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 (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

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

where

- $q$ = stagnation point heat rate for a one foot sphere (BTU/ft²/sec),
- $\rho$ = free stream density (slugs/ft³),
\[ V = \text{relative velocity magnitude (ft/sec)}, \]
\[ h_w = \text{surface enthalpy (BTU/lb_m)}, \]
\[ h_w = 0.24 T_w, \quad \text{(2)} \]
\[ h_o = \text{total enthalpy (BTU/lb_m)}, \]
\[ h_o = 0.24 T_o + \frac{V^2}{50,063} \]
\[ \text{and } T_w = \text{wall temperature (°R)}, \]
\[ T_w = 1000 \left( \frac{q_{\text{ref}}}{0.476 \epsilon} \right)^{0.25} \quad \text{(4)} \]
\[ T_o = \text{free stream temperature (°R)}, \]
\[ \epsilon = \text{surface emissivity.} \]

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

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

\[ q_{\text{panel}} = q_i(\text{lam}) = \Lambda_i C_i q_{\text{ref}}, \quad \text{for } P < R_{oi}, \quad \text{(5)} \]
\[ q_{\text{panel}} = q_i(\text{trans}) = q_i(\text{lam}) \left( \frac{a R - b}{R_{oi}} \right) \left( \frac{P}{K P_{oi}} \right)^3, \quad \text{for } R_{oi} \leq R \leq K R_{oi}, \quad \text{(6)} \]
and
\[ q_{\text{panel}} = q_i(\text{turb}) = q_i(\text{lam}) C_i \left( \frac{R}{K P_{oi}} \right)^3, \quad \text{for } K R_{oi} < \infty. \quad \text{(7)} \]

where \( \Lambda_i = \text{deflection factor} \)
\[ C_i = \frac{q_i(\text{lam})}{q_{\text{ref}}}, \quad \text{for the } i \text{th panel} \]

...function of angle of attack, \( \alpha \),
\[ R = \text{Reynolds number behind a normal shock} \]
\[ = \frac{\rho V}{\nu_v} \]  
\[ R_{oi} = \text{transition onset Reynolds number for the } i \text{th panel}, \]
\[ = \text{function of } \alpha, \]
\[ \nu_v = \text{normal shock viscosity coefficient and } a, b, c, \text{ and } K \text{ are modeling constants.} \]
The deflection factor, \( \Lambda_i \), (Equation (5)) equals one for surfaces not on the elevon or body flap and
\[ \Lambda_i = 1.05 + (9.8 - \alpha) \frac{\Gamma}{5} \]
where \( \alpha \) = angle of attack (degrees)
\[ \Gamma = 0.01966 - 0.0122, \text{ for } 0 \leq \delta \leq 4 \]
\[ \Gamma = 0.02768 - 0.0443, \text{ for } 4 < \delta \leq 8 \]
\[ \Gamma = 0.03678 - 0.11758, \text{ for } 8 < \delta \leq 15 \]
\[ \Gamma = 0.04669 - 0.2665, \text{ for } 15 < \delta \]
and \( \delta \) = 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 \( \alpha \) and interpolated for the appropriate \( \alpha \). \( \nu_v \) is stored in a table as a function of \( V \) and interpolated for the appropriate \( V \). The surface temperature for the \( i \text{th panel} \) as defined in Reference 2 is given by
\[ T_i = 1000 \left( \frac{\varepsilon_i}{0.4761} \right)^{0.25} - 460 \quad (9) \]
where \( \varepsilon_i \) = surface emissivity for the \( i \text{th panel} \).

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 TDAP the free stream density, $\rho$, and temperature, $T_\infty$, (Equation 3) are computed using the SVDS (Reference 3) subroutine ATMOS which represents the 1962 Standard atmosphere. The drag acceleration is defined by

$$\frac{D}{H} = \frac{\bar{q} C_D S}{m} \tag{13}$$

where $C_D = \text{drag coefficient}$

$S = \text{reference area}$

and $m = \text{vehicle mass}$.

$C_D$ is computed using the SVDS subroutine ARLAC (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.

<table>
<thead>
<tr>
<th>VARIABLE</th>
<th>TYPE *</th>
<th>COMMON BLOCK</th>
<th>COMMON LOCATION</th>
<th>DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALPHA</td>
<td>R</td>
<td>BLCK</td>
<td>GNDAT1 (78)</td>
<td>Pitch angle of attack (RAD)</td>
</tr>
<tr>
<td>MASS</td>
<td>R</td>
<td>BLCK</td>
<td>GNDAT1 (128)</td>
<td>Vehicle Mass (slugs)</td>
</tr>
<tr>
<td>V</td>
<td>R</td>
<td>BLCK</td>
<td>XLEC (507)</td>
<td>Initial velocity (ft/sec)</td>
</tr>
<tr>
<td>H</td>
<td>R</td>
<td>BLCK</td>
<td>GNDAT1 (70)</td>
<td>Geodetic altitude (ft)</td>
</tr>
<tr>
<td>NC2M</td>
<td>I</td>
<td>GEN2</td>
<td>WORK2 (330)</td>
<td>Convergence interval for temperature iterator</td>
</tr>
<tr>
<td>NVAL</td>
<td>I</td>
<td>GEN2</td>
<td>WORK2 (331)</td>
<td>Number of values for angle-of-attack table</td>
</tr>
<tr>
<td>DT</td>
<td>R</td>
<td>GEN2</td>
<td>WORK2 (107)</td>
<td>Specified tolerance factor for temperature iterator</td>
</tr>
<tr>
<td>DV</td>
<td>R</td>
<td>GEN2</td>
<td>WORK2 (105)</td>
<td>Increment velocity (ft/sec)</td>
</tr>
<tr>
<td>NP</td>
<td>I</td>
<td>GEN2</td>
<td>WORK2 (108)</td>
<td>TPS panel or control point number</td>
</tr>
<tr>
<td>IOP</td>
<td>I</td>
<td>GEN2</td>
<td>WORK2 (110)</td>
<td>Option for atmospheric model</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>= 0 1962 U.S. Standard atmosphere</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>= 1 July atmosphere at 30 Deg. North Latitude</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>= 2 Jan. atmosphere at 30 Deg. North Latitude</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>= 3 July atmosphere at 60 Deg. North Latitude</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>= 4 Jan. atmosphere at 60 Deg. North Latitude</td>
</tr>
<tr>
<td>VM</td>
<td>R</td>
<td>GEN2</td>
<td>WORK2 (104)</td>
<td>Maximum velocity (ft/sec)</td>
</tr>
<tr>
<td>VARIABLE</td>
<td>TYPE</td>
<td>COMMON BLOCK</td>
<td>COMMON LOCATION</td>
<td>DESCRIPTION</td>
</tr>
<tr>
<td>-----------</td>
<td>------</td>
<td>--------------</td>
<td>----------------</td>
<td>-------------</td>
</tr>
<tr>
<td>IALP</td>
<td>I</td>
<td>GEN2</td>
<td>WORK2 (111)</td>
<td>Option for angle-of-attack</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>= 0 ramped schedule</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>= 1 constant schedule</td>
</tr>
<tr>
<td>TC</td>
<td>R</td>
<td>GEN2</td>
<td>WORK2 (112)</td>
<td>Critical temperature (DEG)</td>
</tr>
<tr>
<td>VALT (I),</td>
<td>R</td>
<td>GEN2</td>
<td>WORK2 (150)</td>
<td>Velocity Table (ft/sec)</td>
</tr>
<tr>
<td>I = 1, NVAL</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>VALP (I),</td>
<td>R</td>
<td>GEN2</td>
<td>WORK2 (114)</td>
<td>Angle-of-attack Table (DEG)</td>
</tr>
<tr>
<td>I = 1, NVAL</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NBAP</td>
<td>I</td>
<td>GEN2</td>
<td>WORK2 (200)</td>
<td>Flag determining thermal</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>boundary option</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>= 0 Does not call TBAP</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>= 1 Calls TBAP</td>
</tr>
<tr>
<td>TSTOP</td>
<td>I</td>
<td>GNDAT2</td>
<td>GNDAT2 (2)</td>
<td>Maximum Phase Time (sec)</td>
</tr>
<tr>
<td>TMAX</td>
<td>I</td>
<td>GNDAT2</td>
<td>GNDAT2 (3)</td>
<td>Maximum Case Time (sec)</td>
</tr>
<tr>
<td>IBAP</td>
<td>I</td>
<td>GEN2</td>
<td>WORK2 (199)</td>
<td>Flag for TBAP driver option</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>= 0 Do not use TBAP driver</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>= 1 Use TBAP driver</td>
</tr>
</tbody>
</table>

*NOTE: Type "R" denotes REAL.
Type "I" denotes INTEGER.*
5.0 OUTPUT DESCRIPTION

Figure 1 gives an example of the initialization 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/H-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**

<table>
<thead>
<tr>
<th>Code</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>NC2M</td>
<td>Maximum number of iterations on critical temperature</td>
</tr>
<tr>
<td>NVAL</td>
<td>Number of values for angle-of-attack table</td>
</tr>
</tbody>
</table>

**Row 3 - 4**

**Input Identification**

<table>
<thead>
<tr>
<th>Code</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>REF</td>
<td>Reference Area (ft²)</td>
</tr>
<tr>
<td>WEIGHT</td>
<td>Weight (lbs)</td>
</tr>
<tr>
<td>VSTART</td>
<td>Initial velocity (ft/sec)</td>
</tr>
<tr>
<td>VSTOP</td>
<td>Final velocity (ft/sec)</td>
</tr>
<tr>
<td>DELTA V</td>
<td>Velocity increment (ft/sec)</td>
</tr>
<tr>
<td>DT</td>
<td>Specified tolerance factor for temperature iterator (°F)</td>
</tr>
</tbody>
</table>

**Row 5 - 6**

**Input Identification**

<table>
<thead>
<tr>
<th>CG (1)</th>
<th>Center of mass X-component (in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CG (2)</td>
<td>Center of mass Y-component (in)</td>
</tr>
<tr>
<td>CG (3)</td>
<td>Center of mass Z-component (in)</td>
</tr>
</tbody>
</table>
FIGURE 1. Example of Initialization Data
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/sec²)

**QDAR**  Dynamic Pressure (lbs/ft²)

**DENSITY**  Density (slug/ft³)

**REY NS**  Normal shock Reynolds number (NS)

**MACH**  Mach number (M)

**TEMP**  Surface temperature (°F)
### TABLE II (CONT'D)

**THERMAL BOUNDARY DATA**

Row 3 - 34 (cont'd)

<table>
<thead>
<tr>
<th>Output identification</th>
<th>Flow characteristic</th>
<th>Body flap setting (DEG)</th>
<th>Elevon setting (DEG)</th>
<th>Angle-of-attack (DEG)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FLOW</td>
<td>Flow characteristic</td>
<td>BDF</td>
<td>ELV</td>
<td>ALP</td>
</tr>
<tr>
<td></td>
<td>= 1 Laminar</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>= 2 Transitional</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>= 3 Turbulent</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Body flap setting</td>
<td>BDF</td>
<td>ELV</td>
<td>ALP</td>
</tr>
<tr>
<td></td>
<td>(DEG)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Elevon setting</td>
<td>BDF</td>
<td>ELV</td>
<td>ALP</td>
</tr>
<tr>
<td></td>
<td>(DEG)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Angle-of-attack</td>
<td>BDF</td>
<td>ELV</td>
<td>ALP</td>
</tr>
<tr>
<td></td>
<td>(DEG)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
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 TRAP is documented in this design note.
The first executable statement is to determine whether to call BAP.

The remainder of subroutine INTG12 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/ft²)
- MACH: Mach number (ND)
- H: Altitude (ft)
- DOM: Drag acceleration (ft/sec²)
- 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**

\[ H = 160000. \text{ Initial altitude} \]

\[ \text{JCAL} = 0 \quad \text{Flag in AR140C to eliminate Call AROCAL} \]

6.2.7 **SUBROUTINE REQUIRED**

- TABLE
- ATMOS
- AR140C
- HTRATE
- TPS
- TI
6.2.8 FLOWCHART

START

INPUTS

OUTPUT

Identification

Labels

Initialize: $H = 160000$.

$NCQ = 0$

$URF = V$

IF $T = 0$

CALL TABLE(NVAL, VALT, VALP, V, ALP)

CALL ATMOS(H, TOP, FANS)

$P = FANS(1)$

$T = FANS(2)$

$Rho = \frac{FANS(3)}{29.174}$

$SS = FANS(4)$

$VTS = FANS(5)$

Calculate $QBAR$:

$MACH = \frac{V}{SS}$

A

REPRODUCIBILITY OF THE
ORIGINAL PAGE IS POOR
CALL TPS
CALL AK140C
70 Continue
CALL H1R1TE
CALL TI

YES NO
NC1L = 0

NO

H0 = H
H = H + 100.
TPO = TP
NC1L = 1.

GO TO 3.

COMPUTE PET:
PET = 100 * (TP - TC) / TC
DUM = ABS(PET)

11

10

11

NO

YES

D3

D7

NO

YES

HC11

HC14

B
6.2.8 Flowchart (Continued)

\[ DUM = H + (H - H_0) \times (T_C - T_P) / (T_P - T_{PO}) \]

\[ H_0 = H \]

\[ T_{PO} = TP \]

\[ H = DUM \]

\[ N_{C2} = N_{C2} + 1 \]

\[ \text{Go To 3} \]

Output:

PET

Compute Drag:

\[ DOM = QUAR \times CO \times S / MASS \]

Output:

V \leq VM

Yes

Return

END

No

END
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/ft³)
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 feet
TEMP  Array of current atmosphere data
IABAP  Option for IBAP driver
  = 0 Do not use IBAP driver
  = 1 Use IBAP driver
6.3.3 OUTPUT:

- **QREF**: Stagnation point heat rate (BTU/ft²-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

<table>
<thead>
<tr>
<th>DATA VES/600</th>
<th>1000</th>
<th>1500</th>
<th>2000</th>
<th>2500</th>
<th>3000</th>
<th>3500</th>
<th>4000</th>
<th>4500</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5000</td>
<td>5500</td>
<td>6000</td>
<td>6500</td>
<td>7000</td>
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</tbody>
</table>

Coefficient of viscosity VS relative velocity

<table>
<thead>
<tr>
<th>DATA VISC</th>
<th>31E-6</th>
<th>351E-6</th>
<th>394E-6</th>
<th>460E-6</th>
<th>541E-6</th>
<th>646E-6</th>
<th>745E-6</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>850E-5</td>
<td>951E-5</td>
<td>1065E-5</td>
<td>117E-5</td>
<td>128E-5</td>
<td>139E-5</td>
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</tr>
<tr>
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<td>150E-5</td>
<td>165E-5</td>
<td>173E-5</td>
<td>181E-5</td>
<td>1865E-5</td>
<td>192E-5</td>
<td>1965E-5</td>
</tr>
<tr>
<td>3</td>
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<td>203E-5</td>
<td>210E-5</td>
<td>217E-5</td>
<td>2275E-5</td>
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<td>251E-5</td>
</tr>
<tr>
<td>4</td>
<td>261E-5</td>
<td>268E-5</td>
<td>275E-5</td>
<td>282E-5</td>
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<td>2925E-5</td>
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<tr>
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<td>323E-5</td>
<td>346E-5</td>
<td>349E-5</td>
<td>346E-5</td>
<td>341E-5</td>
</tr>
<tr>
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<td>296E-5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### 6.3.7 SUBROUTINE REQUIRED

None
Flowchart:

6.3.8 FLOWCHART

START

IV1 = IV1 + 1

300

YES

IPAE ≠ 0

NO

1000

YES

MTPS(IV1) = 3

NO

KNTPS(IV1) = KNTPS(IV1) + 1

KNIT = MOD(KNTPS(IV1))

KNTPS(IV1) = 0

4

KNIT

Δ

MTPS(IV1) ≠ 1

NO

MTPS(IV1) = 2

TPS(IV1) = TMEC

P/XER = 0

DO 1, INRCL

TMEAP(A) = 0.0

QTEC = 0.0

1

GATE (A) = 0.0

NO

1000

YES

J GATE(1) = 1960.

GATE = 0.0

CONTINUE
6.3.8 FLOWCHART (CONTINUED)

\[ DT = T_{incc} - TIPS(2,1) \]

\[ \text{DO } J \text{'s for } I = 1, 2. \]

\[ H_W = 0.24 * T_W A_L L \]
\[ H_O = 0.24 * T E N P(2) + \frac{V(IV)^2}{50063} \]
\[ Q_{REF} = 17700 \cdot \left( \frac{\text{REA}(3) + \text{Rhosl}}{V(IV)} \right)^{3.07} \left( 1 - \frac{H_W}{H_O} \right) \]

\[ Q_{REF} = 0. \text{ if Yes, else NO} \]

\[ Q_{REF} < 0. \text{ if NO, else YES} \]

\[ \text{TWALL} = 1000 \cdot \left( \frac{Q_{REF}}{176 \times 85} \right)^{0.25} \]

\[ \text{CONTINUE} \]

\[ 100 \text{ if YES, else NO} \]

\[ Q_C = \text{PREF} \cdot \left( \frac{\text{PRECH} + \text{QREF}}{\text{PREF} + \text{QREF}} \right) \]
\[ \text{PREF} = Q_{REF}, \text{PRECH} = Q_{REF} \]

\[ 100 \text{ if YES, else NO} \]

\[ J \leq 0 \text{ if NO, else YES} \]
6.3.8 FLOWCHART (CONTINUED)

FLOWCHART

\[ T_{\text{OUT}} = T_{400K} + DT \]

CONTINUE

\[ \text{DO 35} \]
\[ I = 2, 45 \]

\[ V_{\text{ES}(I)} \geq V_{T(IW)} \]

\[ V_{\text{IS}} = \frac{V_{\text{ES}(I-1)} - V_{\text{ISC}(I)}}{V_{\text{ES}(I-1)} - V_{\text{ES}(I)}} (V_{T(IW)} - V_{\text{ES}(I)} + V_{\text{ISC}(I-1)}) \]

\[ R_{\text{KH}} = \frac{\text{ANSW}(3) \cdot \text{RhosL} (V_{T(IW)})}{V_{\text{IS}}} \]

\[ \text{RETURN} \]

\[ \text{IF} \]
\[ \text{Temp} \]
\[ \neq 0 \]

\[ \text{IF} \]
\[ \text{E-C TO 200} \]

\[ \text{RhoeL} = \text{ANSW}(5) \cdot \text{RhosL} \]

\[ R_{\text{KH}} = 5.1 \frac{L}{W} \left( \frac{R_{\text{KH}}}{R_{\text{KH}_{\text{L}}}} \right)^{1.5} \]

\[ \text{C} \]
6.3.8 FLOWCHART (CONTINUED)

(* Diagram *)

DN No.: 1.4-4-5
Page: 28
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/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:

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

6.4.3 OUTPUT:

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>QDT</td>
<td>Heat rate (BTU/ft^2-sec)</td>
</tr>
<tr>
<td>IFS</td>
<td>Flow characteristic</td>
</tr>
<tr>
<td></td>
<td>= 1 (laminar flow)</td>
</tr>
<tr>
<td></td>
<td>= 2 (transitional flow)</td>
</tr>
<tr>
<td></td>
<td>= 3 (turbulence flow)</td>
</tr>
<tr>
<td>RENS</td>
<td>Reynolds number at transition onset</td>
</tr>
</tbody>
</table>

6.4.4 ALGORITHM:

See flowchart Sec. 6.4.9

6.4.5 CALLING SEQUENCE

Call HTRATE
### 6.4.6CONSTANTS REQUIRED

**LAMINAR GDOTL/GDOT STAG VS ALPHA AND PANEL NUMBER**

<table>
<thead>
<tr>
<th>DATA (C(I,K),K=1,13)</th>
<th>C(1,K)</th>
<th>C(2,K)</th>
<th>C(3,K)</th>
<th>C(4,K)</th>
<th>C(5,K)</th>
<th>C(6,K)</th>
<th>C(7,K)</th>
<th>C(8,K)</th>
<th>C(9,K)</th>
<th>C(10,K)</th>
<th>C(11,K)</th>
<th>C(12,K)</th>
<th>C(13,K)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**DATA (C(12,K),K=1,13) / 0.0271, 0.0452, 0.0657, 0.0714, 0.0771, 0.0834, 0.0892, 0.0949, 0.1000, 0.1057, 0.1135, 0.1179, 0.1210**
Alpha table corresponding to LAMINAR QDOTL/QDOT STAG

DATA ALP/10.*15.*20.*25.*27.*30.*32.*35.*37.*40.*42.*45.*50./

Reynolds number at transition onset VS Alpha and Panel number

<table>
<thead>
<tr>
<th>Reynolds number</th>
<th>Panel number</th>
</tr>
</thead>
<tbody>
<tr>
<td>77000, 60000, 46000, 34000, 26000, 22000, 22000,</td>
<td>15000,</td>
</tr>
<tr>
<td>22000,</td>
<td>17000,</td>
</tr>
<tr>
<td>24000, 26400, 26100, 24400, 22800, 21400, 20300,</td>
<td>19500,</td>
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<tr>
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<td>15000, 13500, 14100, 13700, 13100, 12700, 12400, 12300,</td>
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</tr>
<tr>
<td>3100, 3000, 2900, 2800, 2700, 2600, 2500, 2400,</td>
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</tr>
<tr>
<td>2200, 2100, 2000, 1900, 1800, 1700, 1600, 1500,</td>
<td>1400,</td>
</tr>
<tr>
<td>1300, 1200, 1100, 1000, 900, 800, 700, 600, 500,</td>
<td>400,</td>
</tr>
<tr>
<td>300, 200, 100, 00,</td>
<td>0,</td>
</tr>
</tbody>
</table>

Alpha table corresponding to Reynolds number at transition onset.

DATA ALP/1.4-4-5
6.4.7 SUBROUTINE REQUIRED

None
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/ft²-sec)
- **N PANEL**: 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

- \[ C = 24710577 \times 10^{13} \]

6.5.7 SUBROUTINE REQUIRED

None
6.5.8 FLOWCHART (CONT'D)

IF

YES

THEN

IF

THEN

END.
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, : , X1, Y1)

6.6.6 CONSTANTS REQUIRED

N = 1

6.6.7 SUBROUTINE REQUIRED

None
\( N \rightarrow N' = N - 1 \)

Output:

\( Y(k) = Y(k-1) + \frac{(Y(N+1) - Y(N)) \times (X(N+1) - X(N))}{(N+1) - N} \)

RETURN

END
7.0 REFERENCES


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:

<table>
<thead>
<tr>
<th>ICCOMP</th>
<th>Type plot indicator</th>
</tr>
</thead>
<tbody>
<tr>
<td>= 0</td>
<td>Calcomp</td>
</tr>
<tr>
<td>= 1</td>
<td>Microfilm</td>
</tr>
</tbody>
</table>

| KUNIT    | Data tape input unit |

<table>
<thead>
<tr>
<th>NTRAN</th>
<th>Tape type selector</th>
</tr>
</thead>
<tbody>
<tr>
<td>= 0</td>
<td>Input data tape was generated using FORTRAN write statements.</td>
</tr>
<tr>
<td>= 1</td>
<td>Input data tape was generated using NTRANS write statements.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>NCHNR</th>
<th>Plot symbol selector</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>CMOULT</th>
<th>Multiplicative factor</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>XLABEL</th>
<th>Independent axis identification</th>
</tr>
</thead>
<tbody>
<tr>
<td>YLABEL</td>
<td>Dependent axis identification</td>
</tr>
</tbody>
</table>
1.2 **INPUT:** (continued)

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>TITLE</td>
<td>Graph title</td>
</tr>
<tr>
<td>IPNF</td>
<td>Total number of files on data tape for a given plot</td>
</tr>
<tr>
<td>JANF</td>
<td>Actual file number</td>
</tr>
<tr>
<td>NVAR2</td>
<td>Dependent variable</td>
</tr>
<tr>
<td></td>
<td>= 2 Altitude (ft/sec)</td>
</tr>
<tr>
<td></td>
<td>= 3 Drag acceleration (ft/sec²)</td>
</tr>
<tr>
<td></td>
<td>= 4 Dynamic pressure (lbs/ft²)</td>
</tr>
<tr>
<td>L</td>
<td>Number of cards to specify scale parameters</td>
</tr>
<tr>
<td>M</td>
<td>Number of cards to specify axis identification</td>
</tr>
</tbody>
</table>

1.3 **OUTPUT:**

<table>
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<tr>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
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<td>ICCOMP</td>
<td>Calcomp/microfilm indicator</td>
</tr>
<tr>
<td>KUNIT</td>
<td>Data tape input unit</td>
</tr>
<tr>
<td>NTRAN</td>
<td>Tape type selector</td>
</tr>
<tr>
<td>NCHAR</td>
<td>Plot symbol selector</td>
</tr>
<tr>
<td>CMULT</td>
<td>Multiplicative factor</td>
</tr>
<tr>
<td>XLABEL</td>
<td>Independent axis identification</td>
</tr>
<tr>
<td>YLABEL</td>
<td>Dependent axis identification</td>
</tr>
<tr>
<td>TITLE</td>
<td>Plot title</td>
</tr>
<tr>
<td>IPRINT</td>
<td>Print indicator</td>
</tr>
<tr>
<td></td>
<td>= -1 Print plot titles only</td>
</tr>
<tr>
<td></td>
<td>= 0 Suppress print</td>
</tr>
<tr>
<td></td>
<td>= 1 Print plot titles and data points</td>
</tr>
<tr>
<td></td>
<td>= n Print titles and first n data points (n ≠ 1)</td>
</tr>
<tr>
<td>NOIREC</td>
<td>Data tape format indicator</td>
</tr>
<tr>
<td></td>
<td>= 0 Tape contains more than one type of record.</td>
</tr>
<tr>
<td></td>
<td>= 1 Tape contains only one type of record.</td>
</tr>
</tbody>
</table>
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

START

NVAR1 = 1

DO 1 
I = 1, 4

READ BASIC INPUTS

READ L, M, NVAR2

DO 4 
I = 1, L

READ SCALE Specifications

DO 7 
M = 1, M

REL AXIS LIMITS

Independent plot variable: relative velocity

Basic inputs such as: ICComp, KUNIT, NTRAN, NCHAR, etc.
IPNF, number of files for plot
JANF, the actual file number on the data tape
FIGURE 1. Example of GIP Printer Output
Figure 6.2, CONTROL POINT 2 THERMAL BOUNDARIES W/B FLAP.

Critical Temperature = 2500°

Figure 2. Diagram of Thermal Boundaries in B/W Plane.
Figure 73. Control Point 2 Thermal Boundaries 0°/Y Plane.

**BODY FLAP**

Critical Temperature = 2500°
Deflection Angle = 16.3°
Figure 4: Example of thermal data plot in QMSR/V plane.

BODY FLAP
Critical Temperature = 2500°
Deflection Angle = 16.3°

α = 25°
α = 30°
α = 35°
α = 40°