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A FORTRAN PROGRAM FOR THE DETERMINATION OF NOZZLE CONTOURS FOR ROTATIONAL, NON-HOMENTROPIC GAS MIXTURES

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ABSTRACT

A program has been written which generates a nozzle contour and the complete flow field for two dimensional or axisymmetric flows designed to exit parallel to the axis at uniform pressure. The flow is that of a rotational, non-homentropic gas mixture where viscous effects have been neglected and the chemistry is assumed frozen. This report comprises a complete description of the numerical program developed, the analysis being described in Advanced Technology Laboratories Technical Report No. 148 entitled, "The Determination of Nozzle Contours for Rotational, Non-homentropic Gas Mixtures."

I. INTRODUCTION

The overall nozzle configuration is depicted in Figure (1). The numerical procedure and hence the program, may be divided into several basic areas:

(A) Initial Profile. The data is specified at the NPTS data points on the non-characteristic initial line W_1A_1.

(B) Down-Running Characteristics Emanating from Initial Profile. For each data point N on the initial line, a C_- characteristic is calculated emanating from the initial line and ending on the axis. The first C_- characteristic emanates from initial line data point N=2 and the final one from N=NPTS. On a C_- characteristics emanating from point N on the initial line, there are LMAX grid points, where LMAX=2N-1. Note, that to calculate the C_- characteristic, emanating from N, only the value on the initial line and the previous C_- characteristic, emanating from N-1, are required, hence only two successive C_- lines need be stored.

(C) Down-Running Characteristics Emanating from Prescribed Arc. Since the arc is generally a circle of small radius, the grid must be refined in the area of the wall. The mesh points are hence subdivided in the vicinity of wall corresponding to the severity of the turn. In addition, logic is incorporated to force the angle change at the wall between two successive down-running characteristics to be less than one degree

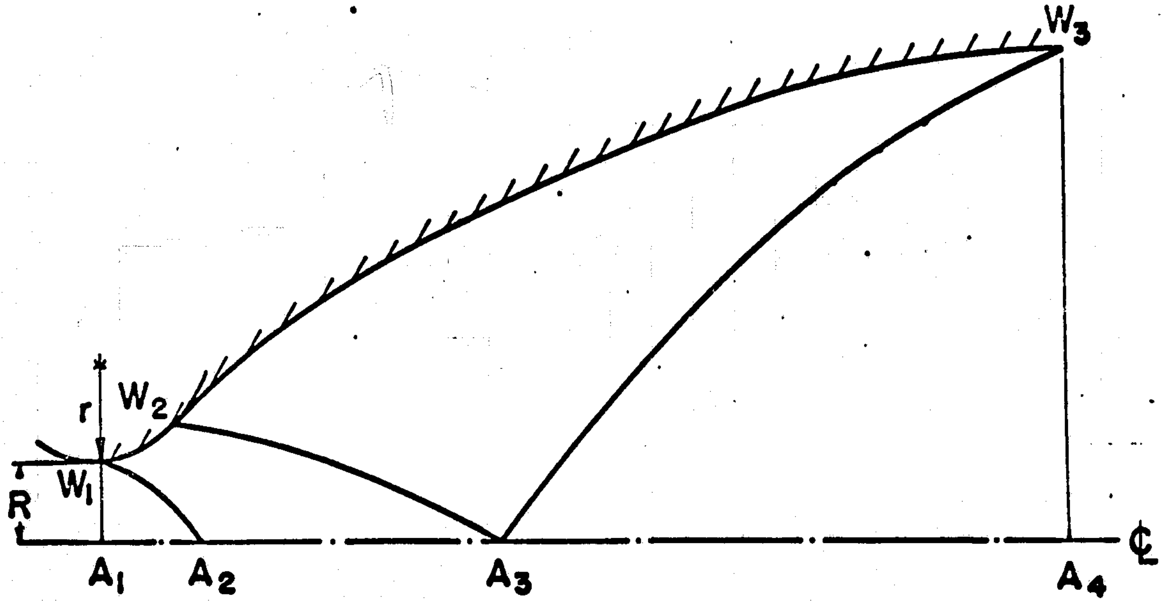


FIGURE 1. OVERALL NOZZLE CONFIGURATION

by further grid subdivision. The calculation along C_- characteristics proceeds from the wall to the axis, and the procedure terminates when the axis pressure falls below design pressure. The characteristic $W_2^{\prime}A_3$, yielding design pressure on the axis is found by interpolation between the two previously calculated C_- lines

(D) Generation of Exit C_+ Characteristic. Let N denote a data point on the down-running characteristic W_2A_3 and $\bar{N}$ denote a data point, having the same value of streamfunction, on the up-running characteristic A_3W_3. All properties are known at N, while at $\bar{N}$, the pressure is design pressure and the flow is parallel to the axis. Since both mass fraction (α_i) and entropy are constant along $N\bar{N}$, knowing the pressure ratio $P_N/P_{\bar{N}}$ yields the temperature $T_{\bar{N}}$ by an iterative procedure. The constancy of stagnation enthalpy then enables the velocity $q_{\bar{N}}$ to be determined. Having properties at the mesh points $\bar{N}$, we then determine the location of the mesh points by use of the streamfunction equation. Having the exit characteristic A_3W_3 calculated, the following information is available without having to proceed with the contour design:

1. nozzle length
2. area ratio
3. complete profiles at exit plane

(E) Contour Calculation. The calculation works along C_- characteristics now working from data points on the exit characteristic back to the wall, whose location is unknown. The wall point calculation is depicted in Figure (2). The wall angle θ_C is obtained by an iterative procedure. For an assumed value of θ_C, point C is located as the intersection of the streamline from D, with the characteristic from B. The correct value of θ_C, is that for which the compatibility relations applied along both AC and BC yield the same pressure P_C to within a prescribed tolerance.

In Section II, the input required is described, while the output description is presented in Section III. A description of the subroutines and functions used in the program is presented in Section IV. The specific machine requirements and time estimates are listed in Section V. A detailed flow chart is presented in Section VI.

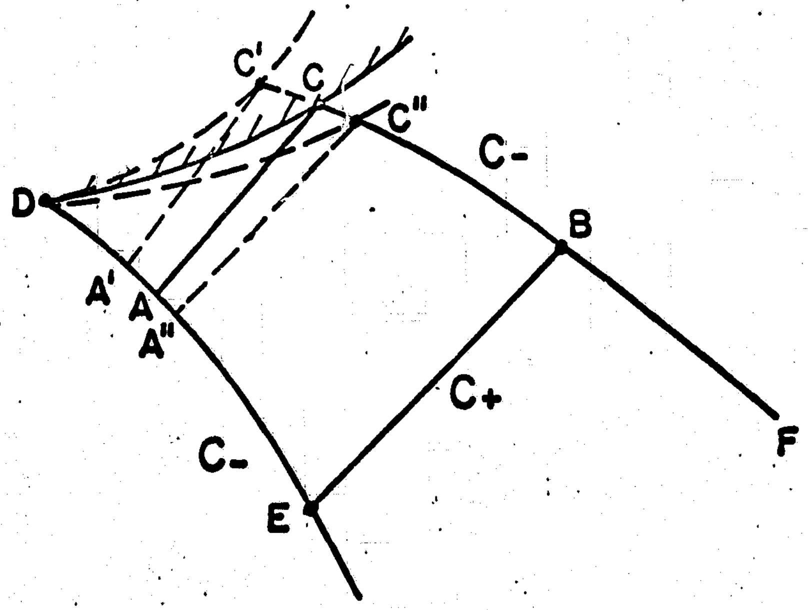


FIGURE 2. NOZZLE DESIGN POINT

II. DESCRIPTION OF INPUT

Card No.	Columns	Format	Description
1	1-5	I5	Type of flow: (0=Two Dimensional, 1=Axisymmetric)
	6-10	I5	Number of data points on initial profile (NPTS)
	11-15	I5	Output indicator (check Description of Output, Section III)
2	1-10	E10.0	Ratio of axial coordinate of wall at initial station to throat radius
	11-20	E10.0	Ratio of radial coordinate of wall at initial station to throat radius
	21-30	E10.0	Initial inclination of wall (in radians)
	31-40	E10.0	Ratio of radius of initial circular arc expansion to throat radius
	41-50	E10.0	Ratio of exit pressure to P_∞
	51-60	E10.0	Throat radius

Card No.	Columns	Format	Description
3	1-10	E10.0	Free stream or reference Mach number
	11-20	E10.0	Free stream or reference temperature (°K)
	21-30	E10.0	Free stream or reference average molecular weight
4	Initial Profile -		There are 2 cards required for each data point as described below. Begin inputting data points at the axis (Point #1) and proceed to the nozzle wall. (Point #NPTS)
4a	1-10	E10.0	Ratio of axial coordinate of data point to throat radius
	11-20	E10.0	Ratio of radial coordinate of data point to throat radius
	21-30	E10.0	Ratio of velocity at data point to free stream velocity
	31-40	E10.0	Ratio of temperature at data point to free stream temperature
	41-50	E10.0	Ratio of pressure at data point to free stream pressure

Card No.	Columns	Format	Description
4a	51-60	E10.0	Flow inclination at data point (in radians)
4b	1-10	E10.0	Mass fraction of H
	11-20	E10.0	Mass fraction of O
	21-30	E10.0	Mass fraction of H_2O
	31-40	E10.0	Mass fraction of H_2
	41-50	E10.0	Mass fraction of O2
	51-60	E10.0	Mass fraction of OH
	61-70	E10.0	Mass fraction of N_2

III. DESCRIPTION OF OUTPUT

(A) Output Indicator Equals 1. If the output indicator equals 1 the following output is obtained:

1. Input (control constants, reference condiitions and initial profile)
2. Down-running characteristic line from initial wall point to axis (W_1A_2 in Figure (1))
3. Line number, number of points on the line and the wall and axis points of C_- characteristic lines between the line (W_1A_2 to W_2A_3 in Figure (1))
4. Down-running characteristic line with axis point pressure equal to design pressure
5. Exit characteristic line (beyond which pressure equals design pressure and flow is parallel to axis) (W_3A_3 in Figure (1))
6. Nozzle design points
7. Exit profile

(B) Output Indicator Equals 0. When the output indicator is set equal to 0 all the output in paragraph A is obtained plus a print-out of data along all the C_- characteristics in the flow field, at a selected number of points along them. This indicator would only be used when a detailed description of the flow field is required such as profiles at intermediary axial stations, which could be obtained by an interpolation procedure along these C_- characteristics.

IV. SUBROUTINES AND FUNCTIONS

(A) Subroutines.

Name	Description
1. THERM	Calculates entropy, S_i, and enthalpy, H_i, from polynomial fits in temperature
2. ALL	Computes subsidiary properties as a function of basic variables (Q,T,P,α_i)

$$C_p = \Sigma\, C_{p_i}\, \alpha_i$$
$$W = (\Sigma \alpha_i/m_i)^{-1}$$
$$\rho = \gamma_\infty\, M_\infty^2\, W\, P/T/W_\infty$$
$$R = R_o/W$$
$$\gamma = C_p/(C_p - R/C_{p\infty})$$
$$M = Q\, M_\infty(\gamma_\infty R_\infty/\gamma/R/T)^{-\frac{1}{2}}$$
$$\mu = \tan\left(1/(M^2 - 1)^{\frac{1}{2}}\right)^{-1}$$

Name	Description
3. COEFF	Sets thermodynamic coefficients as functions of temperature
4. THERMO	Calculates specific heat, C_{p_i}, derivative of specific heat and enthalpy, H_i, of each species from polynomial fits in temperature

	Name	Description
5.	ERROR	Outputs program statement number nearest error and terminates computer run

(B) Functions

	Name	Description
1.	XM1	$\tan(\theta + \mu)$ along C_+ characteristic
2.	XM2	$\tan(\theta - \mu)$ along C_- characteristic
3.	XM3	$\tan(\theta)$ along streamline
4.	F1	A_1 or B_1^* coefficient along $C_\pm$ characteristic
5.	F2	A_2 or B_2^* coefficient along $C_\pm$ characteristic

---

*Note: $P - \theta$ relationship along C_+ characteristic:

$$A_1(p_C - p_A) + \theta_C - \theta_A + A_2(x_2 - x_A) = 0$$

$P - \theta$ relationship along C_- characteristic:

$$B_1(p_C - p_B) - \theta_C + \theta_B + B_2(x_C - x_B) = 0$$

V. MACHINE CONTROL CONSIDERATIONS

1. Machine - program designed for CDC 6600

2. Loader -PPLOADR

3. Estimates for run:

   a. Field Length:

      (1) compile - 64000_8 locations

      (2) loading - 70000_8 locations

   b. CP time: variable depending on number of points and properties of an initial profile and type of flow (approximately 2 minutes for sample case included)

   c. IO: less than 100_8 seconds

   d. Tapes and disks:

      (1) tape 5 - card input

      (2) tape 6 - printed output

      (3) tape 7 - punched output

      (4) no other tapes or disk files are used

   e. Printed output: 7000_8 lines including listing of program for output indicator equals 1, 60000_8 lines for output indicator equals 0.

VI. FLOW CHART

Symbols and References in Flow Chart

Basic variables:

x	-	axial distance/throat radius
y	-	radial distance/throat radius
P	-	pressure/free stream pressure
Q	-	velocity/free stream velocity
T	-	temperature/free stream temperature
TH	-	flow angle
ALP(1-7)	-	mass fractions (seven species)

Subsidiary properties:

CPX	-	specific heat/free stream specific heat
R	-	gas constant (R_0/W)
GAM	-	ratio of specific heats
EM	-	Mach number
XMU	-	Mach angle
RHO	-	density/free stream density

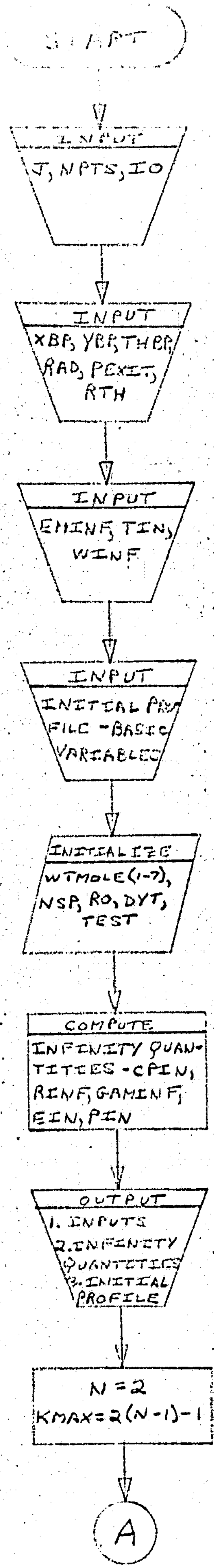
Initial data line - called K LINE - example of variable on this line is X(K)

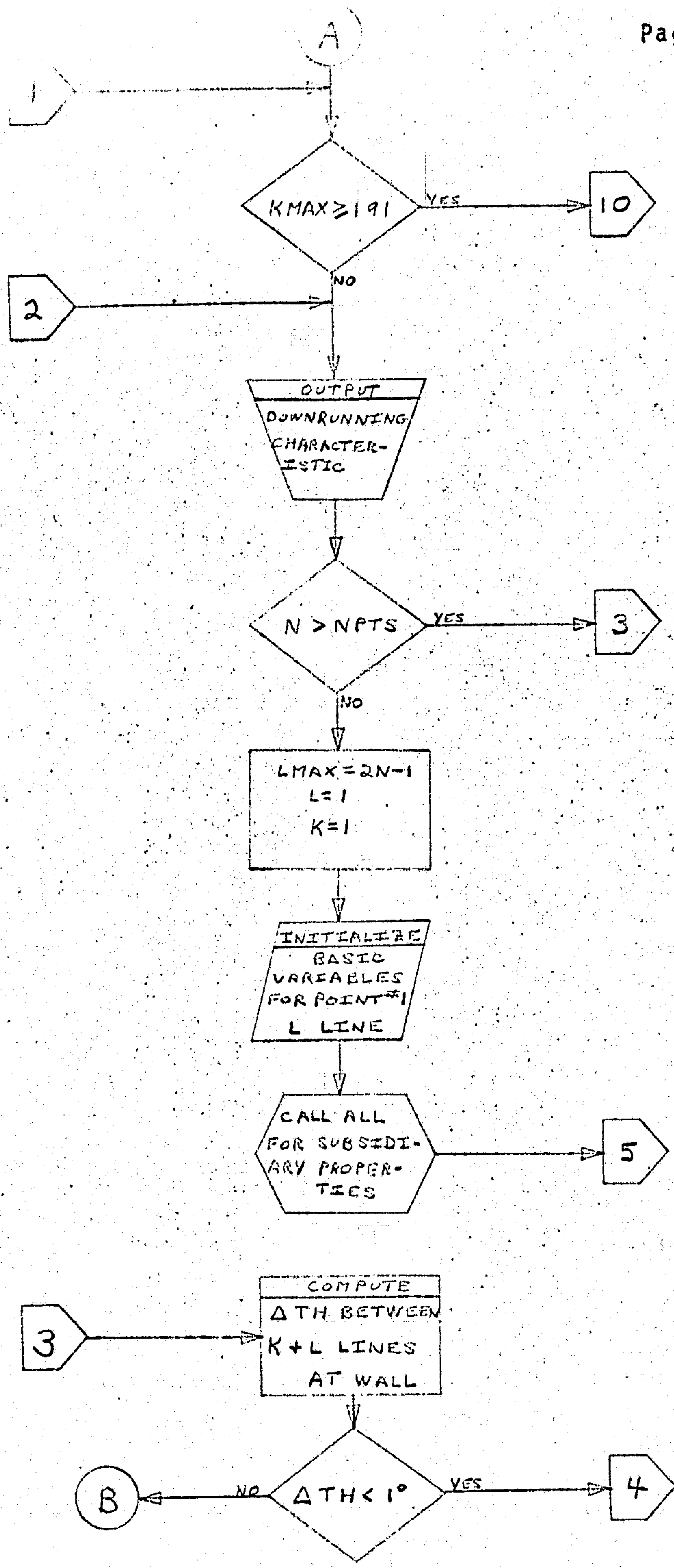
New data line - called L LINE - example of variable on this line is XN(K)

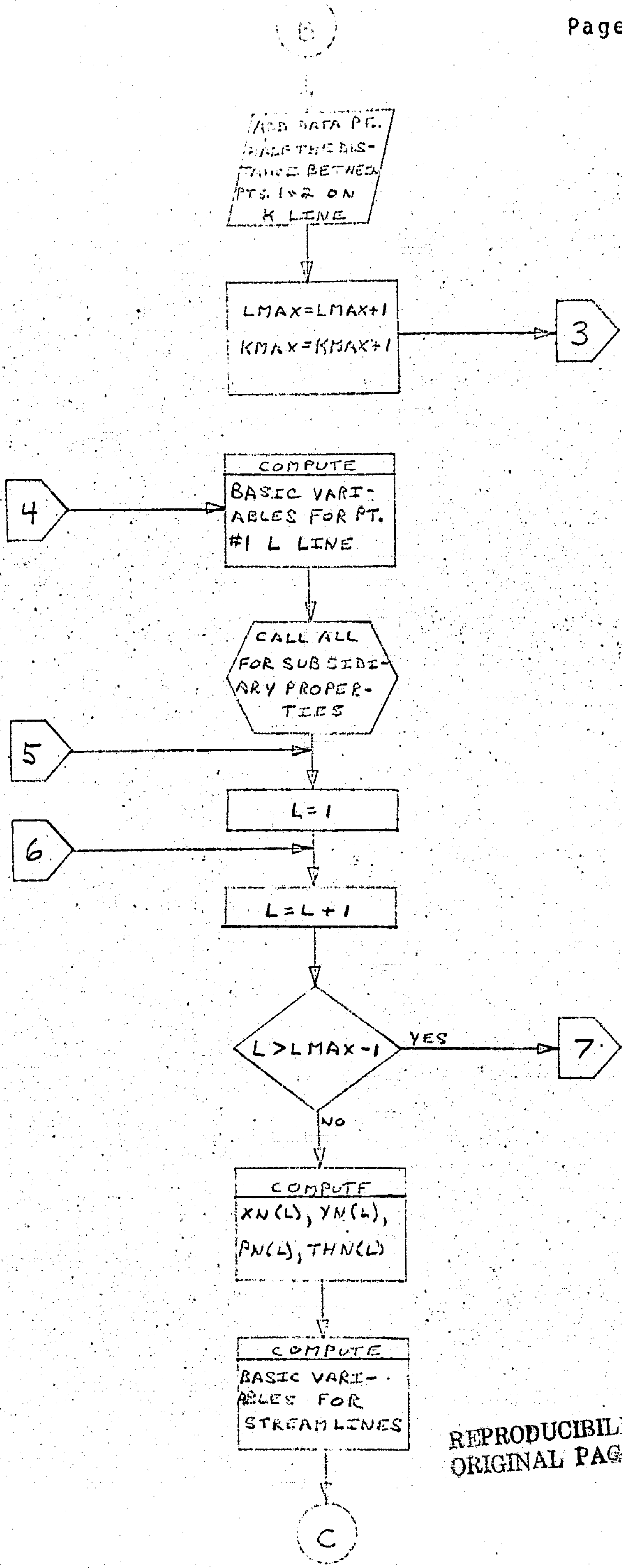
Streamline - example of variable on this line is XD

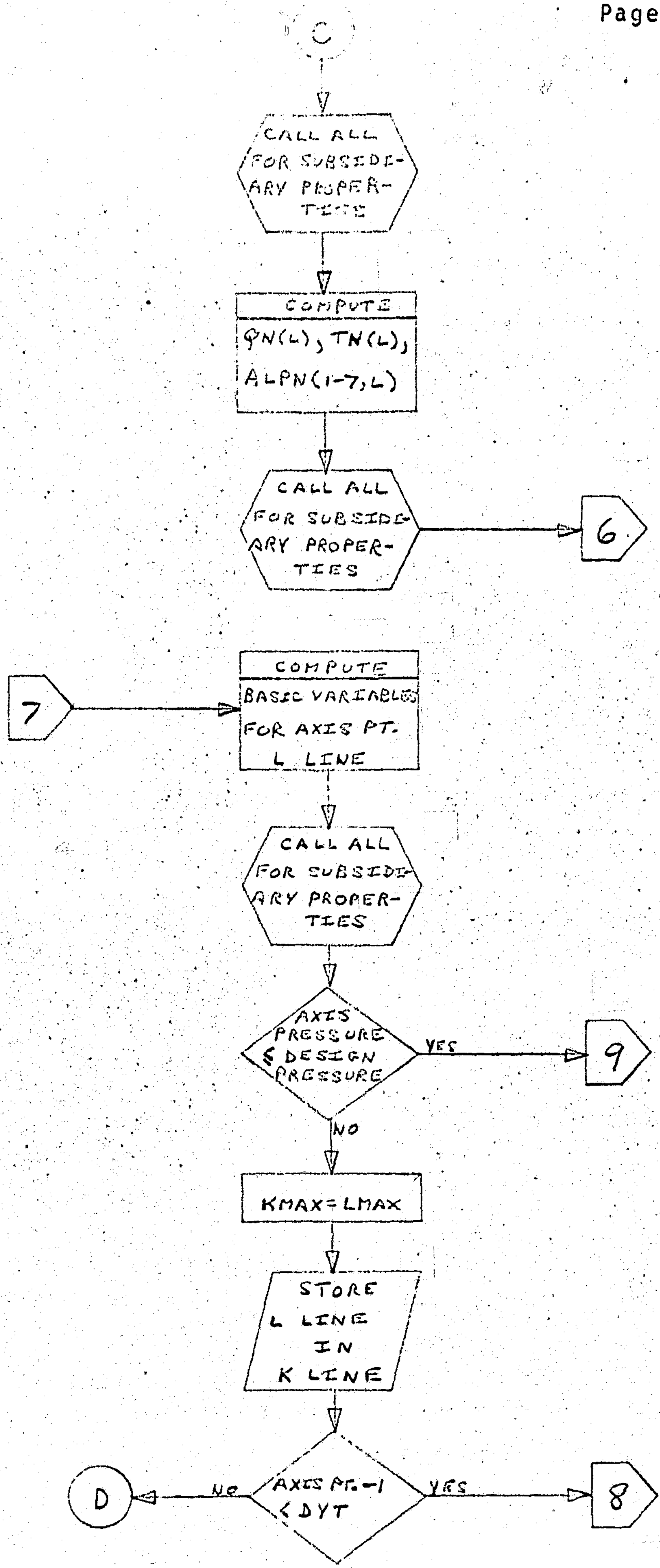
NPTS - number of points on initial profile until down-running line giving design pressure at

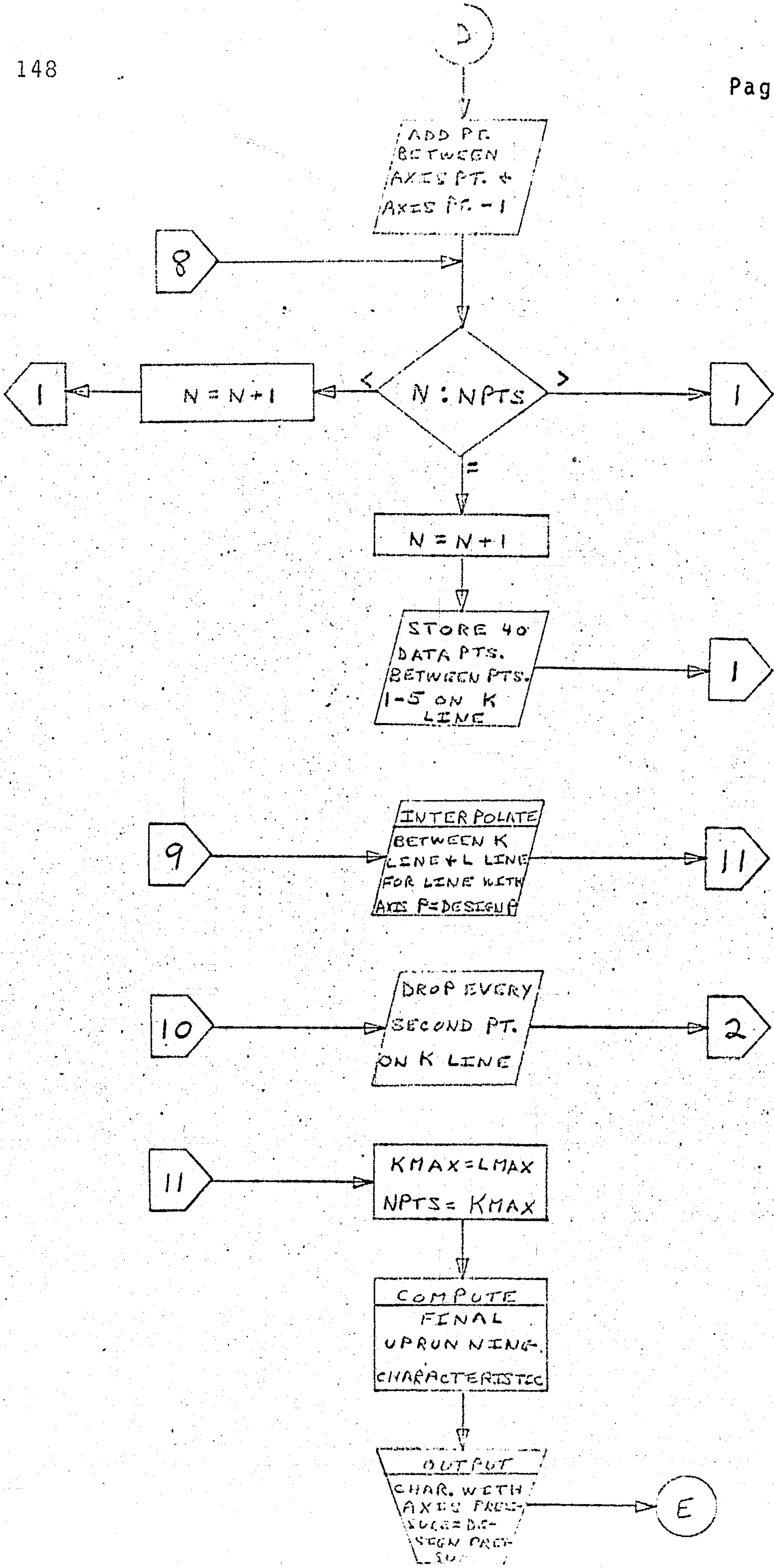
		axis, after this, it is number of points on up-running characteristic lines
N	-	line number from 1 to number of points on initial profile
KMAX	-	number of points on K LINE
LMAX	-	number of points on L LINE
DYT	-	one half averge Δ y on initial profile
NSAVE	-	number of points on both down-running characteristic line giving design pressure at axis and the final up-running characteristic line
LF	-	counter on final up-running characteristic line, for values 1 to NSAVE

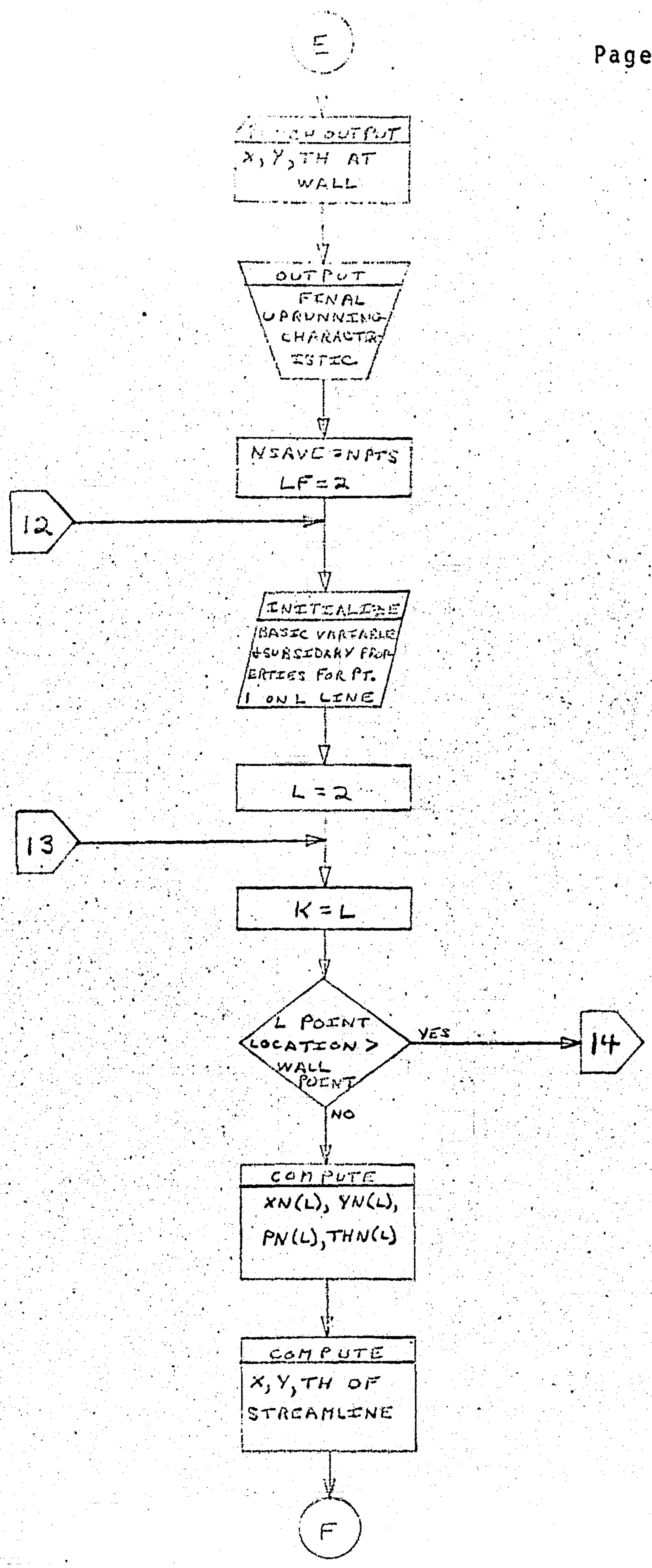

START
INPUT
J, NPTS, IO
INPUT
XBP, YBP, THBP, RAD, PEXIT, RTH
INPUT
EMINF, TIN, WINF
INPUT
INITIAL PRO-FILE - BASIC VARIABLES
INITIALIZE
WTMOLE(1-7), NSP, RO, DYT, TEST
COMPUTE
INFINITY QUANTITIES - CPIN, RINF, GAMINF, EIN, PIN
OUTPUT
1. INPUTS
2. INFINITY QUANTITIES
3. INITIAL PROFILE
N = 2
KMAX = 2(N-1)-1
A

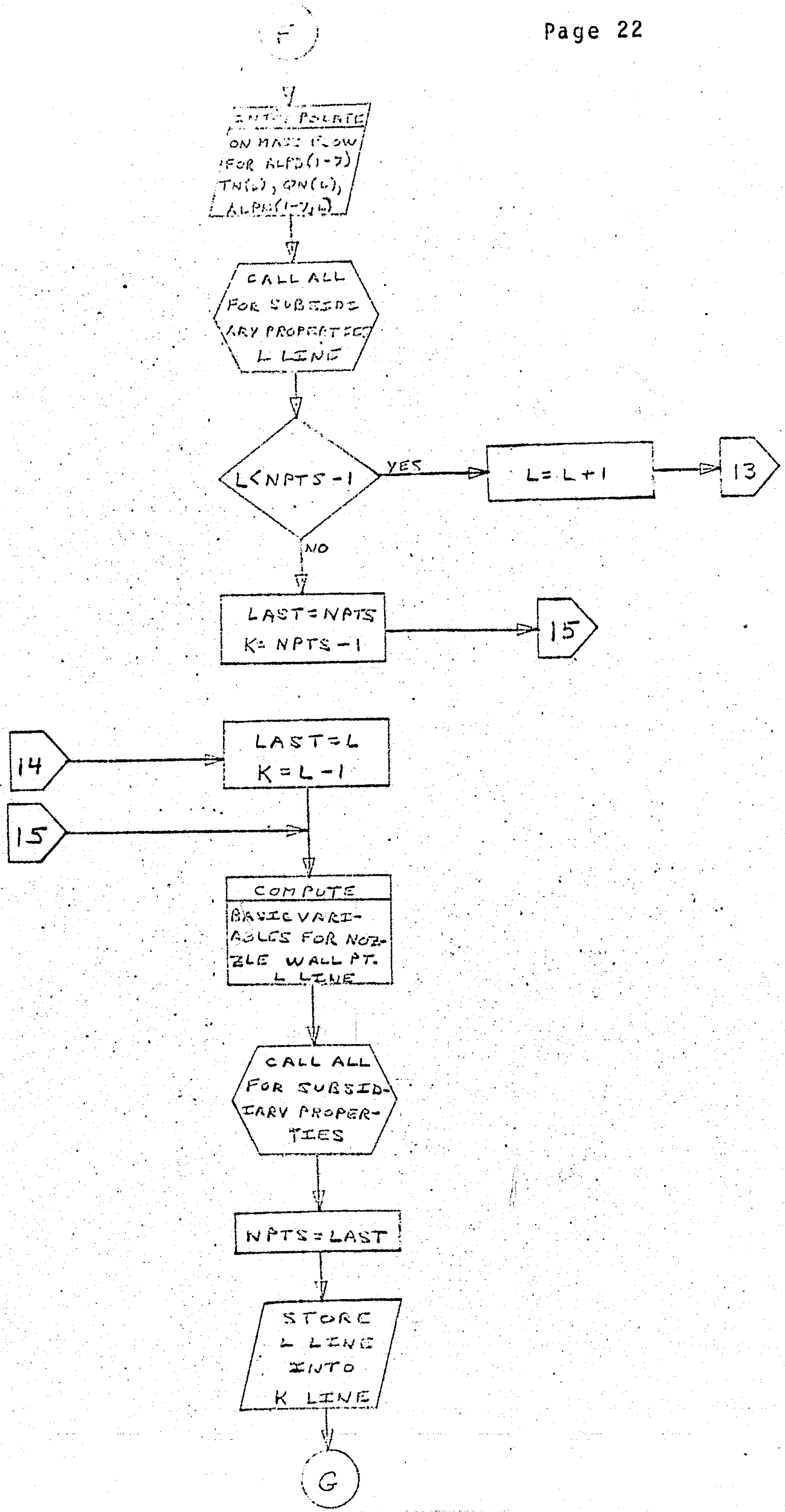

A
1
KMAX≥191
YES
10
NO
2
OUTPUT
DOWNRUNNING CHARACTER-ISTIC
N > NPTS
YES
3
NO
LMAX=2N-1
L=1
K=1
INITIALIZE
BASIC VARIABLES FOR POINT #1 L LINE
CALL ALL FOR SUBSIDI-ARY PROPER-TIES
5
3
COMPUTE
ΔTH BETWEEN K+L LINES AT WALL
ΔTH< 1°
NO
B
YES
4

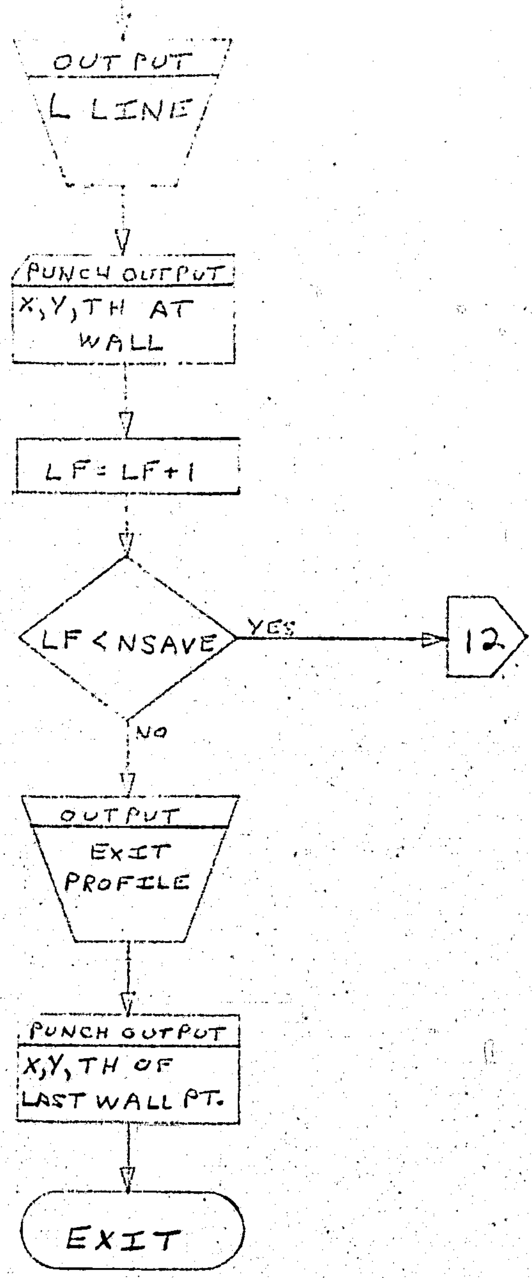

B
ADD DATA PT. HALF THE DIS- TANCE BETWEEN PTS. 1+2 ON K LINE
LMAX=LMAX+1
KMAX=KMAX+1
3
COMPUTE
BASIC VARI- ABLES FOR PT. #1 L LINE
4
CALL ALL FOR SUBSIDI- ARY PROPER- TIES
5
L=1
6
L=L+1
L>LMAX-1
YES
7
NO
COMPUTE
XN(L), YN(L), PN(L), THN(L)
COMPUTE
BASIC VARI- ABLES FOR STREAMLINES
C


C
CALL ALL FOR SUBSIDIARY PROPERTIES
COMPUTE
QN(L), TN(L), ALPN(1-7,L)
CALL ALL FOR SUBSIDIARY PROPERTIES
6
7
COMPUTE
BASIC VARIABLES FOR AXIS PT. L LINE
CALL ALL FOR SUBSIDIARY PROPERTIES
AXIS PRESSURE ≤ DESIGN PRESSURE
YES
9
NO
KMAX=LMAX
STORE L LINE IN K LINE
AXIS PT.-1 < DYT
NO
D
YES
8


D
ADD PT. BETWEEN AXIS PT. + AXIS PT. - 1
8
N : NPTS
<
>
=
N = N+1
1
1
N = N+1
STORE 40 DATA PTS. BETWEEN PTS. 1-5 ON K LINE
1
9
INTERPOLATE
BETWEEN K LINE + L LINE FOR LINE WITH AXIS P=DESIGN P
11
10
DROP EVERY SECOND PT. ON K LINE
2
11
KMAX=LMAX
NPTS= KMAX
COMPUTE
FINAL UPRUNNING CHARACTERISTIC
OUTPUT
CHAR. WITH AXIS PRES-SURE=DE-SIGN PRES-SURE
E


E
PUNCH OUTPUT
X, Y, TH AT WALL
OUTPUT
FINAL UPRUNNING CHARACTR-ISTIC
NSAVE = NPTS
LF = 2
12
INITIALIZE
BASIC VARIABLE & SUBSIDARY PROPERTIES FOR PT. 1 ON L LINE
L = 2
13
K = L
L POINT LOCATION > WALL POINT
YES
14
NO
COMPUTE
XN(L), YN(L), PN(L), THN(L)
COMPUTE
X, Y, TH OF STREAMLINE
F


F
CALL ALL
L LINE
L<NPTS-1
YES
L=L+1
13
NO
LAST=NPTS
K=NPTS-1
15
14
LAST=L
K=L-1
15
COMPUTE
BASIC VARI-
ABLES FOR NOZ-
ZLE WALL PT.
L LINE
CALL ALL
FOR SUBSID-
IARY PROPER-
TIES
NPTS=LAST
STORE
L LINE
INTO
K LINE
G


OUTPUT
L LINE
PUNCH OUTPUT
X, Y, TH AT WALL
LF = LF+1
LF < NSAVE
YES
12
NO
OUTPUT
EXIT PROFILE
PUNCH OUTPUT
X, Y, TH OF LAST WALL PT.
EXIT