in Step 2 using the Adams-Moulton predictor-corrector method to integrate the equations of particle motion.

4. Calculate the local collection efficiency for the body.

The computational procedures used in Steps 1 and 2 are summarized in Subchapter A, and those used in Steps 3 and 4 are described in Subchapters B, C, D, and E.

A. POTENTIAL FLOW ABOUT AN ARBITRARY TWO-DIMENSIONAL BODY

The Douglas two-dimensional potential flow program developed by Hess and Smith [3] is used in the present study for calculating the flow field about body. This computer program uses a distribution of sources, sinks, and/or vortices along the body surface to calculate the potential flow field. The body surface is represented by an arbitary number of straight line segments. In calculating the flow field, contributions from all the sources, sinks, and/or vortices are summed. The accuracy of this method was tested by comparing its predicted velocities and surface pressure coefficients with both analytic solutions and experimental data [3]. Excellent agreement has been found.

In the present study the accuracy of the numerical method was tested by comparing the computed horizontal velocity for a two-dimensional circular cylinder with the analytical solution. Using ten surface elements the velocity error is approximately 2 percent at a distance of one diameter from the cylinder. The error is reduced to 0.5 percent by using 50 surface elements. Therefore, the smaller the surface line segments used, the finer the resolution of the flow field obtained. For the test cases presented in Chapter V of this study, on the order of 150 surface elements have been used and good agreement between the predicted local collection efficiency and the available experimental data [4] is obtained.

The Douglas two-dimensional flow program consists of essentially three parts: a geometry-generating program called SCIRCL, a two-dimensional flow field computer program called 24Y, and a mass flow rate and compressibility correction program for inlet flows called COMBIN-2D. The SCIRCL program generates the geometry input to the potential flow program (24Y) for a given specified analytical shape. Using the input from SCIRCL the 24Y program calculates the flow field at any position in space. The 24Y program is used to generate an input data tape containing the sources, sinks, and vortices which are then used in the particle trajectory program to calculate the velocity field at a particle position x,y. The COMBIN-2D program is used with the 24Y program if it is desired to specify the Mach number within the inlet.

Only limited details of the potential flow program are provided in this study since the major thrust of this study was to develop a program for computing particle trajectories and local collection efficiencies. The already-developed Douglas potential flow program is simply used to provide flow field input [1,2]. For complete details of the potential flow program, the user should consult References 1, 2, and 3.

B. PARTICLE EQUATIONS OF MOTION

In the present study the motion of a water droplet (particle), which is acted on by the potential flow field, does not influence the flow. The forces acting on the particle are considered to be those of lift, drag, and gravity. The motion of the particle is assumed to take place on the x-y plane only. Pitch moment acting on the particle only in the direction normal to the x-y plane is also considered. Figure 2.1 shows the forces acting on the particle and the velocity vectors relative to the motion of the particle. The particle reference line (PRL) of the water droplet shown in Figure 2.1 is not significant for a spherical particle; however, for more arbitrarily shaped particles, e.g., a snowflake, the PRL must be defined relative to the lift, drag, and moment coefficient data available for the given particle shape. The governing equations of the particle motion are derived for the more general case, i.e., arbitrary particle shapes. In turn, the computer program developed in this study and described in Chapter III and Appendices A and B provides the option for general-shaped particles. However, the test case comparisons with experimental data given in Chapter IV are for spherical particles only. A valid drag law for

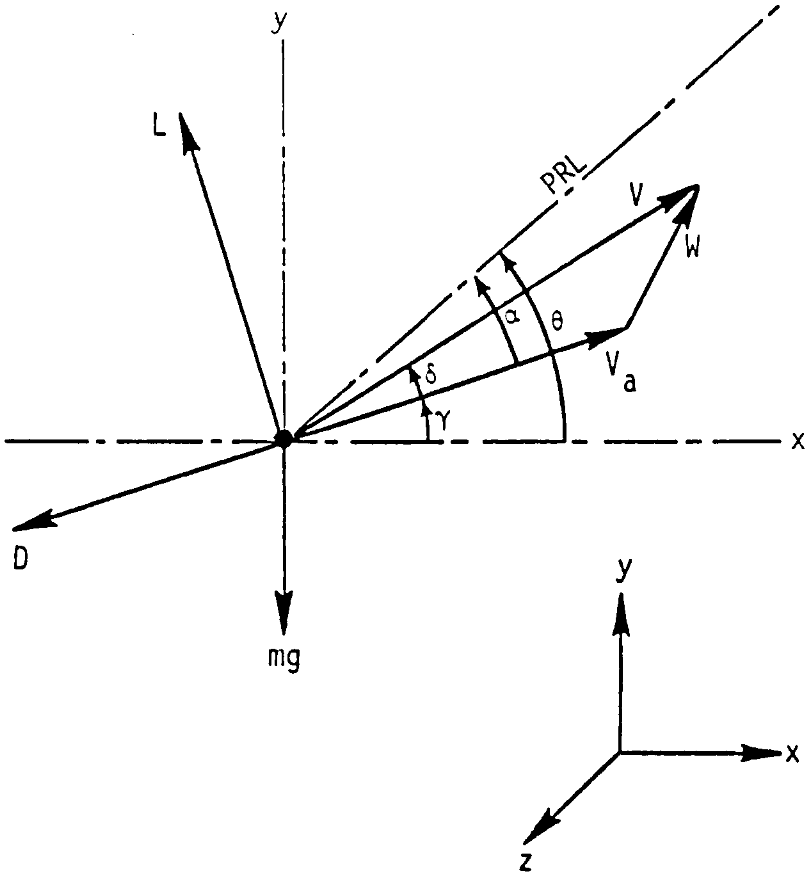


Figure 2.1 Diagram of the velocity vectors and forces acting on a water droplet.

spherical particles is built into the computer program. The user must input lift, drag, and moment coefficient data for general-shaped particles.

The equations of motion of the particle derived from a force balance on a point mass particle as shown in Figure 2.1 are:

$$m\ddot{x} = -\tilde{D} \cos \gamma - \tilde{L} \sin \gamma \qquad (2.1)$$

$$m\ddot{y} = -\tilde{D} \sin \gamma + \tilde{L} \cos \gamma - mg \qquad (2.2)$$

where

$$\gamma = \tan^{-1} \frac{\dot{y} - W_y}{\dot{x} - W_x} \qquad (2.3)$$

The flow field velocity components in the longitudinal and vertical directions, i.e., W_x and W_y, respectively, are obtained from the potential flow program described in Subchapter A. The aerodynamic drag and lift forces are defined as:

$$\tilde{D} = C_d \frac{\rho_a V_a^{\,2}}{2} A$$

$$\tilde{L} = C_\ell \frac{\rho_a V_a^{\,2}}{2} A$$

where A is a characteristic area of the particle, ρ_a is the density of air at the position of the particle, and V_a is the particle velocity relative to the flow field and is defined as:

$$V_a = \sqrt{(\dot{x} - W_x)^2 + (\dot{y} - W_y)^2} \qquad (2.4)$$

For arbitarily shaped particles, expressions for the drag coefficient, C_d, and lift coefficient, C_ℓ, must be provided by the user. They are often approximated with:

$$C_d = C_{do} + C_{d\alpha}\alpha \qquad (2.5)$$

$$C_\ell = C_{\ell o} + C_{\ell\alpha}\alpha \qquad (2.6)$$

where α is the angle between the PRL and the velocity vector $\vec{V}_a$ (Figure 2.1).

Equations 2.1 and 2.2 can be solved given values of the coefficients of Equations 2.5 and 2.6, i.e., C_{do}, $C_{\ell o}$, $C_{d\alpha}$, and $C_{\ell\alpha}$. The angle α is computed from the expression:

$$\alpha = \theta - \gamma \tag{2.7}$$

where the angle θ, generally called pitch angle of the water droplet in aerodynamics, is governed by:

$$\ddot{\theta} = \frac{M}{I_{zz}} \tag{2.8}$$

where I_{zz} is the moment of inertia of mass relative to the z axis. The moment of aerodynamic forces acting on the particle is:

$$M = C_m \frac{\rho_a V_a^2}{2} A \ell_c \tag{2.9}$$

where C_m is approximately:

$$C_m = C_{mo} + C_{m\alpha}\alpha$$

C_{mo} and $C_{m\alpha}$ are constants to be provided by the user depending upon the shape of the particle, and ℓ_c is a reference length.

For a spherical particle with zero angular velocity, the lift force is always zero for potential flow. The governing equations are significantly simplified in this case:

$$m\ddot{x} = -\tilde{D} \cos \gamma \tag{2.10}$$

$$m\ddot{y} = -\tilde{D} \sin \gamma - mg \tag{2.11}$$

where

$$\tilde{D} = C_{do} \frac{\rho_a V_a^2}{2} A \tag{2.12}$$

In the present study C_{do} is the steady-state drag coefficient of a sphere as a function of Reynolds number based on particle diameter, $Re = V_a D/\nu$, as shown in Figure 2.2. The diameter of the spherical particle, D, and the kinematic viscosity of the air, ν, are assumed constant along the particle's trajectory in the present study. The drag law utilized was provided by NASA/LeRC (Figure 2.2 and Table 2.1) [5].

The governing Equations 2.1, 2.2, and 2.8 together with the following definitions form a complete set of equations to describe the motion of particles in the flow fields.

$$\frac{dx}{dt} = \dot{x} \tag{2.13}$$

$$\frac{dy}{dt} = \dot{y} \tag{2.14}$$

$$\frac{d\theta}{dt} = \dot{\theta} \tag{2.15}$$

Integration of the Equations 2.1, 2.2, 2.8, 2.13, 2.14, and 2.15 results in solutions for $\dot{x}$, $\dot{y}$, $\dot{\theta}$, x, y, θ of the particle at time t. For the sphere particles for which the lifting force is omitted, only Equations 2.10, 2.11, 2.13, and 2.14 are integrated. The integration method is described briefly in the next section.

C. PARTICLE TRAJECTORY SOLUTION ALGORITHM

The method utilized for integrating the governing equations of particle motion is the Adams-Moulton predictor-corrector method [6]. The solution is obtained if the summation of the difference between the particle velocities in the x and y directions obtained by the predictor and corrector, respectively, and divided by the value of the solution at the last time step is less than a specified number ε:

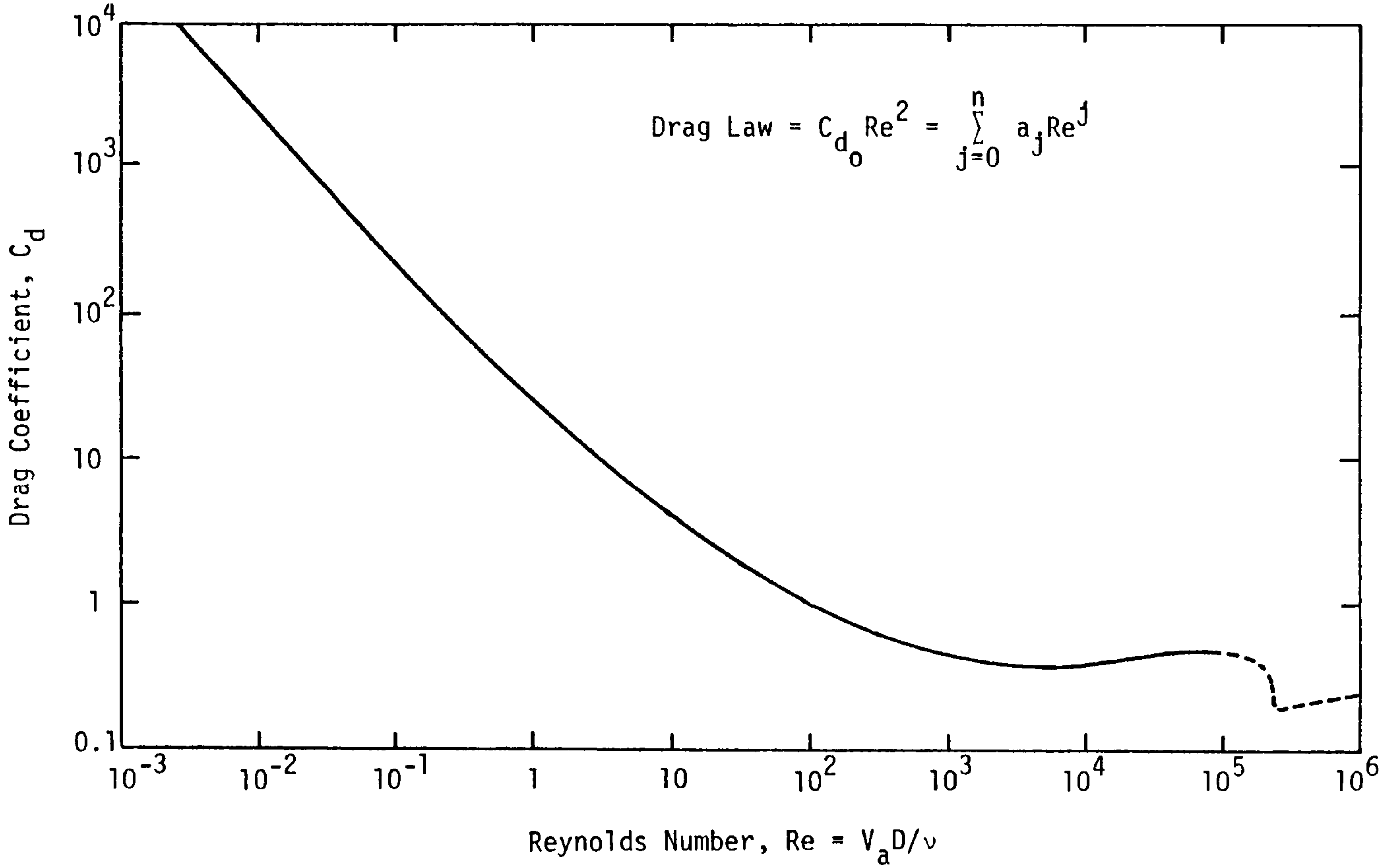


Figure 2.2 Friction (or drag coefficient) for spheres moving relative to a fluid with a velocity, V_∞ [5].

TABLE 2.1. Polynomial Coefficients Relating Best Number (Be) to Reynolds Number for Spherical Particles [5].

$$Be = \sum_{j=0}^{n} a_j Re^j$$

Reynolds Number Range	j	a_j
$0.05 < Re \leq 3$	0	0.0
	1	24.167
	2	3.254
	3	-0.23564
$3 < Re \leq 330$	0	-28.339
	1	38.969
	2	0.73204
	3	-0.00056084
$330 < Re$	0	0.0
	1	93.462
	2	0.37576

where

$$Re = \frac{|\vec{W} - \vec{V}|D}{\nu}$$

Be = Best number ($C_d Re^2$)

D = particle diameter

$\vec{W}$ = inertial velocity of the air ($\vec{W} = W_x\vec{i} + W_y\vec{j}$)

$\vec{V}$ = inertial velocity of the particle ($\vec{V} = \dot{x}\vec{i} + \dot{y}\vec{j}$)

$$\left|\frac{(\dot{X}_{n,predictor} - \dot{X}_{n,corrector})}{\dot{X}_{n-1}}\right| + \left|\frac{(\dot{Y}_{n,predictor} - \dot{Y}_{n,corrector})}{\dot{Y}_{n-1}}\right| \leq \varepsilon$$

The value of ε is specified by the user.

D. COMPUTATION OF COLLECTION EFFICIENCY

Particle trajectories calculated as described in the previous sections are used to establish the relations between the particle's initial position $(-\infty, y_0)$ and the position where it impinges on the body surface, s. s is the length along the body surface measured from the leading edge on the body to the point of particle impingement. The value of s is defined as positive on the lower surface and negative on the upper surface. y_0 is the initial value of the vertical coordinate from which the particle is released (see Figure 2.3). The local collection efficiency, β, is calculated as a function of the distance along the body surface by differentiating $y_0 = y_0(s)$ with respect to s [7]:

$$\beta = -\frac{dy_0}{ds} \tag{2.16}$$

The minus sign is introduced so that β is positive, which is consistent with the definition given in Reference 4.

The overall collection efficiency, E, is defined as:

$$E = \frac{y_{ou} - y_{o\ell}}{h} \tag{2.17}$$

where y_{ou} and $y_{o\ell}$ are the initial y-coordinates of the upper and lower tangent particle trajectories relative to the body of interest and h is the projected height of the body along the vertical coordinate line.

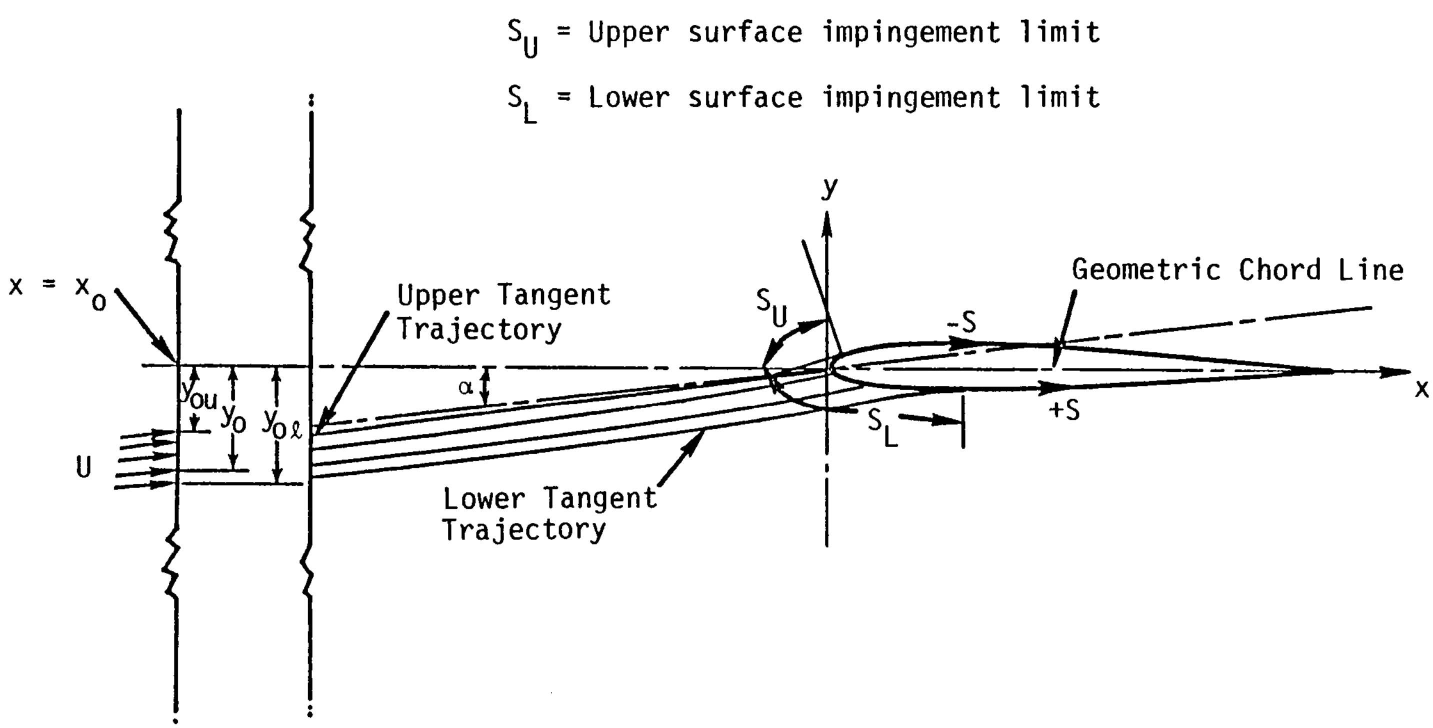


Figure 2.3 Illustration of impingement terminology and water droplet trajectory in an airfoil flow field [7].

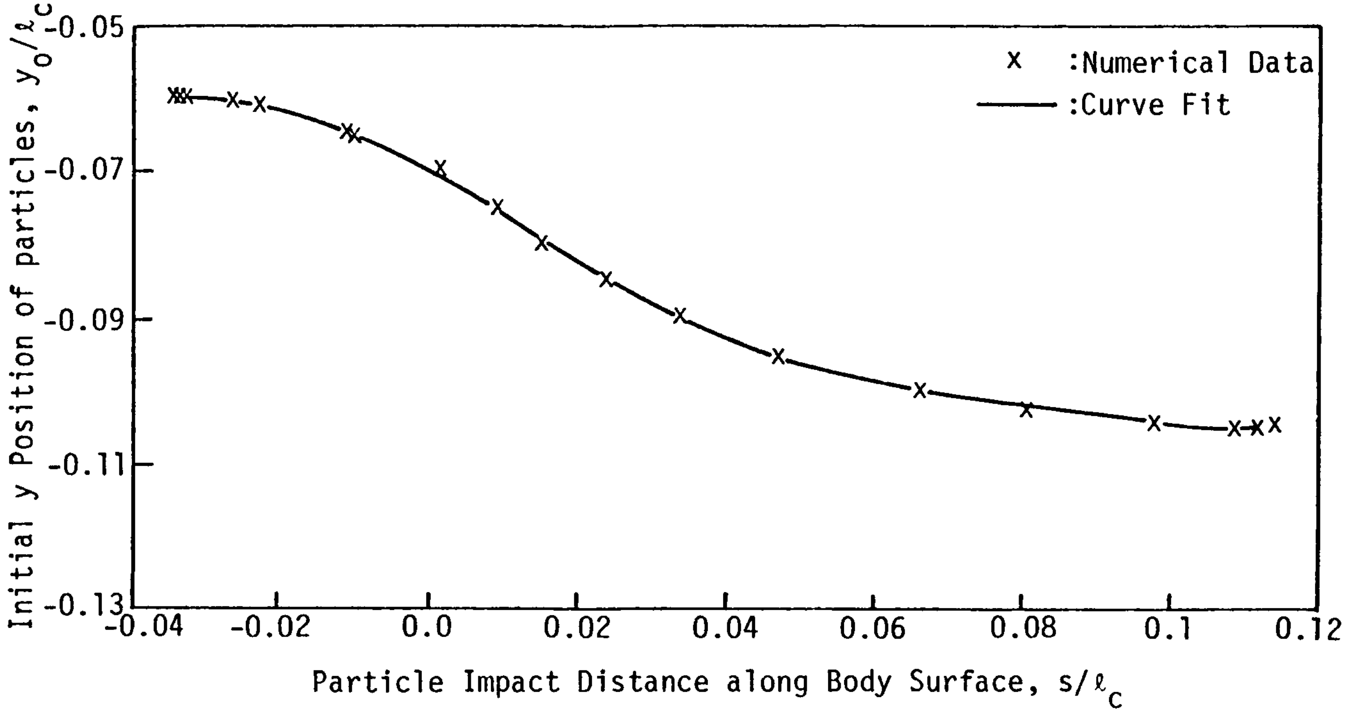
E. GENERAL COMPUTATIONAL PROCEDURE

The general computational procedure to determine the local collection coefficient of a body is carried out as follows. First, the initial conditions for the differential equations governing the particle motion are determined either automatically by the computer program or input manually by the user. These conditions call for specification of an initial particle position x_0, y_0 and an initial particle velocity $\dot{x}_0, \dot{y}_0$. The computer program described in the following sections automatically determines the initial conditions if desired. The initial upstream x-coordinate, x_0, is assigned the value of x at which the difference in the free-stream velocity W_∞ and the local velocity W is less than some small value ε. The value of ε is specified by the user.

To determine the initial vertical coordinate y_0, the computer automatically searches for the upper and lower limits of the y-coordinate, y_{ou} and $y_{o\ell}$, respectively (see Figure 2.3). Any particles released within this region will strike the body. Any particles released outside this region will miss the body and are of no interest to the computation of collection efficiency. The range of vertical position y_{ou} to $y_{o\ell}$ is then divided into a number of increments prescribed by the user. The trajectory of particles leaving each of these vertical positions is calculated and the impingement position of the particle on the body surface, s, is recorded. This collection of $\{y_0; s\}$ values plus those generated during the computer search for y_{ou} and $y_{o\ell}$ are used to express s as a function of the particle's initial vertical coordinate y_0. The value of $\beta = -dy_0/ds$ is then computed by a linear approximation or by curve fitting the total collection of data points $\{y_0, s\}$ to a polynomial curve fit. The degree of the polynomial is specified by the user. The current program allows the user to curve fit the entire set of datum points to one curve or to fit the curve in segments using a prescribed number of points on either side of the specified position (see Figure 2.4). This latter procedure is similar to segment-averaging or segment-curve fitting of the entire curve.

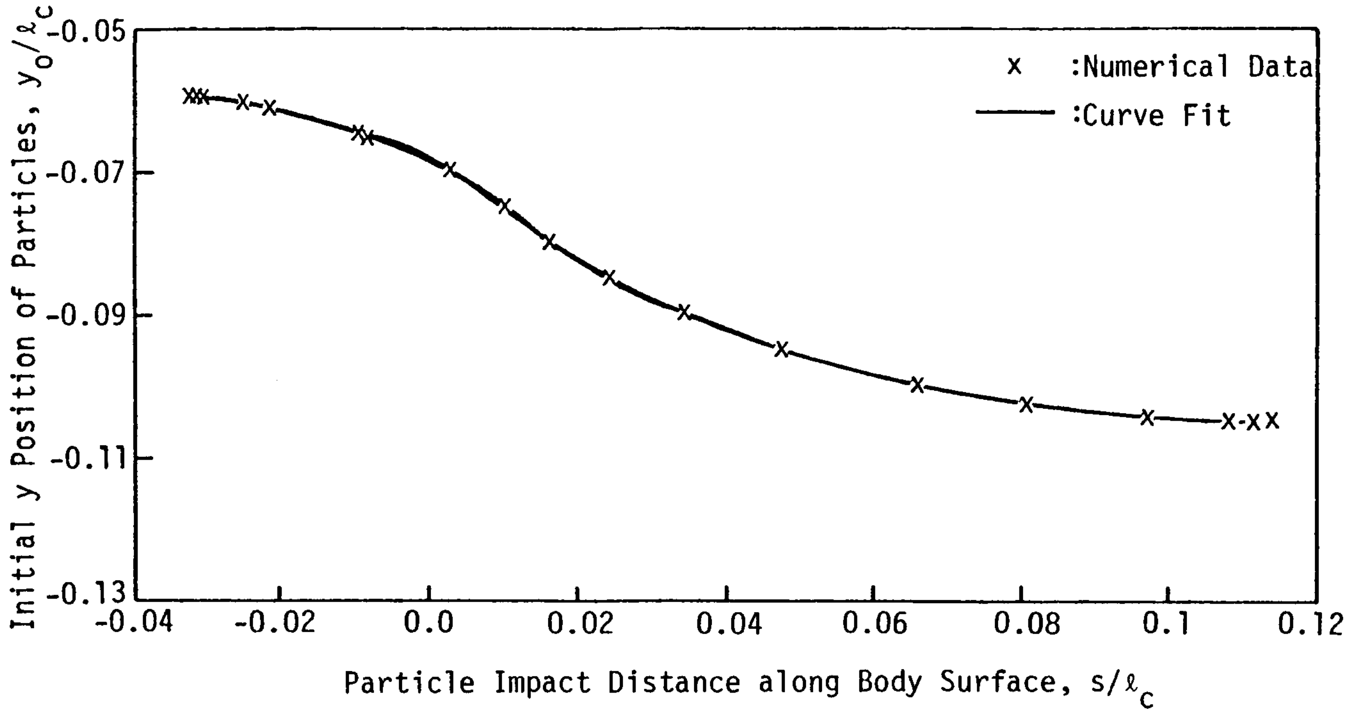
The initial velocity of the particle is prescribed to be equal to the value of the flow field at x_0, y_0, i.e., $\dot{x} = W_x(x_0, y_0)$ and $\dot{y} = W_y(x_0, y_0)$ if not otherwise specified by the user.

The following chapters describe in detail the computer program and necessary user's information to compute particle trajectories and local collection efficiency for two-dimensional airfoils and inlets.



(a) Total data set curve fitting; 6 degree polynomial with all input data. (Joukowski airfoil 0015, $\alpha = 4^\circ$, with walls).

Figure 2.4 Illustration of total data set and segment curve fitting techniques.



(b) Segment curve fitting; 3 degree polynomial with sequential sets of input data. (Joukowski airfoil 0015, $\alpha = 4^\circ$, with walls).

Figure 2.4 (continued).

CHAPTER III

GENERAL DESCRIPTION OF COMPUTER PROGRAMS

The purpose of this chapter is to describe the computer program in sufficient detail so that it can be run successfully. Subchapter A describes some general features of the program which will better enable the user to follow the data input instructions given in Appendix A. A description of the program output is also included in Appendix A. The capabilities and function descriptions of the particle trajectory program are described in Appendix B. The original References 1 and 2 should be consulted if additional information is required. The general features of the program are described in the following subchapters.

A. TYPES OF FLOW

Two-dimensional incompressible potential flow over arbitrarily shaped bodies is considered. The water droplet in the flow field is treated as a solid sphere although the option for a nonspherical particle is provided in the computer program. For nonspherical particles the user must provide expressions for the coefficients of aerodynamic lift, drag, and moment.

B. SURFACE DISTANCE COMPUTATION

The surface distance along the body is computed by summing elements, Δs, determined from a linear approximation, $\Delta s = \sqrt{(\Delta x)^2 + (\Delta y)^2}$. Surface distance is measured from the leading edge of the airfoil with positive values defined on the lower surface and negative value defined on the upper surface, Figure 2.3, page 14.

C. INITIAL LONGITUDINAL COORDINATE, x_0, OF THE PARTICLE TRAJECTORY

The initial longitudinal coordinate position x_0 at which the particle trajectory calculations begin (Figure 2.3, page 14) is automatically determined by the computer program. The value of x_0 is selected by testing the maximum difference between the locally computed value of W and the free-stream velocity W_∞ at successively farther distance upstream. The value of x for which the inequality

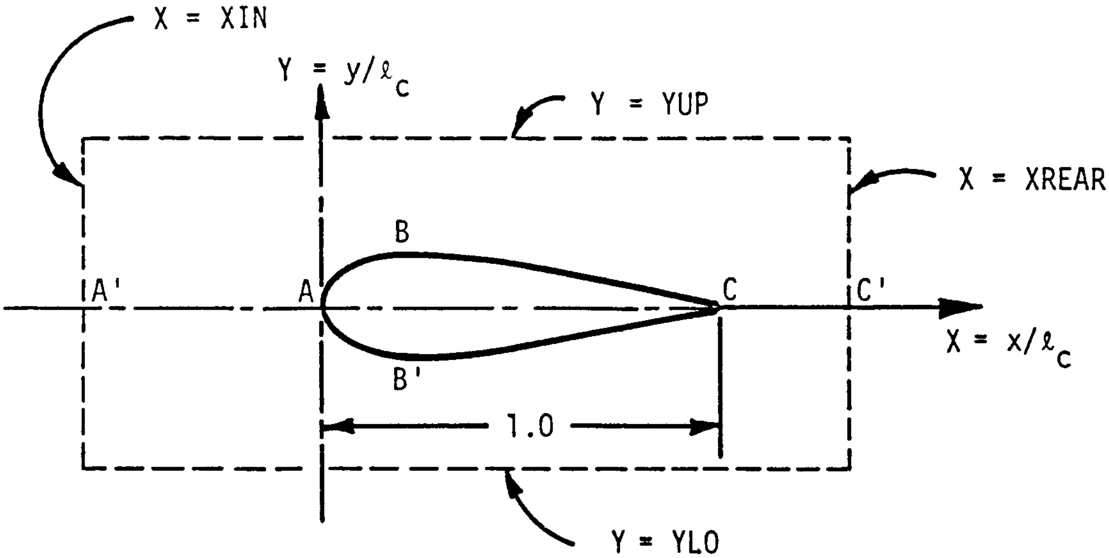
$$\left| 1 - \frac{W}{(W_\infty)} \right|_{max} \leq 0.001 \tag{3.1}$$

is satisfied is designated as x_0. Equation 3.1 is tested over a specified range YYLO $\leq y/\ell_c \leq$ YYUP, where YYLO and YYUP are initial values input by the user. They represent the expected maximum and minimum range of the upstream y-coordinate. ℓ_c is the reference length which is normally the chord length for an airfoil or the mouth diameter for an inlet. This procedure for selecting the initial position of the particle trajectory has been developed so that computer time may be conserved by starting the particle as near the airfoil leading edge as variations in flow field velocity will allow.

D. IMPINGEMENT POSITION OF THE PARTICLE ON THE BODY

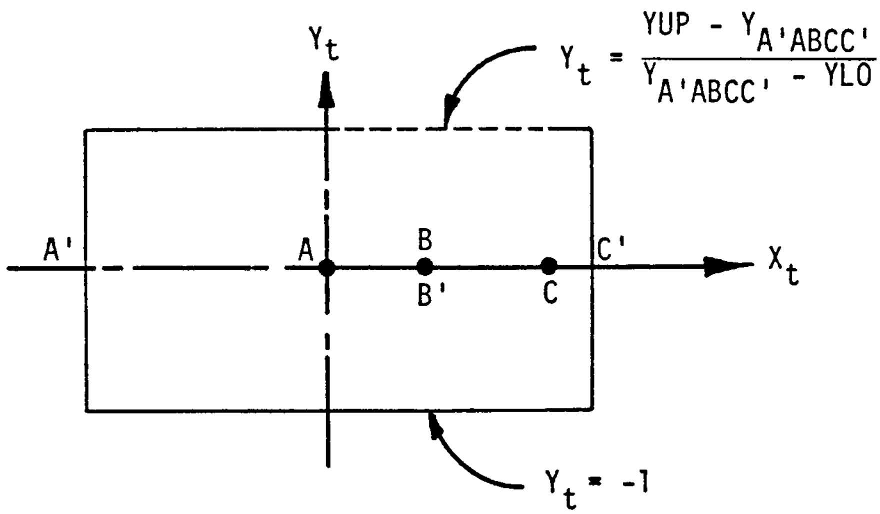
A coordinate transform technique is utilized in determining the position at which a particle strikes the body. The transform technique is illustrated in Figure 3.1. The equations governing the coordinate transform are:

$$X_t = X \tag{3.2a}$$



<u>Note</u>: XREAR is initial input data, YUP and YLO are automatically calculated in the program.

(a) Physical plane



(b) Transformed plane

Figure 3.1 Coordinate transform.

$$Y_t = \frac{Y - YREF}{YREF - YLO} \tag{3.2b}$$

where (see Figure 3.1a)

$YREF = Y_{A'ABCC'}$ if $Y \geq 0.0$

$YREF = Y_{A'AB'CC'}$ if $Y \leq 0.0$

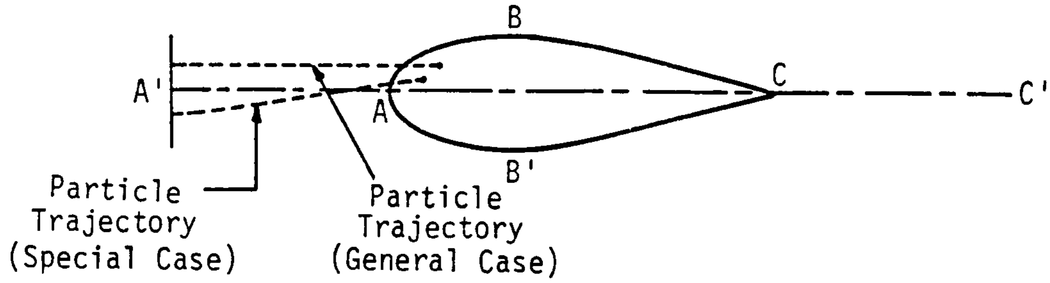
where X and Y are the x- and y-coordinates normalized by the chord length, ℓ_c, respectively. If the particle moves across the coordinate line $Y_t = 0$ in the transformed plane and the X_t position of the particle is greater than the front point of the body of interest, the particle is recorded as having crossed the surface of the body. An iteration procedure, described in the following paragraphs, is then carried out to determine the exact surface location of impingement.

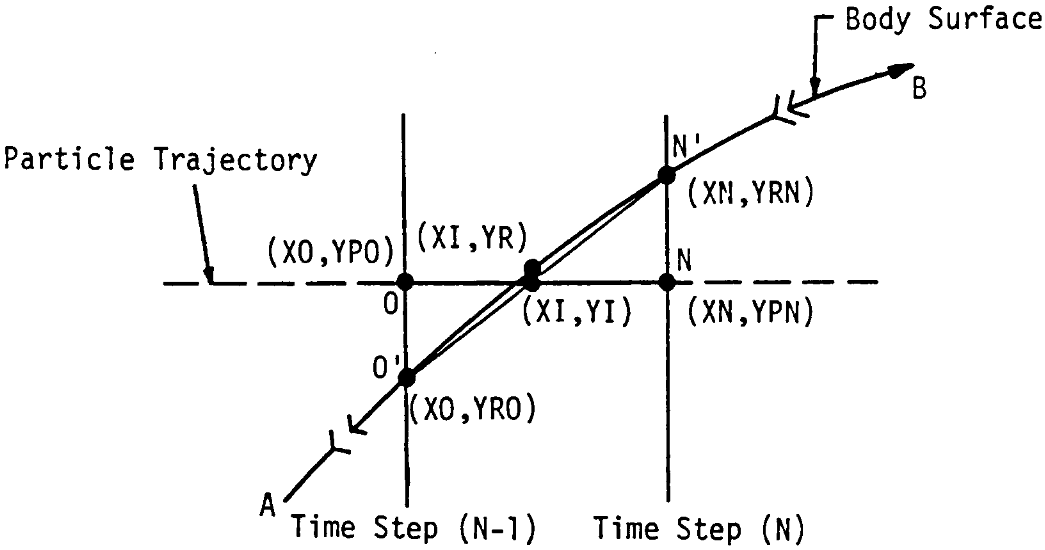
E. COMPUTATION OF SURFACE IMPINGEMENT LOCATION

The method of computing the surface location of particle impingement is described in this paragraph. First a general case and then a special case (see Figure 3.2) are considered.

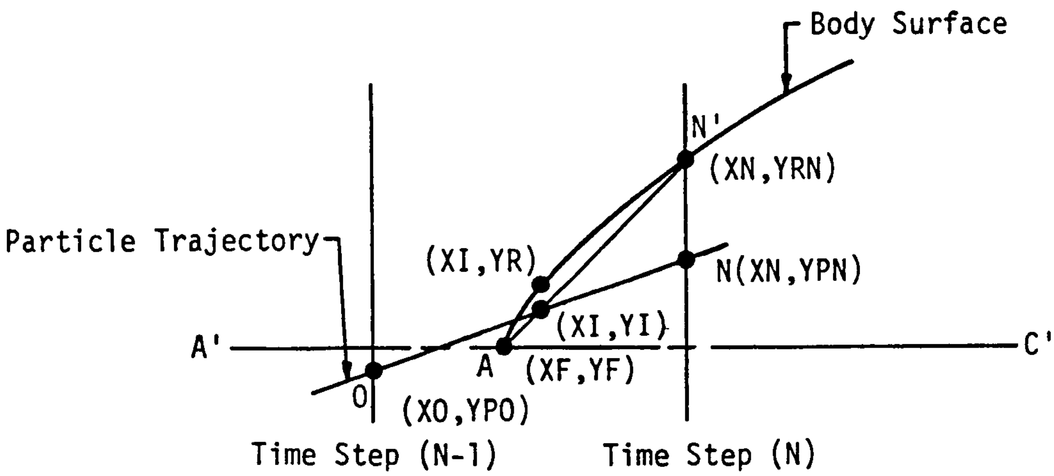
General case. During a time step Δt, consider the particle to cross the body along the line $\overline{ON}$ (see Figure 3.2a). Let the coordinates of the particle at time t be (XO,YPO) and the coordinates at $t = t + \Delta t$ be (XN,YPN). The reference coordinates on the body surface A'ABCC' or A'AB'CC' are XO,YRO and XN,YNR, respectively. The analytical function of the line $\overline{ON}$ is:

$$\frac{Y - YPO}{X - XO} = \frac{YPN - YPO}{XN - XO} \tag{3.4}$$





(a) General case



(b) Special case

Figure 3.2 Illustration of the method of determining the position of particle impingement on the body surface.

The function of the line $\overline{O'N'}$, which joins the two nodal points describing the body surface, is:

$$\frac{Y - YRO}{X - XO} = \frac{YRN - YRO}{XN - XO} \tag{3.5}$$

The coordinates (XI,YI) of the intersection of line $\overline{ON}$ and $\overline{O'N'}$ found by simultaneous solution of Equations 3.4 and 3.5 are:

$$XI = \frac{(XN - XO)(YPO - YRO)}{(YRN - YRO - YPN + YPO)} + XO$$

$$YI = \frac{(YPN - YPO)(YPO - YRO)}{(YRN - YRO - YPN + YPO)} + YPO \tag{3.6}$$

The reference coordinates on the body surface (XI,YR) corresponding to the position (XI,YI) is then found. If $|YI - YR| \leq 10^{-5}$, the point (XI,YR) is regarded as the particle impingement position on the body surface. If $|YI - YR| > 10^{-5}$ the point (XI,YI) is redefined as (XN,YPN) and (XI,YR) as (XN,YRN), respectively. The procedure is repeated until the requirement $|YI - YR| \leq 10^{-5}$ is satisfied.

Special case. Consider the particle crossing the body surface for the special trajectory shown in Figure 3.2b. The function of line $\overline{ON}$ is:

$$\frac{Y - YPO}{X - XO} = \frac{YPN - YPO}{XN - XO} \tag{3.7}$$

and of line $\overline{AN'}$ is

$$\frac{Y - YF}{X - XF} = \frac{YRN - YF}{XN - XF} \tag{3.8}$$

The coordinates (XI,YI) of the point of intersection of line $\overline{ON}$ and line

$\overline{AN'}$ are found as follows: Let

A = (XN - XF)(YPN - YPO) - (YRN - YF)(XN - XO)

B = YPN - YPO

C = YRN - YF

D = XN - XF

E = XN - XO

then

XI = [B·D·XO - E·C·XF + (YF - YPO)·E·D]/A

YI = [D·B·YF - E·C·YPO + (XO - XF)·B·C]/A (3.9)

The same procedure and criteria as for the general case is used to determine the position of particle impact on the body surface.

F. UPSTREAM y-COORDINATE LIMITS $y_{ou}, y_{o\ell}$

The method by which the computer selects the upper and lower trajectory limits y_{ou} and $y_{o\ell}$ is described in this subchapter. A number of options are available to the user depending on the setting of the flags LRANG and LIM. If LRANG=1 and LIM=1, the program searches automatically for the upper and lower limits of the vertical coordinates of the initial particle position y_{ou} and $y_{o\ell}$ (see Figure 2.3, page 14).

The search procedure consists of the computer program initially seeking the range within which y_{ou} and $y_{o\ell}$ lie. This is achieved by computing the particle trajectory from the initial position (XO,YMAX) where YMAX and YMIN are the user's initial guessed values of y_{ou} and $y_{o\ell}$, respectively, and XO = x_o/ℓ_c. If the particle passes under or hits the body, YMAX and YMIN are redefined as $YMAX_{NEW}$ = YMAX + ΔY and $YMIN_{NEW}$ = YMAX where ΔY = YMAX - YMIN. The procedure is then repeated until the particles pass over the body. The current values of YMAX and YMIN then specify the range within which more precise values of y_{ou} and $y_{o\ell}$ are sought. If on the first trajectory calculation the particle had passed over the body then the trajectory from (XO,YMIN) is computed. If the particle again passes over the body then the above procedure is reversed (i.e., $YMAX_{NEW}$ = YMIN and $YMIN_{NEW}$ = YMIN - ΔY).

Once this order of magnitude range of y_{ou} and $y_{o\ell}$ is determined, more precise values of these limits are computed as follows. A particle trajectory from the position Y' = (YMAX + YMIN)/2 is computed. If the particle passes under or hits the body then the next trajectory is computed from Y'_{NEW} = (Y' + YMAX)/2. Alternatively, if it passes under the body then Y'_{NEW} = (Y' + YMIN)/2. Successive halving of the range YMAX to YMIN in this manner continues until convergence is achieved. Convergence is assumed when the difference of the y_o coordinate between two trajectories, for which one impinges on the body and one misses the body, is less than a small value specified by the user. In the program the small number is designated as YLIM. For the test cases given in Chapter IV, YLIM = 10^{-6} m was used. Determination of the values of y_{ou} and $y_{o\ell}$ also provides values of the upper surface impingement limit, s_U, and the lower limit, s_L, respectively.

If the control flags are set such that LRANG=0 and LIM=1, the computer program will search for y_{ou} and $y_{o\ell}$ within the range YMAX and YMIN input by the user. If a poor guess was made and y_{ou} and $y_{o\ell}$ are not in this range, then the program is terminated. If the user desires to compute only one particle trajectory, the flags should be set to LRANG=0 and LIM=0.

G. CALCULATION OF THE LOCAL COLLECTION EFFICIENCY

With the values of y_{ou} and $y_{o\ell}$ determined, the computer divides the range into NPL segments (i.e., $(y_{ou} - y_{o\ell})/NPL$) which represents the number of particles to be computed. Particles are then released from each of the NPL locations. The surface locations of impingement of each particle is then recorded and a collection of coordinates $\{y_o,s\}$ are stored in a file. These values are used to construct the functional relationship between y_o and s from which the local collection efficiency is calculated.

Two methods are used to calculate the local collection efficiency, β. The first method is linear approximation:

$$\beta = - \frac{\Delta y_o}{\Delta s} \tag{3.10}$$

The second method utilizes a polynomial curve fit. The computed values of surface impingement, s, are determined as a function of y_o, i.e., $s = s(y_o)$, by a polynomial curve fit. The value of β is computed by taking the derivative of the polynomial function. The number of coefficient of the polynomial function is input by the user as NCOEF (the order of the polynomial is then NCOEF-1). The total number of points $\{y_o,s\}$ can be curve fit or the function can be curve fit in segments similar to a running average. For segment curve fitting the variable NS=0 and the number of sequential coordinate points used in a segment is specified by the user with the variable NPTS. If NS=1, all points are used. For multi-size distribution cases (NSI>1), only the all-points polynomial curve fit option is available.

CHAPTER IV

TEST CASES FOR PARTICLE TRAJECTORY CALCULATIONS

Application of the computer model and comparison of the computed results with experiment are illustrated in this chapter. Three test cases for water droplet trajectory and local collection coefficient calculations are employed. These cases are:

1. Joukowski airfoil 0015 at 0° angle of attack without walls.
2. Joukowski airfoil 0015 at 4° angle of attack with walls.
3. Two-body case (two-dimensional inlet) at 0° angle of attack.

The input/output step-by-step procedures for applying the program to each test case is described. Details of test cases 1, 2, and 3 are described in Subchapters A, B, and C, respectively. To fully understand the input/output printouts presented in this chapter, the user should coordinate the results with the card structure and input instructions given in Reference 2.

Comparison of the computed results with the additional test cases given in Table 4.1 is also given to further demonstrate the computer program. Results from these runs are graphically compared with experimental data in Subchapter D. Application of the program to a two-dimensional inlet is also described. The program was run for the four cases given in Table 4.2. However, since no experimental data was available for comparison, only one case is described. The computed results shown in this chapter are for a monodispersed droplet size distribution whereas the actual droplet size distribution would be multidispersed. A multidispersed application is described in Chapter VI.

TABLE 4.1. Test Cases Computed with Particle Trajectory Program.

Airfoil	Chord (inches)	α	V_∞ (knots)	D* (μ)	K_0	Ref
NACA 65_A-004	72	0°	--	16.7	0.014	NACA TN 4151
	--	8°	--	16.7	0.014	NACA TN 4151
Joukowski 0015	13	0°	152	16.7	--	NACA TN 3839
	--	4°	152	16.7	--	NACA TN 3839
	--	8°	152	16.7	--	NACA TN 3839
NACA 65_1-212	72	0°	152	16.7	--	NACA TN 3839
	--	4°	152	16.7	--	NACA TN 3839

*The particle diameter is chosen as the median-volume diameter of the particles used in the experiment.

TABLE 4.2. Test Cases for Inlet Configuration.

V (ft/s)	α	Control Station Mach Number	K_0	D (μ)
145.5	0°	0.79	0.014	16.7
145.5	0°	0.40	0.014	16.7
145.5	30°	0.79	0.014	16.7
145.5	30°	0.40	0.014	16.7

A source listing of the particle trajectory computer program is given in Appendix C.

A. JOUKOWSKI AIRFOIL 0015 AT 0° ANGLE OF ATTACK WITHOUT WALLS

The geometry of the Joukowski airfoil 0015 is given in Figure 4.1. The input data for generating the geometry using the program SCIRCL is listed in Table 4.3. The output data file Tape 17 of SCIRCL (Table 4.4) is used directly as the input data file for the two-dimensional

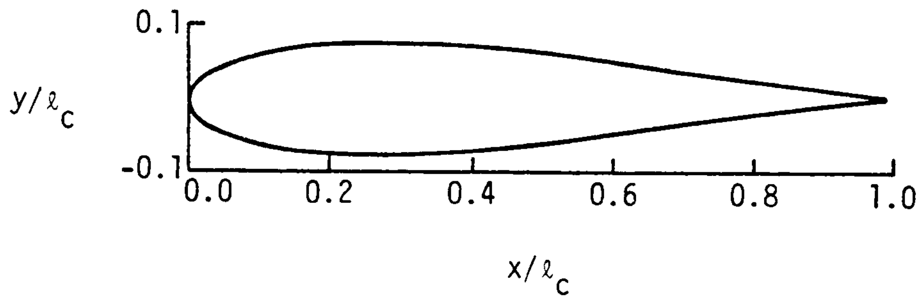


Figure 4.1 Joukowski airfoil 0015 without walls.

TABLE 4.3. Input Data File for Geometry Generation Program SCIRCL.

```
JOUKOWSKI 0015 ATTACK ANGLE 0.0
             0.0       1
TEST        24Y
1.0          0.015      0.015
   1
-0.02    -0.9     0.9        20
1.0          10.0       0.015      1.0
10.
1.00            0.90564
0.0             -0.00696
-3.
0.92487         0.90564       0.70752                     0.67559
-0.00500        -0.00696      -0.03281                    -0.03729
0.0
0.73845         0.70752       0.60934       0.45422       0.35193       0.31897
-0.02846        -0.03281      -0.04638      -0.06467      -0.07253      -0.07401
0.0
0.40259         0.35193       0.24058       0.12040       0.05225       0.03117
-0.06919        -0.07253      -0.07477      -0.06469      -0.04714      -0.03751
0.0          2.          2.
0.07836         0.05225                                   0.0           0.0
-0.05560        -0.04714                                  0.0           0.01
0.0          2.          2.
0.0             0.0                                       0.05225       0.07836
-0.01           0.0                                       0.04714       0.05560
0.0
0.03117         0.05225       0.12040       0.24058       0.35193       0.40259
0.03751         0.04714       0.06469       0.07477       0.07253       0.06919
0.0
0.31897         0.35193       0.45422       0.60934       0.70752       0.73845
0.07401         0.07253       0.06467       0.04638       0.03281       0.02846
-3.
0.67559         0.70752       0.90564                     0.92478
0.03729         0.03281       0.00696                     0.00500
1.0
0.90564         1.0
0.00696         0.0
```

potential flow program [2]. The file is renamed Tape 05. This data file as well as the output data file Tape 21 generated by the potential flow program are used as the input data files for the trajectory program (Appendix A).

In addition to the data files described above, the user must manually create data file Tape 02 (Table 4.5) for the trajectory program.

TABLE 4.4. Input Data File Tape 17 (renumbered Tape 05) for the Potential Flow Program.

1	0 0	JOUKOWSKI 0015 ATTAC			0 0 0	1	1	1	1
	1.00000	0.98412	0.96824	0.95236	0.93648	0.92060			3
	0.90564	0.89283	0.87999	0.86711	0.85417	0.84118			3
	0.82814	0.81502	0.80184	0.78859	0.77525	0.76182			3
	0.74831	0.73470	0.72104	0.70752	0.69325	0.67904			3
	0.66489	0.65080	0.63677	0.62279	0.60886	0.59497			3
	0.58113	0.56731	0.55352	0.53976	0.52602	0.51231			3
	0.49862	0.48496	0.47133	0.45773	0.44418	0.43068			3
	0.41725	0.40392	0.39070	0.37762	0.36474	0.35193			3
	0.33878	0.32651	0.31423	0.30194	0.28963	0.27732			3
	0.26499	0.25268	0.24037	0.22808	0.21581	0.20358			3
	0.19139	0.17926	0.16719	0.15519	0.14328	0.13145			3
	0.11972	0.10809	0.09655	0.08511	0.07378	0.06256			3
	0.05225	0.04221	0.03254	0.02335	0.01498	0.00766			3
	0.00213	0.00000	0.00210	0.00689	0.01310	0.01983			3
	0.02725	0.03519	0.04354	0.05225	0.06175	0.06987			3
	0.07809	0.08639	0.09474	0.10314	0.11158	0.12008			3
	0.12862	0.13722	0.14587	0.15456	0.16331	0.17209			3
	0.18092	0.18979	0.19868	0.20761	0.21657	0.22554			3
	0.23454	0.24355	0.25257	0.26160	0.27064	0.27968			3
	0.28872	0.29775	0.30679	0.31581	0.32483	0.33384			3
	0.34285	0.35193	0.36205	0.37094	0.37992	0.38900			3
	0.39818	0.40743	0.41674	0.42612	0.43554	0.44499			3
	0.45449	0.46400	0.47355	0.48311	0.49269	0.50229			3
	0.51190	0.52152	0.53116	0.54081	0.55047	0.56014			3
	0.56983	0.57952	0.58924	0.59897	0.60871	0.61847			3
	0.62826	0.63807	0.64790	0.65776	0.66764	0.67756			3
	0.68751	0.69749	0.70752	0.71821	0.72897	0.73980			3
	0.75067	0.76147	0.77221	0.78288	0.79348	0.80402			3
	0.81449	0.82489	0.83522	0.84549	0.85568	0.86581			3
	0.87588	0.88587	0.89580	0.90564	0.91569	0.92775			3
	0.94223	0.95667	0.97111	0.98556	1.00000		5	1	3
	0.00000	-0.00117	-0.00234	-0.00351	-0.00469	-0.00586			4
	-0.00696	-0.00830	-0.00972	-0.01121	-0.01277	-0.01439			4
	-0.01607	-0.01780	-0.01958	-0.02140	-0.02325	-0.02513			4
	-0.02704	-0.02897	-0.03091	-0.03281	-0.03482	-0.03681			4
	-0.03879	-0.04074	-0.04267	-0.04457	-0.04644	-0.04828			4
	-0.05008	-0.05184	-0.05356	-0.05524	-0.05687	-0.05846			4
	-0.06001	-0.06150	-0.06294	-0.06432	-0.06564	-0.06690			4
	-0.06809	-0.06919	-0.07020	-0.07111	-0.07189	-0.07253			4
	-0.07333	-0.07395	-0.07443	-0.07480	-0.07504	-0.07516			4
	-0.07515	-0.07502	-0.07476	-0.07438	-0.07388	-0.07324			4
	-0.07246	-0.07155	-0.07049	-0.06927	-0.06789	-0.06634			4
	-0.06458	-0.06260	-0.06036	-0.05779	-0.05481	-0.05126			4
	-0.04714	-0.04332	-0.03852	-0.03274	-0.02603	-0.01822			4
	-0.00923	0.00000	0.00917	0.01723	0.02425	0.03012			4
	0.03536	0.03996	0.04389	0.04714	0.05097	0.05366			4
	0.05601	0.05810	0.05998	0.06168	0.06322	0.06464			4
	0.06593	0.06712	0.06821	0.06920	0.07011	0.07094			4
	0.07168	0.07235	0.07294	0.07346	0.07391	0.07429			4
	0.07460	0.07484	0.07502	0.07513	0.07517	0.07514			4
	0.07505	0.07489	0.07467	0.07438	0.07402	0.07359			4
	0.07310	0.07253	0.07203	0.07153	0.07096	0.07033			4
	0.06964	0.06891	0.06813	0.06731	0.06646	0.06557			4
	0.06464	0.06369	0.06271	0.06170	0.06066	0.05960			4
	0.05851	0.05740	0.05627	0.05511	0.05393	0.05274			4
	0.05152	0.05028	0.04903	0.04775	0.04646	0.04516			4
	0.04383	0.04250	0.04114	0.03978	0.03840	0.03702			4
	0.03562	0.03422	0.03281	0.03131	0.02978	0.02825			4
	0.02671	0.02519	0.02368	0.02219	0.02073	0.01929			4
	0.01788	0.01651	0.01517	0.01386	0.01260	0.01138			4
	0.01020	0.00907	0.00799	0.00696	0.00622	0.00533			4
	0.00426	0.00320	0.00213	0.00107	0.00000		5	1	4
		JOUKOWSKI 0015 ATTACK AN							8
	0.00			1	1		2.000	0	19
1		JOUKOWSKI 0015 ATTACK AN						1	21
	-0.02000	-0.02000	-0.02000	-0.02000	-0.02000	-0.02000			3
	-0.02000	-0.02000	-0.02000	-0.02000	-0.02000	-0.02000			3
	-0.02000	-0.02000	-0.02000	-0.02000	-0.02000	-0.02000			3
	-0.02000	-0.02000					2	1	3
	-0.90000	-0.80526	-0.71053	-0.61579	-0.52105	-0.42632			4
	-0.33158	-0.23684	-0.14211	-0.04737	0.04737	0.14211			4
	0.23684	0.33158	0.42632	0.52105	0.61579	0.71053			4
	0.80526	0.90000					2	1	4

TABLE 4.5. Input Data File Tape 02 for the Particle Trajectory Program.

```
$NBDY *   1       NFL$$     10      NSEAR    50      NEQ$$     4
$LEQM     0       LSYM$      1      LRANG     1
$LIM$     1       LOFT$      0      LPLOT     0      LTNL$     0        LXOR$      1
$G   $    0.0     VINF$   78.0
$DP  $   16.7     RL   $     0.3302 TIMSP    0.0001  YLIM$     0.000001CF   $ 1.0
PRATN     0.0     PIT  $     0.0    PITDT    0.0     XORC$    -4.0      YORC$ 0.1
XREAR     1.00    YLO  $    -0.10   YUP  $   0.10    YMAX$     0.05     YMIN$-0.05
ADEPS     0.0005  ANLFL      0.0    ANLCR    0.0     EPSX$     0.001
NSI$$     1
INITIAL INFUT DATA FOR LOCAL CATCH EFFICIENCY CALCULATIONS
NCOEF     3       NPTS$      7      $ NS$     0
EXPERIMENTAL DATA OF LOCAL CATCH EFFICIENCY :
   13
-0.08          0.045
-0.06          0.105
-0.04          0.235
-0.02          0.485
-0.01          0.601
0.0            0.637
0.01           0.601
0.02           0.485
0.04           0.235
0.06           0.105
0.08           0.045
0.10           0.020
0.15           0.010
```

*The names of the variables including those with $'s are printed to fill the appropriate spaces. Normally, these alphabetic symbols would not be input by the user but are given here to clarify the illustration.

The output data file Tape 06 (Table 4.6) of the trajectory program is shown in Table 4.6. After the initial information relative to the conditions being run, Table 4.6 first shows the initial and input impingement values of the particles used in determining the upper and lower surface limits of impingement. The upper and lower surface limits are then tabulated. Also, the total collection efficiency is specified. Information on the equally spaced ten particle trajectories computed between these limits is given next. The table then lists the initial values y_0 and surface positions of impingement for the total number of particle trajectories computed (in this case 37). The local collection coefficient β versus surface position calculated with the linear approximation is then shown in the table and finally the values of β versus

TABLE 4.6. Output Data File Tape 06 for the Particle Trajectory Program.

```
THE PARTICLES ARE RELEASED FROM X/RL=-4.20000E 00
WHICH IS OBTAINED AT THE   20 LOOP OF   50 LOOPS

PARTICLE   CHORD     TIME      NO. OF     VX        VY       ANGLE    PITCH    PIT      GRAVT.    INERT.    ADAMS
DIAMETER   LENGTH    STEP      DROPLET    REF.      REF.     OF ATK.  ANGLE    DOT      CONSTANT  MOMENT    CRITERIA

1.67E-05  3.30E-01  1.00E-04     10  7.80E 01      0.00     0.00     0.00     0.00     0.00  6.80E-23  5.00E-04


NBDY  ID           XFRNT          YFRNT          XREAR           YREAR          THICK           YUPPP          YLOOO
 1    1          0.00000        0.00000     1.00000E 00        0.00000    1.50330E-01    9.02029E-02    -9.01929E-02
      X0        Y0                         XP        YP           SD          DT           NSTP
-4.19999   0.05000 OUT OF RANGE         0.11830   0.09021                 1.0000E-04       181
-4.19999  -0.05000 OUT OF RANGE         0.11824  -0.09020                 1.0000E-04       181

YMAX=  5.0000E-02    YMIN= -5.0000E-02
-4.19999   0.00000 HIT BODY AT          0.00001   0.00004  -0.00004   1.2500E-05       185
-4.19999   0.02500 OUT OF RANGE         0.18911   0.09080             2.5000E-05       204
-4.19999   0.01250 HIT BODY AT          0.00899   0.01960  -0.02195   2.5000E-05       182
-4.19999   0.01875 HIT BODY AT          0.02272   0.03216  -0.04063   5.0000E-05       181
-4.19999   0.02187 OUT OF RANGE         0.19357   0.09058             2.5000E-05       206
-4.19999   0.02031 HIT BODY AT          0.02860   0.03614  -0.04773   5.0000E-05       182
-4.19999   0.02109 HIT BODY AT          0.03335   0.03889  -0.05321   5.0000E-05       182
-4.19999   0.02148 HIT BODY AT          0.03624   0.04046  -0.05651   5.0000E-05       182
-4.19999   0.02168 HIT BODY AT          0.03911   0.04180  -0.05967   5.0000E-05       183
-4.19999   0.02178 HIT BODY AT          0.04067   0.04254  -0.06140   5.0000E-05       183
-4.19999   0.02183 OUT OF RANGE         0.19354   0.09056             2.5000E-05       206
-4.19999   0.02180 OUT OF RANGE         0.19353   0.09054             2.5000E-05       206
-4.19999   0.02179 HIT BODY AT          0.04086   0.04263  -0.06161   5.0000E-05       183
-4.19999   0.02180 OUT OF RANGE         0.19352   0.09054             2.5000E-05       206
-4.19999   0.02179 HIT BODY AT          0.04753   0.04538  -0.06883   5.0000E-05       183
-4.19999   0.02179 OUT OF RANGE         0.19352   0.09054             2.5000E-05       206

SYMMETRIC FLOW CASE IS COMPUTED

    UPPER SURFACE LIMIT          LOWER SURFACE LIMIT
        ZU            SU             ZL           SL
  0.2179E-01   -0.6883E-01   -0.2179E-01    0.6883E-01

TOTAL COLLECTION EFFICIENCY     2.89930E-01

      X0        Y0                         XP        YP           SD          DT           NSTP
-4.19999   0.02179 HIT BODY AT          0.04753   0.04538  -0.06883   5.0000E-05       183
-4.19999   0.01937 HIT BODY AT          0.02487   0.03368  -0.04325   5.0000E-05       181
-4.19999   0.01695 HIT BODY AT          0.01743   0.02803  -0.03390   5.0000E-05       180
-4.19999   0.01453 HIT BODY AT          0.01237   0.02343  -0.02706   5.0000E-05       181
-4.19999   0.01211 HIT BODY AT          0.00835   0.01889  -0.02099   2.5000E-05       182
-4.19999   0.00969 HIT BODY AT          0.00554   0.01495  -0.01614   5.0000E-05       180
-4.19999   0.00726 HIT BODY AT          0.00317   0.01097  -0.01150   2.5000E-05       182
-4.19999   0.00484 HIT BODY AT          0.00167   0.00727  -0.00746   2.5000E-05       182
-4.19999   0.00242 HIT BODY AT          0.00084   0.00365  -0.00374   2.5000E-05       182
-4.19999   0.00000 HIT BODY AT          0.00001   0.00004  -0.00004   1.2500E-05       185

NO. OF DATA POINTS STORED IN TAPE03 =     37
```

TABLE 4.6 (continued).

I	Z0	SD	BETA
1	2.1793E-02	-6.8828E-02	
2	2.1793E-02	-6.8828E-02	
3	2.1790E-02	-6.1609E-02	
4	2.1777E-02	-6.1396E-02	
5	2.1680E-02	-5.9670E-02	
6	2.1484E-02	-5.6508E-02	
7	2.1094E-02	-5.3211E-02	
8	2.0312E-02	-4.7733E-02	
9	1.9371E-02	-4.3253E-02	
10	1.8750E-02	-4.0625E-02	
11	1.6950E-02	-3.3903E-02	
12	1.4528E-02	-2.7058E-02	
13	1.2500E-02	-2.1952E-02	
14	1.2107E-02	-2.0992E-02	
15	9.6856E-03	-1.6135E-02	
16	7.2642E-03	-1.1498E-02	
17	4.8428E-03	-7.4594E-03	
18	2.4214E-03	-3.7435E-03	
19	0.0000	-3.9757E-05	
20	-2.4214E-03	3.7435E-03	
21	-4.8428E-03	7.4594E-03	
22	-7.2642E-03	1.1498E-02	
23	-9.6856E-03	1.6135E-02	
24	-1.2107E-02	2.0992E-02	
25	-1.2500E-02	2.1952E-02	
26	-1.4528E-02	2.7058E-02	
27	-1.6950E-02	3.3903E-02	
28	-1.8750E-02	4.0625E-02	
29	-1.9371E-02	4.3253E-02	
30	-2.0312E-02	4.7733E-02	
31	-2.1094E-02	5.3211E-02	
32	-2.1484E-02	5.6508E-02	
33	-2.1680E-02	5.9670E-02	
34	-2.1777E-02	6.1396E-02	
35	-2.1790E-02	6.1609E-02	
36	-2.1793E-02	6.8828E-02	
37	-2.1793E-02	6.8828E-02	

LINEAR APPROACH

I	Z0	SD	BETA
36			
1	2.1793E-02	-6.8828E-02	1.8750E-02
2	2.1791E-02	-6.5219E-02	4.2011E-04
3	2.1783E-02	-6.1502E-02	5.7070E-02
4	2.1729E-02	-6.0533E-02	5.6584E-02
5	2.1582E-02	-5.8089E-02	6.1781E-02
6	2.1289E-02	-5.4860E-02	1.1847E-01
7	2.0703E-02	-5.0472E-02	1.4260E-01
8	1.9842E-02	-4.5493E-02	2.1013E-01
9	1.9061E-02	-4.1939E-02	2.3639E-01
10	1.7850E-02	-3.7264E-02	2.6781E-01
11	1.5739E-02	-3.0480E-02	3.5372E-01
12	1.3514E-02	-2.4505E-02	3.9725E-01

TABLE 4.6 (continued).

13	1. 2303E-02	-2. 1472E-02	4. 0959E-01
14	1. 0896E-02	-1. 8564E-02	4. 9855E-01
15	8. 4749E-03	-1. 3816E-02	5. 2212E-01
16	6. 0535E-03	-9. 4785E-03	5. 9962E-01
17	3. 6321E-03	-5. 6015E-03	6. 5163E-01
18	1. 2107E-03	-1. 8916E-03	6. 5377E-01
19	-1. 2107E-03	1. 8519E-03	6. 4003E-01
20	-3. 6321E-03	5. 6015E-03	6. 5163E-01
21	-6. 0535E-03	9. 4785E-03	5. 9962E-01
22	-8. 4749E-03	1. 3816E-02	5. 2212E-01
23	-1. 0896E-02	1. 8564E-02	4. 9855E-01
24	-1. 2303E-02	2. 1472E-02	4. 0959E-01
25	-1. 3514E-02	2. 4505E-02	3. 9725E-01
26	-1. 5739E-02	3. 0480E-02	3. 5372E-01
27	-1. 7850E-02	3. 7264E-02	2. 6781E-01
28	-1. 9061E-02	4. 1939E-02	2. 3639E-01
29	-1. 9842E-02	4. 5493E-02	2. 1013E-01
30	-2. 0703E-02	5. 0472E-02	1. 4260E-01
31	-2. 1289E-02	5. 4860E-02	1. 1847E-01
32	-2. 1582E-02	5. 8089E-02	6. 1781E-02
33	-2. 1729E-02	6. 0533E-02	5. 6584E-02
34	-2. 1783E-02	6. 1502E-02	5. 7070E-02
35	-2. 1791E-02	6. 5219E-02	4. 2011E-04
36	-2. 1793E-02	6. 8828E-02	1. 8750E-02

POLYNOMIAL LEAST SQUARE FIT

NO. OF COEFFICIENTS IS 3
NO. OF POINTS FOR DATA FITTING IS 7

I	Z0	SD	BETA
1	2. 1793E-02	-6. 8828E-02	0. 0000
2	2. 1793E-02	-6. 8828E-02	-3. 7025E-02
3	2. 1788E-02	-6. 1609E-02	3. 7939E-02
4	2. 1780E-02	-6. 1396E-02	4. 0161E-02
5	2. 1691E-02	-5. 9670E-02	5. 6790E-02
6	2. 1467E-02	-5. 6508E-02	8. 8448E-02
7	2. 1119E-02	-5. 3211E-02	1. 2245E-01
8	2. 0276E-02	-4. 7733E-02	1. 7623E-01
9	1. 9392E-02	-4. 3253E-02	2. 2100E-01
10	1. 8780E-02	-4. 0625E-02	2. 4571E-01
11	1. 6901E-02	-3. 3903E-02	3. 1088E-01
12	1. 4578E-02	-2. 7058E-02	3. 8399E-01
13	1. 2479E-02	-2. 1952E-02	4. 4058E-01
14	1. 2058E-02	-2. 0992E-02	4. 5280E-01
15	9. 7461E-03	-1. 6135E-02	5. 0992E-01
16	7. 2160E-03	-1. 1498E-02	5. 6671E-01
17	4. 8082E-03	-7. 4594E-03	6. 0232E-01
18	2. 4669E-03	-3. 7435E-03	6. 2610E-01
19	1. 7110E-05	-3. 9757E-05	6. 3765E-01
20	-2. 4809E-03	3. 7435E-03	6. 2576E-01
21	-4. 8156E-03	7. 4594E-03	6. 0140E-01
22	-7. 2087E-03	1. 1498E-02	5. 6522E-01
23	-9. 7461E-03	1. 6135E-02	5. 0992E-01
24	-1. 2058E-02	2. 0992E-02	4. 5280E-01

TABLE 4.6 (continued).

25	-1. 2479E-02	2. 1952E-02	4. 4058E-01
26	-1. 4578E-02	2. 7058E-02	3. 8399E-01
27	-1. 6901E-02	3. 3903E-02	3. 1088E-01
28	-1. 8780E-02	4. 0625E-02	2. 4571E-01
29	-1. 9392E-02	4. 3253E-02	2. 2100E-01
30	-2. 0276E-02	4. 7733E-02	1. 7623E-01
31	-2. 1119E-02	5. 3211E-02	1. 2245E-01
32	-2. 1467E-02	5. 6508E-02	8. 8448E-02
33	-2. 1691E-02	5. 9670E-02	5. 6790E-02
34	-2. 1780E-02	6. 1396E-02	4. 0161E-02
35	-2. 1788E-02	6. 1609E-02	3. 7939E-02
36	-2. 1793E-02	6. 8828E-02	-3. 7025E-02
37	-2. 1793E-02	6. 8828E-02	0. 0000

35

I	Z0	SD	BETA
1		-6. 8828E-02	0. 0000
2		-6. 1609E-02	3. 7939E-02
3		-6. 1396E-02	4. 0161E-02
4		-5. 9670E-02	5. 6790E-02
5		-5. 6508E-02	8. 8448E-02
6		-5. 3211E-02	1. 2245E-01
7		-4. 7733E-02	1. 7623E-01
8		-4. 3253E-02	2. 2100E-01
9		-4. 0625E-02	2. 4571E-01
10		-3. 3903E-02	3. 1088E-01
11		-2. 7058E-02	3. 8399E-01
12		-2. 1952E-02	4. 4058E-01
13		-2. 0992E-02	4. 5280E-01
14		-1. 6135E-02	5. 0992E-01
15		-1. 1498E-02	5. 6671E-01
16		-7. 4594E-03	6 0232E-01
17		-3. 7435E-03	6. 2610E-01
18		-3. 9757E-05	6. 3765E-01
19		3. 7435E-03	6. 2576E-01
20		7. 4594E-03	6. 0140E-01
21		1. 1498E-02	5. 6522E-01
22		1. 6135E-02	5. 0992E-01
23		2. 0992E-02	4. 5280E-01
24		2. 1952E-02	4. 4058E-01
25		2. 7058E-02	3. 8399E-01
26		3. 3903E-02	3. 1088E-01
27		4. 0625E-02	2. 4571E-01
28		4. 3253E-02	2. 2100E-01
29		4. 7733E-02	1. 7623E-01
30		5. 3211E-02	1. 2245E-01
31		5. 6508E-02	8. 8448E-02
32		5. 9670E-02	5. 6790E-02
33		6. 1396E-02	4. 0161E-02
34		6. 1609E-02	3. 7939E-02
35		6. 8828E-02	0. 0000

TERMINATED: STOP

surface position computed using a polynomial curve fit technique are tabulated. Note that segment curve fitting was used in this case. The computed results presented in Table 4.6 are compared with experimental data from NACA TN 3839 in Figure 4.2. The agreement is believed to be very good.

B. JOUKOWSKI AIRFOIL 0015 AT 4° ANGLE OF ATTACK WITH WALLS

The geometry of the Joukowski airfoil 0015 with walls is given in Figure 4.3. The input data file for generating the geometry with the program SCIRCL is listed in Table 4.7. Note the output now defines three bodies since the airfoil is now considered to be in an infinitely wide wind tunnel. The geometry generated by the program SCIRCL (Tape 17) needs to be modified for use in the 24Y program [2]. The value of ITR in Column 53 of the first card of Tape 17 is changed from zero to either one or three depending on whether an elliptical element is desired.

Card 2, marked with the symbol *, is added to the data file (Table 4.8). The card specifies the coordinates of the center of rotation for the airfoil in the wind tunnel. The airfoil is rotated 4° clockwise (negative) from its original position with the point (x,y) = (0.5,0.0) as the rotation axis.

This modified data file Tape 17 (Table 4.8), the output data file Tape 21 from the potential flow program, and the data file Tape 02 (Table 4.9) generated manually by using the instructions in Reference 2 are input data files for the trajectory program.

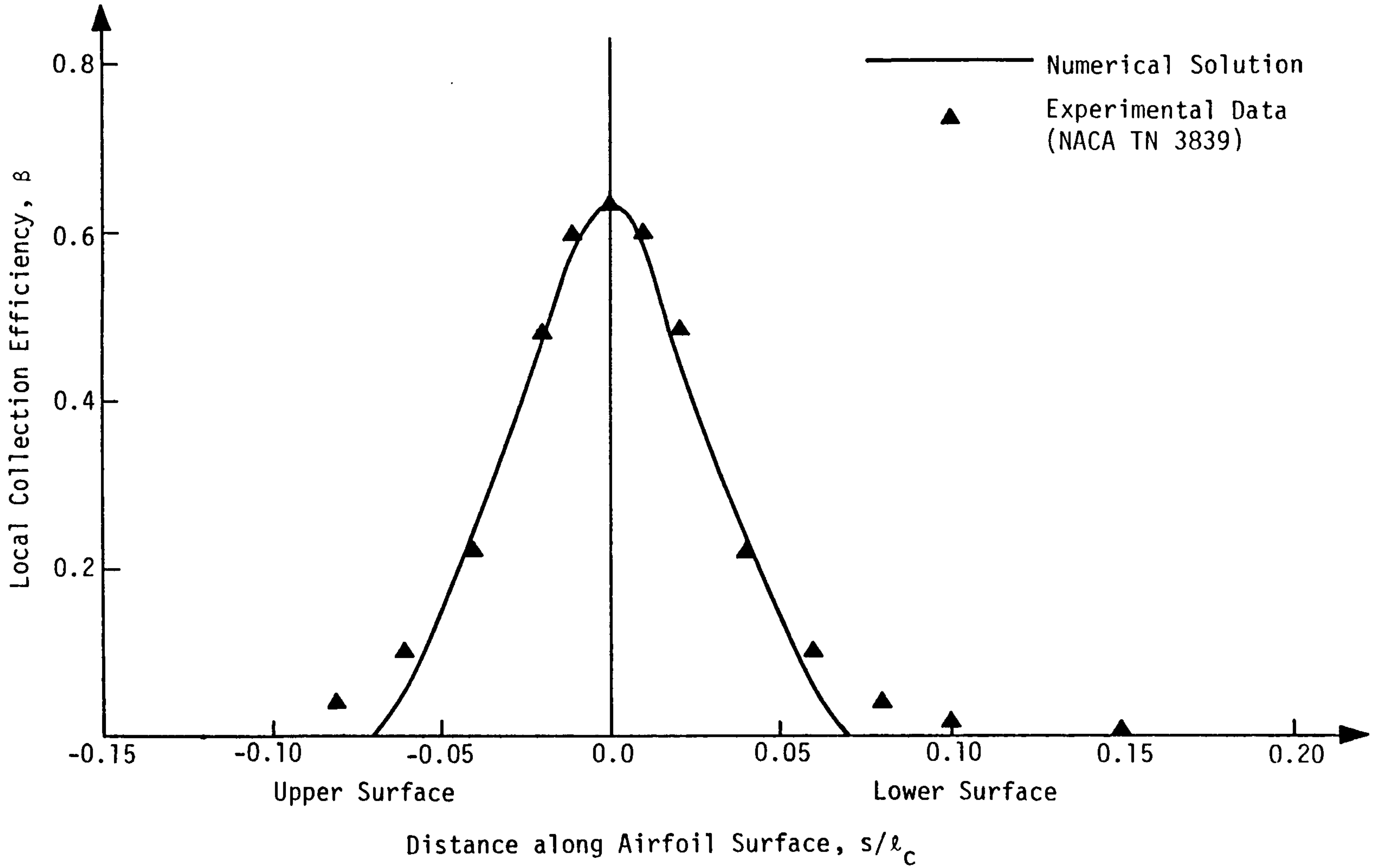


Figure 4.2 Joukowski airfoil 0015, 13-inch chord length, without walls, $\alpha = 0°$.

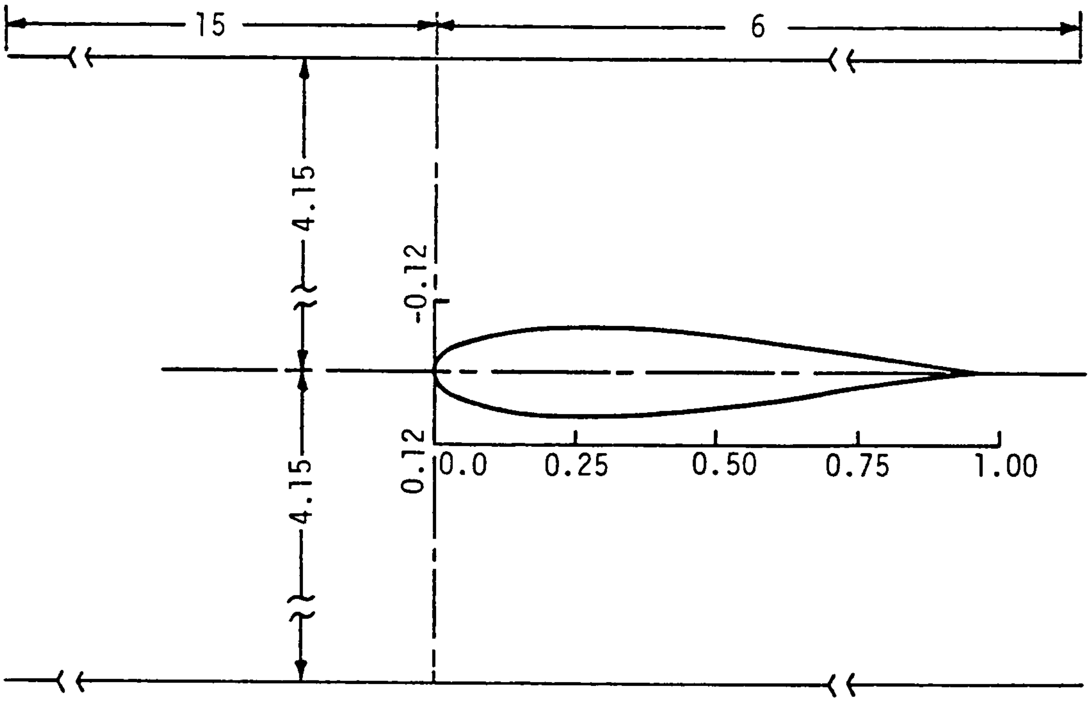


Figure 4.3 Joukowski airfoil 0015 with walls.

TABLE 4.7. Input Data File for Geometry Generation Program SCIRCL.

```
JOUKOWSKI 0015
            0.0     1
TEST      24Y
3.0         0.50        0.50
   1
-0.02   -0.9    0.9      20
1.0         10.0        0.015      0.0
10.
1.00          0.90564
0.0           -0.00696
-3.
0.92487       0.90564     0.70752                 0.67559
-0.00500      -0.00696    -0.03281                -0.03729
0.0
0.73845       0.70752     0.60934     0.45422     0.35193     0.31897
-0.02846      -0.03281    -0.04638    -0.06467    -0.07253    -0.07401
0.0
0.40259       0.35193     0.24058     0.12040     0.05225     0.03117
-0.06919      -0.07253    -0.07477    -0.06469    -0.04714    -0.03751
0.0         2.          2.
0.07836       0.05225                             0.0         0.0
-0.05560      -0.04714                            0.0         0.01
0.0         2.          2.
0.0           0.0                                 0.05225     0.07836
-0.01         0.0                                 0.04714     0.05560
0.0
0.03117       0.05225     0.12040     0.24058     0.35193     0.40259
0.03751       0.04714     0.06469     0.07477     0.07253     0.06919
0.0
0.31897       0.35193     0.45422     0.60934     0.70752     0.73845
0.07401       0.07253     0.06467     0.04638     0.03281     0.02846
-3.
0.67559       0.70752     0.90564                 0.92478
0.03729       0.03281     0.00696                 0.00500
1.0
0.90564       1.0
0.00696       0.0
2.0         2.0         1.0         1.0
```

TABLE 4.7 (continued).

```
1.0
-15.0       0.0
-4.15       -4.15
1.0
0.0         6.0
-4.15       -4.15
3.0      2.0        1.0        1.0
1.0
6.0         0.0
4.15        4.15
1.0
0.0         -15.0
4.15        4.15
```

TABLE 4.8. Input Data File Tape 17 (modified and renumbered Tape 05) for the Potential Flow Program.

```
1  0  1   JOUKOWSKI 0015                        0  0  0  1     1       1  0   1
                                                 -4.0     0.5        0.0     2*
   1.00000   0.98594   0.96009   0.93855   0.92060   0.90564                   3
   0.89283   0.87999   0.86711   0.85417   0.84118   0.82814                   3
   0.81502   0.80184   0.78859   0.77525   0.76182   0.74831                   3
   0.73470   0.72104   0.70752   0.69325   0.67904   0.66489                   3
   0.65080   0.63677   0.62279   0.60886   0.59497   0.58113                   3
   0.56731   0.55352   0.53976   0.52602   0.51231   0.49862                   3
   0.48496   0.47133   0.45773   0.44418   0.43068   0.41725                   3
   0.40392   0.39070   0.37762   0.36474   0.35193   0.33878                   3
   0.32651   0.31423   0.30194   0.28963   0.27732   0.26499                   3
   0.25268   0.24037   0.22808   0.21581   0.20358   0.19139                   3
   0.17926   0.16719   0.15519   0.14328   0.13145   0.11972                   3
   0.10809   0.09655   0.08511   0.07378   0.06256   0.05225                   3
   0.04221   0.03254   0.02335   0.01498   0.00766   0.00213                   3
   0.00000   0.00210   0.00689   0.01310   0.01983   0.02725                   3
   0.03519   0.04354   0.05225   0.06175   0.06987   0.07809                   3
   0.08639   0.09474   0.10314   0.11158   0.12008   0.12862                   3
   0.13722   0.14587   0.15456   0.16331   0.17209   0.18092                   3
   0.18979   0.19868   0.20761   0.21657   0.22554   0.23454                   3
   0.24355   0.25257   0.26160   0.27064   0.27968   0.28872                   3
   0.29775   0.30679   0.31581   0.32483   0.33384   0.34285                   3
   0.35193   0.36205   0.37094   0.37992   0.38900   0.39818                   3
   0.40743   0.41674   0.42612   0.43554   0.44499   0.45449                   3
   0.46400   0.47355   0.48311   0.49269   0.50229   0.51190                   3
   0.52152   0.53116   0.54081   0.55047   0.56014   0.56983                   3
   0.57952   0.58924   0.59897   0.60871   0.61847   0.62826                   3
   0.63807   0.64790   0.65776   0.66764   0.67756   0.68751                   3
   0.69749   0.70752   0.71821   0.72897   0.73980   0.75067                   3
   0.76147   0.77221   0.78288   0.79348   0.80402   0.81449                   3
   0.82489   0.83522   0.84549   0.85568   0.86581   0.87588                   3
   0.88587   0.89580   0.90564   0.91569   0.92775   0.94223                   3
   0.95960   0.98044   1.00000                                     3  1        3
   0.00000  -0.00104  -0.00294  -0.00453  -0.00586  -0.00696                   4
  -0.00830  -0.00972  -0.01121  -0.01277  -0.01439  -0.01607                   4
  -0.01780  -0.01958  -0.02140  -0.02325  -0.02513  -0.02704                   4
  -0.02897  -0.03091  -0.03281  -0.03482  -0.03681  -0.03879                   4
  -0.04074  -0.04267  -0.04457  -0.04644  -0.04828  -0.05008                   4
  -0.05184  -0.05356  -0.05524  -0.05687  -0.05846  -0.06001                   4
  -0.06150  -0.06294  -0.06432  -0.06564  -0.06690  -0.06809                   4
  -0.06919  -0.07020  -0.07111  -0.07189  -0.07253  -0.07333                   4
  -0.07395  -0.07443  -0.07480  -0.07504  -0.07516  -0.07515                   4
  -0.07502  -0.07476  -0.07438  -0.07388  -0.07324  -0.07246                   4
  -0.07155  -0.07049  -0.06927  -0.06789  -0.06634  -0.06458                   4
  -0.06260  -0.06036  -0.05779  -0.05481  -0.05126  -0.04714                   4
  -0.04332  -0.03852  -0.03274  -0.02603  -0.01822  -0.00923                   4
   0.00000   0.00917   0.01723   0.02425   0.03012   0.03536                   4
   0.03996   0.04389   0.04714   0.05097   0.05366   0.05601                   4
   0.05810   0.05998   0.06168   0.06322   0.06464   0.06593                   4
   0.06712   0.06821   0.06920   0.07011   0.07094   0.07168                   4
   0.07235   0.07294   0.07346   0.07391   0.07429   0.07460                   4
   0.07484   0.07502   0.07513   0.07517   0.07514   0.07505                   4
   0.07489   0.07467   0.07438   0.07402   0.07359   0.07310                   4
   0.07253   0.07203   0.07153   0.07096   0.07033   0.06964                   4
   0.06891   0.06813   0.06731   0.06646   0.06557   0.06464                   4
   0.06369   0.06271   0.06170   0.06066   0.05960   0.05851                   4
   0.05740   0.05627   0.05511   0.05393   0.05274   0.05152                   4
   0.05028   0.04903   0.04775   0.04646   0.04516   0.04383                   4
   0.04250   0.04114   0.03978   0.03840   0.03702   0.03562                   4
   0.03422   0.03281   0.03131   0.02978   0.02825   0.02671                   4
   0.02519   0.02368   0.02219   0.02073   0.01929   0.01788                   4
   0.01651   0.01517   0.01386   0.01260   0.01138   0.01020                   4
```

TABLE 4.8 (continued).

```
  0.00907    0.00799    0.00696    0.00622    0.00533    0.00426                4
  0.00298    0.00144    0.00000                                          3  1  4
2  0  0    JOUKOWSKI 0015                        0  0  0          2      1  0  1
-15.00000 -14.50000 -14.00000 -13.50000 -13.00000 -12.50000                   3
-12.00000 -11.50000 -11.00000 -10.50000 -10.00000  -9.50000                   3
 -9.00000  -8.50000  -8.00000  -7.50000  -7.00000  -6.50000                   3
 -6.00000  -5.50000  -5.00000  -4.50000  -4.00000  -3.50000                   3
 -3.00000  -2.50000  -2.00000  -1.50000  -1.00000  -0.50000                   3
  0.00000   0.50000   1.00000   1.50000   2.00000   2.50000                   3
  3.00000   3.50000   4.00000   4.50000   5.00000   5.50000                   3
  6.00000                                                            1  1  3
 -4.15000  -4.15000  -4.15000  -4.15000  -4.15000  -4.15000                   4
 -4.15000  -4.15000  -4.15000  -4.15000  -4.15000  -4.15000                   4
 -4.15000  -4.15000  -4.15000  -4.15000  -4.15000  -4.15000                   4
 -4.15000  -4.15000  -4.15000  -4.15000  -4.15000  -4.15000                   4
 -4.15000  -4.15000  -4.15000  -4.15000  -4.15000  -4.15000                   4
 -4.15000  -4.15000  -4.15000  -4.15000  -4.15000  -4.15000                   4
 -4.15000  -4.15000  -4.15000  -4.15000  -4.15000  -4.15000                   4
 -4.15000                                                            1  1  4
3  0  0    JOUKOWSKI 0015                        0  0  0          2      1  1  1
  6.00000   5.50000   5.00000   4.50000   4.00000   3.50000                   3
  3.00000   2.50000   2.00000   1.50000   1.00000   0.50000                   3
  0.00000  -0.50000  -1.00000  -1.50000  -2.00000  -2.50000                   3
 -3.00000  -3.50000  -4.00000  -4.50000  -5.00000  -5.50000                   3
 -6.00000  -6.50000  -7.00000  -7.50000  -8.00000  -8.50000                   3
 -9.00000  -9.50000 -10.00000 -10.50000 -11.00000 -11.50000                   3
-12.00000 -12.50000 -13.00000 -13.50000 -14.00000 -14.50000                   3
-15.00000                                                            1  1  3
  4.15000   4.15000   4.15000   4.15000   4.15000   4.15000                   4
  4.15000   4.15000   4.15000   4.15000   4.15000   4.15000                   4
  4.15000   4.15000   4.15000   4.15000   4.15000   4.15000                   4
  4.15000   4.15000   4.15000   4.15000   4.15000   4.15000                   4
  4.15000   4.15000   4.15000   4.15000   4.15000   4.15000                   4
  4.15000   4.15000   4.15000   4.15000   4.15000   4.15000                   4
  4.15000   4.15000   4.15000   4.15000   4.15000   4.15000                   4
  4.15000                                                            1  1  4
           JOUKOWSKI 0015                                                     8
            0.00                 1         1              2.000         0 19
1         JOUKOWSKI 0015                                                   1 21
 -0.02000  -0.02000  -0.02000  -0.02000  -0.02000  -0.02000                   3
 -0.02000  -0.02000  -0.02000  -0.02000  -0.02000  -0.02000                   3
 -0.02000  -0.02000  -0.02000  -0.02000  -0.02000  -0.02000                   3
 -0.02000  -0.02000                                                  2  1  3
 -0.90000  -0.80526  -0.71053  -0.61579  -0.52105  -0.42632                   4
 -0.33158  -0.23684  -0.14211  -0.04737   0.04737   0.14211                   4
  0.23684   0.33158   0.42632   0.52105   0.61579   0.71053                   4
  0.80526   0.90000                                                  2  1  4
```

The output data file Tape 06 of the trajectory program is listed in Table 4.10. This table has the same description as given in Subchapter A. The computed results are compared with the available experimental data from NACA TN 3839 in Figure 4.4. Again, the agreement is good.

C. TWO-DIMENSIONAL INLET AT 0° ANGLE OF ATTACK (TWO-BODY CASE)

The geometry of the two-dimensional inlet is given in Figure 4.5. The input data used in the program SCIRCL to generate this geometry is

TABLE 4.9. Input Data File Tape 02 for the Particle Trajectory Program.

```
$NBDY *   3      NPL$$     10      NSEAR    50       NEQ$$     4
$LEQM     0      LSYM$      0      LRANG     1
$LIM$     1      LOPT$      0      LPLOT     0       LTNL$     1        LXOR$     1
$G   $   0.0     VINF$    78.0
$DP  $  16.7     RL   $    0.3302 TIMSP    0.0001   YLIM$   0.000001CF   $ 1.0
PRATK    0.0     PIT  $    0.0     PITDT    0.0      XORC$  -4.0       YORC$ 0.1
XREAR    1.00    YLO  $   -0.10    YUP  $   0.10     YMAX$   0.05      YMIN$-0.11
ADEPS    0.0005  ANLFL     0.0     ANLCR    4.0      EPSX$   0.001
NSI$$     1
INITIAL INPUT DATA FOR LOCAL CATCH EFFICIENCY CALCULATIONS
NCOEF     3      NPTS$      7      $ NS$     0
EXPERIMENTAL DATA OF LOCAL CATCH EFFICIENCY :
   13
-0.08        0.005
-0.06        0.020
-0.04        0.075
-0.02        0.385
-0.01        0.520
 0.0         0.623
 0.01        0.614
 0.02        0.523
 0.04        0.347
 0.06        0.225
 0.08        0.133
 0.10        0.077
 0.15        0.022
```

*The names of the variables including those with $'s are printed to fill the appropriate spaces. Normally, these alphabetic symbols would not be input by the user but are given here to clarify the illustration.

listed in Table 4.11. The output data file Tape 17 of the program SCIRCL is used directly as the input data file, Table 4.12, for the two-dimensional potential flow program.

The output data file Tape 21 of the potential flow program and Tape 02 (Table 4.13) generated manually are the input data files for the trajectory program. In addition to these two data files, the trajectory program requires input data file Tape 05, which is the output data file Tape 17. However, for the two-dimensional inlet case a number of modifications are made to this tape to improve accuracy and consistency of the calculation.

The first modification was to regenerate the body and effectively magnify the nose area where the ice impingement occurs. The need to modify the geometry results from the fact that the dimension statement

TABLE 4.10. Output Data File Tape 06 for the Particle Trajectory Program.

THE PARTICLES ARE RELEASED FROM X/RL=-4. 39878E 00
WHICH IS OBTAINED AT THE 21 LOOP OF 50 LOOPS

PARTICLE DIAMETER	CHORD LENGTH	TIME STEP	NO. OF DROPLET	VX REF.	VY REF.	ANGLE OF ATK.	PITCH ANGLE	PIT DOT	GRAVT. CONSTANT	INERT. MOMENT	ADAMS CRITERIA
1. 67E-05	3. 30E-01	1. 00E-04	10	7. 80E 01	0. 00	4. 00E 00	0. 00	0. 00	0. 00	6. 80E-23	5. 00E-04

NBDY	ID	XFRNT	YFRNT	XREAR	YREAR	THICK	YUPPP	YLOOO
3	1	1. 21796E-03	3. 48782E-02	9. 98782E-01	-3. 48782E-02	1. 56212E-01	1. 09428E-01	-7. 80258E-02

X0	Y0		XP	YP	SD	DT	NSTP
-4. 39878	0. 05000	OUT OF RANGE	-0. 44225	0. 11000		1. 0000E-04	164
-4. 39878	-0. 11000	OUT OF RANGE	1. 00082	-0. 07916		5. 0000E-05	273

YMAX= 5. 0000E-02 YMIN= -1. 1000E-01

-4. 39878	-0. 03000	OUT OF RANGE	0. 08251	0. 11042		5. 0000E-05	190
-4. 39878	-0. 07000	HIT BODY AT	0. 00212	0. 02915	0. 00580	1. 0000E-04	185
-4 39878	-0. 05000	OUT OF RANGE	0. 10933	0. 10992		2. 5000E-05	197
-4 39878	-0. 06000	HIT BODY AT	0. 00557	0. 04622	-0. 01225	5. 0000E-05	187
-4 39878	-0. 05500	OUT OF RANGE	0. 11021	0. 10991		2. 5000E-05	205
-4. 39878	-0. 05750	HIT BODY AT	0. 00988	0. 05216	-0. 01960	2. 5000E-05	189
-4 39878	-0. 05625	HIT BODY AT	0. 01536	0. 05755	-0. 02729	2. 5000E-05	190
-4 39878	-0. 05562	HIT BODY AT	0. 01952	0. 06083	-0. 03259	2. 5000E-05	191
-4. 39878	-0. 05531	OUT OF RANGE	0. 10971	0. 10974		2. 5000E-05	205
-4. 39878	-0. 05547	HIT BODY AT	0. 02139	0. 06225	-0. 03494	2. 5000E-05	191
-4. 39878	-0. 05539	OUT OF RANGE	0. 10960	0. 10969		2. 5000E-05	205
-4. 39878	-0. 05543	HIT BODY AT	0. 02188	0. 06262	-0. 03556	2. 5000E-05	191
-4 39878	-0. 05541	OUT OF RANGE	0. 10957	0. 10968		2. 5000E-05	205
-4. 39878	-0. 05542	OUT OF RANGE	0. 10956	0. 10968		2. 5000E-05	205
-4. 39878	-0. 05542	OUT OF RANGE	0. 10955	0. 10967		2. 5000E-05	205
-4 39878	-0. 05543	OUT OF RANGE	0. 10955	0. 10967		2. 5000E-05	205
-4. 39878	-0. 09000	HIT BODY AT	0. 02339	-0. 00025	0. 04289	1. 2500E-05	193
-4. 39878	-0. 10000	HIT BODY AT	0. 05941	-0. 02028	0. 08423	5. 0000E-05	192
-4. 39878	-0. 10500	OUT OF RANGE	1. 00343	-0. 07680		2. 5000E-05	360
-4 39878	-0. 10250	OUT OF RANGE	0. 99889	-0. 07601		1. 2500E-05	533
-4. 39878	-0. 10125	HIT BODY AT	0. 07030	-0. 02466	0. 09597	6. 2500E-06	245
-4. 39878	-0. 10187	HIT BODY AT	0. 08058	-0. 02819	0. 10684	1. 2500E-05	220
-4. 39878	-0. 10219	OUT OF RANGE	1. 00140	-0. 07588		1. 2500E-05	534
-4. 39878	-0. 10203	HIT BODY AT	0. 08811	-0. 03051	0. 11472	1. 2500E-05	223
-4 39878	-0. 10211	OUT OF RANGE	1. 00133	-0. 07585		1. 2500E-05	534
-4. 39878	-0. 10207	HIT BODY AT	0. 09285	-0. 03192	0. 11966	1. 2500E-05	225
-4 39878	-0. 10209	OUT OF RANGE	1. 00131	-0. 07584		1. 2500E-05	534
-4. 39878	-0. 10208	HIT BODY AT	0. 09350	-0. 03211	0. 12035	1. 2500E-05	225
-4. 39878	-0. 10208	OUT OF RANGE	1. 00130	-0. 07584		1. 2500E-05	534
-4 39878	-0. 10208	OUT OF RANGE	1. 00130	-0. 07584		1. 2500E-05	534

UPPER SURFACE LIMIT ZU	SU	LOWER SURFACE LIMIT ZL	SL
-0. 5543E-01	-0. 3556E-01	-0. 1021E 00	0. 1203E 00

TOTAL COLLECTION EFFICIENCY 2. 98634E-01

X0	Y0		XP	YP	SD	DT	NSTP
-4. 39878	-0. 05543	HIT BODY AT	0. 02188	0. 06262	-0. 03556	2. 5000E-05	191
-4. 39878	-0. 06061	HIT BODY AT	0. 00461	0. 04483	-0. 01056	5. 0000E-05	187
-4. 39878	-0. 06580	HIT BODY AT	0. 00142	0. 03556	-0. 00071	5. 0000E-05	187
-4. 39878	-0. 07098	HIT BODY AT	0. 00234	0. 02772	0. 00724	1. 0000E-04	185
-4. 39878	-0. 07616	HIT BODY AT	0. 00535	0. 02046	0. 01519	5. 0000E-05	187
-4. 39878	-0. 08135	HIT BODY AT	0. 01024	0. 01291	0. 02423	5. 0000E-05	187

TABLE 4.10 (continued).

-4.39878	-0.08653	HIT BODY AT	0.01718	0.00526	0.03458	1.0000E-04	186
-4.39878	-0.09171	HIT BODY AT	0.02733	-0.00314	0.04777	1.2500E-05	195
-4.39878	-0.09690	HIT BODY AT	0.04441	-0.01318	0.06763	2.5000E-05	194
-4.39878	-0.10208	HIT BODY AT	0.09350	-0.03211	0.12034	1.2500E-05	225

NO. OF DATA POINTS STORED IN TAPE03 = 23

I	Z0	SD	BETA
1	-5.5430E-02	-3.5557E-02	
2	-5.5430E-02	-3.5557E-02	
3	-5.5469E-02	-3.4943E-02	
4	-5.5625E-02	-3.2594E-02	
5	-5.6250E-02	-2.7292E-02	
6	-5.7500E-02	-1.9603E-02	
7	-6.0000E-02	-1.2249E-02	
8	-6.0613E-02	-1.0562E-02	
9	-6.5796E-02	-7.1079E-04	
10	-7.0000E-02	5.7981E-03	
11	-7.0980E-02	7.2442E-03	
12	-7.6163E-02	1.5186E-02	
13	-8.1346E-02	2.4231E-02	
14	-8.6530E-02	3.4584E-02	
15	-9.0000E-02	4.2890E-02	
16	-9.1713E-02	4.7772E-02	
17	-9.6896E-02	6.7631E-02	
18	-1.0000E-01	8.4234E-02	
19	-1.0125E-01	9.5968E-02	
20	-1.0187E-01	1.0684E-01	
21	-1.0203E-01	1.1472E-01	
22	-1.0207E-01	1.1966E-01	
23	-1.0208E-01	1.2034E-01	

LINEAR APPROACH

I	Z0	SD	BETA
22			
2	-5.5449E-02	-3.5250E-02	6.3560E-02
3	-5.5547E-02	-3.3768E-02	6.6520E-02
4	-5.5937E-02	-2.9943E-02	1.1788E-01
5	-5.6875E-02	-2.3447E-02	1.6257E-01
6	-5.8750E-02	-1.5926E-02	3.3996E-01
7	-6.0306E-02	-1.1405E-02	3.6331E-01
8	-6.3205E-02	-5.6362E-03	5.2618E-01
9	-6.7898E-02	2.5437E-03	6.4584E-01
10	-7.0490E-02	6.5212E-03	6.7745E-01
11	-7.3571E-02	1.1215E-02	6.5265E-01
12	-7.8755E-02	1.9709E-02	5.7304E-01
13	-8.3938E-02	2.9408E-02	5.0071E-01
14	-8.8265E-02	3.8737E-02	4.1778E-01
15	-9.0856E-02	4.5331E-02	3.5090E-01
16	-9.4305E-02	5.7701E-02	2.6101E-01
17	-9.8448E-02	7.5932E-02	1.8692E-01
18	-1.0062E-01	9.0101E-02	1.0652E-01
19	-1.0156E-01	1.0140E-01	5.7490E-02
20	-1.0195E-01	1.1078E-01	1.9829E-02
21	-1.0205E-01	1.1719E-01	7.8829E-03
22	-1.0207E-01	1.2000E-01	1.4261E-02

TABLE 4.10 (continued).

POLYNOMIAL LEAST SQUARE FIT

NO OF COEFFICIENTS IS 3
NO. OF POINTS FOR DATA FITTING IS 7

I	Z0	SD	BETA
1	-5. 5461E-02	-3. 5557E-02	1. 8533E-02
2	-5. 5461E-02	-3. 5557E-02	1. 8533E-02
3	-5. 5476E-02	-3. 4943E-02	2. 7699E-02
4	-5. 5582E-02	-3. 2594E-02	6. 2726E-02
5	-5. 6120E-02	-2. 7292E-02	1. 4062E-01
6	-5. 7571E-02	-1. 9603E-02	2. 6582E-01
7	-5. 9984E-02	-1. 2249E-02	3. 9386E-01
8	-6. 0653E-02	-1. 0562E-02	4. 2029E-01
9	-6. 5855E-02	-7. 1079E-04	5. 6622E-01
10	-7. 0022E-02	5. 7981E-03	5. 9635E-01
11	-7. 1083E-02	7. 2442E-03	5. 9476E-01
12	-7. 6119E-02	1. 5186E-02	6. 0253E-01
13	-8. 1379E-02	2. 4231E-02	5. 3971E-01
14	-8. 6507E-02	3. 4584E-02	4. 5288E-01
15	-8. 9864E-02	4. 2890E-02	3. 8991E-01
16	-9. 1547E-02	4. 7772E-02	3. 4917E-01
17	-9. 7021E-02	6. 7631E-02	2. 2487E-01
18	-9. 9944E-02	8. 4234E-02	1. 4064E-01
19	-1. 0126E-01	9. 5968E-02	8. 6806E-02
20	-1. 0194E-01	1. 0684E-01	3. 7733E-02
21	-1. 0209E-01	1. 1472E-01	1. 5880E-03
22	-1. 0207E-01	1. 1966E-01	-2. 1098E-02
23	-1. 0208E-01	1. 2034E-01	0. 0000

22

I	Z0	SD	BETA
1		-3. 5557E-02	1. 8533E-02
2		-3. 5557E-02	1. 8533E-02
3		-3. 4943E-02	2. 7699E-02
4		-3. 2594E-02	6. 2726E-02
5		-2. 7292E-02	1. 4062E-01
6		-1. 9603E-02	2. 6582E-01
7		-1. 2249E-02	3. 9386E-01
8		-1. 0562E-02	4. 2029E-01
9		-7. 1079E-04	5. 6622E-01
10		5. 7981E-03	5. 9635E-01
11		7. 2442E-03	5. 9476E-01
12		1. 5186E-02	6. 0253E-01
13		2. 4231E-02	5. 3971E-01
14		3. 4584E-02	4. 5288E-01
15		4. 2890E-02	3. 8991E-01
16		4. 7772E-02	3. 4917E-01
17		6. 7631E-02	2. 2487E-01
18		8. 4234E-02	1. 4064E-01
19		9. 5968E-02	8. 6806E-02
20		1. 0684E-01	3. 7733E-02
21		1. 1472E-01	1. 5880E-03
22		1. 2034E-01	0. 0000

TERMINATED: STOP

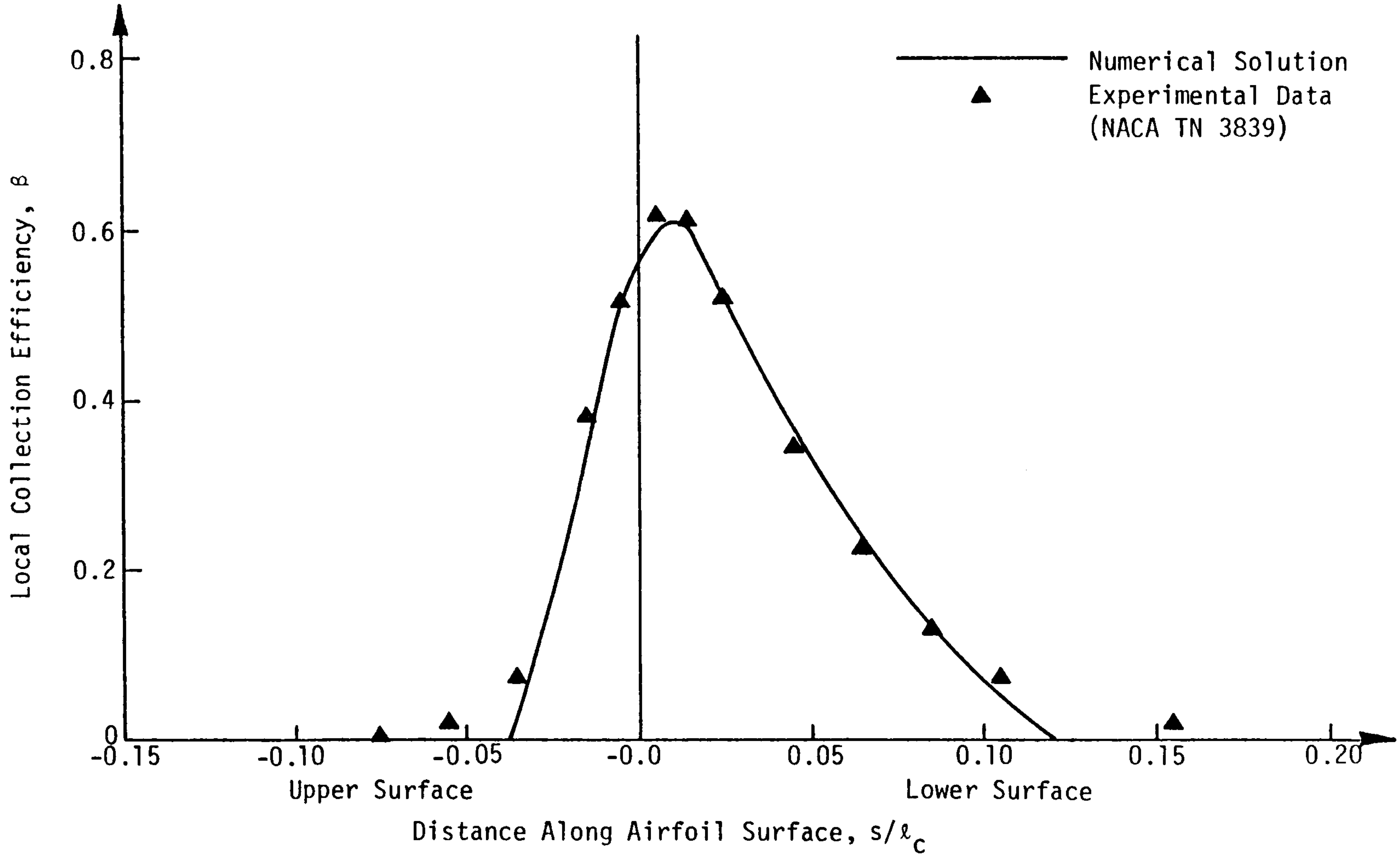


Figure 4.4 Joukowski airfoil 0015, 13-inch chord length, with walls, $\alpha = 4°$.

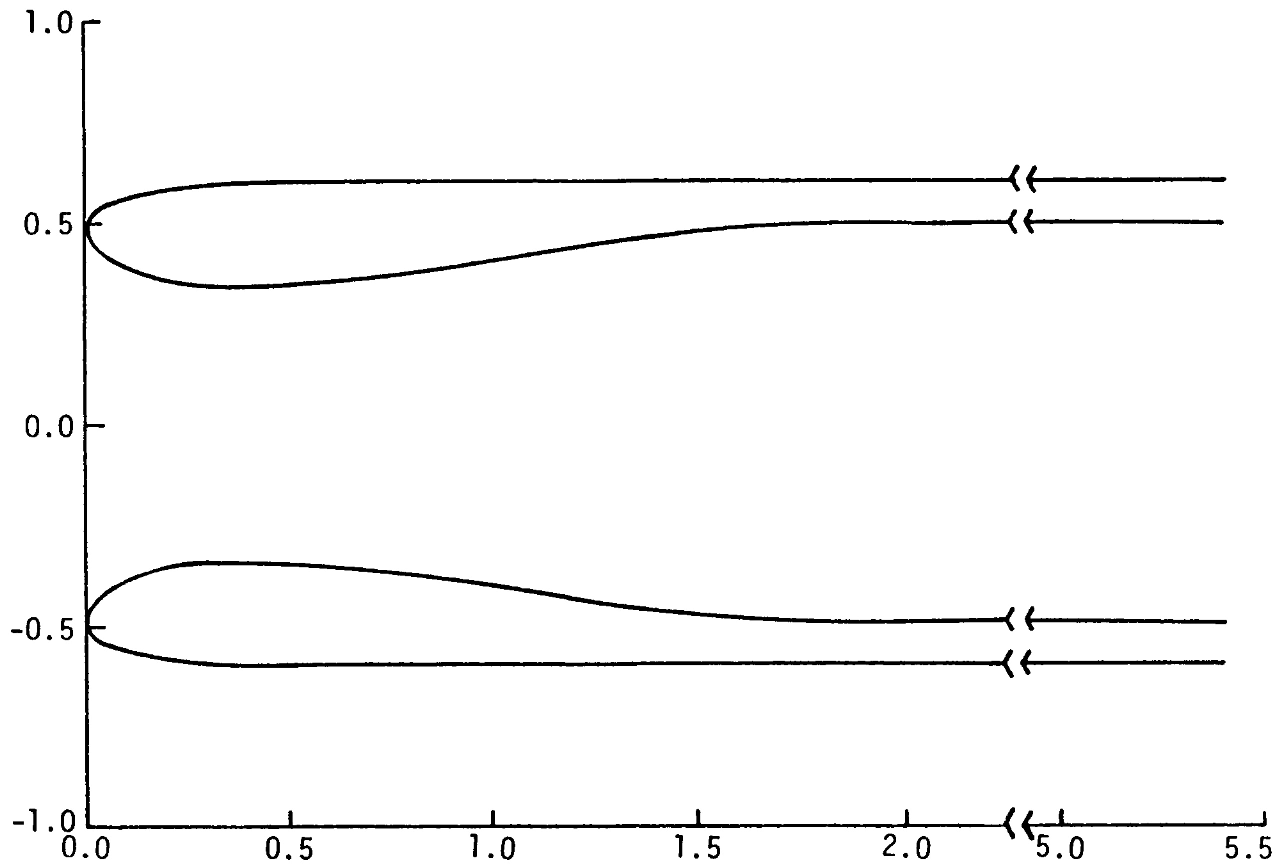


Figure 4.5 Two-body geometry (dimensions are in units of inlet mouth diameter).

TABLE 4.11. Input Data File for SCIRCL.

```
TEST CASE RELEASE 2.0
                               1
BFQC1     24Y
2.0        0.08        0.08        0.0
  1
-0.15   -0.75    0.75       20
1.0        6.0         0.08        0.0
10.
5.41191     1.80532
-0.59535    -0.59535
1.0
1.80532     0.40123
-0.59535    -0.59535
1000.     1.7667     2.2463
0.60132     0.40123                                  0.0          0.0
-0.59535    -0.59535                                 -0.50000     0.0
1000.     2.0        2.0
0.0         0.0                                      0.31509      0.60132
-0.75165    -0.50000                                 -0.34245     -0.34245
-3.0
0.0         0.31509      1.80532                     2.10463
-0.34245    -0.34245     -0.49414                    -0.49414
1.0
1.80532     5.41191
-0.49414    -0.49414
-2.1        0.0
```

TABLE 4.12. Input Data File Tape 17 (renumbered Tape 05) for the Potential Flow Program.

```
1  0  1   TEST CASE RELEASE 2.                  0  0  0           1      1  0    1
   5.41191    5.33176    5.25161    5.17146    5.09131    5.01116             3
   4.93101    4.85086    4.77071    4.69056    4.61041    4.53026             3
   4.45012    4.36997    4.28982    4.20967    4.12952    4.04937             3
   3.96922    3.88907    3.80892    3.72877    3.64862    3.56847             3
   3.48832    3.40817    3.32802    3.24787    3.16772    3.08757             3
   3.00742    2.92727    2.84712    2.76697    2.68682    2.60667             3
   2.52652    2.44637    2.36622    2.28607    2.20592    2.12577             3
   2.04562    1.96547    1.88532    1.80532    1.72732    1.64931             3
   1.57131    1.49330    1.41530    1.33729    1.25929    1.18128             3
   1.10328    1.02527    0.94727    0.86926    0.79126    0.71325             3
   0.63525    0.55724    0.47924    0.40123    0.35087    0.30306             3
   0.25770    0.21471    0.17400    0.13549    0.09916    0.06506             3
   0.03417    0.00900    0.00000    0.00537    0.01839    0.03544             3
   0.05333    0.07472    0.09943    0.12735    0.15844    0.19271             3
   0.23021    0.27100    0.31509    0.35638    0.39816    0.44044             3
   0.48322    0.52649    0.57026    0.61451    0.65924    0.70443             3
   0.75007    0.79615    0.84264    0.88952    0.93677    0.98437             3
   1.03227    1.08046    1.12868    1.17663    1.22427    1.27157             3
   1.31851    1.36505    1.41118    1.45687    1.50210    1.54687             3
   1.59116    1.63496    1.67825    1.72105    1.76335    1.80532             3
   1.84981    1.90320    1.96727    2.04416    2.12434    2.20453             3
   2.28471    2.36490    2.44508    2.52526    2.60545    2.68563             3
   2.76582    2.84600    2.92619    3.00637    3.08656    3.16674             3
   3.24693    3.32711    3.40730    3.48748    3.56767    3.64785             3
   3.72803    3.80822    3.88840    3.96859    4.04877    4.12896             3
   4.20914    4.28933    4.36951    4.44970    4.52988    4.61006             3
   4.69025    4.77043    4.85062    4.93080    5.01099    5.09117             3
   5.17136    5.25154    5.33173    5.41191                           4  1    3
  -0.59535   -0.59535   -0.59535   -0.59535   -0.59535   -0.59535             4
  -0.59535   -0.59535   -0.59535   -0.59535   -0.59535   -0.59535             4
  -0.59535   -0.59535   -0.59535   -0.59535   -0.59535   -0.59535             4
  -0.59535   -0.59535   -0.59535   -0.59535   -0.59535   -0.59535             4
  -0.59535   -0.59535   -0.59535   -0.59535   -0.59535   -0.59535             4
  -0.59535   -0.59535   -0.59535   -0.59535   -0.59535   -0.59535             4
  -0.59535   -0.59535   -0.59535   -0.59535   -0.59535   -0.59535             4
  -0.59535   -0.59535   -0.59535   -0.59535   -0.59535   -0.59535             4
  -0.59535   -0.59535   -0.59535   -0.59535   -0.59535   -0.59535             4
  -0.59535   -0.59535   -0.59535   -0.59535   -0.59535   -0.59535             4
  -0.59535   -0.59535   -0.59535   -0.59535   -0.59426   -0.59174             4
  -0.58811   -0.58347   -0.57783   -0.57109   -0.56301   -0.55309             4
  -0.54043   -0.52257   -0.50000   -0.47104   -0.44696   -0.42741             4
  -0.41230   -0.39814   -0.38513   -0.37347   -0.36330   -0.35482             4
  -0.34827   -0.34400   -0.34245   -0.34279   -0.34381   -0.34549             4
  -0.34781   -0.35074   -0.35427   -0.35836   -0.36298   -0.36810             4
  -0.37368   -0.37967   -0.38602   -0.39269   -0.39962   -0.40676             4
  -0.41403   -0.42139   -0.42872   -0.43593   -0.44294   -0.44970             4
  -0.45615   -0.46224   -0.46792   -0.47314   -0.47786   -0.48204             4
```

TABLE 4.12 (continued).

```
   -0.48564  -0.48865  -0.49102  -0.49274  -0.49379  -0.49414                4
   -0.49414  -0.49414  -0.49414  -0.49414  -0.49414  -0.49414                4
   -0.49414  -0.49414  -0.49414  -0.49414  -0.49414  -0.49414                4
   -0.49414  -0.49414  -0.49414  -0.49414  -0.49414  -0.49414                4
   -0.49414  -0.49414  -0.49414  -0.49414  -0.49414  -0.49414                4
   -0.49414  -0.49414  -0.49414  -0.49414  -0.49414  -0.49414                4
   -0.49414  -0.49414  -0.49414  -0.49414  -0.49414  -0.49414                4
   -0.49414  -0.49414  -0.49414  -0.49414  -0.49414  -0.49414                4
   -0.49414  -0.49414  -0.49414  -0.49414                          4  1      4

2   0  1    TEST CASE RELEASE 2.              0  0  0          2    1  1      1
    5.41191   5.33173   5.25154   5.17136   5.09117   5.01099                3
    4.93080   4.85062   4.77043   4.69025   4.61006   4.52988                3
    4.44970   4.36951   4.28933   4.20914   4.12896   4.04877                3
    3.96859   3.88840   3.80822   3.72803   3.64785   3.56767                3
    3.48748   3.40730   3.32711   3.24693   3.16674   3.08656                3
    3.00637   2.92619   2.84600   2.76582   2.68563   2.60545                3
    2.52526   2.44508   2.36490   2.28471   2.20453   2.12434                3
    2.04416   1.96727   1.90320   1.84981   1.80532   1.76335                3
    1.72105   1.67825   1.63496   1.59116   1.54687   1.50210                3
    1.45687   1.41118   1.36505   1.31851   1.27157   1.22427                3
    1.17663   1.12868   1.08046   1.03227   0.98437   0.93677                3
    0.88952   0.84264   0.79615   0.75007   0.70443   0.65924                3
    0.61451   0.57026   0.52649   0.48322   0.44044   0.39816                3
    0.35638   0.31509   0.27100   0.23021   0.19271   0.15844                3
    0.12735   0.09943   0.07472   0.05333   0.03544   0.01839                3
    0.00537   0.00000   0.00900   0.03417   0.06506   0.09916                3
    0.13549   0.17400   0.21471   0.25770   0.30306   0.35087                3
    0.40123   0.47924   0.55724   0.63525   0.71325   0.79126                3
    0.86926   0.94727   1.02527   1.10328   1.18128   1.25929                3
    1.33729   1.41530   1.49330   1.57131   1.64931   1.72732                3
    1.80532   1.88532   1.96547   2.04562   2.12577   2.20592                3
    2.28607   2.36622   2.44637   2.52652   2.60667   2.68682                3
    2.76697   2.84712   2.92727   3.00742   3.08757   3.16772                3
    3.24787   3.32802   3.40817   3.48832   3.56847   3.64862                3
    3.72877   3.80892   3.88907   3.96922   4.04937   4.12952                3
    4.20967   4.28982   4.36997   4.45012   4.53026   4.61041                3
    4.69056   4.77071   4.85086   4.93101   5.01116   5.09131                3
    5.17146   5.25161   5.33176   5.41191                          4  1      3
    0.49414   0.49414   0.49414   0.49414   0.49414   0.49414                4
    0.49414   0.49414   0.49414   0.49414   0.49414   0.49414                4
    0.49414   0.49414   0.49414   0.49414   0.49414   0.49414                4
    0.49414   0.49414   0.49414   0.49414   0.49414   0.49414                4
    0.49414   0.49414   0.49414   0.49414   0.49414   0.49414                4
    0.49414   0.49414   0.49414   0.49414   0.49414   0.49414                4
    0.49414   0.49414   0.49414   0.49414   0.49414   0.49414                4
    0.49414   0.49414   0.49414   0.49414   0.49414   0.49379                4
    0.49274   0.49102   0.48865   0.48564   0.48204   0.47786                4
    0.47314   0.46792   0.46224   0.45615   0.44970   0.44294                4
    0.43593   0.42872   0.42139   0.41403   0.40676   0.39962                4
    0.39269   0.38602   0.37967   0.37368   0.36810   0.36298                4
    0.35836   0.35427   0.35074   0.34781   0.34549   0.34381                4
    0.34279   0.34245   0.34400   0.34827   0.35482   0.36330                4
    0.37347   0.38513   0.39814   0.41230   0.42741   0.44696                4
    0.47104   0.50000   0.52257   0.54043   0.55309   0.56301                4
    0.57109   0.57783   0.58347   0.58811   0.59174   0.59426                4
    0.59535   0.59535   0.59535   0.59535   0.59535   0.59535                4
    0.59535   0.59535   0.59535   0.59535   0.59535   0.59535                4
    0.59535   0.59535   0.59535   0.59535   0.59535   0.59535                4
    0.59535   0.59535   0.59535   0.59535   0.59535   0.59535                4
    0.59535   0.59535   0.59535   0.59535   0.59535   0.59535                4
    0.59535   0.59535   0.59535   0.59535   0.59535   0:59535                4
    0.59535   0.59535   0.59535   0.59535   0.59535   0.59535                4
    0.59535   0.59535   0.59535   0.59535   0.59535   0.59535                4
    0.59535   0.59535   0.59535   0.59535   0.59535   0.59535                4
    0.59535   0.59535   0.59535   0.59535   0.59535   0.59535                4
    0.59535   0.59535   0.59535   0.59535                          4  1      4
            TEST CASE RELEASE 2.0                                            8
              0.00                     1         1             2.000    0   19
1          TEST CASE RELEASE 2.0                                        1   21
   -0.15000  -0.15000  -0.15000  -0.15000  -0.15000  -0.15000                3
   -0.15000  -0.15000  -0.15000  -0.15000  -0.15000  -0.15000                3
   -0.15000  -0.15000  -0.15000  -0.15000  -0.15000  -0.15000                3
   -0.15000  -0.15000                                              2  1      3
   -0.75000  -0.67105  -0.59211  -0.51316  -0.43421  -0.35526                4
   -0.27632  -0.19737  -0.11842  -0.03947   0.03947   0.11842                4
    0.19737   0.27632   0.35526   0.43421   0.51316   0.59211                4
    0.67105   0.75000                                              2  1      4
```

TABLE 4.13. Input Data File Tape 02 for the Particle Trajectory Program.

```
$NBDY *  2        NFL$$    10       NSEAR    60        NEQ$$     4
$LEOM    1        LSYM$     0       LRANG     1
$LIM$    1        LOPT$     0       LPLOT     0        LTNL$     0       LXOR$    0
$G  $    0.0      VINF$    44.35
$DF $   16.7      RL   $    1.00    TIMSP    0.0010    YLIM$  0.000001CF   $ 1.0
PRATN    0.0      PIT  $    0.0     PITDT    0.0       XORC$ -0.5      YORC$ 0.5
XREAR    0.30     YLO  $   -0.10    YUP  $   0.10      YMAX$ -0.50     YMIN$-0.515
ADEPS    0.0010   ANLFL     0.0     ANLCR    0.0       EPSX$  0.001
NSI$$    1
INITIAL INPUT DATA FOR LOCAL CATCH EFFICIENCY CALCULATIONS
NCOEF      4      NPTS$    10       $ NS$     0
EXPERIMENTAL DATA OF LOCAL CATCH EFFICIENCY :
     1
-0.08        0.045
INITIAL INPUT DATA FOR LOCAL CATCH EFFICIENCY CALCULATIONS
NCOEF      4      NPTS$    10       $ NS$     0
EXPERIMENTAL DATA OF LOCAL CATCH EFFICIENCY :
     1
-0.08        0.045
```

*The names of the variables including those with $'s are printed to fill the appropriate spaces. Normally, these alphabetic symbols would not be input by the user but are given here to clarify the illustration.

in the SCIRCL and 24Y programs is set at 500. Thus, the number of elements used in the two-dimensional body case is limited to 500 for both bodies. To correctly generate the flow field around the inlet a long body is required. Thus, the original geometry input specified surface elements of 0.08 and a total body geometry of length 5.41191 normalized by the mouth diameter of the inlet. This geometry was used to establish the flow field. To magnify the nose area where most of the impingement occurs, the SCIRCL program is run a second time utilizing the input specified in Table 4.14. Here, a surface element of 0.025 and a maximum x-coordinate of 1.85000 is employed. This modification results in a highly refined body geometry in the nose area for calculating particle impingement and collection efficiency. The flow field, of course, is still based on the original longer but coarser grid body shape.

TABLE 4.14. Input Data File for SCIRCL to Modify Geometry for the Particle Trajectory Program.

```
TEST CASE RELEASE 2.0

                         1
BFQC1      24Y
2.0         0.025      0.025     0.0
   1
-0.15    -0.75    0.75      20
1.0         6.0       *0.025     0.0
10.
*1.85000       1.80532
-0.59535       -0.59535
1.0
1.80532        0.40123
-0.59535       -0.59535
1000.       1.7667     2.2463
0.60132        0.40123                                   0.0             0.0
-0.59535       -0.59535                                  -0.50000        0.0
1000.       2.0        2.0
0.0            0.0                                       0.31509         0.60132
-0.75165       -0.50000                                  -0.34245        -0.34245
-3.0
0.0            0.31509      1.80532                      2.10463
-0.34245       -0.34245     -0.49414                     -0.49414
1.0
1.80532       *1.85000
-0.49414       -0.49414
-2.1           0.0
```

A second modification to Tape 17 when it is used as input to the particle trajectory program is required because the discretization error of the flow field computer program close to the body surface is large. This effect is described in detail in Chapter V. To avoid the discretization error, a pseudo-body surface is defined. This surface is generated by simply decreasing the x-coordinates of the body by a value of Dx. The value of Dx is input on the second card on Tape 05, Table 4.15. Additionally, the value of ITR [2] is set equal to one. For the test case computed here, the value of Dx used is -0.002.

Utilizing the modified version of Tape 17 (renumbered Tape 05) along with Tape 21 and Tape 02 described previously, the computer program was run and the output data file, Tape 06, is shown in Table 4.16. The computed results are shown graphically in Figure 4.6.

TABLE 4.15. Modified Input Data File Tape 17 (renumbered Tape 05) for the Particle Trajectory Program.

```
1  0  1   TEST CASE RELEASE 2.                   0  0  0  1     1      1  0  1
                            -0.002
   1.85000    1.83032    1.80532    1.78025    1.75517    1.73010            3
   1.70503    1.67995    1.65488    1.62981    1.60474    1.57966            3
   1.55459    1.52952    1.50444    1.47937    1.45430    1.42922            3
   1.40415    1.37908    1.35401    1.32893    1.30386    1.27879            3
   1.25371    1.22864    1.20357    1.17849    1.15342    1.12835            3
   1.10327    1.07820    1.05313    1.02806    1.00298    0.97791            3
   0.95284    0.92776    0.90269    0.87762    0.85254    0.82747            3
   0.80240    0.77732    0.75225    0.72718    0.70211    0.67703            3
   0.65196    0.62689    0.60181    0.57674    0.55167    0.52659            3
   0.50152    0.47645    0.45138    0.42630    0.40123    0.37740            3
   0.35477    0.33328    0.31288    0.29351    0.27512    0.25767            3
   0.24110    0.22538    0.21046    0.19630    0.18288    0.17014            3
   0.15806    0.14661    0.13575    0.12546    0.11571    0.10647            3
   0.09773    0.08945    0.08162    0.07422    0.06722    0.06062            3
   0.05439    0.04852    0.04300    0.03782    0.03296    0.02842            3
   0.02420    0.02028    0.01668    0.01347    0.01059    0.00813            3
   0.00600    0.00420    0.00274    0.00162    0.00082    0.00032            3
   0.00006    0.00000    0.00003    0.00012    0.00026    0.00044            3
   0.00069    0.00101    0.00142    0.00195    0.00260    0.00340            3
   0.00438    0.00555    0.00695    0.00862    0.01057    0.01286            3
   0.01552    0.01859    0.02211    0.02614    0.03062    0.03568            3
   0.04123    0.04746    0.05440    0.06211    0.07067    0.08012            3
   0.09053    0.10197    0.11451    0.12823    0.14322    0.15956            3
   0.17733    0.19665    0.21760    0.24030    0.26486    0.28985            3
   0.31509    0.33819    0.36144    0.38484    0.40840    0.43212            3
   0.45600    0.48003    0.50422    0.52856    0.55305    0.57770            3
   0.60250    0.62745    0.65255    0.67779    0.70317    0.72870            3
   0.75436    0.78016    0.80609    0.83214    0.85832    0.88462            3
   0.91103    0.93755    0.96417    0.99090    1.01772    1.04463            3
   1.07162    1.09863    1.12555    1.15238    1.17912    1.20576            3
   1.23230    1.25872    1.28503    1.31123    1.33730    1.36324            3
   1.38905    1.41473    1.44027    1.46567    1.49092    1.51603            3
   1.54099    1.56580    1.59046    1.61496    1.63931    1.66350            3
   1.68754    1.71142    1.73514    1.75871    1.78212    1.80532            3
   1.83021    1.85000                                                2  1  3
  -0.59535   -0.59535   -0.59535   -0.59535   -0.59535   -0.59535            4
  -0.59535   -0.59535   -0.59535   -0.59535   -0.59535   -0.59535            4
  -0.59535   -0.59535   -0.59535   -0.59535   -0.59535   -0.59535            4
  -0.59535   -0.59535   -0.59535   -0.59535   -0.59535   -0.59535            4
  -0.59535   -0.59535   -0.59535   -0.59535   -0.59535   -0.59535            4
  -0.59535   -0.59535   -0.59535   -0.59535   -0.59535   -0.59535            4
  -0.59535   -0.59535   -0.59535   -0.59535   -0.59535   -0.59535            4
  -0.59535   -0.59535   -0.59535   -0.59535   -0.59535   -0.59535            4
  -0.59535   -0.59535   -0.59535   -0.59535   -0.59535   -0.59535            4
  -0.59535   -0.59535   -0.59535   -0.59535   -0.59535   -0.59506            4
  -0.59440   -0.59349   -0.59236   -0.59107   -0.58965   -0.58810            4
  -0.58646   -0.58474   -0.58294   -0.58109   -0.57918   -0.57722            4
  -0.57523   -0.57320   -0.57114   -0.56905   -0.56694   -0.56481            4
  -0.56265   -0.56047   -0.55828   -0.55606   -0.55382   -0.55155            4
  -0.54927   -0.54695   -0.54460   -0.54222   -0.53980   -0.53734            4
  -0.53482   -0.53225   -0.52961   -0.52696   -0.52425   -0.52158            4
  -0.51886   -0.51611   -0.51333   -0.51055   -0.50780   -0.50511            4
  -0.50251   -0.50000   -0.49775   -0.49561   -0.49359   -0.49167            4
  -0.48961   -0.48740   -0.48503   -0.48250   -0.47979   -0.47690            4
  -0.47383   -0.47055   -0.46708   -0.46341   -0.45953   -0.45545            4
  -0.45117   -0.44669   -0.44202   -0.43717   -0.43225   -0.42718            4
  -0.42208   -0.41685   -0.41151   -0.40608   -0.40057   -0.39503            4
  -0.38948   -0.38396   -0.37850   -0.37314   -0.36795   -0.36298            4
  -0.35830   -0.35400   -0.35018   -0.34695   -0.34446   -0.34296            4
  -0.34245   -0.34256   -0.34288   -0.34342   -0.34416   -0.34511            4
  -0.34626   -0.34761   -0.34916   -0.35090   -0.35282   -0.35492            4
  -0.35720   -0.35965   -0.36226   -0.36503   -0.36795   -0.37102            4
  -0.37422   -0.37755   -0.38100   -0.38456   -0.38822   -0.39198            4
  -0.39582   -0.39974   -0.40371   -0.40774   -0.41182   -0.41592            4
  -0.42004   -0.42416   -0.42825   -0.43230   -0.43630   -0.44024            4
  -0.44410   -0.44789   -0.45158   -0.45517   -0.45865   -0.46201            4
  -0.46524   -0.46834   -0.47129   -0.47409   -0.47673   -0.47921            4
  -0.48152   -0.48364   -0.48559   -0.48735   -0.48891   -0.49028            4
  -0.49145   -0.49241   -0.49316   -0.49370   -0.49403   -0.49414            4
  -0.49414   -0.49414                                                2  1  4
2  0  1   TEST CASE RELEASE 2.                   0  0  0  1     2      1  1  1
                            -0.002
   1.85000    1.83021    1.80532    1.78212    1.75871    1.73514            3
   1.71142    1.68754    1.66350    1.63931    1.61496    1.59046            3
   1.56580    1.54099    1.51603    1.49092    1.46567    1.44027            3
   1.41473    1.38905    1.36324    1.33730    1.31123    1.28503            3
   1.25872    1.23230    1.20576    1.17912    1.15238    1.12555            3
   1.09863    1.07162    1.04463    1.01772    0.99090    0.96417            3
   0.93755    0.91103    0.88462    0.85832    0.83214    0.80609            3
   0.78016    0.75436    0.72870    0.70317    0.67779    0.65255            3
   0.62745    0.60250    0.57770    0.55305    0.52856    0.50422            3
   0.48003    0.45600    0.43212    0.40840    0.38484    0.36144            3
   0.33819    0.31509    0.28985    0.26486    0.24030    0.21760            3
```

TABLE 4.15 (continued).

0.19665	0.17733	0.15956	0.14322	0.12823	0.11451			3
0.10197	0.09053	0.08012	0.07067	0.06211	0.05440			3
0.04746	0.04123	0.03568	0.03062	0.02614	0.02211			3
0.01859	0.01552	0.01286	0.01057	0.00862	0.00695			3
0.00555	0.00438	0.00340	0.00260	0.00195	0.00142			3
0.00101	0.00069	0.00044	0.00026	0.00012	0.00003			3
0.00000	0.00006	0.00032	0.00082	0.00162	0.00274			3
0.00420	0.00600	0.00813	0.01059	0.01347	0.01668			3
0.02029	0.02420	0.02842	0.03296	0.03782	0.04300			3
0.04852	0.05439	0.06062	0.06722	0.07422	0.08162			3
0.08945	0.09773	0.10647	0.11571	0.12546	0.13575			3
0.14661	0.15806	0.17014	0.18288	0.19630	0.21046			3
0.22538	0.24110	0.25767	0.27512	0.29351	0.31288			3
0.33328	0.35477	0.37740	0.40123	0.42630	0.45138			3
0.47645	0.50152	0.52659	0.55167	0.57674	0.60181			3
0.62689	0.65196	0.67703	0.70211	0.72718	0.75225			3
0.77732	0.80240	0.82747	0.85254	0.87762	0.90269			3
0.92776	0.95284	0.97791	1.00298	1.02806	1.05313			3
1.07820	1.10327	1.12835	1.15342	1.17849	1.20357			3
1.22864	1.25371	1.27879	1.30386	1.32893	1.35401			3
1.37908	1.40415	1.42922	1.45430	1.47937	1.50444			3
1.52952	1.55459	1.57966	1.60474	1.62981	1.65488			3
1.67995	1.70503	1.73010	1.75517	1.78025	1.80532			3
1.83032	1.85000					2	1	3
0.49414	0.49414	0.49414	0.49403	0.49370	0.49316			4
0.49241	0.49145	0.49028	0.48891	0.48735	0.48559			4
0.48364	0.48152	0.47921	0.47673	0.47409	0.47129			4
0.46834	0.46524	0.46201	0.45865	0.45517	0.45158			4
0.44789	0.44410	0.44024	0.43630	0.43230	0.42825			4
0.42416	0.42004	0.41592	0.41182	0.40774	0.40371			4
0.39974	0.39582	0.39198	0.38822	0.38456	0.38100			4
0.37755	0.37422	0.37102	0.36795	0.36503	0.36226			4
0.35965	0.35720	0.35492	0.35282	0.35090	0.34916			4
0.34761	0.34626	0.34511	0.34416	0.34342	0.34288			4
0.34256	0.34245	0.34296	0.34446	0.34695	0.35018			4
0.35400	0.35830	0.36298	0.36795	0.37314	0.37850			4
0.38396	0.38948	0.39503	0.40057	0.40608	0.41151			4
0.41685	0.42208	0.42718	0.43225	0.43717	0.44202			4
0.44669	0.45117	0.45545	0.45953	0.46341	0.46708			4
0.47055	0.47383	0.47690	0.47979	0.48250	0.48503			4
0.48740	0.48961	0.49167	0.49359	0.49561	0.49775			4
0.50000	0.50251	0.50511	0.50780	0.51055	0.51333			4
0.51611	0.51886	0.52158	0.52425	0.52696	0.52961			4
0.53225	0.53482	0.53734	0.53980	0.54222	0.54460			4
0.54695	0.54927	0.55155	0.55382	0.55606	0.55828			4
0.56047	0.56265	0.56481	0.56694	0.56905	0.57114			4
0.57320	0.57523	0.57722	0.57918	0.58109	0.58294			4
0.58474	0.58646	0.58810	0.58965	0.59107	0.59236			4
0.59349	0.59440	0.59506	0.59535	0.59535	0.59535			4
0.59535	0.59535	0.59535	0.59535	0.59535	0.59535			4
0.59535	0.59535	0.59535	0.59535	0.59535	0.59535			4
0.59535	0.59535	0.59535	0.59535	0.59535	0.59535			4
0.59535	0.59535	0.59535	0.59535	0.59535	0.59535			4
0.59535	0.59535	0.59535	0.59535	0.59535	0.59535			4
0.59535	0.59535	0.59535	0.59535	0.59535	0.59535			4
0.59535	0.59535	0.59535	0.59535	0.59535	0.59535			4
0.59535	0.59535	0.59535	0.59535	0.59535	0.59535			4
0.59535	0.59535	0.59535	0.59535	0.59535	0.59535			4
0.59535	0.59535					2	1	4
TEST CASE RELEASE 2.0								8
0.00			1	1		2.000	0	19
1 TEST CASE RELEASE 2.0							1	21
-0.15000	-0.15000	-0.15000	-0.15000	-0.15000	-0.15000			3
-0.15000	-0.15000	-0.15000	-0.15000	-0.15000	-0.15000			3
-0.15000	-0.15000	-0.15000	-0.15000	-0.15000	-0.15000			3
-0.15000	-0.15000					2	1	3
-0.75000	-0.67105	-0.59211	-0.51316	-0.43421	-0.35526			4
-0.27632	-0.19737	-0.11842	-0.03947	0.03947	0.11842			4
0.19737	0.27632	0.35526	0.43421	0.51316	0.59211			4
0.67105	0.75000					2	1	4

TABLE 4.16. Output Data File Tape 06 for the Particle Trajectory Program.

PARTICLE DIAMETER	CHORD LENGTH	TIME STEP	NO. OF DROPLET	VX REF.	VY REF.	ANGLE OF ATK.	PITCH ANGLE	PIT DOT	GRAVT CONSTANT	INERT. MOMENT	ADAMS CRITERIA
1.67E-05	1.00E+00	1.00E-03	10	4.43E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	6.80E-23	1.00E-03

NBDY	ID	XFRNT	YFRNT	XREAR	YREAR	THICK	YUFFP	YLOOO
2	1	-2.00000E-03	-5.00000E-01	1.84800E+00	-4.94140E-01	2.52900E-01	-3.17160E-01	-6.20640E-01

INITIAL CONDITIONS FOR THE CASE LEQM=1

XO	YO		XP	YP	SD	DT	NSTP
-0.50000	-0.50000	OUT OF RANGE	0.30036	-0.31722		6.2500E-05	211
-0.50000	-0.51500	OUT OF RANGE	0.30269	-0.61459		6.2500E-05	203

YMAX= -5.0000E-01 YMIN= -5.1500E-01

-0.50000	-0.50750	HIT BODY AT	-0.00150	-0.50608	0.00611	6.2500E-05	101
-0.50000	-0.50375	HIT BODY AT	-0.00127	-0.48932	-0.01072	6.2500E-05	103
-0.50000	-0.50188	HIT BODY AT	0.00030	-0.48106	-0.01912	6.2500E-05	104
-0.50000	-0.50094	HIT BODY AT	0.00174	-0.47582	-0.02456	6.2500E-05	106
-0.50000	-0.50047	OUT OF RANGE	0.30406	-0.31691		6.2500E-05	214
-0.50000	-0.50070	HIT BODY AT	0.00232	-0.47402	-0.02646	6.2500E-05	107
-0.50000	-0.50059	HIT BODY AT	0.00279	-0.47269	-0.02786	6.2500E-05	108
-0.50000	-0.50053	HIT BODY AT	0.00310	-0.47181	-0.02880	6.2500E-05	109
-0.50000	-0.50050	HIT BODY AT	0.00335	-0.47111	-0.02954	6.2500E-05	109
-0.50000	-0.50048	HIT BODY AT	0.00348	-0.47074	-0.02993	6.2500E-05	109
-0.50000	-0.50048	OUT OF RANGE	0.30391	-0.31693		6.2500E-05	214
-0.50000	-0.50048	HIT BODY AT	0.00351	-0.47065	-0.03002	6.2500E-05	109
-0.50000	-0.50048	OUT OF RANGE	0.30388	-0.31693		6.2500E-05	214
-0.50000	-0.50048	OUT OF RANGE	0.30386	-0.31693		6.2500E-05	214
-0.50000	-0.51125	OUT OF RANGE	0.30053	-0.61405		6.2500E-05	209
-0.50000	-0.50938	HIT BODY AT	0.00068	-0.51319	0.01357	6.2500E-05	101
-0.50000	-0.51031	OUT OF RANGE	0.30247	-0.61426		6.2500E-05	213
-0.50000	-0.50984	HIT BODY AT	0.00210	-0.51593	0.01666	6.2500E-05	102
-0.50000	-0.51008	OUT OF RANGE	0.30038	-0.61409		6.2500E-05	213
-0.50000	-0.50996	HIT BODY AT	0.00308	-0.51745	0.01846	6.2500E-05	103
-0.50000	-0.51002	HIT BODY AT	0.00381	-0.51856	0.01979	3.1250E-05	147
-0.50000	-0.51005	OUT OF RANGE	0.30011	-0.61407		6.2500E-05	213
-0.50000	-0.51003	OUT OF RANGE	0.30312	-0.61434		6.2500E-05	214
-0.50000	-0.51003	OUT OF RANGE	0.30306	-0.61434		6.2500E-05	214
-0.50000	-0.51002	OUT OF RANGE	0.30302	-0.61433		6.2500E-05	214
-0.50000	-0.51002	OUT OF RANGE	0.30301	-0.61433		6.2500E-05	214
-0.50000	-0.51002	HIT BODY AT	0.00382	-0.51859	0.01982	3.1250E-05	147

UPPER SURFACE LIMIT		LOWER SURFACE LIMIT	
ZU	SU	ZL	SL
-0.5005E+00	-0.3002E-01	-0.5100E+00	0.1982E-01

TOTAL COLLECTION EFFICIENCY 3.77253E-02

XO	YO		XP	YP	SD	DT	NSTP
-0.50000	-0.50049	HIT BODY AT	0.00343	-0.47090	-0.02976	6.2500E-05	109
-0.50000	-0.50155	HIT BODY AT	0.00070	-0.47943	-0.02080	6.2500E-05	104
-0.50000	-0.50261	HIT BODY AT	-0.00045	-0.48443	-0.01567	6.2500E-05	105
-0.50000	-0.50366	HIT BODY AT	-0.00121	-0.48895	-0.01108	6.2500E-05	103
-0.50000	-0.50472	HIT BODY AT	-0.00173	-0.49350	-0.00651	6.2500E-05	103
-0.50000	-0.50578	HIT BODY AT	-0.00198	-0.49876	-0.00124	6.2500E-05	104

TABLE 4.16 (continued).

```
-0.50000  -0.50684  HIT BODY AT    -0.00182  -0.50373   0.00373  6.2500E-05   102
-0.50000  -0.50789  HIT BODY AT    -0.00125  -0.50742   0.00747  6.2500E-05   101
-0.50000  -0.50895  HIT BODY AT    -0.00004  -0.51140   0.01164  6.2500E-05   101
-0.50000  -0.51001  HIT BODY AT     0.00367  -0.51835   0.01954  3.1250E-05   147
NO. OF DATA POINTS STORED IN TAPE03 =     25

  I        ZO           SD          BETA

  1 -5.0048E-01 -3.0024E-02
  2 -5.0048E-01 -2.9935E-02
  3 -5.0049E-01 -2.9763E-02
  4 -5.0050E-01 -2.9544E-02
  5 -5.0053E-01 -2.8796E-02
  6 -5.0059E-01 -2.7863E-02
  7 -5.0070E-01 -2.6455E-02
  8 -5.0094E-01 -2.4560E-02
  9 -5.0155E-01 -2.0803E-02
 10 -5.0188E-01 -1.9123E-02
 11 -5.0261E-01 -1.5675E-02
 12 -5.0366E-01 -1.1084E-02
 13 -5.0375E-01 -1.0717E-02
 14 -5.0472E-01 -6.5087E-03
 15 -5.0578E-01 -1.2403E-03
 16 -5.0684E-01  3.7331E-03
 17 -5.0750E-01  6.1149E-03
 18 -5.0789E-01  7.4688E-03
 19 -5.0895E-01  1.1637E-02
 20 -5.0938E-01  1.3567E-02
 21 -5.0984E-01  1.6657E-02
 22 -5.0996E-01  1.8459E-02
 23 -5.1001E-01  1.9543E-02
 24 -5.1002E-01  1.9794E-02
 25 -5.1002E-01  1.9823E-02


 LINEAR APPROACH

    I        ZO           SD           BETA

  24
    1 -5.0048E-01 -2.9979E-02  4.0710E-02
    2 -5.0049E-01 -2.9849E-02  3.7031E-02
    3 -5.0049E-01 -2.9653E-02  3.7872E-02
    4 -5.0051E-01 -2.9170E-02  3.9127E-02
    5 -5.0056E-01 -2.8329E-02  6.2776E-02
    6 -5.0064E-01 -2.7159E-02  8.3278E-02
    7 -5.0082E-01 -2.5507E-02  1.2362E-01
    8 -5.0124E-01 -2.2681E-02  1.6242E-01
    9 -5.0171E-01 -1.9963E-02  1.9489E-01
   10 -5.0224E-01 -1.7399E-02  2.1185E-01
   11 -5.0313E-01 -1.3379E-02  2.3042E-01
   12 -5.0371E-01 -1.0901E-02  2.3633E-01
   13 -5.0424E-01 -8.6130E-03  2.3078E-01
   14 -5.0525E-01 -3.8745E-03  2.0078E-01
   15 -5.0631E-01  1.2464E-03  2.1270E-01
   16 -5.0717E-01  4.9240E-03  2.7838E-01
```

TABLE 4.16 (continued).

17	-5.0770E-01	6.7918E-03	2.9162E-01
18	-5.0842E-01	9.5528E-03	2.5380E-01
19	-5.0916E-01	1.2602E-02	2.1878E-01
20	-5.0961E-01	1.5112E-02	1.5176E-01
21	-5.0990E-01	1.7558E-02	6.5014E-02
22	-5.0999E-01	1.9001E-02	4.5670E-02
23	-5.1002E-01	1.9669E-02	3.6200E-02
24	-5.1002E-01	1.9808E-02	3.2882E-02

POLYNOMIAL LEAST SQUARE FIT

NO. OF COEFFICIENCTS IS 4
NO. OF POINTS FOR DATA FITTING IS 10

I	ZO	SD	BETA
1	-5.0048E-01	-3.0024E-02	2.0827E-02
2	-5.0048E-01	-2.9935E-02	2.3118E-02
3	-5.0049E-01	-2.9763E-02	2.7499E-02
4	-5.0050E-01	-2.9544E-02	3.2991E-02
5	-5.0053E-01	-2.8796E-02	5.1161E-02
6	-5.0058E-01	-2.7863E-02	7.2514E-02
7	-5.0071E-01	-2.6455E-02	1.0168E-01
8	-5.0093E-01	-2.4560E-02	1.3470E-01
9	-5.0154E-01	-2.0803E-02	1.8601E-01
10	-5.0187E-01	-1.9123E-02	2.0049E-01
11	-5.0261E-01	-1.5675E-02	2.2396E-01
12	-5.0364E-01	-1.1084E-02	2.3002E-01
13	-5.0371E-01	-1.0717E-02	2.2206E-01
14	-5.0464E-01	-6.5087E-03	2.1316E-01
15	-5.0579E-01	-1.2403E-03	2.1971E-01
16	-5.0693E-01	3.7331E-03	2.3162E-01
17	-5.0755E-01	6.1149E-03	2.4267E-01
18	-5.0791E-01	7.4688E-03	2.4285E-01
19	-5.0894E-01	1.1637E-02	2.2179E-01
20	-5.0937E-01	1.3567E-02	1.9616E-01
21	-5.0984E-01	1.6657E-02	1.0905E-01
22	-5.0998E-01	1.8459E-02	4.9421E-02
23	-5.1001E-01	1.9543E-02	9.3301E-03
24	-5.1001E-01	1.9794E-02	-3.7070E-04
25	-5.1001E-01	1.9823E-02	0.0000E+00

I	SD	BETA
24		
1	-3.0024E-02	2.0827E-02
2	-2.9935E-02	2.3118E-02
3	-2.9763E-02	2.7499E-02
4	-2.9544E-02	3.2991E-02
5	-2.8796E-02	5.1161E-02
6	-2.7863E-02	7.2514E-02
7	-2.6455E-02	1.0168E-01
8	-2.4560E-02	1.3470E-01
9	-2.0803E-02	1.8601E-01
10	-1.9123E-02	2.0049E-01

TABLE 4.16 (continued).

11	-1.5675E-02	2.2396E-01
12	-1.1084E-02	2.3002E-01
13	-1.0717E-02	2.2206E-01
14	-6.5087E-03	2.1316E-01
15	-1.2403E-03	2.1971E-01
16	3.7331E-03	2.3162E-01
17	6.1149E-03	2.4267E-01
18	7.4688E-03	2.4285E-01
19	1.1637E-02	2.2179E-01
20	1.3567E-02	1.9616E-01
21	1.6657E-02	1.0905E-01
22	1.8459E-02	4.9421E-02
23	1.9543E-02	9.3301E-03
24	1.9823E-02	0.0000E+00

NBDY	ID	XFRNT	YFRNT	XREAR	YREAR	THICK	YUPPP	YLOOO
2	2	-2.00000E-03	5.00000E-01	1.84800E+00	5.95350E-01	2.52900E-01	6.20640E-01	3.17160E-01

INITIAL CONDITIONS FOR THE CASE LEQM=1

XO	YO		XP	YP	SD	DT	NSTP
-0.50000	0.51201	OUT OF RANGE	0.30265	0.61424		6.2500E-05	205
-0.50000	0.49849	OUT OF RANGE	0.30333	0.31703		6.2500E-05	205

YMAX= 5.1201E-01 YMIN= 4.9849E-01

-0.50000	0.50525	HIT BODY AT	-0.00189	0.49595	0.00406	6.2500E-05	101
-0.50000	0.50863	HIT BODY AT	-0.00051	0.51009	-0.01025	6.2500E-05	97
-0.50000	0.51032	OUT OF RANGE	0.30253	0.61427		6.2500E-05	209
-0.50000	0.50948	HIT BODY AT	0.00095	0.51373	-0.01418	6.2500E-05	98
-0.50000	0.50990	HIT BODY AT	0.00246	0.51650	-0.01733	6.2500E-05	98
-0.50000	0.51011	OUT OF RANGE	0.30065	0.61411		6.2500E-05	209
-0.50000	0.51000	HIT BODY AT	0.00356	0.51819	-0.01934	7.8125E-06	400
-0.50000	0.51006	OUT OF RANGE	0.30017	0.61407		6.2500E-05	209
-0.50000	0.51003	OUT OF RANGE	0.30307	0.61434		6.2500E-05	210
-0.50000	0.51002	HIT BODY AT	0.00376	0.51849	-0.01970	3.1250E-05	143
-0.50000	0.51002	HIT BODY AT	0.00385	0.51864	-0.01988	3.1250E-05	143
-0.50000	0.51003	OUT OF RANGE	0.30305	0.61434		6.2500E-05	210
-0.50000	0.51003	OUT OF RANGE	0.30303	0.61434		6.2500E-05	210
-0.50000	0.51002	OUT OF RANGE	0.30302	0.61433		6.2500E-05	210
-0.50000	0.50187	HIT BODY AT	0.00030	0.48103	0.01915	6.2500E-05	102
-0.50000	0.50018	OUT OF RANGE	0.30125	0.31715		6.2500E-05	210
-0.50000	0.50102	HIT BODY AT	0.00155	0.47644	0.02391	6.2500E-05	104
-0.50000	0.50060	HIT BODY AT	0.00271	0.47291	0.02763	6.2500E-05	106
-0.50000	0.50039	OUT OF RANGE	0.30134	0.31714		6.2500E-05	211
-0.50000	0.50050	HIT BODY AT	0.00337	0.47104	0.02961	6.2500E-05	107
-0.50000	0.50044	OUT OF RANGE	0.30021	0.31718		6.2500E-05	211
-0.50000	0.50047	OUT OF RANGE	0.30405	0.31691		6.2500E-05	212
-0.50000	0.50048	HIT BODY AT	0.00349	0.47072	0.02996	6.2500E-05	107
-0.50000	0.50048	OUT OF RANGE	0.30391	0.31693		6.2500E-05	212
-0.50000	0.50048	OUT OF RANGE	0.30384	0.31694		6.2500E-05	212
-0.50000	0.50048	HIT BODY AT	0.00350	0.47068	0.03000	6.2500E-05	107
-0.50000	0.50048	HIT BODY AT	0.00351	0.47066	0.03002	6.2500E-05	107

UPPER SURFACE LIMIT		LOWER SURFACE LIMIT	
ZU	SU	ZL	SL
0.5100E+00	-0.1988E-01	0.5005E+00	0.3002E-01

TABLE 4.16 (continued).

TOTAL COLLECTION EFFICIENCY 3.77312E-02

XO	YO		XP	YP	SD	DT	NSTP
-0.50000	0.51001	HIT BODY AT	0.00371	0.51842	-0.01962	3.1250E-05	143
-0.50000	0.50896	HIT BODY AT	-0.00003	0.51141	-0.01165	6.2500E-05	98
-0.50000	0.50790	HIT BODY AT	-0.00125	0.50742	-0.00748	6.2500E-05	98
-0.50000	0.50684	HIT BODY AT	-0.00182	0.50373	-0.00374	6.2500E-05	99
-0.50000	0.50578	HIT BODY AT	-0.00198	0.49877	0.00123	6.2500E-05	101
-0.50000	0.50472	HIT BODY AT	-0.00173	0.49351	0.00650	6.2500E-05	100
-0.50000	0.50367	HIT BODY AT	-0.00122	0.48896	0.01108	6.2500E-05	100
-0.50000	0.50261	HIT BODY AT	-0.00045	0.48443	0.01567	6.2500E-05	101
-0.50000	0.50155	HIT BODY AT	0.00070	0.47943	0.02080	6.2500E-05	102
-0.50000	0.50049	HIT BODY AT	0.00342	0.47091	0.02975	6.2500E-05	107

NO. OF DATA POINTS STORED IN TAPE03 = 24

I	ZO	SD	BETA
1	5.1002E-01	-1.9880E-02	
2	5.1002E-01	-1.9701E-02	
3	5.1001E-01	-1.9616E-02	
4	5.1000E-01	-1.9344E-02	
5	5.0990E-01	-1.7332E-02	
6	5.0948E-01	-1.4177E-02	
7	5.0896E-01	-1.1648E-02	
8	5.0863E-01	-1.0249E-02	
9	5.0790E-01	-7.4757E-03	
10	5.0684E-01	-3.7401E-03	
11	5.0578E-01	1.2315E-03	
12	5.0525E-01	4.0550E-03	
13	5.0472E-01	6.5018E-03	
14	5.0367E-01	1.1078E-02	
15	5.0261E-01	1.5670E-02	
16	5.0187E-01	1.9153E-02	
17	5.0155E-01	2.0800E-02	
18	5.0102E-01	2.3914E-02	
19	5.0060E-01	2.7625E-02	
20	5.0050E-01	2.9610E-02	
21	5.0049E-01	2.9755E-02	
22	5.0048E-01	2.9957E-02	
23	5.0048E-01	3.0000E-02	
24	5.0048E-01	3.0020E-02	

LINEAR APPROACH

23

I	ZO	SD	BETA
1	5.1002E-01	-1.9790E-02	3.6966E-02
2	5.1002E-01	-1.9658E-02	4.0069E-02
3	5.1001E-01	-1.9480E-02	3.6079E-02
4	5.0995E-01	-1.8338E-02	5.2515E-02
5	5.0969E-01	-1.5754E-02	1.3390E-01
6	5.0922E-01	-1.2912E-02	2.0563E-01
7	5.0879E-01	-1.0948E-02	2.3233E-01
8	5.0826E-01	-8.8621E-03	2.6433E-01

TABLE 4.16 (continued).

9	5.0737E-01	-5.6079E-03	2.8323E-01
10	5.0631E-01	-1.2543E-03	2.1282E-01
11	5.0552E-01	2.6433E-03	1.8811E-01
12	5.0499E-01	5.2784E-03	2.1532E-01
13	5.0419E-01	8.7900E-03	2.3120E-01
14	5.0314E-01	1.3374E-02	2.3040E-01
15	5.0224E-01	1.7412E-02	2.1171E-01
16	5.0171E-01	1.9976E-02	1.9476E-01
17	5.0129E-01	2.2357E-02	1.6831E-01
18	5.0081E-01	2.5770E-02	1.1386E-01
19	5.0055E-01	2.8618E-02	5.3224E-02
20	5.0049E-01	2.9682E-02	3.8688E-02
21	5.0049E-01	2.9856E-02	3.7382E-02
22	5.0048E-01	2.9979E-02	3.7497E-02
23	5.0048E-01	3.0010E-02	4.1439E-02

POLYNOMIAL LEAST SQUARE FIT

NO. OF COEFFICIENCTS IS 4
NO. OF POINTS FOR DATA FITTING IS 10

I	ZO	SD	BETA
1	5.1002E-01	-1.9880E-02	2.3637E-03
2	5.1002E-01	-1.9701E-02	9.0144E-03
3	5.1002E-01	-1.9616E-02	1.2137E-02
4	5.1001E-01	-1.9344E-02	2.2058E-02
5	5.0990E-01	-1.7332E-02	8.9584E-02
6	5.0947E-01	-1.4177E-02	1.7542E-01
7	5.0896E-01	-1.1648E-02	2.3384E-01
8	5.0862E-01	-1.0249E-02	2.4778E-01
9	5.0793E-01	-7.4757E-03	2.5829E-01
10	5.0703E-01	-3.7401E-03	2.4412E-01
11	5.0584E-01	1.2315E-03	2.2368E-01
12	5.0519E-01	4.0550E-03	2.1430E-01
13	5.0466E-01	6.5018E-03	2.1328E-01
14	5.0363E-01	1.1078E-02	2.1832E-01
15	5.0260E-01	1.5670E-02	2.1653E-01
16	5.0186E-01	1.9153E-02	2.0021E-01
17	5.0154E-01	2.0800E-02	1.8353E-01
18	5.0103E-01	2.3914E-02	1.4346E-01
19	5.0061E-01	2.7625E-02	7.8149E-02
20	5.0049E-01	2.9610E-02	3.1325E-02
21	5.0049E-01	2.9755E-02	2.7699E-02
22	5.0048E-01	2.9957E-02	2.2570E-02
23	5.0048E-01	3.0000E-02	2.1474E-02
24	5.0048E-01	3.0020E-02	2.0959E-02

I	SD	BETA
24		
1	-1.9880E-02	2.3637E-03
2	-1.9701E-02	9.0144E-03
3	-1.9616E-02	1.2137E-02
4	-1.9344E-02	2.2058E-02
5	-1.7332E-02	8.9584E-02
6	-1.4177E-02	1.7542E-01
7	-1.1648E-02	2.3384E-01

TABLE 4.16 (continued).

8	-1.0249E-02	2.4778E-01
9	-7.4757E-03	2.5829E-01
10	-3.7401E-03	2.4412E-01
11	1.2315E-03	2.2368E-01
12	4.0550E-03	2.1430E-01
13	6.5018E-03	2.1328E-01
14	1.1078E-02	2.1832E-01
15	1.5670E-02	2.1653E-01
16	1.9153E-02	2.0021E-01
17	2.0800E-02	1.8353E-01
18	2.3914E-02	1.4346E-01
19	2.7625E-02	7.8149E-02
20	2.9610E-02	3.1325E-02
21	2.9755E-02	2.7699E-02
22	2.9957E-02	2.2570E-02
23	3.0000E-02	2.1474E-02
24	3.0020E-02	2.0959E-02

FORTRAN STOP

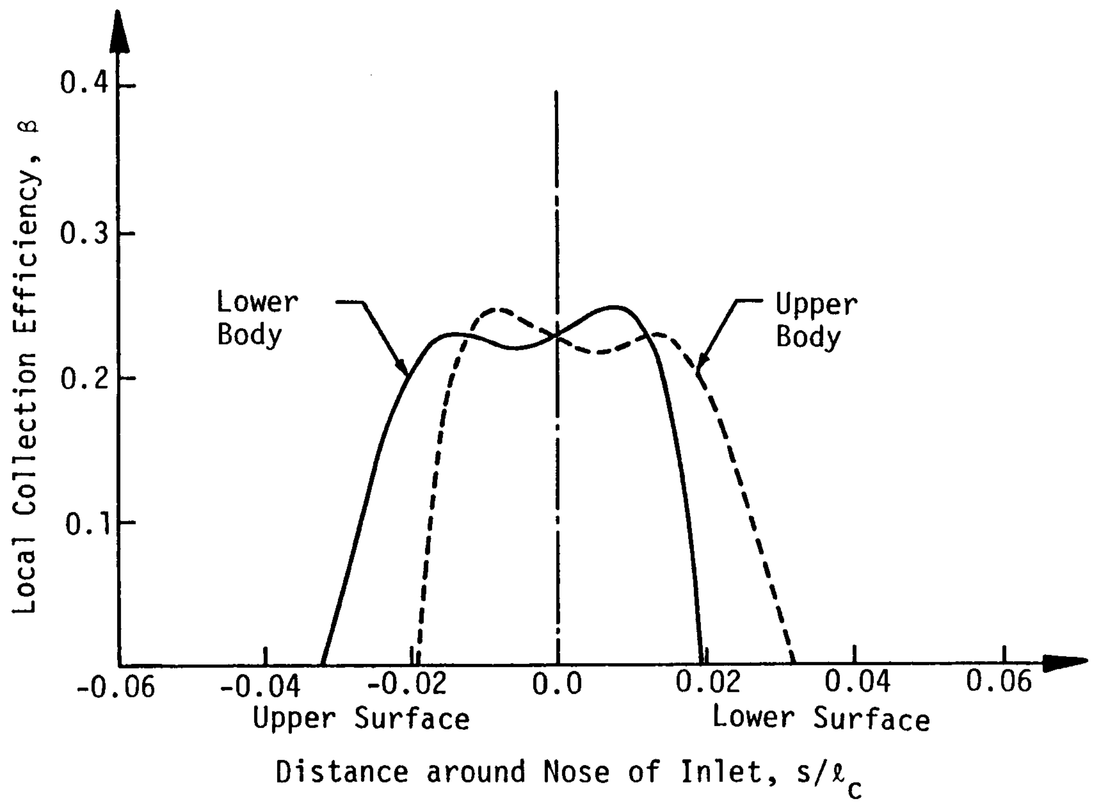


Figure 4.6 Collection coefficient for two-dimensional inlet, $\alpha = 0°$ (experimental data is not available for comparison).

D. ADDITIONAL TEST CASES

Figures 4.7 through 4.12 compare computed results with reported experimental data for the test cases listed in Table 4.1, page 29. The effect of varying the angle of attack is shown on each of the figures and separate figures are used to show the effect of wall conditions. Agreement with experimental results is good, with the exception of the NACA 65_A-004 airfoil at 8° angle of attack. For the Joukowski 0015 airfoil 0° and 4° angle of attack cases, the effect of tunnel walls on the computed results is small. In general, including wall effects on the flow field gives improved agreement with experiment in the nose region of the airfoil. The agreement with the data in the region further from the nose on the lower surface, however, is generally better for the analyses without walls than it is for those with walls. The explanation of this is not clear and further study of this influence is required in order to determine whether the appropriate tunnel wall correction factors are being made for experimental studies.

The tail end of the computed curves for both the upper and lower surfaces depart appreciably from the experimental results. This is shown in Chapter V to be strongly influenced by the particle size distribution. (The computed results shown are for a monodispersed droplet size distribution whereas the actual droplet size distribution would be multidispersed.) The NACA 65_A-004 thin airfoil gives the poorest agreement with experiment.

For the 0° angle of attack case the agreement with experiment is acceptable. The experimental results show a much higher value of β at

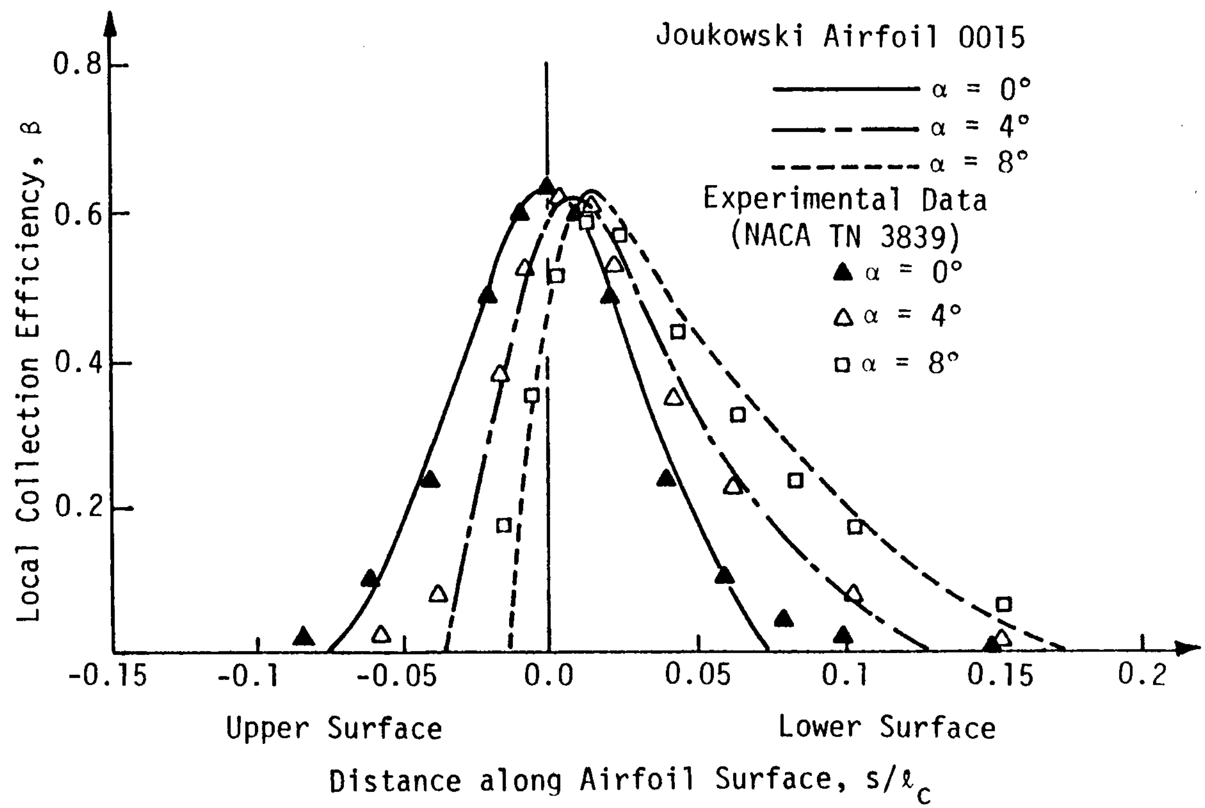


Figure 4.7 Effect of angle of attack on β for Joukowski Airfoil 0015, 13-inch chord length, without walls.

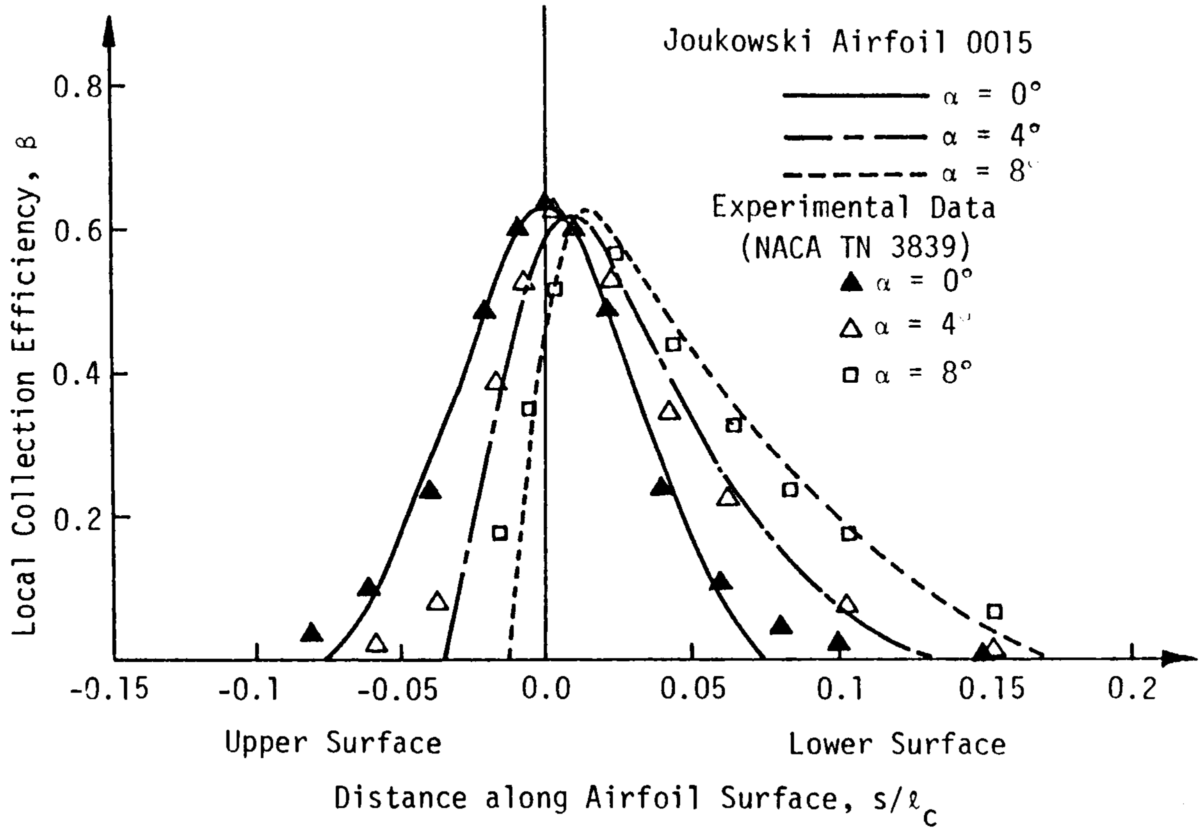


Figure 4.8 Effect of angle of attack on β for Joukowski Airfoil 0015, 13-inch chord length, with walls.

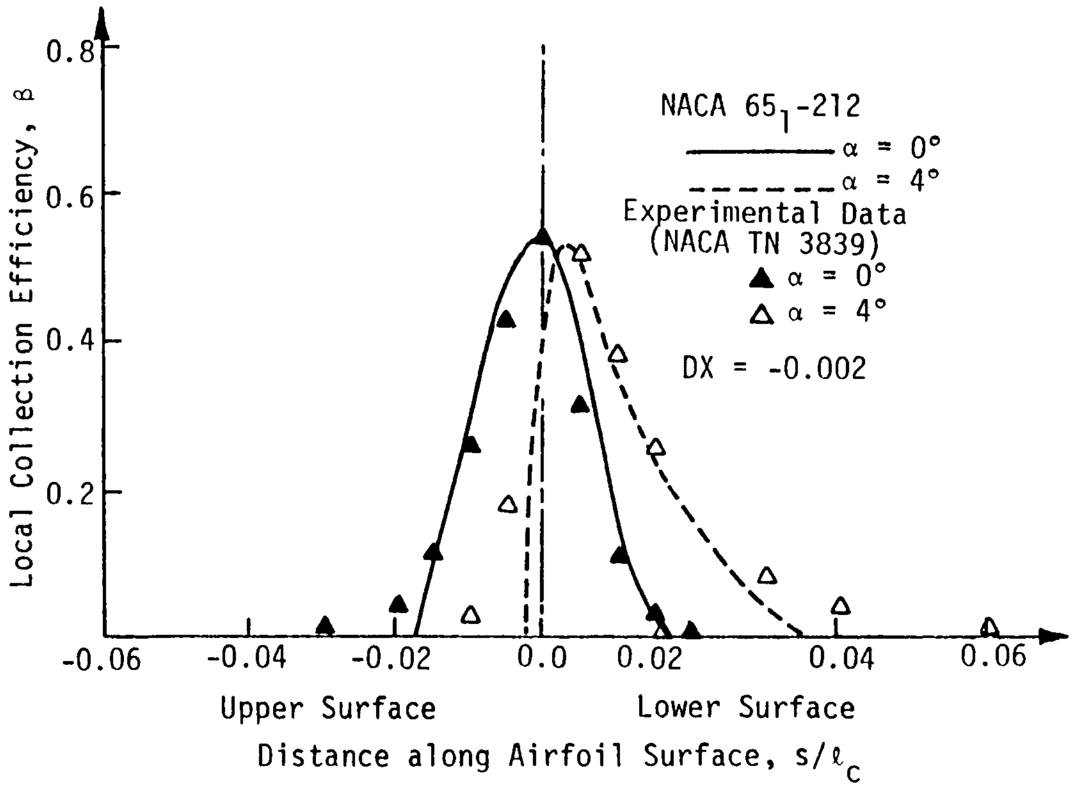


Figure 4.9 Effect of angle of attack on β for NACA 65_1-212 airfoil, 72-inch chord length, without walls.

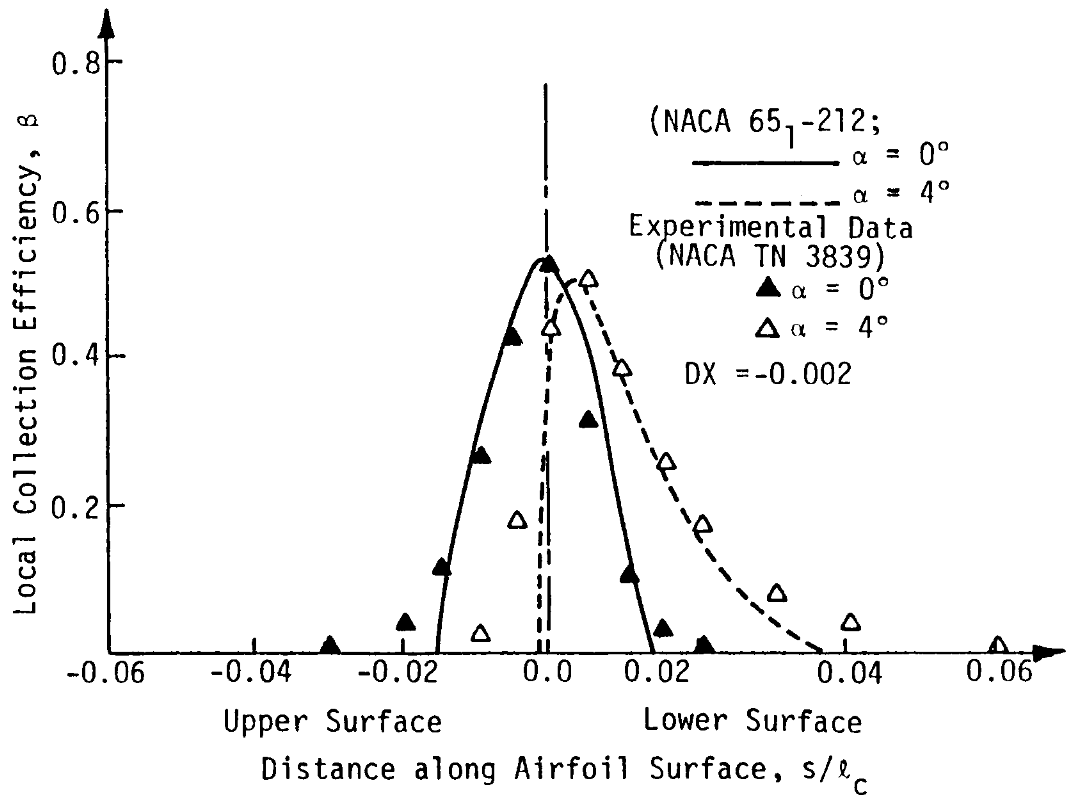


Figure 4.10 Effect of angle of attack on β for NACA 65_1-212 airfoil, 72-inch chord length, with walls.

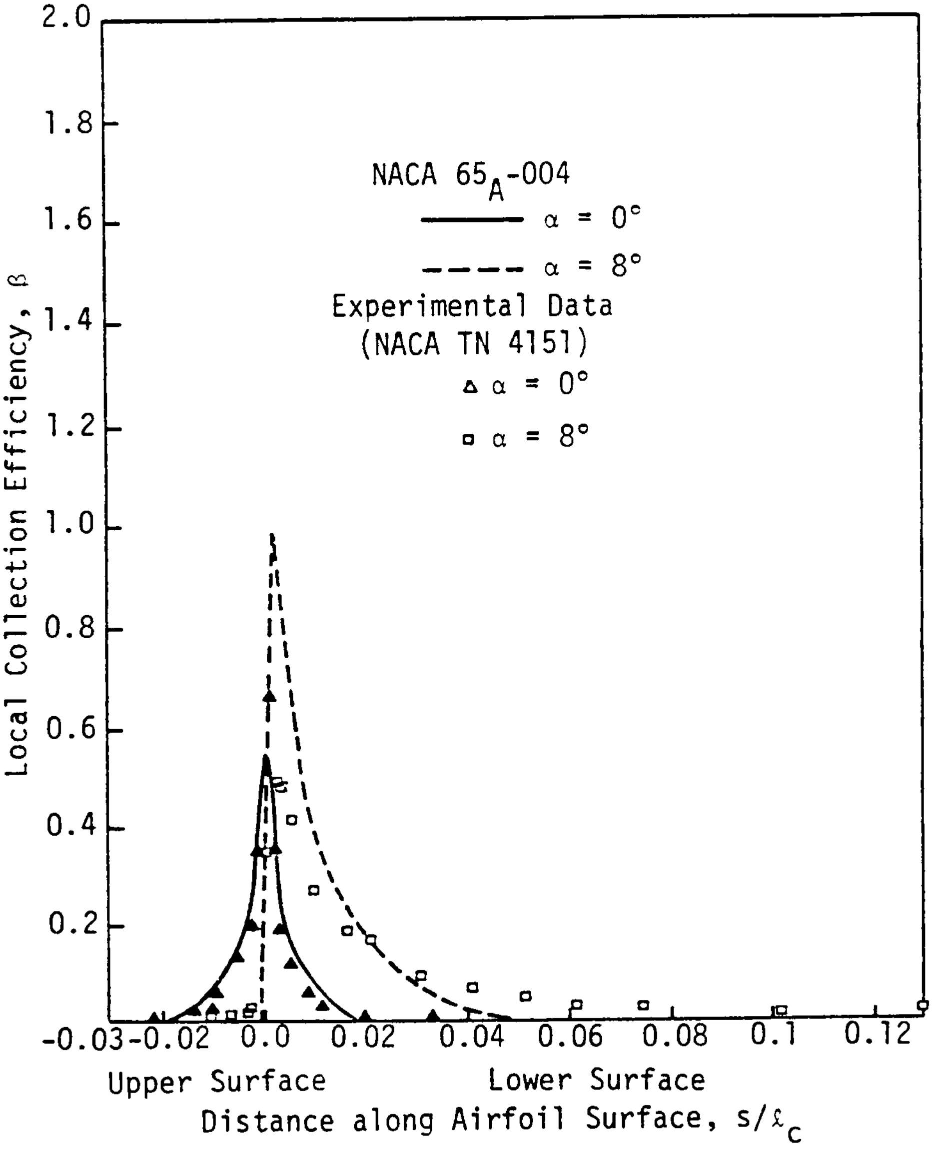


Figure 4.11 Effect of angle of attack on β for NACA 65_A-004 airfoil, 72-inch chord length, without walls.

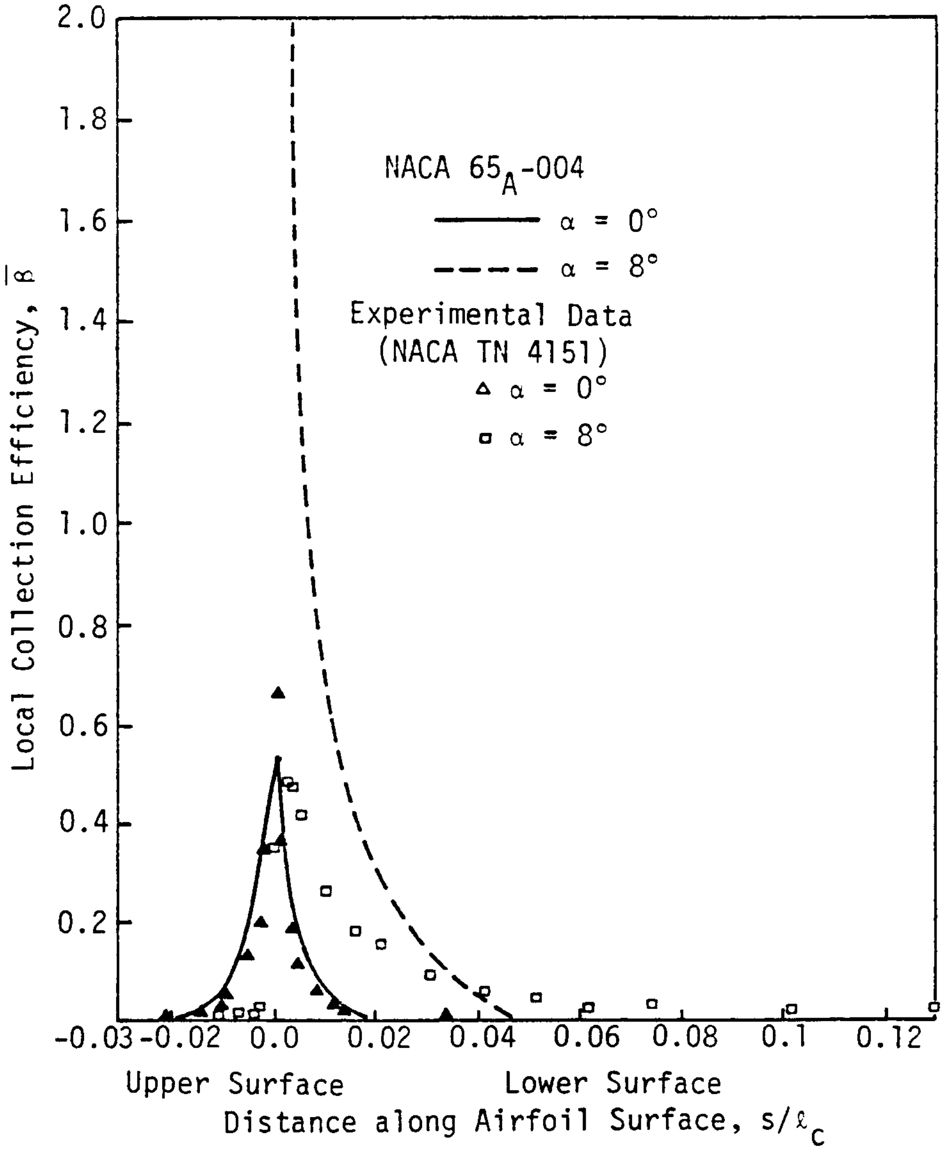


Figure 4.12 Effect of angle of attack on β for NACA 65_A-004 airfoil, 72-inch chord length, with walls.

the nose, however, than the computed results. This is true for either the case with or without walls. On the other hand, for the 8° angle of attack case, the computed results do not agree well with experiment at all. This is to be expected and has been reported by other researchers (see NACA TN 4151 for example). This technical note points out that at an 8° angle of attack the experimentally measured velocity distribution differs markedly from theoretical, predicted values. The experimental stagnation point is further forward, the lower surface and trailing edge velocities are greater, and the upper surface velocities peak at a lower value and describe a region of approximately constant velocity just after the peak. All of these deviations indicate flow separation occurs on the upper surface, a common condition with thin, symmetrical, sharp-nosed airfoils. The effect of flow separation is to reduce the experimental impingement rates below the theoretical values. Thus, the discrepancy between experimental results and computer results using potential flow theory is expected. The above discussion indicates the need to carry out analyses similar to those reported herein but with Navier-Stokes solutions. Computer programs solving the full two-dimensional Navier-Stokes equations including turbulence are available [8,9] and can be readily modified to airfoils. Coupled with the trajectory program many of the difficulties both due to separation and boundary layer effects near the surface would be overcome.

The results presented in this chapter are discussed relative to the assumptions made and some of the computational difficulties encountered during the analysis presented in Chapter V.

CHAPTER V

DISCUSSION OF RESULTS

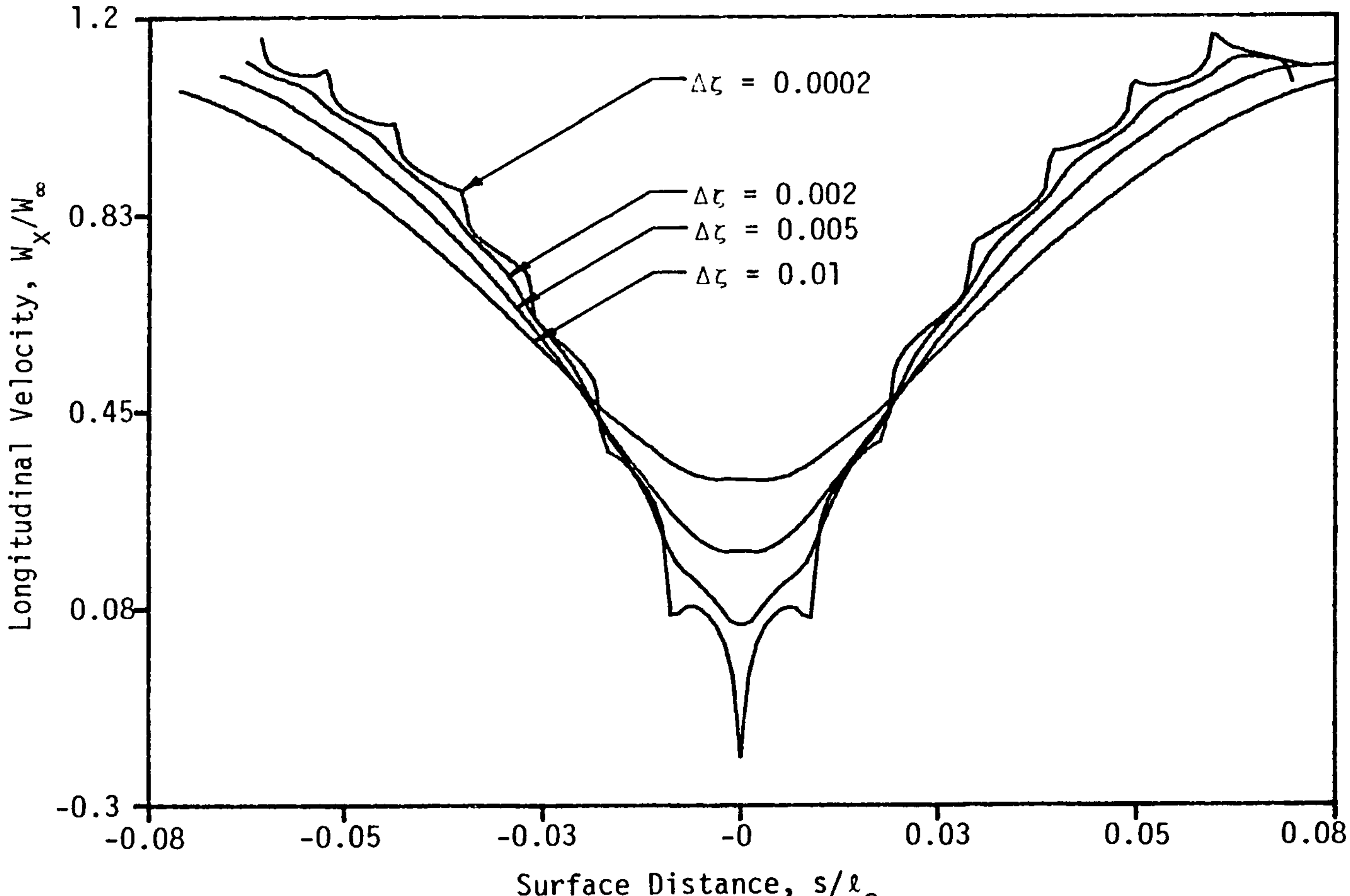
A number of assumptions have been made in relating the computed results to the experimental data. These assumptions along with certain limitations of the theory are described in this chapter.

A. CORRECTION FOR DISCRETIZATION ERROR NEAR BODY

The potential flow computer programs used in this study has a relatively large discretization error very close to the body. Figures 5.1 and 5.2 are plots of the longitudinal and vertical velocities around the nose of the Joukowski airfoil and of the upper body of the two-dimensional inlet, respectively. The velocity is computed for different constant values of separation distance from the body as illustrated in the insert. One observes large peaks or oscillations in the flow field velocity near the surface.

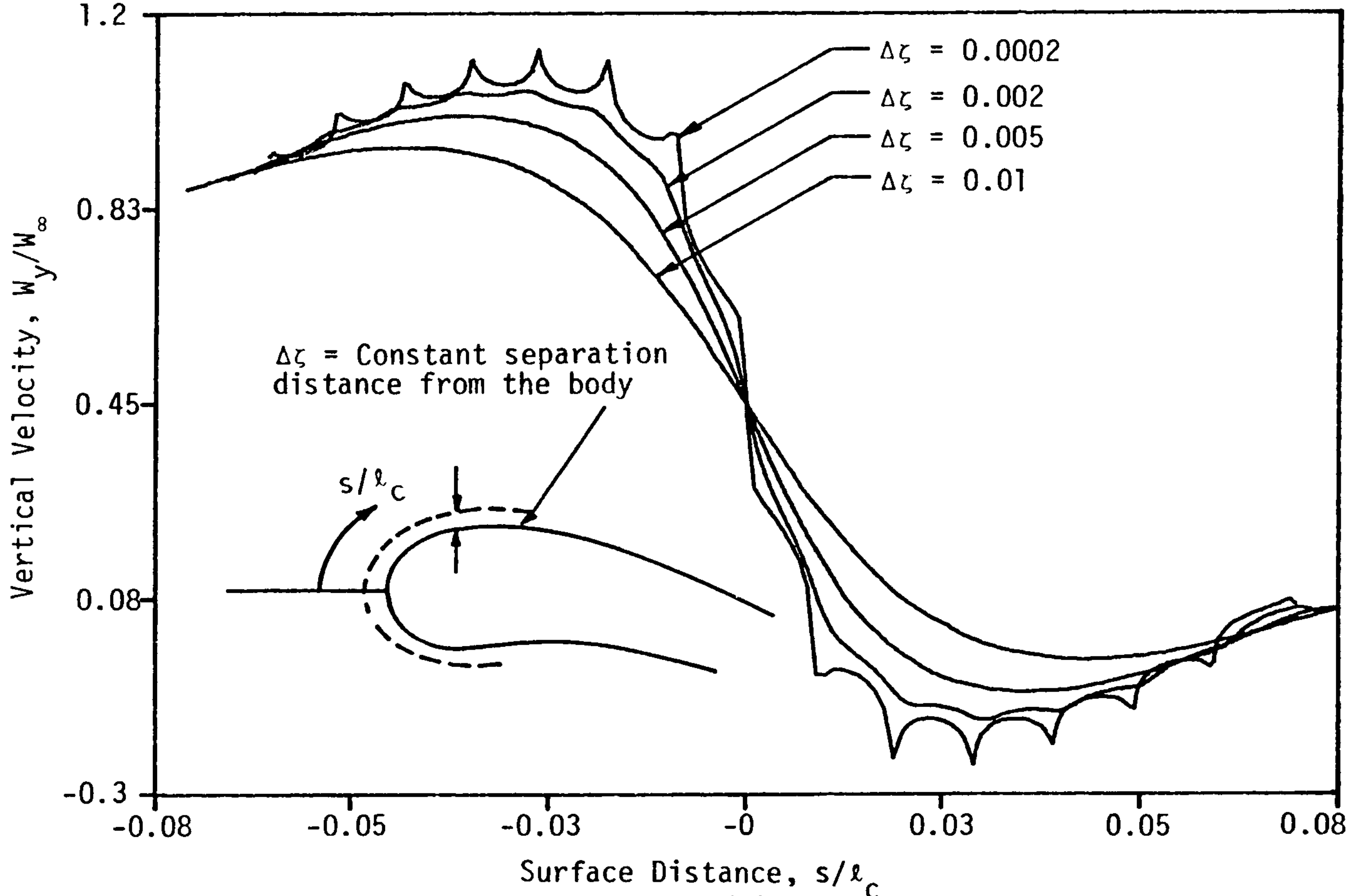
These errors are particularly large for the two-body inlet and have a significant influence on the particle trajectories as illustrated in Figure 5.3.

Figure 5.3a illustrates the trajectory of three different particles released at very small separation distances, y_0, upstream of the body. One observes that the upper particle turns near the nose and flows backward; then again reverses direction and flows around the body. The initially intermediate positioned particle trajectory crosses the lower particle trajectory near the body. It approaches very close to the surface somewhat downstream from the nose and then departs into the



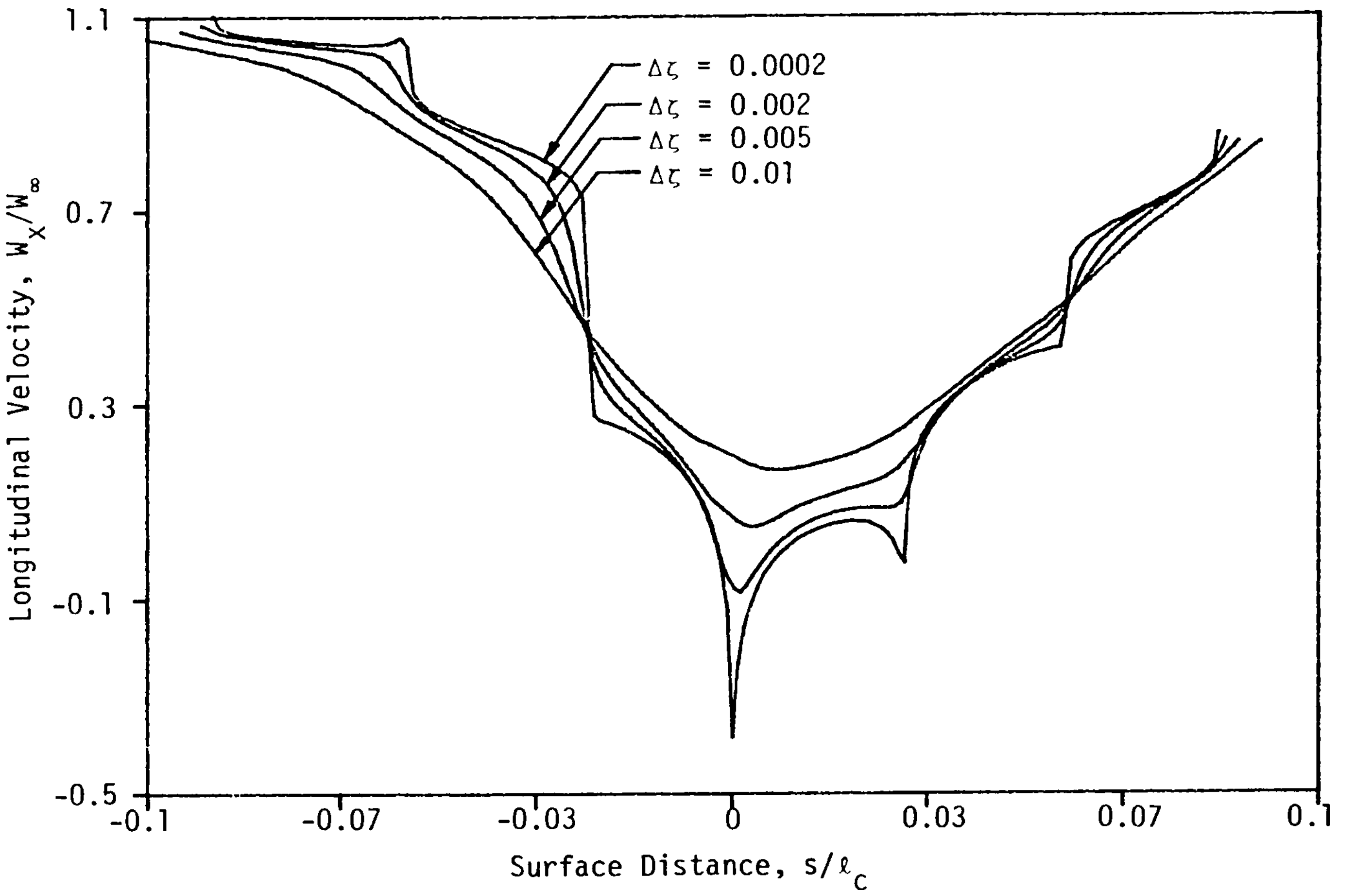
(a)

Figure 5.1 Discretization error in the flow field near the nose of a Joukowski airfoil.



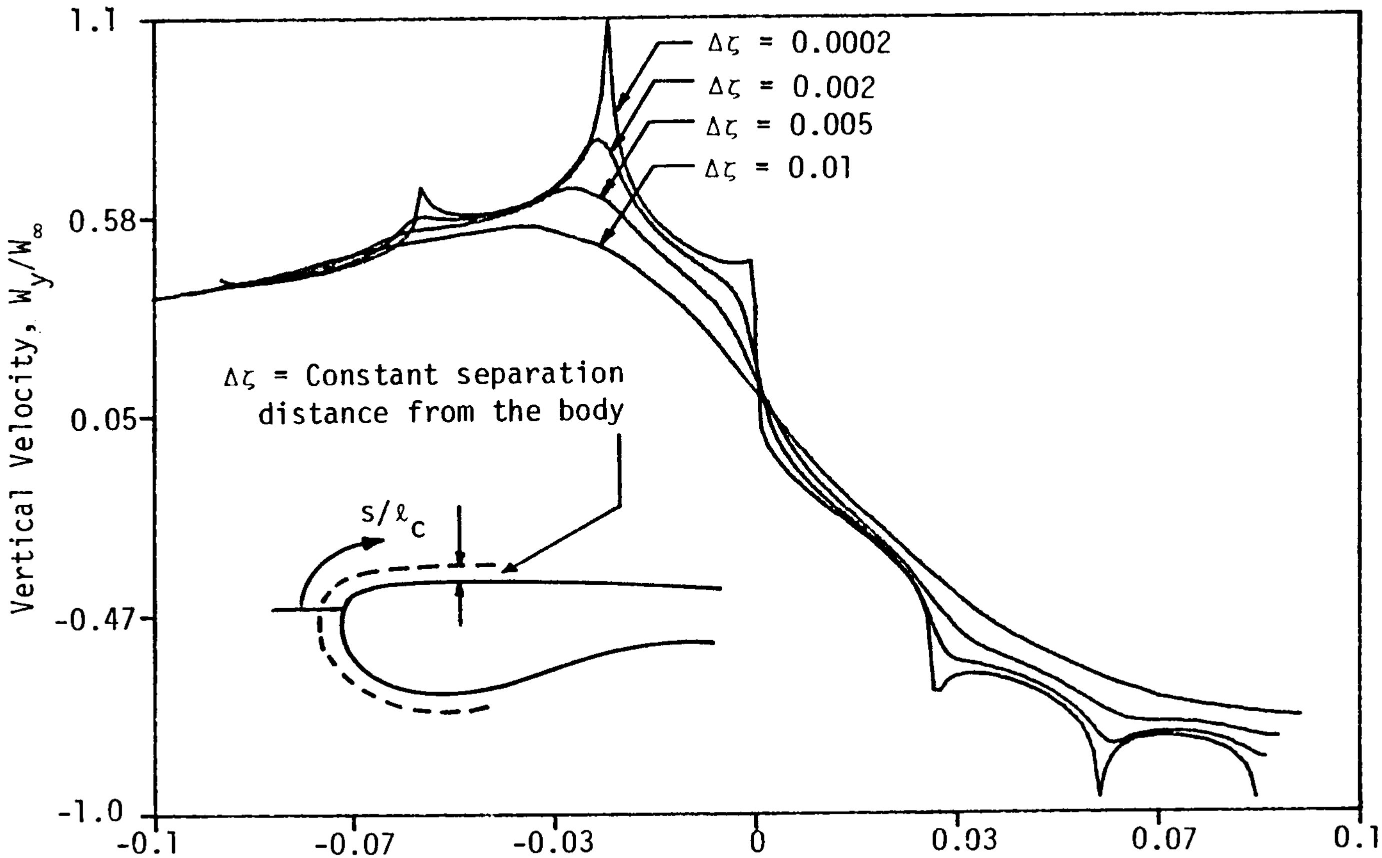
(b)

Figure 5.1 (continued).

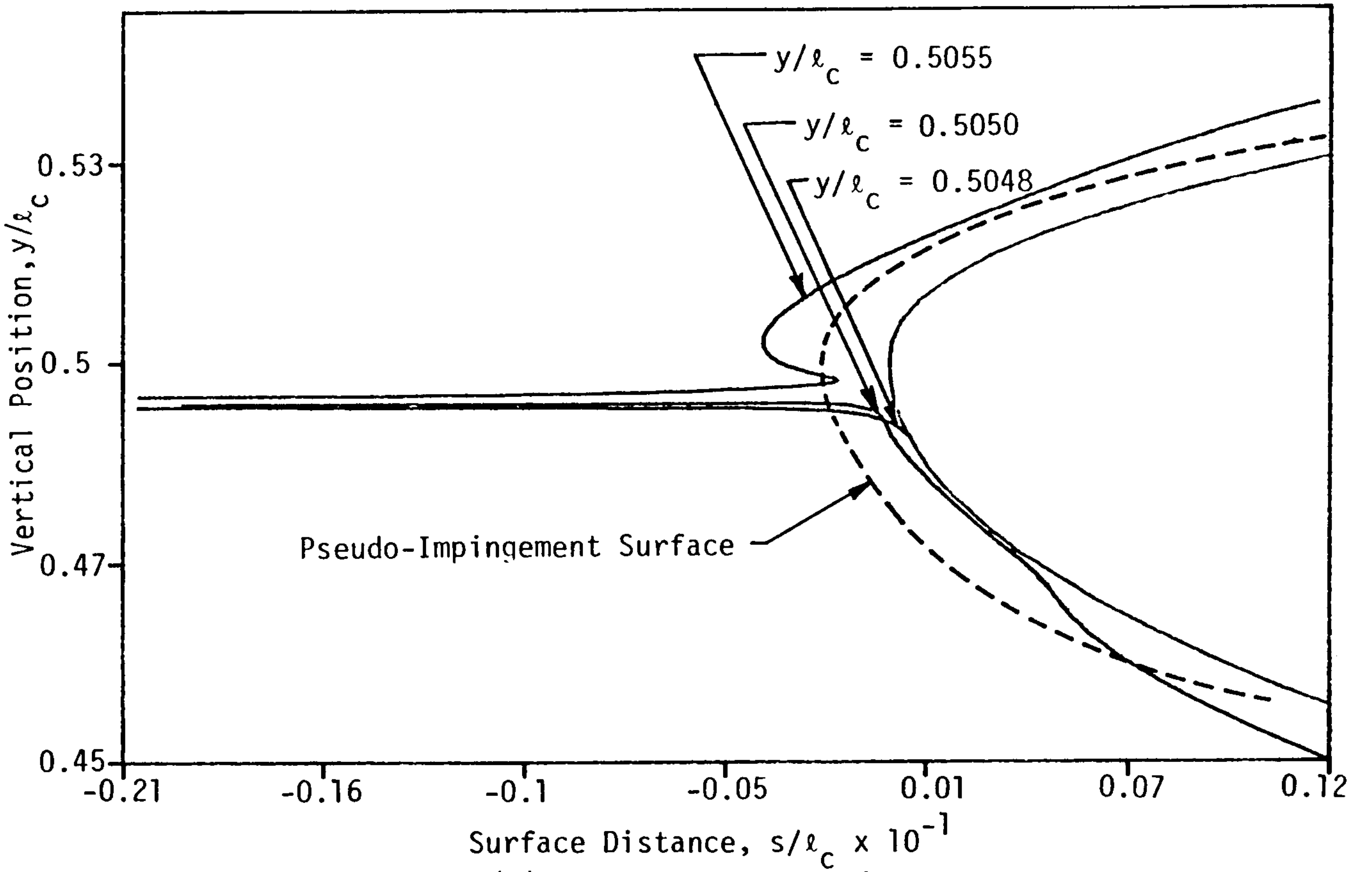


(a)

Figure 5.2 Discretization error in the flow field near the nose of the upper body of a two-dimensional inlet.

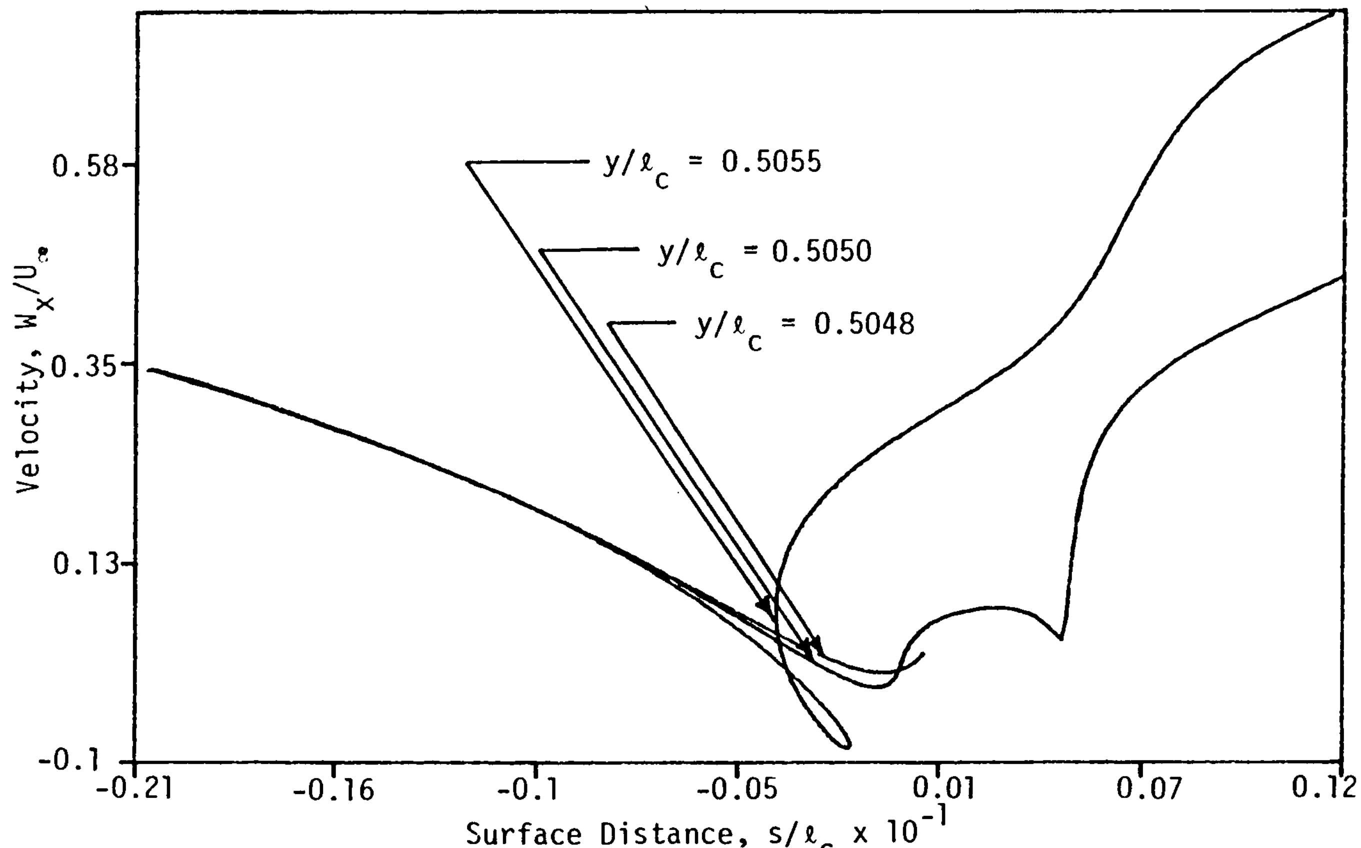


Surface Distance, s/ℓ_c
(b)
Figure 5.2 (continued).



(a) Particle trajectories

Figure 5.3 Influence of flow field velocity discretization error on particle trajectories near the body (body not to scale).



(b) Longitudinal velocity acting on particle along its trajectory

Figure 5.3 (continued).

free-stream without intercepting the body. Finally, the lower particle trajectory impinges on the body. These erratic trajectories are caused by the strong perturbations in the flow field near the body. A plot of the longitudinal wind field velocity component experienced by each particle along its trajectory is shown in Figure 5.3b. This figure clearly illustrates the erratic flow field the particle encounters.

To overcome the effect of the discretization error near the body, an artificial impingement surface is generated by the computer program. This surface is achieved by displacing the surface of the body a small increment DX units in the upstream x direction. For the two-dimensional inlet and the NACA 65_1-212 and 65_A-004 airfoils DX was set equal to -0.002. It is believed this distance encompasses the major area of uncertainty in the flow field. Figure 5.4 illustrates the pseudo-impingement surface for the upper body of the two-body inlet problem. Note in comparing Figure 5.3 with Figure 5.4 that the x scale in Figure 5.3 is highly exaggerated. Figure 5.4, on the other hand, is plotted to scale. To generate the pseudo-impingement surface, the x-coordinate is increased uniformly around the body and the y-coordinate remains constant. Thus, the nose is simply displaced outward as shown in Figure 5.4. The separation distance for the pseudo-surface of 0.002 used in the test cases is optional and is input by the user.

The pseudo-surface is generated in the computer program after the SCIRCL and 24Y programs have been run. Thus, the flow field is not influenced by the creation of the pseudo-surface but only the particle impingement positions.

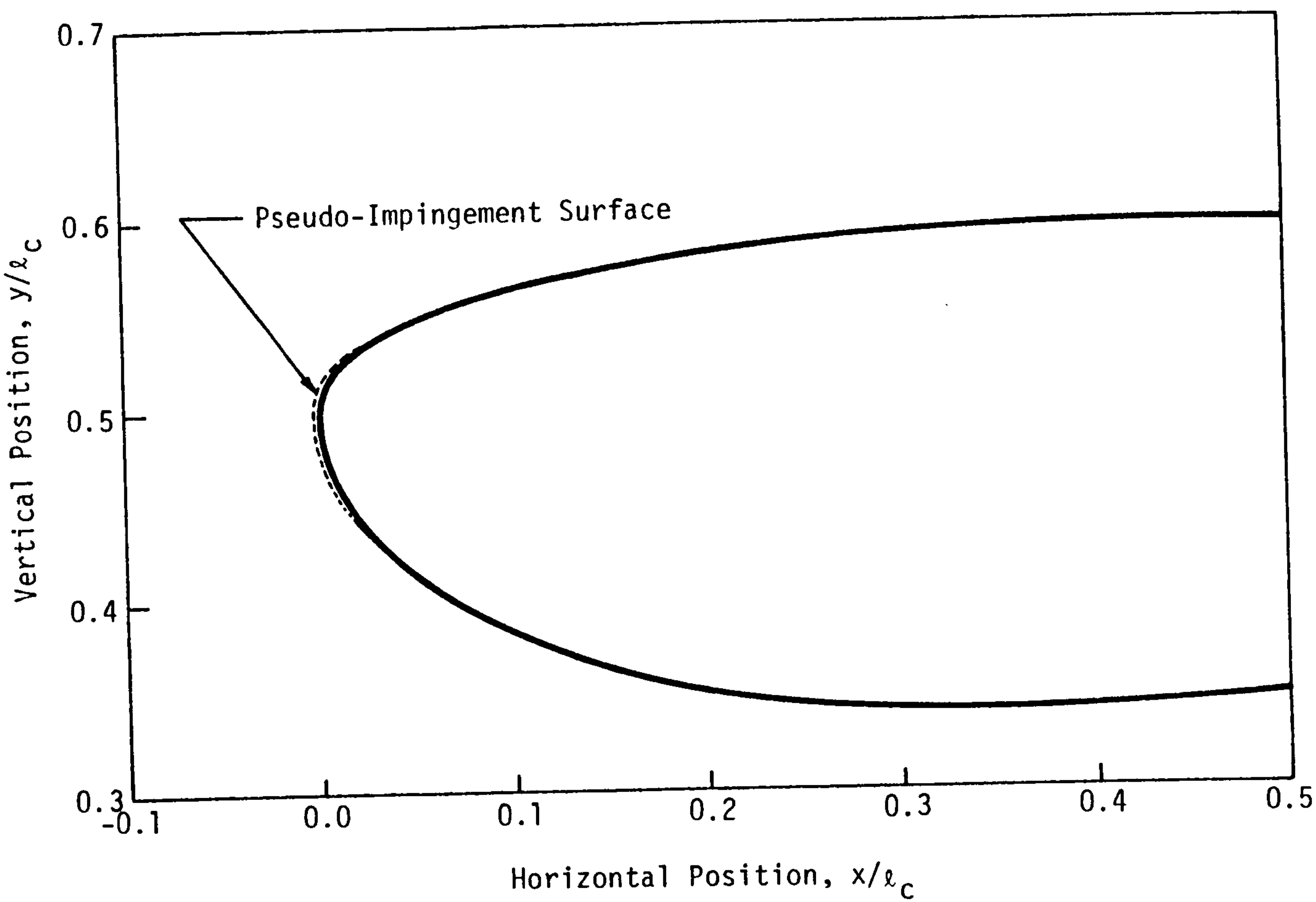


Figure 5.4 Scale drawing showing pseudo-impingement surface for one body of a two-dimensional inlet.

B. ADJUSTMENT OF EXPERIMENTAL DATA

A second assumption involved in comparing the computer results with experiment is that the experimental data need to be adjusted slightly to account for displacement of the leading edge. Although most reports do not clearly specify the exact point from which surface position is measured, it is generally assumed to be the leading edge. The computer solution calculates surface displacement from the foremost point without angle of attack. In the experimental results, the angle of attack displaces this surface upward. Thus the experimental data and the computer results are at slightly different surface locations. To correct for this, the experimental data have been shifted depending upon the angle of attack. The amount of shift is computed by multiplying the leading edge radius of the airfoil times the angle of attack. For the Joukowski airfoil, this amount of correction is 0.0019 units for the 4° angle of attack and 0.0035 units for the 8° angle of attack. The NACA 65_1-212 data are corrected 0.0007 units for the 4° angle of attack. All other data are not corrected.

No other assumptions have been made in comparing the experimental results to the computed results other than those associated with the general theory development described in Chapter II. It is believed that with the small correction factors described, the computer model provides very good agreement with the experimental results particularly in the nose region. At the tail ends of the region of impact, i.e., further along the upper and lower surfaces, the data tend to show a higher accretion rate than the computer model. It is shown in the next section that this effect is associated with the particle distribution. Also, impingement studies generally utilize liquid dyes to measure impingement or local collection efficiencies. The nature of these materials are to flow back over the surface rather than immediately adhere to the surface. True icing conditions, depending on whether one was looking at glazed ice or rime ice, are somewhere in between.

C. LOCAL COLLECTION EFFICIENCY FOR MULTI-SIZED PARTICLE DISTRIBUTIONS

A feature of the particle trajectory program is that it allows the user to analyze the local collection efficiency for a multi-sized particle distribution. The local collection efficiency for a particle size distribution can be derived as follows.

The local water catch is defined as the mass per unit time which impinges upon given unit surface of the airfoil. If we consider the element of area, ds, on the airfoil shown in Figure 5.5, then particles of size D_i passing through dy_o at y_{oi} and particles of size D_j passing through dy_o at y_{oj} will strike ds. For N particle sizes the mass striking ds per unit time is given by:

$$\dot{m} = \sum_{i=1}^{N} \frac{\pi\rho D_i^3}{6} \frac{dn_i}{dt} \tag{5.1}$$

The derivative $dn_i(y_{oi})/dt$ is defined by the expression:

$$\frac{dn_i}{dt} = n_i \frac{d\tilde{V}_i}{dt} = n_i \; dy_{oi} \; V_a b \tag{5.2}$$

where n_i is the number of particles of size i per unit volume. Substituting this expression into Equation 5.1 gives the following results:

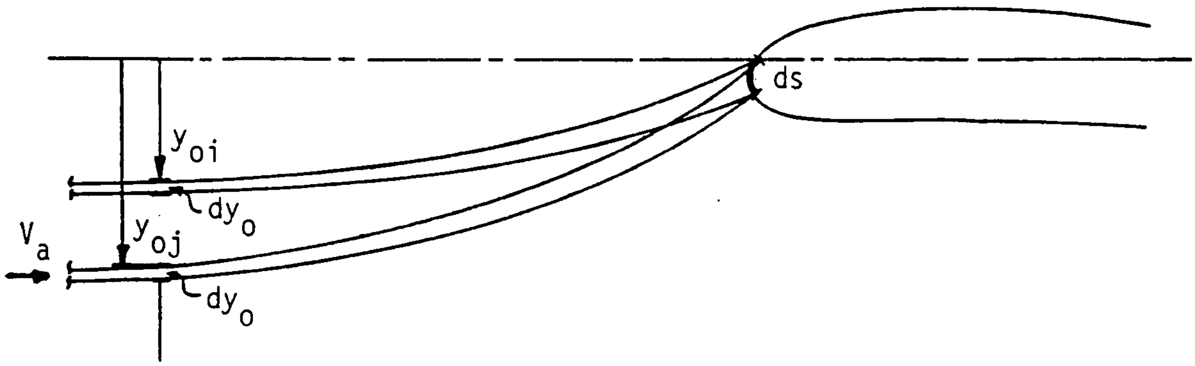


Figure 5.5 Effect of different particle sizes on local water catch.

$$\dot{m} = \sum_{i=1}^{N} \frac{\pi \rho D_i}{6} n_i dy_o(y_{oi}) V_a b \tag{5.3}$$

This represents the mass per unit time which is then divided by the area of impingement, A = bds, where b is the span width of the airfoil. Substituting this into Equation 5.3 results in the following value for the local water catch:

$$R_{w_{local}} = V_a \sum_{i=1}^{N} \frac{\rho \pi n_i D_i^3}{6} \left(\frac{dy_o(s)}{ds} \right)_i \tag{5.4}$$

The fraction of liquid water contained in droplets of size D_i is given by:

$$\eta_i = \frac{\frac{\rho \pi n_i D_i^3}{6}}{LWC} \tag{5.5}$$

where LWC is the liquid water content per unit volume of the flow. Thus, the local water catch can be written as:

$$R_{w_{local}} = (LWC) V_a \sum_{i=1}^{N} \eta_i \left(\frac{dy_o(s)}{ds} \right)_i \tag{5.6}$$

From the definition of the local collection efficiency we arrive at the expression for β as:

$$\beta(s) = \sum_{i=1}^{N} n_i \left(\frac{dy_0(s)}{ds} \right)_i \tag{5.7}$$

The subroutine provided in the particle trajectory program determines water catch characteristics for a given droplet size distribution. The user provides a tabular listing of the ratio of droplet diameters to volume median diameter and the corresponding percentages of liquid water content for a maximum of ten droplet diameter sizes as well as the total liquid water content and the volume median diameter.

An example application of this feature of the program was carried out for the Joukowski airfoil 0015 at 0° angle of attack. The droplet distribution was taken from Reference 10 where the D distribution is recommended as characteristic of wind tunnel sprays. Table 5.1 shows the percentage liquid water content contained within each drop size increment, the ratio of particle diameter to the volume median diameter, and the Cunningham correction factor used for the smaller size particles.

The Cunningham correction factor must be used for very small sized particles ($D < 10\ \mu$) for which molecular slip results in lower drag forces than that calculated by the drag laws employed in the program. Table 5.2 shows the Cunningham correction factor for standard air. This table provides input values for the user.

The volume median diameter for the example application was taken as $16.7\ \mu$. This value was selected from Reference 11.

TABLE 5.1. Particle Size Distribution.

Percentage Liquid Water Content	Ratio of Diameters	Cunningham Correction Factor
0.05	0.31	1.033
0.10	0.52	1.020
0.20	0.71	1.000
0.30	1.00	1.000
0.20	1.37	1.000
0.10	1.74	1.000
0.05	2.22	1.000

Figure 5.6 graphically illustrates the results of the calculation. One observes that the local collection efficiency shows much better agreement at the outskirts of the distribution but shows less favorable agreement at the nose. The poor agreement at the nose suggests that the volume median diameter utilized of 16.7 μ may be somewhat low or the diameter percentages are not completely representative of those for the experimental facility. If a higher percentage of larger particle sizes were utilized, more impact would occur on the nose and a larger contribution to β would occur at this point.

TABLE 5.2. Cunningham Correction Factor for Standard Air.

d (μ)	C	d (μ)	C
0.001	221.600	0.1	2.911
0.002	111.100	0.2	1.890
0.003	74.250	0.3	1.574
0.004	55.830	0.4	1.424
0.005	44.780	0.5	1.337
0.006	37.410	0.6	1.280
0.007	32.150	0.7	1.240
0.008	28.200	0.8	1.210
0.009	25.140	0.9	1.186
0.010	22.680	1.0	1.168
0.020	11.650	2.0	1.084
0.030	7.978	3.0	1.056
0.040	6.151	4.0	1.042
0.05	5.060	5.0	1.034
0.06	4.337	6.0	1.028
0.07	3.823	7.0	1.024
0.08	3.441	8.0	1.021
0.09	3.145	9.0	1.019
		10.0	1.017

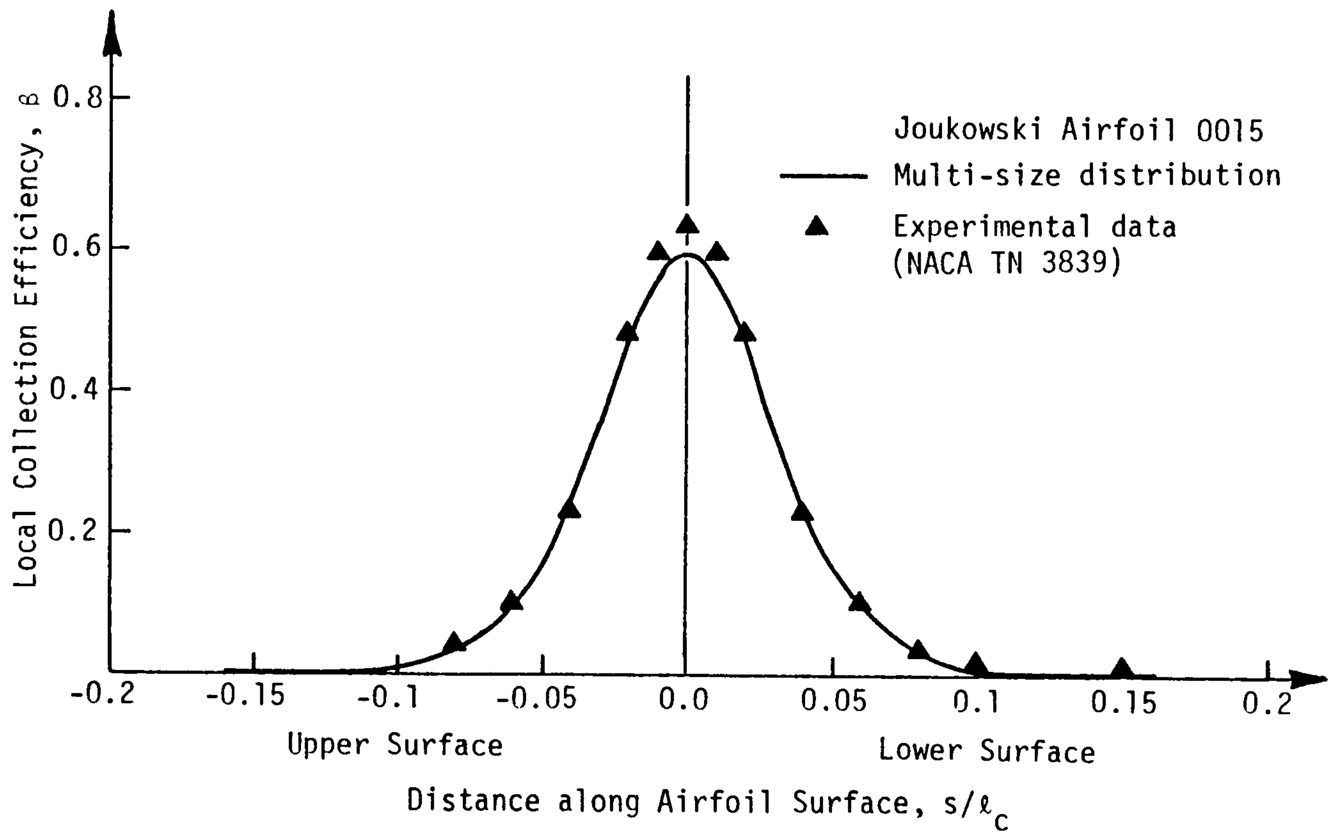


Figure 5.6 Joukowski airfoil 0015, 13-inch chord length, without walls, $\alpha = 0°$.

LIST OF REFERENCES

LIST OF REFERENCES

1. Hawk, J. D., N. O. Stockman, and C. A. Farrell, Jr. "Computer Programs for Calculating Two-Dimensional Potential Flow In and About Propulsion System Inlets," NASA TM-78930, June 1978.

2. Hawk, J. D., and N. O. Stockman. "Computer Program for Calculating Two-Dimensional Potential Flow Through Deflected Nozzles," NASA TM-79144, May 1979.

3. Hess, J. L., and A. M. O. Smith. "Calculation of Potential Flow About Arbitrary Bodies," Progress in Aeronautical Sciences, 8:1-138, (D. Küchemann, editor). Elmsford, New York: Pergamon Press, 1967.

4. Gray, V. H. "Correction Among Ice Measurements, Impingement Rates, Icing Conditions, and Drag Coefficients for Upswept NACA 65_A-004 Airfoil," NACA TN 4151, February 1958.

5. Data provided by Dr. R. Joseph Shaw of NASA Lewis Research Center, Cleveland, Ohio 44135.

6. Conte, S. D., and C. de Boor. Elementary Numerical Analysis: An Algorithmic Approach, second edition. New York: McGraw-Hill Book Company, 1972.

7. Bowden, D. T., A. E. Gensemer, and C. A. Skeen. FAA Technical Report ADS-4, pp. 2-1 - 2-76, December 1963.

8. Shieh, C. F., and W. Frost. "Numerical Solutions of Atmospheric Flow Over Semielliptical Simulated Hills," NASA CR 3430, June 1981.

9. Stocker, H. L., T. E. Scott, C. F. Shieh, and J. E. Caruthers. "Separated Diffuser Flow Analysis," Vol. 1, Report No. AFWAL-TR-81-2085, Wright-Patterson Air Force Base, Ohio, September 1981.

10. Werner, J. B. "Ice Protection Investigation for Advanced Rotary Wing Aircraft," NTIS No. AD-771 182, Springfield, Virginia, August 1973.

11. Gelder, T. F., W. H. Smyers, Jr., and U. von Glahn. "Experimental Droplet Impingement on Several Two-Dimensional Airfoils with Thickness Ratios of 6 to 16 Percent," NACA TN 3839, December 1956.

APPENDICES

APPENDIX A

INPUT INSTRUCTIONS AND PROGRAM OUTPUT

A. PROGRAM INPUT INSTRUCTIONS

A general flowchart for the computer program is shown in Figure A.1. The general procedure for running the program consists of first manually constructing a geometry input data tape, Tape 05. The geometry is specified in terms of a number of coordinate positions on the surface. The origin for the Cartesian coordinate system used to specify the geometry can be selected arbitrarily. The geometry generation computer program, SCIRCL, is then run to create Tape 17 which is the input file for the two-dimensional potential flow program. The format of the output tape, Tape 17, created by SCIRCL is the input to the two-dimensional potential flow program. Input instructions for geometry generation computer program and two-dimensional potential flow code are described in References 1 and 2.

A precaution is required if the geometry is to be rotated relative to the arbitrarily selected coordinate system. In this case Tape 17 requires modifications as described in Reference 2. In particular, Column 53 of Card 1, which is always set equal to zero by SCIRCL, must be changed to either 1 or 3 and Card 2, which is not generated by SCIRCL must be added to the deck.

Also as described in Chapters IV and V, Tape 17 in some cases requires modification when used as input to the particle trajectory program.

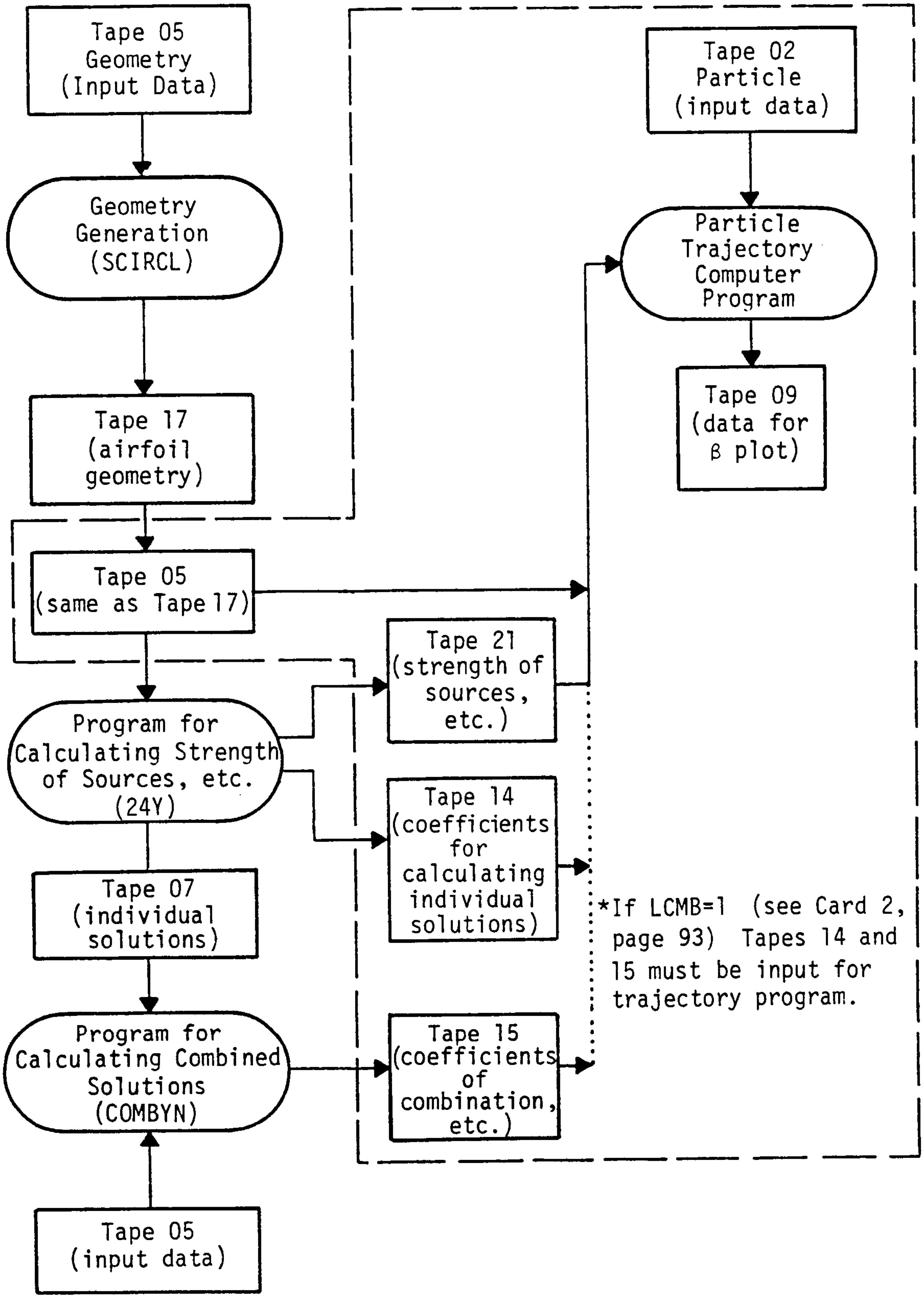


Figure A.1 General flowchart.

Now using Tape 17 as input, which must be renamed Tape 05, the two-dimensional flow code, 24Y, is run and creates Tape 21, Tape 07, and Tape 14. If in addition to specifying values of the free-stream velocity and angle of attack it is desired to specify the weight flow (or average axial velocity) through the control stations, the COMBIN-2D program is used. Tape 07 and another Tape 05 created manually [2] are the inputs to the COMBIN-2D program. This program is then run and creates Tape 15. For two-dimensional flow, Tape 21 is directly provided to the particle trajectory computer program. If the COMBIN-2D program is also used (i.e., if LCMB=1, see Table A.1, Card 2), Tape 14 and Tape 15 must also be directly input to the trajectory program. Additionally, Tape 02, which must be manually created as described in Table A.1, is required to run the particle trajectory program.

Running the particle trajectory program creates the output tapes listed below:

Tape 01: Data stored on Tape 01 is later written to Tape 03. Tape 01=Tape 03 for unsymmetric flow cases.

Tape 03: Data stored on Tape 03 is used for the calculation of collection efficiency.

Tape 04: Tape 04 is created if LOPT≠0 and contains coordinates of the particle trajectories as well as values of the wind speed component as a function of time.

Tape 08: Tape 08 is created if LOPT≠0. Data stored on Tape 08 is used for trajectory plots. The data stored are the x/ℓ_c,y/ℓ_c coordinates of the particle XP, YP for each time step and the surface impingement point SW. SW is initially set at 88.8888. When SW≠88.8888, the particle trajectory is terminated.

Tape 09: Tape 09 contains the local collection efficiency, β, as a function of surface position, s/ℓ_c. The program automatically plots β versus s/ℓ_c at the NASA/LeRC facility.

TABLE A.1. Trajectory Computer Program Input.

Card No.	Column	Code	Routine/ Format	Explanation
1	6-10	NBDY	Main/I5	Number of bodies. =1, one-body case (airfoil without walls) =2, two-body case (inlet without hub) =3, three-body case: i) Airfoil with walls (LNTL=1) ii) Inlet with hub (LNTL≠1).
	16-20	NPL	"	Number of particle trajectories to be computed.
	26-30	NSEAR	"	Maximum number of loops allowed in the search for the upper and lower impingement limits for the case LIM=1 (Card 3).
	36-40	NEQ	"	Number of equations to be solved. NEQ=6 for a lifting, rotating particle; NEQ=4 for a spherical particle undergoing drag only (Chapter II).
	46-50	IHUB	"	Input only for inlet case. =0, without hub (two-body case) ≠0, with hub (three-body case).
2	6-10	LEQM	"	=1, the initial particle velocity is equal to the flow at the initial particle location ≠1, the initial velocity conditions input on Cards 4 and 6 are used as the initial particle velocity.
	16-20	LSYM	"	Symmetric flow field flag. =0, unsymmetric flow field (general case) =1, symmetric flow field (only half plane is computed).
	26-30	LRANG	"	≠0, locates approximate values of y_{ou} and $y_{o\ell}$ (see Chapter III).

TABLE A.1 (continued).

Card No.	Column	Code	Routine/ Format	Explanation
2	36-40	LCMB	Main/I5	=1, Calculates combination solution in the same method of COMBIN-2D program. ≠1, Calculates combination solution in the same method of 24Y program.
	46-50	LCMP	"	Input only when LCMB=1. =1, Calculates compressibility correction. ≠1, No calculation of compressibility correction.
3	6-10	LIM	"	≠0, Calculates surface impingement limits y_{ou} and $y_{o\ell}$. =0, Calculates single particle trajectories; LRANG=0 (see Chapter III).
	16-20	LOPT	"	≠0, Stores details of particle trajectories on data Tape 04.
	26-30	LPLOT	"	≠0, Executes subroutine for plotting local collection efficiency, β, versus surface distance, s/ℓ_c.
	36-40	LTNL	"	=1, Computes flow over airfoil with walls (i.e., wind tunnel simulation). ≠1, Computes flow over airfoil without walls and inlet case.
	46-50	LXOR	"	Control flag for adjusting the upstream x-coordinates, XORC, for upstream position of particle release (see Chapter III). =0, The upstream x-coordinates of particle release is not adjusted. Particles are released from XORC input on Card 6 by user. =1, Particles are released from the x-coordinate position adjusted by the criteria: $\lvert 1 - (W/W_\infty)\rvert \leq$ EPSX.

TABLE A.1 (continued).

Card No.	Column	Code	Routine/ Format	Explanation
4	6-15	G	Main/ F10.0	Acceleration of gravity, m/s^2.
	21-30	YINF	"	Velocity of free-stream, m/s.
5	6-15	DP	"	Particle volume median diameter in microns (10^{-6} m).
	21-30	RL	"	Reference length, e.g., chord length of the airfoil, m.
	36-45	TIMSTP	"	Initial value of the time step used in the Adams-Moulton predictor-corrector method (see Chapter II).
	51-60	YLIM	"	Accuracy criteria for computing the surface impingement limits, YLIM=10^{-5} m is recommended.
	66-75	CP	"	Cunningham correction factor. Use if volume median diameter DP $<$ 10 μ; otherwise, CF=1.
6	6-15	ATK	"	Initial value of the angle, α, Figure 2.1, page 7 (deg).
	36-45	PITDOT	"	Initial value of $\dot{\theta}$ (deg/sec).
	51-60	XORC	"	Upstream x-coordinate position of particle release, y/ℓ_c (NPL=1, LRANG=0, and LIM=0).
7	6-15	XREAR	"	Maximum downstream value of x/ℓ_c for which the flow field is computed.
	21-30	YYLO	"	Minimum value of y/ℓ_c for which the flow field is computed.
	36-45	YYUP	"	Maximum value of y/ℓ_c for which the flow field is computed.
	51-60	YMAX	"	Initial guess of the upper limit y_{ou}/ℓ_c (LIM=1) (see Chapter III).

TABLE A.1 (continued).

Card No.	Column	Code	Routine/ Format	Explanation
7	66-75	YMIN	Main/ F10.0	Initial guess of the lower limit $y_{o\ell}/\ell_c$ (LIM=1) (see Chapter III).
8	6-15	ADEPS	"	Convergence criteria of the Adams-Moulton predictor-corrector method. ADEPS=0.001 is recommended.
	21-30	ANLFLO	"	Angle of flow direction relative to airfoil chord line measured from positive direction of x-axis.
	51-60	EPSX	"	Accuracy criteria for the case LXOR=1 (see Card 3); EPSX=0.001 is recommended.
9	6-10	NSI	Main/I5	Number of droplet size increments.
10	This card is input only when NSI>1.			
	1-10	PLWC	Main/ F10.0	Percentage of liquid water content for each drop size.
	11-20	DPD	"	Distribution of the particle diameter ratio to volume median diameter.
	21-30	CFP	"	Cunningham correction factor corresponding to DPD (see Table 5.2, page 84). If DP×DPD < 10 μ, CFP=1.
Number of 10 cards = NSI.				
11	1-80	TITLE	Main/ 20A4	Initial input data for local collection efficiency calculations.
12	6-10	NCOEF	Main/I5	Number of coefficients of polynomial curve fit for calculating β. The order of the polynomial is NCOEF-1 (see Chapter III).
	21-25	NPTS	"	Number of data points used in curve fitting for computing local collection efficiency (see Chapter III).

TABLE A.1 (continued).

Card No.	Column	Code	Routine/ Format	Explanation
12	36-40	NS	Main/I5	=0, Segment curve fit data. =1, Total curve fit (see Chapter III).
13	1-80	TITLE	Main/ 20A4	Experimental values of local collection efficiency.
14	1-5	NASA	Main/I5	Number of experimental data points input for comparison with computed results.
15	1-10	SFOIL	Main/ F10.5	Surface distance, s/ℓ_c, along the airfoil at the location of the measured value of local collection efficiency.
	11-20	EFC	"	Experimental values of local collection efficiency at positions SFOIL.
16	1-80	XTITL	APLOT/ 20A4	Title of the x-axis.
17	1-80	YTITL	"	Title of the y-axis.
18	6-15	YHEIT	APLOT/ F10.0	Length of the y-axis for graph to be plotted (inches).
	21-30	YMAX	"	Highest value of datum point on y-axis (inches).
	36-45	XMIN	"	Far right value of datum point on x-axis (inches).
19	6-15	XLENG	"	Length of x-axis for graph to be plotted (inches).
	21-30	XMAX	"	Far left value of datum point on x-axis (inches).
	36-45	XMIN	"	Far right value of datum point on x-axis (inches).

Cards 11 through 19 are cycled NBDY times.

The input instructions for running the trajectory computer program are presented in the following and in Table A.1. The instructions are given in terms of an input card deck structure which compares directly with data tapes or files.

There are five input data files used in the trajectory program. They are described in the following:

1. Tape 05 stores the airfoil geometry data. This is the same file as the input file Tape 05 of the potential flow program [2].

2. Tape 21 stores the data for calculating the flow velocities. This is the same file as the output file Tape 21 of the potential flow program.

3. Tape 14, which is one of the output data files of the potential flow program, stores the coefficients for calculating the individual solutions.

4. Tape 15, which is one of the output data files of COMBIN-2D program, stores the coefficients for calculating the combination solution.

Tape 14 and Tape 15 must be input when LCMB=1 (see description of Card 2 in Table A.1).

5. Tape 02 stores the initial input data for the trajectory program. Details are described in the following. The data must be in MKS units with the exception of particle diameter, which is input as microns.

The input deck structure for the particle trajectory program is described below with detailed comments given in Table A.1.

Card No.	Description
1	Number of bodies; degree of governing equations
2	Flow field control flags
3	Trajectory control flags
4	Initial conditions of flow field

Card No.	Description
5, 6, 7, 8	Initial conditions of particles
9	Number of size increments
10 . . 10	This card is input only when NSI>1; number of 10 cards = NSI
11	TITLE of initial input data
12	Input for polynomial least square fit
13	TITLE of experimental data
14	Number of experimental data
15 . . 15	Number of 13 cards = NASA
16, 17, 18, 19	Input for plotting

For more than one body, Cards 11 through 19 are cycled NBDY times.

B. DESCRIPTION OF PROGRAM OUTPUT

The output files of the programs are divided into three categories: (1) output of the geometry generation program, (2) output of the two-dimensional potential flow program, and (3) output of the particle trajectory program. For the first two programs, only the output files related to the present particle trajectory program are described.

C. PROGRAM OUTPUT

1. Geometry Generation Program Output Description

The geometry generation program is named SCIRCL. The output data file Tape 17 of SCIRCL is used as the input data file Tape 05 of the two-dimensional potential flow program and of the particle trajectory program. Tape 17 stores the airfoil geometry data. In general, Tape 17 is the same for both the 24Y and the particle trajectory program; however, in some cases it is modified when used in the trajectory program as described in Reference 2 and Chapter IV. The format of Tape 05 is the same as the input data described in Reference 2.

2. Two-Dimensional Potential Flow Program Output Description

The output data file Tape 21 of the potential flow program is used as the input data file Tape 21 for the particle trajectory program. Tape 21 records all the necessary information including the source, sink, and/or vorticity distributions along the body surfaces for calculating the flow field about the bodies. Note that Tape 21 will not be generated by the two-dimensional potential flow program unless at least one value has been assigned to NRAKE during input to the SCIRCL program. Thus, file Tape 05 must contain one or more off-body points [2].

If LCMB=1 (see Table A.1, Card 2, page 93), then the output data file Tape 14 of the potential flow program is used as the input data file Tape 14 for the particle trajectory program. Data stored on Tape 14 are the coefficients for calculating the individual solutions.

The output data file Tape 07 of the 24Y program is used as the input data file Tape 07 for the COMBIN-2D program. Tape 07 records the coordinates and the corresponding individual solutions for on-body and off-body points.

3. COMBIN-2D Program Output

If LCMB=1 (see Table A.1, Card 2, page 93), then the output data file Tape 15 of the COMBIN-2D program is used as the input data file Tape 15 for the particle trajectory program. Data stored on Tape 15 are the coefficients for evaluating the combination solution.

4. Trajectory Program Output

A data file Tape 04 is generated if LOPT≠0 and contains the values of x, y, $\dot{x}$, $\dot{y}$, θ, and $\dot{\theta}$ for each time step of the particle trajectories. Values of the flow field velocities at the particle locations along the particle trajectory are also contained on this file.

Data file Tape 08 is also generated if LOPT≠0 and contains the particle locations along the computed trajectories for plotting purposes. The data stored on Tape 08 and Tape 04 are nondimensional. Because Tape 04 and Tape 08 are used to record the information at each time step, the program will need much more storage than that generally needed with the option LOPT=0. LOPT≠0 should be used only if a few particle trajectories are to be calculated.

Additionally, information on particle initial position, impingement limits, surface impingement point coordinates, and surface distance are recorded on data file Tape 06 for printout. The computed local collection efficiency, β, is also recorded on Tape 06. The value of β versus surface distance is recorded on Tape 09 for plotting purposes.

Tape 09 is unformatted. The format for Tape 06 will be explained in Chapter IV where test cases are documented. The format for Tape 04 and Tape 08 is illustrated in Table A.2 and Table A.3, respectively.

TABLE A.2. Format for Tape 04 (FORMAT(10E10.3)).

Column	Code	Explanation
1-10	X	Time
11-20	E1	x-coordinate of the particle, x/ℓ_c
21-30	E2	y-coordinate of the particle, y/ℓ_c
31-40	YLAST(5)	Pitch angle of the particle in radians
41-50	E3	x-component velocity of the particle
51-60	E4	y-component velocity of the particle
61-70	YLAST(6)	z-component angular velocity of the particle
71-80	E5	Velocity of the particle relative to the flow field
81-90	W1	x-component velocity of the flow field
91-100	W2	y-component velocity of the flow field

TABLE A.3. Format for Tape 08 (FORMAT(3F10.5)).

Column	Code	Explanation
1-10	XP	x-coordinate of the particle, x/ℓ_c
11-20	YPL	y-coordinate of the particle, x/ℓ_c
21-30	SW(IW)	The parameter is used to indicate the end of each trajectory, i.e., if SW≠88.8888 the trajectory is terminated.

APPENDIX B

PARTICLE TRAJECTORY COMPUTER PROGRAM CAPABILITIES AND FUNCTION DESCRIPTIONS

Details of the particle trajectory computer program are presented in this appendix. Each subroutine is described individually in Subchapter A. A list of FORTRAN variable names is given for each subroutine, and flowcharts are provided to illustrate the order of calculation. Error messages and typical corrective measures are given in Subchapter B, and approximate computational times for the test cases discussed in Chapter IV are given in Subchapter C.

A. MAIN PROGRAM AND SUBROUTINES

1. Main Program

Objective: The main program serves as an executive program for initialization and program control.

Variables: All input initial values of variables and control flags are described in Appendix A.

Y(1)	Value of x
Y(2)	Value of y
Y(3)	Value of $\dot{x}$
Y(4)	Value of $\dot{y}$
Y(5)	Value of θ
Y(6)	Value of $\dot{\theta}$
VINF	Free-stream velocity, W_∞
YP	y/ℓ_c coordinate of current particle location

YHIT	Initial y/ℓ_c coordinate of a particle which impacts body
YMIS	Initial y/ℓ_c coordinate of a particle which moves away from the body
SL	Lower surface impingement limit, s_L/ℓ_c
SU	Upper surface impingement limit, s_U/ℓ_c
ZL	Lower limit, $y_{o\ell}/\ell_c$, corresponding to SL
ZU	Upper limit, y_{ou}/ℓ_c, corresponding to SU

Flowchart: See Figure B.1.

2. Subroutine ADAMS

Objective: Use Adams-Moulton, variable time step, predictor-corrector method to solve the equations of particle motion.

Variables:

YPRED	Adams-Moulton predictor
YCORR	Adams-Moulton corrector
YLAST	Value of function y at previous time step
TSP	Initial time step increment
X	Time

Flowchart: See Figure B.2.

3. Subroutine RANGE

Objective: Locate an approximate range of y_o which contains the limits y_{ou} and $y_{o\ell}$.

Flowchart: See Figure B.3.

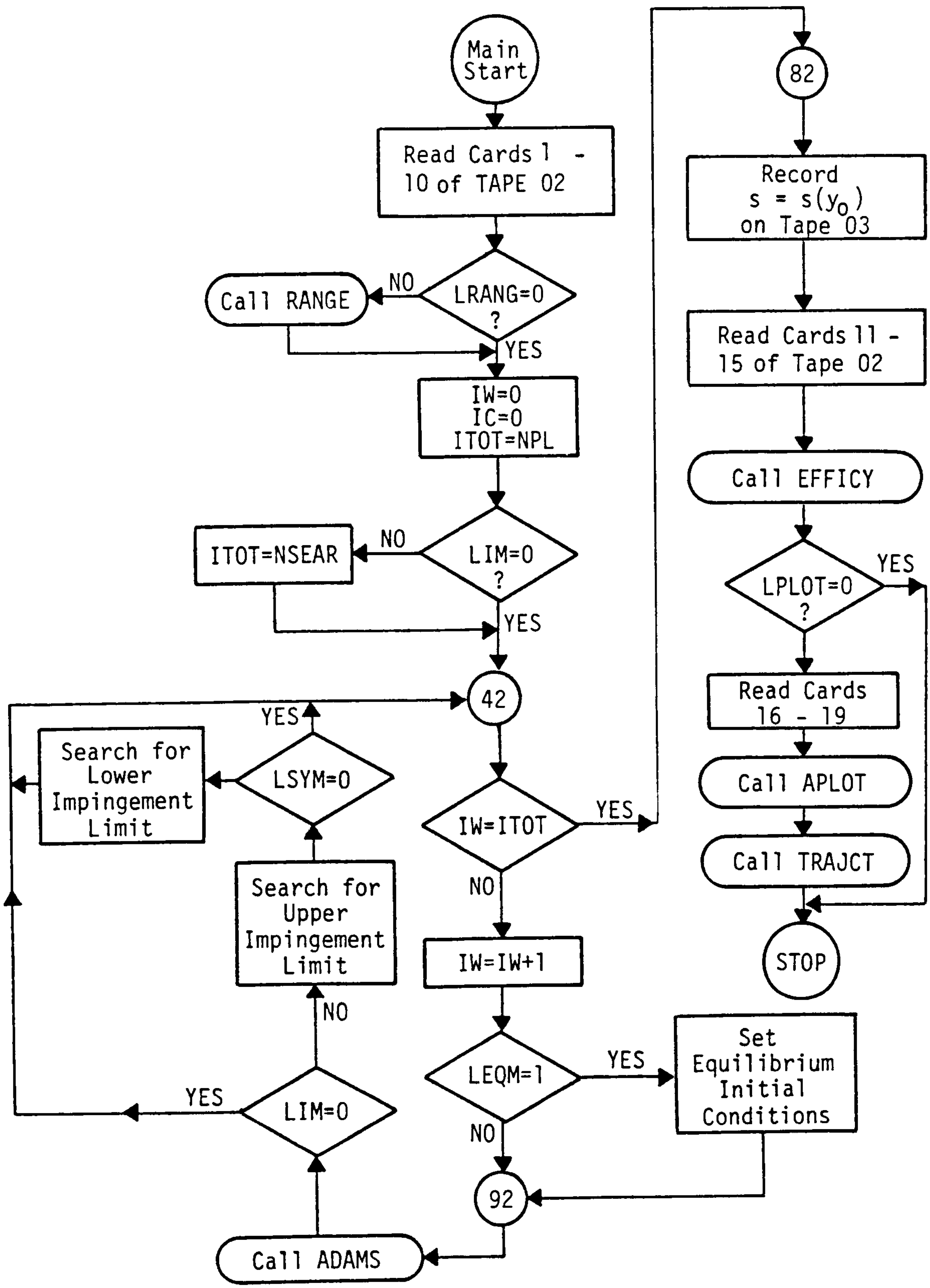


Figure B.1 Flowchart of main program.

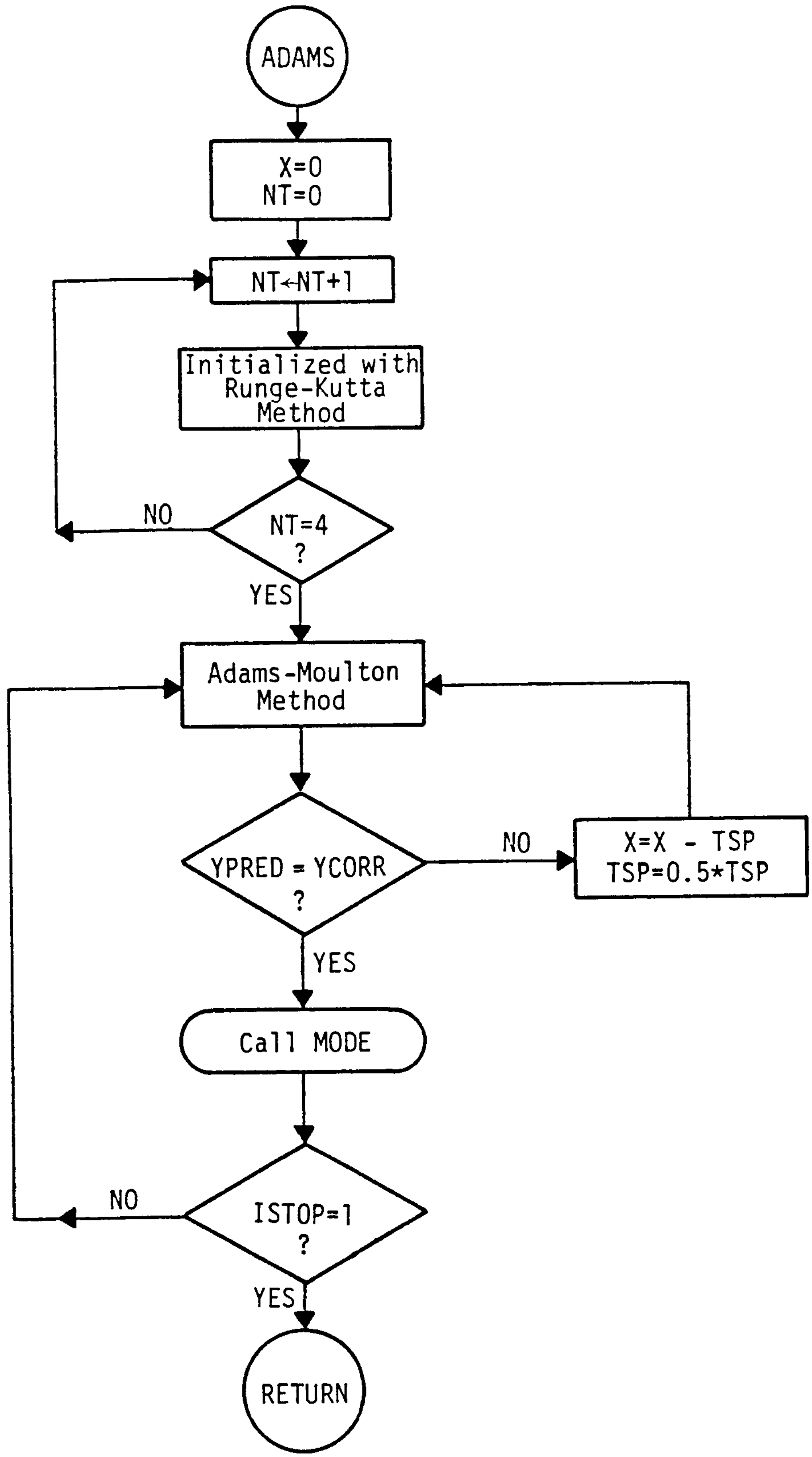


Figure B.2 Flowchart of subroutine ADAMS.

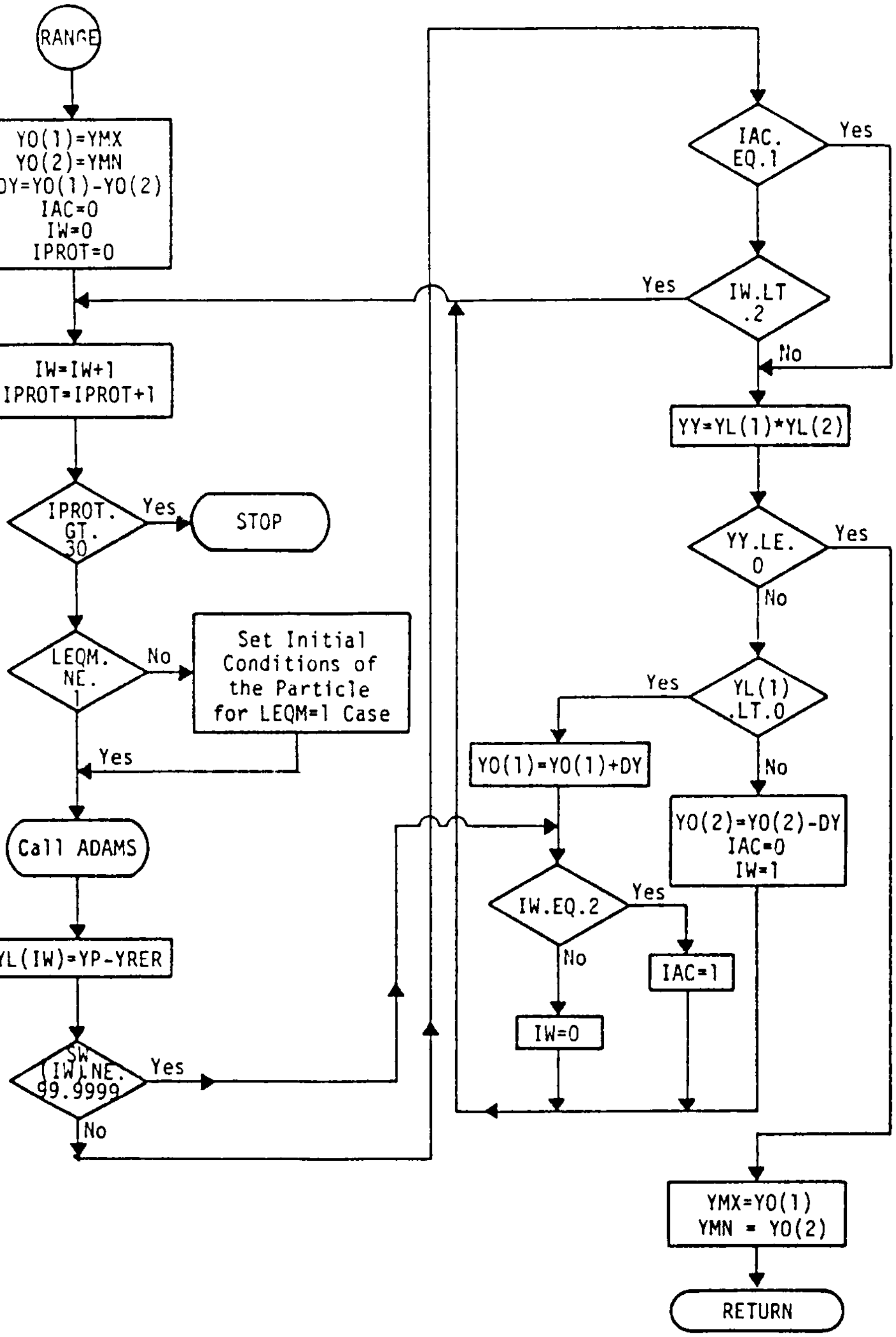


Figure B.3 Flowchart of subroutine RANGE.

4. Subroutine F

Objective: Supply functional form of equations governing the particle motion.

Variables:

T	Time
X	Values of the functions (correspond to Y in main program)
XDOT	Derivatives of x with respect to time (i.e., $\dot{x}$, $\dot{y}$, $\dot{\theta}$, $\ddot{x}$, $\ddot{y}$, $\ddot{\theta}$, see Chapter II)
CL	Coefficient of lift force
CD	Coefficient of drag force
CM	Coefficient of moment

5. Subroutine COEFF

Objective: Supply aerodynamic coefficients CL, CD, and CM.

6. Subroutine MODE

Objective: Determine whether the particle impacts the body. Also, terminate the trajectory calculation for particles which move away from the bodies.

Flowchart: See Figure B.4.

7. Subroutine READIN

Objective: Read geometry coordinates and flow field (Tape 05 and Tape 21).

Flowchart: See Figure B.5.

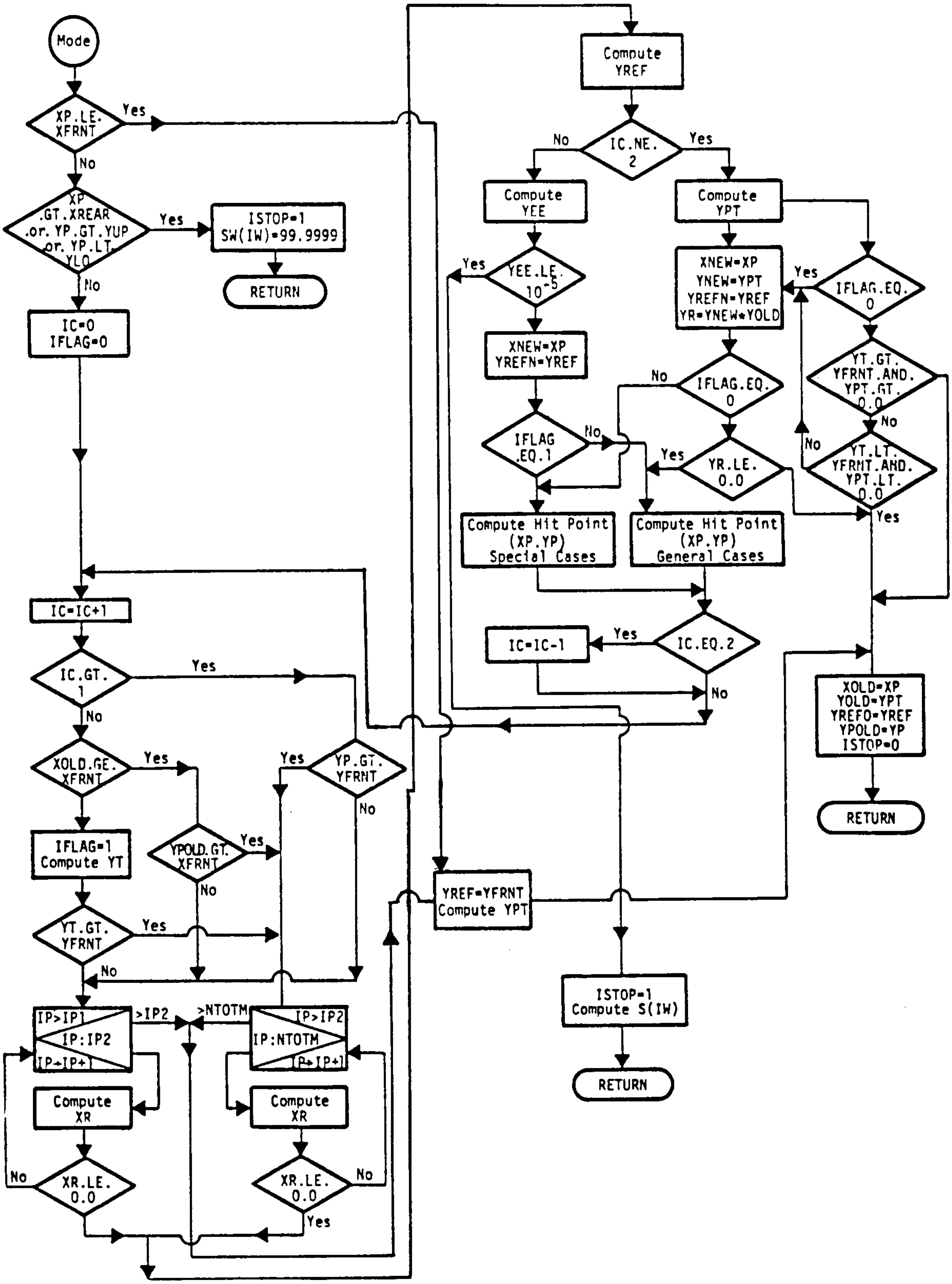


Figure B.4 Flowchart of subroutine MODE.

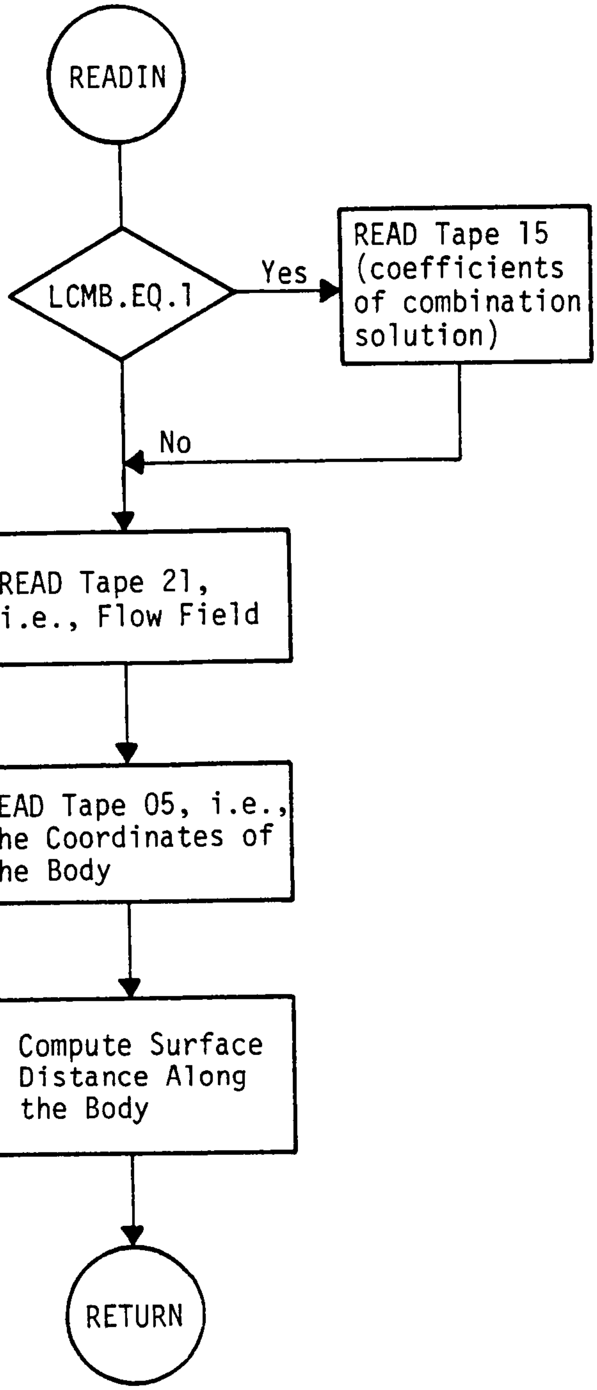


Figure B.5 Flowchart of subroutine READIN.

8. Subroutine VELCTY

Objective: Compute flow velocities for a given position (x,y).

Variables:

X Dimensionless x coordinate, x/ℓ_c, of particle position

Y Dimensionless y coordinate, y/ℓ_c, of particle position

VXC Dimensionless x component velocity, W_x/W_∞, of airflow

VYC Dimensionless y component velocity, W_y/W_∞, of airflow

Flowchart: See Figure B.6.

9. Subroutine COMB2D

Objective: Compute flow velocities which satisfy the initial conditions of free-stream velocity, angle of attack of free-stream, and the weight flow (or average axial velocity) through the control stations. Additionally, this subroutine calculates the compressibility correction.

Variables:

VX Dimensionless x component individual velocity of airflow

VY Dimensionless y component individual velocity of airflow

VXINC Dimensional x component combination velocity of airflow, ft/sec

VYINC Dimensional y component combination velocity of airflow, ft/sec

VXCOM Dimensional x component compressible combination velocity of airflow, ft/sec

VYCOM Dimensional y component compressible combination velocity of airflow, ft/sec

Flowchart: See Figure B.7.

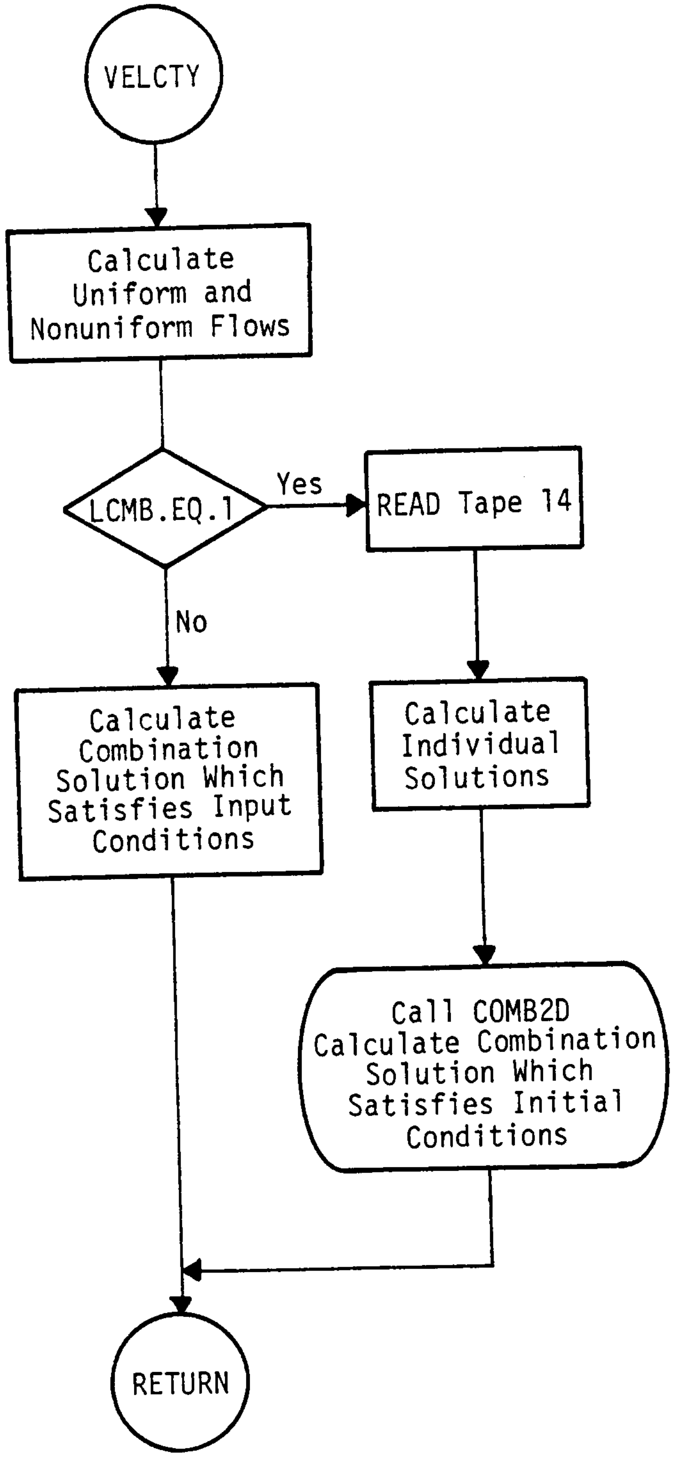


Figure B.6 Flowchart of subroutine VELCTY.

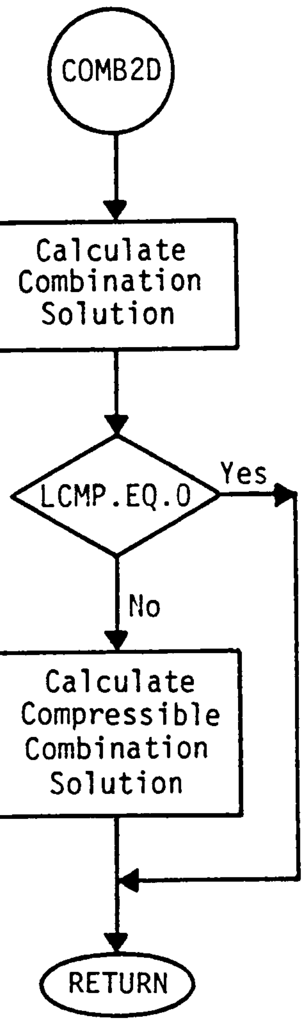


Figure B.7 Flowchart of subroutine COMB2D.

10. Subroutine EFFICY

Objective: Calculate the local collection efficiency, β, using both a linear approximation and a polynomial curve fit interpolation technique.

Variables:

NCOEF Number of coefficients for polynomial curve fit

NPTS Number of data points used for each curve fitting procedure

NS Do-loop index (see flowchart, Figure B.8)

YP Collection efficiency, $\beta = -dy_0/ds$

XIN Value of $s(y_0)$

Flowchart: See Figure B.8

11. Subroutine EF

Objective: Calculate the local collection efficiency, β, for multi-size particle distribution NSI>1 case using a polynomial curve fit interpolation technique.

12. Subroutine LINEAR

Objective: Compute the local collection efficiency by a linear approximation.

Variables:

X Value of s

Y Value of y_0

YP Local collection efficiency, $-dy_0/ds$

13. Subroutine TERP

Objective: Curve fit the $\{s, y_0\}$ data to a polynomial function.

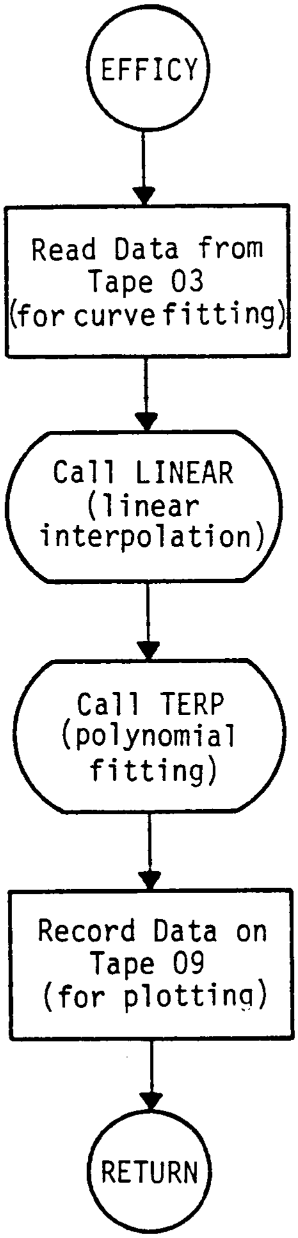


Figure B.8 Flowchart of subroutine EFFICY.

Variables:

XIN	x(s) coordinate at position (x,y)
YOUT	y(s) coordinate at (x,y) obtained by the polynomial data fit
YPOUT	Derivative of y with respect to x, dy/dx (dy_0/ds)
XA	Data set of x-coordinate
YA	Data set of y-coordinate
N1	Index of the first data point used for data fit
N2	Index of the last data point used for data fit
NCOEF	Number of coefficients in the polynomial function
NPTS	Number of data points used in each curve fit procedure

14. Subroutine CHOLES

Objective: Matrix solver called by subroutine TERP.

15. Subroutines APLOT and TRAJCT

Objective: Plot routines for β and for particle trajectories to be furnished by intended users.

B. ERROR MESSAGES

Table B.1 lists the error messages and recommended corrective actions to be taken for the computer program. The particular subroutine in which the error message occurs is also listed in the table. The table is essentially self descriptive and needs no further discussion.

TABLE B.1. Error Messages and Corrective Actions.

Error Message Generated by the Program	Problem and Corrective Action	Error Location
The number of y-coordinates read is not equal to the number of x-coordinates read.	Corrective Action: Check the input data file, Tape 05, for equal number of x- and y-coordinates.	Subroutine READIN
Time-halving loops exceed 100.	Problem: The Adams-Moulton method of solution is not converging to the desired accuracy at the current time step. The problem itself sets NLOOP=100. The value is large enough for all cases investigated in this report where TIMSTP is set equal to 10^{-4}. Corrective Action: 1) Reduce the magnitude of TIMSTP. 2) Increase the size of ADEPS. 3) Check for severe gradients or error in the flow field.	Subroutine ADAMS
IPORT.GE.31 in SUB.RANGE--program stopped.	Problem: Initially guessed values of YMAX and YMIN are too far from the body or ΔY = YMAX - YMIN is too small. Corrective Action: 1) If particles pass below the body, increase the input values of YMAX and YMIN. 2) If particles pass above the body, decrease the input values of YMAX and YMIN. 3) Increase magnitude of ΔY.	Subroutine RANGE

TABLE B.1 (continued).

Error Message Generated by the Program	Problem and Corrective Action	Error Location
FORMAT 172: Number of particle trajectories exceeds NSEAR, program stopped.	Problem: Number of particle trajectories which hit body exceeds the input value of NSEAR (Card 1 on Tape 02). Corrective Action: 1) Increase the input value of NSEAR. NSEAR=50 is recommended. 2) Increase the input value of YLIM (Card 5 on Tape 02). 3) Decrease the input value of NPL (Card 1 on Tape 02).	MAIN
FORMAT 747: Number of trajectories is more than 100, program stopped.	Problem: Number of trajectories calculated exceeds dimension state. Either the program is having difficulty finding limits or specified value of NPL is too large. Corrective Action: 1) Refer to the actions in error message #4. 2) Adjust input values of YMAX and YMIN (Card 7 on Tape 02--refer to error message #3).	MAIN
Particle released between the region ZL-ZU crosses upper or lower impingement limit trajectory, program stopped.	Corrective Action: Check the flow field around the body and increase absolute value of pseudo-surface DX (Card 2 on Tape 05).	MAIN

C. COMPUTER RUN TIMES

Table B.2 provides a listing of the approximate CPU time required to run various test cases reported in Chapter IV of this study. The values are approximate times for running on the NASA/LeRC IBM 370 computer.

TABLE B.2. Approximate CPU Time for the NASA/LeRC IBM 370 Computer.

Bodies Interested	Case Description	Elements	Maximum Storage	Approximate CPU Time (min)
Joukowski airfoil 0015	$\alpha = 0°$ without walls	185	256K	1
	$\alpha = 0°$ with walls	269	256K	1
	$\alpha = 4°$ without walls	185	256K	2
	$\alpha = 4°$ with walls	269	256K	3
	$\alpha = 8°$ without walls	185	256K	4
	$\alpha = 8°$ with walls	269	320K	5
NACA 65_A-004	$\alpha = 0°$ without walls	198	256K	3
	$\alpha = 0°$ with walls	284	256K	4
	$\alpha = 8°$ without walls	198	256K	9
	$\alpha = 8°$ with walls	284	256K	8
NACA 65_1-212	$\alpha = 0°$ without walls	275	320K	12
	$\alpha = 0°$ with walls	361	320K	12
	$\alpha = 4°$ without walls	275	320K	15
	$\alpha = 4°$ with walls	361	320K	15
Two-body inlet	$\alpha = 0°$	334	320K	10
	$\alpha = 30°$	334	320K	20

APPENDIX C

PARTICLE TRAJECTORY COMPUTER PROGRAM LISTING

```
      DIMENSION Y(6),XDOT(6),TITLE(20),XL(1000),YL(1000),N(10),
     1          CFP(10),EP(10)
C-----------------------------------------------------------------------
C--       PROGRAM FOR CALCULATING PARTICLE TRAJECTORIES.
C--       MKS UNITS ARE USED.
C--       THE INITIAL INPUT OF PARTICLE DIAMETER IS IN MICRONS WHICH
C--       IS THEN CONVERTED TO METER IN THE PROGRAM.
C--- INPUT DATA FILES :
C--    TAPE02  :  INITIAL INPUT OF THIS TRAJECTORY CODE
C--    TAPE05  :  AEROFOIL GEOMETRY,   THE SAME FILE TAPE05
C-               USED IN THE NASA POTENTIAL FLOW CODE
C--    TAPE21  :  THE SAME AS THE OUTPUT FILE TAPE21 OF NASA POTENTIAL
C-               FLOW CODE.   USED FOR AIR VELOCITY CALCULATIONS.
C--- OUTPUT DATA FILES :
C--    TAPE01  :  DATA STORED IN TPAE01 IS WRITTEN TO TAPE03 LATTER.
C-               TAPE01=TAPE03 FOR UNSYMMETRIC FLOW CASES
C--    TAPE03  :  DATA USED FOR THE CALCULATION OF COLLECTION EFFICIENCY
C--    TAPE04  :  CREATED IF (LOPT.NE.0) .   CONTAINS DETAILS OF THE
C-               TRAJECTORIES AS WELL AS INFORMATION OF WIND FIELD.
C--    TAPE08  :  CREATED IF(LOPT .NE. 0)
C-               DATA STORED IN TAPE08 IS FOR TRAJECTORY PLOTS.
C-               THE DATA STORED ARE   XP,YP AND SW WITH THE
C-               FORMAT(2X,3F10.5).       IF (SW.NE.88.8888) IMPLIES
C-               THE END OF EACH TRAJECTORY.
C-               XP, YP HAS BEEN NORMALIZED BY CHORD LENGTH.
C--    TAPE09  :  DATA FOR PLOTTING THE COLLECTION EFFICIENCY
C-----------------------------------------------------------------------
      COMMON/OBY/NTOT,XA(500),YA(500)
      COMMON/XTN/XFRNT,YFRNT,XRER,YRER,NTOTAL(5),NBDY,ID
      COMMON/XFR/XF(5),YF(5),XR(5),YR(5),THIK(5),YYMX(5),YYMN(5)
      COMMON/SDS/S(500),SW(100),ZO(100),IS
      COMMON/IN2/XIN,YIN,DPM,RL,VXREF,VYREF,PITDOT,ATK,PIT,VREF,VXP,VYP
      COMMON/F1/Q,CBAR,AMASS,G,YYI,ALFAB,VISCOS
      COMMON/MOD/LOPT,LEQM,XREAR,YLO,YUP
      COMMON/EXA/LCMB,LCMP,IHUB
      COMMON/IMM/IP1,IP2,NTOTM
      COMMON/FR1/IFRNT(5)
      COMMON/DPD1/NSI,PLWC(10),IRS(10),DPD(10),EPT
      COMMON/CDD/CF
      EXTERNAL F
C---- Y(1)=X, Y(2)=Z, Y(3)=X1DOT, Y(4)=Z1DOT, Y(5)=THET
C---- Y(6)=THETD
      REWIND 4
      REWIND 7
      REWIND 8
      DATA PI/3.141592654/
      READ(2,252) NBDY,NPL,NSEAR,NEQ,IHUB
C---- CONTROL FLAGS
      READ(2,252) LEQM,LSYM,LRANG,LCMB,LCMP
      CALL READIN
      READ(2,252) LIM,LOPT,LPLOT,LTNL,LXOR
C---- INITIAL CONDITIONS
      READ(2,254) G,VINF
      READ(2,254) DP,RL,TIMSTP,YLIM,CF
      READ(2,254) PRATK,PIT,PITDOT,XORC,YORC
      READ(2,254) XREAR,YYLO,YYUP,YMAX,YMIN
      READ(2,254) ADEPS,ANLFLO,ANLCRD,EPSX
      READ(2,252) NSI
      IF(NSI.EQ.1)GO TO 2
      DO 3 I=1,NSI
      READ(2,221) PLWC(I),DPD(I),CFP(I)
    3 CONTINUE
    2 BDYATK=ANLFLO
      ANN=BDYATK+ANLCRD
      PEI=PI/180.
      BDYATK=BDYATK*PEI
      ANLCRD=ANLCRD*PEI
      ANLFLO=ANLFLO*PEI
      ADE=ADEPS
      ADEPS=VINF*ADEPS
      VXREF=VINF*COS(ANLFLO)
      VYREF=VINF*SIN(ANLFLO)
      LIMA=LIM
      VREF=SQRT(VXREF*VXREF+VYREF*VYREF)
      VXP=VXREF
      VYP=VYREF
      IF(NBDY.EQ.0)NBDY=1
      IF(ID.EQ.0)ID=1
      YMAX=YMAX*RL
      YMIN=YMIN*RL
      ATK=PRATK
      NSEA=NSEAR
C---- SEARCH THE PROPER X-LOCATION TO RELEASE PARTICALS
      IF(LXOR.EQ.0) GO TO 14
      NMAX=50
      XFRNT=XF(1)
      XIN=XFRNT-0.2
      EPS=EPSX
      DY=(YYUP-YYLO)/10.
      IC=0
```

```
134 CONTINUE
    NC=NC+1
    DWX=0.
    XIN=XIN-0.2
    DO 131 I=1,11
    YP=YYLO+FLOAT(I-1)*DY
    CALL VELCTY(XIN,YP,W1,W2)
    VT=SQRT(W1*W1+W2*W2)
    DW=ABS(1.0-VT)
    IF(DW.GT.DWX) DWX=DW
131 CONTINUE
    IF(NC.GE.NMAX) GO TO 135
    IF(DWX.GT.EPS) GO TO 134
135 WRITE(6,133) XIN,NC,NMAX
    XIN=XIN*RL
    GO TO 15
 14 XIN=XORC*RL
 15 CONTINUE
C---- FINISH SEARCHING
    PEI=PI/180.
    DPM=DP*1.0E-06
    AREA=0.25*PI*DPM*DPM
    RHOP=1.0E03
    AMASS=PI*DPM**3*RHOP/6.0
    YYI=0.4*AMASS*(DPM/2.)**2
    CBAR=DPM
    RHO=1.23
    Q=0.5*RHO*AREA
    VISCOS=1.5E-05
    WRITE(6,439)DPM,RL,TIMSTP,NPL,VXREF,VYREF,ANK,PIT,PITDOT,G,
   1YYI,ADE
    NBY=NBDY
    IF(LTNL.EQ.0) GO TO 954
    NBY=1
    ANLCRD=0.0
954 CONTINUE
    DO 94 IDK=1,NBY
    REWIND 3
    REWIND 9
    ID=IDK
    IF(LTNL .EQ. 1) ID=1
    H=TIMSTP
    XFRNT=XF(ID)
    YFRNT=YF(ID)
    XRER=XR(ID)
    IF(XREAR .GT. XRER) XREAR=XRER
    IP1=1
    NTOTM=NTOTAL(IDK)
    IF(IDK .NE. 1) IP1=NTOTAL(IDK-1)+1
    IP2=IFRNT(IDK)
    YRER=YR(ID)
    THICK=THIK(ID)
    YUP=YYMX(ID)+0.1*THIK(ID)
    YLO=YYMN(ID)-0.1*THIK(ID)
    AO=ABS(ANLFLO)
    YPDW=ABS(YR(ID)-YF(ID))
    IF(AO.GT.0.000001) THICK=YPDW+(XR(ID)-XF(ID))*TAN(BDYATK)
    WRITE(6,271)
    WRITE(6,272)NBDY,ID,XFRNT,YFRNT,XRER,YRER,THICK,YUP,YLO
    IF(ID.EQ.1) GO TO 97
    YMIN=-ZU*RL-0.002
    YMAX=-ZL*RL+0.002
 97 CONTINUE
    DO 211 IJK=1,NSI
    LIM=LIMA
    IS=0
    REWIND 1
    IF(NSI.EQ.1) GO TO 4
    WRITE(6,437) IJK
    DPM=DPD(IJK)*DP
    CF=CFP(IJK)
    DPM=DPM*1.0E-06
    AREA=0.25*PI*DPM*DPM
    AMASS=PI*DPM**3*RHOP/6.0
    YYI=0.4*AMASS*(DPM/2.)**2
    CBAR=DPM
    Q=0.5*RHO*AREA
    WRITE(6,438)DPD(IJK),PLWC(IJK),DPM,YYI
  4 CONTINUE
    IF(LEQM .EQ.1)WRITE(6,186)
    WRITE(6,433)
C---- COMPUTATION OF DROPLET TRAJECTORIES
C---- IF LIM=1 SEARCH THE SURFACE RANGE WHERE THE PARTICLES IMPACT AT
    IF(LRANG.NE.0) CALL RANGE(YMAX,YMIN,TIMSTP,ADEPS,NEQ)
    IW=0
    IUP=2
    YHIT=YMIN
    YMIS=YMAX
    IC=0
    ID1=100
    NSEAR=NSEA
    NTOT=NSEAR
    NFROT=0
    IF(LIM.EQ.1) GO TO 41
    NTOT=NPL*2
```

```
      ITO1=NPL
      IW=NPL
      ZU=YYUP
      ZL=YYLO
      YUP=YYUP
      YLO=YYLO
   41 IUP=IUP-1
C---- IUP=1 SEARCHING UPPER LIMIT
C---- IUP=0 SEARCHING LOWER LIMIT
   42 CONTINUE
      TSP=TIMSTP
      IF(LIM .EQ. 0) GO TO 47
      IF(SW(IW).EQ.99.9999)IW=IW-1
      IF(ABS(YMIS-YHIT) .LE. YLIM) GO TO 75
      YIN=(YHIT+YMIS)/2.
      GO TO 48
   47 IF(NPL .NE. 1) GO TO 85
      YIN=YORC*RL
      GO TO 46
   85 AC=1.0
      DY=ZU-ZL
      IF(LSYM.EQ.1) DY=ZU
      DY=AC*DY/FLOAT(NPL-1)
      YIN=AC*ZU-DY*(IW-ITO1)
      YIN=YIN*RL
   46 IF(IW .EQ. ITOT) GO TO 82
   48 IW=IW+1
      IPROT=IPROT+1
      IF(IPROT.GT.100) GO TO 743
      IF(IW.EQ.1) YAD=YIN
      IF(IW.LE.NSEAR) GO TO 80
      WRITE(6,172)
      GO TO 236
C---- INITIALLY SW(I)=88.8888
C---- SW(I)=SURFACE DISTANCE IF PARTICLE HIT THE BODY
C---- SW(I)=99.9999 IF PARTICLE MOVES OUT OF RANGE
   80 SW(IW)=88.8888
      Y(1)=XIN
      Y(2)=YIN
      Y(3)=VXP
      Y(4)=VYP
      Y(5)=PIT*PEI
      Y(6)=PITDOT*PEI
      IF(LEQM.NE.1) GO TO 92
C---- SET INITIAL CONDITIONS OF THE CASE FOR WHICH THE PARTICLE
C----    IS EQUILIBRIUM IN THE AIR STREAM
      X=XIN/RL
      YP=YIN/RL
      CALL VELCTY(X,YP,WX,WY)
      Y(5)=ATAN(WY/WX)
      Y(3)=WX*VREF
      Y(4)=WY*VREF
      Y(6)=0.
   92 CONTINUE
      ALFAB=ATN*PEI
      CALL ADAMS(Y,XDOT,TIMSTP,ADEPS,IW,YP,NEQ)
      IF (IW.GT.ITO1.AND.SW(IW).EQ.99.9999) GO TO 798
      IF(LIM .EQ. 0) GO TO 42
C---- SEARCHING SURFACE LIMITS
      IF(SW(IW) .EQ. 99.9999) GO TO 72
      YHIT=YIN
      GO TO 42
   72 IF(IW .EQ. 1) GO TO 73
      YMIS=YIN
      GO TO 42
   73 IW=0
      IUP=2
      IF(YP.GT.YFRNT.OR.YP.GT.YRER) GO TO 787
      YHIT=YIN
      GO TO 41
  787 CONTINUE
      YMIS=YIN
      GO TO 41
  798 WRITE(6,793)
      GO TO 236
C---- UPPER LIMIT OR LOWER LIMIT IS FOUND
   75 IC=IC+1
      IF(IC .EQ. 1) GO TO 76
      SL=SW(IW)
      ZL=ZO(IW)
      GO TO 78
   76 CONTINUE
      SU=SW(IW)
      ZU=ZO(IW)
      YMIS=YMIN
      YHIT=YAD
      IF(LSYM.EQ.1) GO TO 79
      GO TO 41
   79 WRITE(6,101)
      SL=-SU
      ZL=-ZU
   78 WRITE(6,321) ZU,SU,ZL,SL
      ITO1=IW
C---- END OF LIMIT SEARCH
C---- TOTAL COLLECTION EFFICIENCY
      IF(THICK.EQ.0) GO TO 99
      E=(ZU-ZL)/THICK
```

```
      IF(NSI.GT. 1) EP(IJK)=E
      IF(NSI .GT. 1) WRITE(6,310)DPM,E
      IF(NSI.GT.1) GO TO 214
      WRITE(6,309) E
  214 CONTINUE
      WRITE(6,433)
      IF(NPL.EQ.0) GO TO 236
      LIM=0
      ITOT=IW+NPL
      NSEAR=ITOT
      ZU=ZU-0.00001
      ZL=ZL+0.00001
      GO TO 42
   32 CONTINUE
      IF(NPL.EQ.1) GO TO 19
      IA=0
      IST=1
  586 ZMAX=ZO(IST)
      IMX=IST
      I1=IST+1
      DO 575 I=I1,ITOT
      ABZ=ABS(ZO(I))
      IF(ABZ.LE.0.0000001) ZO(I)=0.0
      IF(ZO(I).LE.ZMAX) GO TO 575
      IMX=I
      ZMAX=ZO(I)
  575 CONTINUE
      IF(IST .EQ. 1) GO TO 551
      IF(ZO(IMX) .EQ. ZO(IST-1)) GO TO 552
  551 IF(SW(IMX) .GE. 99.9999) GO TO 552
      IF(LSYM.NE.1.AND.ZO(IMX).EQ.0.0) GO TO 552
      IA=IA+1
      WRITE(1) SW(IMX),ZO(IMX)
  552 ZDUM=ZO(IMX)
      SDUM=SW(IMX)
      ZO(IMX)=ZO(IST)
      SW(IMX)=SW(IST)
      ZO(IST)=ZDUM
      SW(IST)=SDUM
      IST=IST+1
      IF(IST .LE. ITOT) GO TO 586
      REWIND 1
      DO 232 I=1,IA
      READ(1) SW(I),ZO(I)
  232 CONTINUE
      IS=IA
      IF(LSYM.EQ.1) IS=IA*2-1
      WRITE(3) IS
      DO 234 I=1,IA
      WRITE(3) SW(I),ZO(I)
  234 CONTINUE
      IRS(IJK)=IS
      IF(IA.EQ.IS) GO TO 211
      IA=IA-1
      DO 233 I=1,IA
      J=IA-I+1
      SWA--SW(J)
      ZOA=-ZO(J)
      WRITE(3) SWA,ZOA
  233 CONTINUE
  211 CONTINUE
      EPT=0.0
      IF(NSI .EQ. 1) GO TO 212
      DO 213 IK=1,NSI
      EPT=EPT+EP(IK)*PLWC(IK)
  213 CONTINUE
C---- CALCULATION OF LOCAL CATCH EFFICIENCY
  212 READ(2,120) (TITLE(I),I=1,20)
      READ(2,252) NCOEF,NPTS,NS
C---- READ NASA/LEWIS DATA WHICH IS THEN STORED IN TAPE09
      READ(2,120) (TITLE(I),I=1,20)
      READ(2,220) NASA
      WRITE(9) NASA
      DO 17 I=1,NASA
      READ(2,221)SFOIL,EFC
      WRITE(9) SFOIL,EFC
   17 CONTINUE
      CALL EFFICY(NCOEF,NPTS,NS)
   19 IF(LPLOT.EQ.0) GO TO 94
      IF(NPL .EQ. 1) GO TO 18
C---- DATA PLOTING
C---- LOCAL CATCH EFFICIENCY
      LDP=0
      REWIND 9
      NA=0
      NSET=2
      DO 11 K=1,NSET
      READ(9) NX
      N(K)=NX
      IN=NA+1
      NA=NA+NX
      DO 1 I=IN,NA
    1 READ(9) XL(I),YL(I)
   11 CONTINUE
      CALL APLOT(XL,YL,N,NSET,LDP,FC,CZ)
```

```
C---- AIRFOIL GEOMETRY
   18 CONTINUE
      LDP=0
      IF(IDK.GT.1) LDP=1
      N(1)=NTOT
      CALL APLOT(XA,YA,N,1,LDP,FC,CZ)
C---- TRAJECTORIES AND AIRFOIL GEOMETRY
      CALL TRAJCT
   94 CONTINUE
      GO TO 236
   99 WRITE(6,861)
      GO TO 236
  743 WRITE(6,747)
C---- FORMATS
  101 FORMAT(/,2X,'SYMMETRIC FLOW CASE IS COMPUTED',/)
  120 FORMAT(20A4)
  133 FORMAT(/,2X,'THE PARTICLES ARE RELEASED FROM X/RL=',1PE12.5,/,
     1    2X,'WHICH IS OBTAINED AT THE',I5,' LOOP OF',I5,' LOOPS')
  172 FORMAT(/,2X,'FORMAT 172:NO. OF PARTICLE TRAJECTORIES EXCEED
     1 NSEAR, PROGRAM STOPPED ')
  186 FORMAT(/,2X,'INITIAL CONDITIONS FOR THE CASE LEGM=1',/)
  220 FORMAT(I5)
  221 FORMAT(3F10.5)
  252 FORMAT(5(5X,I5,5X),I1)
  254 FORMAT(5(5X,F10.0))
  271 FORMAT(/,2X,'NBDY',' ID',12X,'XFRNT',10X,'YFRNT',10X,'XREAR',10X,
     1    'YREAR',10X,'THICK',10X,'YUPPP',10X,'YLOOO')
  272 FORMAT(2X,2I4,6X,7(3X,1PE12.5),/)
  309 FORMAT(//,2X,'TOTAL COLLECTION EFFICIENCY',3X,1PE12.5,/)
  310 FORMAT(/,2X,'TOTAL COLLECTION EFFICIENCY FOR THE DROPLET SIZE='
     1        ,E10.3,'  IS  ',E12.5,/)
  321 FORMAT(/,6X,'UPPER SURFACE LIMIT',9X,'LOWER SURFACE LIMIT',/,
     19X,'ZU',12X,'SU',12X,'ZL',12X,'SL',/,2X,4(E12.4,2X),/,2X)
  433 FORMAT(8X,'XO',8X,'YO',23X,'XP',8X,'YP',8X,'SD',8X,'DT',
     1     10X,'NSTP')
  437 FORMAT(///,1X,'***FOLLOWING OUTPUT IS FOR DROPLET SIZE
     1 DISTRIBUTION-- ',I3,/)
  438 FORMAT(/,2X,'DIAMETER',4X,'PERCENTAGE',4X,'PARTICLE',4X,'INERTIA',
     1       /,2X,'DISTRIBUT.',2X,'OF W. CONT.',3X,'DIAMETER',4X,
     2        'MOMENT',//,2X,4(1PE10.3,3X),/)
  439 FORMAT(/,2X,'PARTICLE',4X,'CHORD',5X,'TIME',5X,'NO. OF',5X,'VX',
     1       8X,'VY',8X,'ANGLE',5X,'PITCH',5X,'PIT',7X,'GRAVT',5X,
     2        'INERT.',4X,'ADAMS',/,2X,'DIAMETER',4X,'LENGTH',4X,
     3       'STEP',5X,'DROPLET',4X,'REF.',6X,'REF.',5X,'OF ATK.',4X,
     4        'ANGLE',5X,'DOT',5X,'CONSTANT',4X,'MOMENT',2X,'CRITERIA',
     5        //,3(1PE9.2,1X),I9,1X,8(1PE9.2,1X),/)
  747 FORMAT(/,'FORMAT 747: NO. OF TRAJECTORIES IS MORE THAN
     1 100, PROGRAM STOPPED')
  764 FORMAT(/,2X,'DATA STORED IN TAPE',I3,2X,'NO. OF DATA',I5,/
     1     ,6X,'S/RL',5X,'YO/RL')
  793 FORMAT(/,2X,'PARTICLE RELEASED BETWEEN THE REGION ZL--ZU
     1 CROSSES UPPER OR LOWER IMPINGEMENT LIMIT TRAJECTORY,
     2 PROGRAM STOPPED')
  861 FORMAT(/,2X,'THICK=0.0--PROGRAM STOPED')
  236 STOP
      END
      SUBROUTINE ADAMS(YLAST,YD1,TSP,EPS,IW,YPL,NEQ)
C---------------------------------------------------------------------
C--      EQUARTION SOLVER
C--      THE ADAMS-MOULTON PREDICTOR-CORRECTOR METHOD IS USED
C---------------------------------------------------------------------
      DIMENSION YD1(6),YLAST(6),YPRED(6),YCORR(6),YP(4,6),XPA(6),YPA(6)
      DIMENSION A1(6),A2(6),A3(6),A4(6)
      COMMON/XTN/XFRNT,YFRNT,XRER,YRER,NTOTAL(5),NBDY,ID
      COMMON/IN2/XIN,YIN,DP,RL,VXREF,VYREF,PITDOT,ATK,PIT,VREF,VXP,VYP
      COMMON/SDS/S(500),SW(100),ZO(100),IS
      COMMON/MOD/LOPT,LEQM,XREAR,YLO,YUP
C---- IW,YPL, AND ALL THE COMMONS ARE USED EITHER
C---- FOR PROGRAM STOP CONTROL OR FOR OPTIONAL PRINTS  .
C---- LOOP FORM TIMESTEP TO START USING SIMPLE RUNGE-KUTTA METHOD
      H=TSP
      X=0.
      ISTOP=0
      MLOOP=100
      DX=TSP
      D24=DX/24.0
      DO 11 NT=1,4
      X1=X
      DO 1 J=1,NEQ
      YPRED(J)=YLAST(J)
    1 YCORR(J)=YPRED(J)
      CALL F(X1,YCORR,YD1)
      DO 2 J=1,NEQ
      A1(J)=H*YD1(J)
    2 YCORR(J)=YPRED(J)+A1(J)/2.
      X1=X1+H/2.
      CALL F(X1,YCORR,YD1)
      DO 3 J=1,NEQ
      A2(J)=H*YD1(J)
    3 YCORR(J)=YPRED(J)+A2(J)/2.
      CALL F(X1,YCORR,YD1)
      DO 4 J=1,NEQ
      A3(J)=H*YD1(J)
    4 YCORR(J)=YPRED(J)+A3(J)
      X1=X1+H/2.
```

```
      CALL F(X1,YCORR,YD1)
      DO 5 J=1,NEQ
      A4(J)=H*YD1(J)
    5 YLAST(J)=YLAST(J)+(A1(J)+2.*(A2(J)+A3(J))+A4(J))/6.
      X=X1
      DO 11 NV=1,NEQ
   11 YP(NT,NV)=YD1(NV)
      NSTF=0
   20 CONTINUE
      DO 50 ILOOF=1,NLOOF
      X=X+DX
      NSTF=NSTF+1
C---- SIMPLE ADAMS FREDICTION
      DO 30 NV=1,NEQ
   30 YFRED(NV)=YLAST(NV)+H024*(55.0*YP(4,NV)-59.0*YP(3,NV)
     1+37.0*YP(2,NV)-9.0*YP(1,NV))
      XFR=YFRED(1)/RL
      YFL=YFRED(2)/RL
      IF(XFR .LT. XFRNT) GO TO 111
      CALL MODE(XFR,YFL,ISTOF,IW,DX,NSTF)
      IF(ISTOF .NE. 0) GO TO 52
  111 CALL F(X,YFRED,YD1)
C---- BASFORD CORRECTION
      DLYMAX=0.0
      DO 31 NV=1,NEQ
      YCORR(NV)=YLAST(NV)+H024*(9.0*YD1(NV)+19.0*YP(4,NV)
     1-5.0*YP(3,NV)+YP(2,NV))
      IF(NV.NE.3.AND.NV.NE.4) GO TO 31
      DLYMAX=DLYMAX+ABS((YFRED(NV)-YCORR(NV))/YLAST(NV))
   31 CONTINUE
      IF(ABS(DLYMAX) .LE. EFS) GO TO 32
C---- HALVE DX
      DO 42 NV=1,NEQ
      DO 41 I=1,4
      XFA(I)=FLOAT(I)
   41 YFA(I)=YP(I,NV)
      YP(2,NV)=YP(3,NV)
      CALL TERP(2.5,YP1,YPPD,XFA,YFA,1,4,3,4)
      YP(1,NV)=YP1
      CALL TERP(3.5,YP3,YPPD,XFA,YFA,1,4,3,4)
      YP(3,NV)=YP3
   42 CONTINUE
      NSTF=NSTF-1
      X=X-DX
      DX=0.50*DX
      H024=DX/24.0
      GO TO 50
C---- SHIFT VARAIABLE FOR NEXT STEF
   32 CONTINUE
      DO 35 NV=1,NEQ
      YP(1,NV)=YP(2,NV)
      YP(2,NV)=YP(3,NV)
      YP(3,NV)=YP(4,NV)
      YP(4,NV)=YD1(NV)
   35 YLAST(NV)=YCORR(NV)
C---- PROGRAM STOF CONTROL AND OFTIONAL FRINT CONTROL
      XF=YLAST(1)/RL
      YFL=YLAST(2)/RL
      CALL MODE(XF,YFL,ISTOF,IW,DX,NSTF)
      IF(ISTOF.NE.0) GO TO 52
      IF(LOFT.EQ.0) GO TO 94
      WRITE(8,117) XF,YFL,SW(IW)
  117 FORMAT(3F10.5)
      CALL VELCTY (XF,YFL,W1,W2)
      WX=-W1*VREF
      WZ=-W2*VREF
      V=((YLAST(3)+WX)**2.0+(YLAST(4)+WZ)**2.0)**0.5
      ALFA=ATAN((-WZ-YLAST(4))/(WX+YLAST(3)))+YLAST(5)
      E1=YLAST(1)/RL
      E2=YLAST(2)/RL
      E3=YLAST(3)/VREF
      E4=YLAST(4)/VREF
      E5=V/VREF
      WRITE(4,105)X,E1,E2,YLAST(5),E3,E4,YLAST(6),E5,W1,W2
  105 FORMAT(10E10.3)
   94 CONTINUE
C---- *******    END OF STOF CONTROL     *********
      GO TO 20
   50 CONTINUE
      WRITE(6,100)
      STOP
  100 FORMAT(6X,'TIME-HALVING LOOFS EXCEED 100')
   52 RETURN
      END
      SUBROUTINE RANGE(YMX,YMN,TIMSTF,ADEFS,NEQ)
C-----------------------------------------------------------------------
C--   SEARCH THE UFSTREAM Y-RANGE SUCH THAT NONE OF THE FARTICLES
C--    OUTSIDE THE RANGE WILL HIT THE AIRFOIL.
C-----------------------------------------------------------------------
       DIMENSION YO(2),YL(2),Y(6),XDOT(6)
       COMMON/IN2/XIN,YIN,DF,RL,VXREF,VYREF,FITINT,ATK,FIT,VREF,VXF,VYF
       COMMON/XTN/XFRNT,YFRNT,XRER,YRER,NTOTAL(5),NBDY,ID
       COMMON/SDS/S(500),SW(100),ZO(100),IS
       COMMON/MOD/LOFT,LEQM,XREAR,YLO,YUF
       FI=3.14159254/180.
```

```
      YO(1)=YMX
      YO(2)=YMN
      IAC=0
      DY=1.0*(YO(1)-YO(2))
      IW=0
      IPROT=0
    1 ISTOP=0
      IW=IW+1
      IPROT=IPROT+1
      IF(IPROT.GT.30) GO TO 33
      SW(IW)=88.8888
      YIN=YO(IW)
      Y(1)=XIN
      Y(2)=YIN
      Y(3)=VXP
      Y(4)=VYP
      Y(5)=PIT*PI
      Y(6)=PITDOT*PI
      IF(LEQM.NE.1) GO TO 92
C---- SET INITIAL CONDITIONS OF THE CASE FOR WHICH THE PARTICLE
C---- IS EQUILIBRIUM IN THE AIR STREAM
      XINN=XIN/RL
      YINN=YIN/RL
      CALL VELCTY(XINN,YINN,WX,WY)
      Y(5)=TAN(WY/WX)
      Y(3)=WX*VREF
      Y(4)=WY*VREF
      Y(6)=0.
   92 CONTINUE
      YKL=YO(2)/RL
      YKU=YO(1)/RL
      IF(YKU.GT.YUP) YUP=YKU
      IF(YLO.GT.YKL) YLO=YKL
      CALL ADAMS(Y,XDOT,TIMSTP,ADEPS,IW,YP,NEQ)
      YL(IW)=YP-YRER
      IF(SW(IW).NE.99.9999) GO TO 10
      IF(IAC.EQ.1) GO TO 29
      IF(IW.LT.2) GO TO 1
   29 YY=YL(1)*YL(2)
      IF(YY.LE.0.0) GO TO 13
      IF(YL(1).LT.0.0) GO TO 11
      GO TO 12
   10 IF(IW.EQ.2) GO TO 12
   11 YO(1)=YO(1)+DY
      IF(IW.EQ.2) IAC=1
      IW=0
      GO TO 1
   12 YO(2)=YO(2)-DY
      IAC=0
      IW=1
      GO TO 1
   13 YMX=YO(1)
      YMN=YO(2)
      YO(1)=YO(1)/RL
      YO(2)=YO(2)/RL
      WRITE(6,21) YO(1),YO(2)
      GO TO 34
   33 WRITE(6,24)
      STOP
   21 FORMAT(/,2X,'YMAX=',1PE12.4,3X,'YMIN=',1PE12.4)
   24 FORMAT(//,'IPROT .GE. 31 IN SUB.RANGE - PROGRAM STOPPED')
   34 RETURN
      END
      SUBROUTINE F(T,X,XDOT)
C-----------------------------------------------------------------------
C--   GOVERNING EQUATIONS OF THE PARTICLE MOTION
C-----------------------------------------------------------------------
      DIMENSION X(6),XDOT(6)
      COMMON/IN2/XIN,YIN,DP,RL,VXREF,VYREF,PITDOT,ATK,PIT,VREF,VXP,VYP
      COMMON/F1/Q,CBAR,AMASS,G,YYI,ALFAB,VISCOS
      COMMON/CDD/CF
C---- XDOT(1)=X1DOT, XDOT(2)=Z1DOT, XDOT(3)=X2DOT
C---- XDOT(4)=Z2DOT, XDOT(5)=THETD, XDOT(6)=TH2DOT
      PI=3.141592654
      XP=X(1)/RL
      YP=X(2)/RL
      CALL VELCTY (XP,YP,W1,W2)
      WX=-VREF*W1
      WZ=-VREF*W2
      VX=X(3)+WX
      VY=X(4)+WZ
      V=SQRT(VX*VX+VY*VY)
      RE=V*DP/VISCOS
      CALL COEFF(RE,CD,CL,CM)
      CD=CD/CF
      IF(CL .EQ. 0.0 .AND. CM.EQ.0.0) GO TO 20
      IF(VX.EQ.0.) GO TO 17
      GAMMA=ATAN(VY/VX)
      IF(VX.LT.0.) GAMMA=GAMMA+PI
      IF(VX.GT.0.0.AND.VY.LT.0.0) GAMMA=GAMMA+2.*PI
      GO TO 19
   17 GAMMA=0.5*PI
      IF(VY.LT.0.) GAMMA=1.5*PI
   19 CONTINUE
      ALFA=X(5)-GAMMA
      ALFAD=ALFA-ALFAB
      ALFAB=ALFA
      AL=Q*V*V*CL
      AD=Q*V*V*CD
```

```
      AM=Q*V*V*CM*CBAR
      XDOT(1)=X(3)
      XDOT(2)=X(4)
      XDOT(5)=X(6)
      CGAMMA=COS(GAMMA)
      SGAMMA=SIN(GAMMA)
      XDOT(3)=-(AL/AMASS)*SGAMMA-(AD/AMASS)*CGAMMA
      XDOT(4)=(AL/AMASS)*CGAMMA-(AD/AMASS)*SGAMMA-G
      XDOT(6)=AM/YYI
      GO TO 21
   20 CONTINUE
      XDOT(1)=X(3)
      XDOT(2)=X(4)
      XDOT(5)=X(6)
      XDOT(3)=-CD*Q*V*VX/AMASS
      XDOT(4)=-CD*Q*V*VY/AMASS
      XDOT(6)=0.
   21 RETURN
      END
      SUBROUTINE COEFF(RE,CD,CL,CM)
C-----------------------------------------------------------------------
C--   COEFFICIENTS OF AERODYNAMIC FORCES AND OF MOMENTS
C-----------------------------------------------------------------------
      CL=0.
      CM=0.
      IF(RE .EQ. 0.0) GO TO 22
      CD=24.0/RE
      IF(RE.LE.0.05) GO TO 14
      IF(RE.LE.3.0) GO TO 2
      IF(RE.GT.330) GO TO 5
      A0=-28.339
      A1=38.969
      A2=0.73204
      A3=-0.00056084
      GO TO 10
    2 A0=0.0
      A1=24.167
      A2=3.2540
      A3=-0.23564
      GO TO 10
    5 A0=0.0
      A1=93.462
      A2=0.37576
      A3=0.0
   10 R2=RE*RE
      CD=(A0+A1*RE+A2*R2+A3*R2*RE)/R2
      GO TO 14
   22 CD=0.0
   14 RETURN
      END
      SUBROUTINE MODE(XP,YP,ISTOP,IW,T,NSTP)
C-----------------------------------------------------------------------
C--   DECIDES WETHER THE PARTICLE HIT THE AIRFOIL OR NOT
C-----------------------------------------------------------------------
      COMMON/SDS/S(500),SW(100),ZO(100),IS
      COMMON/XFR/XX(5),YY(5),XB(5),YB(5),THIK(5),YYMX(5),YYMN(5)
      COMMON/IN2/XIN,YIN,DP,RL,VXREF,VYREF,PITDOT,ATK,PIT,VREF,VXP,VYP
      COMMON/GBY/NTOT,X(500),Y(500)
      COMMON/MOD/LOFT,LEQM,XREAR,YLO,YUP
      COMMON/XTN/XFRNT,YFRNT,XRER,YRER,NTOTAL(5),NBDY,ID
      COMMON/IMM/IP1,IP2,NTOTM
      XF=(XP-XFRNT)*RL
      IF(ABS(XF).LE.0.00001) XP=XFRNT
      IC=0
      IFLAG=0
      II=0
      IF(XP.LE.XFRNT) GO TO 27
      IF(XP .GT. XREAR .OR. YP .GT. YUP .OR. YP .LT. YLO) GO TO 52
C---- FIND X-POSITION OF PARTICLE RELATIVE TO X(I) AND X(IL)
   13 IC=IC+1
      IF(IC .GT. 1) GO TO 7
      IF(XOLD .GE. XFRNT) GO TO 5
      IFLAG=1
      YT=(YP-YPOLD)/(XP-XOLD)*(XFRNT-XOLD)+YPOLD
      IF(YT .GT. YFRNT) GO TO 3
      GO TO 6
    5 IF(YPOLD .GT. YFRNT) GO TO 3
      GO TO 6
    7 IF(YP .GT. YFRNT) GO TO 3
    6 CONTINUE
      DO 2 IP=IP1,IP2
      I=IP2-IP
      IL=IP2-IP+1
      IF(I .EQ. 0) GO TO 27
      XR=(XP-X(I))*(XP-X(IL))
      IF(XR .LE. 0.) GO TO 29
    2 CONTINUE
      GO TO 27
    3 CONTINUE
      DO 4 IP=IP2,NTOTM
      IL=IP
      I=IP+1
      IF(I .EQ. NTOTM+1) GO TO 27
      XR=(XP-X(I))*(XP-X(IL))
      IF( XR .LE. 0.) GO TO 29
    4 CONTINUE
```

```
   27 YREF=YFRNT
      IF(YP .EQ. YFRNT.AND.XP.EQ.XFRNT) GO TO 51
      YPT=(YP-YREF)/(YREF-YLO)
      GO TO 33
   29 YREF=((Y(I)-Y(IL))/(X(I)-X(IL)))*(XP-X(IL))+Y(IL)
      IF(IC .NE. 2) GO TO 31
      II=II+1
      YEE=ABS(YREF-YP)
      IF(YEE .LE. 0.00001) GO TO 51
      IF(II .GT. 20) GO TO 51
      XNEW=XP
      YREFN=YREF
      IF(IFLAG .EQ. 1) GO TO 9
      GO TO 34
C---- FIND THE PARTICULAR TRAJ. ACROSS THE BODY SURFACE OR NOT
   31 YPT=(YP-YREF)/(YREF-YLO)
      IF(IFLAG .EQ. 0) GO TO 8
      IF(YT .GT. YFRNT .AND. YPT.GT. 0.0) GO TO 33
      IF(YT .LT. YFRNT .AND. YPT.LT. 0.0) GO TO 33
    8 XNEW=XP
      YNEW=YPT
      YREFN=YREF
      YR=YNEW*YOLD
C---- FIND INTERSECTION POINT OF SPECIAL CASE
      IF(IFLAG .EQ. 0) GO TO 86
    9 A=(XNEW-XFRNT)*(YP-YPOLD)-(YREFN-YFRNT)*(XNEW-XOLD)
      B=YP-YPOLD
      C=YREFN-YFRNT
      D=XNEW-XFRNT
      E=XNEW-XOLD
      XP=(B*D*XOLD-C*E*XFRNT+(YFRNT-YPOLD)*E*D)/A
      YP=(D*B*YFRNT-E*C*YPOLD+(XOLD-XFRNT)*B*C)/A
      GO TO 1
   86 IF(YR .LE. 0.0) GO TO 34
   33 XOLD=XP
      YOLD=YPT
      YREFO=YREF
      YPOLD=YP
      ISTOP=0
      RETURN
C---- FIND INTERSECTION POINT OF GENERAL CASE
   34 XP=(XNEW-XOLD)*(YPOLD-YREFO)/(YREFN-YREFO-YP+YPOLD)+XOLD
      YP=(YP-YPOLD)*(YPOLD-YREFO)/(YREFN-YREFO-YP+YPOLD)+YPOLD
    1 CONTINUE
      IF(IC.EQ.2) IC=IC-1
      GO TO 13
   51 YP=YREF
      GO TO 55
C---- PRINTS DATA IF PARTICLE MOVES OUT OF RANGE
   52 XN=XIN/RL
      YN=YIN/RL
      WRITE(6,53) XN,YN,XP,YP,T,NSTP
   53 FORMAT(2F10.5,'  OUT OF RANGE   ',2F10.5,10X,1PE12.4,I10)
      ISTOP=1
      SW(IW)=99.9999
      ZO(IW)=YN
      GO TO 57
C---- END OF DATA PRINT IF PARTICLE MOVES OUT OF RANGE
C---- INTERPOLATION OF SURFACE DISTANCE
   55 CONTINUE
      DO 24 IQ=IP1,NTOTM
      I=IQ
      IM=I+1
      IF(YP .GT. YFRNT) GO TO 25
      GO TO 21
   25 I=NTOTM+IP1-IQ
      IM=I-1
   21 XR1=(XP-X(I))*(XP-X(IM))
      IF(XR1.GT.0.) GO TO 24
      P=(S(I)-S(IM))/(X(I)-X(IM))*(XP-X(IM))+S(IM)
      GO TO 59
   24 CONTINUE
   59 CONTINUE
      YN=YIN/RL
      XN=XIN/RL
      SW(IW)=P
      IS=IS+1
      ZO(IW)=YN
      WRITE(6,56) XN,YN,XP,YP,P,T,NSTP
   56 FORMAT(2F10.5,'  HIT BODY AT    ',3F10.5,1PE12.4,I10)
      ISTOP=1
   57 CONTINUE
      RETURN
      END
      SUBROUTINE READIN
      DIMENSION TTITLE(7)
      COMMON/XFR/XF(5),YF(5),XR(5),YR(5),THIK(5),YYMX(5),YYMN(5)
      COMMON/EXA/LCMB,LCMP,IHUB
      COMMON/TP15/ABCD(4),ATOTAL,VC15,RSORTC,NX15
      COMMON/FRI/IFRNT(5)
      COMMON/OBY/NTOT,X(500),Y(500)
      COMMON/SD3/S(500),SW(100),ZO(100),IS
      COMMON/NUM/N,M,IND,IBTOT,LIFTOT
      COMMON/XTN/XFRNT,YFRNT,XRER,YRER,NTOTAL(5),NBDY,IBD
      COMMON/ELD/XO(500),YO(500),SA(500),CA(500),CURV(500),DL(500)
      COMMON/SIF/CD(500),CF(500),CG(500),CI(500),WF(500),CSIG(500)
     1       ,CK(12),SIG(500)
      COMMON/FLG/INL(10),NL(10),LIFT(10),IBMF(10),IFST(10),ISEC(10)
```

```
C---- READ INFORMATION FOR CALCULATING WIND VELOCITIES
      EPS=0.0000001
      DR=0.01745329
      REWIND 15
      REWIND 21
      IF(LCMB.EQ.1) READ(15)(ABCD(I),I=1,4),ATOTAL,VC15,RSORTC,NX15
      READ(21) N,M,IND,IBTOT,LIFTOT
      READ(21) IF01,IF02,IF14
      READ(21) XO,YO,SA,CA,CURV,DL
      READ(21) CD,CF,CG,CI,WF,CSIG,CK
      READ(21) INL,NL,LIFT,IBMF,IFST,ISEC
      REWIND 5
C---- READ X-, Y-, COORDINATES
C---- READ TITLE
      LX=0
      LY=0
      NTOT=0
      DO 41 K=1,NBDY
      READ(5,20) ID,ISV,ILIFT,TTITLE,IPARA,IFIRST,ISECND,ITR,
     1INORM,IBOD,IDOLD,IPVOR,LAST,ITYPE
   20 FORMAT(3(I1,2X),1X7A4,5X9(I1,2X),1XI1)
    1 CONTINUE
      IF(ITR.EQ.1)READ(5,30)CHORD,XMULT,YMULT,DX,DY,THETA,XTO,YTO,ITYPE
   30 FORMAT(7(F8.0,1X),F8.0,I1)
C---- READ X-COORDINATES
      L=LX
  280 READ(5,290)(X(L+I),I=1,6),INO,ISTAT,ITYPE
  290 FORMAT(6F10.0,4XI1,2XI1,3XI1)
      IF(INO .LE. 0 .OR. INO .GT. 6) INO=6
      L=L+INO
      IF(ISTAT .EQ. 0) GO TO 280
      LX=L
C---- READ Y-COORDINATE
      L=LY
      ITYPE=4
  300 READ(5,290)(Y(L+I),I=1,6),INO,ISTAT,ITYPE
      IF(INO .LE. 0 .OR. INO .GT. 6) INO=6
      L=L+INO
      IF(ISTAT .EQ. 0) GO TO 300
      LY=L
      IF(LY .EQ. LX) GO TO 350
      WRITE(6,310)LY,LX
  310 FORMAT(1H1,'THE NUMBER OF Y-COORDINATES READ IS NOT EQUAL TO
     1 THE NUMBER OF X-COORDINATES READ ')
      STOP
  350 CONTINUE
      IIB=NTOT+1
      IIA=NTOT+2
      NTOT=LX
      S(IIB)=0.0
      XXO=X(IIB)
      DO 2 I=IIA,NTOT
      DDX=X(I)-X(I-1)
      DDY=Y(I)-Y(I-1)
      S(I)=S(I-1)+SQRT(DDX*DDX+DDY*DDY)
      IF(X(I).GT.XXO) GO TO 2
      XXO=X(I)
      NNO=I
    2 CONTINUE
      SO=S(NNO)
      DO 4 I=IIB,NTOT
      S(I)=SO-S(I)
    4 CONTINUE
      NTOTAL(K)=NTOT
      IF(ITR.NE.1) GO TO 41
      IF(ABS(XMULT).LT.EPS)XMULT=1.0
      IF(ABS(YMULT).LT.EPS)YMULT=1.0
      COST=COS(THETA*DR)
      SINT=SIN(THETA*DR)
      DO 190 IBY=IIB,NTOT
      XTOD=X(IBY)-XTO
      YTOD=Y(IBY)-YTO
      X(IBY)=(XTO+XTOD*COST-YTOD*SINT+DX)*XMULT
      Y(IBY)=(YTO+XTOD*SINT+YTOD*COST+DY)*YMULT
  190 CONTINUE
   41 CONTINUE
C---- CALCULATION OF SURFACE DISTANCE
      IA=1
      NTOT=NTOTAL(1)
      XMAX=X(1)
      XOO=X(1)
      YMIN=Y(1)
      YMAX=Y(1)
      DO 91 K=1,NBDY
      IF(K.EQ.1) GO TO 51
      IA=NTOTAL(K-1)+1
      NTOT=NTOTAL(K)
      XMAX=X(IA)
      XOO=X(IA)
      YMAX=Y(IA)
      YMIN=Y(IA)
   51 IB=IA+1
      DO 21 I=IB,NTOT
      IF(X(I).GE.XOO) GO TO 31
      XOO=X(I)
      IO=I
      GO TO 21
```

```
81 IF(X(I).LT.XMAX) GO TO 21
   XMAX=X(I)
   NR=I
21 CONTINUE
   IFRNT(K)=NO
   XF(K)=X(NO)
   YF(K)=Y(NO)
   XR(K)=X(NR)
   YR(K)=Y(NR)
   DO 61 I=IB,NTOT
   IF(Y(I).GT.YMIN) GO TO 62
   YMIN=Y(I)
   GO TO 61
62 IF(Y(I).LT.YMAX) GO TO 61
   YMAX=Y(I)
61 CONTINUE
   THIK(K)=YMAX-YMIN
   YYMX(K)=YMAX
   YYMN(K)=YMIN
91 CONTINUE
   RETURN
   END
   SUBROUTINE VELCTY(X,Y,VXC,VYC)
C-----------------------------------------------------------------------------------
C--   WIND VELOCITY CALCULATIONS
C-----------------------------------------------------------------------------------
   DIMENSION   A(500), B(500),VXT(12),VYN(12)
   COMMON/VEX/VX(12),VY(12)
   COMMON/FFR/XF(5),YF(5),XR(5),YR(5),THIK(5),YYMX(5),YYMN(5)
   COMMON/EXA/LCMB,LCMF,IHUB
   COMMON/IN2/XIN,YIN,DF,RL,VXREF,VYREF,PITDOT,ATK,PIT,VREF,VXP,VYP
   COMMON/XTN/XFRNT,YFRNT,XRER,YRER,NTOTAL(5),NBDY,ID
   COMMON/NUM/N,M,IND,IBTOT,LIFTOT
   COMMON/ELD/XO(500),YO(500),SA(500),CA(500),CURV(500),DL(500)
   COMMON/GCF/CD(500),CF(500),CG(500),CI(500),WF(500),CSIG(500)
  1         ,CK(12),SIG(500)
   COMMON/FLG/INL(10),NL(10),LIFT(10),IBMF(10),IFST(10),ISEC(10)
C  SET SOME QUANTITIES
10 SAI = 0.0
   CAI = 1.0
   DSI = 0.0
C
   JJ = 0
   K = 2
C
   DO 150 IB = 1,IBTOT
   IF (IBMF(IB) .LT. 0)  GO TO 150
C
C  COUNTER FOR ELEMENT GEOMETRY
   J = INL(IB) - 1
C  COUNTERS FOR A,B ARRAYS
   JI = JJ + 1
   JF = JJ + NL(IB)
C
C  JJ IS COUNTER FOR THE CURRENT ELEMENT
C
C  ZERO OUT A&B ARRAYS
   DO 30 JJ1 = JI,JF
   A(JJ1) = 0.0
30 B(JJ1) = 0.0
C
   JJ = JI
   JJ1 = JJ + 1
   JJ3 = JJ1 + 1
   GO TO 50
40 JJ3 = JJ + 1
50 J = J + 1
   AO = XYFORM(X, Y, DSI, SAI, CAI, IFST(IB), XO(J), YO(J),
  1        DL(J), SA(J), CA(J), ISEC(IB), A1, AC, AF, BO, B1, BC, BF)
   B(JJ ) = B(JJ ) + BO
   A(JJ) = A(JJ) + AO
C
C
   IF (IFST(IB) .EQ. 0)  GO TO 80
   IF (IFST(IB) - 2)60,70,60
C
C  FIRST TERMS OF FIRST ORDER
60 A(JJ ) = A(JJ ) -        (CF(J) + CD(J))*A1
   B(JJ ) = B(JJ ) -        (CF(J) + CD(J))*B1
   A(JJ1) = A(JJ1) +        CD(J)*A1
   B(JJ1) = B(JJ1) +        CD(J)*B1
   A(JJ3) = A(JJ3) +        CF(J)*A1
   B(JJ3) = B(JJ3) +        CF(J)*B1
C
70 IF (IFST(IB) .LT. 2)  GO TO 80
C
C  CURVATURE TERM OF FIRST ORDER
   A(JJ ) = A(JJ ) + DL(J)*CURV(J)*AC
   B(JJ ) = B(JJ ) + DL(J)*CURV(J)*BC
C
80 IF (ISEC(IB) .EQ. 0)  GO TO 110
   IF (ISEC(IB) - 2)90,100,90
C
C  FIRST TERMS OF SECOND ORDER
90 A(JJ ) = A(JJ ) - (CG(J) + CI(J))*AF
   B(JJ ) = B(JJ ) - (CG(J) + CI(J))*BF
   A(JJ1) = A(JJ1) + CG(J)*AF
```

```
      B(JJ1) = B(JJ1) + CG(J)*BP
      A(JJ3) = A(JJ3) + CI(J)*AP
      B(JJ3) = B(JJ3) + CI(J)*BP
C
  100 IF (ISEC(IB) .LT. 2)  GO TO 110
C
C  CURVATURE TERM OF SECOND ORDER
      A(JJ ) = A(JJ ) + 2.0*AP*(DL(J)*CURV(J))**2
      B(JJ ) = B(JJ ) + 2.0*BP*(DL(J)*CURV(J))**2
C
  110 JJ1 = JJ
      JJ = JJ + 1
      IF (JJ - JF)40,120,130
C
  120 JJ3 = JJ1 - 1
      GO TO 50
  130 JJ = JJ - 1
C
C
      IF (LIFT(IB) .EQ. 0)  GO TO 150
      VN = 0.0
      VT = 0.0
      DO 140 J = JI,JF
      VN = VN-  B(J)*WF(J)
  140 VT = VT + A(J)*WF(J)
C
      K = K + 1
      VXT(K)= VT
      VYN(K)= VN
  150 CONTINUE
C
C  SET UNIFORM ONSET FLOWS
C  ALPHA = 0
      VXT(1)= CAI
      VYN(1)=-SAI
C
C  ALPHA = 90
      VXT(2)= SAI
      VYN(2)= CAI
C
C  SET INPUT NON-UNIFORM ONSET FLOWS
      M1 = LIFTOT + 2
      IF (M .EQ. M1)  GO TO 170
      M2 = M1 + 1
      DO 160 K = M2, M
      VXT(K) = 0.0
  160 VYN(K) = 0.0
  170 CONTINUE
C   CALCULATE INDIVIDUAL FLOWS
      IF(LCMB .NE. 1) GO TO 200
      REWIND 14
      DO 190 K=1,M
      READ(14)(SIG(IJK),IJK=1,N)
      VX(K)=VXT(K)
      VY(K)=VYN(K)
      DO 180 J=1,N
      VX(K)=VX(K)+B(J)*SIG(J)
  180 VY(K)=VY(K)+A(J)*SIG(J)
  190 CONTINUE
C
      GO TO 221
C  CALCULATE COMBINED FLOW
  200 VXC = 0.0
      VYC = 0.0
      DO 210 K = 1,M
      VXC = VXC +VXT(K)*CK(K)
  210 VYC = VYC +VYN(K)*CK(K)
C
      DO 220 J = 1,N
      VXC = VXC + B(J)*CSIG(J)
  220 VYC = VYC + A(J)*CSIG(J)
  221 CONTINUE
      IF(LCMB .NE. 1) RETURN
      CALL COMB2D(VXC,VYC)
      RETURN
      END
      FUNCTION  XYFORM (XI, YI, DSI, SINI, COSI, IFST,
     1                  XJ, YJ, DSJ, SINJ, COSJ, ISEC,
     2                  A1, AC, AF, BO, B1, BC, BF)
C
C
C  THIS ROUTINE ACTUALLY CALCULATES THE INDUCED VELOCITY
C  ARRAY ELEMENTS A AND B.
C
C
      DATA E1,E2/169.0,11.111/,EO,EY/0.0001,0.01/
C
C
      DX = XI - XJ
      DY = YI - YJ
      ROSQ = DX**2 + DY**2
      DSJSQ = DSJ**2
C
      IF (ROSQ .LT. DSJSQ*E1)  GO TO 10
C
```

```
C   USE FAR FIELD FORMULAS
      VX = 2.*DSJ/ROSG
      VY = VX*DY
      VX = VX*DX
      AO = -VX*SINI + VY*COSI
      XYFORM = AC
      BO =  VX*COSI + VY*SINI
      IF ((IFST .EQ. 0) .AND. (ISEC .EQ. 0))  RETURN
      SC = SINI*COSJ
      SS = SINI*SINJ
      CS = COSI*SINJ
      CC = COSI*COSJ
      SSCC = (SS - CC)*VX*VY/12.0
      CSSC = (CS + SC *VX*VY/12.0
      DXR = 1.0 - 2.0*DX**2/ROSQ
      DYR = 1.0 - 2.0*DY**2/ROSQ
      DDR = DSJSQ/(ROSQ*6.0)
C
      A1 = DDR*(SC*DXR - CS*DYR) - SSCC
      B1 =-DDR*(CC*DXR + SS*DYR) + CSSC
      AC =-DDR*(SS*DXR + CC*DYR) - CSSC
      BC = DDR*(CS*DXR - SC*DYR) - SSCC
      AP = AO/12.0
      BP = BO/12.0
      RETURN
C
C   USE NEAR FIELD FORMULAS
   10 X = DX*COSJ + DY*SINJ
      Y = DY*COSJ - DX*SINJ
      S = SINI*COSJ - COSI*SINJ
      C = COSI*COSJ + SINI*SINJ
C
      IF (ROSQ .GT. DSJSQ*E2)  GO TO 20
C
C   USE EXACT FORMULAS
      XB = X/DSJ
      YB = Y/DSJ
      RO = XB**2 + YB**2
      RD = XB**2 - YB**2
      R1 = RO + XB + 0.25
      R2 = RO - XB + 0.25
C
      VX = +ALOG((ROSQ+DSJ*X+0.25*DSJSQ)/(ROSQ-DSJ*X+0.25*DSJSQ))
      Y = Y*DSJ
      X = ROSQ - 0.25*DSJSQ
      VY = 2.0*ATAN2(Y,X)
      IF ((IFST .EQ. 0) .AND. (ISEC .EQ. 0))  GO TO 30
C
      VXO = VX
      VYO = VY
      VX1 = YB*VYO + XB*VXO - 2.0
      VY1 = XB*VYO - YB*VXO
      VXC = -2.0*VY1 + XB*YB/(R1*R2)
      VYC = 2.0*(VX1 + 1.0)-2.*(RO**2 - 0.25*RD)/(R1*R2)
      VXP = RD*VXO +  2.0*XB*(YB*VYO - 1.0)
      VYP = RD*VYO -  2.0*YB*(XB*VXO - 1.0)
C
      GO TO 30
C
C
C   USE MULTIPOLE FORMULAS
   20 AE = X*DSJ/ROSQ
      BE = Y*DSJ/ROSQ
      ASQ = X**2/ROSQ
      ESQ =DSJSQ/ROSQ
      VX  = 2.0*AE*(1.0 + (ASQ - 0.75)*ESQ/3.0)
      VY  = 2.0*BE*(1.0 + (ASQ - 0.25)*ESQ/3.0)
      IF ((IFST .EQ. 0) .AND. (ISEC .EQ. 0))  GO TO 30
      A4 = 0.15*(8.0*ASQ*(ASQ - 1.0) + 1.0)*ESQ
      VX1 = ESQ*(2.0*ASQ - 1.0 + A4)/6.0
      VY1 = AE*BE*(1.0 + 0.3*(2.0*ASQ - 1.0)*ESQ)/3.0
      VXC = AE*BE*(1.0 + 0.3*(6.0*ASQ - 1.0)*ESQ)/3.0
      BSQ = Y**2/ROSQ
      VYC = ESQ*(2.0*BSQ - 1.0 -0.5*A4)/6.0
      VYP = (1.0 + (ASQ - 0.25)*ESQ*0.6)/6.0
      VXP = AE*VYP
      VYP = BE*VYP
C
C
   30 CONTINUE
      XYFORM = -S*VX + C*VY
      BO = C*VX + S*VY
      IF ((IFST .EQ. 0) .AND. (ISEC .EQ. 0))  RETURN
      A1 = -S*VX1 + C*VY1
      AC = -S*VXC + C*VYC
      AP = -S*VXP + C*VYP
C
      B1= C*VX1 + S*VY1
      BC = C*VXC + S*VYC
      BP = C*VXP + S*VYP
C
C
      RETURN
      END
```

```
      SUBROUTINE COMB2D(VXC,VYC)
      COMMON/EXA/LCMB,LCMP,IHUB
      COMMON/VEX/VX(12),VY(12)
      COMMON/IN2/XIN,YIN,DP,RL,VXREF,VYREF,PITDOT,ATK,PIT,VREF,VXP,VYP
      COMMON/TP15/A(4),ATOTAL,VC,RSORTC,NX
      VINF=VREF*100.0/(2.54*12.0)
      VXINC=0.0
      VYINC=0.0
      DO 10 I=1,3
      VXINC=A(I)*VX(I)+VXINC
      VYINC=VYINC+A(I)*VY(I)
   10 CONTINUE
      IF(IHUB .EQ. 0) GO TO 11
      VXINC=VXINC-A(3)*VX(4)+A(4)*(VX(5)-VX(4))
      VYINC=VYINC-A(3)*VY(4)+A(4)*(VY(5)-VY(4))
      GO TO 12
   11 VXINC=VXINC-A(3)*VX(4)
      VYINC=VYINC-A(3)*VY(4)
   12 VRE=SQRT(VXINC*VXINC+VYINC*VYINC)
      VXC=VXINC/VINF
      VYC=VYINC/VINF
      IF(LCMP.EQ.0)RETURN
C---- TO APPLY THE COMPRESSIBILITY CORRECTION
      EXCON=1.095*ATOTAL*125.0/216.0
      VCHK=ATOTAL/SQRT(1.2)
      VRECOM=VRE/RSORTC**(VRE/VC)
      VA=0.2*(VRECOM/ATOTAL)**2
      IF(VA.GT.1.0) GO TO 35
      PSI=(1.0-VA)**3.5
      GO TO 40
   35 PSI=0.0
   40 CONTINUE
      IF((VRECOM.LT.VCHK).OR.(ABS(NX).NE.1)) GO TO 15
      IF((VRECOM/VCHK).GT.2.0) GO TO 15
      RHORTC=VRECOM*PSI**0.715/EXCON
      IF(RHORTC.EQ.0.0) RHORTC=1.0
      VRECOM=VCHK*(1.0+(VRECOM/VCHK-1.0)**(1.0/RHORTC))
   15 VXCOM=VXINC*VRECOM/VRE
      VYCOM=VYINC*VRECOM/VRE
      VXC=VXCOM/VINF
      VYC=VYCOM/VINF
      RETURN
      END
      SUBROUTINE LINEAR(X,Y,IMAX,IMIN)
      DIMENSION X(1),Y(1)
      IM=IMAX-1
      NTOT=IMAX-IMIN
      WRITE(6,199) NTOT
  199 FORMAT(I5)
      DO 10 I=IMIN,IM
      XMN=0.5*(X(I+1)-X(I))
      YMN=0.5*(Y(I+1)-Y(I))
      AX=ABS(XMN)
      IF(AX.LE.0.0000001) GO TO 10
      YP=-YMN/XMN
      XMN=X(I)+XMN
      YMN=Y(I)+YMN
      WRITE(6,93) I,YMN,XMN,YP
   93 FORMAT(2X,I5,3(1PE12.4))
   10 CONTINUE
      RETURN
      END
      SUBROUTINE EFFICY(NCOEF,NPTS,NS)
      IMPLICIT REAL*8(A-H,O-Z)
      REAL*4 XIN,YYP,YYD,YOUT,YPOUT,XMAX,XMIN,XMA,XMI,DPD,PLWC,EPT,
     1       XA(1000),YA(1000)
      REAL*4 XBTA(100),YBTA(100)
      COMMON/COEF/A(20,21)
      COMMON/COEF1/B(20,30)
      COMMON/COEF2/XMA(10),XMI(10)
      COMMON/DPD1/NSI,PLWC(10),IRS(10),DPD(10),EPT
      REWIND 3
      N1=1
      N2=0
      NN=NCOEF+1
      DO 1 IJK=1,NSI
      NN1=NCOEF+IJK
      IF(IJK .EQ. NSI/2) NDA=IRS(IJK)
      READ(3) NDATA
      IF(NS.EQ.1 .OR. NSI .GT. 1) NPTS=NDATA
      N2=NDATA+N2
      DO 543 I=N1,N2
      READ(3) XA(I),YA(I)
      IF(ABS(XA(I)).LE.0.0000001) XA(I)=0.0
  543 CONTINUE
      IF(NSI.GT.1) WRITE(6,72)IJK
      IF(NSI .GT. 1) WRITE(6,71)DPD(IJK),PLWC(IJK)
      WRITE(6,73) NDATA
      WRITE(6,90)
      DO 97 I=N1,N2
   97 WRITE(6,93) I,YA(I),XA(I)
      IF(NSI .EQ. 1) GO TO 2
      XMIN=XA(N1)
      XMI(IJK)=XA(N1)
      XMAX=XA(N2)
```

```
      XMA(IJK)=XA(N2)
      IF(XA(N1).LE.XMIN) XMIN=XA(N1)
      IF(XA(N2).GE.XMAX) XMAX=XA(N2)
      XIN=XA(N1)
      CALL TERP(XIN,YOUT,YPOUT,XA,YA,N1,N2,NCOEF,NPTS)
      DO 3 II=1,NCOEF
      B(II,NN1)=A(II,NN)
    3 CONTINUE
      N1=NDATA+N1
    1 CONTINUE
      WRITE(6,198) XMIN,XMAX,EPT
      CALL EF(XMAX,XMIN,NDA,NSI,NCOEF,PLWC)
      RETURN
    2 WRITE(6,99)
      WRITE(6,91)
      NTOT=N2-N1+1
      CALL LINEAR (XA,YA,N2,N1)
      WRITE(6,70) NCOEF,NPTS
      IAC=0
      NTOA=NTOT
      NN=NCOEF+1
      WRITE(6,91)
      DO 20 I=N1,N2
      IAC=IAC+1
      XIN=XA(I)
      IF(NS.EQ.1.AND.I.GT.1) GO TO 21
      CALL TERP(XIN,YOUT,YPOUT,XA,YA,N1,N2,NCOEF,NPTS)
   21 IF(NS.EQ.1) GO TO 22
      YYP=YOUT
      YYD=-YPOUT
      GO TO 23
   22 YYD=0.0
      YYP=A(1,NN)
      DO 9 J=2,NCOEF
      IF(XA(I) .EQ. 0.0) XA(I)=0.0000001
      YYP=YYP+A(J,NN)*XA(I)**(J-1)
      YYD=YYD+(J-1)*A(J,NN)*XA(I)**(J-2)
    9 CONTINUE
      YYD=-1.*YYD
   23 IF(YYD.LT.0.0) GO TO 27
      WRITE(6,93) I,YYP,XA(I),YYD
      GO TO 28
   27 NTOA=NTOA-1
      IAC=IAC-1
      IF(I.EQ.N1.OR.I.EQ.N2) GO TO 29
      WRITE(6,93) I,YYP,XA(I),YYD
      GO TO 20
   29 YYD=0.0
      WRITE(6,93)I,YYP,XA(I),YYD
      NTOA=NTOA+1
      IAC=IAC+1
   28 YBTA(IAC)=YYD
      XBTA(IAC)=XA(I)
   20 CONTINUE
      WRITE(6,92)
      WRITE(6,199)NTOA
      WRITE(9)NTOA
      DO 24 I=1,NTOA
      WRITE(6,95)I,XBTA(I),YBTA(I)
      WRITE(9) XBTA(I),YBTA(I)
   24 CONTINUE
C---- FORMATS
   70 FORMAT(/,2X,'POLYNOMINAL LEAST SQUARE FIT',//,2X,
     1        'NO. OF COEFFICIENCTS IS ',I3,/,
     2       2X,'NO. OF POINTS FOR DATA FITTING IS',I3,/)
   71 FORMAT(/,2X,'DIAMETER',4X,'PERCENTAGE',
     1          /,2X,'DISTRIBUT.',2X,'OF W. CONT.',
     2          //,2X,2(1PE10.3,3X),/)
   72 FORMAT(///,1X,'***FOLLOWING OUTPUT IS FOR DROPLET SIZE
     1  DISTRIBUTION -- ',I3,/,
     2  3X,'(THE DATA ARE USED TO DO CURVE FITTING)',/)
   73 FORMAT(/,2X,'NO. OF DATA POINTS STORED IN TAPE03 = ',I6,/)
   90 FORMAT(/,5X,'I',6X,' ZO ',7X,' SD',/)
   91 FORMAT(/,5X,'I',6X,' ZO ',7X,' SD',8X,' BETA',/)
   92 FORMAT(/,5X,'I',6X,'SD',8X,'BETA',/)
   93 FORMAT(2X,I5,3(1PE12.4))
   95 FORMAT(2X,I5,2(1PE12.4))
   99 FORMAT(/,2X,'LINEAR APPROACH',/)
  198 FORMAT(///,1X,'FOLLOWING OUTPUT IS FOR THE OVERALL
     1 MULTI-SIZE CASE',//,4X,'UPPER SURFACE LIMIT',9X,
     2'LOWER SURFACE LIMIT',/,12X,'SU',26X,'SL',/,6X,
     32(1PE12.4,17X),//,2X,'TOTAL COLLECTION EFFICIENCY',
     43X,1PE12.5,/)
  199 FORMAT(I5)
      RETURN
      END
      SUBROUTINE EF(XMAX,XMIN,NDA,NSI,NCOEF,PLWC)
      IMPLICIT REAL*8(A-H,O-Z)
      DIMENSION XA(100),PLWC(1),XBTA(100),YBTA(100)
      REAL*4 XMAX,XMIN,PLWC,YYD,DES,XMA,XMI,XA
      COMMON/COEF1/B(20,30)
      COMMON/COEF2/XMA(10),XMI(10)
      DES=(XMAX-XMIN)/FLOAT(NDA-1)
      IAC=0
      NTOA=NDA
```

```
      WRITE(6,70)NCOEF
      WRITE(6,92)
      DO 1 IJ=1,NDA
      IAC=IAC+1
      YYD=0.0
      XA(IJ)=XMAX-DES*(NDA-IJ)
      DO 2 I=1,NSI
      IF(XA(IJ) .GT. XMA(I).OR. XA(IJ).LT. XMI(I)) GO TO 2
      NN=NCOEF+I
      DO 2 J=2,NCOEF
      IF(XA(IJ) .EQ. 0.0) XA(IJ)=0.0000001
      YYD=YYD+(J-1)*B(J,NN)*XA(IJ)**(J-2)*PLWC(I)
    2 CONTINUE
      YYD=-1.*YYD
      IF(YYD .LT. 0.0) GO TO 27
      WRITE(6,93) IJ,XA(IJ),YYD
      GO TO 28
   27 NTOA=NTOA-1
      IAC=IAC-1
      IF(IJ.EQ.1.OR.IJ.EQ.NDA) GO TO 29
      WRITE(6,93)IJ,XA(IJ),YYD
      GO TO 1
   29 YYD=0.0
      WRITE(6,93) IJ,XA(IJ),YYD
      NTOA=NTOA+1
      IAC=IAC+1
   28 YBTA(IAC)=YYD
      XBTA(IAC)=XA(IJ)
    1 CONTINUE
      WRITE(6,92)
      WRITE(6,199)NTOA
      WRITE(9)NTOA
      DO 24 I=1,NTOA
      WRITE(6,95)I,XBTA(I),YBTA(I)
      WRITE(9) XBTA(I),YBTA(I)
   24 CONTINUE
C---- FORMATS
   70 FORMAT(/,2X,'POLYNOMIAL LEAST SQUARE FIT',//,2X,
     1        'NO. OF COEFFICIENCTS IS ',I3,/,
     2        2X,'WITH WHOLE DATA SETS',/)
   92 FORMAT(/,5X,'I',6X,'SD',8X,'BETA',/)
   93 FORMAT(2X,I5,3(1PE12.4))
   95 FORMAT(2X,I5,2(1PE12.4))
  199 FORMAT(I5)
      RETURN
      END
      SUBROUTINE TERP(XIN,YOUT,YPOUT,XA,YA,N1,N2,NCOEF,NPTS)
C---- DOES SIMPLE NCOEF POLYNOMIAL LEAST SQUARES FIT TO NPTS OF XA, YA
      IMPLICIT REAL*8(A-H,O-Z)
      REAL*4 XIN,YOUT,YPOUT,XA(1),YA(1)
      DIMENSION F(1000,20),Y(1000)
      COMMON/COEF/A(20,21)
      NCM1 = NCOEF - 1
      NCOL = NCOEF + 1
C---- SEARCH XA FOR XIN
      DO 1 IF=N1,N2
      I=IF
      IF(XIN.LE.XA(IF))GO TO 5
    1 CONTINUE
    5 CONTINUE
      IMIN=I-NPTS/2
      IF(IMIN .LT. N1) IMIN=N1
      IMAX=IMIN+NPTS-1
      IF(IMAX.GT.N2) IMAX=N2
      IMIN=IMAX-NPTS+1
      III = 0
      DO 2 II = IMIN,IMAX
      III = III + 1
      F(III,1) = 1.0
      DO 3 JJ = 2,NCOEF
    3 F(III,JJ) = XA(II)**(JJ-1)
    2 Y(III) = YA(II)
      A(1,1) = NPTS
      DO 10 J = 1,NCOEF
      DO 20 I = J,NCOEF
      IF(I.EQ.1.AND.J.EQ.1)GO TO 20
      SUM = 0.0
      DO 11 ISUM = 1,NPTS
   11 SUM = SUM + F(ISUM,I)*F(ISUM,J)
      A(J,I) = SUM
      A(I,J) = SUM
   20 CONTINUE
      SUM = 0.0
      DO 50 I = 1,NPTS
   50 SUM = SUM + Y(I)*F(I,J)
      A(J,NCOL) = SUM
   10 CONTINUE
      CALL CHOLES(A,NCOEF,NCOL,1)
      YOUT=A(1,NCOL)
      YPOUT=0.0
      DO 4 I=2,NCOEF
      IF(XIN .EQ.0.0) XIN=0.0000001
      YOUT=YOUT+A(I,NCOL)*XIN**(I-1)
    4 YPOUT=YPOUT+(I-1)*A(I,NCOL)*XIN**(I-2)
      RETURN
      END
```

```
      SUBROUTINE CHOLES(A,N,M,MATSYM)
C---- CDPD MATRIX SOLUTION ROUTINE FROM DON TODD ON 4-24-80
      REAL*8 A(20,21),SUM,TEMP
      IF(A(1,1).NE.0.0) GO TO 47
      DO 37 J=2,N
      IF(A(J,1).EQ.0.0) GO TO 37
      IFLIP=J
      GO TO 27
   37 CONTINUE
      GO TO 54321
   27 DO 57 K=1,M
      TEMP=A(IFLIP,K)
      A(IFLIP,K)=A(1,K)
      A(1,K)=TEMP
   57 CONTINUE
   47 DO 2 J=2,M
      A(1,J)=A(1,J)/A(1,1)
    2 CONTINUE
      DO 6 I=2,N
      DO 7 J=2,M
      IF(MATSYM.EQ.0)GO TO 49
      IF(I-J)69,68,67
   49 IF(J.GT.I)GO TO 69
   68 K=J-1
      SUM=0.0
      DO 3 IR=1,K
      SUM=SUM+A(I,IR)*A(IR,J)
    3 CONTINUE
      A(I,J)=A(I,J)-SUM
      GO TO 7
   69 K=I-1
      SUM=0.0
      DO 4 IR=1,K
      SUM=SUM+A(I,IR)*A(IR,J)
    4 CONTINUE
      IF(A(I,I).EQ.0.0) GO TO 54321
      A(I,J)=(A(I,J)-SUM)/A(I,I)
      GO TO 7
   67 A(I,J)=A(J,I)*A(J,J)
    7 CONTINUE
    6 CONTINUE
      DO 52 K=2,N
      I=N+1-K
      SUM=0.0
      LL=I+1
      DO 51 IR=LL,N
      SUM=SUM+A(I,IR)*A(IR,M)
   51 CONTINUE
      A(I,M)=A(I,M)-SUM
   52 CONTINUE
      GO TO 12345
54321 N=-1
12345 RETURN
      END
      SUBROUTINE APLOT (U,YL,N,K,LDP,FC,CZ)
      DIMENSION U(1),YL(1),N(1)
      DIMENSION XTITL(20),YTITL(20)
      DIMENSION DSNAME(9)
      DATA IDP/1/,DSNAME/'SAVE','PLOT',7*'    '/
C---- K:      NO. OF DATA SETS
C---- N(K):  NO. OF DATA POINTS IN KTH DATA SET
C---- U:      X-COORDINATE
C---- YL:     Y-COORDINATE
      IF(LDP .EQ. 1) GO TO 19
      READ(2,100) (XTITL(I),I=1,20)
      READ(2,100) (YTITL(I),I=1,20)
      READ(2,101)YHEIT,YMAX,YMIN
      READ(2,101)XLENG,XMAX,XMIN
  100 FORMAT(20A4)
  101 FORMAT(5(5X,F10.0))
      CZ=(YMAX-YMIN)/YHEIT
      FC=(XMAX-XMIN)/XLENG
      CALL CCBEGN(10.0,1.0)
      CALL BEGID(IDP)
      CALL PLOT(1.,2.5,-3)
      CALL AXIS(0.,0.,XTITL,-80,XLENG,0.,XMIN,FC,0.0)
      CALL PLOT(0.,0.,3)
      CALL AXIS(0.,0.,YTITL,80,YHEIT,90.,YMIN,CZ,0.0)
      CALL PLOT(0.,YHEIT,3)
      CALL PLOT(XLENG,YHEIT,2)
      CALL PLOT(XLENG,0.,2)
      CALL PLOT(0.0,0.0,3)
   19 CONTINUE
      NK=-1
      JN=0
      DO 14 I=1,K
      J1=JN+1
      JN=JN+N(I)
      NK=NK+2
      DO 13 J=J1,JN
      Z=(YL(J)-YMIN)/CZ
      X=(U(J)-XMIN)/FC
      IF(J .EQ. J1) CALL PLOT(X,Z,3)
      IF(Z.GT.YHEIT) GO TO 13
```

```
      IF(LDF.EQ.1) GO TO 17
      IF(I.NE.K) GO TO 67
   17 CALL PLOT(X,Z,2)
      GO TO 13
   67 CONTINUE
      CALL SYMBOL(X,Z,0.14,NK,0.,-1)
   13 CONTINUE
      CALL PLOT(0.0,0.0,3)
   14 CONTINUE
      CALL ENDID(IDF,-1,DSNAME)
      CALL CCBEGN(-1.0,1.0)
      RETURN
      END
      SUBROUTINE TRAJCT
      RETURN
      END
```

VITA

Ho-Pen Chang was born in Taichung, Taiwan, Republic of China, on July 5, 1953. He attended elementary school in that city. He received his high school education in Taipen. In June, 1977, he graduated from the National Cheng Kung University, Tainan, Taiwan, where he received his Bachelor of Science degree with a major in Aeronautical Engineering.

In the following two years, he served in the China Army as a second lieutenant. In the fall of 1979 he was employed as a teaching assistant in the National Cheng Kung University.

He entered the Graduate School at The University of Tennessee Space Institute in September, 1980, as a graduate research assistant for the Atmospheric Science Division. He received his Master of Science degree in Aerospace Engineering in June, 1982.