Automation Techniques for Thermal Analysis of Spacecraft Systems

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The evaluation of the design and performance of current and future hypersonic flight vehicles, including the Shuttle Orbiter, National Aerospace Plane (NASP), and assured crew return vehicle (ACRV), requires rigorous and very extensive thermal analyses. These analyses are imperative to ensure that the design of spacecraft systems is adequate and that safety margins are proper for given mission requirements. Conventionally, thermal analyses have been performed manually, that is, without the aid of integrated automatic procedures for constructing nodalized thermal models, incorporating initial and boundary conditions, and performing other necessary modifications. These manual processes require considerable manpower that could be utilized for other tasks. In order to improve these time-consuming and tedious analysis procedures, an engineering concept and methodology for automating thermal analysis has been developed and implemented for the thermal analysis of the Space Shuttle Orbiter. This paper discusses this new methodology.

Nomenclature

A = heat transfer area
a = coefficient of smoothing equation
b = coefficient of smoothing equation
c = convection effectivity factor, Btu/fr^2-h-°F
C_p = specific heat, Btu/lbm-°F
F = heating multiplication factor
h = convection film coefficient Btu/ft^2-h-°F
k = thermal conductivity, Btu/ft-h-°F
P = pressure of the ingested air at local time
P' = pressure of the ingested air at air vent opening time
q_{cc} = heat flux due to IML cooling
q_{ch} = heat flux due to convective heating
q_{ri} = heat flux due to radiation interchange
q_{rr} = heat flux due to reradiation
q_s = heat flux incident on surface
q_t = total heat flux
T = temperature of the ingested air at local time
T' = temperature of the ingested air at air vent opening time
T_i = temperature of node i
T_f = temperature of fluid
T_j = temperature of node j
T_{fr} = frame temperature
T_{sk} = skin temperature at gradient location
T_{ss} = skin temperature at one-dimensional TMM location
$T_{\Delta i}$ = temperature of equivalent mass of nearby heavy structure
T_w = wall temperature
V = velocity of the ingested air at local time
V' = velocity of the ingested air at air vent opening time
X/L = ratio of Orbiter X coordinate to Orbiter length L
ZLV = Z direction local vertical
α = solar absorptivity
ϵ = emissivity
f = configuration factor (view factor)
ρ = density, lbm/ft^3
σ = Stefan-Boltzmann constant, 1.714×10^{-9} Btu/h-ft^2-°R^4
θ = time

Received May 30, 1989; revision received Dec. 1, 1989; accepted for publication April 20, 1990.

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Introduction

THERMAL analyses are required for Space Shuttle Orbiter certification. Generally, there are four major branches, namely, 1) structural thermal gradient analysis; 2) thermal protection system (TPS) thermal analysis for acreage (75% of the TPS area) and penetrations (remaining 25%); 3) thermal control system (TCS) thermal analysis; and 4) other design support thermal analysis, such as the sizing of TPS materials and heat sinks.

Regardless of the type of the thermal analyses performed, however, engineers always have to construct thermal math models (TMMs) that simulate the systems they intend to evaluate. The TMMs are nodalized networks that represent the physical system in terms of thermal capacitances and resistances at each nodal point; all nodal points are connected to each other using thermal properties, such as specific heat and thermal conductivities, and optical properties, such as emissivities and reflectivities. In order to simulate flight environments, analysts subject these nodal points to initial and boundary conditions, and the transient or steady-state temperature responses are calculated based on those conditions.

The initial and boundary conditions usually consist of initial-temperature distributions; edge conditions at the boundary nodes, such as aeroheating during ascent and entry; plume heating; solar flux; and reradiation to space. Also included are radiation interchange among structural members, internal convection of the structure due to vent-ingested air during the terminal area energy management (TAEM) portion of flight, purge after touchdown, and so on.

Preparation of the nodalized thermal network for all of these conditions, including the construction and/or modification of the TMMs, would require considerable time and effort. Furthermore, each of the different types of analyses needs to serve its unique function, such as predicting maximum temperatures, determining minimum TPS thicknesses, or defining thermal gradients. In order to make clear the scope of these analyses, the paper briefly presents the hardware that is frequently modeled for thermal analyses of the Space Shuttle Orbiter, especially structural thermal gradient analyses, which are most difficult to perform but are mandatory for spacecraft loads cycle analysis aimed at expanding the Orbiter's capability.

The two hardware components of the Orbiter that are most often modeled for thermal gradient evaluation are the TPS and structures. TPS materials consist of three types of silica tiles and two types of blankets. The tiles are referred to as high temperature reusable surface insulation (HRSI), fibrous refractory composite insulation (FRCI), and low temperature reusable surface insulation (LRSI). The blankets are flexible reusable surface insulation (FRSI) and advanced flexible reusable surface insulation (AFRSI).

The thermophysical properties of these TPS components are utilized in the TMMs to account for thermal conduction and heat storage capacity that result in temperature changes due to boundary conditions, such as convective and radiative heating incident on the TPS surface; radiation interchange; and reradiation.[1] Orbiter structures are, in general, constructed of aluminum skin and stringers, aluminum honeycomb, or graphite epoxy honeycomb. These structures and any internal structures, such as main frames, canted frames, beams, and inner and outer caps, are modeled in the TMMs.

A typical structural TMM, which comprises TPS and structure, is illustrated in Fig. 1. This model represents the Space Shuttle Orbiter's midfuselage configuration, which includes the lower fuselage, the wing glove, and part of the side fuselage. Each rectangle in the model is a nodal element assumed to be at a homogeneous temperature that results from the lumped-mass thermal modeling method. These nodal elements are connected to their adjacent elements at their centroids in all three directions (X, Y, and Z in Cartesian coordinates) using the previously mentioned thermophysical properties.

Once the thermal nodal network is complete, the next step is to incorporate the initial and boundary conditions that are appropriate for given analysis environments, such as ascent and entry preparation temperatures, and ascent and entry flight environments. These conditions are incorporated into the nodalized thermal network by painstakingly assigning initial temperatures to all nodes of the model, applying flight environments (e.g., heating and pressure profiles) to the boundary nodes, setting up reradiation to sink temperatures, establishing radiation interchange mechanisms, and identifying internal convective heating or cooling for the structural nodes. This process may take a few hours or several weeks, depending on the complexity of the model and the analysis environments. The nature of the incorporation of the initial and the boundary conditions is discussed in detail later.

The completed TMMs are then evaluated using various finite-difference techniques to obtain the temperature responses at every node as a function of trajectory time. These techniques include forward difference, backward difference,

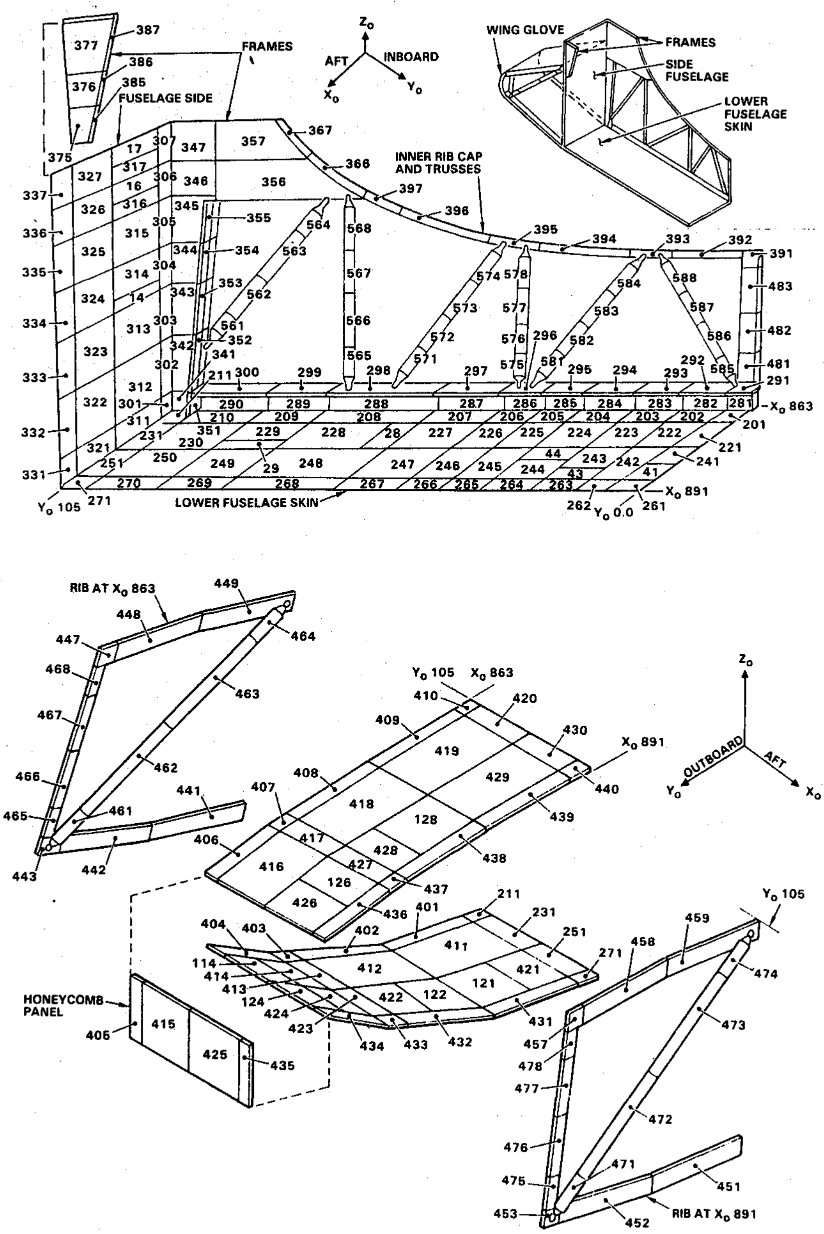

Fig. 1 TMM 132 fuselage at wing glove intersection nodal diagram – X_o 863–891.

central difference, Crank-Nicolson, and alternating direction implicit (ADI) methods.

Background

Thermal gradient distributions of the Space Shuttle Orbiter must be defined to ensure that the orbiter's thermal capabilities are not exceeded on the planned missions. Basically, two types of thermal gradient analyses are performed: commit-to-flight (CTF) and Orbiter loads cycle (full-scale Orbiter structural loads analysis).

CTF thermal analysis is performed for each mission to define the structural temperature distributions at 25 critical gradient locations. The CTF analysis is required for four distinct flight environments: end of mission (EOM), abort once around (AOA), abort from orbit (AFO), and transatlantic abort landing (TAL). Thus, a total of 100 TMMs must be evaluated. All of the CTF TMMs must be re-evaluated when flight environments change in response to changes in mission objectives (payload change), trajectory variations due to changes in the Orbiter's weight and center of gravity, and the surface roughness changes resulting from refurbishment of the TPS. The number of TMMs that have to be reanalyzed, then, is 200, 300, and even 400, depending on the significance of the changes. Therefore, the amount of engineering effort that is required for the evaluation tasks is drastically increased even though the same hardware models are used for the tasks.

For a loads cycle thermal gradient analysis, the number of TMMs needed for a single thermal case consisting of one on-orbit attitude (initial condition) and entry heating environments is 130 for each side of the Orbiter. For the most common Orbiter loads cycle analysis, which consists of at least 10 thermal cases, total number of TMMs is 2600. The most recently completed loads analysis on OV-103 consisted of 29 different thermal cases that resulted in the evaluation of 7540 TMMs. Approximately 87,200 man-hours (42 man-years) were dedicated to the OV-103 loads analysis.

However, of the 87,200 man-hours spent on the tasks, about 70% of the time was spent implementing initial and boundary conditions into the TMMs, modifying TMMs, and reviewing evaluation results. Consequently, it was almost mandatory to develop an automated thermal analysis methodology that would significantly reduce manpower for future thermal analyses.

The methodology had to be capable of flawlessly evaluating large numbers of TMMs with automatic implementation capabilities of initial and boundary conditions and versatile enough to handle various types of thermal analyses, such as structural gradient, TPS acreage and penetrations, and design support, including the sizing of TPS and heat sinks. This resulted in the development of the automated thermal analysis program Thermal Magic, which reduces the manpower requirements by more than a factor of 10.

Discussion

Thermal Math Model Data Base

The algorithm of the Thermal Magic program is designed to construct or retrieve the necessary TMMs from the TMM data base and modify the baseline TMMs to suit the purpose of the thermal analyses performed. As mentioned previously, the TMMs used in the Orbiter thermal analyses are mostly for the TPS evaluation or structural evaluation. As a result, the automation process for the TMM data files is developed for the most frequently used models. These include TPS acreage, sizing, structural gradient, smoothing, and penetration

```
OV102
EOM
 (1)  (2)   (3) (4)(5) (6)  (7)  (8)   (9)  (10) (11)(12) (13) (14)(15)
4200 7200 1.13 5 30 .14 1500   69    1    1    1    0    0   11 200
               .03      1.0 4200 5646 6029  0
4200 7200 1.16 5 35 .13 1501   69    1    1    1    0    0   11 200
               .05      1.0 4200 5646 6029  0
4200 7200 1.12 5 37 .15 1502   54    1    1    1    0    0   11 200
               .04      1.0 4200 5646 6029  0
 .    .    .   .   .  .   .    .   .   .   .    .    .    .    .   .

4200 7200 0.75 1 87 .14 6999   69  .94    1    1    0    0   11 200
               .04      1.0 4200 5646 6029  0
 .    .    .   .   .  .   .    .   .   .   .    .    .    .    .   .
ENDT
AOA
 .    .    .   .   .  .   .    .   .   .   .    .    .    .    .   .

ENDT
AFO
 .    .    .   .   .  .   .    .   .   .   .    .    .    .    .   .

ENDT
TAL
 .    .    .   .   .  .   .    .   .   .   .    .    .    .    .   .

   0 3000 0.16 3 11 .04 3600   35  .72    1    1    0    0   11 201
0 .6 4.13   .6   .04    0.0  693 1853 2156  0
 .    .    .   .   .  .   .    .   .   .   .    .    .    .    .   .

ENDT
ENDV
OV103
EOM
 .    .    .   .   .  .   .    .   .   .   .    .    .    .    .   .

AOA
 .    .    .   .   .  .   .    .   .   .   .    .    .    .    .   .

ENDT
ENDV
OV104
 .    .    .   .   .  .   .    .   .   .   .    .    .    .    .   .

ENDV
```

(1) START TIME
(2) END TIME
(3) TPS THICKNESS
(4) TPS TYPE
(5) INITIAL TEMPERATURE
(6) SKIN THICKNESS
(7) AEROHEATING BP
(8) BP INDEX
(9) VIEW FACTOR
(10) – (13) HEATING FACTORS
(14) AEROHEATING DATA SET NUMBER
(15) TRAJECTORY CODE (FIRST TWO DIGITS) AND SIZING CODE (LAST DIGIT)

Fig. 2 TMM body point file for acreage TPS.

TMMs, which are evaluated using the XF0031 multidimensional heat conduction program.[2] However, the same algorithm can be easily expanded to accept the TMM formats required by other thermal analyzer programs.

TPS Acreage and Sizing TMMs

TPS acreage and sizing TMMs are simplified quasi-one-dimensional structural models that simulate TPS and the aluminum structure at a local point on the Orbiter. The purpose of these one-dimensional TMMs is to evaluate the maximum temperatures of the TPS and structure or to determine the thicknesses of the TPS or the heat sinks to keep the temperatures of the components below their allowable limits. Since these TMMs are relatively easy to construct using a model generator program,[3] instead of maintaining actual TMMs in the data base, the Thermal Magic program simply utilizes the file that contains the information on the locations to be analyzed and actually constructs them.

The data maintained in this file include the thicknesses of the TPS (initial thicknesses for sizing) and structure at the analysis locations, material types (HRSI, LRSI, FRCI, AFRSI, and FRSI), the aeroheating body point (BP), the

```
OV103
EOM
TMM027
    4      1 TMM027 OV-103 Forward fuselage 6.0 loads analysis
    1      1     1                              1      1
    2      1                     1       1      1      1
    3      1                     1             -4      1       1
    4      2     50   4200   7200              -4    0.5      60
  500            Section data
    1     70      1   -0.1    3.4    5.6       x2    y21
    2     70      1    0.1    3.4    8.6       x3    y22
    .      .      .      .      .      .        .      .
  345     70      5    0.5   0.11    1.2     x346   y366
END
   50            Material data
    1    9.0    -25    -24    -24    -24-31054 HRSI
    .      .      .      .      .      .       .      .
    5    175     -2     -1     -1     -1        2024 ALUMINUM
END
 .
   75            Heat flux data (aeroheating)
    1    1.0-31051    1.0
    .      .      .      .
END
   75            Heat flux data (solar flux)
    1    1.0 -6000   0.85
    .      .      .      .
END
   50            Reradiation to sink
    1    0.8   -470   0.85
    .      .      .      .
END
   25            Radiation interchange data
  345    0.8
    .      .      .
END
 .
  999SFA         Radiation interchange view factor
  345    445   0.12
    .      .      .
END
 .
   99            Convection data (IML cooling)
 9999     80          4200   5646   6150     98      1
  345                                        98
    .
END
 .
   50            Known temperature data
    1    100
    .      .
  345     12
    .      .
END
   50   4200   6150      CRT graphs
    1      1      2      3      .      .      .
    .      .      .      .      .      .      .
END
 .
 3105     77   -994   4200                                OE
 .                other tables, etc

ENDT
TMM028
 .

ENDT
 .

TMMxxx
 .

ENDT
ENDV
```

Fig. 3 Structural gradient TMM file.

heating factor, the location view factor, and trajectory related parameters. An example of this file is presented in Fig. 2.

Structural Gradient TMMs

The structural gradient TMMs are multidimensional models (two or three dimensions) that consist of TPS and various complex structural members. The objective of these TMMs is to define the structural temperature gradients between the primary skin structure and the frames, between skin structure and skin structure, between the frame inner and outer caps, etc.

These TMMs are inherently very complicated and difficult to construct. Hence the program maintains files that contain all existing TMMs for the different Orbiter structures. However, because of the size of the models, it is not practical to create a single TMM file that contains all existing models for OV-102, OV-103, OV-104, and OV-105 even though OV-104 and OV-105 are structurally identical to OV-103.

In order to maximize the efficiency and the maintainability of the TMM files, the Orbiter structure was divided into 11 different regions according to structural similarities and the corresponding TMM files were created. These 11 regions are forward fuselages 1 and 2, midfuselages 1 and 2, the aft fuselage, wing, elevon, payload bay doors, vertical tail, orbital maneuvering system (OMS) pod, and body flap.

Figure 3 presents the typical gradient TMM file. The TMMs are formatted not only to the automation algorithm, but also to the thermal analyzer requirements.[2] As shown in Fig. 3, the TMM file can contain many TMMs as long as the size of the temperature outputs does not exceed the limits of the computer memory allocation and the output processing capabilities of the peripherals. Nevertheless, it is good practice to keep both the TMM and the output files within a manageable size.

Smoothing TMMs

The smoothing TMMs (interpolation TMMs) are required to complete the structural thermal gradient analysis. The TMMs are used to calculate thermal gradient data where structural gradient TMMs do not exist. The smoothing calculations are performed using the correlations developed based on the temperature differences observed between the gradient TMMs and the one-dimensional TMMs evaluated at the same structural locations.

The smoothing correlations employ temperature extrapolation equations that define the sensitivity of heavy structure temperatures to the temperatures of surrounding skin panels. The correlations are, in general, expressed in terms of temperature differences between the two locations:

$$T_{sk}\,(2) = T_{sk}\,(1) + [T_{ss}\,(2) - T_{ss}\,(1)]$$

$$T_{fr}\,(2) = T_{fr}\,(1) + a\Delta T_{ss} + b\Delta T_{\Delta \bar{t}}$$

The TMM file used in the smoothing analysis is basically the same as the TPS acreage file except that each smoothing location is given an identifier, for example, L0877105, S1006400, or U0392062. This identifier is placed before each entry of the input data for the one-dimensional model generator. The letter L in the identifier indicates the lower surface, S the side surface, and U the upper surface. The first four digits indicate the X coordinate of the Orbiter and the last three, the Y or Z coordinate.

Penetration TMMs

The penetration TMMs, like the structural gradient TMMs, are multidimensional models that handle particular components of the Orbiter systems. The TMMs are analyzed to predict the maximum temperatures of the TPS singularities. The program maintains the files that contain all penetration TMMs. The format used by the program is the same as the format for the gradient TMMs (see Fig. 3).

Initial Conditions

As illustrated in Fig. 1, the thermal gradient TMMs are constructed with many nodal elements, each of which is assumed to be at a certain homogeneous temperature. In order to start the transient temperature calculations, however, the analyst needs to assign proper starting temperatures to all of the nodes. These temperatures are normally called the initial temperatures of the system. Depending on the number of nodal elements in the TMM network, the incorporation of the initial-temperature distribution could be very simple and fast when the system is at one starting temperature or it could be extraordinarily complicated and time consuming if the conditions are complex, as in Space Shuttle thermal gradient TMMs.

The program uses two methods for automatically implementing the initial condition in the TMMs: 1) the TMM BP method (also called the aeroheating BP method) and 2) the TMM known temperature relaxation method. When the TMM is at one starting temperature, the program uses the first method to identify the location of the TMM by the aeroheat-

```
  BP p1 p2 p3 p4 p5 p6 p7 p8 p9 s1 s2 s3 s4 s5 s6 s7 s8 s9 c1 c2
 100 11 24 32-48 58 13 96 43 12 39 11 89 23 45 18 29-51 90 75 90
1020 13 54 11-42 54 12 97 49 14 32 16 80 22 43 11 25-55 24 75 97
1100 16 23 35 59 78 33 46 73 22120 31 69 73 35 58 49-41 50 75120
1101 18 44 24-43 58 63 16-43 22 37 13 89 26 47 19 22-53103 75103
1200 11 24 32-48 58 13 96 43 12 39 11 89 23 45 18 29-51 90 75 96
1300 11 24 32-48 58 13 96 43 12 39 11 89 23 45 18 29-51 90 75 90
  .   .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .
  .   .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .

2550 31 54 22-58 28 53 86 53 62 29 41 19  3 35 10  9-51  0 75 86
  .   .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .
  .   .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .

3600 31 54 22-58 28 53 86 53 62 29 41 19  3 35 10  9-51  0 75 86
  .   .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .
  .   .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .

4470 31 54 22-58 28 53 86 53 62 29 41 19  3 35 10  9-51  0 75 86
  .   .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .

6999  2  4  3  5 10 11 23  0 72 52 11  4  2  1 12 34 83 12 75 83
```

```
Key:  BP = body point, p = port, s = starboard, c = p and s combined
      p1 is 6.0 loads case 1 port, etc.
```

Fig. 4 Initial-temperature file.

```
SNODE     X       Y      Z    RBP  HFTR    CODE        IBP
TMM038
   36 385.5    0.0 432.4   3120 1.049      X  3120   3200   3250
   37 390.5    0.0 432.4   3120 1.049      X
   38 395.5    0.0 432.4   3120 1.049      X
   39 399.3    0.0 432.4   3120 1.049      X
   40 400.3    0.0 432.4   3120 1.049      X
   41 402.1    0.0 432.4   3120 1.049      X
   42 406.0    0.0 432.4   3120 1.049      X
   43 411.0    0.0 432.4   3120 1.049      X
   44 416.0    0.0 432.4   3120 1.049      X
END
TMM039
 .  .      .      .      .      .      .      .      .      .      .

END
TMM040
 .  .      .      .      .      .      .      .      .      .      .

END
TMM132
   11 877.5   24.2    272   1500 1.007      Y  1500   1501   1502
                                                 1503   1504   1505
                                                 1506   1507   1508
   21 877.5   66.9    274   1501 1.000      Y
    1 877.5  100.3    279   1502 1.002      Y
   13 877.5  114.8    280   1503 1.000      Y
    2 877.5  134.4    286   1504 1.049      Y
    3 877.5  145.7    290   1506 1.000      Y
    4 877.5  153.5    295   1507 0.994      Y
    5 877.5  159.7    299   1508 1.068      Y
    6 877.5  153.5    347   4310 1.000      X  4310   4320   4330
    7 877.5  145.7    347   4320 1.000      X
    8 877.5  134.4    357   3506 1.000      Z  3506   3505   3504
    9 877.5  114.8    357   3506 1.000      Z
   10 877.5  106.8    357   3506 1.000      Z
   12 877.5  105.0    357   3506 1.000      Z
END
 .  .      .      .      .      .      .      .      .      .      .
 .  .      .      .      .      .      .      .      .      .      .

TMMxxx
  810  1456  124.3  270.9   1952 .9925      Y  1950   1952   1954
 .  .      .      .      .      .      .      .      .      .      .

END
```

KEY:

SNODE = SURFACE NODES OF GRADIENT TMMs

X, Y, Z = ORBITER COORDINATE

RBP = REFERENCE BODY POINT

HFTR = HEATING FACTORS ON SURFACE NODES

CODE = HEATING INTERPOLATION DIRECTION

IBP = BODY POINT USED FOR INTERPOLATION

Fig. 5 TMM BP file for structural TMMs.

ing BPs on the Shuttle Orbiter surface, which are locations where aeroheating and plume heating, shear stress, enthalpy, and pressure environments are defined as a function of trajectory time.

The TMM BP method requires an initial-temperature file in which temperatures are sorted by BPs and various on-orbit cases. An example of the initial-temperature file is presented in Fig. 4. Also contained in the file are 20 different cases of initial conditions that were obtained from the Orbiter geometric thermal math models (GTMMs), which define the entry temperature distributions on the Orbiter before entry. This file is organized so that each initial condition can be called out by specifying an initial-temperature code in the program input card. This is discussed in the program execution section.

Additionally, the TMM BP method requires TMM BP files that define the relationship between TMMs and BPs. These files list all of the BPs used in every TMM to guide the program from one file to another until the proper initial temperatures have been incorporated into the TMMs. Figures 2 and 5 illustrate TMM BP files for TPS acreage and structural gradient TMMs, respectively.

The logic of the TMM BP method is that, when the TMM is accessed by the controlling program, the Thermal Magic program identifies the aeroheating BPs called out in the TMMs, extracts the initial temperatures of the corresponding BPs from the proper column of the initial-temperature file, and incorporates the temperatures into the TMMs. This logic mimics the manual method of obtaining initial temperatures and implementing them in the TMMs. For the TPS acreage, sizing, smoothing, and penetration analyses, this method suffices since the analyses are either simplified one-dimensional point analyses or are confined to a very specific location that is known to be or assumed to be at one initial temperature.

However, for the analyses of complicated structural TMMs that encompass several areas of the Orbiter, the TMM BP method is not adequate because different areas of the Orbiter have different initial temperatures. In this case, the method for simplified point analyses cannot assign valid temperatures to all nodes of the TMMs although a portion or some nodes of TMMs will be assigned a correct temperature by the TMM BP method. In order to compensate for this shortcoming, another temperature file, called KNOWNTEMP, is used in conjunction with the TMM BP file.

The KNOWNTEMP file defines the initial temperatures of the specific nodes of the TMMs so that all nodes are properly assigned valid initial temperatures. But because of the large number of nodes existing in the TMMs, it is almost impossible to make a file that contains all of the nodes of every TMM. To minimize effort in creating the KNOWNTEMP file while ensuring reasonable distribution of initial temperatures in the entire TMM, a group of surface and structural nodes were selected for the assignment of correct initial temperatures. The nodes selected include outermost insulation nodes, such as TPS surface, and representative boundary structural nodes.

When the initial temperatures have been implemented in the selected nodes of the TMMs, the program performs the temperature calculation until the steady-state solution is obtained for all of the nodes of the system. The final temperature distribution is achieved by solving the steady-state heat equation:

$$K_x \frac{\partial^2 T}{\partial x^2} + K_y \frac{\partial^2 T}{\partial_y{}^2} + K_z \frac{\partial^2 T}{\partial z^2} = 0$$

where K_x, K_y, and K_z are thermal conductivities in the X, Y, and Z directions, respectively. This is called the known-temperature relaxation method. Figure 6 shows the result of the initial implementation of the temperatures, and Fig. 7 presents the temperature distribution after the temperature relaxation method is executed. Judging from the previous analysis results, the known-temperature relaxation method is the most economical and efficient way of automating initial-temperature implementation procedures for complex TMMs. An example of the KNOWNTEMP file is shown in Fig. 8.

Boundary Conditions

Aeroheating and Plume Heating Environments

The Orbiter heating environments used in Space Shuttle thermal analyses are characterized by the aeroheating BPs. All TMMs, whether TPS acreage, smoothing, penetrations, or structural gradients, must always have aeroheating BPs as their source of heating during ascent and entry flight. The aeroheating environments are defined at every BP location as a function of trajectory time.

The aeroheating environments are normally stored in the form of compressed data (machine language) on tapes or on devices called diskpacks. These heating values are stored using the numbers assigned to the BPs and can be called out by specifying their index locations.

The manual method used in the past for Orbiter thermal analyses forces engineers to specify the index numbers of all of the BPs needed in the analyses and manually input them into the TMMs. This process took considerable effort and also was subject to many errors. This problem was overcome by standardizing the heating card format so that the Thermal Magic program can identify the BP heating card location in the TMMs and implement the proper index numbers of the required BPs using the information it retrieves from the heating storage tapes or diskpacks. An example of the BP heating card (shown as 3150 77 -994 4200 OE) is presented in Fig. 3.

It is important to remember that the thermal gradient TMMs use not only the heating called out from the diskpacks or the tapes, but also heating multiplication factors. These heating factors are required because the locations of the TMM surface nodes rarely coincide with the exact locations of the BPs. Consequently, heating incident on the TMM surface

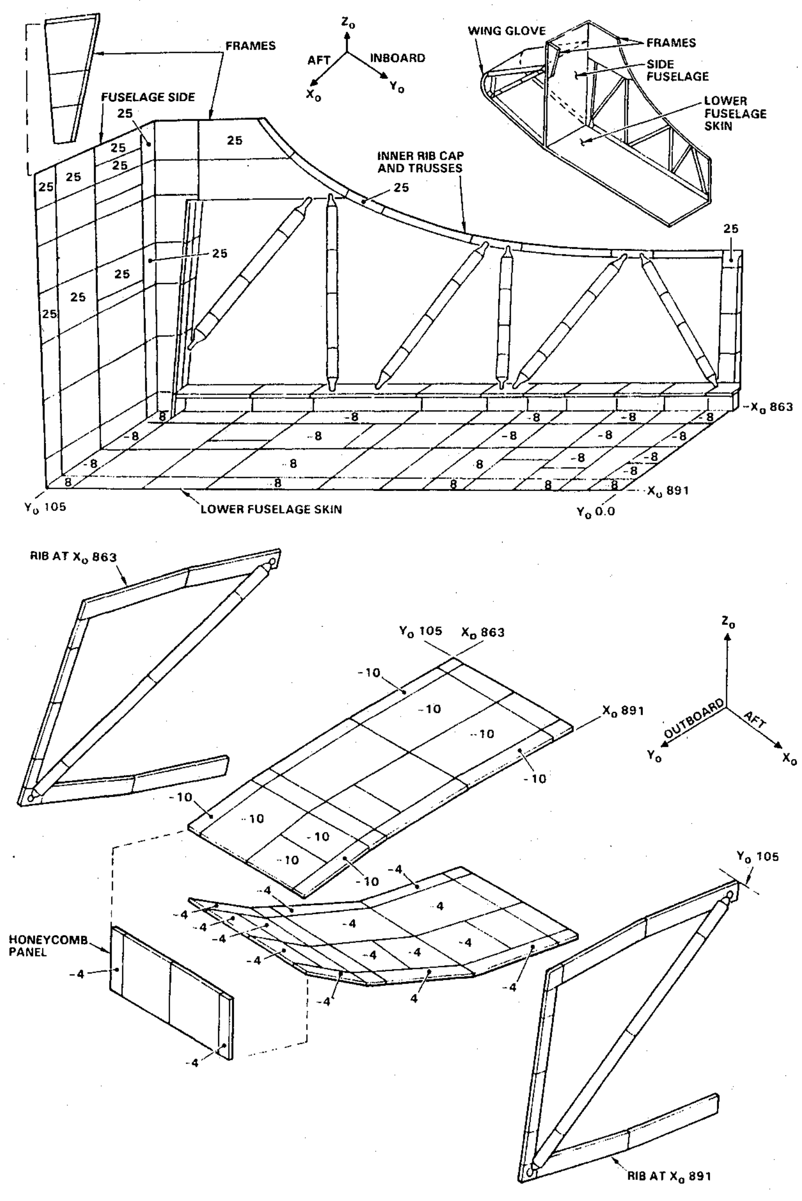

Fig. 6 Starting implementation of initial conditions for TMM 132 fuselage at wing glove intersection.

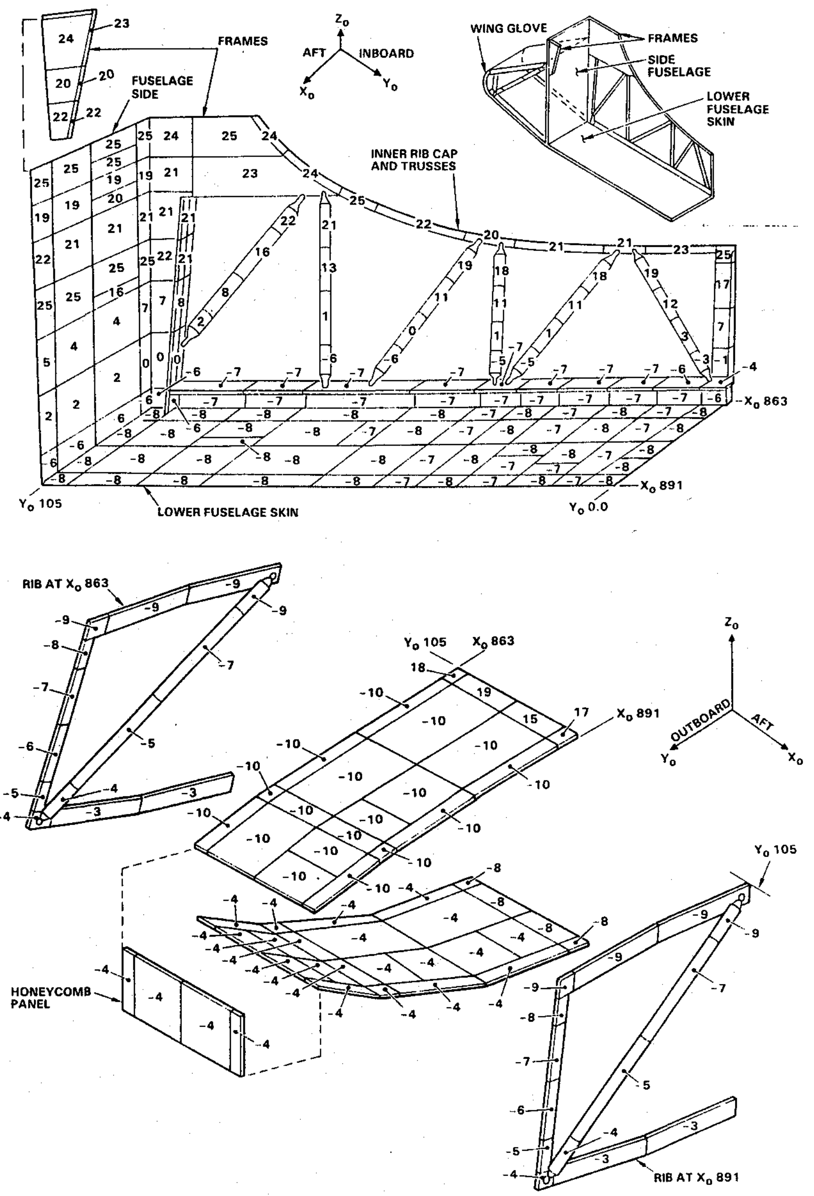

Fig. 7 Initial-temperature distribution after relaxation for TMM 132 fuselage at wing glove intersection.

needs to be interpolated to simulate the heating profiles at the nodal points accurately. These heating interpolations were done manually by using the coordinates of the adjacent BPs and nodal points. This process requires considerable time simply because there are so many surface nodes whose heating needs to be interpolated. The Thermal Magic program handles this interpolation automatically when users specify the interpolation option. The direction in which heating interpolation is performed is defined in the TMM BP files (Fig. 5) as codes X, Y, or Z. An example of this option is presented in the program execution section.

The plume heating environments required in the TMMs can be treated similarly. These environments are essentially the same as the aeroheating environments except that the sources of plume heating are the Space Shuttle main engines (SSMEs), the solid rocket boosters (SRBs), or the reaction control systems. Plume heating is only differentiated from aeroheating by the storage locations on the tapes or diskpacks. Therefore, the plume heating enviroments can be easily implemented in the TMMs by assigning different heating table numbers while using the same aeroheating BP numbers. For this purpose, the table numbers used in the program were organized as shown in Table 1.

Table 1 BP table organization

BP table no.	Description	Trajectory[a]
− (BP × 10 + 1)	Convective aeroheating	OE or AE
− (BP × 10 + 2)	Radiative aeroheating	OE or AE
− (BP × 10 + 3)	Enthalpy	OE or AE
− (BP × 10 + 4)	Pressure	OE or AE
− (BP × 10 + 5)	Shear stress	OE or AE
− (BP × 10 + 6)	Convective plume heating	OA or PA
− (BP × 10 + 7)	Radiative plume heating	OA or PA
− (BP × 10 + 8)	Enthalpy	OA or PA
− (BP × 10 + 9)	Shear stress	OA or PA

[a]OE = Orbiter entry; AE = Orbiter ascent and entry combined; OA = Orbiter ascent; PA = plume ascent.

The required trajectory information is provided in the columns of the BP heating cards (...OE in Fig. 3) so that the program can recognize the types of heating. Using this trajectory code and its associated index numbers allocated to the required BPs, analysts can easily call out the aeroheating and plume heating environment for the TMMs automatically.

It should be noted, however, that the TMMs for the structural gradient analyses should have adequate heating table callouts so that the program does not encounter inconsistencies between the BPs and corresponding table callouts. This is required because of the characteristics of the thermal analyzer codes used as a subroutine of this automation program.[2] For the simplified one-dimensional TMMs, the heating table number is automatically assigned by the model generator program, and therefore this inconsistency does not exist.[3]

The heat equation used by the thermal analyzer codes[2] for the temperature calculation on the boundary TPS nodes is

$$q_{ch} = F\alpha A q_s$$

where α is the absorptivity for solar heat flux or a heating multiplication factor.

Flight Pressure Environments

Pressure environments are also required in the Orbiter thermal analyses because thermal properties, especially the thermal conductivities of the TPS materials, are pressure dependent. Like the heating environments, the flight pressure environments are defined at each BP location as a function of trajectory time. These pressure environments are needed for determining the thermal conductivities of the TPS materials as a function of pressure and temperature. These conductivities are calculated based on linear interpolation between the two pressure values at each temperature level, that is,

$$k(p) = \{[k(p_2) - k(p_1)](p - p_1)/(p_2 - p_1)\} + k(p_1)$$

They are then used for calculating the transient thermal conductances and resistances of the TMM nodes.

The Thermal Magic program utilizes the same BP heating cards to identify the pressure tables needed in the TMMs and calls out the flight pressure profiles of the required BPs from the data storage devices. This is performed by locating correct indices of those BPs based on the automatic index implementation method previously discussed.

Conduction

A conduction heat transfer mechanism is established in the TMMs based on a conventional resistance-capacitance network. Temperature distributions at all nodal points at any time are obtained by evaluating the heat equation:

$$\rho C_p \frac{\partial T}{\partial \Theta} = K_x \frac{\partial^2 T}{\partial x^2} + Ky \frac{\partial^2 T}{\partial y^2} + K_z \frac{\partial^2 T}{\partial z^2}$$

In the boundary of the solution domain, the condition to be satisfied is

$$-K \frac{\partial T}{\partial n} = q_t$$

where $\partial T/\partial n$ is a temperature derivative in a normal direction and $q_t = q_{ch} + q_{ri} + q_{rr}$.

Reradiation

The reradiation to space is established in the TMMs to account for the energy that emanates from the hot surface of a system. The heat flux arising from this is calculated on the TPS surface nodes using the equation

$$q_{rr} = \sigma A \epsilon_f (T_i^4 - T_{\text{sink}}^4)$$

Presently, the program does not need to change any of the data specified in the reradiation block since the automation program recognizes the data format of this boundary condition and accurately rebuilds the boundary conditions for the temperature evaluation.

```
 Node  p1 p2 p3 p4 p5 p6 p7 p8 p9 s1 s2 s3 s4 s5 s6 s7 s8 s9 c1 c2
TMM080
   301 13 56 18-42 58 13 95 47 18 33 26 30 72 23 81 45-65 24 75 37
   318 26 33 15 49 58 23 66 33 82 20 26 65 72 34 56 48 41 10 75 20
   308 18 44 24-43 58 23 66 43 22 37 13 89 26 47 19 22-53103 75 13
   336 21 34 22-48 58 19 76 43 19 38 12 88 21 42 18 29-51 90 75 96
   337 11 24 32-48 58 13 96 43 12 39 11 89 23 45 18 29-51 90 75 90
    .   .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .
    .   .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .

  824  31 54 22-58 28 53 86 53 62 29 41 19  3 35 10  9-51  0 75 86
END
    .   .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .
    .   .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .
    .   .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .

TMM132
    11  1 33 42 34 87 24 67 22 10 25 21 -6 27 36 62 50  1 23 75 90
     .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .

   208 31 54 22-58 -8 13 36 63 32 28 45 13 -3 33 12 19-51  0 75 16
   228 31 54 22-58 -8 13 36 63 32 28 45 13 -3 33 12 19-51  0 75 16
     .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .

END
     .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .
     .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .
     .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .

TMM200
     3 21 24 34 11 24 46 28 24 65 -2 34 -1 34 53 32 43 67 23 64 32
     .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .

    13 23 27 33 12 26 44 28 20 63 -6 39 -5 32 56 38 42 65 26 64 38
     .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .

END
 .
 .

TMMxxx
     .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .

END
```

Fig. 8 KNOWNTEMP file for structural TMMs.

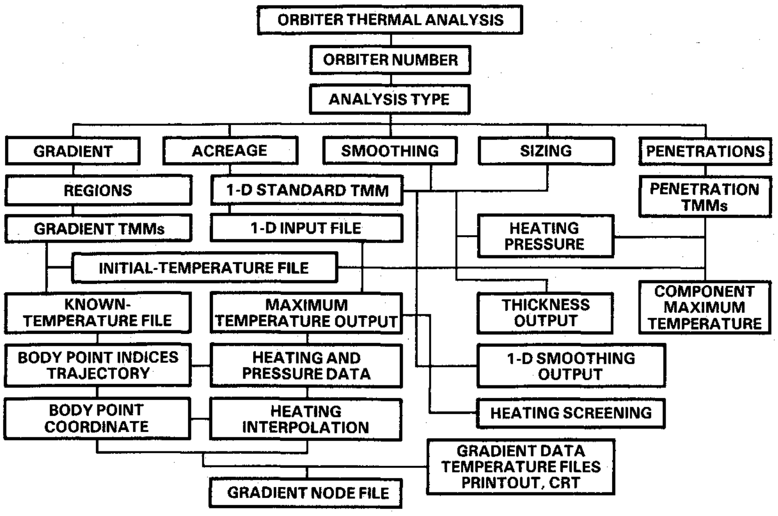

Fig. 9 Orbiter thermal analysis program flow diagram.

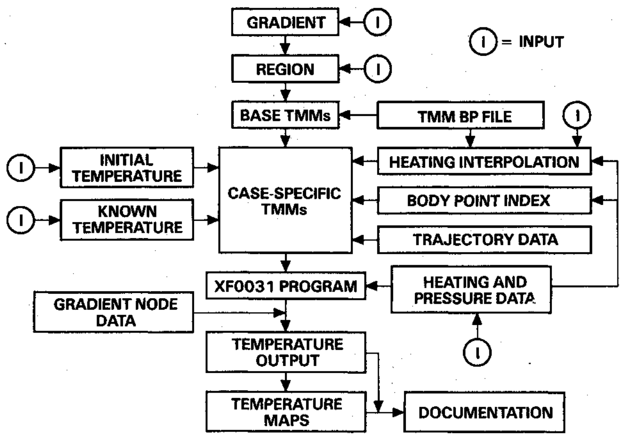

Fig. 10 Typical analysis flow of gradient TMMs.

Radiation Interchange

The radiation interchange boundary condition is set up in all structural gradient TMMs to account for heat transfer between structural members, i.e., between the skin and frames, skin and skin, frames and frames, etc. The automation program recognizes the data format of this boundary condition and precisely reconstructs the TMMs for the temperature evaluation.

The temperature is calculated based on the regular radiation equation:

$$q_{ri} = \sigma A \epsilon_f (T_i^4 - T_j^4)$$

Internal Convective Cooling

Internal convective cooling is a forced convective heat transfer mechanism that takes place after the Orbiter vents are opened during re-entry. The vents are located on the port and starboard sides of the Orbiter. The vent doors are designed to open when the velocity of the Orbiter reaches approximately 2400 fps. This usually occurs at an altitude of approximately 80,000 ft in order to alleviate structural aerodynamic loads. As a result, air is ingested through the vent openings and starts to cool the hot skin structures or heat the cool structures.

This heat transfer mechanism can be described using Newtons well-known law of cooling:

$$q_{cc} = hA(T_w - T_f)$$

The convection film coefficient h has been empirically developed using flight data available from Orbiter developmental flights. The empirical equation of the film coefficient is formulated as follows[4]:

$$h = c[(T/T')(V/V')(P'/P)]^{1.6}$$

This forced convective heat transfer takes place only during TAEM, which begins when the vents open. Each trajectory has its own characteristics, and the exact time when the Orbiter reaches the velocity of 2400 fps differs from mission to mission. Therefore, it was necessary for the program to have the capability to automatically implement the correct event times for the air vent opening and touchdown. The program reads these trajectory parameters from the user input and incorporates them into the convection data block of the TMMs. This is established by assigning a code word to the TMMs so that the program identifies the exact location of the flight parameters for TAEM and touchdown. An example of a code word in Fig. 3 is 9999.......98.

Known-Temperature Data

The known-temperature data block is used to assign predetermined fixed temperatures or temperature histories to any nodes in the TMMs. This data block is often used for implementing the system initial temperatures, as discussed previously; but it is also used to drive the TMM surface or structure nodes in a prescribed manner, for instance, to simulate the actual flight temperatures obtained from thermocouples.

The Thermal Magic program identifies the code word KNO built into the TMM data files and automatically assigns known-temperature data. The temperature calculation is carried out using the equation:

$$T_i = T(\theta)$$

where θ denotes time.

Program Execution

Automation Flow Diagram

The flow diagram of the Thermal Magic program is presented in Fig. 9 to aid in understanding the process of the automation. The diagram has been made as concise as possible to show the data links between the data base files; however, an example of the detailed analysis flow for the typical gradient analysis is shown in Fig. 10.

Inputs

The execution of the program requires users to define various parameters in an input card. The input card must contain the following information: the Orbiter number; the type of analysis; the trajectory code; event times for entry interface, TAEM, and touchdown; the flight environment data set number; the heating screening code; and the initial-temperature code. An input card is illustrated in Fig. 11 with a brief description of the input data.

Job Submittal and Job Control Language

The job submittal of the program is achieved by sending an input to a remote host computer using job control language (JCL). JCL contains the user input as well as the information on the program and storage locations of all required data base files, such as TMM files, initial-temperature files, known-temperature files, TMM BP files, BP coordinate files, and the one-dimensional standard TMM file. Temperature outputs are usually stored as computer files with hard-copy printouts of summary temperatures available (maximum temperatures and representative gradients at TAEM and touchdown), but users can specifically define the types of outputs they require. These include temperatures and transient-temperature history outputs and graphs in both hard copy and microfiche. An example of a JCL is illustrated in Fig. 12. It should be noted that the JCL presented is for the IBM host computer, and data allocations are presented only for reference.

The sample JCL is for evaluating thermal gradients on the Orbiter's wing; however, the same JCL set can be stacked with different inputs for calculating thermal gradient data on all 11 regions. The same area can also be analyzed repeatedly for

```
xxx103 2000G EOM  4200  5975  6352  200P  214   0 2.0  -1 2000
C -  6.0 loads thermal gradient analysis  EOM  Area(xxx)
C -  +ZLV initial condition port
```

Input	Description
xxx	Areas—FD1, FD2, LID, MID, AFT, WNG, EVN, CBS, VTL, OMS, BFP
103	Orbiter number—102, 103, 104, 105
2000	Number of BPs in data set 1
G	Analysis code—G = gradient, A = acreage, P = penetrations, S = smoothing, Z = sizing
EOM	Trajectory code—EOM, AOA, AFO, TAL
4200	Entry interface—4200 (EOM, AOA, AFO), 682 (TAL)
5975	Air vent opening time
6352	Touchdown time
200	Data set number 1—flight environment data set
P	BP print bypass code for gradient analysis
214	Data set number 2—reference data set for comparisons
0	Heating screening code for gradient TMMs—1 or 0
2.0	Heating screening factor for TPS acreage TMMs—%
-1	Initial temperature code—1 through 20
2000	Number of BPs in data set 2

Fig. 11 Inputs and descriptions.

```
//$TTxxx  JOB ' HONG  .          DEPT        EDPM          CCC3 ,
//         REGION=3072K,TIME=60,MSGLEVEL=1
//*MAIN    ORG=RM001,LINES=500
//*FORMAT  PR,DDNAME=SYSUT2,DEST=RM001PR5,FORMS=FICH
//*FORMAT  PR,DDNAME=FT36F001,DEST=RM001
//G        EXEC PGM=CERT31
//STEPLIB  DD DSNAME=$TTxxx.CERTSH.LOAD
//FT02F001 DD DSNAME=&&TAPE02,UNIT=SYSDA,SPACE=(TRK,(99,9)),
//         DCB=(BLKSIZE=12000,RECFM=VBS,LRECL=X,BUFNO=1)
//FT03F001           .         .          .          .
//  :                :         :          :          :
//FT12F001 DD DSN=$TTxxx.DATA.SET187,UNIT=3380,DISP=SHR,
//         VOL=SER=TTLIBA
    :                :         :          :          :
//FT19F001 DD DSN=$TTxxx.STD1DTMM.DATA,DISP=SHR
//  :                :         :          :          :
//FT26F001 DD DSN=$TTxxx.GRADTMM.DATA,SIDP=SHR
//FT29F001 DD DSN=$TTxxx.TMMBP.DATA,DISP=SHR
//  :                :         :          :          :
//FT30F001 DD DSN=$TTxxx.DATA.SET214,UNIT=3380,DISP=(SHR,KEEP)
    :                :         :          :          :
//G.SYSIN  DD*
WNG103 2000G EOM  4200  5975  6352  187P  200  0   0  -5 2000
C - OV-103 6.0 loads,area(wing) Initial condition ; Top sun
/*
//FICHE    EXEC PGM=IEBGENER
//SYSPRINT DD SYSOUT=A
    :                :         :          :          :
/*
//
```

Fig. 12 Sample JCL.

various initial conditions by specifying the proper initial-temperature codes in each set of the JCL. These types of job execution can save a considerable amount of job preparation time and also minimize errors since the JCL can be standardized easily to suit any job objective.

The documentation of the analysis results must be mentioned here. Conventionally, the job outputs were reviewed manually by summarizing the temperature data at the representative TMM nodal points to verify the validity of the calculation. However, with the capability of the automation program to summarize temperatures and the proper definition of the output destination in JCL, the temperature review process is shortened significantly. The output of the automation program includes temperature summary printouts that document the maximum temperatures of the TPS and the structure at all BP locations evaluated (acreage, sizing, and smoothing), component maximum temperatures and their time of occurrence (penetrations), and maximum skin temperatures and representative thermal gradients at TAEM and touchdown.

Application

It is expected that the automation techniques obtained from the Shuttle Orbiter thermal analyses could be applied easily to the development of other hypersonic re-entry vehicles, such as NASP and ACRV. Any spacecraft that is designed to withstand ascent, on-orbit, and re-entry environments should have TPS. However, since the design of TPS materials is closely related to vehicle weight, which directly affects the operational cost and performance of the spacecraft, it is imperative to design adequate TPS materials in terms of their minimum required thicknesses.

From the thermal standpoint, usually two things must be considered in determining the proper types and thicknesses of TPS materials: the maximum temperature allowable limits of the skin and TPS components and thermal gradients. The minimum thicknesses of the materials that are required to protect the primary skin from excessive heat during flight or from the extreme coldness of space vary largely, depending on their locations on the spacecraft.

Therefore, in order to adequately define TPS thicknesses for spacecraft, it is necessary to perform a large number of TPS sizing analyses. Sizing analyses have been performed on a local area basis, i.e., at each BP location, using manually built, one-dimensional sizing TMMs. Thus, engineering time was directly related to the number of sizing analyses performed. Furthermore, coverage of the areas of the spacecraft was almost always somewhat compromised to meet pressing delivery schedules. Even after the sizing task was complete, a significant amount of engineering time was required for verification analyses of the faired TPS thicknesses, maximum temperature evaluations, and thermal gradient definitions.

With the automated analysis procedures discussed in this paper, however, such tasks can be performed easily even when thermal analyses are required for every location on the spacecraft and must be repeated many times. And other capabilities of the automation program, such as smoothing techniques, permit the preliminary airframe design to be performed to eliminate thermal load problems in the early stages of spacecraft design.

Heating interpolation and screening features of the Thermal Magic program can be applied to many different types and stages of the thermal analysis. The trajectory difference can be evaluated easily by performing the heating interpolation option of the program, and heating screening would help reduce the amount of work to a minimum level by bypassing TMMs in areas where the heating changes are believed to be negligible.

In summary, the automation program, which was developed to minimize the engineering time required for Orbiter thermal analyses, is believed to be a very effective engineering tool for evaluating the design and performance of current and future hypersonic flight vehicle systems.

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