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MCDONNELL DOUGLAS TECHNICAL SERVICES CO.
HOUSTON ASTRONAUTICS DIVISION

SPACE SHUTTLE ENGINEERING AND OPERATIONS SUPPORT

DESIGN NOTE NO. 1.4-4-5

THERMAL BOUNDARIES ANALYSIS PROGRAM DOCUMENT

MISSION PLANNING, MISSION ANALYSIS AND SOFTWARE FORMULATION

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2.0 INTRODUCTION

The digital program TBAP has been developed to provide thermal boundaries in the D/M-relative velocity (D-V), dynamic pressure-relative velocity ($\bar{q}$-V), and altitude-relative velocity (h-V) planes. These thermal boundaries are used to design and/or analyze Shuttle Orbiter entry trajectories. The TBAP has been used extensively in supporting the Flight Performance Branch of the NASA in evaluating candidate trajectories for the Thermal Protection System design trajectory.

3.0 DISCUSSION

The method used in TBAP to establish thermal boundaries is to find a reference heat rate for a given velocity and altitude, input the reference heat rate into a simplified heating model resulting in the definition of the surface temperature for a selected panel or control point and then iterate on altitude until the panel temperature matches the critical temperature input for that panel. D/M and dynamic pressure are then found corresponding to the altitude-velocity point. This process is then repeated for a different velocity until the desired range of velocities is spanned.

The assumptions made in developing TBAP are that simplified heating models (References 1 and 2) can be used to determine surface temperature and that atmospheric density and free stream temperature can be modeled using the 1962 Standard Atmosphere.

The reference heat rate for the panels and control points as given in Reference 1 is

$$\dot{q}_{ref} = 0.82\ (17700)\ \sqrt{\rho}\left(\frac{V}{10^4}\right)^{3.07}\left(1 - \frac{h_w}{h_o}\right) \tag{1}$$

where

$\dot{q}$ = stagnation point heat rate for a one foot sphere (BTU/ft²/sec),

ρ = free stream density (slugs/ft³),

V = relative velocity magnitude (ft/sec),

h_w = surface enthalpy (BTU/lb$_m$),

$$h_w = .24\ T_w, \tag{2}$$

h_o = total enthalpy (BTU/lb$_m$),

$$h_o = .24\ T_\infty + \frac{V^2}{50{,}063} \tag{3}$$

and T_W = wall temperature (°R),

$$T_W = 1000\left(\frac{\dot{q}_{ref}}{.476\,\varepsilon}\right)^{.25} \tag{4}$$

T_∞ = free stream temperature (°R),

and ε = surface emissivity.

NOTE: Since T_W, (equation (4)), is not independent of q_{ref}, an initial value of T_W is assumed and two passes are made through equation (1) in defining q_{ref}.

The individual panel or control point heat rate (Reference 1 and 2) for laminar, transitional and turbulent flow are defined by

$$q_{panel} = q_{i(lam)} = A_i C_i q_{ref}, \text{ for } R < R_{oi}, \tag{5}$$

$$q_{panel} = q_{i(trans)} = q_{i(lam)} \left(\frac{a\,R}{R_{oi}} - b\right)\left(\frac{R}{K\,R_{oi}}\right)^{.3}, \text{ for } R_{oi} \leq R \leq K\,R_{oi}, \tag{6}$$

and

$$q_{panel} = q_{i(turb)} = q_{i(lam)}c\left(\frac{R}{K\,R_{oi}}\right)^{.3}, \text{ for } K\,R_{oi} \leq R, \tag{7}$$

where A_i = deflection factor,

$C_i = \dfrac{q_{i(lam)}}{q_{ref}}$, for the i_{th} panel

= function of angle of attack, α,

R = Reynolds number behind a normal shock

$$= \frac{\rho V}{\mu_v} , \tag{8}$$

R_{oi} = transition onset Reynolds number for the ith panel,

= function of α,

and μ_v = normal shock viscosity coefficient and a, b, c, and K are modeling constants. The deflection factor, Δ_i, (Equation (5)) equals one for surfaces not on the elevon or body flap and

$$\Delta_i = 1.05 + (9.8 - \frac{\alpha}{5}) \Gamma$$

where α = angle of attack (degrees)

$\Gamma = .0196\delta - .0122$, for $0 \leq \delta \leq 4$

$\Gamma = .0276\delta - .0443$, for $4 < \delta \leq 8$

$\Gamma = .03676\delta - .11758$, for $8 < \delta \leq 15$

$\Gamma = .04669\delta - .2665$, for $15 < \delta$

and δ = deflection angle (body flap or elevon) for surfaces on the body flap or elevon.

C_i and R_{oi} are stored in tables in TBAP as functions of α and interpolated for the appropriate α. μ_v is stored in a table as a function of V and interpolated for the appropriate V. The surface temperature for the i_{th} panel as defined in Reference 2 is given by

$$T_i = 1000 \left(\frac{q_{panel}}{.4761 \ \epsilon_i} \right)^{.25} - 460 \tag{9}$$

where ϵ_i = surface emissivity for the i_{th} panel.

Using Equations 1 through 9, a regula falsi method is used to solve for the altitude at which panel temperature is equal to a critical temperature.

That is

$$h_{i+1} = h_i + \left[\frac{\Delta h}{\Delta T}\right]_i (T_C - T_i) \tag{10}$$

is initialized with an altitude h_i, $\frac{\Delta h}{\Delta T}$ calculated numerically by

$$\frac{\Delta h}{\Delta T} = \frac{h_i - h_{i-1}}{T_i - T_{i-1}}, \tag{11}$$

and an iteration process continued until T_i converges to T_C within an input convergence criterion.

The dynamic pressure is defined by

$$\bar{q} = \frac{1}{2} \rho V^2. \tag{12}$$

In TBAP the free stream density, ρ, and temperature, T_∞, (Equation 3) are computed using the SVDS (Reference 3) subroutine ATMOS which represents the 1962 Standard atmosphere. The drag acceleration is defined by

$$D/M = \frac{\bar{q}\ C_D S}{m}. \tag{13}$$

where C_D = drag coefficient

S = reference area

and m = vehicle mass.

C_D is computed using the SVDS subroutine AR14C (Reference 3).

4.0 INPUT DESCRIPTION

The TBAP input data consists of data from the SVDS base data tape (Reference 3) for an entry run and data for the following variables which are in common arrays.

VARIABLE	TYPE *	COMMON BLOCK	COMMON LOCATION	DESCRIPTION
ALPHA	R	BLCK	GNDAT1 (78)	Pitch angle of attack (RAD)
MASS	R	BLCK	GNDAT1 (128)	Vehicle Mass (slugs)
V	R	BLCK	XLEC (507)	Initial velocity (ft/sec)
H	R	BLCK	GNDAT1 (70)	Geodetic altitude (ft)
NC2M	I	GEN2	WORK2 (330)	Convergence interval for temperature iterator
NVAL	I	GEN2	WORK2 (331)	Number of values for angle-of-attack table
DT	R	GEN2	WORK2 (107)	Specified tolarance factor for temperature iterator
DV	R	GEN2	WORK2 (105)	Increment velocity (ft/sec)
NP	I	GEN2	WORK2 (108)	TPS panel or control point number
IOP	I	GEN2	WORK2 (110)	Option for atmospheric model = 0 1962 U.S. Standard atmosphere = 1 July atmosphere at 30 Deg. North Latitude = 2 Jan. atmosphere at 30 Deg. North Latitude = 3 July atmosphere at 60 Deg. North Latitude = 4 Jan. atmosphere at 60 Deg. North Latitude
VM	R	GEN2	WORK2 (104)	Maximum velocity (ft/sec)

VARIABLE	TYPE *	COMMON BLOCK	COMMON LOCATION	DESCRIPTION
IALP	I	GEN2	WORK2 (111)	Option for angle-of-attack = 0 ramped schedule = 1 constant schedule
TC	R	GEN2	WORK2 (112)	Critial temperature (DEG)
VALT (I), I = 1, NVAL	R	GEN2	WORK2 (150)	Velocity Table (ft/sec)
VALP (I), I = 1, NVAL	R	GEN2	WORK2 (114)	Angle-of-attack Table (DEG)
NBAP	I	GEN2	WORK2 (200)	Flag determining thermal boundary option = 0 Does not call TBAP = 1 Calls TBAP
TSTOP	I	GNDAT2	GNDAT2 (2)	Maximum Phase Time (sec)
TMAX	I	GNDAT2	GNDAT2 (3)	Maximum Case Time (sec)
IBAP	I	GEN2	WORK2 (199)	Flag for TBAP driver option = 0 Do not use TBAP driver = 1 Use TBAP driver

* NOTE: Type "R" denotes REAL.

Type "I" denotes INTEGER.

5.0 OUTPUT DESCRIPTION

Figure 1 gives an example of the intialization data which is output from TBAP. Table I defines the data in Figure 1.

Figure 2 gives an example of line printer output of thermal boundary data for a given panel from TBAP. Table II defines the data in Figure 2.

Plots of thermal data from TBAP (see Appendix A Figures 3, 4, 5) are presented in the D/M-relative velocity, altitude-relative velocity, and dynamic pressure-relative velocity planes respectively for control point 2 (body flap).

TABLE I.

INITIALIZATION DATA

Row 1 - 2

Input identification

NC2M	Maximum number of iterations on critical temperature
NVAL	Number of values for angle-of-attack table

Row 3 - 4

Input identification

REF AREA	Reference Area (ft^2)
WEIGHT	Weight (lbs)
VSTART	Initial velocity (ft/sec)
VSTOP	Final velocity (ft/sec)
DELTA V	Velocity increment (ft/sec)
DT	Specified tolarance factor for temperature iterator (°F)

Row 5 - 6

Input identification

CG (1)	Center of mass X-component (in)
CG (2)	Center of mass Y-component (in)
CG (3)	Center of mass Z-component (in)

```
NCIM NVAL
200    0
 REF AREA       WEIGHT         VSTART         VSTOP          DELTA V        DT
.26900000+04   .38499971+06   .10033997+05   .26000000+05   .50000000+03   .10000000+00
   CG(1)          CG(3)
 87075000+03   .37500000+03
```

FIGURE 1. Example of Initialization Data

NP	IUP	IALP	TC
27	0	1	.25000000+04

REL VEL	ALTITUDE	O/M	WBAR	DENSITY	REY NO.	O REY NO.	MACH	TEMP	FLOW	BDF	ELV	ALP
10000.0	137410.1	65.864	295.4	.5909-05	.3078+05	.1470+04	9.5	2491.1	3	16.3	16.3	30.0
10500.0	142199.3	58.979	264.9	.4005-05	.2568+05	.1470+04	9.9	2511.1	3	16.3	16.3	30.0
11000.0	147565.9	51.526	231.5	.3027-05	.2105+05	.1470+04	10.3	2512.0	3	16.3	16.3	30.0
11500.0	152809.3	45.238	203.3	.3075-05	.1742+05	.1470+04	10.7	2510.8	3	16.3	16.3	30.0
12000.0	157670.8	40.604	182.6	.2536-05	.1449+05	.1470+04	11.1	2512.8	3	16.3	16.3	30.0
12500.0	162033.7	36.224	163.0	.2066-05	.1201+05	.1470+04	11.6	2507.5	3	16.3	16.3	30.0
13000.0	167403.7	32.941	148.2	.1754-05	.1002+05	.1470+04	12.0	2506.0	3	16.3	16.3	30.0
13500.0	171652.4	30.210	136.0	.1492-05	.8395+04	.1470+04	12.5	2504.8	3	16.3	16.3	30.0
14000.0	176001.7	27.798	125.2	.1277-05	.7125+04	.1470+04	13.0	2504.5	3	16.3	16.3	30.0
14500.0	180171.1	25.643	115.5	.1099-05	.6105+04	.1470+04	13.5	2504.1	3	16.3	16.3	30.0
15000.0	184212.6	23.677	106.7	.9465-06	.5289+04	.1470+04	14.1	2503.8	3	16.3	16.3	30.0
15500.0	188137.4	21.879	98.6	.8212-06	.4628+04	.1470+04	14.6	2503.5	3	16.3	16.3	30.0
16000.0	191849.8	20.310	91.6	.7157-06	.4061+04	.1470+04	15.1	2503.2	3	16.3	16.3	30.0
16500.0	195726.6	18.637	84.1	.6178-06	.3527+04	.1470+04	15.7	2494.5	3	16.3	16.3	30.0
17000.0	199220.4	17.377	78.4	.5428-06	.3155+04	.1470+04	16.2	2495.9	3	16.3	16.3	30.0
17500.0	202567.2	16.265	73.4	.4796-06	.2826+04	.1470+04	16.8	2497.3	3	16.3	16.3	30.0
18000.0	205971.1	15.181	68.6	.4233-06	.2540+04	.1470+04	17.4	2496.7	3	16.3	16.3	30.0
18500.0	207576.7	15.117	68.3	.3992-06	.2439+04	.1470+04	17.9	2500.1	2	16.3	16.3	30.0
19000.0	208853.4	15.221	68.8	.3609-06	.2369+04	.1470+04	18.5	2500.6	2	16.3	16.3	30.0
19500.0	210070.2	15.330	69.2	.3641-06	.2303+04	.1470+04	19.0	2500.5	2	16.3	16.3	30.0
20000.0	211243.0	15.448	69.7	.3487-06	.2242+04	.1470+04	19.6	2500.4	2	16.3	16.3	30.0
20500.0	212339.6	15.564	70.3	.3346-06	.2185+04	.1470+04	20.1	2500.3	2	16.3	16.3	30.0
21000.0	213367.2	15.728	70.9	.3217-06	.2131+04	.1470+04	20.6	2500.2	2	16.3	16.3	30.0
21500.0	214388.7	15.880	71.6	.3098-06	.2081+04	.1470+04	21.2	2500.2	2	16.3	16.3	30.0
22000.0	215347.0	16.049	72.3	.2987-06	.2035+04	.1470+04	21.7	2500.1	2	16.3	16.3	30.0
22500.0	216219.2	16.235	73.1	.2890-06	.1990+04	.1470+04	22.3	2500.1	2	16.3	16.3	30.0
23000.0	217054.1	16.437	74.0	.2799-06	.1949+04	.1470+04	22.8	2500.0	2	16.3	16.3	30.0
23500.0	217853.5	16.647	74.9	.2714-06	.1910+04	.1470+04	23.4	2500.0	2	16.3	16.3	30.0
24000.0	218617.3	16.863	75.9	.2635-06	.1873+04	.1470+04	23.9	2500.0	2	16.3	16.3	30.0
24500.0	219353.4	17.145	76.9	.2561-06	.1838+04	.1470+04	24.5	2499.9	2	16.3	16.3	30.0
25000.0	220057.4	17.436	77.9	.2492-06	.1806+04	.1470+04	25.0	2499.9	2	16.3	16.3	30.0
25500.0	220711.8	17.750	79.0	.2429-06	.1775+04	.1470+04	25.5	2499.9	2	16.3	16.3	30.0
26000.0	222108.6	17.927	77.7	.2360-06	.1753+04	.1470+04	26.1	2498.7	2	16.3	16.3	30.0

FIGURE 2. Example Printout of Thermal Boundary Data

TABLE II

THERMAL BOUNDARY DATA

Row 1 - 2

Input identification

NP	TPS panel or control point number
IOP	Option for atmospheric model
	= 0 1962 U.S. Standard atmosphere
	= 1 July atmosphere at 30 degrees north latitude
	= 2 Jan. atmosphere at 30 degrees north latitude
	= 3 July atmosphere at 60 degrees north latitude
	= 4 Jan. atmosphere at 60 degrees north latitude
IALP	Option for angle-of-attack
	= 0 ramped schedule
	= 1 constant schedule
TC	Critical temperature (°F)

Row 3 - 34

Output identification

REL VEL	Relative velocity (ft/sec)
ALTITUDE	Altitude (ft)
D/M	Drag acceleration (ft/sec^2)
QBAR	Dynamic Pressure (lbs/ft^2)
DENSITY	Density (slug/ft^3)
REY NO	Normal shock Reynolds number (ND)
MACH	Mach number (ND)
TEMP	Surface temperature (°F)

TABLE II (CONT'D)

THERMAL BOUNDARY DATA

Row 3 - 34 (cont'd)

Output identification

FLOW	Flow characteristic
	= 1 Laminar
	= 2 Transitional
	= 3 Turbulent
BDF	Body flap setting (DEG)
ELV	Elevon setting (DEG)
ALP	Angle-of-attack (DEG)

6.0 SUBROUTINE DOCUMENTATION

The following sections define TBAP subroutines. The subroutines ATMOS and AR140C are current SVDS (Reference 3) routines and hence are not documented in this note.

6.1 INTGI2

6.1.1 PURPOSE: INTGI2

Subroutine INTGI2 calls the BAP routine.

6.1.2 INPUT

NBAP Flag determining thermal boundary option

= 0 Does not call TBAP

= 1 Calls TBAP

6.1.3 OUTPUT

None applicable to BAP

6.1.4 ALGORITHM

None applicable to BAP

6.1.5 CALLING SEQUENCE

Call INTGI2

6.1.6 CONSTANT REQUIRED

None required

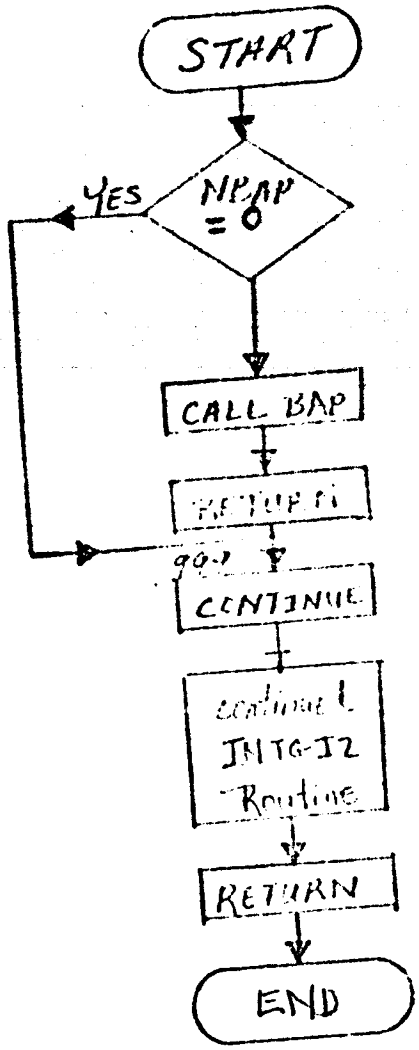
6.1.7 SUBROUTINE REQUIRED

BAP

Other routines not applicable to BAP

* NOTE: Only the portion of INTGI2 applicable to TBAP is documented in this design note.

6.1.8 FLOWCHART



The first executable statement is to determine whether to call BAP.

The remainder of subroutine INTGI2 is unchanged. (see Reference 3)

6.2 BAP

6.2.1 PURPOSE: BAP is the executive routine used to sequence other routines in calculating thermal boundaries.

6.2.2 INPUT:

NP	TPS panel or control point number
V	Initial velocity (ft/sec)
VM	Maximum velocity (ft/sec)
DV	Velocity increment (ft/sec)
IALP	Angle-of-attack option flag
	= 0 ramped schedule
	= 1 constant schedule
DT	Temperature convergence criterion (°F)
NC2M	Convergence interval specification

6.2.3 OUTPUT:

Input identification labels

QBAR	Dynamic Pressure (lbs/ft^2)
MACH	Mach number (ND)
H	Altitude (ft)
DOM	Drag acceleration (ft/sec^2)
V	Relative velocity (ft/sec)

Write ENDFILE on UNIT 8

6.2.4 ALGORITHM

See flowchart Sec. 6.2.8

6.2.5 CALLING SEQUENCE

Call BAP

6.2.6 CONSTANTS REQUIRED

H = 160000. Inital altitude

JCAL = 0 Flag in AR140C to eliminate Call AROCAL

6.2.7 SUBROUTINE REQUIRED

TABLE

ATMOS

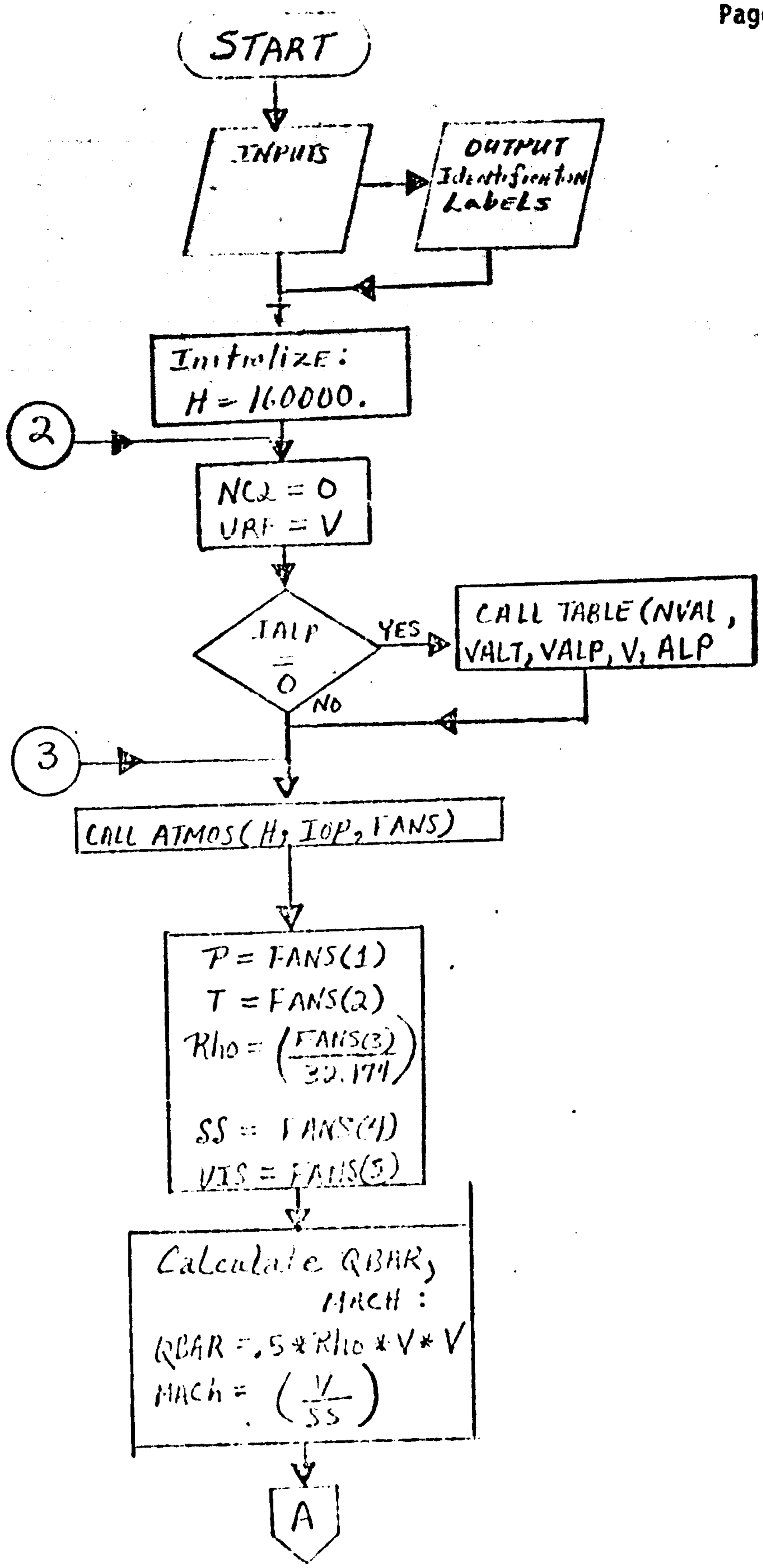
AR140C

HTRATE

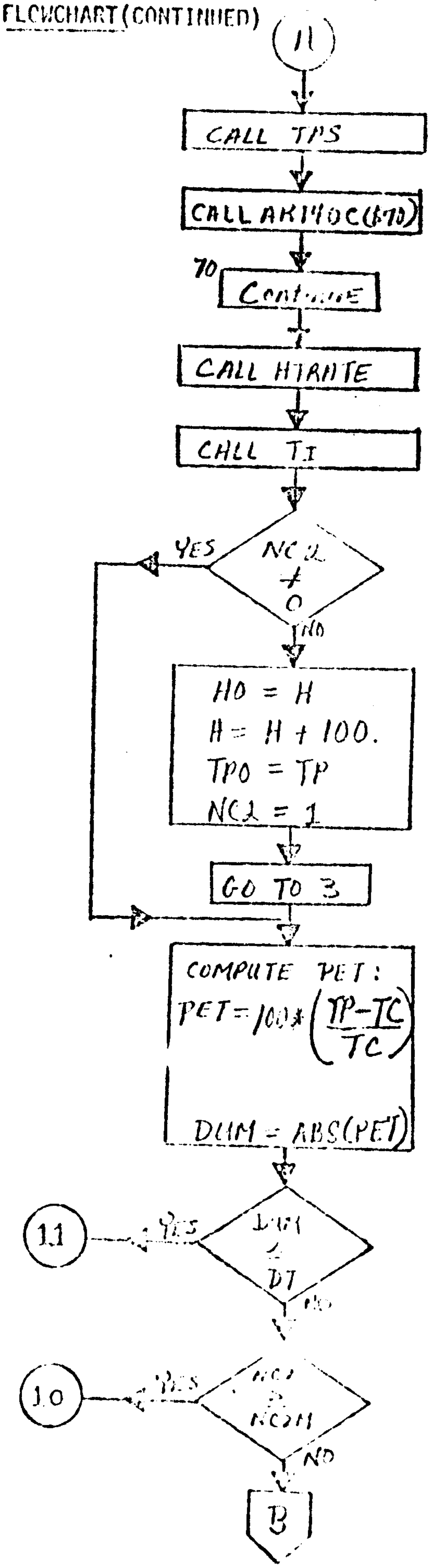
TPS

TI

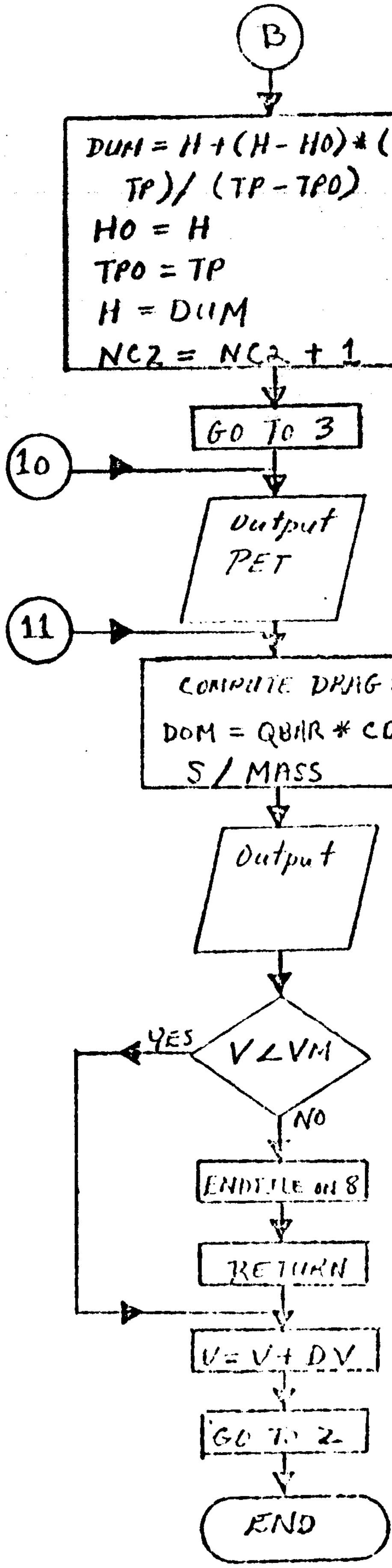
6.2.8 FLOWCHART



6.2.8 FLOWCHART(CONTINUED)



6.2.8 FLOWCHART (CONTINUED)



6.3 TPS

6.3.1 PURPOSE: TPS

Subroutine TPS calculates normal shock Reynolds number and the stagnation point convective heat rate for a one foot radius sphere.

6.3.2 INPUT:

IREN	Reynold's number computational option flag
KNTTPS	Number of integration step sizes since the last TPS Model Computational update
NPANEL	Number of TPS panels and control points
RHOSL	Density at sea level (slug/ft^3)
ANSW (3)	Ratio for density at altitude to density at sea level
IV	Vehicle number
MTPS	Thermal Protection Option = 0 TPS is not simulated = 1 Initialization pass of TPS = 2 Execute TPS logic (Initialization completed) = 3 Print TPS summary
NTPS	Number of SVDS integration cycles per TPS integration step
VT	Relative Velocity (ft/sec)
T400K	Time at altitude of 400000 feets
TEMP	Array of current atmosphere data
IBAP	Option for TBAP driver = 0 Do not use TBAP driver = 1 Use TBAP driver

6.3.3 OUTPUT:

QREF Stagnation point heat rate (BTU/ft^2-sec)

REN Reynolds number behind a normal shock

6.3.4 ALGORITHM

See flowchart Sec. 6.3.8

6.3.5 CALLING SEQUENCE

Call TPS

6.3.6 CONSTANTS REQUIRED

Relative velocity table corresponding to VISC array

```
 DATA VES/600.,1000.,1500.,2000.,2500.,3000.,3500.,4000.,4500.,
1     5000.,5500.,6000.,6500.,7000.,7500.,8000.,8500.,9000.,9500.,
2     10000.,10500.,11000.,11500.,12000.,12500.,13000.,13500.,14000.
3    ,14500.,15000.,15500.,16000.,16500.,17000.,17500.,18000.,
4     20000.,22000.,25000.,25500.,25800.,26000.,26080.,26100.,
5     30000./
```

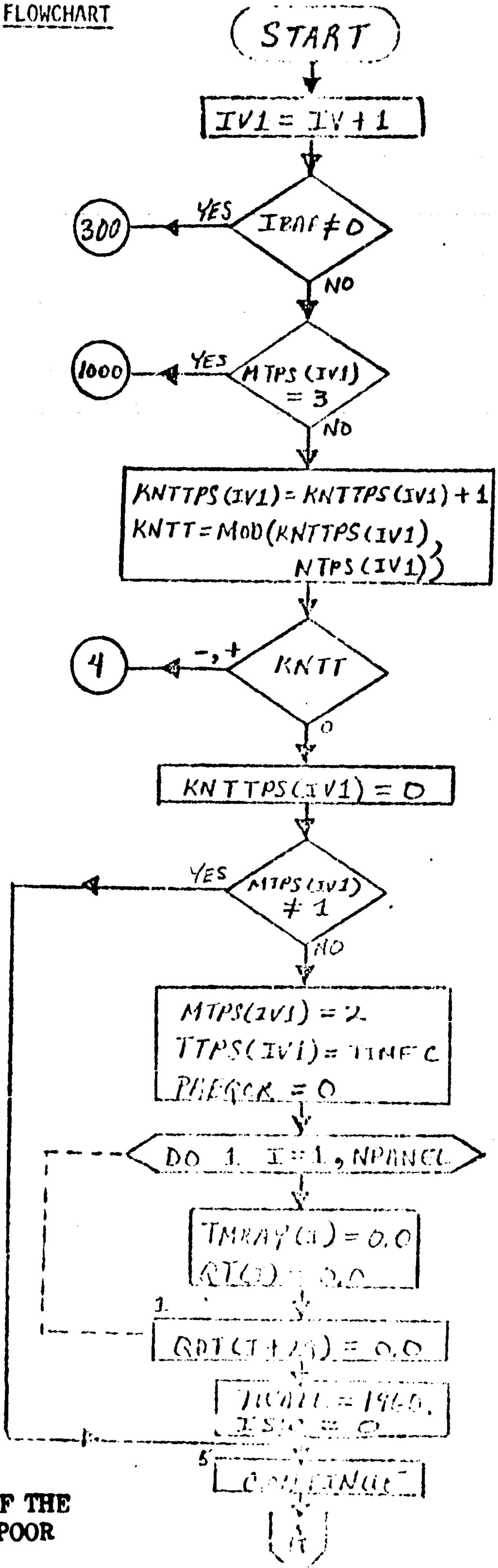
Coefficient of viscosity VS relative velocity

```
 DATA VISC/.310E-6,.351E-6,.394E-6,.460E-6,.541E-6,.646E-6,.745E-6.
1     .850E-6,.951E-6,.1065E-5,.117E-5,.128E-5,.138E-5,.147E-5,
2     .1565E-5,.1655E-5,.1735E-5,.181E-5,.1865E-5,.192E-5,.1965E-5,
3     .2E-5,.203E-5,.210E-5,.217E-5,.2275E-5,.240E-5,.251E-5,
4     .261E-5,.268E-5,.275E-5,.282E-5,.289E-5,.2925E-5,.297E-5,
5     .3E-5,.311E-5,.323E-5,.345E-5,.349E-5,.348E-5,.341E-5,.337E-5.
6     .286E-5,.286E-5/
```

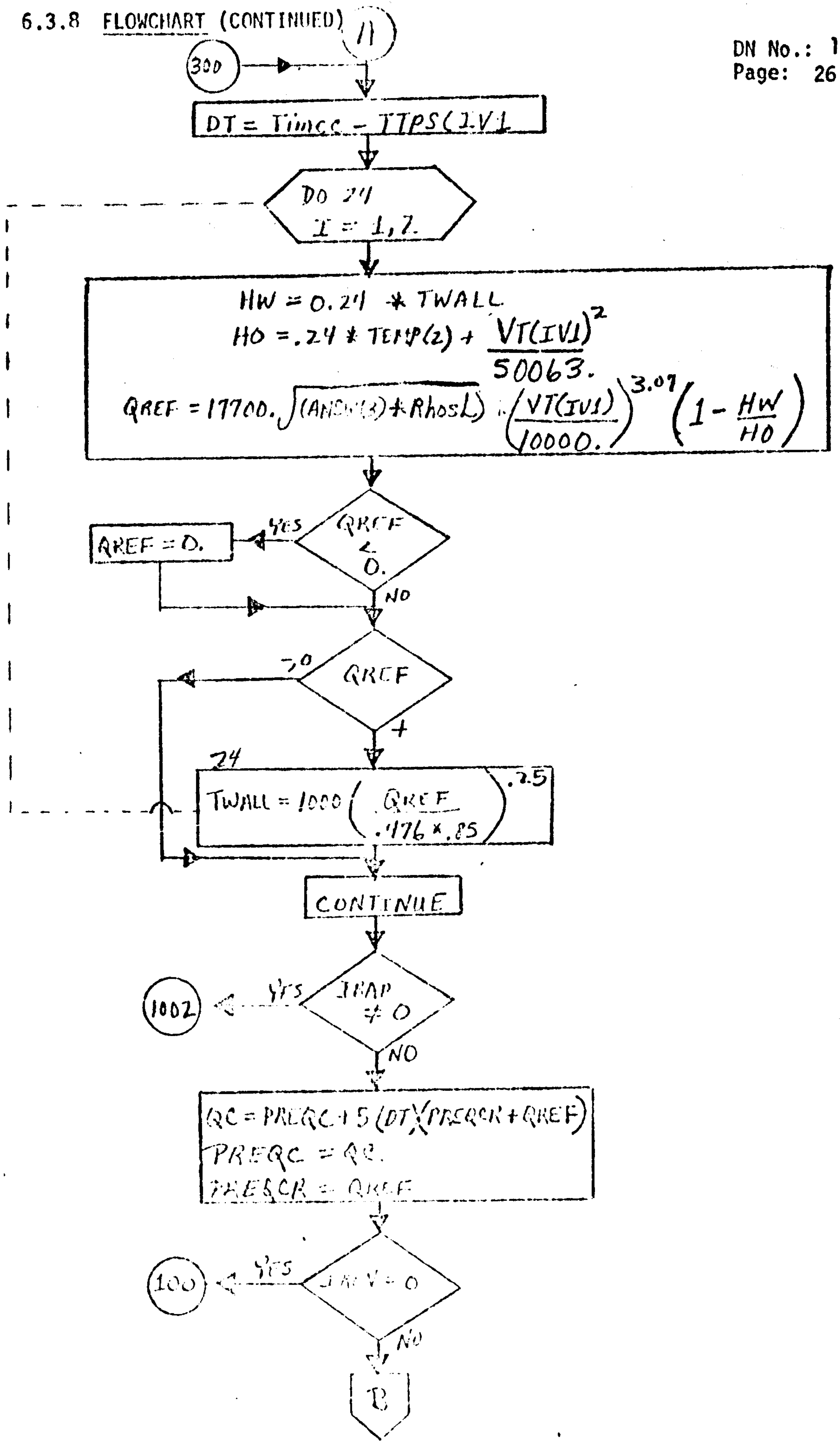
6.3.7 SUBROUTINE REQUIRED

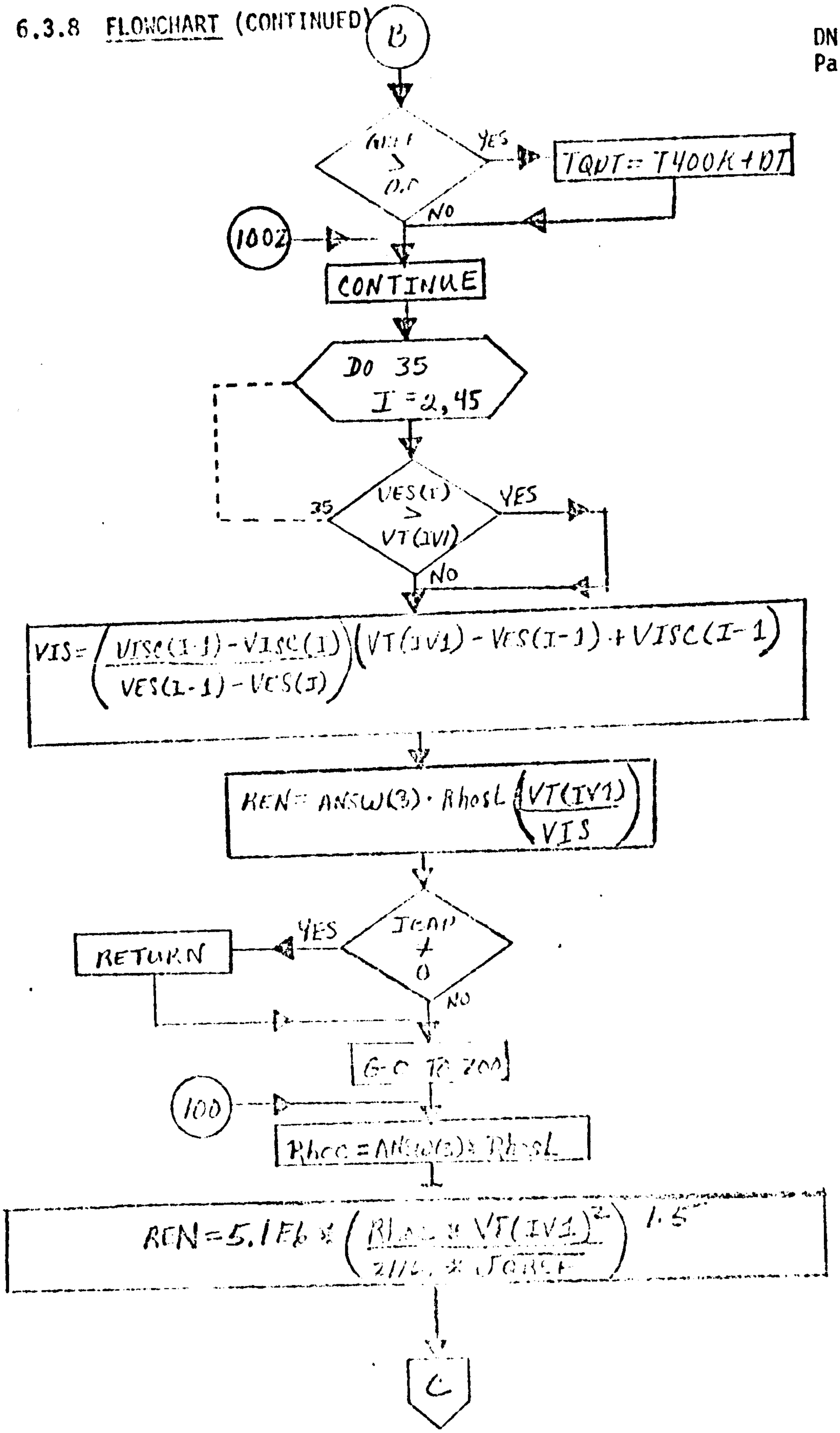
None

6.3.8 FLOWCHART

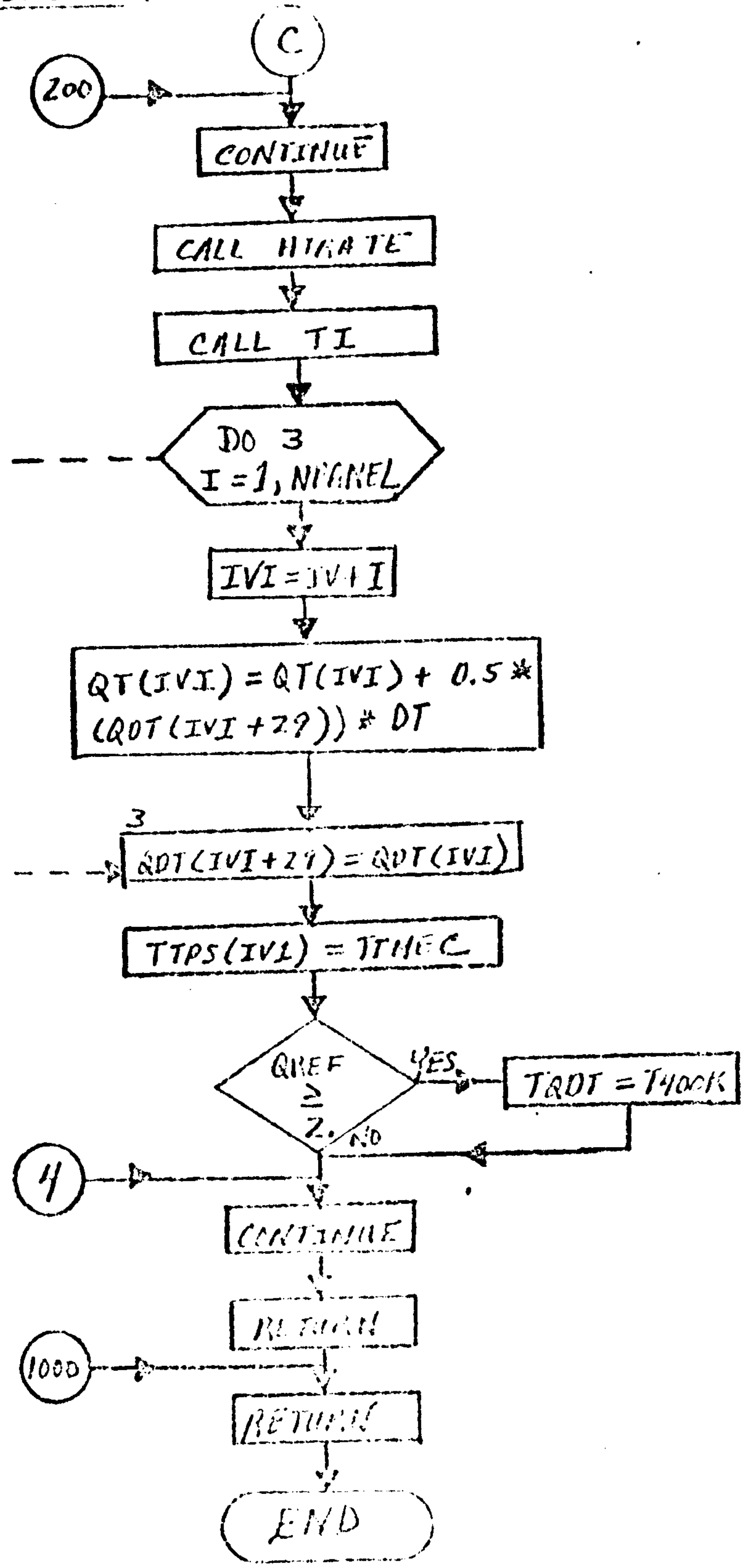


6.3.8 FLOWCHART (CONTINUED)




B
YES
TQUT = T400K + DT
NO
1002
CONTINUE
DO 35
I = 2, 45
35
VES(I)
>
VT(IV1)
YES
NO
VIS = (VISC(I-1) - VISC(I)) / (VES(I-1) - VES(I)) (VT(IV1) - VES(I-1)) + VISC(I-1)
REN = ANSW(3) · RhosL (VT(IV1) / VIS)
YES
RETURN
NO
0
100
C

6.3.8 FLOWCHART (CONTINUED)



6.4 HTRATE

6.4.1 PURPOSE: HTRATE

Subroutine HTRATE determines the flow characteristic (laminar, transitional, or turbulence) for a given panel and computes the corresponding heat rate.

6.4.2 INPUT:

ALPHA	Angle-of-attack (RAD)
NPANEL	Numberof TPS panels and control points
QDOTC	Stagnation convective heat rate (BTU/ft²-sec)
IV	Vehicle number
REY	Reynolds number behind a normal shock
DELVTR	Angle of deflection (body flap and elevon) (RAD)
IBAP	Option for TBAP driver = 0 Do not use TBAP driver = 1 Use TBAP driver
NP	TPS panel or control point number

6.4.3 OUTPUT:

QDT	Heat rate (BTU/ft²-sec)
IFS	Flow characteristic = 1 (laminar flow) = 2 (transitional flow) = 3 (turbulence flow)
RENS	Reynolds number at transition onset

6.4.4 ALGORITHM

See flowchart Sec. 6.4.9

6.4.5 CALLING SEQUENCE

Call HTRATE

6.4 HTRATE

6.4.1 PURPOSE: HTRATE

Subroutine HTRATE determines the flow characteristic (laminar, transitional, or turbulence) for a given panel and computes the corresponding heat rate.

6.4.2 INPUT:

ALPHA	Angle-of-attack (RAD)
NPANEL	Number of TPS panels and control points
QDOTC	Stagnation convective heat rate (BTU/ft^2-sec)
IV	Vehicle number
REY	Reynolds number behind a normal shock
DELVTR	Angle of deflection (body flap and elevon) (RAD)
IBAP	Option for TBAP driver = 0 Do not use TBAP driver = 1 Use TBAP driver
NP	TPS panel or control point number

6.4.3 OUTPUT:

QDT	Heat rate (BTU/ft^2-sec)
IFS	Flow characteristic = 1 (laminar flow) = 2 (transitional flow) = 3 (turbulence flow)
RENS	Reynolds number at transition onset

6.4.4 ALGORITHM

See flowchart Sec. 6.4.9

6.4.5 CALLING SEQUENCE

Call HTRATE

6.4.6 CONSTANTS REQUIRED

LAMINAR QDOTL/QDOT STAG VS ALPHA AND PANEL NUMBER

```
      DATA (C(1,K),K=1,13) /.5510,.5170,.4850,.4540,.4400,.4310,.4390,
     *                      .4400,.4390,.4370,.4340,.4330,.4310/
      DATA (C(2,K),K=1,13) /.1540,.1620,.1740,.1980,.2160,.2300,.2300,
     *                      .2300,.2300,.2300,.2380,.2550,.3050/
      DATA (C(3,K),K=1,13) /.0240,.0570,.0899,.1220,.1370,.1530,.1670,
     *                      .1810,.1920,.1940,.1900,.1800,.1380/
      DATA (C(4,K),K=1,13) /.0200,.0340,.0550,.0839,.1000,.1170,.1350,
     *                      .1510,.1660,.1810,.1940,.2050,.2230/
      DATA (C(5,K),K=1,13) /.0290,.0320,.0420,.0620,.0759,.0880,.1000,
     *                      .1100,.1210,.1320,.1430,.1540,.1750/
      DATA (C(6,K),K=1,13) /.0290,.0300,.0340,.0430,.0530,.0630,.0699,
     *                      .0780,.0870,.0960,.1040,.1140,.1310/
      DATA (C(7,K),K=1,13) /.4020,.3610,.3210,.2840,.2670,.2530,.2400,
     *                      .2300,.2230,.2200,.2200,.2200,.2200/
      DATA (C(8,K),K=1,13) /.2435,.2462,.2490,.2518,.2535,.2550,.2565,
     *                      .2582,.2599,.2617,.2637,.2660,.2713/
      DATA (C(9,K),K=1,13) /.0970,.0989,.1080,.1260,.1430,.1750,.2140,
     *                      .2280,.2260,.2120,.1960,.1870,.1610/
      DATA (C(10,K),K=1,13)/.0170,.0460,.0690,.0849,.0899,.0950,.1030,
     *                      .1100,.1170,.1220,.1260,.1310,.1350/
      DATA(C(11,K),K=1,13)/0.0271,.04,.0529,.06571,.07143,.07714,.0836[illegible],
     *.08929,.09429,.09857,.1036,.1079,.11357/

      DATA(C(12,K),K=1,13)/.0129,.02143,.03429,.04143,.04779,.055,.058[illegible]
     *,.06143,.06421,.06707,.06929,.07143,.075/
      DATA (C(13,K),K=1,13)/13*0.058/
      DATA (C(14,K),K=1,13)/.0400,.0400,.0400,.0400,.0400,.0400,.0400,
     *                      .0400,.0400,.0400,.0400,.0400,.0400/
      DATA (C(15,K),K=1,13)/.0042,.0042,.0042,.0042,.0042,.0042,.0042,
     *                      .0042,.0042,.0042,.0042,.0042,.0042/
      DATA (C(16,K),K=1,13)/.0104,.0093,.0082,.0069,.0064,.0057,.0036,
     *                      .0015,.0015,.0015,.0015,.0015,.0015/
      DATA (C(17,K),K=1,13)/.1020,.0820,.0620,.0420,.0320,.0220,.0135,
     *                      .0075,.0051,.0051,.0051,.0051,.0051/
      DATA (C(18,K),K=1,13)/.0873,.0644,.0438,.0259,.0186,.0128,.0086,
     *                      .0065,.0059,.0050,.0050,.0050,.0050/
      DATA(C(19,K),K=1,13)/.00401,.00635,.008696,.01107,.01231,.01338,
     *.014415,.01542,.01639,.01739,.018227,.019064,.02003/
      DATA (C(20,K),K=1,13)/.0340,.0340,.0340,.0340,.0340,.0340,.0340,
     *                      .0340,.0340,.0340,.0340,.0340,.0340/
      DATA (C(21,K),K=1,13)/.0120,.0120,.0120,.0120,.0120,.0120,.0120,
     *                      .0120,.0120,.0120,.0120,.0120,.0120/
      DATA (C(22,K),K=1,13)/.0150,.0150,.0150,.0150,.0150,.0150,.0150,
     *                      .0150,.0150,.0150,.0150,.0150,.0150/
      DATA (C(23,K),K=1,13)/.0082,.0082,.0082,.0082,.0082,.0082,.0082,
     *                      .0082,.0082,.0082,.0082,.0082,.0082/
      DATA (C(24,K),K=1,13)/.0086,.0088,.0088,.0088,.0086,.0086,.0086,
     *                      .0086,.0086,.0086,.0086,.0086,.0086/
      DATA (C(25,K),K=1,13)/.0330,.0770,.1000,.1250,.1360,.1450,.1560,
     *                      .1650,.1740,.1810,.1860,.1910,.1950/
      DATA (C(26,K),K=1,13)/.4590,.4770,.4920,.5030,.5070,.5100,.5100,
     *                      .5060,.4970,.4870,.4770,.4770,.4670/
      DATA (C(27,K),K=1,13)/0.007,.018,.026,.033,.036,.04,.043,
     *                      .0[illegible],.0[illegible],.0511,.0540,.0570,.0620/
      DATA (C(28,K),K=1,13)/.[illegible],.[illegible],.[illegible],.8000,.[illegible],.[illegible],.[illegible],
     *                      .[illegible],.[illegible],.[illegible],.3[illegible],.3[illegible],.2[illegible]/
      DATA (C(29,K),K=1,13) /.047,.[illegible],.111,.1[illegible],.1[illegible],.1[illegible],.1[illegible],
     *                      .17[illegible],.[illegible],.171,.1[illegible],.[illegible],.213/
```

PRODUCIBILITY OF THE
[illegible]IGINAL PAGE IS POOR

Alpha table corresponding to LAMINAR QDOTL/QDOT STAG

```
DATA ALP/10.,15.,20.,25.,27.5,30.,32.5,35.,37.5,40.,42.5,45.,50./
```

Reynolds number at transition onset VS Alpha and Panel number

```
DATA (RTRANS(1,L),L=1,14)/233000.,183000.,137000.,116000.,96000.,
*     77000.,60000.,46000.,34000.,26000.,22000.,22000.,22000.,
*     22000./
DATA (RTRANS(2,L),L=1,14)/140000.,108000.,81000.,69000.,60000.,
*     51000.,45000.,39000.,34000.,29000.,26000.,23000.,20000.,
*     15000./
DATA (RTRANS(3,L),L=1,14)/86500.,65300.,48200.,40800.,34400.,
*     29800.,25800.,22500.,19900.,17900.,16200.,15000.,14100.,
*     12900./
DATA (RTRANS(4,L),L=1,14)/15600.,16000.,17000.,18000.,20300.,
*     24500.,26400.,26100.,24400.,22800.,21400.,20300.,19500.,
*     18600./
DATA (RTRANS(5,L),L=1,14)/10000.,10100.,10600.,11100.,12100.,
*     13500.,14200.,14100.,13700.,13100.,12700.,12400.,12300.,
*     12300./
DATA (RTRANS(6,L),L=1,14)/12100.,11100.,10400.,10000.,9800.,
*     9600.,9500.,9400.,9400.,9300.,9300.,9200.,9200.,9200./
DATA (RTRANS(7,L),L=1,14)/38700.,31000.,24500.,21600.,19400.,
*     17500.,16000.,14600.,13300.,12300.,11200.,10200.,9300.,7500./
DATA (RTRANS(8,L),L=1,14)/25000.,19600.,15000.,13500.,12500.,
*     11800.,11300.,10600.,9800.,8800.,7800.,6700.,5500.,3100./
DATA (RTRANS(9,L),L=1,14)/20100.,15000.,10600.,9300.,9000.,9300.,
*     9700.,10500.,10500.,9600.,6900.,4500.,3400.,2700./
DATA (RTRANS(10,L),L=1,14)/9200.,8500.,7600.,7100.,6460.,5750.,
*     5090.,4210.,3540.,3020.,2670.,2430.,2380.,2380./
DATA (RTRANS(11,L),L=1,14)/8100.,6700.,5380.,4740.,4150.,3600.,
*     3100.,2650.,2280.,1990.,1730.,1580.,1500.,1480./
DATA (RTRANS(12,L),L=1,14)/15400.,12200.,9400.,8200.,7200.,6700.,
*     6500.,6000.,5000.,3800.,3200.,2700.,2200.,1000./
DATA(RTRANS(13,L),L=1,14)/14*14400./
DATA (RTRANS(14,L),L=1,14)/14*42000./
DATA (RTRANS(15,L),L=1,14)/14*28400./
DATA (RTRANS(16,L),L=1,14)/14*37000./
DATA(RTRANS(17,L),L=1,14)/14*54000./
DATA(RTRANS(18,L),L=1,14)/14*50000./
DATA (RTRANS(19,L),L=1,14)/3970.,3300.,2650.,2340.,2040.,1750.,
*     1500.,1260.,1090.,950.,850.,780.,720.,660./
DATA (RTRANS(20,L),L=1,14)/14*11900./
DATA (RTRANS(21,L),L=1,14)/14*5000./
DATA (RTRANS(22,L),L=1,14)/14*135000./
DATA (RTRANS(23,L),L=1,14)/14*67000./
DATA (RTRANS(24,L),L=1,14)/14*77000./
DATA (RTRANS(25,L),L=1,14)/6450.,4870.,3500.,2920.,2480.,2100.,
*     1820.,1550.,1360.,1200.,1100.,1000.,920.,880./
DATA (RTRANS(26,L),L=1,14)/14*92000./
DATA (RTRANS(27,L),L=1,14)/4200.,3400.,2660.,2340.,2020.,1730.,
*     1470.,1250.,1070.,910.,810.,740.,710.,700./
DATA (RTRANS(28,L),L=1,14)/14*100000./
DATA (RTRANS(29,L),L=1,14)/8600.,6870.,5300.,4630.,4100.,3650.,
*     3250.,2970.,2700.,2500.,2320.,2190.,2080.,1900./
```

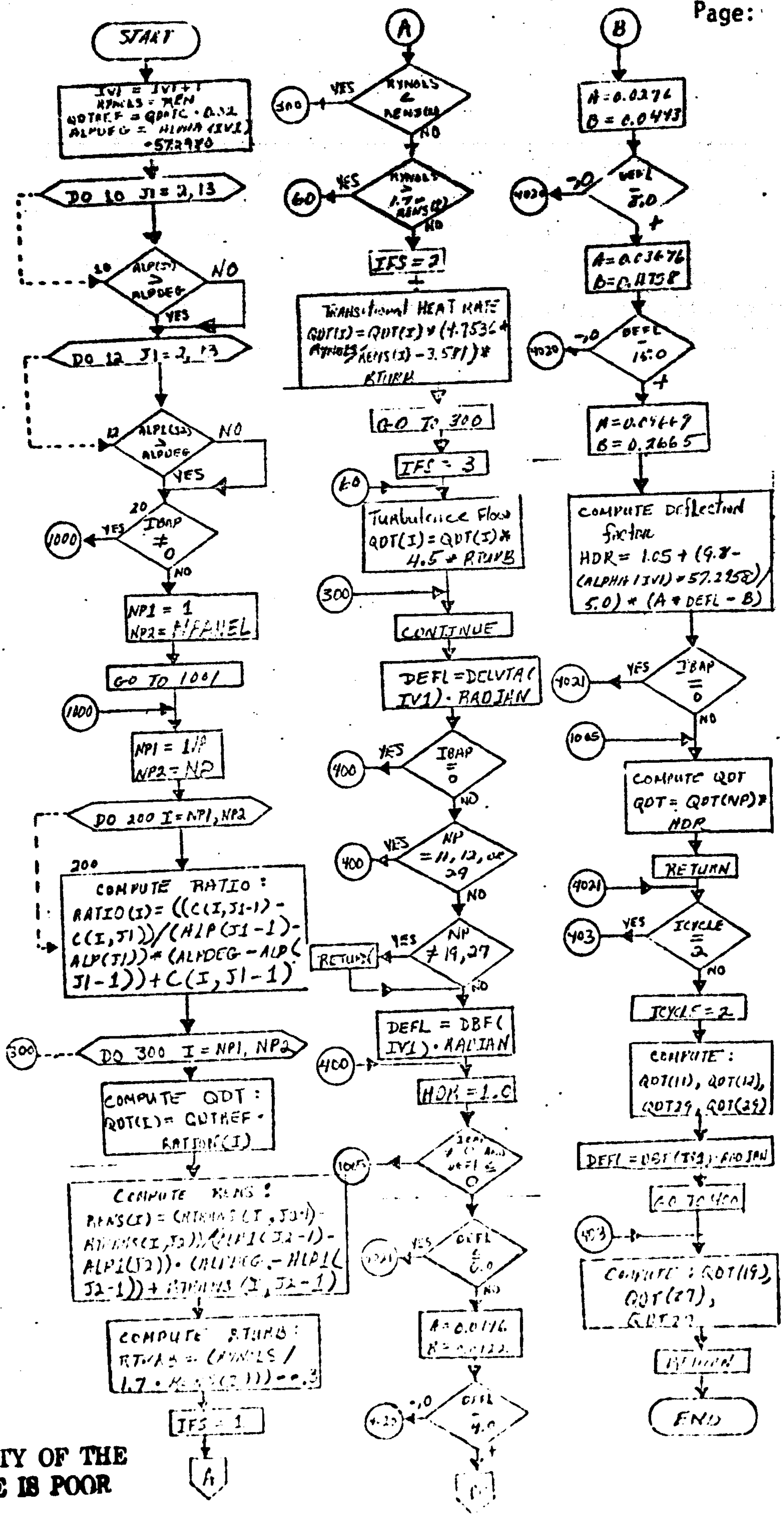
Alpha table corresponding to Reynolds number at transition onset.

```
DATA ALP1/10.,15.,20.,22.5,25.,27.5,30.,32.5,35.,37.5,40.,42.5,
```

6.4.7 SUBROUTINE REQUIRED

None

6.4.8 FLOWCHART



6.5 TI

6.5.1 PURPOSE: TI

Subroutine TI computes the surface temperature as a function of heat rate.

6.5.2 INPUT:

QDT	Heat rate (BTU/ft^2-sec)
NPANEL	Array of TPS panels and control points
NP	TPS panel or control point number
IV	Vehicle number

6.5.3 OUTPUT:

Common

TARY	Array of panel surface temperatures (°F)

6.5.4 ALGORITHM

See flowchart Sec. 6.5.8

6.5.5 CALLING SEQUENCE

None

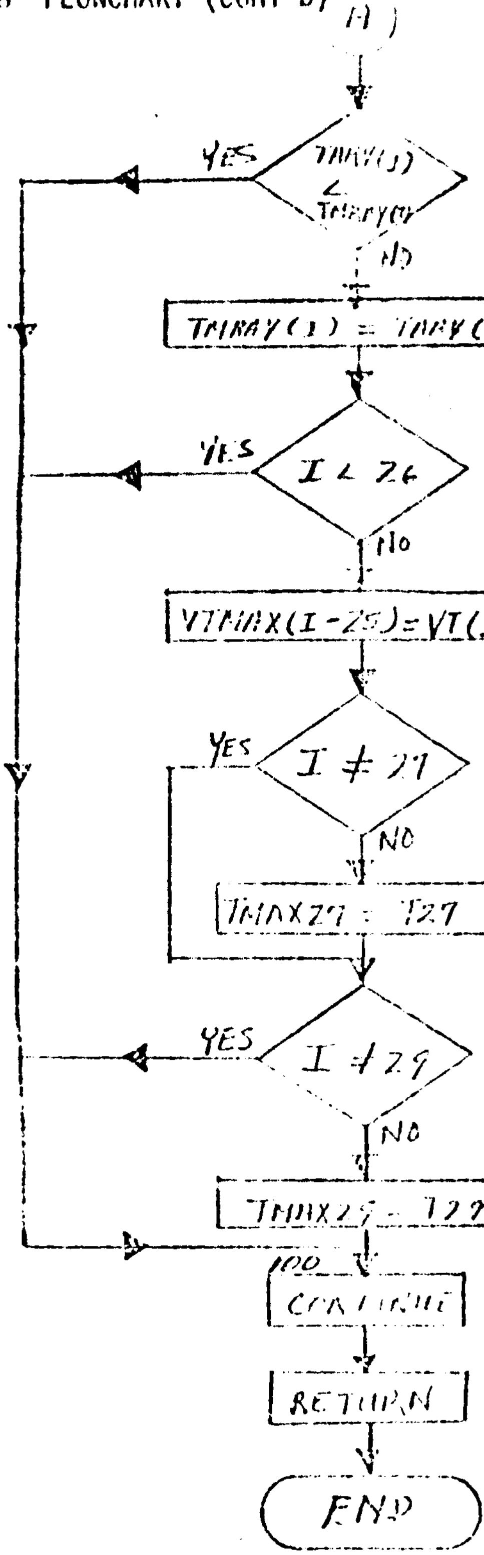
6.5.6 CONSTANTS REQUIRED

C = .24710577 E + 13

6.5.7 SUBROUTINE REQUIRED

None

6.5.8 FLOWCHART (CONT'D)



6.0 TABLE

6.6.1 PURPOSE: TABLE

Subroutine TABLE is a linear interpolation routine.

6.6.2 INPUT

NVAL	Number of values
X(I), I = 1, NVAL	Independent variable array
Y(I), I = 1, NVAL	Dependent variable array
X1	Independent variable

6.6.3 OUTPUT

Y1	Dependent variable

6.6.4 ALGORITHM

See flowchart Sec. 6.6.8

6.6.5 CALLING SEQUENCE

Call TABLE (NVAL, X, Y, X1, Y1)

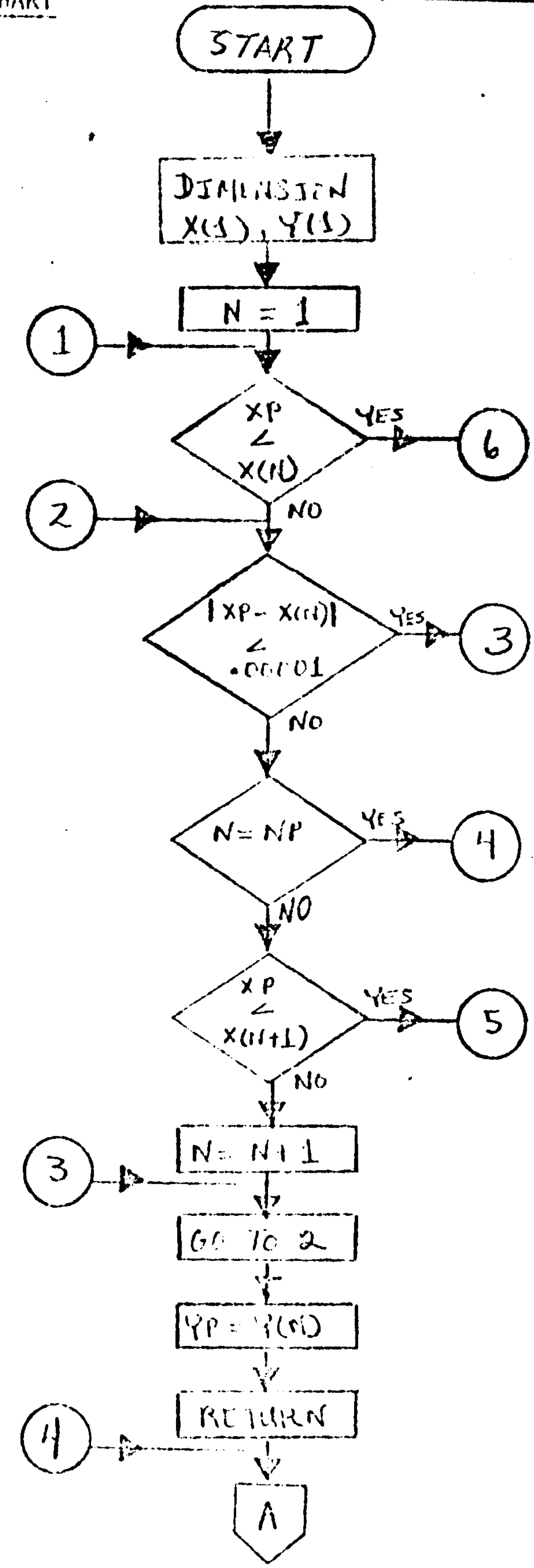
6.6.6 CONSTANTS REQUIRED

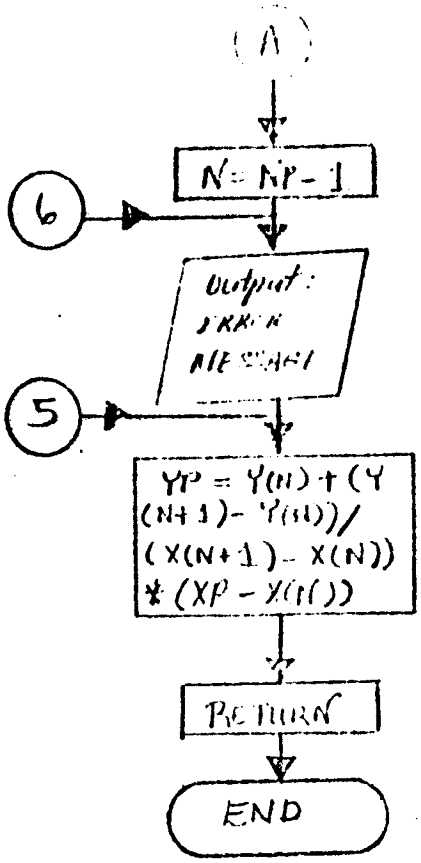
N = 1

6.6.7 SUBROUTINE REQUIRED

None

6.6.8 FLOWCHART




A
N = NP - 1
6
Output:
ERROR
MESSAGE
5
YP = Y(N) + (Y(N+1) - Y(N))/(X(N+1) - X(N)) * (XP - X(N))
RETURN
END

7.0 REFERENCES

1. James W. Tolin, Jr., "Shuttle Orbiter Thermal Protection System Simplified Math Model for the 089B Vehicle."

2. G. W. Mauss, "RI/Houston Simplified Weight Syntheses Program Content," Rockwell International Internal Letter SEH-ITA-74-156, November 4, 1974.

3. Software Development Branch, "Space Vehicle Dynamic Simulation (SVDS) Program Description," Johnson Space Center Internal Note No. 73-FM-85, May 23, 1973.

4. J. K. Isherwood, "Generalized Plot Program, TRWPLT User's Manual," TRW Document 11176-H594-R0-00, August, 1970.

APPENDIX A

PROGRAM GIP

1.0 GENERATE INPUT PROGRAM (GIP)

GIP is an auxiliary program which accepts a tape of thermal boundaries data from TBAP and plots the thermal boundaries using the TRWPLT (Reference 4) routine. The GIP was written to facilitate the method of inputting data into the TRWPLT routine. An example of the printed output from GIP is given in Figure 1. Examples of thermal boundaries which were plotted using GIP and TRWPLT are presented in Figures 2, 3, and 4.

1.1 PURPOSE:

GIP accepts a data tape from TBAP, processes the data, and outputs calcomp or microfilm plots.

1.2 INPUT:

ICCOMP — Type plot indicator

= 0 Calcomp
= 1 Microfilm

KUNIT — Data tape input unit

NTRAN — Tape type selector

= 0 Input data tape was generated using FORTRAN write statements.
= 1 Input data tape was generated using NTRANS write statements.

NCHAR — Plot symbol selector

CMULT — Multiplicative factor

XLABEL — Independent axis identification

YLABEL — Dependent axis identification

1.2 INPUT: (continued)

TITLE	Graph title
IPNF	Total number of files on data tape for a given plot
JANF	Actual file number
NVAR2	Dependent variable
	= 2 Altitude (ft/sec)
	= 3 Drag acceleration (ft/sec^2)
	= 4 Dynamic pressure (lbs/ft^2)
L	Number of cards to specify scale parameters
M	Number of cards to specify axis identification

1.3 OUTPUT:

ICCOMP	Calcomp/microfilm indicator
KUNIT	Data tape input unit
NTRAN	Tape type selector
NCHAR	Plot symbol selector
CMULT	Multiplicative factor
XLABEL	Independent axis identification
YLABEL	Dependent axis identification
TITLE	Plot title
IPRINT	Print indicator
	= -1 Print plot titles only
	= 0 Suppress print
	= 1 Print plot titles and data points
	= n Print titles and first n data points ($n \neq 1$)
NOIREC	Data tape format indicator
	= 0 Tape contains more than one type of record.
	= 1 Tape contains only one type of record.

1.3 OUTPUT: (continued)

LINGER — End-of-file frame advance indicator

= 0 Frame or graph will be advanced normally.
= 1 The variables specified by the first PLOT card following the ENDFIL card will be plotted on the current plot.

SKIP — Number of end-of-file marks to forward positioned over

NOADV — Frame advance indicator

= 0 Frame or graph will be advanced normally.
= 1 The variable in the PLOT list will be plotted on the same graph as the previous plots.

PLOT — Specifies variable to be plotted

ENDLST — Plot list termination symbol

ENDPLT — Plot input termination symbol

ENDRUN — Job termination symbol

REWIND — Rewind the input data tape

1.4 CALLING SEQUENCE

Not applicable

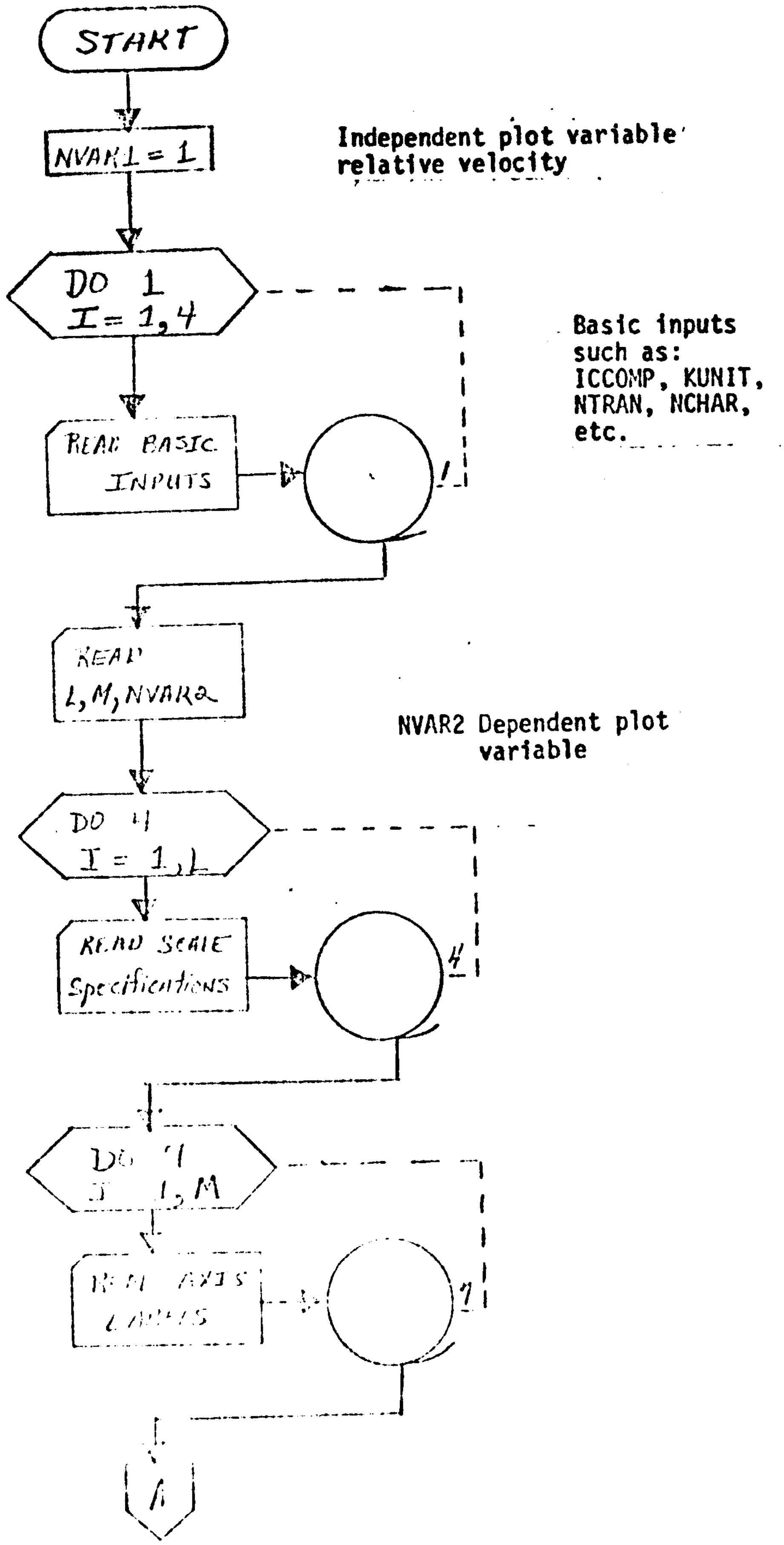
1.5 CONSTANTS REQUIRED

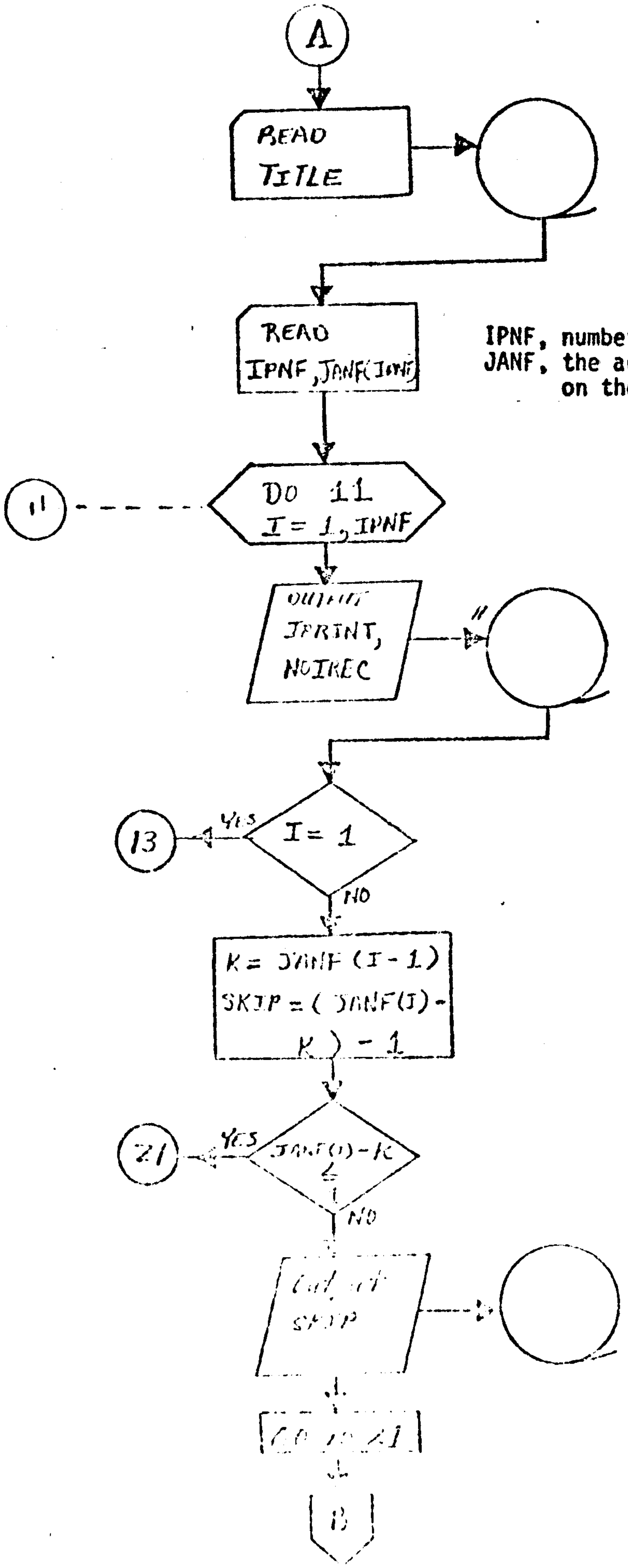
NVAR1 = 1

1.6 SUBROUTINE REQUIRED

None

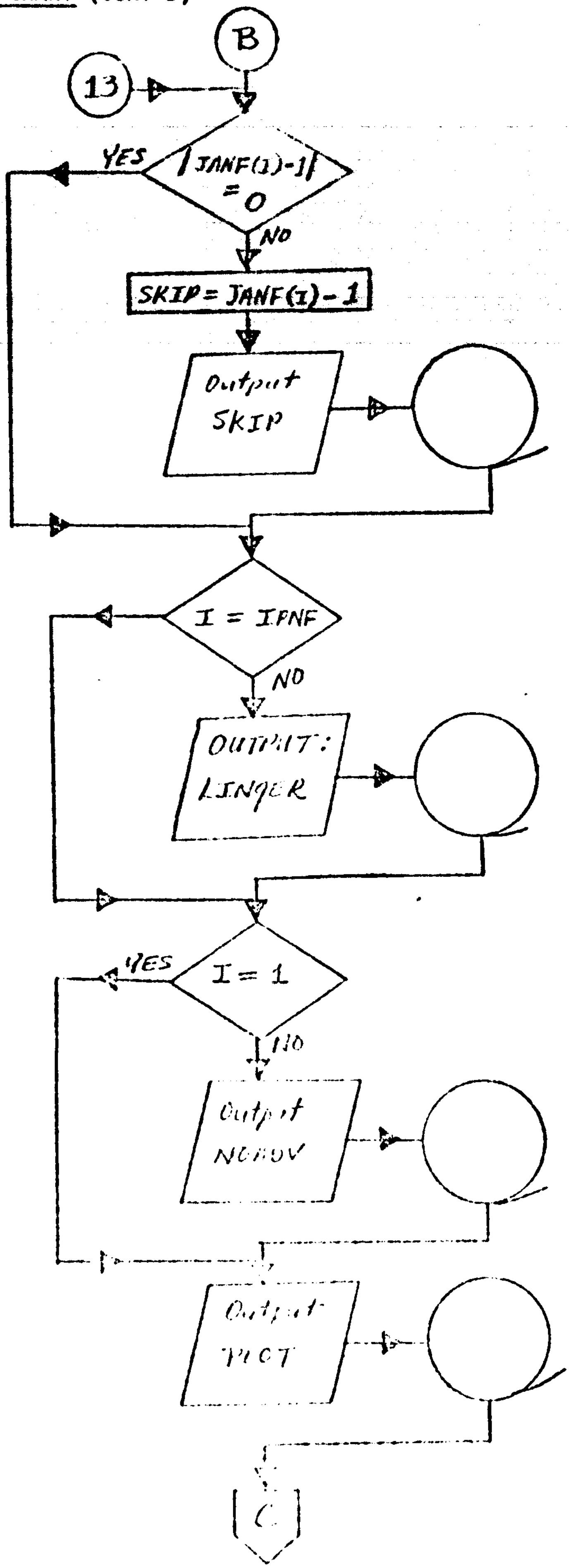
1.7 FLOWCHART



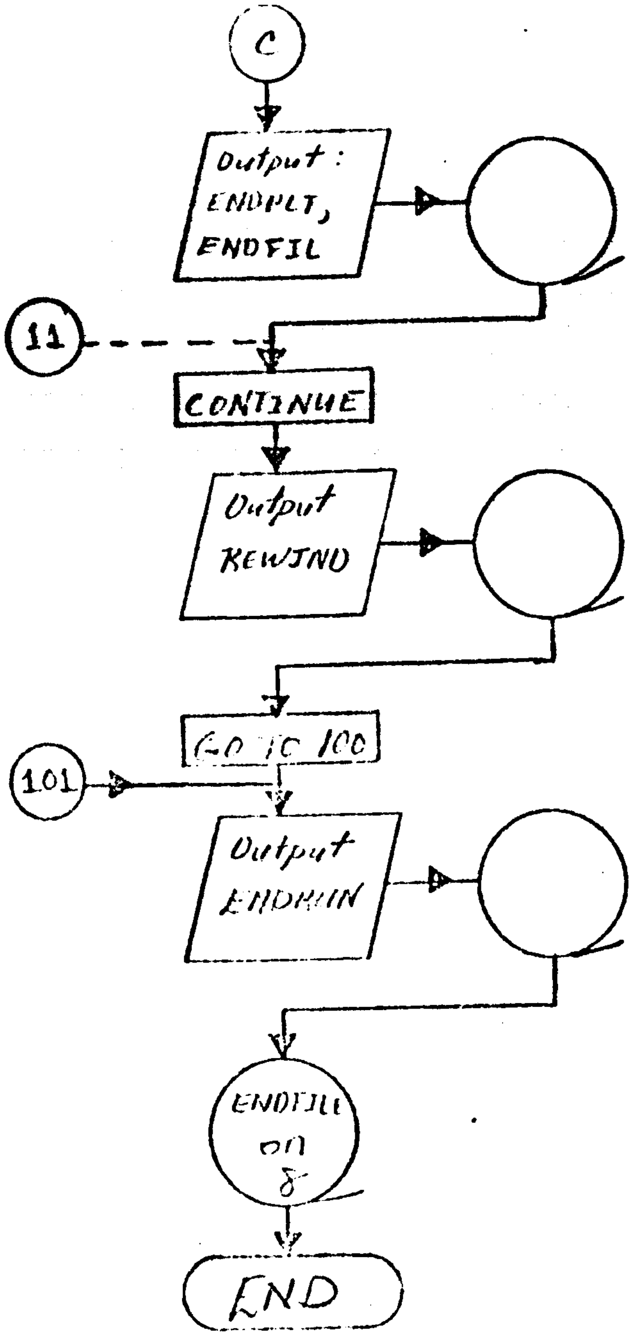


IPNF, number of files for plot
JANF, the actual file number
on the data tape

1.7 FLOWCHART (CONT'D)



1.7 FLOWCHART (CONT'D)



```
[illegible]=1 *
[illegible]=8 *
[illegible]=2 *
[illegible]=5,5,5,5,5,5,5*
[illegible] *
[illegible]=RELATIVE VELOCITY, F/S
[illegible]=ALTITUDE,FT.
TITLE = ID = FIGURE  . CONTROL POINT 2 THERMAL BOUNDARIES H/V PLANE.
IPRINT = 1*
[illegible] = 1*
[illegible] = 1*
 PLOT= 1, 2,ENDLST     *
[illegible] *
[illegible] *
[illegible] = 1*
[illegible] = 1*
[illegible] = 1*
[illegible] = 1 *
 PLOT= 1, 2,ENDLST     *
[illegible] *
[illegible] *
[illegible] = 1*
[illegible] = 1*
[illegible] = 1 *
 PLOT= 1, 2,ENDLST     *
[illegible] *
[illegible] *
[illegible] *
[illegible] *
[illegible] DYNAMIC PRESSURE, LBS. PER FT. SQUARED
TITLE = ID = FIGURE  . CONTROL POINT 2 THERMAL BOUNDARIES QBAR/V PLANE.
[illegible] = 1*
[illegible] = 1*
[illegible] = 1*
 PLOT= 1, [illegible],ENDLST     *
[illegible] *
[illegible] *
[illegible] = 1*
[illegible] = 1*
[illegible] = 1*
[illegible] = 1 *
 PLOT= 1, [illegible],ENDLST     *
[illegible] *
[illegible] *
[illegible] = 1*
[illegible] = 1*
[illegible] = 1 *
 PLOT= 1, [illegible],ENDLST     *
[illegible] *
[illegible] *
[illegible] *
[illegible] *
[illegible] DRAG ACCELERATION, FT. PER SEC. SQUARED
TITLE = ID = FIGURE  . CONTROL POINT 2 THERMAL BOUNDARIES D/V PLANE.
[illegible] = 1*
[illegible] = 1*
[illegible] = 1*
 PLOT= 1, 3,ENDLST     *
[illegible] *
[illegible] *
[illegible] = 1*
[illegible] = 1*
[illegible] = 1*
[illegible] = 1 *
 PLOT= 1, 3,ENDLST     *
[illegible] *
[illegible] *
[illegible] = 1*
[illegible] = 1*
[illegible] = 1 *
 PLOT= 1, 3,ENDLST     *
[illegible] *
[illegible] *
[illegible] *
```

FIGURE 1. Example of GIP Printer Output

FIGURE 6.2. CONTROL POINT 2 THERMAL BOUNDARIES H/V PLANE .

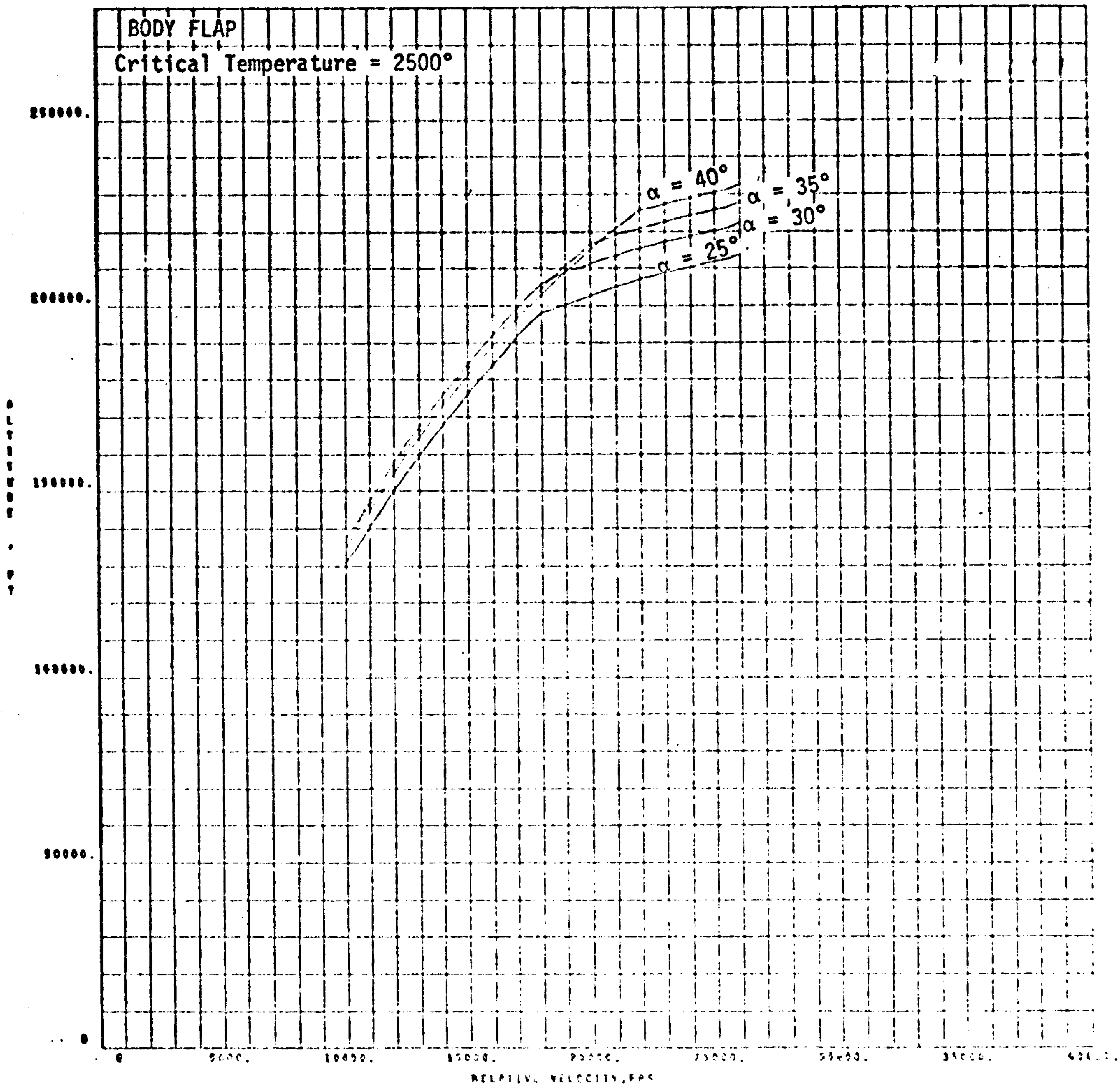


Figure 2. Example of Thermal Data Plot in H/V Plane.

FIGURE 73. CONTROL POINT 2 THERMAL BOUNDARIES D/V PLANE.

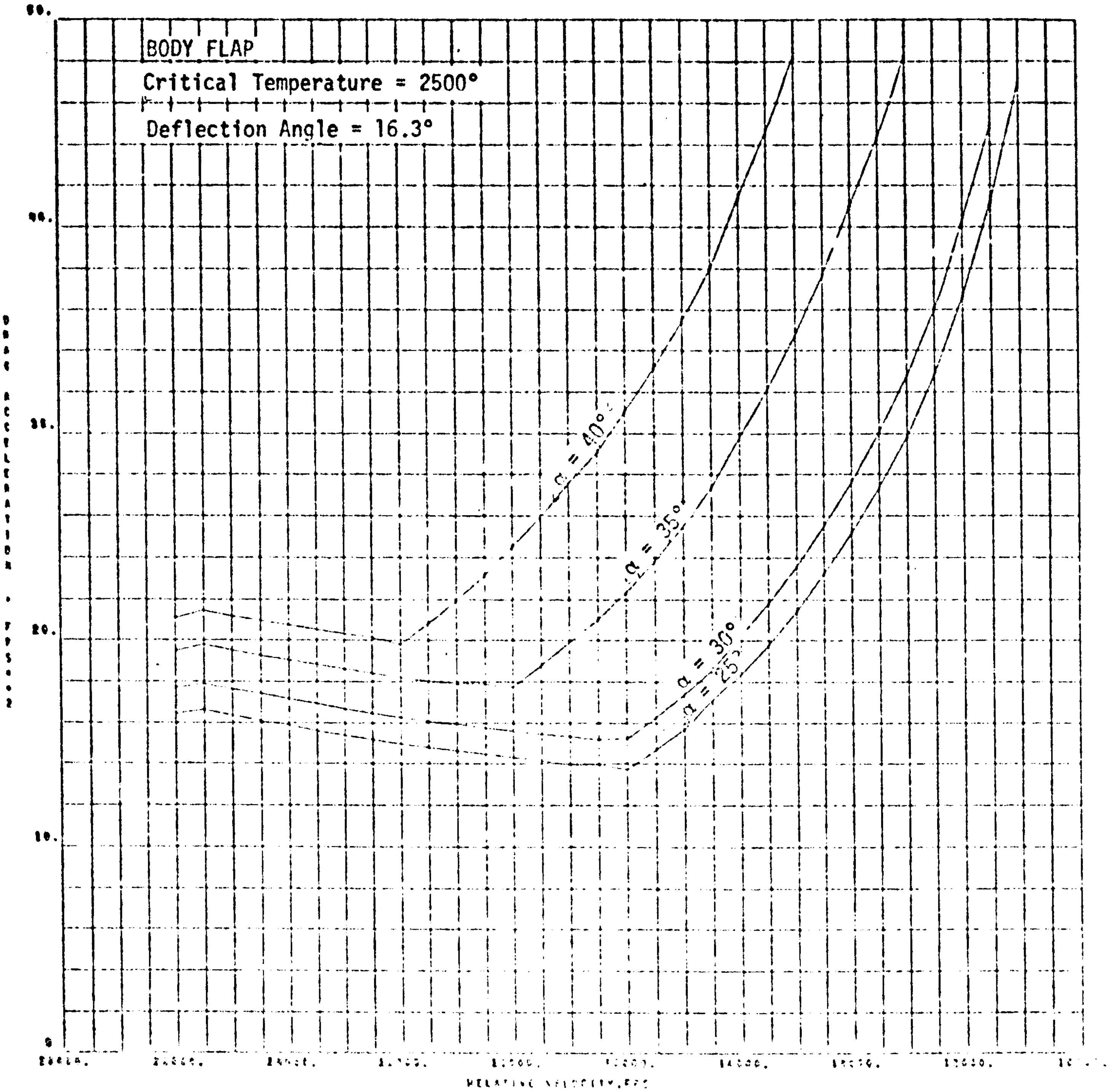


Figure 3. Example of Thermal Data Plot in D/V Plane.

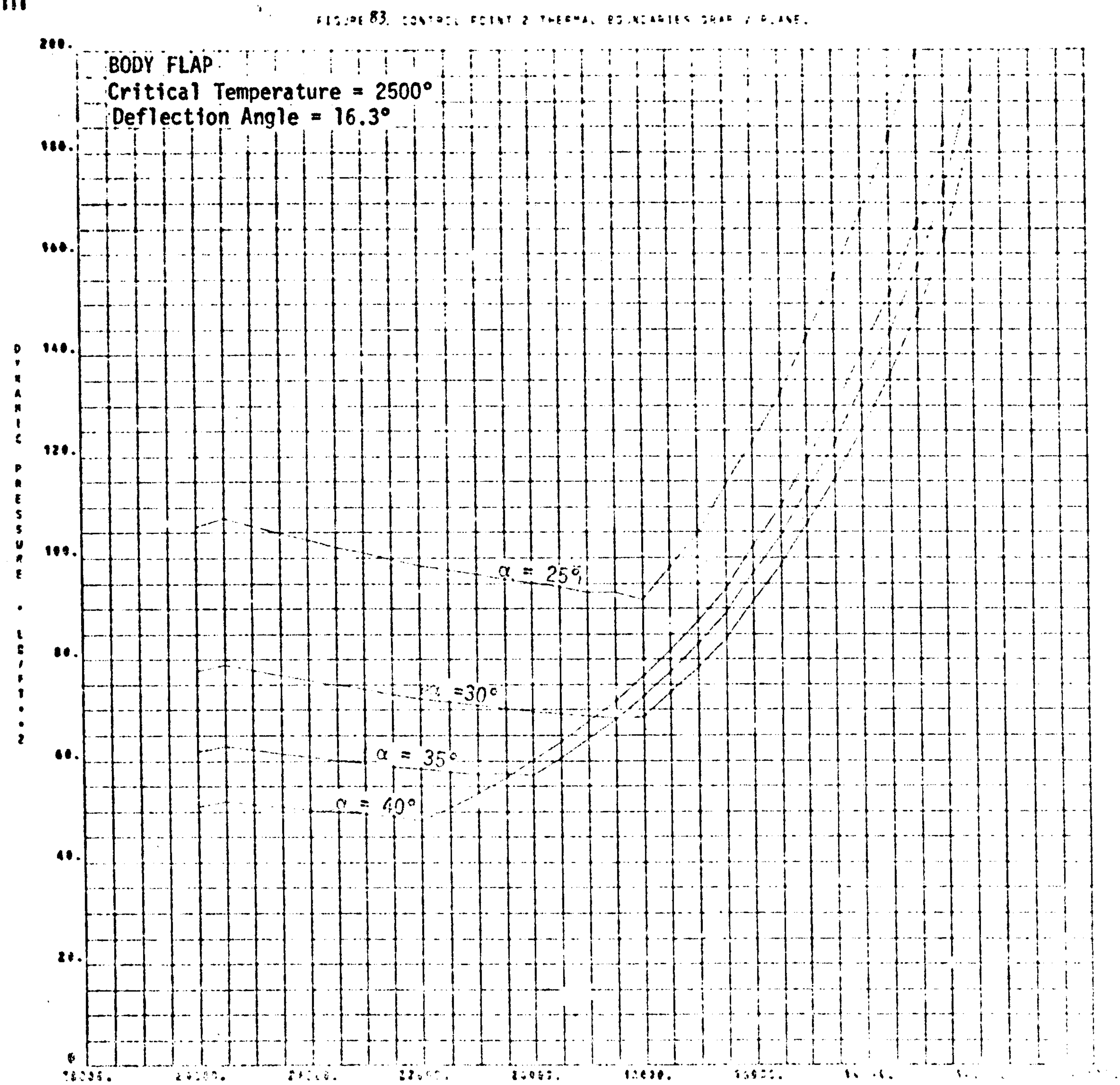


Figure 4. Example of Thermal Data Plot in QBAR/V Plane.