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A COMPUTER PROGRAM FOR VARIABLE-GEOMETRY SINGLE-STAGE AXIAL COMPRESSOR TEST DATA ANALYSIS (UD0400)

C. HERBERT LAW

TECHNOLOGY BRANCH
TURBINE ENGINE DIVISION

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This report describes a computer program that is designed for the analysis of single-stage axial compressor data. The axisymmetric flow of a thermally perfect compressible fluid is assumed, and the streamline curvature method of solution is employed. Details of the blade geometry may be computed or input, and a detailed account of the flow through the blading may be obtained. The analysis is limited to a single-stage compressor, but inlet guide vanes may be included. Variable geometry is permitted in both

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the inlet guide vanes and the stator vanes. An option in the analysis is to match computed and experimental static pressures at any radius by varying annulus blockage or relative flow deviation angles.

PREFACE

This interim report was prepared by Dr. C. Herbert Law of the Technology Branch, Turbine Engine Division, Aero Propulsion Laboratory, Air Force Wright Aeronautical Laboratories (AFSC), Wright-Patterson AFB, Ohio. The work was accomplished between 1 June 1980 and 31 May 1981.

The report represents results from a portion of the effort of the Compressor Research Group, supervised by Dr. Arthur J. Wennerstrom, and was conducted under Work Unit 27, Task S1, of Project 2307, "Turbomachinery Fluid Mechanics."

This report describes Program UD0400, which was assembled from modified versions of Programs UD0100 and UD0200. The primary author of these three programs was Richard M. Hearsey (currently employed by the Boeing Commercial Aircraft Company, Seattle, WA) under contract by the University of Dayton Research Institute, Dayton, OH during the period June 1971 through September 1978. This report was assembled in part from four previous reports written by Mr. Hearsey: Aerospace Research Laboratory technical reports ARL 73-0177 (Volumes 1 and 2) and ARL 74-0131 and Hearsey Technology technical reports HT7701 and HT7808. Without the excellent technical support of Mr. Hearsey, this report could not have been written.

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LIST OF ILLUSTRATIONS

LIST OF SYMBOLS

A	Area
A	Component of momentum equation
A	Coefficient in spline-curve equation system
a	Speed of sound in fluid
a	Coefficient of specific heat polynomial
B	Component of momentum equation
B	1-Blockage due to blades (Equation 12)
B	1-Blockage due to blades and wakes/boundary layers (Equation 36)
B	Coefficient in spline-curve equation system
b	Coefficient of specific heat polynomial
Cp	Specific heat at constant pressure
Cv	Specific heat at constant volume
c	Coefficient of specific heat polynomial
D	Diffusion factor
D	Coefficient in spline-curve equation system
d	Coefficient of specific heat polynomial
E	Arbitrary error in streamline location
e	Coordinate in direction of computing station, increasing with radius
e	Coefficient of specific heat polynomial
f	Coefficient of specific heat polynomial
g	Acceleration due to gravity
H	Total enthalpy
h	Static enthalpy
i	Incidence angle
J	Joules equivalent
M	Mach number
M	Coefficient in spline-curve equation system
m	Meridional coordinate, that is, intersection of axisymmetric streamsurface with r-x plane, increasing in direction of flow
P	Total pressure
p	Static pressure

LIST OF SYMBOLS (Continued)

R	Radius of circle defining blade section meanline
R	Gas constant
r	Radius
r_c	Radius of curvature of streamsurfaces as seen in meridional plane
s	Entropy
T	Total temperature
t	Static temperature
U	Blade speed
V	Velocity
v	Specific volume
W	Flow rate
w	Specific weight
x	Axial coordinate, common to cartesian and cylindrical systems, increasing in direction of flow
x	Independent variable in spline-curve theory
y	Coordinate in cartesian system perpendicular to axial-radial plane of cylindrical system, increasing in direction of rotor rotation
y	Dependent variable in spline-curve theory
z	Coordinate in cartesion system in radial direction that is also the blade stack axis, increasing with radius
α	Flow angle, defined by $\tan \alpha = V_\theta/V_m$
β	Blade section angle, the angle made by the intersection of the blade mean surface and the axisymmetric streamsurface with the meridional plane, positive in direction of rotor rotation
γ	Ratio of specific heats
γ	Station lean angle, defined by $\tan \gamma = dx/dr$ (along the computing station)
δ	Deviation angle
ϵ	Blade lean angle, the angle made by the intersection of the blade mean surface and the computing station with the radial direction, positive for sweep-back relative to rotor rotation
η	Efficiency
θ	Angular coordinate in cylindrical system, positive in direction of rotor rotation
λ	The gradient $\partial r/\partial x$ on a blade mean surface at constant z

π 3.14159265.....

ρ Density

σ Cascade solidity (ratio of chord to spacing)

ϕ The gradient dr/dx on a streamline

$\bar{\omega}$ Relative total pressure loss coefficient

Subscripts

h   Hub

m   Meridional

p   Pressure surface

R   Relative

s   suction surface

T   Total

t   Tip (casing)

x   Projected onto a constant-x plane

θ Circumferential

1   Inlet

2   Outlet

SECTION I

INTRODUCTION

This report describes a computer program that has been developed
for the analysis of single-stage variable-geometry axial compressor
test data. The purpose of the program is to determine details of the
flow within a compressor from test measurements and a geometric des-
cription of the compressor. Performances of each blade row are calcu-
lated and expressed in terms of conventional parameters. This computer
program (UD0400) consists essentially of modified forms of two computer
programs (UD0100 and UD0200 as described in References 1 and 2) which
have been incorporated into a single program in order to provide a
convenient means of analyzing test data from variable geometry compres-
sors. The blade geometry definition section of the program (UD0100)
provides a complete or partial definition of one or more blade geome-
tries. The aerodynamic analysis section of the program (UD0200) per-
forms an aerodynamic analysis of the compressor consistent with the
geometry of the compressor and the experimental measurements. During
a single run of the program (UD0400), up to three entries may be made
into the blade geometry definition section (once for each blade-row;
inlet guide vane, rotor, and stator) and any number of entries may be
made into the aerodynamic analysis section (UD0200) provided that each
test data set was obtained from the same compressor geometry.

Either of the separate sections of the computer program may be
executed separately. Normally the blade geometry definition section will
be executed only once for each fixed blade-row, but this section will be
executed every run for each variable blade-row. Once the fixed blade
geometry data have been obtained they may be stored on disc and retrieved
as needed. The variable blade geometry data must, however, be generated
once for each blade configuration and stored on disc, or computed anew
during each execution of the computer program. Computing the variable
blade geometry data during each run offers several advantages including
less operator interaction and not being restricted to prescribed variable
blade configurations.

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The aerodynamic analysis solves a system of equations which includes a full treatment of the axisymmetric equations of motion of an inviscid fluid, including blade-force terms, and the assumption of a thermally-perfect gas as the working fluid. The equations are solved in finite difference form by the streamline curvature method. Computing stations may be located within the blade-rows, as well as at the blade edges and in the duct regions of the compressor. This permits a detailed picture of the flow through the blade-rows to be constructed, albeit on an axisymmetric basis and by making certain assumptions regarding the build-up of losses and deviation within the blades. The computing stations need not be radial and may be curvilinear, defined by a series of points. The aerodynamic analysis is performed using the geometry of the stage and the experimental measurements as inputs. The geometric input data will have been generated by one or more executions of the blade geometry definition section of the program during the same run or a previous run. In addition to providing blade geometry data, the blade geometry definition section may also provide a partial definition of the locations of the computing stations. Given the experimental measurements for one or more test points, any number of test points may be analyzed in one run of the program provided that the compressor configuration is the same for all test points. The blade geometry definition section may be entered only once for each variable blade-row during a single run.

Output from the program includes printed details of the blade geometries, flow field within the compressor, blade and stage performance, CALCOMP plots of several blade and stage performance parameters, and punch-card output of blade and stage performance parameters for future plot generation.

The computer program is written in standard FORTRAN IV and should be compatible with all modern medium-to-large computing systems, with few or no changes to the coding. All development running was done on either a CDC 6600 system incorporating CALCOMP plotting software or an IBM 370 system incorporating DISSPLA software at Wright-Patterson Air Force Base, Ohio.

This report is divided into a number of sections each describing one aspect of one of the two program sections or of the combined program. The first section following this introduction describes the scope and general methods of the program and each section. The next section describes the input data requirements of the program and defines all input variables. A description of the output data follows this section. The next section specifically deals with the theory and methods used in the blade geometry definition section (UD0100). This is followed by several sections dealing specifically with the theory and methods used in the aerodynamic analysis section (UD0200). Finally, in the last section, a discussion of the implementation of the program on a computing system is presented.

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SECTION II

SCOPE AND GENERAL METHODS OF THE PROGRAM

1. PROGRAM OPERATIONS

Program UD0400 consists essentially of modified forms of two programs (UD0100 and UD0200) which have been incorporated into a single program. The purpose of the program is to provide a convenient means of analyzing test data obtained from single-stage variable-geometry axial compressors. The blade geometry definition section (UD0100) may be used to provide a partial definition of the locations of the computing stations used in the aerodynamic section in addition to providing blade geometry data. The need to execute the blade geometry definition section is indicated by the blade setting angle defined by the test data. The aerodynamic section may be used to provide an analysis for any number of test cases involving the same blade setting angles.

Program UD0400 is flexible in regard to the number of entries made into the blade geometry definition section (UD0100), including zero. During an execution of UD0400, the aerodynamic analysis section (UD0200) may or may not be executed, and if it is, may be supplied with all its required input data directly by the user, if so desired. In short, program UD0400 provides all of the capabilities of programs UD0100 and UD0200 separately, plus adding the convenience of automatic internal transfer of data between sections.

Program UD0400 is capable of handling up to three blade-rows in the single-stage configuration, including an inlet guide vane (IGV). The IGV (if one exists) is handled somewhat differently from the rotor and stator blade-rows. Rather than using experimental data to define the IGV outlet flow angle and total pressure distribution, the user must supply these data. The IGV performance at any setting angle is defined by specifying "design-point" performance and the effects of restagger on performance. If incidence and deviation angles are required, IGV blade geometry data must be supplied (by the user or from UD0100).

The quantities that the blade geometry definition section (UD0100) determines are blade angles and blockages at locations which will be computing stations in a subsequent analysis performed by the aerodynamic analysis section (UD0200). Two blade angles are calculated: the blade

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section angles at a series of arbitrary radii where the stream surfaces
are taken to be cylindrical, and the blade lean angle defined as the angle
between the blade mean surface and the intersection of the computing
station and the meridional plane, projected onto a plane at a constant
axial location. The blade blockages at the same radii are computed as the
ratio of circumference blocked by blade metal to the total circumference.

The aerodynamic analysis of the compressor stage is performed assuming
that the flow is axisymmetric and that the effects of the blades may be
represented by force fields. The working fluid is assumed to be an inviscid,
thermally-perfect, compressible fluid, and thus there is no transport of
mass or energy normal to the streamline direction. The analysis is performed
on computing stations located at the blade edges and in the duct regions of
the compressor. The computing stations need not be radial and may be curvi-
linear, defined by a series of points. Computing stations may also be
located within the blade-rows to obtain a more detailed picture of the flow
field through the stage.

The equation system is solved by the streamline curvature technique.
This consists basically of the following elements:

(1) An initial estimate is made for the streamline pattern.

(2) The continuity and momentum equations are solved at each
computing station in turn. (The result is a function of
the assumed streamline pattern.)

(3) The estimated streamline pattern is refined on the basis
of the mass flow distributions computed in Step 2. The
objective here is to make the flow within each streamtube
the same at all computing stations.

(4) If overall convergence criteria have been met, proceed to
Step 5; otherwise return to Step 2.

(5) From the velocity distribution and streamline locations
calculated during the last pass through the iterative
procedure above, and the original input data, all the
desired output data may be computed.

Relatively stringent criteria have been set for the convergence of
the solution. The solution of the continuity and momentum equations in
Step 2 above is iterative, and these are deemed to be converged when
the total mass flow at the computing station is within one part in 4000

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of the specified value, and the meridional velocities computed on two successive iterations agree at all radii to within one part in 4000. The overall convergence criteria referred to in Step 4 above are that the proportion of total mass flow in each streamtube must be constant to within one part in 1000, and that the meridional velocity at each mesh point must agree on two successive passes to within one part in 1000.

The momentum equation is solved by the program in finite difference form, and a precise analysis of the errors involved has not been made. However, these are believed to be much smaller than those due to the simplifications involved in the formulation of the flow model. The program has been written to handle up to 21 streamlines and 24 computing stations, and the traverse data may generally be input for up to 21 radial locations.

2. PROGRAM INPUT DATA

Input data to the program are comprised of geometric data to define each blade-row geometry and the compressor flow path configuration, test measurement data to define compressor performance, and user-option data to define the analysis methods employed by the program and various output forms and devices. Input data to the blade geometry definition section (UD0100) include a design configuration description of the blade surfaces in cartesian coordinates, a generalized statement of the desired locations of computing stations, and a restagger angle for the blade-row if it is variable and different from the design value. If a non-zero restagger angle is input (DEL), the cartesian section description of the blade is rotated DEL degrees about a single point for the entire blade. The assumption is made that the axis of blade rotation is parallel to the Z-axis of the blade cartesian coordinate data, which is a radial line. Having made this rotation, the program performs the usual geometric analysis of the data and computes new locations for each affected computing station.

The input data requirements for the aerodynamic analysis section (UD0200) vary depending upon the degree of sophistication desired in the calculation. As a minimum, the compressor annulus geometry, radial total temperature traverse data downstream of either the rotor or the stator, two total pressure traverse data sets, and the stage exit swirl distribution are required. One total pressure traverse is the radial distribution

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of (circumferential) mean total pressure at the stage exit, and the other, to yield rotor outlet total pressure, is either the peak stage outlet total pressure at each radius, or simply the rotor outlet total pressure. Of course, the inlet conditions and flow rate, and gas properties are required. From these data, the rotor and stator relative inlet Mach numbers and loss coefficients, as well as the flow field characteristics at each computing station are determined. The IGV (if one exists) is handled somewhat differently in that the user supplies "design-point" outlet flow angle and total pressure distributions, and optionally, the effects of restagger of the IGV. Therefore, the IGV performance at any setting angle is "defined" rather than computed or measured.

If details of the blade-row geometries are included in the input data to the aerodynamic analysis section, two further areas of computation are made possible. First, the incidence angles, deviation angles, and diffusion factors for the blade-rows may be calculated. Second, computing stations may be located within the blade-rows to obtain a more detailed picture of the flow field through the stage. In this case generalized relationships for the variation of the deviation angles and loss coefficients within the blades as a function of their overall values must also be specified. This requirement reflects the unavailability of experimental data from within the blade rows.

SECTION III

INPUT DATA

1. DATA FORMAT

Three input data formats are used: alphanumeric, integer, and real.
Each record, or card, contains only one type of data, and normal FORTRAN
convention indicates which are the integer quantities. The alphanumeric
format is used for the title cards, and consists of 72 characters starting
in the first column. The integers are entered in fields of 6 characters,
with up to 12 numbers per card. No decimal point may be used, and the
number should be right-justified within the allocated field. The real
numbers are entered in fields of 12 with up to 6 numbers per card, and
a decimal point should be included to ensure correct interpretation of the
data. Then the number may be placed anywhere within the allocated field.

As described later in the section "Program Structure and Implementa-
tion" input data may be read from up to five different files. Here, the
variable containing the FORTRAN unit number is shown for each input record.

In the following chart, one line corresponds to one card, except
where it has been necessary to use two lines to complete the description
of one card.

(LOG1)   N100 N200 NWITE

The following data occur N100 times (which may be zero):

(LOG1)   TITLE
(LOG1)   NZ NBLADE NWHICH NPRINT NINPUT
(LOG1)   Z This line occurs NZ times
(LOG1)   NX
(LOG1)   NXII
(LOG1)   XSTN RSTN This line occurs NXII times   ⎤ This group ⎤ This
                                                     ⎦ occurs NX   ⎥ group
                                                       times   ⎥ occurs
                                                                   ⎥ only if
                                                                   ⎦ NWHICH=0

(LOG3)   DEL
(LOG1)   Z XLE YLE XTE YTE This line occurs NZ times   ⎤ This
(LOG1)   XR YR XSHIFT   ⎥ group
                                                           ⎥ occurs
(LOG1)   NX   ⎥ only if
(LOG1)   FX(1) FX(2) ... FX (NX)   ⎦ NWHICH=1

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(LOGK)	NS INSIST		This
(LOGK)	XS YS This line occurs NS times		group
(LOGK)	NP		occurs
(LOGK)	XP YP This line occurs NP times		NZ times

Note: LOGK = LOG1 if NINPUT = 0

LOGK = LOG9 if NINPUT = 1

This terminates the data that occurs N100 times, for the UD0100 section of the program. The following data, for the UD0200 section of the program, occurs if N0200 is greater than zero.

(LOG1)	TITLE1
(LOG1)	NSTNS NSTRMS NMAX NFORCE NPRSS NTEMP
	NSTN1 NSTN2 NOROTR NOSTAT NL NPLOT

(LOG1)	NSPEC NHUBSG NCASEG		This
(LOG7)	NDPS	This grouo	group
(LOG7)	RSTNA XSTNA This line occurs NDPS times	only occurs if NSPEC=0	occurs NSTNS times
(LOG1)	RSTN XSTN This line occurs NSPEC times, which may be zero		

(LOG1)	NHUB NCASG		
(LOG1)	NPHUB NTPHUB	This group	This
(LOG1)	XHUB RHUB This line occurs NPHUB times	occurs NHUB times	group only occurs if NSPEC=0
(LOG1)	NPCASE NTPCAS	This group	at least once
(LOG1)	XCASE RCASE This line occurs NPCASE times	occurs NCASG times	

(LOG1)	NCALC NDATA NBL	This
(LOG8)	NDATA2 This line occurs only if NDATA=-1	group occurs
(LOGJ)	DATRAD DATBET DATEPS DATAB DATHET This line occurs NDATA times, unless NDATA=-1. Then, it occurs NDATA2 times. LOGJ=LOG1 unless NDATA=-1, when LOGJ=LOG8.	for stations 2 through NSTNS

The following data describing the performance of the IGV only occurs if NCALC=5 at one station in the above data.

(LOG1)	NOIGV NV1
(LOG1)	VR1 VBETA VLOSS This line occurs NV1 times
(LOG1)	NV2 NV3

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(LOG1)	VR2		This group occurs NV2 times, which may be zero
(LOG1)	DGAM DDEL DLOSS This line occurs NV3 times		
(LOG1)	NV5 NV4		This group only occurs if NOIGV>0
(LOG1)	VR3	This group occurs NV5 times	
(LOG1)	VXM VDEV This line occurs NV4 times		

This is the end of the optional IGV data.

(LOG4)	NR1 NR2 NR3 NTF		This group only occurs if NOROTR>0
(LOG4)	R1M RLOSS This line occurs NR1 times		
(LOG4)	RRD	This group occurs NR3 times	
(LOG4)	R2M RDEV This line occurs NR2 times		
(LOG4)	NS1 NS2 NS3		This group occurs only if NOSTAT>0
(LOG4)	S1M SLOSS This line occurs NS1 times		
(LOG4)	RSD	This group occurs NS3 times	
(LOG4)	S2M SDEV This line occurs NS2 times		
(LOG4)	NCASE		
(LOG4)	PSCALE PLOWER DAMPF		
(LOG4)	NSAVE NNMAX MFORCE NEX NTCR NCARD NDPQ		

The remainder of the data occurs NCASE times

(LOG3)	TITLE
(LOG3)	GASR FRCAIR FLOW RPM PIN TIN
(LOG3)	TRATIO PRATIO RESTAG
(LOG3)	NRP
(LOG3)	RRP PR This line occurs NRP times
(LOG3)	NRT
(LOG3)	RRT TR This line occurs NRT times
(LOG3)	NSP
(LOG3)	RSP PS PSM This line occurs NSP times
(LOG3)	NST
(LOG3)	RST TS This line occurs NST times
(LOG3)	NSA
(LOG3)	RSA SA This line occurs NSA times
(LOG3)	NWSO
(LOG3)	XWSO WSPO This line occurs NWSO times (NWSO may be zero)
(LOG3)	NWSI
(LOG3)	XWSI WSPI This line occurs NWSI times (NWSI may be zero)
(LOG3)	NPSR

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(LOG3)   XPSR RPSR PSSR This line occurs NPSR times (NPSR may be zero)

(LOG4)   BLCKGE BDIST DEL DELDST BFRAC This line occurs NSTNS times

(LOG4)   NMACHI(1) NMACHI(2)...NMACHI(NSTNS)

     (There are NSTNS values of NMACHI, up to 12 per card).

(LOG4)   NJUMP

2. DEFINITION OF INPUT DATA ITEMS

a. Main program data:

N100
    The number of entries to be made to the UD0100-section of the program. May be zero or any positive value.

N200
    If N200 is greater than zero, the UD0200-section of the program will be entered.

NWITE
    If NWITE=1, a message is written out that for a CDC 6000-series computing system, will ask the operator to print the output on plain paper.

b. UD0100-section data:

TITLE
    An alphanumeric job title of up to 72 characters.

NZ
    The number of constant-z planes on which blades are defined. $3 \leq NZ \leq 15$

NBLADE
    The number of blades in the blade-row.

NWHICH
    If NWHICH=0, the UD0100-section of the program performs as Program UD0100.

    If NWHICH=1, additional data is read in, and (1) the blade sections are rotated by a specified angle and (2) computing station location data is generated.

NPRINT
    If NPRINT=1, the input section coordinates (XS, YS, XP, YP) are not listed.

NINPUT
    If NINPUT=0, the blade section definitions (NS, INSIST, XS, YS NP, XP, YP) are read from unit LOG1. If NINPUT=1, they are read from unit LOG9.

Z
    The Z-coordinates of the constant-z planes must be in order of increasing magnitude. The origin is on the compressor axis.

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NX   The number of stations where output is to be generated. $1 \le NX \le 12$ if NWHICH = 0; $2 \le NX \le 12$ if NWHICH = 1.

NXII   The number of points defining a station. $1 \le NXII \le 15$. If NXII=1, the station is assumed to be radial at the single axial coordinate given.

XSTN, RSTN   The axial coordinate and radius of a point defining a station. The axial coordinate increases in the direction of flow. The radii must be in order of increasing magnitude.

DEL   The blade sections defined by XS, YS, XP, YP are rotated DEL degrees anticlockwise. The center for the rotation is the point (XR, YR) for each section.

XLE, YLE   'X' and 'Y' coordinates of a point representing the leading edge of the blade section that lies at the 'Z' given on the same card. These data are used to locate the leading edge computing station. Where a series of points on the leading edge arcs for a blade are known, a "like" point should be selected for each section.

XTE, YTE   'X' and 'Y' coordinates of a point representing the trailing edge of the blade section that lies at the 'Z' given on the same card. These data are used to locate the blade trailing edge computing station.

XR, YR   See DEL (above).

XSHIFT   When the computing station data generated are output for use in UD0200, the quantity XSHIFT is added to the x-coordinates. XSHIFT is thus the difference between origins of axial coordinates of similar points in UD0200 and UD0100.

FX   When NWHICH=1, data describing the location of NX computing stations is generated. The first and last are always at the blade leading and trailing edges, respectively. FX(2) through FX(NSTNS-1), if NSTNS>2,

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define the fractions of meridional chord where the intermediate stations lie. (FX(1) and FX(NSTNS) are not used.)

NS   The number of points defining the 's' surface of the blade section. The designation of either surface of the blade as the 's' surface is arbitrary and has no significant effect upon the results. Must satisfy $3 \leq NS \leq 65$.

INSIST   If INSIST=1, the blade mean line will be linearly extrapolated, if necessary, rearwards to give results at the intersections with each station. If INSIST=0, no rearward extrapolations are made. (Extrapolations forward are always made, if necessary). The reason for this option is that partial sections may exist for a typical compressor blade where the blade height decreases towards the rear, and in the case where the cartesian blade description is obtained by inspection of parts. In such a case, the specification of the section will cease at some fraction of the chord length short of the trailing edge. Then linear extrapolation of the blade mean line would not yield reasonable values, and INSIST should be set equal to zero. For completely specified sections, INSIST should be set equal to 1 so that should the intended trailing edge station in fact miss the trailing edge of the blade by some small distance, data will nevertheless be generated.

XS, YS   The X- and Y-coordinates, respectively, of a point on the 's' surface of the blade. These must be in order of increasing 'X' (which increases in the direction of the flow). The Y-coordinate direction increases in the direction of rotor rotation.

NP, XP, YP   These correspond to NS, XS, YS and apply to the 'p' surface.

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c. UD0200-section data:

TITLE1
Alphanumeric title for job. Up to 72 characters may be used starting in column 1.

NSTNS
The number of computing stations. Must satisfy $3 \leq NSTNS \leq 24$.

NSTRMS
The number of streamlines to be computed through the flow field. Must satisfy $3 \leq NSTRMS \leq 21$. Eleven will frequently be satisfactory.

NMAX
The maximum permitted number of passes through the iterative solution procedure. Thirty will be adequate in most cases.

NFORCE
The maximum number of arbitrary passes through the iterative solution procedure. Five will be adequate in most cases.

NPRSS
If NPRSS=0, the rotor outlet total pressure is obtained from instrumentation at station NSTN1. If NPRSS=1, the rotor outlet total pressure is obtained from instrumentation at station NSTN2.

NTEMP
If NTEMP=0, the stage total temperature rise is obtained from instrumentation at station NSTN1. If NTEMP=1, the stage total temperature rise is obtained from instrumentation at station NSTN2.

NSTN1
Station number for instrumentation following the rotor.

NSTN2
Station number for instrumentation following the stator.

NOROTR
Number of blades in rotor. If NOROTR=0, no details of rotor geometry are used in the computations.

NOSTAT
Number of blades in stator. If NOSTAT=0, no details of stator geometry are used in the computations.

NL
The maximum number of lines per page of printed output. If NL is set to zero, it is reset to 60.

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NPLOT   If NPLOT=0, no CALCOMP plots are produced. If
               NPLOT=1 or 2, the computed stage static pressure
               distribution is shown, with experimental values,
               if any, included. A separate plot is made for each
               test point. If NPLOT=1, rotor and stator perform-
               ance parameters are plotted, a separate graph being
               created for each test point. (When more than a few
               test points are analyzed, an excessive amount of
               paper is output). Incidence angle, relative inlet
               Mach number, total pressure loss coefficient, devia-
               tion angle, and diffusion factor are plotted for each
               blade-row, against radius in inches. If NPLOT=2,
               rotor and stator performance parameters are plotted,
               values of each parameter for all test points being
               placed on one graph. The parameters plotted are as
               for NPLOT=1, and also the ratio of blade exit merid-
               ional velocity to compressor inlet critical velocity.
               (Critical velocity is the velocity when the Mach
               number is unity). In this case, the parameters are
               plotted against the ratio of radius to (local) tip
               radius. If NPLOT=3, the same blade performance plots
               are made as for NPLOT=2, but the static pressure
               distribution plots are not made.

NSPEC   When positive, this is the number of points used to
               define the computing station. Then $2 \leq NSPEC \leq 21$. The
               first and last points define the compressor hub and
               casing, respectively. When zero, the computing station
               definition is assembled from data generated by UD0100
               (on LOG7), and hub and casing contour data supplied
               directly by the user. From whichever source, the
               total number of points used to define all computing
               stations must not exceed 200.

NHUBSG   This only has significance if NSPEC=0. Then it is the
               number of the hub segment that is to be used to deter-
               mine the hub radius at the computing station. (The
               name NHUBSG is false; the program temporarily uses
               NDATA for this data item).

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NCASEG   This only has significance if NSPEC=0. Then it is
                the number of the casing segment that is to be used
                to determine the casing radius at the computing
                station. (The name NCASEG is false; the program
                temporarily uses NBL for this data item).

NDPS   When NSPEC=0, NDPS specifies the number of points
                of 'X' and 'R' that are read from unit LOG7 to
                define the computing station. (The name NDPS is
                false; the program temporarily uses NCALC for this
                data item).

RSTNA,   'X' and 'R' coordinates of points along the computing
XSTNA   station in order of increasing radius. These points
                define the line or curve of the station, but the
                first and last points do not define the hub and
                casing. (The names RSTNA, XSTNA are false; the
                program uses RSTN and XSTN).

RSTN, XSTN   The radius and axial coordinate of a point defining
                a computing station. These must start on the hub and
                finish on the casing.

NHUB   The number of hub contour segments that are to be
                input. 1<NHUB<5.

NCASG   The number of casing contour segments that are to
                be input. 1<NCASG<5.

NPHUB   The number of points making up the hub segment defini-
                tion. When NTPHUB=0, NPHUB<21. Also, the sum of all
                NPHUB<50.

NTPHUB   The location of the point or the computing station at
                the hub if found from the intersection of the XSTNA,
                RSTNA curve and the XHUB, RHUB curve. The XSTNA,
                RSTNA data is always spline-fit interpolated. The
                XHUB, RHUB data is spline-fit if NTPHUB=0, or inter-
                polated linearly point-to-point if NTPHUB=1.

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XHUB, RHUB	A point defining the hub contour in order of increasing axial coordinate. Sufficient points should be used to enable an accurate determination of the hub radius at the computing station(s) that use these data to be made.
NPCASE, NTPCAS XCASE, RHUB	These four items describing the casing correspond to the four items described above for the hub.
NCALC	If NCLAC=0, the computing station follows a blade-free space. Enthalpy, entropy, and angular momentum are maintained constant along streamlines from the previous computing station.
	If NCALC=1, the station follows a blade-free space as for NCALC=0, and additionally is at a blade leading edge.
	If NCALC=2, the station is within a blade. Details of the blade geometry must be given.
	If NCALC=3, the station is at the stator trailing edge.
	If NCALC=4, the station is at the rotor trailing edge.
	If NCALC=5, the station is at the trailing edge of an IGV.
	Note that a rotor and stator must be defined, but an IGV is optional.
NDATA	The number of radial locations at which blade geometry is given. May be zero unless NCALC=2. The NDATA is subject to the following restrictions; $1 \leq NDATA \leq 21$, and $\Sigma NDATA \leq 200$ (all stations). If NDATA is set to -1, this indicates that data will be found on unit LOG8 (having been created by UD0100).
NBL	If NBL=0, the blockage is held fixed according to the input data items BLCKGE and BDIST (which are described below).

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If NBL=1, the blockage is determined iteratively so that the input experimental value of static pressure on the casing is reproduced. BDIST is maintained at its input value, and the input value of BLCKGE is used as a first estimate. The experimental value is obtained by linearly interpolating (or extrapolating) from the input table of values to the appropriate axial coordinate. Thus, NWSO must be not less than 2 for this option.

If NBL=2, BDIST is held at its input value and BLCKGE is determined by linear interpolation (as a function of axial coordinate) from the first station upstream and downstream where NBL=2. Thus, this option must not be used at the first or last station.

If NBL=3, the match between experimental and computed casing static pressures is obtained by varying the blade deviation angles rather than blockage value at the computing station. The blockage distribution is held fixed as specified by BLCKGE and BDIST. The flow angle at any radius will be given by the sum of the blade angle (given by DATBET and DATEPS and the streamline shape), and the "fixed" deviation given by RDEV (or, for the case of a stator, SDEV and the trailing edge deviation), and a "variable" deviation angle component. This latter component has a linear variation from hub to case, the new input item DELDST being the ratio of (variable) hub deviation to the mid-radius value (compare with BDIST). The midradius value is determined iteratively to give the desired match at the casing; a starting value of DEL is read in. DEL is given in degrees, and for conventionally positive rotor deviation would be negative.

If NBL=4, the procedure is the same as if NBL=3, except that the midradius value of blockage, BLCKGE, is not used, and instead a further data item BFRAC redefines BLCKGE as BFRAC times the value of BLCKGE

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at the blade-row trailing edge. (The trailing edge
value would generally itself be determined iteratively
using NBL=1.)

If NBL=5, the blockage is determined iteratively so
that the input experimental value of static pressure
at an intermediate radius is reproduced. BDIST is
maintained at its input value, and the input value
of BLCKGE is used as a first estimate. The experi-
mental value is determined by first finding the
coordinates of the intersection of the computing
station (described by a spline-curve through the
points) and the line along which experimental static
pressures are given (described by a series of straight.
lines joining the specified points). The experimental
static pressure is then linearly interpolated as
functions of axial coordinate. Thus NPSR must not be
less than two for this option. (Note the similarity
to the NBL=1 option).

If NBL=6, a match between experimental and computed
static pressure at an intermediate radius is sought by
varying the flow deviation angle at the station. The
blockage is specified as a fraction of blade-row trail-
ing edge deviation on the same streamline. Thus, the
only difference between this option (NBL=6) and the
NBL=4 option is the method of specifying the experi-
mental static pressure, which is as for the case NBL=5.

Note: NBL=3, 4, and 6 can only be used at a station
that is within a blade-row. Within the rotor blade
and if NTF=1, NBL must not be 3, 4, or 6.

NDATA2   When NDATA=-1, NDATA2 on LOG8 defines the number of
radii where blade geometry are given. The name NDATA2
is false; the data item actually redefines NDATA.

DATRAD   The radius at which the blade parameters are given.
Units: inches.

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DATBET	The blade section angle at radius DATRAD, defined as the angle between the blade mean surface and the meridional plane on a cylinder. It is taken positive in the direction of rotor rotation, so that rotor angles are generally negative, stator angles generally positive. Units: degrees.
DATEPS	The blade lean angle at radius DATRAD. DATEPS is defined as the projection onto a constant-x plane of the angle made by the intersection of the blade mean surface and the computing station with the radial direction. Sweep-back relative to rotor rotation is taken to be positive. Units: degrees.
DATAB	The blade blockage at radius DATRAD. This is defined as the ratio of blocked to total circumference.
DATHET	The angular coordinate of the intersection of the blade mean surface with the computing station. It is measured from any radial line, and taken to be positive in the direction of rotor rotation. Units: radians.
	Note: It may be omitted for stations not at the blade edges, and the sign convention is arbitrary.
NOIGV	The number of blades in the IGV row.
	If NOIGV is set to zero, no details of the IGV blade geometry are used in the calculation and there must be no stations within the IGV.
NV1	The number of radii where the IGV "design performance" is given. $1 \leq NV1 \leq 21$.
VR1	Radius where the IGV design performance is given. These data must be in order of increasing magnitude.
VBETA	Outlet flow angle (degrees) at radius VR1. The tangent of the angle is (tangential velocity component)/(axial velocity component).
VLOSS	Total pressure loss coefficient at radius VR1 based upon <u>outlet</u> dynamic head.

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NV2   The number of radii where the effect on IGV perform-
ance of a change in setting angle is given. $0 \leq NV2 \leq 21$.
If NV2=0, the IGV design-point performance is used
regardless of setting angle.

NV3   The number of changes in setting angle (at each
radius) that are used to describe the variable
geometry effects. $1 \leq NV3 \leq 11$.

VR2   Radius at IGV trailing edge where following data
apply. VR2 must increase. If NV2=1, then VR2 is
without significance.

DGAM   Change in IGV setting angle from "design value".
These data must increase.

DDEL   Change in IGV outlet flow angle corresponding to
DGAM. Measured in the stream surface plane.

DLOSS   Ratio of total pressure loss coefficient to design
value, when setting angle is changed by DGAM.

NV5   Number of radii where following data is specified.
$1 \leq NV5 \leq 21$.

NV4   Number of meridional chord locations read at each
radius to describe IGV internal deviation. $1 \_ NV4 \leq 11$.

VR3   Radius at IGV trailing edge where following deviation
data apply.

VXM   Fraction of meridional chord. These data must
increase.

VDEV   Ratio of deviation angle at point defined by VXM to
value at trailing edge. Should rise from some small
value near leading edge to 1.0 at trailing edge.

NR1   The number of points on the meridionally-projected
chord where the fraction of total loss is specified
for the rotor. Must satisfy $2 \leq NR1 \leq 11$.

NR2   The number of points on the meridionally-projected
chord where the deviation angle or enthalpy-rise
fraction is specified for the rotor. Must satisfy
$2 \leq NR2 \leq 11$.

NR3   The number of radial locations at which the devia-
            tion angle or enthalpy-rise fraction distribution
            is specified. Must satisfy 1<NR3<21 but if NR3 is
            set equal to zero, it is reset to 1.

NTF   If NTF=0, deviation angles are specified within the
            rotor.

            If NTF=1, fractions of rotor enthalpy rise are speci-
            fied.

R1M   The fraction of meridional chord length where RLOSS
            is specified. The NR1 values must be in ascending
            order, generally will start at zero, and should end
            with 1.0.

RLOSS   The fraction of final rotor loss coefficient that
            applies at part-chord point R1M. The value of 1.0
            should be entered for the trailing edge.

RRD   The radius at the rotor trailing edge where the
            following deviation angle or enthalpy-rise fraction
            distribution applies. If NR3=1, RRD has no signifi-
            cance; the single curve is applied at all radii.
            Units: inches.

R2M   The fraction of meridional chord length where RDEV is
            specified. The NR2 values must be in ascending order,
            generally will start at zero, and should end with 1.0.

RDEV   When NTF=0, RDEV is the rotor deviation angle at point-
            chord point R2M. In this case, RDEV would normally be
            negative and is in degrees. When NTF=1 RDEV is the
            fraction of rotor enthalpy-rise that occurs at point-
            chord point R2M. RDEV would normally vary from zero
            at the leading edge to 1.0 at the trailing edge.

            When NR3 is greater than 1, RDEV will be interpolated
            from each of the NR3 curves as a function of chord,
            and then the resulting distribution will be interpo-
            lated as a function of trailing edge radius.

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NS1, NS2, NS3, S1M, SLOSS, RSD, S2M, SDEV	These correspond exactly to the definitions given above for the rotor internal performance, but apply to the stator, <u>except</u> that SDEV is the fraction of the stator trailing edge deviation angle, with no alternative.
NCASE	The number of test points to be analyzed. Must satisfy $1 \leq \text{NCASE} \leq 20$.
PSCALE	If PSCALE$\neq$0.0, it is the scale in psi/inch for the static pressure plots. (If PSCALE=0.0, a value of 5.0 is used).
PLOWER	If PLOWER$\neq$0.0, it is the minimum value of static pressure on the static pressure plots. (If PLOWER= 0.0, a value of 10.0 is used).
DAMPF	The constant shown as 8 in Equation 90 will be replaced by DAMPF if a value other than zero is given. A reduction to 6.0 or 4.0 has been found necessary to increase the damping sufficiently so that stability is maintained in some cases.
NSAVE	If NSAVE=0, each test point calculation starts with a new initial-streamline-pattern estimate. If NSAVE=1, and the preceding calculation was successful, the streamline pattern will be retained as a first estimate.
NNMAX	If NNMAX$\neq$0, it overwrites the value of NMAX previously read in.
MFORCE	If MFORCE$\neq$0, it overwrites the value of NFORCE previously read in.
NEX	Experimental probe values of total pressure and total temperature are not generally available at the annulus walls and hence extrapolation is required. If NEX=0, the experimental data are linearly extrapolated. If NEX=1, experimental data in the outer-wall region are linearly extrapolated, but at one half of the slope implied by the experimental data. If NEX=2, the same modification to the extrapolation procedure is also made in the inner-wall region.

NTCR	The program includes a procedure for correction of the total temperature probe readings input as TR and TS. This is _not_ executed if NTEMP=1 and NTCR=0; the input values are assumed to be corrected. The correction is made if NTEMP=0 or NTCR=1.
NCARD	If NCARD=0, no special action is taken.
	If NCARD = 1, output data are placed onto unit 6, which is equated to the PUNCH file. These data include the rotor and stator blade performance data (inlet and outlet radii, inlet Mach number, incidence, deviation, loss coefficient, and 3-D D-factor) on each streamline, computed static pressures at hub, mid, and tip streamlines, experimental static pressures, and test point compressor performance results. This output is generated for each test point analyzed.
NPDQ	If NDPQ=0, no special action is taken.
	If NDPQ=1, additional printout is generated which is the static pressure difference across the blades at each meshpoint from blade leading edge to blade trailing edge. If the number of blades in any row is set to zero, the pressure differences are computed for ten blades.
TITLE	A title card for the test point; 72 alphanumeric characters starting in column 1.
GASR	The gas constant. Units: ft lbs/lb deg Rankine.
FRCAIR	The fraction of the gas by mass that is dry air; the remainder is taken to be water vapor.
FLOW	The flow rate. Units: lbs/sec.
RPM	The compressor rotational speed. Units: rev. per minute.
PIN	The compressor inlet total pressure. Units: lbs/sq. in. abs.
TIN	The compressor inlet total temperature: Units: deg. Rankine.

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TRATIO	Not used in the calculation.
PRATIO	The ratio of actual compressor inlet total pressure at test time to the value PIN. This will be other than 1.0 if the test data are corrected to some standard inlet condition before submission to Program UD0200. (It is used in the correction of the total temperature probe data.)
RESTAG	For cases that include an IGV, this is the change in setting angle from its "design value". This would generally equal DEL in the input to UD0100. For a conventional machine with positive rotation, a positive RESTAG value would correspond to "closing" of the IGV row. Units: degrees.
NRP	The number of radial locations at which the total pressure is given at station NSTN1. Must satisfy $1 \leq NRP \leq 21$.
RRP	The radius at station NSTN1 where the total pressure is given. Must be in ascending order. Units: inches.
PR	The total pressure at radius RRP. Units: lbs/sq. in. abs.
NRT	The number of radial locations at which the total temperature is given at station NSTN1. Must satisfy $1 \leq NRT \leq 21$.
RRT	The radius at station NSTN1 where the total temperature is given. Must be in ascending order. Units: inches.
TR	The total temperature at radius RRT. Units: deg. Rankine.
NSP	The number of radial locations at which the total pressures are given at station NSTN2.
RSP	The radius at station NSTN2 where the total pressures are given. Must be in ascending order. Units: inches.

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PS   The circumferential average total pressure at radius
            RSP. Units: lbs/sq/in. abs.

PSM   The peak total pressure at radius RSP. Units: lbs/
            sq/in. abs.

NST   The number of radial locations at which the total
            temperature is given at station NSTN2. Must satisfy
            $1 \leq NST \leq 21$.

RST   The radius at station NSTN2 where the total tempera-
            ture is given. Must be in ascending order. Units:
            inches.

TS   The circumferentially averaged total temperature at
            radius RST. Units: deg. Rankine.

NSA   The number of radial locations at which the whirl
            angle is given at station NSTN2. Must satisfy
            $1 \leq NSA \leq 21$.

RSA   The radius at station NSTN2 where the whirl angle is
            given. Must be in ascending order. Units: inches.

SA   The circumferentially averaged whirl angle at radius
            RSA. The whirl angle is defined by tan(SA)=whirl
            velocity/meridional velocity, and is positive in the
            direction of rotor rotation. Units: degrees.

NWSO   The number of points on the casing where the static
            pressure is given. Must satisfy $0 \leq NWSO \leq 22$, except
            that if NBL=1, for any station, $NWSO \neq 2$.

XWSO   The axial coordinate at which the casing static
            pressure is specified. Must be in ascending order.
            Units: inches.

WSPO   Casing static pressure at point XWSO. Units: lbs/
            sq. in. abs.

NWSI   The number of points on the hub where the static
            pressure is given. Must satisfy $0 \leq NWSI \leq 22$.

XWSI   The axial coordinate at which the hub static pressure
            is specified. Units: inches.

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WSPI   Hub static pressure at point XWSI. Units: lbs/sq.
                in. abs. Note: The hub static pressures are not
                used in any calculations, but are displayed on the
                stage static pressure distribution plot if NPLOT≠0.

NPSR   The number of points at specified, intermediate radii
                where the static pressure is given. Must satisfy
                0≤NSPR≤20, except that if NBL=5 or 6 for any station
                NPSR≥2.

XPSR   The axial coordinate at which the intermediate static
                pressure is specified. Must be supplied in ascending
                order. Units: inches.

RPSR   The radius at which the intermediate static pressure
                is specified. Units: inches.

PSSR   Static pressure at point (XPSR, RPSR). Units: lbs/sq.
                in. abs.

BLCKGE,   The annulus boundary layer and wake blockage is accounted
BDIST   for by a distributed blockage. BLCKGE is the fraction
                of the circumference at midradius that is blocked, and
                BDIST is the ratio of the blockage at the hub to the
                midradius value, BLCKGE. The radial distribution is
                linear.

DEL, DELDST   When NBL=3, 4, or 6, the flow deviation angle at the
                station is varied in order to match computed and
                experimental static pressures. DEL (units: degrees)
                is the first estimate of the variable component of
                deviation angle at midradius, and DELDST is the ratio
                of hub deviation to midradius deviation. The variation
                with radius is linear.

BFRAC   When NBL=4 or 6, BFRAC is the fraction of trailing
                edge blockage that is to be applied at the station.
                BLCKGE is used for the first pass through the calcu-
                lation. BDIST applies throughout.

NMACHI   If NMACHI is zero, the subsonic solution to the con-
                tinuity equation is obtained. If NMACHI is 1, the

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supersonic solution to the continuity equation is
obtained. Note that NMACHI may be validly set equal
to 1 only if NCALC=2.

NJUMP   If NJUMP=0, normal computation follows. If NJUMP=1,
the program skips the computation and reads in the
next set of test data. Must be zero for the last
set of test data.

SECTION IV

OUTPUT DATA

1. INTRODUCTION

The output from Program UD0400 consists of printer, card punch, and
plotter output data. The printed output consists of two sections; output
data from the UD0100 section and from the UD0200 section. Each section
of data may occur more than once or may be absent, depending on the number
of blade geometry definitions generated and the number of experimental
cases analyzed. In each section, the printed output is divided into two
classes; regular output and diagnostic output. The regular and diagnostic
outputs for each section are discussed in detail below.

2. SECTION UD0100 REGULAR OUTPUT

The blade geometry definition printed output consists of two parts;
first a listing of the input data and second a listing of the results
computed by the program. The listing of the input blade section coordinate
data to the UD0100 section of the program may be omitted by use of the
NPRINT=1 option. If the data are listed (NPRINT=0), they show the coordi-
nates as input, that is, before any rotation is applied to them. If
NWHICH=1, the additional input data involved is listed and also the x-r
coordinates of the derived computing stations are shown. The x-values
shown are relative to the same origin as was used to input the data for
UD0100. The quantity XSHIFT is added to these data however, before they
are written out to file TAPE7 (unit LOG7).

The results computed by the UD0100 section are printed and output
onto a second unit file TAPE8 (unit LOG8) in a format directly compatible
with the input data requirements for the UD0200 section. For each computing
station, given first is the number of radii at which data are given.
This will not necessarily equal the number of constant-z planes at which
data were input if partially-defined sections are involved. Next are
given the radii at which the blade mean lines on each of the input data
planes intersect the station, and, at each radius, the blade section angle,
the blade lean angle, the blockage, and the angular coordinate of the
intersection of the blade mean line with the station. The blade section

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angle is the angle made by the intersection of the blade mean line and a cylinder with the meridional (axial-radial) plane. It is taken positive in the direction of rotor rotation. The blade lean angle is the projection onto a constant-x plane of the angle made by the intersection of the blade mean surface and the station with a locally radial line. This is taken positive for sweep-back relative to rotor rotation. Both the blade section angle and the blade lean angle are given in degrees. The blockage is the fraction of the circumference at the given radius that is blocked by the blades. The angular coordinate of the intersection of the blade mean line with the station is measured from the radial line that is also the z-coordinate. It is taken positive in the direction of rotor rotation, and is given in radians.

3. SECTION UD0100 DIAGNOSTIC OUTPUT

There are two iterative procedures in section UD0100 and they both have associated messages that will be printed should they fail to converge. If the determination of the coordinates of a point on the mean line of a blade section fails, the following message will appear:

MEANLINE DETERMINATION ITERATION FAILS

J=XXX NO. OF POINT ON P SURFACE = XXX

Here J is the number of the constant-z plane. If the determination of the axial coordinate of the intersection of the blade mean line with a computing station fails, the following message will appear:

ITERATION FOR XHERE FAILS I = XX

Here I is the computing station number. In both cases, the program will terminate execution and an input data error should be suspected.

4. SECTION UD0200 REGULAR OUTPUT

The aerodynamic analysis regular printed output consists of four parts: the fixed data printout, the test data printout, the printout of computed results, and data that are plotted on a CALCOMP plotter (if desired). The fixed data printout consists of all the input data items that are read in only once per program execution and displayed in the order in which they are read in. This includes principally the compressor geometry and some "constants". Where computing station data are read from

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file TAPE7 (presumably having been created by the UD0100 section), the number of the hub and casing segments that are to be used to find the two wall radii are given. Then, the wall segment data will also be listed, followed by the calculated wall radii for each station that has the NSPEC=0 input option. Where an IGV occurs, the input data is listed under appropriate headings. IGV total pressure loss coefficients, both input and as shown in the computed results, are based upon outlet dynamic head.

Next, all the input data that are peculiar to the test point are listed, in the order in which they are read in. This data consists mainly of the experimental measurements. Then follow the computed results for the test point. These two outputs repeat for each new test point considered. The computed results are output station-by-station for all computing stations. If the calculation fails, the output will only be generated for stations up to the station where failure has occurred. For every computing station there appears a flow field description giving details of the flow relative to a stationary or absolute coordinate system. Only two items require any explanation. The whirl angle is defined as the angle whose tangent is the ratio of whirl velocity to meridional velocity. The radius of curvature of the meridional projection of the streamlines is shown as zero for the case of a straight line, when, of course, the actual value is infinite. (For this reason, the actual computation is based on curvature.) For computing stations that are at a blade leading or trailing edge, or located within a blade, a printout of data describing aspects of the blade section and its performance is made. The blade section angle is interpolated from the input data, and transformed from the value for a cylindrical section to that applying on the computed stream surface according to the blade lean angle and streamline slope angle. The blade lean angle is simply interpolated from the input data. The relative flow angle differs from the blade section angle by the amount of the incidence or deviation angle, which is also given. The relative total pressure loss coefficient reflects the loss up to the station for the blade section, referenced to the blade inlet relative dynamic head. The pressure ratio, normalized temperature rise, isentropic efficiency, and polytropic efficiency are cumulative for the compressor through to the relevant computing station, and are based upon

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stagnation conditions. This applies to both the streamline and integrated values.

Following the flow description for the last computing station, print-outs are made of the rotor and stator blade section overall performances. (The latter or both of these outputs will not occur, however, if the calculation has not successfully progressed to the stator trailing edge, or the rotor trailing edge, respectively.) The streamline inlet and outlet radii, the relative inlet Mach number, the incidence and (final) deviation angles, the (final) loss coefficient, the blade section angles at inlet and exit, and the blade lean angles at inlet and exit are reiterations of data that was previously printed in the station-by-station output. Note that in this section, the rotor incidence and deviation angles are conventionally signed. Additionally, computed quantities are diffusion factor, static pressure rise coefficicient, relative velocity ratio (sometimes called de Haller number), and normalized total enthalpy-rise. Diffusion factors are calculated on a conventional two-dimensional basis, and also accounting for the effects of radius change.

The next data that are output, describe the wake and boundary layer blockages that have been incorporated into the calculation. For each station there is shown the midradius blockage, the distribution factor, and the blockage integrated along the computing station. The midradius blockage will be the input value BLCKGE if NBL for the station is 0, the value calculated to give a casing static pressure match if NBL is 1, or an interpolated value if NBL is 2. The distribution factor is the input value BDIST, and the integrated blockage will only differ discernably from the midradius value if BDIST is different from 1.0, and the computing station has a low hub/tip ratio.

The printed output for each test-point is concluded with a summary of the compressor running conditions and a statement of the success or other-wise of the calculation. If the calculation has successfully converged, the following message appears:

THE CALCULATION IS CONVERGED PASS xx.

The pass number is the number of loops that have been made through the over-all iterative procedure. If the calculation is unconverged after all per-mitted iterations have taken place, the following message will appear:

THE CALCULATION IS UNCONVERGED IVFAIL = xx

IFFAIL = xx   PASS xx

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IVFAIL refers to the number of mesh points where, from the penultimate to final passes, the meridional velocity differed by more than one part in a thousand. IFFAIL is the number of stream tubes (defined by the hub and each streamline to the casing) where the fraction of the total flow differed by more than one part in a thousand from the correct value. Should this message occur, and the two counts be, say, one tenth or less of their maximum possible values, the calculation can probably be taken as accurate. If larger counts occur, the program should be rerun with a larger permitted number of passes specified. In the event that the calculation has failed, the following message will appear:

THE CALCULATION FAILED AT STATION xx PASS xx

Normally the pass number will be the first pass after all "forced" passes (that is those where arbitrary numbers are introduced if required) have expired. A data error should be suspected, but it is possible that experimental data may be collected that is not compatible with the flow model incorporated into the computer program.

If NCARD = 1 is selected, punch-card output is generated on unit 6 for each test point analyzed which may be used to generate plots through another plotting program. This option is useful when CALCOMP software is not available or plots in a different format than those generated by UD0400 are desired. These punch-card data include:

(1) Rotor and stator blade performance data (streamline number, inlet and outlet radii, inlet Mach number, incidence, deviation, loss coefficient, and 3-D D-factor), one card per streamline in an (I4,F10.4,F9.4,F8.4,2F9.3, 2F8.4,F9.4) format.

(2) Computed static pressures and experimental static pressures. The first card contains the number of computing stations, number of casing experimental presssures, number of hub experimental pressures, and number of intermediate pressures in a 4I5 format. Then follow the computed hub static pressures (axial coordinate and static pressure in a 2F10.4 format, one card per computing station), the computed mid static pressures, the computed tip static pressures, casing experimental static pressures, hub experimental static pressures, and intermediate experimental static pressures.

(3) Test point compressor performance results (test point number, flow

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rate, rotor RPM, rotor total pressure ratio, rotor isentropic efficiency, stage total pressure ratio, stage isentropic efficiency, and ratio of flow-to-choked flow) in an (I12,F9.5,F9.2,F9.6,F9.7,F9.6,F9.7,F9.7) format.

The test data printout and results for the test point are repeated for each of the NCASE test points to be analyzed. Following the results for the last test point, a summary table showing the results for each point is printed. The data displayed are all a reiteration of the final performance figures noted for each point, with the addition of the ratio of the flow rate to the inlet choking flow rate. The inlet choking flow rate is computed on a one-dimensional basis from the inlet total pressure and temperature and the area at the rotor inlet. The area is based upon rotor tip and hub radius; that is, the station is assumed to be radial.

The remaining regular output is the optional CALCOMP plots. If NPLOT is 1 or 2, static pressure distribution plots are made. A separate graph is created for each test point, and the computed static pressure distributions on the hub, mid, and casing streamlines are plotted. Also shown are any experimental values that were included in the input data. Ten further plots show for both rotor and stator, the radial variation of relative inlet Mach number, incidence angle, relative total pressure loss coefficient, deviation angle, and diffusion factor. (The diffusion factor computed with radius change effects is plotted.) When NPLOT=2 (or 3), nondimensional meridional velocity profile plots are also made. If NPLOT=3, the same blade performance plots are made as for NPLOT=2, but the static pressure distribution plots are not made. If NPLOT is 1, a separate group of plots is made for each test point, and if NPLOT is 2, the results for all test points are plotted on one set of graphs. (Generally, this option is recommended as it will permit comparisons of values at different running conditions to be readily made, and also the amount of paper produced is more reasonable!)

5. SECTION UD0200 DIAGNOSTIC OUTPUT

During the execution of the program certain difficulties may arise which result in the issue of one or more diagnostic messages. All the possible diagnostic messages are detailed here, and also given a number. Reference is made to these numbers in a later section.

Messages 4 through 9 are only printed if the iterative pass number is greater than NFORCE, the last pass during which arbitrary numbers are

inserted into the solution, if required, without the calculation being abandoned. On prior passes, only the corrective action described is taken, and the calculation proceeds.

a. Message No. 1

STATION xx LAST = xx TOO MUCH STATION SPECIFICATION DATA

This message will occur if more than 200 points are given in the input data to specify the geometry of the computing stations. LAST is the excessive cumulative total number of points reached at the specified station. Program execution ceases.

b. Message No. 2

STATION xx LAST = xx TOO MUCH BLADING DATA

This message will occur if more than 200 radial locations are used in the input data to specify blading geometry. LAST is the excessive cumulative total number of points reached at the specified station. Program execution ceases.

c. Message No. 3

FUNCTION FF2 HAS NOT CONVERGED

Function subprogram FF2 computes temperature as a function of enthalpy and, because specific heat is given by a fifth-order polynomial function of temperature, the calculation is iterative. If the calculation does not converge, this message is emitted, and the last estimate of the temperature is used. Twenty cycles of calculation are permitted, and the calculation is taken to be converged if the determined temperature corresponds to an enthalpy that is within one part in a million of the correct (input) value.

d. Message No. 4

PASS xx STATION xx STREAMTUBE xx ITERATION xx UNREAL
STATIC ENTHALPY

During the iterative solution of the momentum and continuity equations, the static temperature is repeatedly re-estimated as a function of the total enthalpy and the velocity. This message relates to the determination of the static temperature during computation of the momentum equation. A lower limit of 10.0 BTU per lb is set for the static enthalpy (from

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which the static temperature is determined). If this limit is violated, the static enthalpy is arbitrarily set equal to 10.0. Also, if the pass number is greater than NFORCE, the above message is printed. Additionally, if this occurs during the last permitted iteration for the solution of the momentum and continuity equations (20 are allowed) and failure of the solution has not been previously noted during the current pass, a flag is set to record failure of the solution. Then computation ceases, and results are printed for stations through to the station where failure has been noted.

e. Message No. 5

PASS xx STATION xx STREAMTUBE xx ITERATION xx EXPONENTIAL
ARGUMENT LIMITED TO 88.0

Computation of the meridional velocity profile from the momentum equation involves evaluating an exponential which assumes excessive values only when unreasonable velocity profiles are implied. An upper limit of 88.0 is set for the argument to the exponential function. The logic of events if this limit is exceeded is the same as described above for message No. 4.

f. Message No. 6

PASS xx STATION xx STREAMLINE xx ITERATION xx VM = J*x.xxxxExx

The momentum equation yields at each streamline the square of the meridional velocity. Gradients of enthalpy, entropy, and so forth specified to the computation could yield negative values for the square of the merid-ional velocity, which, in the case of this program, would indicate an incom-patibility between the flow model and the experimental data. In the program, a lower limit on the meridional velocity of 1.0 feet per second is set. The logic of events if this limit is violated is the same as described above for message No. 4. The final number printed in the message is the square root of the modulus of the square of the offending meridional velocity.

g. Message No. 7

PASS xx STATION xx STREAMTUBE xx ITERATION xx STATIC ENTHALPY
UNREAL

The meaning of this message and the logic of associated events is identical to that for message No. 4, except that in this case the limit on static enthalpy is applied during computation of the continuity equation.

h. Message No. 8

PASS xx STATION xx ITERATION xx CONTINUITY SWITCH REQUIRED

During the iterative solution of the continuity and momentum equations, the type of solution (subsonic or supersonic) that is being generated is continuously monitored. In the event that the velocity profile determined during any iteration constitutes a solution of the wrong type, the midradius meridional velocity (the starting point for the velocity profile determination) is modified not to give a flow more nearly equal to the desired value, but to give a solution of the correct type. This action is termed a continuity switch. The logic regarding the setting of the failure flag and printing of the above message are the same as for message No. 4. Therefore, the message will normally only appear in the results if the flow rate specified at the computing station is greater than the maximum possible. In marginal cases, a solution may be found by increasing NFORCE in the input data.

i. Message No. 9

PASS xx STATION xx UNCONVERGED   FLOW/SPECIFIED
FLOW = xx.xxxxx   VOLD/VNEW(HUB) = xx.xxxxx   VOLD/
VNEW(CASE) = xx.xxxxx

Up to 20 attempts are permitted to iteratively solve the continuity and momentum equations at each station during each pass. The solution is taken to be converged if the flow rate at the station is within one part in 4000 of the correct value, and the meridional velocities at every streamline agree on two consecutive iterations to within the same tolerance. If all 20 iterations are expired without convergence being achieved, and the pass number is greater than NFORCE, the above message is printed. If the pass number given is less than the pass number for which final results are printed, no particular significance attaches to the message, except that the (final) solution was somewhat more difficult to obtain than the norm. If the pass number given equals that for which the final results are printed, then the three ratios printed may be examined to see to what extent the solution is unconverged. If the results are to be used, the ratios should all be within, say, one part in 500 of unity. Note however that if one of the preceeding five messages has occurred in addition to this message, it becomes of secondary significance. If the solution is at all badly unconverged, the overall convergence criteria are unlikely to be met. Therefore, this message will generally only appear alone for the final pass if that pass is the last permitted, and overall convergence has not been

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achieved.

j. Message No. 10

STATION xx STREAMLINE xx ISENTROPIC TEMPERATURE CHANGE
NOT CONVERGED

In order to compute efficiency it is necessary to determine the
isentropic temperature change corresponding to the actual total pressure
ratio on each streamline. This is done iteratively, and the above message
will appear if the calculation is unconverged after the permitted 20 itera-
tions. The calculation is taken to be converged when the total temperature
change determined corresponds to an outlet pressure that is within one part
in 1,000,000 of the correct value. No corrective action is taken; the com-
putation proceeds using the last estimated value for the temperature change.

k. Message No. 11

PASS xx STATION xx ITERATION FOR STATIC PRESSURE POINT LOCATION
FAILS

When NBL = 5 or 6, an iterative procedure is used to determine the
location of the point where the computing station intersects the line joining
the two static pressure points that span the computing station. (A point may
be precisely on the computing station but the procedure is expected neverthe-
less.) The procedure is deemed to be converged if the radius determined on
the computing station is constant on two successive iterations to within
0.001 inches. The above message will occur if this criterion is not met
after 20 attempts, and execution will be terminated.

l. Message No. 12

PASS xx STATION xx STREAMTUBE xx ITERATION xx
EXPONENTIAL ARGUMENT LIMITED TO -88.0

This corresponds to message No. 5 except that in this case the
argument is less than -88.0.

m. Message No. 13

PASS xx STATION xx STREAMLINE xx ITERATION xx
VM/VM(MID) = xx.xxx   VM(MID) = x.xxExx

In the solution of the momentum equation, no meridional velocity is
permitted to be more than 3.0 times the value on the mid-streamline. If this
limit is violated, the above message appears, and the limiting value is
imposed. If the condition occurs when the pass number is greater than NFORCE
and during the last permitted iteration (for the solution of the momentum and

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continuity equations), computation ceases, and results are printed through to the station where the failure has occurred.

    n.   Message No. 14

        PASS xx STATION xx STREAMLINE xx ITERATION xx
        STATIC ENTHALPY BELOW LIMIT - LOSS COEFFICIENT CALCULATION

In calculating the relative total pressure loss coefficient, the static enthalpy at the blade-row inlets is computed. If a value less than approximately 0.41 of the compressor inlet total enthalpy is determined, this limiting value is imposed, and the above message appears. If this would occur on the final pass, for which results are printed, the corresponding loss coefficients would be invalid.

SECTION V

THEORY AND METHODS

1. SECTION UD0100

    a. Nomenclature and Equations

        The calculations that are made in the UD0100 section of the
program revolve mainly around the blade section mean lines. The blade
sections are defined on constant-z input data planes by the X-Y coordi-
nates of points on the section surfaces. The X-Y coordinates of each
point describing the sections are changed to X'-Y' coordinates by
rotating the point DEL degrees anticlockwise about the point (XR, YR),
as shown in Figure 1.
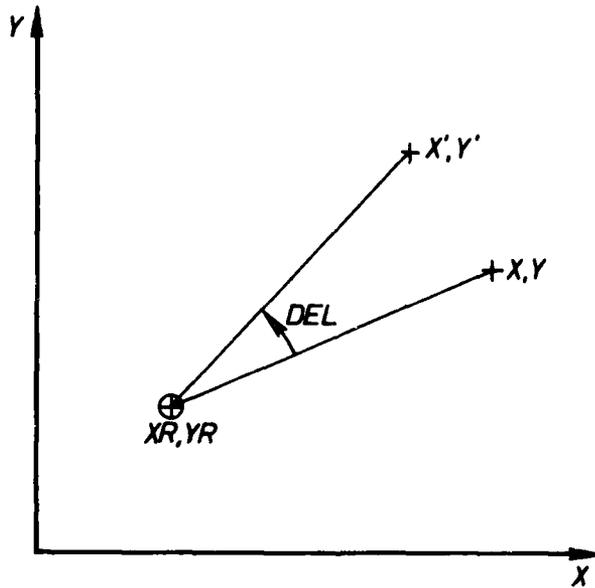
Figure 1. Blade Coordinate Rotation

Because a single point (XR, YR) is used for the entire blade, the assumption is being made that the axis of rotation of the blade is parallel to the z-axis of the blade cartesian coordinate data, which is a radial line.

Having made the coordinate transformations, the mean line is defined as the curve passing through the centers of all circles that are simultaneously tangent to both blade section surfaces. From Figure 2,

$$R = \frac{((y_p - y_s) \cos \alpha_s - (x_p - x_s) \sin \alpha_s)}{(1 + \cos(\alpha_p - \alpha_s))} \tag{1}$$

$$x_s = x_p + R(\sin \alpha_s + \sin \alpha_s) \tag{2}$$

$$x_{mean} = x_p + R \sin \alpha_p \tag{3}$$

$$y_{mean} = y_p - R \cos \alpha_p . \tag{4}$$

Now, considering the blade in cylindrical polar coordinates, the mean lines each define a surface of revolution. The corresponding coordinates are

$$r = \sqrt{z^2 + y^2} \tag{5}$$

and

$$\theta = \tan^{-1}(y/z) \tag{6}$$

$$(\text{and } x = x) . \tag{7}$$

Then the blade angle on the surface of revolution is

$$\beta_{z-constant} = \tan^{-1}(r d\theta/dx) . \tag{8}$$

The blade lean angle along a computing station is given by

$$\epsilon_x = \theta - \tan^{-1}(dy/dz) . \tag{9}$$

The blade angle on a cylindrical section through the blade is related to the constant-z value by

$$\tan \beta_{r-constant} = \frac{\tan \beta_{z-constant} + \tan \epsilon_x \tan \lambda}{1 - \tan \gamma \tan \lambda} \tag{10}$$

where

$$\lambda = dr/dx \tag{11}$$

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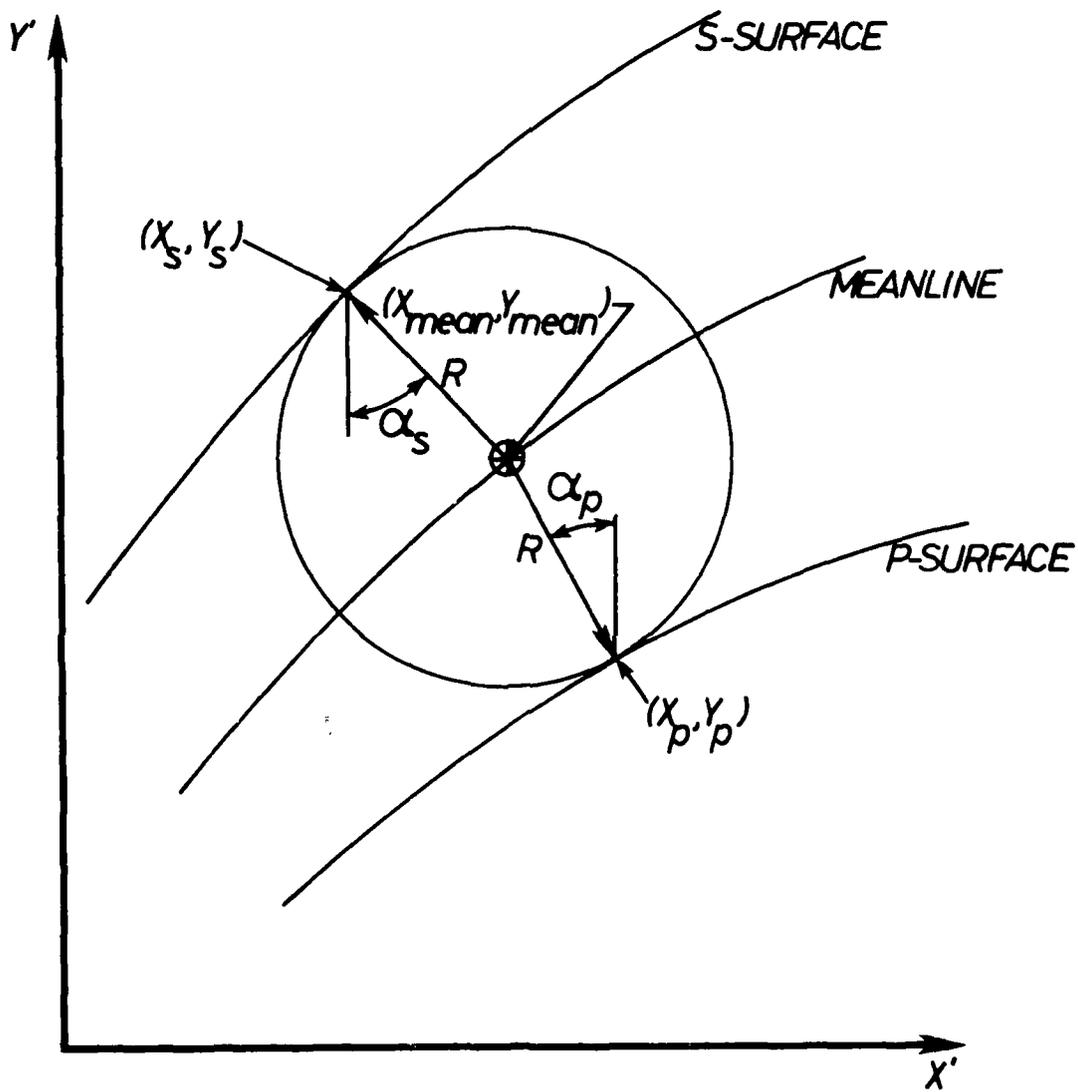
Figure 2. Geometry of Blade Section Meanline Determination

on the surface of revolution. Equation 10 is derived in Reference 3. The blockage due to the blade is found by considering the coordinates of the two surfaces of the blade at a given 'x', and is given by

$$B = \frac{\sin^{-1}(y_p/r) - \sin^{-1}(y_s/r)}{2\pi} \times \text{no. of blades}. \tag{12}$$

Equations 1 through 12 enable properties of the blade sections defined by constant-z planes to be determined. Interpolation and/or extrapolation will generally be required to obtain values at points relevant to the aerodynamic analysis, that is, at the radii where streamlines are calculated to lie.

b. Iterative Solution of Equation 1

Given the coordinates of a series of points defining the p- and s-surfaces of the blade section, it is required to determine the coordinates of a series of points on the mean line. (The designation of either surface as the p- or s-surface is quite arbitrary. It will have an insignificant effect upon the result of the calculation.) A point is determined on the mean line to correspond to each point on the p-surface. Here "corresponds" means "is the center of a circle that is tangent to the given point on the p-surface and some point on the s-surface". In the event that the point on the s-surface is obtained by extrapolation of the surface beyond the leading edge of the blade (i.e., the first point specified), the mean line point so derived is discarded. A mean line point derived at the trailing edge by extrapolation of the s-surface will be retained or discarded. This feature is intended to enable the user to place a trailing-edge station at the actual blade edge without losing data points because both surfaces do not extend to this axial location. The iterative solution of Equation 1 proceeds as follows:

(1) Select a point on the p-surface, noting its coordinates, x_p and y_p. Determine the surface slope at this point, $\tan \alpha_p$ (=dy_p/dx_p). (The methods used to determine slopes and for interpolations is described below.)

(2) Estimate the corresponding x-coordinate on the s-surface, x_s, as being equal to x_p.

(3) Determine the y-coordinate and surface slope at x_s; y_s, and α_s, respectively.

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(4) Calculate the circle radius, R, from Equation 1.

(5) Refine the estimate of x_s by applying Equation 2.

(6) Return to Step 3 until the solution is converged, which is taken to be when

$$\frac{|R_j - R_{j-1}|}{yp - ys} \leq .001.$$

(7) The coordinates of the center of the circle, i.e., the point on the mean line that has been determined, are calculated from Equations 3 and 4.

c. Iterative Determination of Coordinates of Intersection of Surface of Revolution with Computing Station.

The location of this intersection is required because this is the point where the blade parameters are obtained. The determination proceeds as follows:

(1) Estimate the x-coordinate (x) to be the first value defining the computing station, that is, generally, the axial location of the station at the hub. (In the special case of an "upright" computing station, this estimate will be correct, leading to immediate convergence.)

(2) Interpolate the radius (r) on the surface of revolution at the estimated 'x'.

(3) Interpolate the axial coordinate (x) on the computing station at the 'r' derived in Step 2.

(4) Return to Step 2 until the solution is converged, which is taken to be when

$$|x_j - x_{j-1}| \leq .00001.$$

(The program will normally be used with dimensions of inches.)

d. Interpolation and Determination of Derivatives

All interpolation and derivative determination in section UD0100 is performed by curve fitting the data with a spline curve, and then evaluating the curve, or its analytic derivative, at the desired location. The

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spline curve consists of a series of algebraic cubics, one equation pertaining to the interval between each adjacent pair of data points. The four coefficients of a cubic equation enable the first and second derivatives of the two equations that apply at each point to be made equal, in addition to passing the curve through the data points. Conditions must be arbitrarily imposed at the two end-points, and the selected condition for both ends is that the second derivative at the end point is equal to the value at the adjacent point. Should extrapolation (rather than interpolation) be required, this is performed linearly at the slope of the spline curve at the appropriate end points.

The cubic equation between data points n - 1 and n is

$$y = \frac{M_{n-1}}{6} \frac{(x_n - x)^3}{(x_n - x_{n-1})} + \frac{M_n}{6} \frac{(x - x_{n-1})^3}{(x_n - x_{n-1})} + (x_n - x) \left[\frac{y_{n-1}}{x_n - x_{n-1}} - \frac{M_{n-1}}{6} (x_n - x_{n-1}) \right] +$$

$$(x - x_{n-1}) \left[\frac{y_n}{x_n - x_{n-1}} - \frac{M_n}{6} (x_n - x_{n-1}) \right] \qquad (13)$$

and its derivative is

$$\frac{dy}{dx} = - \frac{M_{n-1}}{2} \frac{(x_n - x)^2}{(x_n - x_{n-1})} + \frac{M_n}{2} \frac{(x - x_{n-1})^2}{(x_n - x_{n-1})} + \left(\frac{y_n - y_{n-1}}{x_n - x_{n-1}} \right) -$$

$$\left(\frac{M_n - M_{n-1}}{6} \right) (x_n - x_{n-1}) . \qquad (14)$$

The coefficients M_n are found by first calculating three series of coefficients, A_n, B_n, and D_n. These are determined from

$$\left. \begin{array}{l} A_1 = 1.0 \\ B_1 = -1.0 \\ D_1 = 0.0 \end{array} \right\} \qquad (15)$$

and

$$A_n = \frac{(x_{n+1} - x_{n-1})}{3} - \frac{(x_n - x_{n-1})}{6} \frac{B_{n-1}}{A_{n-1}}$$

$$B_n = \frac{x_{n+1} - x_n}{6}$$

$$D_n = \frac{y_{n+1} - y_n}{x_{n+1} - x_n} - \frac{y_n - y_{n-1}}{x_n - x_{n-1}} - \frac{x_n - x_{n-1}}{6} \frac{D_{n-1}}{A_{n-1}} \qquad (16)$$

The subscript n in Equations 16 is varied from 2 to N, the total number of data points. Then the M coefficients may be determined from

$$M_N = \frac{A_N D_{N-1}}{A_N B_{N-1} - A_{N-1} B_N} \qquad (17)$$

and

$$M_n = \frac{D_n - B_n M_{n+1}}{A_n} . \qquad (18)$$

In Equation 18, n is varied from N − 1 to 1.

    e. Computing Station Location Determination

        Because rotation of the blade will lead to axial movement of the blade edges, section UD0100 may also be used to determine computing station locations. Given X and Y at the leading edge of a blade section at design setting, after rotation X' and Y' are obtained as for any other point. Then for the leading edge computing station,

$$X_{le} = X'$$
$$r_{le} = \sqrt{Y'^2 + Z^2} . \qquad (19)$$

A series of such points, at each Z-value, will define that station axial location. The trailing edge station location may be found similarly. For intermediate stations, if any are desired, the fraction of blade section meridional chord, F, is given. Then for an intermediate station,

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$$X = X_{le} + F(X_{te} - X_{le})$$

$$r = r_{le} + F(r_{te} - r_{le}).$$

(20)

f. Computational Sequence

The execution of section UD0100 follows the following sequence. The calculations are related to the FORTRAN program by means of the identification field in the columns 73 through 78 of the program cards:

(1) Read and print input data defining the number and location of the constant-z planes, and the number and location of the stations where output data are to be generated. (034430 through 034740)

(2) Read and print input data defining the blade restagger, blade leading and trailing edges, center of rotation, and computing station spacing. (034760 through 034930)

(3) Rotate blade edge coordinates, calculate computing station coordinates, and print results. (034940 through 035190)

(4) A sequence is started that is performed for each constant-z plane. (035300)

(5) The points defining the s- and p-surfaces of the blade section are read in and printed. (035310 through 035430)

(6) Rotate the blade section coordinates by the restagger angle. (035460 through 035540)

(7) Determine the coordinates of points on the mean line using Equations 1 through 4. (035550 through 035800)

(8) Determine the cylindrical polar coordinate equivalents to the cartesian coordinates determined in Step 7 using Equations 5 through 7. (035810 through 035840)

(9) Determine (iteratively) the coordinates of the intersections of each station with the mean line. The mean line is linearly extrapolated upstream if required, but downstream if required only if INSIST = 1. (035850 through 036000)

(10) Determine at the intersection of each computing station with the mean line, the following quantities: $d\theta/dx$, dr/dx, θ, y_s, and y_p. (036010 through 036050)

(11) At the intersection of each computing station with the mean line, determine $rd\theta/dx$ ($= \tan \beta_z$ constant) and the blockage B using Equation 12. (036060 through 036120)

(12) This terminates the loop commenced in Step 4. (036130)

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(13) A sequence is started that is performed for each station. (036150)

(14) The various quantities determined previously are shifted in their storage areas if "partial sections" have left the first elements of the arrays unused. (036160 through 036240)

(15) The y- and z-coordinates of the intersection of the mean line of each blade section with the computing station are obtained. (036250 through 036270)

(16) By spline-fitting the y and z data found above, the derivative dy/dz is found at each section. (036280)

(17) For each section, the angle ϵ_x is found from Equation 9 and the blade section angle for a cylindrical section through the blade is found from Equation 10. (036290 through 036340)

(18) The calculated blade parameters are written on units LOG2 (for printing) and LOG8 (for punching). (036350 through 036420)

(19) This terminates the loop commenced in Step 13. (036430)

(20) The subroutine always returns control to the main program in an attempt to compute a further data set. (036440)

2. SECTION UD0200

a. Flow Model and Governing Equations

The fluid flowing through the compressor is assumed to be an inviscid, thermally-perfect gas. The flow is taken to be axisymmetric, with the effects of blades represented by distributed body forces. It is further assumed that there is no transfer of mass or energy normal to the local flow direction.

Calculations of conditions within the compressor are made at a series of computing stations distributed along the flow path. The stations may be radial lines, nonradial lines, or arbitrary curves. This permits the stations to be located at strategic points in the flow such as at blade edges. However, they must nowhere be parallel to the local flow direction (as seen in meridional projection) and, in fact, the equations are more readily solved as the station and local (meridional) flow direction approach the perpendicular condition.

The equation of state for a thermally-perfect gas is:

$$p = wRt. \tag{21}$$

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The specific heat at constant pressure is defined (arbitrarily) as:

$$Cp = a + bt + ct^2 + dt^3 + et^4 + ft^5. \tag{22}$$

Thus, the enthalpy at temperature t_1 (with reference to the enthalpy at a temperature of absolute zero) is:

$$h = \int_0^{t_1} Cpdt \tag{23}$$

$$= at_1 + \frac{b}{2}t_1^2 + \frac{c}{3}t_1^3 + \frac{d}{4}t_1^4 + \frac{e}{5}t_1^5 + \frac{f}{6}t_1^6. \tag{24}$$

The total enthalpy is given by

$$H = h + \frac{V^2}{2gJ}. \tag{25}$$

The corresponding total temperature may be found by solving the following equation for T.

$$H = aT + \frac{b}{2}T^2 + \frac{e}{3}T^3 + \frac{d}{4}T^4 + \frac{e}{5}T^5 + \frac{f}{6}T^6. \tag{26}$$

The first law of thermodynamics may be expressed as

$$dh = tds + \frac{vdp}{J}. \tag{27}$$

For an isentropic process ds = 0, and substituting from Equations 21, 22, and 23, we may obtain upon integrating between limits:

$$\frac{p_2}{p_1} = \exp\left\{ \frac{J}{R}\left(a\,\log_e\frac{t_2}{t_1} + b\,(t_2 - t_1) + \frac{c}{2}\,(t_2^2 - t_1^2) + \right.\right.$$
$$\left.\left. \frac{d}{3}\,(t_2^3 - t_1^3) + \frac{e}{4}\,(t_2^4 - t_1^4) + \frac{f}{5}\,(t_2^5 - t_1^5) \right) \right\} \tag{28}$$

and also

$$\frac{\rho_2}{\rho_1} = \exp\left\{ \frac{J}{R}\left((a - \frac{R}{J})\,\log_e\frac{t_2}{t_1} + b\,(t_2 - t_1) + \frac{c}{2}\,(t_2^2 - t_1^2) + \right.\right.$$
$$\left.\left. \frac{d}{3}\,(t_2^3 - t_1^3) + \frac{e}{4}\,(t_2^4 - t_1^4) + \frac{f}{5}\,(t_2^5 - t_1^5) \right) \right\}. \tag{29}$$

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Conditions 1 and 2 may be static and static, total and static, or total and total, so long as they are isentropically related.

The speed of sound in a gas is given by the general relationship

$$a^2 = \frac{dp}{d\rho} . \tag{30}$$

Using Equations 21 and 29 in differential form together with the relationship

$$Cp - Cv = R/J \tag{31}$$

the speed of sound is found to be given by

$$a^2 = g\gamma Rt. \tag{32}$$

Equation 27 may also be used to determine entropy variations. Rearranging and substituting from Equation 21 yields, upon integrating between limits,

$$s_2 - s_1 = a \log_e \frac{t_2}{t_1} + b (t_2 - t_1) + \frac{c}{2} (t_2^2 - t_1^2) + \frac{d}{3} (t_2^3 - t_1^3) +$$

$$\frac{e}{4} (t_2^4 - t_1^4) + \frac{f}{5} (t_2^5 - t_1^5) - \frac{R}{J} \log_e \frac{p_2}{p_1} . \tag{33}$$

Conditions 1 and 2 may be both either total or static. The polytropic efficiency of a process is defined by

$$\eta_\infty = \frac{dh_{isentropic}}{dh} . \tag{34}$$

Thus, from Equation 27

$$\eta_\infty dh = \frac{vdp}{J} . \tag{35}$$

By making the usual substitutions and integrating between limits (assuming the polytropic efficiency to be constant throughout the process); we obtain

$$\eta_\infty = \frac{\frac{R}{J} \log_e (p_2/p_1)}{\{ a \log_e (t_2/t_1) + b (t_2 - t_1) + \frac{c}{2} (t_2^2 - t_1^2) + \frac{d}{3} (t_2^3 - t_1^3) +}$$

$$\frac{e}{4} (t_2^4 - t_1^4) + \frac{f}{5} (t_2^5 - t_1^5) \} . \tag{36}$$

It is conventional in aeroengine applications to compute efficiencies on a total-to-total basis.

The continuity equation is applied at each computing station in the form

$$W = \int_{hub}^{case} V_m \cos (\phi + \gamma) w dA \qquad (37)$$

which may be rewritten

$$W = \int_{hub}^{case} V_m \cos \phi (1 - \tan \gamma \tan \phi) w B 2\pi r dr. \qquad (38)$$

In order to determine on which branch of the continuity equation a particular velocity profile lies, and also to estimate what velocity level change is required to satisfy continuity at a computing station, the rate of change of flow with midradius meridional velocity is required. (Any convenient reference location could replace midradius.) It is not possible to derive a simple, closed-form expression for this gradient when the specific heat is a function of the form of Equation 22. Fortunately a very precise value is not generally necessary, and therefore, the derivation is made based upon the assumption of a constant specific heat. *Two slightly different derivations are required.* When the tangential velocity component is fixed, Equation 38 is rewritten as

$$W = \int_{hub}^{case} V_m \cos \phi (1 - \tan \phi \tan \gamma) w_T (1 - \frac{V^2}{2gJCpT})^{\frac{1}{\gamma-1}} B 2\pi r dr. \qquad (39)$$

The velocity V is given by

$$V^2 = V_m^2 + V_\theta^2 \qquad (40)$$

and the following substitution is made for the meridional velocity component

$$V_m = V_{m_{mid}} \times V_m / V_{m_{mid}} . \qquad (41)$$

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By making the assumption that

$$\frac{d}{dV_{m_{mid}}} \left(\frac{V_m}{V_{m_{mid}}} \right) = 0 \qquad (42)$$

the following result is obtained

$$\frac{dW}{dV_{m_{mid}}} = \int_{hub}^{case} \frac{V_m}{V_{m_{mid}}} \cos \emptyset \ (1 - \tan \emptyset \tan \gamma) w (1 - M_m^2) B 2\pi r dr. \qquad (43)$$

When the relative outlet flow angle from a blade is fixed, Equation 38 is rewritten as

$$W = \int_{hub}^{case} V_m \cos \emptyset (1 - \tan \emptyset \tan \gamma) w_{TR} (1 - \frac{V_R^2}{2gJCpT_R})^{\frac{1}{\gamma-1}} B 2\pi r dr. \qquad (44)$$

The relative velocity V_R is given by

$$V_R = V_m / \cos \alpha_R \qquad (45)$$

and Equation 42 is assumed again. This leads to the result

$$\frac{dW}{dV_{m_{mid}}} = \int_{hub}^{case} \frac{V_m}{V_{m_{mid}}} \cos \emptyset (1 - \tan \emptyset \tan \gamma) w (1 - M_R^2) B 2\pi r dr. \qquad (46)$$

Thus, in the special case of radially uniform flow, the branch point in the continuity equation occurs when $M_m = 1$ if the tangential velocity component is fixed, and when $M_R = 1$ if the relative outlet flow angle is fixed. In the general case no single Mach number in the flow is indicative, although the flow exhibits the same basic characteristics.

The validity of Equations 43 and 46 has been discussed by Marsh and Hearsey in Reference 4. In practice, these equations have proved reliable.

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The form of momentum equation selected for this application is

$$V_m \frac{dV_m}{de} = \sin(\emptyset + \gamma)V_m\frac{dV_m}{dm} + \cos(\emptyset + \gamma)\frac{V_m^2}{r_c} - \frac{V_\theta}{r}\frac{d}{de}(rV_\theta) +$$

$$\frac{dH}{de} - t\frac{ds}{de} - \tan \epsilon \frac{V_m}{r}\frac{d}{dm}(rV_\theta) +$$

$$t\frac{ds}{dm}\cos^2 \alpha_R \times \left(\sin(\emptyset + \gamma) - \tan \epsilon \tan \alpha_R\right) . \qquad (47)$$

This equation is presented (somewhat unclearly) by Horlock in Reference 5. It was also independently derived by Wennerstrom in Reference 6. The assumption of axisymmetric flow has been incorporated into this equation. The last two terms reflect the effect of blade forces; the penultimate term is related to the change in angular momentum produced by the blades, and the last term is related to frictional forces on the blades and any other losses (entropy rises) in the flow. These two terms are only assigned non-zero values at computing stations that are within blade rows and at blade edges.

The change in total enthalpy that occurs along a streamline as it passes through a rotor is given by the Euler turbomachine equation

$$H_2 - H_1 = (U_2 V_{\theta_2} - U_1 V_{\theta_1})/gJ. \qquad (48)$$

b.   Subsidiary Relationships and Definitions

The total pressure ratio across a blade row is related to the ideal or isentropic value by

$$P_2/P_1 = (P_2/P_1)_{isentropic} \times P_{2R}/P_{2R \ isentropic} . \qquad (49)$$

The isentropic total pressure ratio is given by Equation 28 as a function of the inlet and outlet total temperatures, which in turn are given by Equations 26 and 47. The ratio of actual to ideal relative outlet total pressure is related to the relative total pressure loss coefficient by

$$P_{2R}/P_{2R \ isentropic} = 1 - \bar{\omega} \left(\frac{P_{1R}}{P_{2R}}\right)_{isentropic} \left(1 - \frac{P_1}{P_{1R}}\right) . \qquad (50)$$

The isentropic relative total pressure ratio is given by Equation 28 as a function of the relative total temperatures, which in turn are related to

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the relative enthalpies by Equation 26. The ratio of the relative total enthalpies is given by

$$H_{2R}/H_{1R} = 1 + \frac{U_2^2}{2gJH_{1R}} \left\{ 1 - \left(\frac{r_1}{r_2}\right)^2 \right\} . \tag{51}$$

The diffusion factor for a two-dimensional compressor blade section is defined by

$$D = 1 - V_{2R}/V_{1R} + \frac{V_{\theta R1} - V_{\theta R2}}{2\sigma V_{1R}} . \tag{52}$$

A "three-dimensional" diffusion factor is defined by determining the relative whirl velocities that would exist if the blade section lay entirely at the mean of the inlet and outlet radii, and the absolute angular momentums were unchanged. Then we replace $V_{\theta R1}$ in Equation 52 by $V_{\theta R1_e}$, where

$$V_{\theta R1_e} = \frac{V_{\theta 1} \cdot r_1}{r_m} - U_1 \tag{53}$$

and similarly

$$V_{\theta R2_e} = \frac{V_{\theta 2} \cdot r_2}{r_m} - U_2 \tag{54}$$

where

$$r_m = (r_1 + r_2)/2 \cdot 0. \tag{55}$$

In general, the mean flow direction through the blade-row is not the same as the local blade meanline direction. At the blade leading edge, the difference is called the incidence angle, and is defined by

$$i = \alpha_R - \beta . \tag{56}$$

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Elsewhere in the blade, the difference is called the deviation angle, and is defined similarly

$$\delta = \alpha_R - \beta. \tag{57}$$

The isentropic efficiency of compression is defined in the conventional manner as the ratio of the total enthalpy change required to isentropically create the given total pressure rise to the actual total enthalpy-rise. For the purposes of computing "integrated" values of both isentropic and polytropic efficiency (defined by Equation 36), mean values of total temperature and total pressure are required. A simple flow-weighted mean total temperature is used, and the mean total pressure is taken to be given by

$$\frac{P_{mean}}{P_{inlet}} = F_2 \left(\frac{\Sigma F_1 (P/P_{inlet}) \cdot T_{inlet} \cdot \delta W}{T_{inlet} \Sigma \delta W} \right) \tag{58}$$

where F_1 is the isentropic temperature ratio corresponding to the given pressure ratio, and F_2 is the isentropic pressure ratio corresponding to the given temperature ratio. The summations are made for all stream tubes from hub to casing.

The static pressure rise coefficient is the ratio of the static pressure rise across the blade section to the relative inlet dynamic head.

The normalized total enthalpy-rise is the ratio of the total enthalpy-rise across the blade section (times gJ) to the square of the blade speed at the outlet radius.

c. Computing Station Definition

In UD0200, the first and last points used to define a computing station also define the hub and casing contours, respectively. However, the data generated by UD0100, just described, only describe the axial location of the stations; the extent of the data is controlled radially by the range of Z-values of the cartesian blade descriptions. To handle this situation, UD0200 is supplied with data that describes the wall contours, and the points where the station definition intersects the walls are found and entered as the first and last points of the station definition. Some data which is outside of the flow path may then be discarded. This is illustrated in Figure 3.

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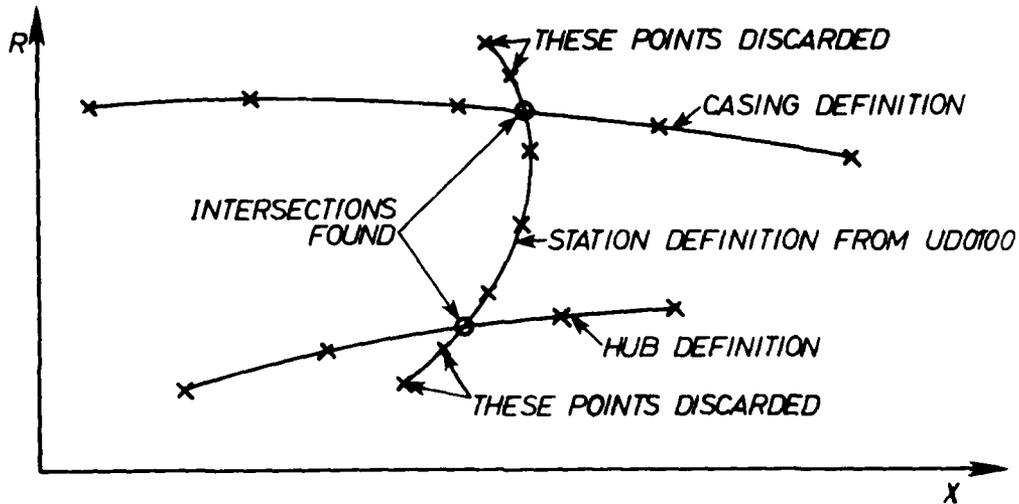
Figure 3. Computing Station End Point Definition

The points that define the station are always spline-fit through all supplied points; any superfluous end-points are discarded after the intersections have been determined. The user may specify spline-fit or linear interpolation for the wall segments.

The method used to determine the intersections is as follows:

(1)   Estimate the radius of the intersection to be that of the wall at the previous computing station.

(2)   Interpolate the corresponding axial coordinate from the computing station definition.

(3)   Re-estimate the radius by interpolation from the wall contour data at the axial coordinate found in Step 2.

(4)   If the two estimates of radius differ by more than 0.0005, return to Step 2 with the radius estimate found in Step 3.

Up to ten loops through the procedure are permitted in the program. If the procedure is not then converged, a diagnostic message is printed and execution halts.

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d. Interpolation and Integration

Interpolations are required to determine quantities at stream-
line locations from tabulated input data. There are two "types" of data
to be handled; the blade geometry, and the experimental test data. The
former can reasonably be presumed to plot "smoothly", and hence, this data
is fitted with a spline-curve for interpolation. The test data, however,
may be somewhat uneven, and use of a spline-curve then would exaggerate
the irregularities. Linear interpolation is therefore employed in this
case.

The theory of the spline-curve was given previously. In this
case, however, different boundary conditions are imposed at the two ends
of the curve; here the second derivative is made equal to zero. Conse-
quently, the following changes are made to Equations 15 and 17 for this
case:

$$M_1 = M_N = 0$$
$$B_1 = 0.0 \tag{59}$$

Several integrations are performed in the program, including the
evaluation of the continuity equation and its derivative forms, Equations
39, 43, and 46. In each case, trapezoidal integration is used. Adequate
accuracy is obtained through the use of a sufficiently fine mesh of points.

e. Solution of Momentum Equation

Equation 47 may be written in the form

$$\frac{dv^2_m}{de} + A(e)V^2_m = B(e) \tag{60}$$

where

$$A(e) = 2 \left[\frac{\tan \epsilon}{rV_m} \frac{d}{dm} (rV_\theta) - \frac{\cos (\phi + \gamma)}{r_c} - \frac{\sin (\phi + \gamma)}{V_m} \frac{dV_m}{dm} \right] \tag{61}$$

and

$$B(e) = 2 \left[\frac{dH}{de} - \frac{tds}{de} - \frac{V_\theta}{r} \cdot \frac{d}{de} (rV_\theta) + \frac{tds}{dm} \cos^2\alpha_R \sin (\phi + \gamma) - \tan \epsilon \tan \alpha_R) \right] . \tag{62}$$

If A and B are assumed invariant with e, the integrating factor technique may be applied to Equation 60 yielding, upon integrating between limits 1 and 2,

$$V_{m_2}^2 = V_{m_1}^2 e^{- A (e_2 - e_1)} + (1 - e^{- A (e_2 - e_1)}) B/A. \tag{63}$$

In order to keep small the error caused by assuming A and B to be constants, the interval (e_2-e_1) must be kept sufficiently small that a single, mean value may reasonably be assumed. This is accomplished by using Equation 60 to step from one streamline to the next (up to 21 streamlines may be used). In the event that A is zero, Equation 63 fails, and the following alternative equation applies:

$$V_{m_2}^2 = V_{m_1}^2 + B (e_2 - e_1). \tag{64}$$

In the computer program, the switch from Equation 63 to Equation 64 is made not for zero A, but when the magnitude of A is so small that numerical inaccuracies are liable to occur.

The derivatives (in Equations 61 and 62) in the "e" direction are determined from the values of the function on the two streamlines bounding the interval (e_2-e_1) thus:

$$\left(\frac{dF}{de} \right)_{e_1 \to e_2} = \frac{F_2 - F_1}{e_2 - e_1}$$

$$= \frac{F_2 - F_1}{r_2 - r_1} \cos \gamma. \tag{65}$$

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Here γ is the value of the station lean angle at mid-interval, and is related to the computing station geometry by

$$\tan \gamma = dx/dr. \tag{66}$$

This gradient is found from the analytic derivative of a spline-curve passed through the data points describing the computing station.

The derivatives in the "m" direction are determined from values of the function on the same streamline at the computing station under consideration, and the two adjacent stations, thus:

$$\left(\frac{dF}{d_m}\right)_I = \left(\frac{F_{I+1} - F_I}{m_{I+1} - m_I} + \frac{F_I - F_{I-1}}{m_I - m_{I-1}}\right) \bigg/ 2.0 \quad . \tag{67}$$

At the first and last computing stations, these gradients are assumed to be zero.

Also involved in Equations 60 and 62 are the streamline slopes and curvatures. The slopes, and rates of change of slope, are determined from

$$\left(\frac{Dr}{Dx}\right)_I = \tan\phi_I = \left(\frac{r_{I+1} - r_I}{x_{I+1} - x_I} + \frac{r_I - r_{I-1}}{x_I - x_{I-1}}\right) \bigg/ 2.0 \tag{68}$$

and

$$\left(\frac{D^2 r}{Dx^2}\right)_I = \left(\frac{D \tan \phi}{Dx}\right)_I = \frac{\left(\dfrac{r_{I+1} - r_I}{x_{I+1} - x_I} - \dfrac{r_I - r_{I-1}}{x_I - x_{I-1}}\right)}{(x_{I+1} - x_{I-1})/2.0} \quad . \tag{69}$$

The curvatures then follow from combining the first and second derivatives in the conventional manner. At the first and last computing stations, the streamlines are assumed to have no curvature, and the slopes are calculated from

$$\left(\frac{Dr}{Dx}\right)_I = \tan \phi_I = \frac{r_{I \pm 1} - r_I}{x_{I \pm 1} - x_I} \quad . \tag{70}$$

The iterative determination of the meridional velocity distribution at a computing station is accomplished by the following procedure:

(1) The assumed streamline pattern leads to streamline slopes and curvatures, through Equations 68 and 69. A meridional velocity component profile is assumed; during the first pass through the compressor it is taken to be radially uniform, and subsequently the results obtained on the previous pass are assumed.

(2) All terms in Equations 61 and 62 are calculated.

(3) Assuming the previous value of the midradius meridional velocity to apply, Equation 63 (or 64) is applied repeatedly to step from the midradius streamline to each wall, yielding a new meridional velocity profile.

(4) The meridional velocity profile is not taken to be that given in Step 3, but a relaxation factor is applied, thus

$$V_{m_{new}} = V_{m_{previous}} + R (V_{m_{calculated}} - V_{m_{previous}}). \quad (71)$$

The relaxation factor R is obtained by consideration of the effect of changes in meridional velocity upon the enthalpy gradient in Equation 47. When the absolute whirl velocity is specified, or relative flow angle is specified but the blade-row is stationary, the enthalpy gradient is independent of meridional velocity. Hence,

$$R = 1.0 . \quad (72)$$

When the relative flow angle for a rotating blade-row is specified, differentiation of Equation 48 yields

$$gJ \frac{dH}{dV_m} = U \tan \alpha_R. \quad (73)$$

The momentum equation, in simplified form accounting for an enthalpy gradient only, is

$$\frac{dV_m}{dr} = \frac{gJ}{V_m} \frac{dH}{dr}. \quad (74)$$

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If then at some radius the correct meridional velocity is
perturbed an amount ΔV_m, from Equations 73 and 74, a recal-
culation of the enthalpy and meridional velocity shows a
perturbation from the original value of ΔV_m. U tan α_R/V_m,
or a change from the proposed value of ΔV_m (U tan α_R/V_m - 1).
In order to correct the velocity the relaxation factor R is
therefore given by

$$R\Delta V_m \left(\frac{U \tan \alpha_R}{V_m} - 1 \right) = -\Delta V_m$$

or

$$R = \frac{1}{1 - \dfrac{U \tan \alpha_R}{V_m}} \quad . \tag{75}$$

(5) In the event that the new velocity profile differs from the
assumed profile by more than a specified tolerance, the calcu-
lation returns to Step 2.

f. Solution of Continuity Equation

Satisfaction of the continuity equation at a computing station
depends upon correctly estimating the midradius meridional velocity component.
Then, as described above, the velocities at all other radii are prescribed
by the momentum equation. This establishes the total flow at the computing
station. Generally, continuity is not satisfied (to within the desired
tolerance) by the initial midradius velocity estimate, and a refined estimate
must be made. The gradient of flow with velocity (Equation 43 or 46 as appro-
priate) is used for this. If it is assumed that the gradient is constant in
the region between the flow computed and the flow desired, then the midradius
meridional velocity can be refined using

$$\Delta V_m = (V_{m_{mid}})_{previous} \times (W_{desired} - W_{computed}) / \frac{dW}{dV_{m_{mid}}} \quad . \tag{76}$$

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Of course, the gradient is not constant, decreasing (in magnitude) as the maximum-flow point is approached (M = 1 for simple flows). Hence, when refinement leads to the new velocity being closer to the maximum flow value, the velocity increment will be underestimated and vice versa. This is desirable, as it is computationally inconvenient to unintentionally cross the branch-point in the continuity equation. Because, as was described above, the procedure for the solution of the momentum equation requires meridional velocity estimates at all radii (rather than at midradius only), the velocity increment (Equation 76) is applied to the computed velocity profile at all radii.

There are two circumstances when the branch-point will be crossed. First, the initial velocity estimate may be such that the gradient computed by Equation 43 (or Equation 46) is of the wrong sign. Then a new "first estimate" must be made that will produce a gradient of the correct sign. This is easily achieved by multiplying the existing meridional velocity profile by, say, 0.9 if a switch to a subsonic solution is required, or 1.111 if a switch to a supersonic solution is required. Several applications of the factor may be required. (In the case of a specified absolute whirl velocity, Equation 43, the branch-point is when the flow-weighted mean value of $(1 - M_m^2)$ is negative, so that subsonic solutions only are permitted.) The second circumstance, when the branch-point is crossed (or, at least, potentially crossed) is when the specified flow is larger than the maximum possible flow. Then the velocity increment given by Equation 76 would make the solution type change, and a switch back to the correct type would be indicated. However, as no solution is possible, the computational sequence must be monitored to detect this anomaly. One situation which can occur when the specified flow through a blade row is very close to the maximum possible is that the specified flow cannot apparently be passed with the currently assumed streamline pattern. What is required is that the calculation be forced to proceed with some arbitrary numbers inserted where necessary so that the streamline pattern may be refined until a valid solution is obtained. As indicated above, repeated crossings of the branch-point will occur, first when Equation 46 predicts the velocity increment to satisfy the continuity equation, and again when a deliberate switch is made to regain the correct solution type. Now consider a case where a subsonic solution is sought. A range of "plausible" velocities is established. As a lower limit, the highest velocity that

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yields a subsonic solution and less flow than desired is noted. As an upper limit, the lowest velocity that yields a supersonic solution is noted. (Where a supersonic solution is required, this procedure is reversed.) Outside of this range, the flow will be farther from the desired value than within it. Hence, successive values of the mid-radius velocity are constrained to be within this range. Further, this range is continuously refined by constraining the velocity to be not within 2% of extremes of the hitherto defined plausible range, when, without restriction, the velocity would fall outside the range.

g. Iterative Determination of Streamline Locations

The estimates of streamline locations (that is, radii at each computing station) are refined by applying the condition that a constant flow should pass through each streamtube. The flow distributions established by solving the momentum and continuity equations at each station are used to predict at what radius each streamline should lie in order that it divides the flow into the same, specified proportion at each computing station. Subsequent recalculation of the flow distributions (that is, solution of the momentum and continuity equations at each station) based upon the revised streamline locations yield different flow distributions and thus, potentially the iteration will not rapidly converge, or may diverge. The behavior of this procedure may be determined from the following analysis. (This analysis is based upon one given by Wilkinson for plane two-dimensional flows in Reference 7.)

As we are concerned here with the effect of streamline mislocations only, we examine a simplified form of the momentum equation (Equation 47).

$$\frac{dV_m}{dr} = \frac{V_m}{r_c}.$$

(77)

Assuming that only small deviations from midradius meridional velocity occur, we approximate Equation 77 by

$$\frac{dV_m}{dr} = \frac{V_{m_m}}{r_c}$$

(78)

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where V_m is the midradius meridional velocity. For radial computing stations uniformly spaced Δx apart in a uniform, cylindrical flow, presume an error in streamline location of E at one station only. The corresponding radius of curvature at that station will be given by

$$r_c = -\Delta x^2 / 2E. \tag{79}$$

The radial distribution of meridional velocity, from Equations 78 and 79, is then

$$V_m(r) = V_{m_m} \left\{ 1 + \frac{2E}{\Delta x^2} (V_m - r_m) \right\}. \tag{80}$$

The mass flux is proportional to $(V_m \rho)$, and again we approximate the distribution using

$$V_m \rho = (V_m \rho)_m + (V_m - V_{m_m}) K \tag{81}$$

where

$$K = \left(\frac{d(\rho V_m)}{dV_m} \right)_m. \tag{82}$$

For a high radius ratio, the flow between radii r_1 and r_2 is proportional to $\int_{r_1}^{r_2} V_m \rho \, dr$, and from Equations 80 and 81

$$\int_{r_1}^{r_2} V_m \rho = (V_m \rho)_m \left\{ (r_2 - r_1) + \frac{2EK'}{\Delta x^2} \left[r_m (r_2 - r_1) - \frac{(r_2^2 - r_1^2)}{2} \right] \right\} \tag{83}$$

where

$$K' = K / \rho_m \tag{84}$$

and r_m is the midradius. Equation 83 gives the mass flux distribution that will be predicted by the momentum equation. To determine where the stream-line which should be at midradius will be predicted to lie, we seek the

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radius which divides the flow in half. This may be found by solving the following equation for r_x

$$.5 = \int_{r_h}^{r_x} V_m \rho \, dr \Bigg/ \int_{r_h}^{r_t} V_m \rho \, dr \qquad (85)$$

where r_h and r_t are the hub and tip radii respectively, i.e., $r_m = (r_h + r_t)/2.0$. Substituting from Equation 83 into Equation 85, and approximating $(r_x - r_h)$ by $(r_m - r_h)$, this yields

$$r_x = r_m - \frac{E(r_t - r_h)^2 \cdot K'}{4\Delta x^2} \qquad . \qquad (86)$$

Now, due to original error E, the previous radius was $r_m + E$, so that the shift in radius is

$$r_x - (r_m + E) = -E\left(1 + \frac{K'}{4}\left(\frac{\Delta R}{\Delta x}\right)^2\right) \qquad (87)$$

where

$$\Delta R = r_t - r_h .$$

To make the shift connect, that is equal to $-E$, the relaxation factor should be

$$R = \frac{1}{1 + \frac{K'}{4}\left(\frac{\Delta R}{\Delta x}\right)^2} \qquad . \qquad (88)$$

Now the case considered, where the error E is imposed at one station only, is one extreme. It produces the largest curvatures, and, without a relaxation factor, the largest shifts in radius from one pass to the next. The other extreme is when the error is imposed at all stations, producing

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no curvature. In this case, damping will cause the streamline shift to be underestimated. An optimum relaxation factor may be defined as one which gives the same undershoot for the "long-wave" case as overshoot for the "short-wave" case. Calling this optimum factor F, and equating the ratio of residual error to original error for these two cases (with the sign change indicated by the undershoot/overshoot).

$$F - 1 = 1 - F \left(1 + \frac{K'}{4}(\frac{\Delta R}{\Delta x})^2\right) \tag{89}$$

so that

$$F = \frac{1}{1 + \frac{K'}{8}(\frac{\Delta R}{\Delta x})^2} \ . \tag{90}$$

It remains to evaluate K'. From Equations 82 and 84

$$K' = K/\rho_m$$

$$= \frac{1}{\rho_m} \left(\frac{d(\rho V_m)}{dV_m}\right)_m \ . \tag{91}$$

Consider the case where the whirl velocity is fixed. We may write

$$\rho V_m = \rho_T \cdot \frac{\rho}{\rho_T} \cdot V_m$$

where ρ_T is the total density, and

$$\rho_T \cdot \frac{\rho}{\rho_T} \cdot V_m = \rho_T \cdot V_m \left(1 - \frac{V_m^2 + V_\theta^2}{2gJC_pT}\right)^{\frac{1}{\gamma - 1}} \ . \tag{92}$$

(assuming a perfect gas)

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The only variable in Equation 92 is V_m, so we may differentiate w.r.t. V_m to obtain

$$\frac{1}{\rho} \frac{d(\rho V_m)}{dV_m} = 1 - M_m^2 \tag{93}$$

where

$$M_m = V_m/a. \tag{94}$$

In the case where the relative flow angle is fixed, we write

$$\rho V_m = \rho_{TR} \cdot \frac{\rho}{\rho_{TR}} V_m$$

where ρ_{TR} is the relative total density and thus

$$\rho V_m = \rho_{TR} \cdot V_m \left(1 - \frac{V_m^2 (1 + \tan^2\alpha_R)}{2gJC_p T_R} \right)^{\frac{1}{\gamma - 1}}. \tag{95}$$

Again the only variable is V_m, and we may differentiate to obtain

$$\frac{1}{\rho} \frac{d(\rho V_m)}{dV_m} = 1 - M_R^2 \tag{96}$$

where

$$M_R = V_m \sqrt{1 + \tan^2\alpha_R} \ /a. \tag{97}$$

Hence

$$K' = \frac{1}{\rho_m} \left(\frac{d(\rho V_m)}{dV_m} \right)_m$$

$$= (1 - M^2)_m \tag{98}$$

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where

$$M = V_m/a \text{ if the whirl velocity is fixed, and}$$

$$= V_m \sqrt{1 + \tan^2 \alpha_R} \quad /a \text{ if the relative flow angle is fixed.}$$

h. Iterative Determination of Flow Area for a Given Static Pressure

One option in the program is to determine the blockage coefficient at a computing station such that the computed static pressure for the casing matches an experimental value. The method employed is to make a calculation of the static pressure (as part of the solution of the continuity and momentum equations), incorporating the input blockage value, and then to refine the blockage on every subsequent iteration, using

$$\Delta A = \Delta p / \frac{dp}{dA} \tag{99}$$

where

ΔA is the change in flow area, and

Δp is the difference between the desired static pressure and the value computed.

The gradient dp/dA is required. The following derivations assume a perfect gas. First consider the case when the whirl velocity is fixed.

One-dimensional continuity gives

$$p = \frac{WRt}{V_m A} = \frac{WRT}{V_m A} \left(1 - \frac{V_\theta^2 + V_m^2}{2gJC_pT} \right) . \tag{100}$$

Differentiating Equation 100 yields

$$\frac{dp}{dA} = -\frac{p}{A} \left(1 + \frac{dV_m}{dA} \left(\frac{A}{V_m} + \frac{WR}{gJC_pp} \right) \right) . \tag{101}$$

Reverting to the continuity equation again,

$$A = \frac{W}{wV_m} . \tag{102}$$

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Differentiating Equation 102 and using also

$$\frac{w}{w_T} = \left(1 - \frac{V_m^2 + V_\theta^2}{2gJC_pT}\right)^{\frac{1}{\gamma - 1}}$$ (103)

we may obtain

$$-\frac{dA}{dV_m} - \frac{W}{wV_m^2}(1 - M_m^2).$$ (104)

Combining Equations 101 and 104 gives the desired result

$$\frac{dp}{dA} = \frac{\gamma M_m^2}{1-M_m^2} \cdot \frac{P}{A} \quad .$$ (105)

This is in agreement with the value given in a table of influence coefficients presented by Anderson, Heiser, and Jackson in Reference 8.

For the case when the relative flow angle is fixed, the total velocity is given by

$$v^2 = V_m^2(1 + \tan^2\alpha_R).$$ (106)

For the fixed whirl velocity case it is given by

$$v^2 = V_m^2 + V_\theta^2.$$ (107)

Replacing Equation 107 with Equation 106 in the above derivation gives the following result.

$$\frac{dp}{dA} = \frac{\gamma M_R^2}{1-M_R^2} \cdot \frac{P}{A} .$$ (108)

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When NBL = 5 or 6, an iterative procedure is used to determine the location of the intersection of the computing station with the line joining the two static pressure points that span the computing station. The procedure is executed regardless of whether a static pressure is specified precisely on the computing station or the computing station is upstream or downstream of all the static pressure points. In the latter case, linear interpolation between static pressure points becomes linear extrapolation from the two appropriate end values. The procedure employed is as follows:

(1) The radius is estimated as the arithmetic mean of the radii at points where static pressures are specified.

(2) The axial location on the computing station at the estimated radius is found by spline-fit interpolation of the points defining the station. (Linear interpolation is used if only two points define the station.)

(3) A new estimate of the radius is found by linear interpolation between the coordinates of the static pressure specification points at the axial location found in Step 2.

(4) If the new and old radii estimates vary by more than 0.001 inches, Step 2 is reentered.

When NBL = 3, 4, or 6, the flow deviation angle at the computing station is adjusted to give the desired static pressure match. The method of calculation is very similar to that used for the case when NBL = 1. In this case, the flow area is varied by changing the relative flow angle (and hence deviation angle) rather than the blockage fraction. Using Equation 108 and relating flow area to relative flow angle gives

$$\cos \alpha_{R_{new}} = \cos \alpha_{R_{old}} \left[1 + \frac{\Delta p (1 - M_R^2)}{\gamma M_R^2 \, p} \right] \tag{109}$$

where α_R is relative flow angle

Δp is the difference between the desired static pressure and value computed.

The calculation is performed using the mid-streamline value of relative flow angle. The sign of the new relative flow angle is set negative if the computing

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station is within the rotor, and a new value for DEL, the midradius addi-
tional deviation is found. Then, as noted in the description of NBL in
the input data description, the relative flow angle at any radius is given
by

$$\alpha_R = \beta + a + b + cr \tag{110}$$

where α is the blade angle, determined from the input data items DATBET and
DATEPS

β is the "fixed" deviation, determined from the input data items RRD,
R2M, and RDEV in the case of the rotor, and the input data items
RSD, S2M, SDEV and the trailing edge deviation angle in the case
of the stator

b,c are arranged so that when r = midradius, b + cr = DEL, and when
r = hub radius, b + cr = DEL x DELDST

The inlet choking condition is required in order to compute the
ratio of actual flow rate to choking flow rate, and also to nondimensionalize
the meridional velocity profiles that are plotted when NPLOT = 2 or 3.
Because the working fluid is assumed to be an ideal gas, an iterative calcu-
lation is required to find the velocity which corresponds to a Mach number
of unity. The procedure used is as follows:

(1) Estimate critical velocity from rotor face area, flow rate, and
inlet total density.

(2) Determine static enthalpy from inlet total enthalpy and estimated
velocity.

(3) Determine corresponding static temperature, ratio of specific
heats, and hence speed of sound.

(4) If the estimated critical velocity and the speed of sound agree
within 0.1 ft/sec, deem the calculation to have converged.

(5) If the calculation has not converged, reestimate the critical
velocity as the mean of the previous estimate and the sound
speed determined in Step 3. Control returns to Step 2.

i. Convergence Criteria

Four checks are incorporated into the overall iterative procedure to
determine if the solution is "converged". Two relate to the continuity equa-
tion, and two to the momentum equation.

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In the iterative solution of the momentum and continuity equations at a station for a fixed streamline pattern, a check is made upon the total flow level. This is considered correct if it is within one part in 4000 of the specified value. A check is also made upon the meridional velocity profile, and this is considered converged if it is reproduced from one iteration to another to within one part in 4000 at each mesh point.

Two further checks are made from one overall pass to the next which determine if the overall solution is converged. A continuity check is made upon the streamlines; the area between the hub and each streamline must, at all stations, contain the same fraction of the total flow, to within five parts in 1000. Also, the meridional velocities at each mesh point must be reproduced from one pass to the next to within five parts in 1000.

j. Probe Reading Corrections

Total pressures and total temperatures used in the calculation of the flow through the test compressor are deduced from values given by probes in the flow, and the readings generally need some "correction" to yield true stagnation conditions. The corrections made are a function of the types of probes presumed to be used in the associated experiment, and if probes different to those described here are used, some minor modifications to the program may be required.

The total pressure probes are presumed to be a Kiel-type probe which is insensitive to incoming flow direction over a wide range of angles. (Alternatively, one may presume that the probe is aligned with the flow direction for each reading.) Then the only correction required is for the effect of a normal shock wave if the incoming flow is supersonic. A perfect gas is assumed, and the classic normal shock relation is used, so that:

$$P_{stream} = P_{probe} \Bigg/ \left(\left(\frac{(\gamma + 1)M^2}{(\gamma - 1)M^2 + 2} \right)^{\frac{\gamma}{\gamma - 1}} \left(\frac{\gamma + 1}{2\gamma M^2 - (\gamma - 1)} \right)^{\frac{1}{\gamma - 1}} \right)$$

(111)

where

M is the local Mach number, and

γ is the ratio of specific heats.

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In the program, γ is calculated to correspond to static conditions upstream of the shock.

The total temperatures are assumed to be obtained from small slot-vented probes, in particular, the type referred to as Probe 6 by Stickney in Reference 9. The stream total temperature is related to the temperature of the probe by:

$$T_{stream} = T_{probe} \Big/ \left(F_3(M) - F_4(P/P_{ref})(1 - F_3(M)) \right) \qquad (112)$$

where

$F_3(M)$ is the recovery ratio as a function of Mach number at the reference total pressure (1 atmosphere), and

$F_4(P/P_{ref})$ is the variation of recovery ratio with total pressure.

For Probe 6, $F_3(M)$ was obtained from Figure 6 of Reference 9. The values used are as follows:

Mach Number	Recovery Ratio at Reference Total Pressure (14.6944 lbs/sq. in. abs.
0	1.0
0.2	0.9991
0.4	0.9978
0.6	0.9960
0.8	0.9944
1.0	0.9929
1.2	0.9919
1.4	0.9907
1.6	0.9900
1.8	0.9895
2.0	0.9890

Spline-curve interpolation is used to obtain the value corresponding to any Mach number. The total pressure correction function was found in Reference 9 to be adequately represented by the analytic form

$$F_4(P/P_{ref}) = (P/P_{ref})^n - 1.0 \qquad (113)$$

where, for Probe 6, $n = -0.8$.

k. Fluid Properties

The fluid is assumed to be a thermally-perfect gas (as detailed in Section V) and to be composed of a mixture of air and water vapor in the proportions (by mass) m of air to (1 − m) of water vapor. Here m is the input data item FRCAIR. The associated gas constant is the input data item GASR. The specific heat at constant pressure of the mixture is given by Equation 22, and each of the six coefficients is determined from the following relationship.

$$K_j = mK_j \text{ (air)} + (1 - m)K_j \text{ (water vapor)} \qquad (114)$$

where K_j (air) and K_j (water vapor) are as follows.

j	K_j (air)	K_j (water vapor)	Mixture Coefficient Designation
1	.25037964	.43483286	a
2	−.08081282 · 10^{-3}	.1098044 · 10^{-3}	b
3	.23122066 · 10^{-6}	−.52292623 · 10^{-6}	c
4	−.34160919 · 10^{-9}	1.0182121 · 10^{-9}	d
5	.27497128 · 10^{-12}	−.79236516 · 10^{-12}	e
6	−.085548936 · 10^{-15}	.22724483 · 10^{-15}	f

The coefficients listed above were determined from specific heat values presented by Keenan and Kaye in Reference 10. Table 2 for air and Table 16 for water vapor. They represent all significant figures in the tables between temperatures of 450 and 1,000 degrees Rankine.

If the program is to be used outside of these temperature limits, or for gases other than an air/water vapor mixture, some modifications to the program will be necessary.

l. Blade Angle Relations

The blade section angle given in the input data is the angle between the blade mean surface and the meridional plane on a cylinder. For the aerodynamic analysis, the angle on a stream surface is required; the angles are related by

$$\tan \beta_{\text{stream surface}} = \cos \phi \, (1 - \tan \gamma \, \tan \phi) \, \tan \beta_{\text{cylinder}} - \tan \phi \, \tan \epsilon_x) .$$

$$(115)$$

This equation, which is an inverted form of Equation 10, is derived in Reference 3.

The blade lean angle in the input data (ϵ_x) is the angle between the blade mean surface and the radial direction (at the computing station), projected onto a constant-x plane. For the momentum equation computation (ϵ), the angle seen normal to the computing station is required, and these angles are related by

$$\tan \epsilon = \tan \epsilon_x / \cos \gamma . \tag{116}$$

m. Stagnation Point

In the event that a compressor inlet including a "bullet-nose" is in the geometry to be analyzed, a stagnation point is introduced there into the flow field. The method of solution used for the momentum equation is unable to handle this, and so a special provision is introduced into the program. At the stagnation point, a velocity of zero is "written" directly into the results, and the integration of the momentum equation inwards from the midradius streamline is made only to the second streamline (that is, the first streamline in from the stagnation point). The integrations for the continuity equation are made in the usual manner, that is including the stagnation point.

The stagnation point, if one exists, must be upstream of the rotor, and is detected by the program as the last station where the "hub" radius is zero. Although the radius of curvature here is actually zero, the value seen in the results is still computed from Equations 68 and 69. This is not used in any calculation as the momentum equation is not integrated across the innermost streamtube.

n. Pressure Differences

The pressure differences across the blades are found from

$$\Delta p = \frac{2\pi \rho V_m}{N} \frac{d(rV_\theta)}{dm} \tag{117}$$

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where Δp is the static pressure difference across the blade

       ρ is the density

       V_m is the meridional velocity component

       V_θ is the tangential velocity component

       r is radius

       m is the streamline direction in the meridional plane

       N is the number of blades

The streamwise gradient is found from a mean upstream and downstream difference, so that at a blade trailing edge the value computed will be of the order of one half that computed within the blade. At the leading edge, however, the computed value is doubled, which is equivalent to using a downstream difference only, as the upstream difference will be zero.

SECTION VI

PROGRAM STRUCTURE

1. PROGRAM ORGANIZATION

Program UD0400 has been written as a standard FORTRAN program,
with one main program and a number of subprograms. The program is main-
tained as a CDC Scope UPDATE Library File and the deck names and their
contents, in order of occurence, are as follows:

Deck Name	Contents
$U4M$	Program UD0400 (Main Program)
$$CM	COMMON Deck
MN	Subroutine UD0200
$G2$	Subroutine G2
FF	Functions FF1, FF2, FF3, FF4, and FF5
$A2$	Subroutine A2X
$B2$	Subroutine B2X
$C2$	Subroutine C2
$D2$	Subroutine D2
$E2$	Subroutine E2
$H2$	Subroutine H2
$I2$	Subroutine I2
$F2$	Subroutine F2
$J2$	Subroutine J2
$K2$	Subroutine K2
$U1$	Subroutines UD0100, TZ and ROTATE
LL	Subroutine LL
MM	Subroutine MM
DAT4	Sample input data

2. PROGRAM ELEMENTS AND THEIR FUNCTIONS

a. Program UD0400 (Main Program)

The main program controls the flow of the program between
the two main Subroutines UD0100 (blade geometry definition section) and
UD0200 (aerodynamic analysis section). The program defines the input and
output files and the internal scratch files. The program calls Subroutine

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UD0100 once for each blade geometry definition required. Subroutine UD0200 is called only once if one or more aerodynamic analyses are to be performed.

b.   Subroutine UD0200

Subroutine UD0200 is the "main program" for the aerodynamic analysis section of the program. This subroutine controls the logical flow of the program between the subprograms which perform the calculations in the aerodynamic analysis. The overall logic for Subroutine UD0200 is shown in Figure 3. This is essentially a flow-chart of the subroutine, and shows all the important logical points and all calls to the other subprograms. Some significant points are as follows. Subroutine A2X, which reads the fixed input data, is only entered once. Upon completing the NCASE analyses, the subroutine returns control to the main program which terminates execution. The first action for each test point analysis is to read some unique analysis option parameters and then enter Subroutine B2X, which reads the test data. Subroutine C2, which is entered once per pass through the compressor, determines the total pressure distributions at rotor and stator exit, the total temperature distribution at the rotor exit (which then pertains throughout the rest of the compressor), and the rotor exit whirl velocity distribution. Thus, although the calculation will march through the compressor station by station, these quantities are determined at the outset. Subroutine D2, which handles the solution of the continuity and momentum equations, is one large loop executed for each station. Therefore, a complete pass is made through the flow field without returning to Subroutine UD0200. The logic of Subroutine D2 is discussed further below. Note that IVFAIL and IFFAIL are set to record the number of unconverged mesh points and stream tubes in the flow field, and that if the calculation fails when IPASS is greater than NFORCE, ILAST records the station number where failure occured. A pass through the flow field comprises one entry to Subroutine C2 followed by one entry to Subroutine D2, and this sequence is repeated until one of three conditions is fulfilled. The conditions are either that all permitted passes have been made, or that the failure flag ILAST has been set, or that the solution is converged. Then Subroutine F2 is entered to produce the regular printed output, which includes a statement of the reason for the termination of the calculation. If a separate plot of blade performance parameters for each test point is specified, Subroutine J2 is entered. Subroutine K2 will be entered if one set of plots for all test points is specified, and all test

SUBROUTINE UD0200

```
START
                              ┌──────────────────────┐
        ┌────────────────────►│ SUBROUTINE A2X       │
        │                     │ Read fixed data      │
        │                     └──────────────────────┘
ICASE=1
READ PSCALE,PLOWER,DAMPF,NSAVE,
+NNMAX,NFORCE,NEX,NTCR,NCARD,NDPQ
                                      ┌──────────────────────┐
                                      │ SUBROUTINE B2X       │
                                      │ Read test data       │
                                      └──────────────────────┘
READ NJUMP
IF(NJUMP.EQ.0)──────────┐
NCASE=NCASE-1           │

X1=FLOW*GASR*TIN/(PIN*(R(NSTRMS,1)**2-R(1,1)**2)*PI)
DO 113 J=1,NSTRMS
T(J,1)=TIN
P(J,1)=PIN
VM(J,1)=X1
VW(J,1)=0.0
IPASS=1
                        ┌─────────────────────────────┐
                        │ SUBROUTINE C2               │
                        │ Interpolate test pressures  │
                        │ and temperatures            │
                        └─────────────────────────────┘
IVFAIL=0
IFFAIL=0
ILAST=0
                        ┌─────────────────────────────┐
                        │ SUBROUTINE D2               │
                        │ Solve momentum and continuity│
                        │ equations. Set IVFAIL and IFFAIL.│
                        │ If calculation fails and IPASS.GT.│
                        │ NFORCE, set ILAST=I(the current│
                        │ station number).            │
                        └─────────────────────────────┘
IF(IPASS.EQ.NMAX.OR.ILAST.NE.0)──────►
IF(IFFAIL.EQ.0.AND.IVFAIL.EQ.0)──────►
IPASS=IPASS+1
                        ┌─────────────────────────────┐
                        │ SUBROUTINE F2               │
                        │ Regular output              │
                        └─────────────────────────────┘
IF(NPLOT.EQ.1)──────────────────────► SUBROUTINE J2
                                       Plot separate graphs
IF(NPLOT.EQ.2.AND.ICASE.EQ.NCASE)───► SUBROUTINE K2
                                       Plot combined graphs
IF(ICASE.EQ.NCASE)──────────┐
ICASE=ICASE+1               │
                         RETURN
```

FIGURE 4. Overall Logic of Subroutine UD0200.

points have been computed. If all test points have been computed, program execution ceases; otherwise, Subroutine B2X is reentered to read in the test data for the next test point.

c. Subroutine G2

Subroutine G2 performs interpolations and slope determinations. The subroutine provides both spline-curve fitting and linear point-to-point fitting alternatives.

d. Function FF1

Function FF1 gives enthalpy as a function of temperature by solving Equation 26.

e. Function FF2

Function FF2 gives temperature as a function of enthalpy by iteratively solving Equation 26 by Newton's method.

f. Function FF3

Function FF3 gives the ratio of specific heats as a function of temperature by solving Equations 22 and 31.

g. Function FF4

Function FF4 gives the entropy difference between two states that are defined by their temperatures and pressures, by solving Equation 33.

h. Function FF5

Function FF5 gives the isentropic pressure ratio corresponding to two given temperatures by solving Equation 28.

i. Subroutine A2X

Subroutine A2X reads and lists the "fixed" input data (those data items that are read in only once per program execution) read by the aerodynamic analysis (UD0200) section of the program.

j. Subroutine B2X

Subroutine B2X reads and lists the "test" input data (those data items that are read in for each test point to be analyzed) read by the aerodynamic analysis (UD0200) section of the program.

k. Subroutine C2

Subroutine C2 handles the interpolation of the experimental total temperatures and pressures on each streamline at the instrumentation computing stations. These are corrected from probe-to-stream values. The whirl velocity distribution at the rotor exit is also calculated.

l. Subroutine D2

Subroutine D2 iteratively determines the solution to the momentum and continuity equations at each computing station. Rotor and stator loss coefficients and deviation angles are also computed. This is the major calculational subroutine of the aerodynamic analysis (UD0200) section. The logic in Subroutine D2 is shown in Figure 4.

In the flow-chart (Figure 4), the numbers shown in the left column correspond to the FORTRAN statement numbers in the coding. Where a message number is shown in parentheses, the corresponding diagnostic message may be produced, as described in the previous section. Some significant points in the logic are as follows. The subroutine is essentially one large loop performed (potentially) for each computing station. Subroutine H2 is entered to determine, for the station being computed, the streamline slopes and curvatures, and some terms in the momentum equation. Subroutine I2 determines the radial distribution of blockage due to annulus wall boundary layers and blade wakes. The radial distributions of total temperature, total pressure, and whirl velocity are required for solution of the momentum and continuity equations, and these quantities are determined in various ways depending upon the location of the computing station. At the inlet station they are specified directly in the input data. At stations following a blade-free space, they are dictated by constancy of enthalpy, entropy, and angular momentum alcng streamlines from the previous computing station. For stations that are within a blade-row, they are estimated in Subroutine E2. At the rotor exit, they have already been determined in Subroutine C2, which also determines the total pressure and temperature at the stator exit. The stator exit whirl velocity distribution is estimated in Subroutine D2 from the downstream experimental flow angle data. The iterative solution of the momentum and continuity equations is then commenced. The gradients in the direction of the computing station of total enthalpy, entropy, and angular momentum are determined, leading to a new estimate of the meridional

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SUBROUTINE D2

ENTER
(A) → DO 630 I=1,NSTNS

| SUBROUTINE H2 |
| Determine streamline characteristics |
| and some terms in momentum equation |

| SUBROUTINE I2 |
| Determine blockage due to |
| boundary layers and wakes |

GO TO (110,110,130,140,180),NCALC(I)
110 P,T,rV_θ constant from previous station

130 ───────────→ | SUBROUTINE E2 |
| Determine P,T,V_θ within blade row only |

140 Determine V_θ after stator

180 ITER=0
     VMIN=10000.0
     VMAX=0.0
(B) → 190 ITER=ITER+1
     IF(ITER.GT.1.AND.NCALC(I).NE.2)
     Calculate dH/de, dS/de, drV_θ/de
230 Compute momentum equation (messages nos. 4, 5, and 6)

     IF(NCALC(I).EQ.2) → | SUBROUTINE E2 |
| Reestimate P,T,V_θ within blade row only |

     IF(ITER.EQ.ITMAX)
     IF(Momentum equation unconverged)
340 Compute continuity equation (message no. 7)
     IF(dW/dV_m.LE.0.0)
(C) ← IF(NMACH(I).EQ.1)
     IF(W<$W_{specified}$)VMAX=$V_{m_{mid}}$

410 ΔV_m=ΔW/dW/dV_m
     Restrain $|\Delta V_m| \le .1V_{m_{mid}}$ and VMIN>($V_{m_{mid}}$+ΔV_m)>MAX

(D) ←

420 IF(NMACH(I).EQ.0)
     IF(W< $W_{specified}$)VMIN=$V_{m_{mid}}$

430 (Message no. 8) ←

(E)

Figure 5. Logic of Subroutine D2.

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(E)

IF(V$_{m_{mid}}$.LT.VMIN)VMIN=V$_{m_{mid}}$

ΔV_m=-.1V$_{m_{mid}}$

Restrain ΔV_m so that V$_{m_{mid}}$+ΔV_m>VMAX

(C) →480 (Message no. 8)

IF(V$_{m_{mid}}$.GT.VMAX)VMAX=V$_{m_{mid}}$

ΔV_m=.1V$_{m_{mid}}$

Restrain ΔV_m so that V$_{m_{mid}}$+$\Delta \dot V_m$<VMIN

(D) →510 V$_m$=V$_m$+ΔV_m, all radii

IF(Continuity and momentum equations are converged)

IF(ITER.EQ.ITMAX)

IF(NCALC(I).EQ.2)→

SUBROUTINE E2
Reestimate P,T,V$_\theta$ within blade row only

(B)

→550 (Message no. 9)

→580 IF(I is at a blade leading edge)Calculate $\bar\omega$

IF(I is at a stator trailing edge)Calculate δ_s

IF(I is at a rotor trailing edge)Calculate δ_R

IF(I is at an instrumentation plane)Calculate M

Check overall convergence, set IVFAIL, IFFAIL

Reestimate streamline radii

IF(solution failed .AND.IPASS.GT.NFORCE)

IF(NBL(I).EQ.1)→

SUBROUTINE I2
Iterative reestimate of blockage

(A) ←630 End of DO loop for stations

→RETURN

Figure 5 continued.

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velocity profile from the momentum equation. Then, if the computing station
is within a blade row, Subroutine E2 is reentered to obtain a revised esti-
mate of the total pressure, total temperature, and whirl velocity distribu-
tions based on the new meridional velocity profile. Unless all permitted
iterations have taken place, a degree of convergence of the momentum equation
is required before the continuity equation is evaluated. This is because the
flow and rate of change of flow with meridional velocity that are computed
from the continuity equation are associated with the midradius meridional
velocity, and, if the calculations are based upon an unconverged (that is,
invalid) meridional velocity profile, an incorrect relationship may be
deduced. For this purpose, the meridional velocity profile is taken to be
converged if, at every streamline, the change in velocity is less than five
parts in 1000. Application of the continuity equations consists of deter-
mining the flow rate and rate of change of flow with (midradius) meridional
velocity, and then adjusting the velocity level accordingly. Next, a check
is made upon the convergence of the momentum and continuity equations. The
solution is taken to be converged when the flow rate is within one part in
4000 of the specified value, and the meridional velocity at each streamline
has changed on two consecutive iterations by less than the same proportions.
If the solution is not converged and all permitted iterations have not taken
place, a further iteration is started. For stations that are within a blade
row, Subroutine E2 is reentered to obtain revised estimates of total tempera-
ture, total pressure, and whirl velocity. If no further iterations are to
be made, a blade row loss coefficient or deviation angle distribution, or
instrumentation plane Mach number distribution may be determined, depending
upon the location of the computing station. The overall convergence of the
solution at the computing station is then checked. The overall solution is
taken to be converged if the meridional velocities computed on two consecutive
passes agree to within one part in 1000, and the proportion of the total flow
in each streamtube is correct to within the same tolerance. The streamline
radii are reestimated next. If the solution failed and the pass number is
greater than NFORCE, execution of Subroutine D2 terminates, and control re-
turns to Subroutine UD0200. Otherwise, if iterative determination of the
blockage at the station is specified, Subroutine I2 is reentered to obtain
a refined estimate of the blockage at the computing station. Control then
returns to the beginning of Subroutine D2 to perform the entire procedure
for each remaining computing station.

m. Subroutine E2

Subroutine E2 determines, for computing stations that are
within blade rows, the relative flow angles, total temperature, total
pressure, whirl velocity, and some components of the momentum equation.

n. Subroutine H2

Subroutine H2 determines the streamline characteristics
(slope and curvature), and most terms of the momentum equation. It deter-
mines the values of terms that are not a function of meridional velocity
and therefore need no revision as the iterative solution of the momentum
and continuity equations proceeds.

o. Subroutine I2

Subroutine I2 determines the radial distribution of blockage
due to annulus wall boundary layers and blade wakes, according to the input
data terms BLCKGE and BDIST. If iterative determination of the blockage to
create a match between computed and observed casing static pressure is
specified, BLCKGE is recalculated.

p. Subroutine F2

Subroutine F2 produces the aerodynamic analysis regular printed
output and, if specified, creates the static pressure distribution plot. Sub-
routine F2 takes no part in the determination of the solution. The ordinate
of the static pressure plot is pressure and the abscissa is the axial coordi-
nate. The lower unit and scale of the ordinate are specified by the user, but
the length of the axis is fixed at 6 inches. The subroutine automatically
sets the lower unit of the abscissa so that the whole flow field is included
in the plot. The scale of the abscissa is fixed at one inch of axial coordi-
nate per one inch of plot.

If the user specifies that blade performance plots are to be
generated in which all test point results are contained on a single plot for
each parameter, the necessary data are written onto a scratch file for subse-
quent plotting. These plots are generated in another subroutine.

q. Subroutine J2

Subroutine J2 plots blade performance parameters when separate
plots for each test point for each parameter are specified. The abscissa for
each plot is the ratio of radius to tip radius, and the scale is automatically

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set so that a four-inch long axis is created. The ordinates are the various parameters plotted, and, with the scales selected, all reasonable variations of the parameters should fall within approximately a four-inch spread. The starting point values for the ordinates are selected automatically, based upon the lowest value of the parameter to be plotted. The plots are fully labeled.

r. Subroutine K2

Subroutine K2 produces plots of the blade performance parameters when values of each parameter for all test points are to be plotted on one graph. Subroutine K2 is a modified form of Subroutine J2.

s. Subroutine UD0100

Subroutine UD0100 is the "main program" for the blade geometry definition section of the program. The functions, procedures, and methods used in Subroutine UD0100 have already been discussed in previous sections.

t. Subroutine T2

Subroutine T2 performs the interpolations, slope determinations, and linear extrapolations required in the blade geometry definition section of the program.

u. Subroutine ROTATE

Subroutine ROTATE performs the blade coordinate rotation transformations required in the blade geometry definition section of the program.

v. Subroutine LL

Subroutine LL performs the line-counting function required to prepare the printed output.

w. Subroutine MM

Subroutine MM reads and prints the inlet guide vane input data (if an IGV exists).

SECTION VII

PROGRAM IMPLEMENTATION

1. PROGRAM CODING AND STRUCTURE

Program UD0400 has been written in standard FORTRAN IV and will be
compatible with all contemporary computing systems having a FORTRAN com-
piler with few or no modifications. The program was originally developed
using a CDC 6600 system and has also been used on an IBM 370 system.
Some minor modifications are required to change from one system to the
other or if CALCOMP software is not available. These modifications are
discussed below.

There is one nonstandard coding feature which was introduced to
run the program on the CDC 6600 system - the PROGRAM statement at the be-
ginning of the main program (UD0400). The PROGRAM statement defines ten
peripheral units referred to within the program. This statement should be
deleted if the program is to be run on another type of system.

Within the program, reference is made to ten peripheral units: LOG1,
LOG2, LOG3, LOG4, LOG5, LOG6, LOG7, LOG8, LOG9, and TAPE10. The peripheral
unit assignments are made at the beginning of the main program (UD0400) and
passed throughout the program so that if changes are required they need
only be made once. The file assignments and contents are as follows:

FORTRAN NOMENCLATURE	PERIPHERAL UNIT	CONTENTS
LOG1	TAPE1	Input data
LOG2	TAPE6	Printed output
LOG3	TAPE3	Input data
LOG4	TAPE4	Input data
LOG5	TAPE5	Internal scratch file
LOG6	TAPE2	Punch-card output
LOG7	TAPE7	Internal scratch file
LOG8	TAPE8	Internal scratch file
LOG9	TAPE9	Input data
-	TAPE10	CALCOMP plot output

The contents of the input data files (LOG1, LOG3, LOG4, and LOG9) are
defined in Section III. The internal scratch file LOG5 is only required

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if NPLOT=2 is selected, and is used to store the blade performance data
to be plotted after all test points have been analyzed. The internal
scratch files LOG7 and LOG3 are used to transfer blade geometry data from
the UD0100 section of the program to the UD0200 section. All printed
output is contained on file LOG2. All punch-card type output is contained
on file LOG6. The peripheral unit TAPE10 contains the CALCOMP plot
output.

2. PROGRAM USE AND MODIFICATIONS

A typical example of the Job-Control-Language (JCL) necessary to
execute Program UD0400 on a CDC 6600 system with CALCOMP software is
as follows:

```
JOB,CM100000,T50,IO50.      P750232,LAW,54738.
ATTACH,UD0400,UD0400,CY=3.
ATTACH,TAPE1,UD0400DATA,CY=1.
ATTACH,TAPE3,UD0400DATA,CY=3.
ATTACH,TAPE4,UD0400DATA,CY=4.
ATTACH,TAPE9,UD0400DATA,CY=9.
ATTACH,CCPLOT,CCPLOT1038,ID=LIBRARY,SN=ASD.
LIBRARY=CCPLOT.
REQUEST,TAPE10,*Q.
UD0400,PL=30000.
ROUTE,TAPE10,TID-AP,ST=CSA,DC=PR,FC=NP,FID=LAWAO.
6/7/8/9 END OF JOB
```

In this example, input data files TAPE1, TAPE3, TAPE4, and TAPE9 are at-
tached from permanent files. The program (compiled and loaded) is attach-
ed as UD0400. Permanent file CCPLOT1038 contains the CALCOMP software
routines for the CALCOMP Model 1038 plotter. File TAPE10 contains the
CALCOMP plot output from the program.

In the event that CALCOMP software is not available on a system
where the program is to be run, it may be necessary to provide dummy sub-
routines for PLOTS, PLOT, PLOTE, AXIS, SCALE, LINE, NUMBER, and SYMBOL to
avoid unsatisfied external reference errors during compilation. A typical
dummy subroutine might be:

```
SUBROUTINE SCALE(A,B,C,D)
RETURN
END
```

On an IBM 370 system it may be necessary to also provide a dummy subroutine
for EOF.

On the IBM 370 system, the PROGRAM statement at the beginning of the main program (UD0400) is deleted and all files are defined in the JCL. A typical example on an IBM 370 system without CALCOMP software is as follows:

```
//LAW              JOB   (55555,450,60,8),LAW-PHASE2-DATA,
//        REGION=316K,TIME=10,NOTIFY=LAW
//ONE              EXEC FORTHCL,PARM.FORT=ID
//*
//* LOAD PROGRAM UD0400
//*
//FORT.SYSIN       DD    DISP=SHR,DSN=LAW.UD0400.FORTMOD.FORT(MAIN2)
//LKED.OLDLMOD     DD    DSN=LAW.UD0400.LOAD,DISP=SHR
//LKED.SYSIN       DD    *
          INCLUDE   OLDLMOD(MAIN)
          ENTRY MAIN
//TWO              EXEC PGM=IEBGENER
//*
//* COPY DATA TO SCRATCH DATA SET - &&TAPE1
//*
//SYSPRINT         DD    DUMMY
//SYSIN            DD    DUMMY
//SYSUT2           DD    UNIT=DISK,VOL=SER=OSSY01,
//        DSN=&&TAPE1,DISP=(NEW,PASS),SPACE=(1600,(100,10)),
//        DCB=(LRECL=80,BLKSIZE=1600,RECFM=FB)
//SYSUT1           DD    DSN=LAW.UD0400.DATA(TAPE1),DISP=SHR
//THREE            EXEC PGM=IEBGENER
//*
//* COPY DATA TO SCRATCH DATA SET - &&TAPE3
//*
//SYSPRINT         DD    DUMMY
//SYSIN            DD    DUMMY
//SYSUT2           DD    UNIT=DISK,VOL=SER=OSSY01,
//        DSN=&&TAPE3,DISP=(NEW,PASS),SPACE=(1600,(100,10)),
//        DCB=(LRECL=80,BLKSIZE=1600,RECFM=FB)
//SYSUT1           DD    DSN=LAW.PUNCH.DATA(P810408),DISP=SHR
//FOUR             EXEC PGM=IEBGENER
//*
//* COPY DATA TO SCRATCH DATA SET - &&TAPE4
//*
//SYSPRINT         DD    DUMMY
//SYSIN            DD    DUMMY
//SYSUT2           DD    UNIT=DISK,VOL=SER=OSSY01,
//        DSN=&&TAPE4,DISP=(NEW,PASS),SPACE=(1600,(100,10)),
//        DCB=(LRECL=80,BLKSIZE=1600,RECFM=FB)
//SYSUT1           DD    DSN=LAW.UD0400.DATA(TAPE4),DISP=SHR
//FIVE             EXEC PGM=IEBGENER
//*
//* COPY DATA TO SCRATCH DATA SET - &&TAPE9
//*
```

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```
//SYSPRINT          DD    DUMMY
//SYSIN             DD    DUMMY
//SYSUT2            DD    UNIT=DISK,VOL=SER=OSSY01,
//        DSN=&&TAPE9,DISP=(NEW,PASS),SPACE=(1600,(100,10)),
//        DCB=(LRECL=80,BLKSIZE=1600,RECFM=FB)
//SYSUT1            DD    DSN=LAW.UD0400.DATA(TAPE9),DISP=SHR
//SIX               EXEC  PGM=*.ONE.LKED.SYSLMOD,
//        COND=((4,LT,ONE.FORT),(4,LT,ONE.LKED))
//*
//* EXECUTE PROGRAM UD0400
//*
//FT01F001          DD    DSN=&&TAPE1,DISP=(OLD,DELETE)
//FT02F001          DD    SYSOUT=B
//FT03F001          DD    DSN=&&TAPE3,DISP=(OLD,DELETE)
//FT04F001          DD    DSN=&&TAPE4,DISP=(OLD,DELETE)
//FT05F001          DD    UNIT=DISK,VOL=SER=OSSY01,
//        SPACE=(1600,(100,10)),DCB=(LRECL=80,BLKSIZE=1600,RECFM=FB)
//FT06F001          DD    SYSOUT=A
//FT07F001          DD    UNIT=DISK,VOL=SER=OSSY01,
//        SPACE=(1600,(100,10)),DCB=(LRECL=80,BLKSIZE=1600,RECFM=FB)
//FT08F001          DD    UNIT=DISK,VOL=SER=OSSY01,
//        SPACE=(1600,(100,10)),DCB=(LRECL=80,BLKSIZE=1600,RECFM=FB)
//FT09F001          DD    DSN=&&TAPE9,DISP=(OLD,DELETE)
//
```

SECTION VIII

FORTRAN NOMENCLATURE

All the important variables in the program and their uses are given
here.

Variable	Description
ABROTM	Mach number on each streamline at instrumentation plane NSTN1 (downstream of rotor)
ABSTAM	Mach number on each streamline at instrumentation plane NSTN2 (downstream of stage)
BDIST	Ratio of wake and boundary layer blockage at hub to midradius value (one value per station)
BLCKGE	Blockage due to blade wakes and annulus wall boundary layers at midradius (one value per station)
B1	Blockage at mid-streamtube due to blading
B2	Blockage at mid-streamtube determined from BLCKGE and BDIST
CPPG	$\cos(\emptyset + \gamma)$ on each streamline
CR	Streamline curvature, on each streamline
C1	$\pi/180.0$
DATAB	Input data values of blockage due to blades
DATBET	Input data values of blade section angle
DATEPS	Input data values of blade lean angle
DATHET	Input data values of blade angular coordinate
DATRAD	Input data values of radius for blade properties
DEL	Blade section angle of rotation
DELF	Target flow distribution for streamtubes
DR	"Three-dimensional" rotor diffusion factor on each streamline
DRDZ2	$(\Delta r/\Delta x)^2$ for streamline relocation relaxation factor, one value per station

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DRVWDM $\qquad \dfrac{\tan \epsilon}{r} \dfrac{drV_\theta}{dm}$ on each streamline

DS $\qquad$ "Three-dimensional" stator diffusion factor on each streamline

DVMDM $\qquad \sin (\emptyset + \gamma) dV_m/dm$ on each streamline

EJ $\qquad$ Joules equivalent

EPS $\qquad \tan \epsilon$ on each streamline

FLOW $\qquad$ Flow rate specified in input data

FRCAIR $\qquad$ Fraction of working fluid that is air, by mass

FX $\qquad$ Fraction of meridional chord where intermediate stations lie

G $\qquad$ Acceleration due to gravity

GAMA $\qquad \tan \gamma$ on each streamline

GASR $\qquad$ Gas constant

H1R $\qquad$ Relative total enthalpy at blade inlet on each streamline

ICASE $\qquad$ Test point number being analyzed

IFFAIL $\qquad$ Number of unconverged streamtubes

ILAST $\qquad$ Records station number if solution has failed

IMID $\qquad$ NSTRMS/2 + 1

INSIST $\qquad$ Blade data extrapolation option indicator

IPASS $\qquad$ Iterative pass number

IRLE $\qquad$ Station number at rotor leading edge

IRT $\qquad$ Station number at rotor trailing edge

ISLE $\qquad$ Station number at stator leading edge

IST $\qquad$ Station number at stator trailing edge

ISTOP $\qquad$ Last station at which results are to be output

ISTRT1 $\qquad$ Location within data arrays at which first station geometry specification data is stored, one value per station

ISTRT2	Location within data arrays at which first blade geometry data item is stored, one value per station
ITUB	NSTRMS - 1
IVFAIL	Number of unconverged mesh points
LNCT	Number of lines printed on current output page
LOG1	Fixed input data unit number
LOG2	Standard output unit number
LOG3	Experimental input data unit number
LOG4	User-supplied input data unit number
LOG5	Scratch file unit number
LOG6	Punch-card output unit number
LOG7	Scratch file unit number
LOG8	Scratch file unit number
LOG9	Blade coordinate input data unit number
NBL	Input indicator for handling blockage due to wakes and boundary layers, one value per station
NBLADE	The number of blades in a blade row
NCALC	Input indicator specifying type of calculation, one value per station (except station 1)
NCASE	Number of test points to be analyzed
NDATA	Number of blade data points, one value per station
NFORCE	Last pass number when arbitrary numbers will be inserted into solution if necessary
NINPUT	Indicator for blade section coordinate input data source
NL	Maximum number of printed lines per output page
NMACH	Solution type indicator for continuity equation, one value per station
NMAX	Maximum permitted number of iterative passes

NOROTR	Number of blades in rotor
NOSTAT	Number of blades in stator
NP	Number of points defining the 'p' surface of the blade section
NPLOT	Indicator for CALCOMP plots
NPRINT	Indicator for blade section coordinate printout
NPRSS	Indicator specifying which instrumentation plane gives rotor outlet total pressure
NRP	Number of total pressure data points at instrumentation plane NSTN1
NRT	Number of total temperature data points at instrumentation plane NSTN1
NR1	Number of points for rotor internal loss curve
NR2	Number of points for rotor internal deviation curves
NR3	Number of radii where rotor internal deviation curves are given
NS	Number of points defining the 's' surface of the blade section
NSA	Number of radii where flow angles are given at instrumentation plane NSTN2
NSP	Number of radii where total pressures are given at instrumentation plane NSTN2
NSPEC	Number of points defining computing station geometry, one value per station
NST	Number of radii where total temperature is given at instrumentation plane NSTN2
NSTNS	Number of computing stations
NSTN1	Station number at instrumentation plane downstream of rotor
NSTN2	Station number at instrumentation plane downstream of stage
NSTRMS	Number of streamlines
NS1	Number of points for stator internal loss curve
NS2	Number of points for stator internal deviation curves

NS3	Number of radii where stator internal deviation curves are given
NTEMP	Indicator specifying which instrumentation plane gives total temperature at rotor outlet
NWHICH	Indicator for blade section rotation
NWSI	Number of experimental wall static pressure readings on inner wall
NWSO	Number of experimental wall static pressure readings on outer wall
NX	Number of stations where output is to be generated
NXII	Number of points defining a station
NZ	Number of constant-z planes on which blade sections are defined
OMPP	$(1 - p/P_R)$ at blade leading edge, on each streamline
P	Total pressure; first subscript streamline number, second station number
PHI	$\emptyset$, radians, on each streamline
PI	π
PIN	Inlet total pressure
PR	Experimental total pressures at instrumentation plane NSTN1
PRATIO	Ratio of actual compressor inlet total pressure at test time to the value PIN
PS	Circumferentially averaged experimental total pressures at instrumentation plane NSTN2
PSM	Circumferential peak experimental total pressures at instrumentation plane NSTN2
R	Streamline radius, subscripted as P
RDEV	Rotor deviation angles on each streamline
RF	Relaxation factor used in iterative solution of momentum equation
RI	Rotor incidence angles on each streamline
RLOSS	Ratio of local to final loss coefficient within rotor
ROTDEV	Rotor deviation angles on each streamline

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RPM	Rotor rotational speed
RRD	Radius at which rotor internal deviation curve applied
RRP	Radii at which total pressures are given at instrumentation plane NSTN1
RRT	Radii at which total temperatures are given at instrumentation plane NSTN1
RSA	Radii at which flow angles are given at instrumentation plane NSTN2
RSD	Radius at which stator internal deviation curve applies
RSP	Radii at which total pressures are given at instrumentation plane NSTN2
RST	Radii at which total temperatures are given at instrumentation plane NSTN2
RSTN	Radius at a point defining computing station geometry
RTEMP	Array used to store streamline radii at previous computing station as determined on previous pass
R1M	Fractions of meridional chord where rotor internal loss are given
R2M	Fractions of meridional chord where rotor internal deviation angles are given
SA	Experimental flow angles at instrumentation plane NSTN2
SDEV	Stator deviation angles on each streamline
SI	Stator incidence angles on each streamline
SLOSS	Ratio of local to final loss coefficient within stator
SPPG	$\sin(\phi + \gamma)$ on each streamline
STADEV	Stator deviation angles on each streamline
S1M	Fractions of meridional chord where stator internal loss are given
S2M	Fractions of meridional chord where stator internal deviation are given
T	Total temperature, subscripted as P
TANA	Tangent of blade section angle on each streamline

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TANR	Tangent of relative flow angle on each streamline
TAPE10	CALCOMP output unit
TDSDM	$\cos^2\alpha_R \frac{ds}{dm} (\sin(\emptyset + \gamma) - \tan\epsilon \tan\alpha_R)$ on each streamline
TFW	Fraction of total flow passing between hub and streamline, one value for each streamline
TIN	Inlet total temperature
TITLE	Title for UD0200 section test point input data or title for UD0100 section input data
TITLE1	Title for UD0200 section fixed input data
TR	Experimental total temperatures at instrumentation plane NSTN1
TS	Experimental total temperatures at instrumentation plane NSTN2
T1R	Relative total temperature at blade inlet on each streamline
VM	Meridional velocity, subscripted as P
VV	Meridional velocity on each streamline during iterative solution of momentum and continuity equations
VW	Whirl velocity, subscripted as P
WR	Rotor relative total pressure loss coefficient on each stream-line
WS	Stator relative total pressure loss coefficient on each stream-line
WSPI	Experimental static pressures on inner wall
WSPO	Experimental static pressures on outer wall
XLE	'X' coordinate of a point representing the leading edge of the blade section
XMR	Relative Mach number at rotor inlet on each streamline
XMS	Mach number at stator inlet on each streamline
XP	The x-coordinate of a point on the 'p' surface of a blade
XR	'X' coordinate of the center of rotation for the blade section

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XS	The x-coordinate of a point on the 's' surface of a blade
XSHIFT	Quantity added to the blade section station coordinates to align the blade origin with the compressor origin
XSTN	Axial coordinate of a point defining computing station geometry
XTE	'X' coordinate of a point representing the trailing edge of the blade section
XWSI	Axial coordinate of a point where inner wall static pressure is given
XWSO	Axial coordinate of a point where outer wall static pressure is given
YLE	'Y' coordinate of a point representing the leading edge of the blade section
YP	The y-coordinate of a point on the 'p' surface of a blade
YR	'Y' coordinate of the center of rotation for the blade section
YS	The y-coordinate of a point on the 's' surface of a blade
YTE	'Y' coordinate of a point representing the trailing edge of the blade section
Z	The z-coordinates of the constant-z planes, the origin is on the compressor axis

SECTION IX

SAMPLE OUTPUT FROM PROGRAM UDO400

The printed output for a single test point is reproduced on the following pages. The analysis is performed for a single-stage compressor with an inlet guide vane. Three blade row geometries are determined prior to one test point analysis. In the sample, the inlet guide vanes and stator vanes are variable but set at their design values (0.0 deg.). Each of the three blade geometry definition printed outputs consist of two parts: a listing of the user input data and a listing of the computed results. In this sample, all of the blade section coordinate input data printout has been omitted. For each blade row, data are computed and printed which define the computing stations at leading and trailing edges. Note that the sequence of blade geometry printouts is the same as the sequence in which the air flow encounters the blades in the aerodynamic analysis.

The aerodynamic analysis printed output follows next and consists of three parts: the fixed input data, the experimental data, and the computed aerodynamic results. The fixed input data printout consists of all the input data which are read only once per program execution, including principally the compressor geometry and some "constants." Computing station data are printed next which define the hub and casing segments over each of the blade-rows, followed by the calculated wall radii for each leading and trailing edge computing station. Printed next are station calculation specification and blading data that include a listing of the data computed by the previous three executions of the blade geometry definition section of the program. IGV performance data and rotor and stator generalized performance specifications are then printed.

Next, all of the input data peculiar to the test point are listed, consisting mainly of the experimental data and distributed blockage specifications. For this sample, stage outlet temperatures and peak stage outlet pressures are used to compute compressor performance. The computed results are printed next, station-by-station, followed by printouts of the rotor and stator blade section overall performances. The printed output is concluded by listing the wake and boundary layer blockages incorporated into the calculation and a summary of the running conditions for the test point.

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```
PROGRAM J00400 (UD0100 AND UD0200 COMBINED)
***************************************************

        NUMBER OF ENTRIES TO UD0100 = 3
        NUMBER OF ENTRIES TO UD0200 = 1
```

PROGRAM J00100

RUN TITLE =   IGV BLADE GEOMETRY CALCULATION
NZ = 13 NBLADE = 36 NWHICH = 1 NPRINT = 1 NINPUT = 1

BLADE RESTAGGER = 0.000

J	Z	XLE	YLE	XTE	YTE
1	3.8000	-1.3658	.0050	.5790	.0313
2	4.1000	-1.1205	.0121	.6343	.0067
3	4.4000	-.9217	.0183	.6897	-.0178
4	4.7000	-.8222	.0229	.7456	-.0381
5	5.0000	-.7842	.0279	.8018	-.0532
6	5.3000	-.7833	.0336	.8576	-.0691
7	5.6000	-.7840	.0394	.9136	-.0863
8	5.9000	-.7837	.0455	.9695	-.1042
9	6.2000	-.8061	.0522	1.0256	-.1244
10	6.5000	-.8663	.0598	1.0815	-.1494
11	6.8000	-.9668	.0678	1.1374	-.1811
12	7.1000	-1.1203	.0758	1.1932	-.2216
13	7.4000	-1.3075	.0835	1.2489	-.2630

XR =   0.0000 YR =   0.0000 XSHIFT = -12.6770

NX = 2

I	FX
1	0.0000
2	1.0000

STATION 1

NXI = 13

XSTN	RSTN
-1.3658	3.8000
-1.1205	4.1000
-.9217	4.4000
-.8222	4.7001
-.7842	5.0001
-.7833	5.3001
-.7840	5.6001
-.7837	5.9002
-.8061	6.2002
-.8663	6.5003
-.9668	6.8003
-1.1203	7.1004
-1.3075	7.4005

STATION 2

NXI = 13

XSTN	RSTN
.5790	3.8001
.6343	4.1000
.6897	4.4000
.7456	4.7002
.8018	5.0003

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```
            .8576      5.3005
            .9136      5.6007
            .9695      5.9009
           1.0256      6.2012
           1.0815      6.5017
           1.1374      6.8024
           1.1932      7.1035
           1.2489      7.4047
```

STATION   1 NRR = 13

RADIUS	ALPHA	EPS	B	THETA
3.8000	−2.5006	−1.3353	.0135	.0014
4.1000	−2.6265	−1.1200	.0125	.0031
4.4000	−2.7814	−.7585	.0116	.0043
4.7001	−2.8069	−.5955	.0107	.0050
5.0001	−3.0377	−.7140	.0100	.0057
5.3001	−3.0281	−.7376	.0093	.0064
5.6001	−2.9993	−.7243	.0087	.0071
5.9002	−2.9954	−.7582	.0081	.0078
6.2002	−3.0118	−.8741	.0076	.0085
6.5003	−3.0700	−.9789	.0072	.0093
6.8003	−3.2297	−.9664	.0067	.0101
7.1004	−3.7275	−.8884	.0064	.0107
7.4005	−4.1962	−.8224	.0060	.0114

STATION   2 NRR = 13

RADIUS	ALPHA	EPS	B	THETA
3.8002	5.1064	5.1567	.0149	.0095
4.1000	2.8744	4.9172	.0139	.0028
4.4000	.1684	4.2280	.0130	−.0029
4.7001	−2.8304	2.8548	.0123	−.0070
5.0002	−4.5887	2.2707	.0116	−.0096
5.3004	−6.0628	2.5074	.0109	−.0121
5.6006	−7.5113	2.5027	.0104	−.0145
5.9008	−8.9091	2.5812	.0100	−.0168
6.2011	−10.2191	3.1398	.0095	−.0192
6.5016	−11.5775	4.0183	.0092	−.0222
6.8023	−12.9691	5.4833	.0089	−.0259
7.1033	−14.3257	6.2322	.0086	−.0305
7.4045	−15.3340	5.7346	.0083	−.0348

```
PROGRAM JD0100
--------------

RUN TITLE =     ROTOR 1 BLADE GEOMETRY CALCULATION
NZ = 11 NBLADE = 34 NWHICH = 1 NPRINT = 1 NINPUT = 1

BLADE RESTAGGER =   0.000

        J       Z        XLE       YLE       XTE       YTE

        1     4.5000   -1.4827    1.0325    1.7542    .8730
        2     4.7500   -1.4710    1.1104    1.6806    .5636
        3     5.0000   -1.4527    1.1810    1.6071    .2543
        4     5.2500   -1.4281    1.2343    1.5336   -.0551
        5     5.5000   -1.4087    1.2776    1.4601   -.3645
        6     5.7500   -1.3884    1.3134    1.3849   -.6503
        7     6.0000   -1.3649    1.3404    1.3193   -.8443
        8     6.2500   -1.3417    1.3636    1.2572   -.9725
        9     6.5000   -1.3178    1.3719    1.1994   -1.0747
       10     6.7500   -1.2934    1.3777    1.1459   -1.1776
       11     7.0000   -1.2728    1.4025    1.0877   -1.2653

XR =   0.0000  YR =    0.0000  XSHIFT =  -9.9985

NX =  2

    I      FX

    1    0.0000
    2    1.0000
```

STATION 1

NXI = 11

```
        XSTN      RSTN

      -1.4827    4.6169
      -1.4710    4.8781
      -1.4527    5.1376
      -1.4281    5.3931
      -1.4087    5.6464
      -1.3884    5.8981
      -1.3649    6.1479
      -1.3417    6.3970
      -1.3178    6.6432
      -1.2934    6.8892
      -1.2728    7.1391
```

STATION 2

NXI = 11

```
        XSTN      RSTN

       1.7542    4.5839
       1.6806    4.7833
       1.6071    5.0065
       1.5336    5.2503
       1.4601    5.5121           107
       1.3849    5.7867
       1.3193    6.0591
       1.2572    6.3252
       1.1994    6.5882
```

```
              1.1459      6.8520
              1.0877      7.1134


STATION   1 NRR = 11

RADIUS        ALPHA        EPS          B         THETA

  4.6183     -52.2904     -4.7773      .0172       .2268
  4.8795     -52.7924     -3.6635      .0169       .2309
  5.1390     -53.4238      -.6320      .0166       .2331
  5.3946     -53.3391      2.6566      .0158       .2320
  5.6479     -53.8188      4.0539      .0154       .2293
  5.8995     -54.3619      5.9147      .0151       .2256
  6.1493     -55.0767      6.6850      .0148       .2208
  6.3984     -55.8658      8.6445      .0146       .2158
  6.6443     -56.5129     11.1771      .0144       .2090
  6.8906     -57.9189      8.5194      .0145       .2023
  7.1405     -58.7963      3.1278      .0142       .1987


STATION   2 NRR = 11

RADIUS        ALPHA        EPS          B         THETA

  4.5853      54.1364     62.2089      .0177       .1932
  4.7841      47.3259     57.9709      .0145       .1195
  5.0068      39.1632     54.0736      .0122       .0520
  5.2502      29.0829     50.5734      .0108      -.0094
  5.5117      16.6664     47.1791      .0104      -.0652
  5.7860       -.3799     37.9711      .0106      -.1116
  6.0583     -14.1101     23.5421      .0109      -.1389
  6.3243     -22.3885     14.7451      .0110      -.1535
  6.5873     -27.4116     12.8096      .0112      -.1630
  6.8509     -31.2704     11.5410      .0115      -.1718
  7.1123     -35.5278      7.0459      .0114      -.1780
```

```
PROGRAM J00100
--------------

RUN TITLE =      STATOR 1 BLADE GEOMETRY CALCULATION
NZ = 10 NBLADE = 54 NWHICH = 1 NPRINT = 1 NINPUT = 1

BLADE RESTAGGER =  0.000

    J       Z        XLE       YLE       XTE       YTE

    1     5.6500    -.8313    -.5088    .7352     .3089
    2     5.8000    -.7118    -.4299    .7438     .2264
    3     5.9500    -.6540    -.3808    .7515     .1611
    4     6.1000    -.6445    -.3551    .7597     .1198
    5     6.2500    -.6802    -.3486    .7667     .0917
    6     6.4000    -.7356    -.3526    .7747     .0708
    7     6.5500    -.7905    -.3596    .7824     .0508
    8     6.7000    -.8454    -.3736    .7906     .0309
    9     6.8500    -.9011    -.3960    .7982     .0109
   10     7.0000    -.9565    -.4251    .8060    -.0111

XR =    0.0000  YR =   0.0000  XSHIFT =  -7.3747

NX =   2

    I      FX

    1     0.0000
    2     1.0000
```

STATION 1

NXI = 10

```
        XSTN       RSTN

       -.8313     5.6729
       -.7118     5.8159
       -.6540     5.9622
       -.6445     6.1103
       -.6802     6.2597
       -.7356     6.4097
       -.7905     6.5599
       -.8454     6.7104
       -.9011     6.8614
       -.9565     7.0129
```

STATION 2

NXI = 10

```
        XSTN       RSTN

        .7352     5.6584
        .7438     5.8044
        .7515     5.9522
        .7597     6.1012
        .7667     6.2507
        .7747     6.4004
        .7824     6.5502
        .7906     6.7001
        .7982     6.8500
        .8060     7.0000
```

STATION 1 NRR = 10

RADIUS	ALPHA	EPS	B	THETA
5.6732	43.6575	-37.4645	.0200	-.0906
5.8162	40.9769	-27.0955	.0185	-.0748
5.9625	39.6002	-17.3400	.0175	-.0647
6.1106	38.2358	-9.1446	.0166	-.0589
6.2600	37.5022	-3.0856	.0160	-.0565
6.4100	37.2908	-1.0055	.0155	-.0558
6.5601	37.4268	.4927	.0151	-.0556
6.7106	37.5422	3.7048	.0149	-.0564
6.8617	38.9109	6.5332	.0148	-.0584
7.0131	40.7306	8.6051	.0148	-.0613

STATION 2 NRR = 10

RADIUS	ALPHA	EPS	B	THETA
5.6582	-1.9591	34.0410	.0147	.0538
5.8042	-5.3636	28.8225	.0145	.0382
5.9520	-9.5374	20.9675	.0144	.0262
6.1011	-12.5577	13.5078	.0142	.0188
6.2506	-15.2306	9.7496	.0139	.0138
6.4003	-17.4455	8.1099	.0137	.0102
6.5502	-19.5264	8.0418	.0135	.0069
6.7000	-21.8752	7.7435	.0133	.0038
6.8500	-24.6548	7.9634	.0131	.0008
7.0000	-27.9610	8.6835	.0131	-.0024

FIXED DATA PRINTOUT

BASELINE AERODYNAMIC ANALYSIS - ACROSS BLADE

NUMBER OF STATIONS	= 14
NUMBER OF STREAMLINES	= 11
MAXIMUM NUMBER OF ITERATIONS	= 80
MAXIMUM NUMBER OF ARBITRARY ITERATIONS	= 10
TOTAL PRESSURE SOURCE INDICATOR	= 1
TOTAL TEMPERATURE SOURCE INDICATOR	= 1
STATION NUMBER FOR ROTOR EXIT DATA	= 9
STATION NUMBER FOR STAGE EXIT DATA	= 11
NUMBER OF ROTOR BLADES	= 34
NUMBER OF STATOR BLADES	= 54
MAXIMUM NUMBER OF LINES PER PAGE	= 60
NPLOT	= 0

ANNULUS SPECIFICATION

STATION 1 SPECIFIED BY 2 POINTS

RSTN	XSTN
5.2393	-19.2000
13.7718	-19.2000

STATION 2 SPECIFIED BY 2 POINTS

RSTN	XSTN
5.2393	-17.6000
11.6279	-17.6000

STATION 3 SPECIFIED BY 2 POINTS

RSTN	XSTN
4.7749	-16.1000
9.6179	-16.1000

STATION 4 SPECIFIED BY 2 POINTS

RSTN	XSTN
4.1658	-14.8500
8.1444	-15.0000

```
STATION  5  13 POINTS  HUB SEGMENT 1  CASE SEGMENT 1

    RSTN          XSTN

    3.8000        -14.0428
    4.1000        -13.7975
    4.4000        -13.5987
    4.7001        -13.4992
    5.0001        -13.4612
    5.3001        -13.4603
    5.6001        -13.4610
    5.9002        -13.4607
    6.2002        -13.4831
    6.5003        -13.5433
    6.8003        -13.6438
    7.1004        -13.7973
    7.4005        -13.9845

STATION  6  13 POINTS  HUB SEGMENT 1  CASE SEGMENT 1

    RSTN          XSTN

    3.8001        -12.0980
    4.1000        -12.0427
    4.4000        -11.9873
    4.7002        -11.9314
    5.0003        -11.8752
    5.3005        -11.8194
    5.6007        -11.7634
    5.9009        -11.7075
    6.2013        -11.6514
    6.5017        -11.5955
    6.8024        -11.5396
    7.1035        -11.4838
    7.4047        -11.4281

STATION  7  11 POINTS  HUB SEGMENT 2  CASE SEGMENT 2

    RSTN          XSTN

    4.6169        -11.4812
    4.8781        -11.4695
    5.1376        -11.4512
    5.3931        -11.4266
    5.6464        -11.4072
    5.8981        -11.3869
    6.1479        -11.3634
    6.3970        -11.3402
    6.6432        -11.3163
    6.8892        -11.2919
    7.1391        -11.2713
```

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STATION 8   11 POINTS HUB SEGMENT 2 CASE SEGMENT 2

```
   RSTN          XSTN

   4.5839        -8.2443
   4.7833        -8.3179
   5.0065        -8.3914
   5.2503        -8.4649
   5.5121        -8.5384
   5.7867        -8.6136
   6.0591        -8.6792
   6.3252        -8.7413
   6.5883        -8.7991
   6.8520        -8.8526
   7.1134        -8.9108
```

STATION 9   10 POINTS HUB SEGMENT 3 CASE SEGMENT 3

```
   RSTN          XSTN

   5.6729        -8.2060
   5.8159        -8.0865
   5.9622        -8.0287
   6.1103        -8.0192
   6.2597        -8.0549
   6.4097        -8.1103
   6.5599        -8.1652
   6.7104        -8.2201
   6.8614        -8.2758
   7.0129        -8.3312
```

STATION 10   10 POINTS HUB SEGMENT 3 CASE SEGMENT 3

```
   RSTN          XSTN

   5.6584        -6.6395
   5.8044        -6.6309
   5.9522        -6.6232
   6.1012        -6.6150
   6.2507        -6.6080
   6.4004        -6.6000
   6.5502        -6.5923
   6.7001        -6.5841
   6.8500        -6.5765
   7.0000        -6.5687
```

STATION 11 SPECIFIED BY 2 POINTS

```
   RSTN          XSTN

   5.7600        -6.3220
   7.0000        -6.3220
```

STATION 12 SPECIFIED BY 2 POINTS

```
  RSTN              XSTN

  5.7600           -6.0000
  7.0000           -6.0000
```

STATION 13 SPECIFIED BY 2 POINTS

```
  RSTN              XSTN

  5.7600           -5.7000
  7.0000           -5.7000
```

STATION 14 SPECIFIED BY 2 POINTS

```
  RSTN              XSTN

  5.7600           -5.4000
  7.0000           -5.4000
```

NO HUB SEGMENTS = 3   NO CASE SEGMENTS = 3

HUB SEGMENT 1   8 POINTS   NTERP = 0

```
  XHUB              RHUB

-14.8500           4.1658
-13.9000           3.9738
-13.4620           3.9625
-13.0240           3.9988
-12.5860           4.0839
-12.2980           4.1680
-12.0100           4.2761
-11.8430           4.3475
```

HUB SEGMENT 2   8 POINTS   NTERP = 0

```
  XHUB              RHUB

-11.5760           4.4225
-11.4870           4.5025
-10.8814           4.7580
-10.2928           4.9900
 -9.7041           5.2050
 -9.1155           5.4065
 -8.5585           5.5830
 -8.4269           5.6165
```

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HUB SEGMENT 3   8 POINTS   NTERP= 0

   XHUB   RHUB

   -8.3269   5.6370
   -8.2269   5.6510
   -7.9080   5.6820
   -7.5891   5.7030
   -7.2701   5.7190
   -6.9512   5.7340
   -6.6323   5.7580
   -6.5279   5.7600

CASING SEGMENT 1   8 POINTS   NTERP= 0

   XCASE   RCASE

   -15.0000   8.1444
   -13.9000   7.2661
   -13.4200   7.0948
   -12.9400   7.0114
   -12.4600   7.0000
   -11.9800   7.0000
   -11.5000   7.0000
   -11.4276   7.0000

CASING SEGMENT 2   2 POINTS   NTERP= 1

   XCASE   RCASE

   -11.3551   7.0000
    -8.6742   7.0000

CASING SEGMENT 3   2 POINTS   NTERP= 1

   XCASE   RCASE

   -8.5006   7.0000
   -6.4857   7.0000

STATION 5 CALCULATED END-POINTS

RHUB=   3.97366 XHUB=   -13.89843
RCASE=   7.26523 XCASE=   -13.89827

STATION 6 CALCULATED END-POINTS

RHUB=   4.27599 XHUB=   -12.01026
RCASE=   7.00000 XCASE=   -11.50296

STATION 7 CALCULATED END-POINTS

RHUB=   4.50302 XHUB=   -11.48578
RCASE=   7.00000 XCASE=   -11.28232

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STATION 8 CALCULATED END-POINTS

RHUB=   5.58772   XHUB=   -8.55968
RCASE=   7.00000 XCASE=   -8.88498

STATION 9 CALCULATED END-POINTS

RHUB=   5.65106   XHUB=   -8.22646
RCASE=   7.00000 XCASE=   -8.32649

STATION 10 CALCULATED END-POINTS

RHUB=   5.75795   XHUB=   -6.63353
RCASE=   7.00000 XCASE=   -6.56870

STATION CALCULATION SPECIFICATION AND BLADING DATA

STATION 2   NCALC = 0   NDATA =   0   NBL = 0

STATION 3   NCALC = 0   NDATA =   0   NBL = 0

STATION 4   NCALC = 0   NDATA =   0   NBL = 0

BLADE DATA FROM UD0100 FOR STATION 5

STATION 5   NCALC = 1   NDATA = 13   NBL = 0

RADIUS	BETA	EPSILON	BLOCKAGE	THETA
3.8000	-2.5006	-1.3353	.01353	.0014
4.1000	-2.6265	-1.1200	.01251	.0031
4.4000	-2.7814	-.7585	.01158	.0043
4.7001	-2.8069	-.5955	.01071	.0050
5.0001	-3.0377	-.7140	.00995	.0057
5.3001	-3.0281	-.7376	.00926	.0064
5.6001	-2.9993	-.7243	.00870	.0071
5.9002	-2.9954	-.7582	.00811	.0078
6.2002	-3.0118	-.8741	.00759	.0085
6.5003	-3.0700	-.9789	.00718	.0093
6.8003	-3.2297	-.9664	.00674	.0101
7.1004	-3.7275	-.8884	.00636	.0107
7.4005	-4.1962	-.8224	.00602	.0114

BLADE DATA FROM UD0100 FOR STATION 6

STATION 6   NCALC = 5   NDATA = 13   NBL = 1

RADIUS	BETA	EPSILON	BLOCKAGE	THETA
3.8002	5.1064	5.1567	.01492	.0095
4.1000	2.8744	4.9172	.01389	.0028
4.4000	.1684	4.2280	.01302	-.0029
4.7001	-2.8304	2.8548	.01226	-.0070
5.0002	-4.5887	2.2707	.01156	-.0096
5.3004	-6.0628	2.5074	.01095	-.0121
5.6006	-7.5113	2.5027	.01043	-.0145
5.9008	-8.9091	2.5812	.00996	-.0168
6.2011	-10.2191	3.1398	.00952	-.0192
6.5016	-11.5775	4.0183	.00919	-.0222
6.8023	-12.9691	5.4833	.00885	-.0259
7.1033	-14.3257	6.2322	.00857	-.0305
7.4045	-15.3340	5.7346	.00832	-.0348

BLADE DATA FROM UD0100 FOR STATION 7

STATION 7   NCALC = 1   NDATA = 11   NBL = 2

RADIUS	BETA	EPSILON	BLOCKAGE	THETA
4.6183	-52.2904	-4.7773	.01724	.2268
4.8795	-52.7924	-3.6635	.01695	.2309
5.1390	-53.4238	-.6320	.01657	.2331
5.3946	-53.3391	2.6566	.01584	.2320
5.6479	-53.8188	4.0539	.01542	.2293
5.8995	-54.3619	5.9147	.01508	.2256
6.1493	-55.0767	6.6850	.01482	.2208
6.3984	-55.8658	8.6445	.01455	.2158
6.6443	-56.5129	11.1771	.01441	.2090
6.8906	-57.9189	8.5194	.01451	.2023
7.1405	-58.7963	3.1278	.01417	.1987

BLADE DATA FROM UD0100 FOR STATION 8

STATION 8   NCALC = 4   NDATA = 11   NBL = 1

RADIUS	BETA	EPSILON	BLOCKAGE	THETA
4.5853	54.1364	62.2089	.01767	.1932
4.7841	47.3259	57.9709	.01452	.1195
5.0068	39.1632	54.0736	.01223	.0520
5.2502	29.0829	50.5734	.01083	-.0094
5.5117	16.6664	47.1791	.01039	-.0652
5.7860	-.3799	37.9711	.01064	-.1116
6.0583	-14.1101	23.5421	.01087	-.1389
6.3243	-22.3885	14.7451	.01099	-.1535
6.5873	-27.4116	12.8096	.01116	-.1630
6.8509	-31.2704	11.5410	.01153	-.1718
7.1123	-35.5278	7.0459	.01143	-.1780

BLADE DATA FROM UD0100 FOR STATION 9

STATION 9   NCALC = 1   NDATA = 10   NBL = 2

RADIUS	BETA	EPSILON	BLOCKAGE	THETA
5.6732	43.6575	-37.4645	.02003	-.0906
5.8162	40.9769	-27.0955	.01853	-.0748
5.9625	39.6002	-17.3400	.01745	-.0647
6.1106	38.2358	-9.1446	.01658	-.0589
6.2600	37.5022	-3.0856	.01597	-.0565
6.4100	37.2908	-1.0055	.01547	-.0558
6.5601	37.4268	.4927	.01508	-.0556
6.7106	37.5422	3.7048	.01486	-.0564
6.8617	38.9109	6.5332	.01475	-.0584
7.0131	40.7306	8.6051	.01476	-.0613

BLADE DATA FROM UD0100 FOR STATION 10

STATION 10   NCALC = 3   NDATA = 10   NBL = 1

RADIUS	BETA	EPSILON	BLOCKAGE	THETA
5.6582	-1.9591	34.0410	.01471	.0538
5.8042	-5.3636	28.8225	.01453	.0382
5.9520	-9.5374	20.9675	.01438	.0262
6.1011	-12.5577	13.5078	.01417	.0188
6.2506	-15.2306	9.7496	.01391	.0138
6.4003	-17.4455	8.1099	.01370	.0102
6.5502	-19.5264	8.0418	.01345	.0069
6.7000	-21.8752	7.7435	.01329	.0038
6.8500	-24.6548	7.9634	.01314	.0008
7.0000	-27.9610	8.6835	.01312	-.0024

STATION 11   NCALC = 0   NDATA = 0   NBL = 1

STATION 12   NCALC = 0   NDATA = 0   NBL = 1

STATION 13   NCALC = 0   NDATA = 0   NBL = 1

STATION 14   NCALC = 0   NDATA = 0   NBL = 1

NUMBER OF IGV BLADES = 0

DESIGN PERFORMANCE AT 11 RADII

RADIUS	BETA	LOSS COEFF
4.2761	.2500	.02886
4.5853	-1.6670	.02967
4.8895	-3.1280	.03048
5.1885	-4.3870	.03134
5.4810	-5.5940	.03233
5.7653	-6.7670	.03338
6.0396	-7.8910	.03442
6.3020	-8.9990	.03551
6.5509	-10.1120	.03674
6.7842	-11.1720	.03801
7.0000	-12.1360	.03920

```
RESTAGGER DATA GIVEN AT  0 RADII    0 POINTS PER RADIUS

ROTOR GENERALISED PERFORMANCE   LOSS  2PTS    DEVIATION  2PTS

        M-COORD   LOSS COEFF/TOTAL LOSS COEFF

        0.0000              0.0000
        1.0000              1.0000

OUTLET RADIUS = 0.0000

        M-COORD    DELTA R*VW/TOTAL DELTA R*VW

        0.0000              0.0000
        1.0000              1.0000

STATOR GENERALISED PERFORMANCE   LOSS  2PTS    DEVIATION  2PTS

        M-COORD   LOSS COEFF/TOTAL LOSS COEFF

        0.0000              0.0000
        1.0000              1.0000

OUTLET RADIUS = 0.0000

        M-COORD    DEVIATION/TOTAL DEVIATION

        0.0000              0.0000
        1.0000              1.0000

NUMBER OF TEST POINTS TO BE ANALYSED =   1

PSCALE= 0.00 PLOWER=  0.00 DAMPF=  6.000
NSAVE= 1 NNMAX=  0 MFORCE=  0 NEX= 2 NTCR= 0
NCARD= 1 NDPQ= 0
```

TEST DATA PRINTOUT FOR POINT NO. 1

    TEST POINT TITLE   =   810522101

    GAS CONSTANT   = 53.4270
    AIR MASS FRACTION   =   .99763
    FLOWRATE   = 17.2752
    ROTOR SPEED   = 12510.0
    INLET TOTAL PRESSURE   = 14.6940
    INLET TOTAL TEMPERATURE   = 518.708
    T IN/T IN(STD)   = 1.03585
    P IN/P IN(STD)   =   .96697
    IGV RESTAGGER ANGLE   = 0.00000

    ROTOR OUTLET TOTAL PRESSURE (3 POINTS)

       RADIUS   PRESSURE

       5.7660   19.4433
       6.2910   19.4880
       6.8490   19.9646

    ROTOR OUTLET TOTAL TEMPERATURE (3 POINTS)

       RADIUS   TEMPERATURE

       5.7660   560.857
       6.2910   558.395
       6.8490   562.719

    STAGE OUTLET TOTAL PRESSURES (7 POINTS)

       RADIUS   MEAN PRES   PEAK PRES

       5.9200   19.7479   19.9017
       6.0750   18.8650   19.6966
       6.2290   18.5541   19.5896
       6.3830   18.8847   19.5202
       6.5380   19.2559   19.6150
       6.6910   19.1011   19.5846
       6.8460   18.8933   19.4046

    STAGE OUTLET TOTAL TEMPERATURES (7 POINTS)

       RADIUS   TEMPERATURE

       5.9200   565.643
       6.0750   564.931
       6.2290   563.479
       6.3830   563.157
       6.5380   564.616
       6.6910   564.923
       6.8460   567.012

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STAGE OUTLET FLOW ANGLES (3 POINTS)

RADIUS	ANGLE
6.0750	-8.672
6.3830	-5.541
6.6910	-6.035

CASING STATIC PRESSURES (17 POINTS)

X-COORD	PRESSURE
-16.9000	14.6291
-14.0000	13.5996
-11.5000	13.1881
-11.0430	13.3567
-10.8020	13.0268
-10.5620	13.0511
-10.3220	13.4971
-10.0820	14.0377
-9.8410	14.5643
-9.6010	14.9577
-9.3610	15.2637
-9.1200	15.2379
-8.4270	15.1894
-6.5690	13.9593
-6.3220	14.3328
-4.7560	14.5478
-3.6910	14.5143

HUB STATIC PRESSURES (6 POINTS)

X-COORD	PRESSURE
-16.9000	14.2602
-14.0000	14.3354
-11.8900	13.8931
-11.6770	13.4681
-5.9800	13.4643
-5.7300	14.4985

INTERMEDIATE RADIUS STATIC PRESSURES (3 POINTS)

X-COORD	RADIUS	PRESSURE
-7.8180	6.3140	12.8747
-7.3750	6.3140	13.0273
-6.9320	6.3140	12.8803

DISTRIBUTED BLOCKAGE SPECIFICATION

STATION	BLOCKAGE	DIST. FACTOR	MID ADD. DEVIATION	DIST. FACTOR	FRAC. TE BLOCKAGE
1	0.0000	1.0000	0.000	0.000	0.000
2	.0020	1.0000	0.000	0.000	0.000
3	.0023	1.0000	0.000	0.000	0.000
4	.0020	1.0000	0.000	0.000	0.000
5	.0020	1.0000	0.000	0.000	0.000
6	.0180	1.0000	0.000	0.000	0.000
7	.0173	1.0000	0.000	0.000	0.000
8	.0627	1.0000	0.000	0.000	0.000
9	.0655	1.0000	0.000	0.000	0.000
10	.0888	1.0000	0.000	0.000	0.000
11	.0888	1.0000	0.000	0.000	0.000
12	.0888	1.0000	0.000	0.000	0.000
13	.0888	1.0000	0.000	0.000	0.000
14	.0888	1.0000	0.000	0.000	0.000

SOLUTION TYPE INDICATORS

STATION	1	2	3	4	5	6	7	8	9	10	11	12	13	14
NMACH	0	0	0	0	0	0	0	0	0	0	0	0	0	0

NJUMP= 0

STAGE OUTLET TOTAL TEMPERATURES ARE USED
PEAK STAGE OUTLET PRESSURES ARE USED FOR ROTOR PRESSURE RISE

STATION 1 FLOW FIELD DESCRIPTION

RADIUS	-----VELOCITIES------			--TEMPERATURES--		--PRESSURES---	
	MERID	TANGEN	TOTAL	TOTAL	STATIC	TOTAL	STATIC
5.2393	89.28	0.00	89.28	518.708	518.045	14.694	14.628
5.8786	89.28	0.00	89.28	518.708	518.045	14.694	14.628
6.5560	89.28	0.00	89.28	518.708	518.045	14.694	14.628
7.2795	89.28	0.00	89.28	518.708	518.045	14.694	14.628
8.0557	89.28	0.00	89.28	518.708	518.045	14.694	14.628
8.8892	89.28	0.00	89.28	518.708	518.045	14.694	14.628
9.7818	89.28	0.00	89.28	518.708	518.045	14.694	14.628
10.7303	89.28	0.00	89.28	518.708	518.045	14.694	14.628
11.7251	89.28	0.00	89.28	518.708	518.045	14.694	14.628
12.7476	89.28	0.00	89.28	518.708	518.045	14.694	14.628
13.7718	89.28	0.00	89.28	518.708	518.045	14.694	14.628

RADIUS	MACH	---ANGLES---		RADIUS OF	SPECIFIC
	NO	WHIRL	SLOPE	CURVATURE	WEIGHT
5.2393	.0800	0.00	0.00	0.000	.0761
5.8786	.0800	0.00	-10.48	0.000	.0761
6.5560	.0800	0.00	-19.68	0.000	.0761
7.2795	.0800	0.00	-27.69	0.000	.0761
8.0557	.0800	0.00	-34.62	0.000	.0761
8.8892	.0800	0.00	-40.54	0.000	.0761
9.7818	.0800	0.00	-45.45	0.000	.0761
10.7303	.0800	0.00	-49.29	0.000	.0761
11.7251	.0800	0.00	-51.96	0.000	.0761
12.7476	.0800	0.00	-53.32	0.000	.0761
13.7718	.0800	0.00	-53.27	0.000	.0761

STATION 2 FLOW FIELD DESCRIPTION

RADIUS	-----VELOCITIES------			--TEMPERATURES--		--PRESSURES---	
	MERID	TANGEN	TOTAL	TOTAL	STATIC	TOTAL	STATIC
5.2393	179.01	0.00	179.01	518.708	516.044	14.694	14.432
5.5828	167.72	0.00	167.72	518.708	516.369	14.694	14.464
5.9836	159.64	0.00	159.64	518.708	516.589	14.694	14.485
6.4399	153.79	0.00	153.79	518.708	516.741	14.694	14.500
6.9513	148.99	0.00	148.99	518.708	516.862	14.694	14.512
7.5208	144.08	0.00	144.08	518.708	516.982	14.694	14.524
8.1563	138.04	0.00	138.04	518.708	517.124	14.694	14.538
8.8706	130.22	0.00	130.22	518.708	517.298	14.694	14.555
9.6800	120.56	0.00	120.56	518.708	517.499	14.694	14.575
10.5991	109.84	0.00	109.84	518.708	517.705	14.694	14.595
11.6279	99.88	0.00	99.88	518.708	517.879	14.694	14.612

RADIUS	MACH	---ANGLES---		RADIUS OF	SPECIFIC
	NO	WHIRL	SLOPE	CURVATURE	WEIGHT
5.2393	.1606	0.00	-8.80	-5.187	.0754
5.5828	.1504	0.00	-14.63	-11.247	.0755
5.9836	.1432	0.00	-20.26	-82.325	.0756
6.4399	.1379	0.00	-25.76	25.117	.0756
6.9513	.1336	0.00	-31.11	14.234	.0757
7.5208	.1292	0.00	-36.26	12.130	.0757
8.1563	.1237	0.00	-41.07	12.531	.0758
8.8706	.1167	0.00	-45.40	15.108	.0758
9.6800	.1080	0.00	-49.05	21.886	.0759
10.5991	.0984	0.00	-51.79	45.092	.0760
11.6279	.0895	0.00	-53.27	-115916.354	.0760

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STATION 3 FLOW FIELD DESCRIPTION

RADIUS	-----VELOCITIES------			--TEMPERATURES--		--PRESSURES---	
	MERID	TANGEN	TOTAL	TOTAL	STATIC	TOTAL	STATIC
4.7749	231.99	0.00	231.99	518.708	514.233	14.694	14.255
5.0772	225.33	0.00	225.33	518.708	514.486	14.694	14.280
5.4128	219.77	0.00	219.77	518.708	514.692	14.694	14.300
5.7795	215.22	0.00	215.22	518.708	514.856	14.694	14.316
6.1761	211.33	0.00	211.33	518.708	514.994	14.694	14.329
6.6034	207.48	0.00	207.48	518.708	515.129	14.694	14.342
7.0655	202.71	0.00	202.71	518.708	515.291	14.694	14.358
7.5718	195.70	0.00	195.70	518.708	515.523	14.694	14.381
8.1401	184.63	0.00	184.63	518.708	515.873	14.694	14.415
8.8028	167.38	0.00	167.38	518.708	516.378	14.694	14.464
9.6179	142.17	0.00	142.17	518.708	517.027	14.694	14.528

RADIUS	MACH	---ANGLES---		RADIUS OF	SPECIFIC
	NO	WHIRL	SLOPE	CURVATURE	WEIGHT
4.7749	.2085	0.00	-21.72	-9.653	.0747
5.0772	.2025	0.00	-21.31	-15.940	.0748
5.4128	.1974	0.00	-21.97	-37.320	.0749
5.7795	.1933	0.00	-23.59	245.475	.0749
6.1761	.1898	0.00	-26.07	33.776	.0750
6.6034	.1863	0.00	-29.33	20.310	.0750
7.0655	.1820	0.00	-33.30	16.206	.0751
7.5718	.1757	0.00	-37.90	15.405	.0752
8.1401	.1657	0.00	-42.97	17.709	.0753
8.8028	.1501	0.00	-48.25	28.690	.0755
9.6179	.1274	0.00	-53.26	13364.005	.0757

STATION 4 FLOW FIELD DESCRIPTION

RADIUS	-----VELOCITIES------			--TEMPERATURES--		--PRESSURES---	
	MERID	TANGEN	TOTAL	TOTAL	STATIC	TOTAL	STATIC
4.1658	205.48	0.00	205.48	518.708	515.197	14.694	14.349
4.5293	219.88	0.00	219.88	518.708	514.688	14.694	14.299
4.8916	231.76	0.00	231.76	518.708	514.241	14.694	14.256
5.2559	241.71	0.00	241.71	518.708	513.850	14.694	14.218
5.6243	250.13	0.00	250.13	518.708	513.506	14.694	14.185
5.9988	257.36	0.00	257.36	518.708	513.200	14.694	14.155
6.3816	263.61	0.00	263.61	518.708	512.930	14.694	14.129
6.7763	268.71	0.00	268.71	518.708	512.704	14.694	14.108
7.1897	271.80	0.00	271.80	518.708	512.565	14.694	14.094
7.6354	270.60	0.00	270.60	518.708	512.619	14.694	14.099
8.1444	259.49	0.00	259.49	518.708	513.109	14.694	14.147

RADIUS	MACH	---ANGLES---		RADIUS OF	SPECIFIC
	NO	WHIRL	SLOPE	CURVATURE	WEIGHT
4.1658	.1845	0.00	-19.01	4.565	.0751
4.5293	.1975	0.00	-17.43	5.451	.0749
4.8916	.2083	0.00	-17.13	6.278	.0747
5.2559	.2173	0.00	-17.88	6.916	.0746
5.6243	.2250	0.00	-19.44	7.233	.0745
5.9988	.2315	0.00	-21.67	7.163	.0743
6.3816	.2372	0.00	-24.56	6.779	.0742
6.7763	.2419	0.00	-28.28	6.261	.0742
7.1897	.2447	0.00	-33.04	5.810	.0741
7.6354	.2436	0.00	-39.11	5.635	.0741
8.1444	.2335	0.00	-46.90	6.374	.0743

STATION 5 FLOW FIELD DESCRIPTION

RADIUS	VELOCITIES			TEMPERATURES		PRESSURES	
	MERID	TANGEN	TOTAL	TOTAL	STATIC	TOTAL	STATIC
3.9737	217.39	0.00	217.39	518.708	514.778	14.694	14.308
4.3055	241.45	0.00	241.45	518.708	513.860	14.694	14.219
4.6323	262.71	0.00	262.71	518.708	512.969	14.694	14.133
4.9534	281.07	0.00	281.07	518.708	512.139	14.694	14.053
5.2716	297.76	0.00	297.76	518.708	511.335	14.694	13.976
5.5869	314.16	0.00	314.16	518.708	510.501	14.694	13.897
5.8991	331.06	0.00	331.06	518.708	509.594	14.694	13.811
6.2128	348.18	0.00	348.18	518.708	508.627	14.694	13.719
6.5342	365.33	0.00	365.33	518.708	507.609	14.694	13.623
6.8758	381.94	0.00	381.94	518.708	506.577	14.694	13.527
7.2652	395.40	0.00	395.40	518.708	505.706	14.694	13.446

RADIUS	MACH NO	ANGLES		RADIUS OF	SPECIFIC
		WHIRL	SLOPE	CURVATURE	WEIGHT
3.9737	.1953	0.00	-1.20	3.924	.0749
4.3055	.2171	0.00	-1.22	4.449	.0746
4.6323	.2364	0.00	-2.20	4.895	.0743
4.9534	.2531	0.00	-3.76	5.216	.0740
5.2716	.2684	0.00	-5.61	5.379	.0737
5.5869	.2834	0.00	-7.50	5.374	.0734
5.8991	.2989	0.00	-9.45	5.208	.0730
6.2128	.3147	0.00	-11.65	4.893	.0727
6.5342	.3305	0.00	-14.40	4.446	.0723
6.8758	.3459	0.00	-18.19	3.928	.0720
7.2652	.3584	0.00	-24.44	3.371	.0717

RADIUS	BLADE-ANGLES		REL FLOW	DEV/INC	LOSS	BLADE	REL	REL
	SECTION	LEAN	ANGLE		COEFF	SPEED	MACH #	VELOCITY
3.9737	0.00	0.00	0.000	0.000	0.0000	0.0	.1953	217.39
4.3055	0.00	0.00	0.000	0.000	0.0000	0.0	.2171	241.45
4.6323	0.00	0.00	0.000	0.000	0.0000	0.0	.2364	262.71
4.9534	0.00	0.00	0.000	0.000	0.0000	0.0	.2531	281.07
5.2716	0.00	0.00	0.000	0.000	0.0000	0.0	.2684	297.76
5.5869	0.00	0.00	0.000	0.000	0.0000	0.0	.2834	314.16
5.8991	0.00	0.00	0.000	0.000	0.0000	0.0	.2989	331.06
6.2128	0.00	0.00	0.000	0.000	0.0000	0.0	.3147	348.18
6.5342	0.00	0.00	0.000	0.000	0.0000	0.0	.3305	365.33
6.8758	0.00	0.00	0.000	0.000	0.0000	0.0	.3459	381.94
7.2652	0.00	0.00	0.000	0.000	0.0000	0.0	.3584	395.40

RADIUS	REL PRESS	REL TEMP	PRESS RATIO	DELTA T ON T	ISENTR EFF	POLYTR EFF
3.9737	14.694	518.708	1.000	0.000	1.0000	1.0000
4.3055	14.694	518.708	1.000	0.000	1.0000	1.0000
4.6323	14.694	518.708	1.000	0.000	1.0000	1.0000
4.9534	14.694	518.708	1.000	0.000	1.0000	1.0000
5.2716	14.694	518.708	1.000	0.000	1.0000	1.0000
5.5869	14.694	518.708	1.000	0.000	1.0000	1.0000
5.8991	14.694	518.708	1.000	0.000	1.0000	1.0000
6.2128	14.694	518.708	1.000	0.000	1.0000	1.0000
6.5342	14.694	518.708	1.000	0.000	1.0000	1.0000
6.8758	14.694	518.708	1.000	0.000	1.0000	1.0000
7.2652	14.694	518.708	1.000	0.000	1.0000	1.0000

STATION 6 FLOW FIELD DESCRIPTION

RADIUS	-----VELOCITIES------			--TEMPERATURES--		--PRESSURES---	
	MERID	TANGEN	TOTAL	TOTAL	STATIC	TOTAL	STATIC
4.2760	280.08	1.17	280.08	518.708	512.185	14.676	14.040
4.5455	303.87	-7.41	303.96	518.708	511.025	14.672	13.926
4.8143	325.43	-15.57	325.80	518.708	509.881	14.668	13.813
5.0824	344.51	-23.48	345.31	518.708	508.792	14.664	13.707
5.3504	360.99	-31.72	362.38	518.708	507.787	14.660	13.609
5.6194	375.10	-40.39	377.26	518.708	506.872	14.657	13.520
5.8901	387.03	-49.36	390.17	518.708	506.048	14.653	13.440
6.1631	396.89	-58.62	401.19	518.708	505.323	14.649	13.369
6.4390	404.81	-68.49	410.56	518.708	504.690	14.646	13.307
6.7179	411.36	-78.96	418.87	518.708	504.117	14.642	13.251
7.0000	418.00	-89.76	427.53	518.708	503.507	14.637	13.191

RADIUS	MACH	---ANGLES---		RADIUS OF	SPECIFIC
	NO	WHIRL	SLOPE	CURVATURE	WEIGHT
4.2760	.2522	.24	16.51	5.019	.0739
4.5455	.2740	-1.40	13.75	5.775	.0734
4.8143	.2941	-2.74	10.98	6.720	.0730
5.0824	.3120	-3.90	8.34	7.863	.0726
5.3504	.3278	-5.02	5.93	9.206	.0722
5.6194	.3415	-6.15	3.88	10.614	.0719
5.8901	.3535	-7.27	2.11	12.405	.0716
6.1631	.3637	-8.40	.55	14.461	.0713
6.4390	.3725	-9.60	-.84	16.194	.0711
6.7179	.3802	-10.87	-2.09	15.669	.0708
7.0000	.3883	-12.12	-3.17	11.867	.0706

RADIUS	BLADE-ANGLES		REL FLOW	DEV/INC	LOSS	BLADE	REL	REL
	SECTION	LEAN	ANGLE		COEFF	SPEED	MACH #	VELOCITY
4.2760	0.00	0.00	.240	0.000	.0289	0.0	.2522	280.08
4.5455	0.00	0.00	-1.397	0.000	.0296	0.0	.2740	303.96
4.8143	0.00	0.00	-2.740	0.000	.0303	0.0	.2941	325.80
5.0824	0.00	0.00	-3.899	0.000	.0310	0.0	.3120	345.31
5.3504	0.00	0.00	-5.022	0.000	.0319	0.0	.3278	362.38
5.6194	0.00	0.00	-6.146	0.000	.0328	0.0	.3415	377.26
5.8901	0.00	0.00	-7.268	0.000	.0338	0.0	.3535	390.17
6.1631	0.00	0.00	-8.401	0.000	.0349	0.0	.3637	401.19
6.4390	0.00	0.00	-9.603	0.000	.0362	0.0	.3725	410.56
6.7179	0.00	0.00	-10.865	0.000	.0377	0.0	.3802	418.87
7.0000	0.00	0.00	-12.120	0.000	.0392	0.0	.3883	427.53

RADIUS	REL	REL	PRESS	DELTA T	ISENTR	POLYTR
	PRESS	TEMP	RATIO	ON T	EFF	EFF
4.2760	14.676	518.708	.999	0.000	1.0000	1.0000
4.5455	14.672	518.708	.998	0.000	1.0000	1.0000
4.8143	14.668	518.708	.998	0.000	1.0000	1.0000
5.0824	14.664	518.708	.998	0.000	1.0000	1.0000
5.3504	14.660	518.708	.998	0.000	1.0000	1.0000
5.6194	14.657	518.708	.997	0.000	1.0000	1.0000
5.8901	14.653	518.708	.997	0.000	1.0000	1.0000
6.1631	14.649	518.708	.997	0.000	1.0000	1.0000
6.4390	14.646	518.708	.997	0.000	1.0000	1.0000
6.7179	14.642	518.708	.996	0.000	1.0000	1.0000
7.0000	14.637	518.708	.996	0.000	1.0000	1.0000

STATION 7 FLOW FIELD DESCRIPTION
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RADIUS	-----VELOCITIES------			--TEMPERATURES--		--PRESSURES---	
	MERID	TANGEN	TOTAL	TOTAL	STATIC	TOTAL	STATIC
4.5030	370.49	1.12	370.49	518.708	507.293	14.676	13.577
4.7133	380.41	-7.15	380.48	518.708	506.669	14.672	13.515
4.9362	390.38	-15.19	390.68	518.708	506.015	14.668	13.451
5.1699	400.28	-23.08	400.95	518.708	505.339	14.664	13.384
5.4121	409.24	-31.36	410.44	518.708	504.698	14.660	13.322
5.6606	416.72	-40.10	418.64	518.708	504.132	14.657	13.266
5.9156	422.99	-49.15	425.83	518.708	503.627	14.653	13.216
6.1769	428.00	-58.49	431.98	518.708	503.189	14.649	13.173
6.4443	430.82	-68.43	436.22	518.708	502.883	14.646	13.141
6.7183	430.35	-78.95	437.53	518.708	502.787	14.642	13.129
7.0000	426.61	-89.76	435.95	518.708	502.902	14.637	13.136

RADIUS	MACH	---ANGLES---		RADIUS OF	SPECIFIC
	NO	WHIRL	SLOPE	CURVATURE	WEIGHT
4.5030	.3353	.17	21.89	-34.741	.0721
4.7133	.3445	-1.08	18.79	-140.608	.0719
4.9362	.3540	-2.23	15.90	89.103	.0716
5.1699	.3635	-3.30	13.24	38.627	.0714
5.4121	.3724	-4.38	10.79	27.086	.0711
5.6606	.3800	-5.50	8.56	23.235	.0709
5.9156	.3867	-6.63	6.47	21.787	.0707
6.1769	.3925	-7.78	4.51	22.273	.0706
6.4443	.3965	-9.03	2.69	25.604	.0704
6.7183	.3977	-10.40	1.10	37.891	.0704
7.0000	.3962	-11.88	.00************		.0704

RADIUS	BLADE-ANGLES		REL FLOW	DEV/INC	LOSS	BLADE	REL	REL
	SECTION	LEAN	ANGLE		COEFF	SPEED	MACH #	VELOCITY
4.5030	-48.75	-5.07	-52.934	4.186	0.0000	491.6	.5562	614.68
4.7133	-49.91	-4.52	-53.901	3.988	0.0000	514.6	.5846	645.66
4.9362	-51.05	-3.16	-54.833	3.786	0.0000	538.9	.6141	677.79
5.1699	-52.06	-.19	-55.731	3.671	0.0000	564.4	.6445	710.89
5.4121	-52.60	2.80	-56.666	4.069	0.0000	590.8	.6756	744.72
5.6606	-53.45	4.14	-57.656	4.203	0.0000	618.0	.7070	778.92
5.9156	-54.18	6.00	-58.673	4.493	0.0000	645.8	.7389	813.56
6.1769	-55.06	6.80	-59.713	4.650	0.0000	674.3	.7711	848.65
6.4443	-55.96	9.24	-60.835	4.877	0.0000	703.5	.8034	884.04
6.7183	-56.90	10.94	-62.088	5.186	0.0000	733.4	.8356	919.33
7.0000	-58.38	6.29	-63.455	5.072	0.0000	764.2	.8676	954.59

RADIUS	REL	REL	PRESS	DELTA T	ISENTR	POLYTR
	PRESS	TEMP	RATIO	ON T	EFF	EFF
4.5030	16.753	538.706	.999	0.000	1.0000	1.0000
4.7133	17.035	541.328	.998	0.000	1.0000	1.0000
4.9362	17.350	544.207	.998	0.000	1.0000	1.0000
5.1699	17.699	547.351	.998	0.000	1.0000	1.0000
5.4121	18.088	550.802	.998	0.000	1.0000	1.0000
5.6606	18.520	554.565	.997	0.000	1.0000	1.0000
5.9156	18.996	558.644	.997	0.000	1.0000	1.0000
6.1769	19.521	563.050	.997	0.000	1.0000	1.0000
6.4443	20.104	567.835	.997	0.000	1.0000	1.0000
6.7183	20.749	573.024	.996	0.000	1.0000	1.0000
7.0000	21.462	578.622	.996	0.000	1.0000	1.0000

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STATION 8 FLOW FIELD DESCRIPTION
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RADIUS	-----VELOCITIES------			--TEMPERATURES--		--PRESSURES---	
	MERID	TANGEN	TOTAL	TOTAL	STATIC	TOTAL	STATIC
5.5877	687.35	467.50	831.26	566.010	508.584	20.008	13.759
5.6772	677.19	451.64	813.98	565.838	510.777	19.958	13.948
5.7792	666.44	434.59	795.62	565.636	513.032	19.900	14.141
5.8942	652.65	414.30	773.04	565.178	515.518	19.768	14.327
6.0215	643.11	389.66	751.94	564.357	517.372	19.654	14.498
6.1597	637.68	363.11	733.81	563.408	518.661	19.574	14.652
6.3081	632.24	343.47	719.51	563.294	520.275	19.529	14.788
6.4658	631.87	335.29	715.32	564.595	522.079	19.614	14.912
6.6322	628.76	317.40	704.34	564.902	523.682	19.587	15.024
6.8099	610.45	311.92	685.52	566.869	527.825	19.417	15.124
7.0000	600.44	298.76	670.67	568.050	530.682	19.315	15.221

RADIUS	MACH	---ANGLES---		RADIUS OF	SPECIFIC
	NO	WHIRL	SLOPE	CURVATURE	WEIGHT
5.5877	.7513	34.22	15.66	-10.103	.0729
5.6772	.7341	33.70	13.86	-10.548	.0736
5.7792	.7159	33.11	12.22	-11.572	.0743
5.8942	.6939	32.41	10.75	-13.240	.0749
6.0215	.6738	31.21	9.32	-15.512	.0755
6.1597	.6567	29.66	7.92	-19.007	.0761
6.3081	.6430	28.51	6.47	-24.170	.0766
6.4658	.6381	27.95	4.98	-33.143	.0770
6.6322	.6273	26.78	3.42	-53.771	.0773
6.8099	.6082	27.07	1.77	-122.620	.0772
7.0000	.5934	26.45	0.00	0.000	.0773

RADIUS	BLADE-ANGLES		REL FLOW	DEV/INC	LOSS	BLADE	REL	REL
	SECTION	LEAN	ANGLE		COEFF	SPEED	MACH #	VELOCITY
5.5877	-2.88	45.39	-11.714	8.835	-.0251	610.0	.6344	701.97
5.6772	-5.85	42.55	-13.944	8.096	-.0169	619.8	.6292	697.75
5.7792	-9.46	38.29	-16.415	6.954	-.0088	630.9	.6252	694.76
5.8942	-13.21	32.31	-19.348	6.133	.0073	643.5	.6209	691.71
6.0215	-16.99	25.38	-22.601	5.614	.0083	657.4	.6242	696.60
6.1597	-20.62	19.24	-25.879	5.257	.0001	672.5	.6343	708.75
6.3081	-23.86	15.05	-28.634	4.777	.0046	688.7	.6437	720.34
6.4658	-26.63	13.20	-30.391	3.760	.0153	705.9	.6535	732.53
6.6322	-28.93	12.72	-32.892	3.957	.0231	724.0	.6670	748.80
6.8099	-31.09	11.93	-35.256	4.170	.0771	743.4	.6633	747.57
7.0000	-33.64	9.26	-37.781	4.137	.1030	764.2	.6722	759.71

RADIUS	REL	REL	PRESS	DELTA T	ISENTR	POLYTR
	PRESS	TEMP	RATIO	ON T	EFF	EFF
5.5877	18.042	549.545	1.362	.091	1.0109	1.0104
5.6772	18.213	551.245	1.358	.091	1.0061	1.0058
5.7792	18.403	553.152	1.354	.090	1.0003	1.0003
5.8942	18.582	555.284	1.345	.090	.9871	.9876
6.0215	18.854	557.700	1.338	.088	.9845	.9852
6.1597	19.211	560.405	1.332	.086	.9908	.9911
6.3081	19.541	563.392	1.329	.086	.9850	.9856
6.4658	19.867	566.664	1.335	.088	.9722	.9733
6.6322	20.246	570.267	1.333	.089	.9609	.9625
6.8099	20.317	574.251	1.321	.093	.8926	.8968
7.0000	20.604	578.622	1.314	.095	.8541	.8597

STATION 8 INTEGRATED PERFORMANCE: PRESSURE RATIO = 1.335
ISEN. EFF.= .962 POLY. EFF.= .963 DELTA T ON T = .090

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STATION 9 FLOW FIELD DESCRIPTION

RADIUS	-----VELOCITIES------			--TEMPERATURES--		--PRESSURES---	
	MERID	TANGEN	TOTAL	TOTAL	STATIC	TOTAL	STATIC
5.6511	762.66	462.26	891.81	566.010	499.906	20.008	12.955
5.7488	753.97	446.01	876.02	565.838	502.057	19.958	13.133
5.8547	744.83	428.99	859.54	565.636	504.233	19.900	13.310
5.9688	732.29	409.12	838.83	565.178	506.699	19.768	13.488
6.0913	722.92	385.19	819.14	564.357	508.593	19.654	13.656
6.2215	716.38	359.51	801.53	563.408	510.015	19.574	13.815
6.3590	709.27	340.72	786.86	563.294	511.839	19.529	13.966
6.5051	706.68	333.26	781.32	564.595	513.865	19.614	14.107
6.6596	701.90	316.10	769.79	564.902	515.659	19.587	14.234
6.8243	684.73	311.26	752.15	566.869	519.861	19.417	14.341
7.0000	676.35	298.76	739.40	568.050	522.625	19.315	14.427

RADIUS	MACH NO	---ANGLES---		RADIUS OF CURVATURE	SPECIFIC WEIGHT
		WHIRL	SLOPE		
5.6511	.8129	31.22	7.33	-8.026	.0698
5.7488	.7968	30.61	6.18	-9.600	.0705
5.8547	.7801	29.94	5.27	-10.999	.0711
5.9688	.7595	29.19	4.56	-12.149	.0717
6.0913	.7403	28.05	3.98	-13.856	.0724
6.2215	.7234	26.65	3.51	-16.358	.0730
6.3590	.7089	25.66	3.00	-20.310	.0735
6.5051	.7025	25.25	2.36	-25.642	.0740
6.6596	.6909	24.24	1.67	-35.003	.0744
6.8243	.6724	24.45	.90	-63.335	.0744
7.0000	.6592	23.83	0.00	0.000	.0744

RADIUS	BLADE-ANGLES		REL FLOW ANGLE	DEV/INC	LOSS COEFF	BLADE SPEED	REL MACH #	REL VELOCITY
	SECTION	LEAN						
5.6511	43.52	-39.09	31.220	-12.298	0.0000	0.0	.8129	891.81
5.7488	41.44	-31.93	30.606	-10.832	0.0000	0.0	.7968	876.02
5.8547	40.50	-24.41	29.940	-10.564	0.0000	0.0	.7801	859.54
5.9688	39.84	-16.96	29.191	-10.645	0.0000	0.0	.7595	838.83
6.0913	38.86	-10.12	28.050	-10.813	0.0000	0.0	.7403	819.14
6.2215	38.24	-4.28	26.649	-11.595	0.0000	0.0	.7234	801.53
6.3590	37.86	-1.42	25.659	-12.202	0.0000	0.0	.7089	786.86
6.5051	37.78	-.23	25.248	-12.533	0.0000	0.0	.7025	781.32
6.6596	37.65	2.54	24.244	-13.404	0.0000	0.0	.6909	769.79
6.8243	38.59	5.92	24.445	-14.141	0.0000	0.0	.6724	752.15
7.0000	40.57	8.44	23.832	-16.738	0.0000	0.0	.6592	739.40

RADIUS	REL PRESS	REL TEMP	PRESS RATIO	DELTA T ON T	ISENTR EFF	POLYTR EFF
5.6511	20.008	566.010	1.362	.091	1.0109	1.0104
5.7488	19.958	565.838	1.358	.091	1.0061	1.0058
5.8547	19.900	565.636	1.354	.090	1.0003	1.0003
5.9688	19.768	565.178	1.345	.090	.9871	.9876
6.0913	19.654	564.357	1.338	.088	.9845	.9852
6.2215	19.574	563.408	1.332	.086	.9908	.9911
6.3590	19.529	563.294	1.329	.086	.9850	.9856
6.5051	19.614	564.595	1.335	.088	.9722	.9733
6.6596	19.587	564.902	1.333	.089	.9609	.9625
6.8243	19.417	566.869	1.321	.093	.8926	.8968
7.0000	19.315	568.050	1.314	.095	.8541	.8597

STATION 9 INTEGRATED PERFORMANCE: PRESSURE RATIO = 1.335
ISEN. EFF.= .962 POLY. EFF.= .963 DELTA T ON T = .090

STATION 10   FLOW FIELD DESCRIPTION

RADIUS	-----VELOCITIES------			--TEMPERATURES--		--PRESSURES---	
	MERID	TANGEN	TOTAL	TOTAL	STATIC	TOTAL	STATIC
5.7580	797.56	-164.57	814.36	566.010	510.897	20.204	14.116
5.8341	792.26	-151.56	806.63	565.838	511.768	19.990	14.065
5.9216	784.25	-136.96	796.12	565.636	512.966	19.739	14.020
6.0219	756.08	-117.88	765.21	565.178	516.520	19.171	13.989
6.1365	732.45	-99.10	739.13	564.357	518.961	18.742	13.975
6.2633	726.47	-82.29	731.11	563.408	518.990	18.627	13.974
6.3976	745.95	-69.67	749.20	563.294	516.650	18.919	13.980
6.5361	766.20	-74.66	769.83	564.595	515.347	19.251	13.986
6.6810	757.75	-76.75	761.62	564.902	516.699	19.112	13.987
6.8358	746.80	-78.63	750.93	566.869	520.013	18.908	13.979
7.0000	741.47	-81.13	745.90	568.050	521.822	18.790	13.960

RADIUS	MACH	---ANGLES---		RADIUS OF	SPECIFIC
	NO	WHIRL	SLOPE	CURVATURE	WEIGHT
5.7580	.7343	-11.66	2.11	-15.761	.0745
5.8341	.7267	-10.83	1.70	-16.931	.0741
5.9216	.7164	-9.91	1.33	-18.725	.0737
6.0219	.6863	-8.86	1.02	-21.475	.0730
6.1365	.6613	-7.70	.86	-24.677	.0726
6.2633	.6541	-6.46	.80	-28.413	.0726
6.3976	.6718	-5.34	.73	-33.570	.0729
6.5361	.6912	-5.57	.54	-43.575	.0731
6.6810	.6829	-5.78	.33	-62.455	.0730
6.8358	.6712	-6.01	.15	-114.343	.0725
7.0000	.6655	-6.24	0.00	0.000	.0721

RADIUS	BLADE-ANGLES		REL FLOW	DEV/INC	LOSS	BLADE	REL	REL
	SECTION	LEAN	ANGLE		COEFF	SPEED	MACH #	VELOCITY
5.7580	-5.42	30.71	-11.659	-6.239	-.0278	0.0	.7343	814.36
5.8341	-7.06	27.41	-10.830	-3.773	-.0047	0.0	.7267	806.63
5.9216	-9.26	22.70	-9.906	-.646	.0244	0.0	.7164	796.12
6.0219	-11.37	17.13	-8.861	2.514	.0950	0.0	.6863	765.21
6.1365	-13.37	12.30	-7.705	5.667	.1521	0.0	.6613	739.13
6.2633	-15.55	9.54	-6.462	9.089	.1645	0.0	.6541	731.11
6.3976	-17.49	8.12	-5.336	12.155	.1096	0.0	.6718	749.20
6.5361	-19.38	8.04	-5.565	13.816	.0659	0.0	.6912	769.83
6.6810	-21.59	7.77	-5.784	15.806	.0887	0.0	.6829	761.62
6.8358	-24.38	7.91	-6.011	18.370	.1004	0.0	.6712	750.93
7.0000	-27.96	8.68	-6.245	21.716	.1074	0.0	.6655	745.90

RADIUS	REL	REL	PRESS	DELTA T	ISENTR	POLYTR
	PRESS	TEMP	RATIO	ON T	EFF	EFF
5.7580	20.204	566.010	1.375	.091	1.0443	1.0423
5.8341	19.990	565.838	1.360	.091	1.0116	1.0111
5.9216	19.739	565.636	1.343	.090	.9725	.9736
6.0219	19.171	565.178	1.305	.090	.8811	.8855
6.1365	18.742	564.357	1.275	.088	.8180	.8242
6.2633	18.627	563.408	1.268	.086	.8136	.8197
6.3976	18.919	563.294	1.288	.086	.8712	.8757
6.5361	19.251	564.595	1.310	.088	.9068	.9103
6.6810	19.112	564.902	1.301	.089	.8757	.8803
6.8358	18.908	566.869	1.287	.093	.8044	.8112
7.0000	18.790	568.050	1.279	.095	.7650	.7730

STATION 10   INTEGRATED PERFORMANCE: PRESSURE RATIO = 1.301
ISEN. EFF.= .871 POLY. EFF.= .876 DELTA T ON T = .090

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STATION 11 FLOW FIELD DESCRIPTION
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RADIUS	-----VELOCITIES------			--TEMPERATURES--		--PRESSURES---	
	MERID	TANGEN	TOTAL	TOTAL	STATIC	TOTAL	STATIC
5.7600	782.40	-164.51	799.50	566.010	512.892	20.204	14.310
5.8349	771.53	-151.54	786.27	565.838	514.464	19.990	14.326
5.9215	758.76	-136.96	771.02	565.636	516.236	19.739	14.335
6.0213	726.44	-117.89	735.95	565.178	520.172	19.171	14.338
6.1358	700.44	-99.11	707.42	564.357	522.775	18.742	14.337
6.2630	694.17	-82.29	699.03	563.408	522.805	18.627	14.336
6.3975	715.18	-69.67	718.57	563.294	520.388	18.919	14.337
6.5358	736.80	-74.66	740.58	564.595	519.021	19.251	14.338
6.6805	728.09	-76.76	732.12	564.902	520.363	19.112	14.337
6.8354	716.11	-78.64	720.41	566.869	523.747	18.908	14.333
7.0000	708.73	-81.13	713.36	568.050	525.770	18.790	14.333

RADIUS	MACH	---ANGLES---		RADIUS OF	SPECIFIC
	NO	WHIRL	SLOPE	CURVATURE	WEIGHT
5.7600	.7195	-11.87	.19	-48.243	.0752
5.8349	.7065	-11.11	.08	-104.438	.0751
5.9215	.6917	-10.23	-.01	-1294.769	.0748
6.0213	.6577	-9.22	-.07	220.809	.0743
6.1358	.6306	-8.05	-.08	202.508	.0739
6.2630	.6231	-6.76	-.05	552.867	.0739
6.3975	.6420	-5.56	-.03	-4773.781	.0743
6.5358	.6626	-5.79	-.04	682.774	.0745
6.6805	.6542	-6.02	-.07	238.781	.0743
6.8354	.6416	-6.27	-.06	227.880	.0738
7.0000	.6341	-6.53	0.00	0.000	.0735

STATION 12 FLOW FIELD DESCRIPTION
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RADIUS	-----VELOCITIES------			--TEMPERATURES--		--PRESSURES---	
	MERID	TANGEN	TOTAL	TOTAL	STATIC	TOTAL	STATIC
5.7600	779.09	-164.51	796.27	566.010	513.321	20.204	14.352
5.8349	769.07	-151.54	783.86	565.838	514.780	19.990	14.357
5.9214	756.60	-136.96	768.89	565.636	516.509	19.739	14.362
6.0211	724.04	-117.89	733.58	565.178	520.462	19.171	14.366
6.1356	697.59	-99.11	704.58	564.357	523.107	18.742	14.369
6.2628	691.03	-82.29	695.92	563.408	523.166	18.627	14.371
6.3974	712.14	-69.68	715.54	563.294	520.748	18.919	14.372
6.5356	733.88	-74.66	737.66	564.595	519.379	19.251	14.373
6.6804	724.90	-76.76	728.95	564.902	520.748	19.112	14.374
6.8352	712.44	-78.64	716.76	566.869	524.183	18.908	14.375
7.0000	704.78	-81.13	709.44	568.050	526.234	18.790	14.377

RADIUS	MACH	---ANGLES---		RADIUS OF	SPECIFIC
	NO	WHIRL	SLOPE	CURVATURE	WEIGHT
5.7600	.7163	-11.92	0.00	0.000	.0754
5.8349	.7042	-11.15	-.01	-5592.043	.0752
5.9214	.6896	-10.26	-.02	-77626.543	.0749
6.0211	.6554	-9.25	-.03	2998.866	.0744
6.1356	.6279	-8.09	-.03	1539.631	.0740
6.2628	.6202	-6.79	-.03	1263.199	.0740
6.3974	.6391	-5.59	-.02	1194.344	.0744
6.5356	.6597	-5.81	-.02	1125.969	.0746
6.6804	.6511	-6.04	-.02	1131.409	.0744
6.8352	.6381	-6.30	-.02	1624.541	.0739
7.0000	.6304	-6.57	0.00	0.000	.0736

STATION 13   FLOW FIELD DESCRIPTION
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RADIUS	-----VELOCITIES------			--TEMPERATURES--		--PRESSURES---	
	MERID	TANGEN	TOTAL	TOTAL	STATIC	TOTAL	STATIC
5.7600	776.15	-164.51	793.39	566.010	513.701	20.204	14.389
5.8348	766.09	-151.54	780.93	565.838	515.160	19.990	14.394
5.9213	753.56	-136.97	765.91	565.636	516.890	19.739	14.399
6.0210	720.84	-117.90	730.41	565.178	520.847	19.171	14.403
6.1355	694.20	-99.11	701.24	564.357	523.498	18.742	14.407
6.2627	687.58	-82.30	692.49	563.408	523.562	18.627	14.409
6.3973	708.76	-69.68	712.18	563.294	521.148	18.919	14.411
6.5356	730.55	-74.66	734.35	564.595	519.784	19.251	14.412
6.6803	721.45	-76.76	725.52	564.902	521.163	19.112	14.414
6.8352	708.84	-78.64	713.19	566.869	524.608	18.908	14.416
7.0000	701.11	-81.13	705.78	568.050	526.664	18.790	14.418

RADIUS	MACH	---ANGLES---		RADIUS OF	SPECIFIC
	NO	WHIRL	SLOPE	CURVATURE	WEIGHT
5.7600	.7135	-11.97	0.00	0.000	.0755
5.8348	.7013	-11.19	-.01	106238.951	.0753
5.9213	.6866	-10.30	-.02	30791.490	.0751
6.0210	.6523	-9.29	-.03	12211.811	.0745
6.1355	.6247	-8.13	-.03	6090.542	.0742
6.2627	.6169	-6.83	-.02	3964.485	.0742
6.3973	.6359	-5.61	-.01	3316.676	.0745
6.5356	.6565	-5.84	-.01	3396.072	.0747
6.6803	.6478	-6.07	-.01	4139.618	.0745
6.8352	.6347	-6.33	-.01	7046.453	.0741
7.0000	.6269	-6.60	0.00	0.000	.0738

STATION 14   FLOW FIELD DESCRIPTION
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RADIUS	-----VELOCITIES------			--TEMPERATURES--		--PRESSURES---	
	MERID	TANGEN	TOTAL	TOTAL	STATIC	TOTAL	STATIC
5.7600	773.04	-164.51	790.35	566.010	514.102	20.204	14.428
5.8348	762.92	-151.54	777.83	565.838	515.562	19.990	14.433
5.9212	750.33	-136.97	762.73	565.636	517.294	19.739	14.438
6.0208	717.43	-117.90	727.05	565.178	521.255	19.171	14.443
6.1353	690.63	-99.11	697.71	564.357	523.909	18.742	14.446
6.2626	683.96	-82.30	688.89	563.40°	523.975	18.627	14.449
6.3972	705.24	-69.68	708.67	563.294	521.562	18.919	14.451
6.5355	727.11	-74.66	730.93	564.595	520.201	19.251	14.453
5.6802	717.93	-76.76	722.02	564.902	521.584	19.112	14.455
6.8351	705.21	-78.64	709.58	566.869	525.034	18.908	14.457
7.0000	697.41	-81.13	702.12	568.050	527.093	18.790	14.459

RADIUS	MACH	---ANGLES---		RADIUS OF	SPECIFIC
	NO	WHIRL	SLOPE	CURVATURE	WEIGHT
5.7600	.7105	-12.01	0.00	0.000	.0756
5.8348	.6982	-11.23	-.01	0.000	.0755
5.9212	.6835	-10.35	-.02	0.000	.0752
6.0208	.6491	-9.33	-.03	0.000	.0747
6.1353	.6213	-8.17	-.02	0.000	.0743
6.2626	.6134	-6.86	-.02	0.000	.0743
6.3972	.6325	-5.64	-.01	0.000	.0747
5.5355	.6532	-5.86	-.01	0.000	.0749
6.6802	.6444	-6.10	-.01	0.000	.0747
6.8351	.6312	-6.36	-.01	0.000	.0742
7.0000	.6234	-6.64	0.00	0.000	.0739

ROTOR PERFORMANCE

LOCAT-ION	INLET RADIUS	OUTLET RADIUS	INLET M. NO	INCID-ENCE	DEVIA-TION	LOSS COEFF	2-D D FACTOR	3-D D FACTOR
1	4.5030	5.5877	.5562	4.186	8.835	-.0251	-.0661	-.0551
2	4.7133	5.6772	.5846	3.948	8.092	-.0169	-.0052	.0036
3	4.9362	5.7792	.6141	3.786	6.948	-.0088	.0497	.0566
4	5.1699	5.8942	.6445	3.671	6.127	.0073	.1004	.1056
5	5.4121	6.0215	.6756	4.069	5.609	.0083	.1361	.1399
6	5.6606	6.1597	.7070	4.203	5.253	.0001	.1594	.1621
7	5.9156	6.3081	.7389	4.493	4.774	.0046	.1832	.1851
8	6.1769	6.4658	.7711	4.650	3.758	.0153	.2073	.2085
9	6.4443	6.6322	.8034	4.877	3.455	.0231	.2234	.2241
10	6.7183	6.8099	.8356	5.186	4.169	.0771	.2598	.2601
11	7.0000	7.0000	.8676	5.072	4.137	.1030	.2781	.2781

LOCAT-ION	DELTA P ON Q	REL V RATIO	DELTA H/U**2	SECTION-ANGLES INLET	SECTION-ANGLES OUTLET	LEAN-ANGLES INLET	LEAN-ANGLES OUTLET
1	.0573	1.1420	.7649	-48.75	-2.88	-5.07	45.39
2	.1229	1.0807	.7383	-49.91	-5.85	-4.52	42.55
3	.1769	1.0250	.7094	-51.05	-9.46	-3.16	38.29
4	.2185	.9730	.6753	-52.06	-13.21	-.19	32.31
5	.2469	.9354	.6356	-52.60	-16.99	2.80	25.38
6	.2637	.9099	.5948	-53.45	-20.62	4.14	19.24
7	.2719	.8854	.5657	-54.18	-23.86	6.00	15.05
8	.2740	.8632	.5541	-55.06	-26.63	6.80	13.20
9	.2703	.8470	.5302	-55.96	-28.93	9.24	12.72
10	.2618	.8132	.5243	-56.90	-31.09	10.94	11.93
11	.2504	.7959	.5084	-58.38	-33.64	6.29	9.26

STATOR PERFORMANCE

LOCAT-ION	INLET RADIUS	OUTLET RADIUS	INLET M. NO	INCID-ENCE	DEVIA-TION	LOSS COEFF	2-D D FACTOR	3-D D FACTOR
1	5.6511	5.7580	.8129	-12.298	-6.239	-.0278	.2182	.2176
2	5.7488	5.8341	.7968	-10.832	-3.772	-.0047	.2180	.2175
3	5.8547	5.9216	.7801	-10.564	-.645	.0244	.2187	.2183
4	5.9688	6.0219	.7595	-10.645	2.514	.0950	.2337	.2333
5	6.0913	6.1365	.7403	-10.813	5.668	.1521	.2396	.2393
6	6.2215	6.2633	.7234	-11.595	9.090	.1645	.2212	.2209
7	6.3590	6.3976	.7089	-12.202	12.155	.1096	.1727	.1725
8	6.5051	6.5361	.7025	-12.533	13.816	.0659	.1380	.1379
9	6.6596	6.6810	.6909	-13.404	15.806	.0887	.1295	.1294
10	6.8243	6.8358	.6724	-14.141	18.370	.1004	.1205	.1205
11	7.0000	7.0000	.6592	-16.738	21.716	.1074	.1071	.1071

LOCAT-ION	DELTA P ON Q	REL V RATIO	DELTA H/U**2	SECTION-ANGLES INLET	SECTION-ANGLES OUTLET	LEAN-ANGLES INLET	LEAN-ANGLES OUTLET
1	.1646	.9132	0.0000	43.52	-5.42	-39.09	30.71
2	.1366	.9208	0.0000	41.44	-7.06	-31.93	27.41
3	.1077	.9262	0.0000	40.50	-9.26	-24.41	22.70
4	.0798	.9122	0.0000	39.84	-11.37	-16.96	17.13
5	.0531	.9023	0.0000	38.86	-13.37	-10.12	12.30
6	.0276	.9121	0.0000	38.24	-15.55	-4.28	9.54
7	.0025	.9521	0.0000	37.86	-17.49	-1.42	8.12
8	-.0220	.9853	0.0000	37.78	-19.38	-.23	8.04
9	-.0461	.9894	0.0000	37.65	-21.59	2.54	7.77
10	-.0713	.9984	0.0000	38.59	-24.38	5.92	7.91
11	-.0956	1.0088	0.0000	40.57	-27.96	8.44	8.68

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WAKE AND BOUNDARY LAYER BLOCKAGES (PERCENT)

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STATION        1     2     3     4     5     6     7     8     9    10
MID BLOCKAGE  0.0    .2    .2    .2    .2   1.7   2.3   8.6   8.4   7.7
DIST FACTOR   1.0   1.0   1.0   1.0   1.0   1.0   1.0   1.0   1.0   1.0
INT BLOCKAGE  0.0    .2    .2    .2    .2   1.7   2.3   8.6   8.4   7.7


STATION       11    12    13    14
MID BLOCKAGE  6.9   6.7   6.5   6.2
DIST FACTOR   1.0   1.0   1.0   1.0
INT BLOCKAGE  6.9   6.7   6.5   6.2
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SUMMARY   POINT NO.   1   THE CALCULATION IS CONVERGED   PASS   16

TEST POINT TITLE =   810522101

FLOW = 17.28 SPEED = 12510.0 PRESSURE RATIO = 1.301
ISENTROPIC EFFY = .8710 POLYTROPIC EFFY= .8757 DEL T/T= .0895

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