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THREE DIMENSIONAL HEAT TRANSFER PROGRAM

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I. Summary

An IBM 7094, three dimensional, heat transfer program for satellite application is discussed. The program may be applied to all phases of spacecraft life, from launch to orbital quasi-steady state. Launch phase heating includes inputs by radiation from the hot fairing and free molecule flow heating after nose cone ejection. Orbital heat fluxes are accounted for by direct sunlight, earth-reflected sunlight, and earth-emitted input to the satellite.

Internal heat exchange by conduction and radiation is determined, provided the appropriate conductances, radiation view factors, and effective emittances are known.

A simplified analysis of an active thermal controlled spacecraft is incorporated into the program. One or more surfaces may contain shutter systems which have optical properties specified as a function of shutter opening. The program evaluates the feasibility of any configuration based upon maintaining an internal component within its tolerable temperature limits.

The program employs a matrix inversion subroutine (Gauss Elimination Method) to solve the heat balance equations.

II. General Discussion

In practice, the thermal analysis of a spacecraft consists of the development of the thermal model which represents a fine mesh of interconnected isothermal nodes. The appropriate relationship between nodes regarding thermal conduction and radiation interchange must be established.

The general energy balance for each node of a thermal model may be written

$$P_n + S\alpha_s Ap_n + q_{alb_n} + q_{es_n} + \sum_m C_{nm}(T_m - T_n) + \sum_m \sigma E_{nm} F_{nm} \cdot (T_m^4 - T_n^4) + q_{a_n} + q_{F_n} = \sigma \epsilon_n A_{s_n} T_n^4 + WC_{p_n} \frac{dT_n}{dt_n} \quad (1)$$

where

P_n = internal power dissipation of node n

S = solar constant

α_s = solar absorptance

Ap_n = instantaneous projected area for sunlight of node n

q_{alb_n} = absorbed earth-reflected solar radiation (albedo)

q_{es_n} = absorbed earth-emitted radiation (earthshine) by node n

σ = Stefan-Boltzmann constant

ϵ_n = infrared emittance of node n

As_n = surface area of node n

WCp_n = heat capacity of node n

dT/dt = time rate of change of node n temperature

C_{nm} = thermal conductance between nodes n and m

E_{nm} = effective emittance between nodes n and m

F_{nm} = shape factor area product between nodes n and m

q_{an} = free molecule flow heating to node n

q_{Fn} = radiation from fairing absorbed by node n (when fairing is present external radiation sources are 0)

The solution of the n simultaneous equations shown above is performed by the IBM 7094 digital computer with a matrix inversion routine (Gauss Elimination Method). However, since the inversion applies only to linear simultaneous equations, the fourth power temperature terms must be linearized. This is done by retaining the first two terms in the Taylor Expansion around T_n.

$$
\begin{aligned}
T_n^4 &= (T_{in} + dT)^4 = T_{in}^4 + 4T_{in}^3\, dT + \frac{4\cdot 3}{2!} T_{in}^2\, dT^2 + \cdots \\
T_n^4 &\cong T_{in}^4 + 4\, T_{in}^3\, dT \\
T_n^4 &\cong 4\, T_{in}^3\, T_n - 3T_{in}^4
\end{aligned}
\tag{2}
$$

where T_{in} is (a) the initial value of T_n for steady state conditions or (b) the temperature at the beginning of time increment Δt during transient cases. Substituting this result into (1), the general equation in matrix form becomes

$$
\begin{aligned}
&[B_{nm}] \times [T_n] = [D_n] \\
&\text{where } B_{nm} = -C_{nm} - 4\sigma E_{nm} F_{nm} T_{im}^3, \ (n \neq m) \\
&\qquad B_{nm} = \sum_m C_{nm} + \sum_m 4\sigma E_{nm} F_{nm} T_{in}^3 + 4\sigma \epsilon_n As_n T_{in}^3 \\
&\qquad\qquad + WCp_n / \Delta t, \ (n = m)
\end{aligned}
\tag{3}
$$

$$
\begin{aligned}
D_n = {} & S\alpha_s Ap_n + P_n + q_{alb_n} + q_{es_n} + q_{a_n} + q_{F_n} + \frac{WCp_n}{\Delta t} T_{in} \\
& + 3\sigma\epsilon_n As_n T_{in}^4 + \sum_m 3\sigma E_{nm} F_{nm} (T_{in}^4 - T_{im}^4)
\end{aligned}
$$

Since this procedure is an approximation, the error involved may be significant when T_{in} and T_n vary by more than a few degrees. For steady state problems an iterative procedure is required to approach the correct value of T_n. Convergence is not reached until all nodal temperature changes are reduced to within a specified tolerance. Experience has shown that if initial temperature estimates are within $50^{o}C$ of the converged values, only 2 - 3 iterations are required before the results are virtually constant.

Transient problems employ the same matrix inversion routine except each calculation represents the net energy exchange during a specific time interval. Since the solution of simultaneous equations is implicit, instability of the temperatures is not a problem. Thus, the results of high conductance and (or) low heat capacity do not adversely affect the numerical solution as they do in most explicit techniques. Care, however, must be taken in choosing a time interval. Although instability will not occur, no guarantee exists that the resulting temperatures are correct. For instance, calculations during a normal orbit at one minute intervals may be satisfactory since the environmental heat fluxes do not vary significantly (except perhaps at sunrise and sunset). However, when considering the launch phase, calculations must be on a second basis due to the rapid rise and attenuation of fairing and free molecule flow heating rates. The short time interval is required both to obtain accurate integrated heat fluxes as well as to minimize significant temperature oscillations on spacecraft skins and externally mounted components (lightweight). The same argument can be applied to sunrise and sunset periods during the orbital phase. The two major considerations used to determine the calculating time are, therefore:

(1) Accuracy in obtaining integrated heat flux, and

(2) Change in nodal temperature during a time increment.

The effect of these inputs depends upon the particular requirements of the problem.

The most straightforward procedure regarding (2) is to permit the program to calculate the time interval based upon a specified permissible temperature change. This method, by necessity, involves an iteration for the time increment determination. At present, the program provides only for a specified calculating time. The value is based primarily on previous experience gained with respect to the particular situation.

III. Discussion of Specific Environments

A. Launch Phase

The thermal environment encountered by the payload during launch consists primarily of radiation from the hot nose cone prior to fairing ejection and free molecule flow heating thereafter. Because of the short time involved (3 to 5 minutes) the concern is generally for spacecraft skins and (or) externally mounted components.

Each surface element (or node) is assumed to view primarily one portion of the fairing whose temperature history is known. The fairing is generally divided isothermally into nose cap, cone, and cylindrical sections.

Upon ejection of the fairing, the infrared radiation source is replaced by aerodynamic or free molecule flow heating, The extent of this heating is based upon the kinetic energy available ($1/2\ \rho v^3$) of the impinging air and the projected area of the corresponding surface normal to the velocity vector. It is conservatively assumed that all of the kinetic energy of the air is imparted to the impinged surface. The analysis in this case depends upon a knowledge of the vehicle's trajectory in addition to the surface projected area.

B. Orbital Phase

1. Solar Input

The solar input may be a constant value per surface node or a time-dependent variable. The variation may be due to change in orientation with respect to the sun as well as eclipse by the earth. The possibility of internodal shading or reflections must be pre-determined since the program employs only net solar flux to a surface.

2. Earthshine and Albedo

Earthshine and albedo generally represent between 15% and 30% of the total energy input to a near earth satellite. At present, constant or average values per orbit are used. Albedo may be combined with the solar input if a transient variation is deemed necessary.

3. Internal Power

Internal power can be read in only as a constant.

IV. Active Control Option

The purpose of the active control option is to evaluate the design feasibility of simple shutter systems. One control temperature with specified limits is taken within the spacecraft. The effective absorptance and emittance as a function of shutter opening must be known. The results indicate whether the system can handle the imposed extremes in thermal environment.

V. Alternate Transient Solution

In many instances (especially when many nodes are involved) the implicit matrix inversion technique becomes inefficient from the standpoint of computer time. A simple finite different explicit solution has been programmed as an alternative. This option proves advantageous if high conductances and/or low heat capacity are not present to restrict the calculating time interval to extremely small values. The small time interval is necessary to prevent instability of the nodal temperatures. It has been shown with a 25 node problem that the finite difference solution offers no time saving over the matrix inversion.