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Optimization of Thermal Systems With Sensitive Optics, Electronics, and Structures

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SECTION 1

INTRODUCTION

The purpose of the work reported here was to develop a computational strategy by which spacecraft thermal designers could devise an optimal thermal control system to minimize thermal distortion. Control would be maintained by the optical coating pattern chosen for the external surfaces and the heaters chosen to supplement the coatings. The coatings and heaters were to maintain the required temperatures, temperature differences, changes in temperatures and changes in temperature differences for specified equipment and elements of the structure. A strategy appropriate to computer-aided design was anticipated.

Most spacecraft use optical coatings and heaters for temperature control. The optical coatings are placed on the external surfaces to control the amount of sunlight absorbed and the amount of infrared radiation emitted. If the temperature control obtained with the coatings is adequate, the design imposes no weight or power penalties on the mission. However, for the increasingly sophisticated mission-related equipment, such as optical telescopes, the temperatures must be controlled closer than is possible with coatings alone. The uncertainty in the coating properties and the changes in the coating properties over the mission life usually result in an unacceptable temperature range. In addition, the vehicles must usually operate in many different orientations, with respect to the sun, so that a coating pattern appropriate for one flight might be totally inappropriate for another. Therefore, the coatings must be supplemented with another temperature-control method. The method normally chosen is thermostatically controlled heaters. These are accurate, light, reliable, and easily applied to any part of the structure or equipment. However, heaters draw power and therefore impose both weight and power penalties on the mission.

The pioneering work in the optimal thermal design of spacecraft was done by Costello and others in 1968 (Ref. 1). Temperatures were to be controlled by coatings alone. In addition, only the time-average temperatures were considered, with the time period being the orbit period. Casagrande attempted to extend this work to include the fluctuations in temperatures during the orbit (Ref. 2); however, he was successful only for ideal cylindrical satellites with one internal node. Neither investigator considered the uncertainties in the coating properties; therefore, neither method has found much use in industry.

In the present work, we focused on the development of a practical tool for the designer: an optimization program compatible with his present analytical tools and useful in the conceptual-design phase. We initially examined the general problem of spacecraft temperature control, including all phases of the mission and all phases of the design process. Indeed, the optimization criteria developed are generally applicable. However, the primary need appears to be in the conceptual-design phase, when the weight and power penalties have an important impact on mission planning. After the weight and power budgets are established, optimization is less important; it usually consists of maximizing the design margins within the budgets.

We have succeeded in developing an optimization strategy including all of the elements normally considered by the designer: various vehicle orientations, various equipment power dissipations, coating-property uncertainties, uncertainties in the internal thermal conductances, and coating-property changes.

The method uses the same thermal model data the designer develops for his analyses; there is no extra work. He can use his intuition to speed the optimization process and to simplify the resultant heater arrangement, but he can also use the process as is. We have demonstrated how the optimization process can be computerized. The results will be in the form of a specification of the coating pattern to be used on each external surface, the heater capacities required for each node, the average power required for each mission, and the maximum and minimum temperatures expected for each node. However, the method is limited to quasi-steady-state temperatures. The designer must select time periods over which steady-state temperatures are representative of the mission temperatures. Because most sensitive equipment is located well inside the vehicle, his selection is usually not difficult and the orbital period is adequate.

SECTION 2

BACKGROUND

The complexity of the mathematics describing the optimization problem presented in the following section, gives some indication of the complexity of the problem facing the thermal designer. There are too many variables to permit a manual, systematic search for the optimal design. Usually the designer will start with a simple model of the vehicle with a uniform external coating pattern, and compute the resultant temperatures. He may vary the coating pattern to offset some of the extreme temperatures (if he can foresee the effects for all possible missions and vehicle orientations) or he may select a uniform coating pattern that keeps the equilibrium temperatures low, and then select heaters to maintain the desired node temperatures. As the vehicle design becomes more definite, he builds a more detailed thermal model of the vehicle, computes the temperatures for representative missions, and modifies the design -- usually as little as possible -- in the search for a coating pattern that keeps the heater power within the budget predicted with his original simple model. Most of the design modifications are in the form of interior insulation, thermal straps, special component mounting procedures, and, if necessary, heat pipes. Usually it is too difficult to pick an external coating pattern because the thermally most severe missions or vehicle orientations then become difficult to identify.

The Coating Selection Program developed by Costello under NASA contract in 1968 was an early attempt to assist the designer (Ref. 1). Initially the program was used extensively. Some of the early optimizations indicated that some spacecraft for which the designer selected a black coating would have performed better thermally with a polished surface. However, for tight temperature control, the uncertainty in the properties of the polished surface gave unacceptable uncertainties in the equipment temperatures. The Coating Selection Program soon fell out of use and the designers went back to their semi-intuitive methods.

To avoid the shortcomings of the Coating Selection Program, we interviewed many thermal designers and some systems engineers. Our own experience in thermal design helped. From the interviews, we developed a list of elements that should be considered in the thermal design process. From these, we synthesized a strategy that included all of the elements.

The two-tier aspect of the design process was an important consideration in developing the strategy. Early in the design process, the weight and power budgets are undefined. The thermal models usually consist of at most several hundred nodes, and design tradeoffs can have an important impact on the mission. Later in the design process, the designers seek to increase the design margins within the fixed budgets. We have chosen to develop the thermal-optimization procedure for the early stage of design because at that point it has a greater impact on the mission.

SECTION 3

DEFINITION OF THE OPTIMIZATION PROBLEM

3.1 SIMPLE EXAMPLE

Before presenting the precise mathematical formulation of the optimization problem, we will present a sample problem. The rigorous mathematical definition of the optimization problem tends to become confusing because so many symbols are required. The sample problem will help in understanding the more abstract equations presented in the next section.

Consider the three-node problem shown schematically in Figure 1. The vehicle is divided into two external nodes, Node 1 and Node 2, and one internal node, Node 3. The vehicle can be envisioned as two concentric cylinders that are infinitely long.

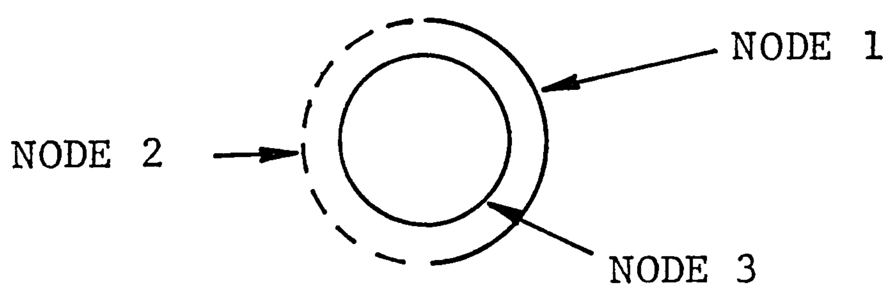


Figure 1. Three-Node Problem

To keep the problem simple, we will linearize the radiation terms. The heat-balance equations for the nodes can then be written:

$$
\begin{aligned}
0 &= K_{13} \cdot (T_3 - T_1) + K_{12} \cdot (T_2 - T_1) + a_1 \cdot S_1 + e_1 \cdot (E_1 - H_1 \cdot T_1) + Q_1 \\
0 &= K_{23} \cdot (T_3 - T_2) + K_{12} \cdot (T_1 - T_2) + a_2 \cdot S_2 + e_2 \cdot (E_2 - H_2 \cdot T_2) + Q_2 \qquad (1) \\
0 &= K_{13} \cdot (T_1 - T_3) + K_{23} \cdot (T_2 - T_3) + Q_3
\end{aligned}
$$

Where

K_{ij} = the conductance between Node i and Node j

T_i = the temperature of Node i

a_i = the solar absorptance of Node i

S_i = the solar radiation on Node i

e_i = the infrared emittance of Node i

E_i = the earth radiation onto Node i

H_i = the thermal conductance to space from Node i

Q_i = the electrical energy input to Node i either as heater power or as equipment dissipation.

The a_i and e_i are determined by the patchwork of coatings put on these nodes. For example, if a solar absorptance of 0.6 is desired, 50% of the surface might be coated with black paint and 50% with polished aluminum. The corresponding emittance might be 0.55. In what follows, we strive to find the percentages, or fractions (f_i) of each surface that should be covered by each of the several coatings available for use on spacecraft. These fractions are the independent variables, or design variables, of the optimization problem. They will be chosen to minimize the weight associated with the heater power.

3.2 GENERALIZED PROBLEM DEFINITION

3.2.1 Objective Function

We want to minimize the weight penalty (W) of the thermal control system, which is the weighted sum of the heater energy required for the most severe environment (Q), and the weighted sum of the heater capacities (C_n's). The weighting factor for Q will be the weight of the power system, including the solar cells and batteries, as required to meet the maximum energy demand. The weighting factor for the heater capacities will be the weights of the heaters and heater controllers as well as the weight of the harnessing required to carry the power to the heaters. The C_n's could depend on n, the node number, because the length of the harness could depend on n. In equation form, the function to be minimized is:

$$W = \left[\max\ ab \cdot Q + bb \cdot \sum (C_n) + ae \cdot Q + be \cdot \sum (C_n)\right] \tag{2}$$

where

Q = $\max\left[\sum(Q_{nm})\right]$ = maximum over all missions, m, of the total power demand, summed over all of the nodes, n

Q_{nm} = orbital-average power demand for node n in mission m

C_n = $\max\ (Q_{nm})$ = heater capacity for node (n) which is equal to the maximum power demand over all missions (m)

ab = weight that must be added to the power system to provide an additional unit of the power, based on power demand at the beginning of the mission

ae = weight that must be added to the power system to provide an additional unit of power, based on the power demand at the end of the mission

bb = weight of the heaters and associated controls, which is usually proportional to the heater capacity, based on the power demand at the beginning of the mission

be = weight of the heaters and associated controls, which is usually proportional to the heater capacity, based on the power demand at the end of the mission.

The weight penalty must be evaluated based on conditions at the beginning and at the end of the mission and the maximum penalty selected as the optimization criterion. At the beginning of the mission the output of the power supply, such as solar cells, is high because there have been no failures and no deterioration of the cells or batteries. For example, at the beginning of the mission, the power system usually supplies 32 volts. At the end of the mission the voltage can be as low as 22 volts. Therefore, a high demand for power at the end of the mission is more serious than at the beginning. However, the heaters and controllers must be sized to handle the maximum voltage. Therefore, both phases of the mission must be included.

There is usually a fixed amount of power and weight associated with simply having a heater, independent of the size of the heater. Some power is required to sense the temperature (independent of the amount of power supplied). The weights of the sensor and the controller are nearly independent of the size. However, if these fixed weight penalties were added to W, they would not vary with coating patterns and heater locations; therefore, they would not enter the optimization process. Consequently, there is no need to carry these terms in the expression for W.

3.2.2 Design Variables

The design variables in the optimization process are f_{nc}, the fractions of the area of node (n) that are covered with coating (c). For each coating pattern, the heater capacities and powers are determined by the heat-balance equations and the temperature restrictions, all of which are constraints placed on the optimization process. The restriction on f_{nc} is

$$0.0 \leq f_{nc} \leq 1.0 \tag{3}$$

The coating properties consist of the solar absorptance (a) and the infrared emittance (e). These are subject to a range of uncertainty, (da) and (de), and to changes, (ca) and (ce), from the beginning to the end of the mission. Two sets of nominal temperatures must be computed for the beginning and the end of each mission. Both sets must be tested against the design requirements. In addition, the uncertainties will result in uncertainties in the node temperatures; therefore, each computed nominal temperature must be re-computed to include its range of uncertainty. The upper and lower limits of this range are the temperatures to be used in determining whether the node temperatures will be held within the allowable limits.

3.2.3 Constraints

The design constraints are

- The temperature of each node (n) during each mission (m) must be within the prescribed lower and upper limits (L_n) and (U_n). The weighted-average temperatures of each designer-defined group of nodes must be within the prescribed limits (GL_n) to (GU_n).
- The temperature difference between each pair of nodes (n) and (j) must be within the prescribed limits (L_{nj}) to (U_{nj}).
- The weighted-average temperature differences between each designer-defined group of nodes must be within the prescribed limits (GL_{nj}) to (GU_{nj}).

These conditions are written:

$$L_n \leq T_{nm} \leq U_n \tag{4-1}$$

$$GL_n \leq \sum (WT_n \cdot T_{nm})/N \leq GU_n \tag{4-2}$$

$$L_{nj} \leq T_{nm} - T_{jm} \leq U_{nj} \tag{4-3}$$

$$GL_{nj} \leq \sum (WT_n \cdot T_{nm})/N - \sum (WT_j \cdot T_{jm})/J \leq GU_{nj} \tag{4-4}$$

where WT_n is the weighting factor for node n for computing the weighted average temperature of a group of nodes. Each of the T's in the foregoing constraints must be interpreted as the nominal temperatures for the beginning and the end of the missions, plus or minus the uncertainties.

In addition to these design limits, the First Law of Thermodynamics must be satisfied. We can write the heat balance equation for each node (n) in the form

$$\begin{aligned} &\sum \left[K_{nj} \cdot (T_{nm}-T_{jm})\right] + \sum \left[R_{nj} \cdot (B_{nm}-B_{jm})\right] \\ &\quad = Q_{nm} + D_{nm} + \sum (a_c \cdot f_{nc}) \cdot S_{nm} \cdot A_n + \sum (e_c \cdot f_{nc}) \\ &\quad \cdot A_n \cdot (E_{nm}-B_{nm}) \end{aligned} \tag{5}$$

Where

B_{nm} = blackbody radiation at temperature T_{nm}

T_{nm} = temperature of node n in mission m

K_{nj} = conductance between nodes n and j

R_{nj} = radiant interchange factor between nodes n and j

Q_{nm} = heater power for node n in mission m

D_{nm} = equipment electrical heat dissipation into node n in mission m

a_c = solar absorptance of coating c

f_{nc} = fraction of the external area of node n covered by coating c

S_{nm} = solar flux on node n in mission m

A_n = external surface area of node n

e_c = infrared emittance of coating c

E_{nm} = infrared environmental flux incident on node n in mission m.

The sums on the left-hand side of Eq. (5) are over the j nodes that are thermally connected to node n. The sums on the right-hand side of this equation are over the c coatings that might be applied to node n.

The heat-balance equation is also used to determine the uncertainties in the node temperatures as a result of the uncertainties in the coating properties. If the coating-property half-ranges, da and de, correspond to three standard deviations so that they encompass 99.6 percent of the possibilities, then the corresponding uncertainties in the temperatures can be computed as the root-sum-of-squares (rss) of the uncertainties due to each coating-property uncertainty. Therefore T in the foregoing constraint inequalities must be interpreted as the temperature, determined from the nominal coating properties, plus or minus the uncertainty in the temperature. The more stringent of the plus or minus limits is to be used in satisfying the inequalities.

With a manageable increase in computational complexity (but possibly a burdensome increase in input requirements) the optimization process can be enhanced to include failed missions. Reduced temperature-control requirements could be included if the acceptable temperature limits (L_n, U_n, G_n, GU_n, etc.) were made mission dependent.

SECTION 4

COMPUTATIONAL METHODS

The practicality of the optimization strategy depends on the computational cost. There are so many complex computations that a computer is clearly required. However, even with the computer, the computations could be too lengthy to be practical. Therefore, we have examined the computational methods in use today and typical solution times so that we can estimate the cost of running the optimization strategy on a computer.

Four types of computations are required:

- Solving the heat-balance equations
- Determining the effect of uncertainties on the temperatures
- Computing the derivatives of the objective function with respect to the design variables
- Selecting the next set of design variables on the path toward the optimum design.

Each type is considered in the following paragraphs.

If there are M missions, N nodes, P models based on different internal conductances, C coatings, K heaters/temperature-sensitive nodes, and I iterations to find the minimum, then the number of equations that must be solved is as shown in Table I. To help in recognizing the dominant problem, we have included in Table I the number of computations required for a typical problem containing 20 missions, 150 nodes, 4 models, 5 coatings, 30 heaters, 30 temperature-sensitive nodes, and 25 iterations. Note that the number of computations doubles because all cases must be considered at the beginning and at the end of the mission. It is evident that the uncertainties and the derivatives of the uncertainties dominate the computational effort.

TABLE I

THE NUMBER OF SIMULTANEOUS EQUATIONS TO BE SOLVED

Set of Equations	Number of Equations	Number of Times Solved	Typical Number of Times
Heat Balance	N	2MPI	4,000
Uncertainties	N	4MPCI	40,000
Derivatives of W	2C	I	25
Derivatives of T	N	2MPKI	120,000
Derivatives of dT	N	2MPKCI	600,000

4.1 SOLVING THE HEAT-BALANCE EQUATIONS

A review of the available computer programs reveals that the following methods for solving simultaneous equations are in common use:

1. Gaussian elimination
2. Successive over-relaxation (SOR)
3. Gauss-Seidel
4. Conjugate gradient
5. Choleski factorization
6. Matrix inversion.

All operate on the linearized equations and require iteration on the non-linear terms. The Newton-Raphson technique is the most popular method for linearizing the equations, although the resultant set of equations is no longer symmetric. Of the six solution techniques, Gaussian elimination is the most popular. No commercially available programs use matrix inversion, although matrix inversion was found to be the most economical (Ref. 1).

The data Costello generated in Reference 1 showed that matrix inversion requires approximately one-sixth of the computation time required by SOR. Therefore, its running times are comparable to the incomplete Choleški (IC) methods. In addition, matrix inversion gives the derivatives that are required for the optimization. Thus, it is the most promising of the solution methods.

The data-storage requirement of matrix inversion had previously been considered prohibitive and the accuracy of the inversion is a constant worry. However, with present-day computers, especially those with virtual memory, the storage requirements are less important and inaccuracies can be circumvented by iteration.

If we anticipate the problem of determining the uncertainties in the temperatures, as a result of the uncertainties in the coating properties, we can eliminate most of the methods. To determine the uncertainties, we must calculate the derivative of each temperature with respect to each coating property. The uncertainty in the temperature is equal to the root-sum-of-squares of the derivatives, multiplied by the uncertainty in the corresponding coating property. In effect, we must determine each term in a matrix, square each term individually, and sum the rows.

The only methods that need be considered are those which yield the derivatives directly. Consider a method that does not yield the derivatives directly, such as Gaussian-elimination. Counting the solutions for the beginning and the end of the mission, the heat-balance equation must be solved 2MPI times (4000 times) to determine the temperatures. For each of the 2MPI times, the derivative of K temperatures with respect to 2C coating properties (one solar absorptance and one infrared emittance per coating) must be calculated so that the uncertainties can be determined. Therefore, 2KC (300) derivatives must be computed. If the derivatives are determined by Gaussian elimination, the derivatives of all temperatures with respect to the 2C (10) coating properties are determined simultaneously. Therefore, 4MPIC (40,000) sets of N (150) equations must be solved in the course of a solution to the optimization problem.

For the Gaussian-elimination method to be competitive with the matrix-inversion method, it must be 2C times faster than the matrix method. The results in Reference 1 indicate that the two have comparable speeds; the matrix-inversion method is faster if the inverse can be determined only once. Therefore, Gaussian elimination will require approximately a factor of 2C longer running time.

Of the methods listed, only the Choleski and matrix inversion methods can produce the inverse matrix. The Choleski method is limited to symmetric matrices; it is probably faster than direct matrix inversion. Therefore, the choice of the two methods depends on whether we want to restrict the problems to the most common case in which the conductances are symmetric. This restriction would prevent the use of the method to problems with fluid flow. This restriction would also prevent the use of a one-way conductor, as permitted by the most popular public domain thermal-analysis program, SINDA. One-way conductors are artificial, so that little would be lost by imposing this restriction; however, this restriction may require the user to modify his thermal model and would thereby violate one of the desirable characteristics of the optimization program: not adding to the modeling burden of the user. The limitation to non-flow problems is sufficiently restrictive to conclude that the matrix-inversion procedure should be used.

To solve the system of equations by matrix inversion, we recast equation (5) in the form

$$\sum \left[G_{nj} \cdot (T_{nm}-T_{jm}) \right] = V_{nm} + \sum \left[G_{nj} \cdot (T_{nm}-T_{jm}) \right] \tag{6}$$

Where

$$V_{nm} = Q_{nm} + D_{nm} + \sum (a_c \cdot f_{nc}) \cdot S_{nm} \cdot A_n + \sum (e_c \cdot f_{nc}) \cdot A_n \cdot (E_{nm}-B_{nm})$$
$$-\sum \left[K_{nj} \cdot (T_{nm}-T_{jm}) \right] - \sum \left[R_{nj} \cdot (B_{nm}-B_{jm}) \right] . \tag{7}$$

Note that V_{nm} is the residual of Eq. (5). When V_{nm} is zero, T_{nm} is the solution. The equation is solved iteratively by assuming T_{nm}, computing V_{nm}, and solving Eq. (6) for the new T_{nm} (on the left-hand side). The solution is obtained by inverting the matrix of coefficients (G_{nj}) which is equal to the conductance (K_{nj}) plus the linearized radiation coupling. According to the study done in Reference 1, the computation time is minimized if the linearization is done symmetrically. Then

$$G_{nj} = K_{nj} + R_{nj} \cdot (T_{nm} \cdot T_{nm} + T_{jm} \cdot T_{jm}) \cdot (T_{nm} + T_{jm}) = K_{nj} + RL_{njm} \tag{8}$$

In addition, the same inverse can be used for all missions if the temperatures are chosen to be the maximum expected for all missions. Therefore, the inverse needs to be computed only once for a given optimization. Updating may be beneficial after several sets of design variables are evaluated. An approximate inverse might also be useful. The approximate G_{nj} for mission (m) is

$$G_{njm} = K_{nj} + RL_{nj} + RL_{njm} - RL_{nj} \tag{9}$$

Where

RL_{nj} = the second term on the right hand side of equation (8) with the temperatures equal to the maximum

RL_{njm} = the second term on the right hand side of equation (8) with the temperatures equal to those of mission m.

We can write

$$G_{njm} = (K_{nj} + RL_{nj}) \cdot \left[I_{nj} + (K_{nj} + RL_{nj})^{-1} \cdot (RL_{njm} - RL_{nj}) \right] \tag{10}$$

where

I_{nj} = the identity matrix.

If the last term is small, we can form the approximate inverse of G_{njm}

$$(G_{njm})^{-1} = \left[I_{nj} - (G_{nj})^{-1} \cdot (RL_{njm} - RL_{nj}) \right] \cdot (G_{nj})^{-1}. \tag{11}$$

This equation gives a first-order correction to G_{nj} that is an approximation to G_{njm}.

4.2 DETERMINING THE TEMPERATURE DERIVATIVES

The differential of Eq. (6) yields

$$\sum \left[G_{nj} \cdot (dT_{nm} - dT_{jm}) \right] = dV_{nm} + \sum \left[G_{nj} \cdot (dT_{nm} - dT_{jm}) \right] \tag{12}$$

Where

$$\begin{aligned} dV_{nm} = {} & dQ_{nm} + dD_{nm} + \sum (da_c \cdot f_{nc}) \cdot S_{nm} \cdot A_n \\ & + \sum (de_c \cdot f_{nc}) \cdot A_n \cdot (E_{nm} - B_{nm}) \\ & - \sum \left[K_{nj} \cdot (dT_{nm} - dT_{jm}) \right] - \sum \left[R_{nj} \cdot (dB_{nm} - dB_{jm}) \right] \\ & + \sum (a_c \cdot df_{nc}) \cdot S_{nm} \cdot A_n + \sum (e_c \cdot df_{nc}) \\ & \cdot A_n \cdot (E_{nm} - B_{nm}) \\ & + \sum (e_c \cdot f_{nc}) \cdot A_n \cdot (dE_{nm} - dB_{nm}) \end{aligned} \tag{13}$$

where the prefix (d) indicates a differential. The derivative dT_{nm}/dQ_{nm} is obtained from Eq. (13) by setting the other differentials to zero. The remaining derivatives are obtained by use of the chain rule. For example:

$$dT_{nm}/da_c = dT_{nm}/dQ_{nm} \cdot dQ_{nm}/da_c \tag{14}$$

and

dQ_{nm}/da_c is obtained from Eq. (13).

Therefore, all of the sensitivities and all of the derivatives of the temperatures with respect to the design variables can be computed with a minimum of work. Some savings in effort might be achievable if the derivatives and sensitivities are evaluated only for the thermally critical missions; however, there is no clear method for selecting the thermally critical missions without first evaluating dT_{nm}/dQ_{nm}.

The uncertainties in the temperatures are

$$\delta T_{nm} = \left[\sum (dT_{nm}/da_c \cdot \delta a_c)^2 + \sum (dT_{nm}/de_c \cdot \delta e_c)^2 \right]^{1/2} \tag{15}$$

where the sums are over the c coatings. The derivatives of the temperature uncertainties with respect to the design variables f_{nc} are:

$$\frac{d\left(\delta T_{nm}\right)}{df_{nc}} = \frac{1}{\delta T_{nm}} \sum \left[\frac{dT_{nm}}{da_c} \frac{d^2 T_{nm}}{df_{nc} da_c} (\delta a_c)^2 + \frac{dT_{nm}}{de_c} \frac{d^2 T_{nm}}{df_{nc} de_c} (\delta e_c)^2 \right] \tag{16}$$

4.3 DETERMINING THE DERIVATIVE OF THE WEIGHT (W)

The derivatives of W with respect to the fractional area coverages, f_{nc}, determine the direction of the step to the next coating pattern (the next design). These derivatives are best obtained by the chain rule. The first step is to determine the sensitivities of the heater powers to f_{nc}. Suppose we have a set of T_{nm} and δT_{nm} for one set of heater powers. Suppose the set of T_{nm} and δT_{nm} does not meet the thermal requirements. Because we know dT/dQ, we have the approximation:

$$dT_{nm}/dQ_{nm} \cdot (Q_{nm}' - Q_{nm}) = T_{nm}' - T_{nm} \tag{17}$$

where (') indicates the Q or T after the heater power is increased to meet the temperature requirements. In this equation, Q and T are known and the temperature requirements dictate T'. Therefore, we have a system of linear equations to determine Q'. Note that Eq. (17) represents only K equations (one for each temperature-controlled node), although these K equations must be solved for each of M missions. Gaussian elimination will probably be the most suitable solution method, because there is no a priori knowledge of the condition of the matrix, dT/dQ.

Solving for Q' would be simple if it were not for the fact that Q' cannot physically be negative. If we solve the system of equations for Q' and find that some values are negative, we have no method for determining which should be set to zero to minimize the weight penalty. This problem is similar to that of the classical regression problem: if we are limited to 5 coefficients in a regression involving 10 independent variables, which 5 should be chosen? There is no solution to the regression problem, so we can expect to find no solution to the Q' problem. Therefore, if Q' is negative we would set the most negative Q' to zero. After this is done, we must re-solve the system of equations for the remaining Q'.

The derivative of W with respect to f_{nc} can now be determined. We have from Eq. (2)

$$W = \max \left[ab \cdot Q + bb \cdot \sum (C_n) + ae \cdot Q + be \cdot \sum (C_n) \right] \tag{18}$$

so

$$\frac{dW}{df_{nc}} = ab \bullet \frac{dQ}{df_{nc}} + bb \bullet \sum \frac{dC_n}{df_{nc}} + ae \bullet \frac{dQ}{df_{nc}} + be \bullet \sum \frac{dC_n}{df_{nc}} .$$

The Q in this equation is evaluated for the mission that has the highest total heater power. The C_n in this equation is summed over all of the heated nodes (C_n is the maximum heater power for node n, considering all of the missions). dQ/df_{nc} is the product of dT/df_{nc} and dQ/dT from Eq. (17). Similarly, dC_n/df_{nc} is determined from dQ/df_{nc}, but for the particular mission that determines each particular heater capacity.

4.4 COMPUTING THE NEXT SET OF DESIGN VARIABLES

The foregoing equations give the objective function and its derivatives. These data make hill-climbing techniques, such as the maximum-rate-of-descent method, suitable for the optimization. CONMIN (Ref. 5) is a standard computer routine based on hill-climbing techniques that is particularly suitable for the thermal optimization problem. It is designed especially to handle constraints on the dependent and independent variables.

The selection of CONMIN followed an analysis of the needs of the thermal optimization strategy and a review of CONMIN's capabilities. The requirements were met by CONMIN as follows:

- CONMIN is able to use analytical derivatives as well as finite differences.
- CONMIN is able to handle non-linear constraints and the particular form of the objective function. CONMIN also has a feature that permits the user to select the error band on satisfying the constraints, so that the time spent satisfying the heat-balance constraint can be controlled.
- CONMIN has a re-start capability.
- CONMIN can handle upper and lower bounds on the independent variables.
- CONMIN has the capability of evaluating all constraints or only those that are active. This capability will be especially useful because the tradeoff must be made to determine if considering all constraints at every step sufficiently reduces the number of erroneous steps.
- CONMIN has the capability of starting with a nonfeasible solution. It uses a penalty function to search for a feasible solution.
- CONMIN allows for many input constants that permit the user to control the parameters of the optimization, such as step size.

Unlike many optimization problems, the present strategy does not have a problem of scaling disparate independent variables, such as pressure and temperature, because all of our independent variables are area ratios.

4.5 ESTIMATED COMPUTATION TIMES

The practicality of the optimization strategy depends on the cost of performing the computations. Two sets of computations are required: the temperatures and the temperature derivatives.

At each step, the program must determine the temperatures for all of the nodes for the beginning and end of the mission for M missions. Therefore, the heat-balance equations must be solved 2MI times. If there are P models, to incorporate uncertainties in the internal conductances, then the temperatures must be determined 2MPI times. However, the way that the powers for K heaters are to be determined requires re-solving the heat-balance equations from 1 to K times per set of coatings evaluated. On the average, we can expect K/2 re-analyses for the heater sizes. Therefore, the total number of solutions to the heat-balance equation will be KMPI for each optimization problem.

Computation of the temperature derivatives requires approximately the same amount of work as solving the heat-balance equations, although the equations for the derivatives are linear. The derivatives must be determined for each mission, for the beginning and end of the mission, and for each model. Therefore, 2MPI computations are required. Because we have used the matrix-inversion technique, the sensitivities can be determined from the derivatives with little extra work.

By combining the estimates for the two sets of computations, we find that the problem is similar to solving the heat-balance equation MPI $\cdot$ (K + 2) times. For the problem size estimated at the beginning of Section 4, the heat-balance equation would be solved $20 \cdot 4 \cdot 25 \cdot (30 + 2) = 64000$ times. This time can be compared to the time now used to simulate the transient responses of spacecraft. For example, it is not uncommon to use 5-minute time steps to analyze the temperature response of spacecraft over 48 hours, in search of the quasi-steady-state solution. This computation requires solving the heat-balance equations 576 times. If 100 variations are considered, as part of the evaluation of the performance for 20 missions, the coating uncertainties, and the internal-conductance uncertainties, the optimization time would be comparable to the design evaluation time.

Run times for typical spacecraft for a 48-hour simulation are 1 hour on a VAX11/780. For the 64000 solutions, approximately 110 hours would be required on the VAX11/780. If a vector processor were used, this time could be reduced by a factor of 10 (Ref. 3). Another factor-of-10 time reduction would be realized if a Cyber 175 were used. A third factor-of-10 time reduction could be achieved with a Univac 1100/80 with dual array processors. On this last machine, the CPU time would be 0.11 hours. As indicated in Reference 3, a 190-node problem can be solved 100 times in 8 CPU seconds on a CYBER 203. Therefore, 64000 solutions would require 1.42 hours without a vector processor and 0.5 hours with a vector processor. Thus, the run times for the optimization will be long but not unreasonable, especially because the output from the optimization will reduce the need for some of the studies normally done and because the optimization will not be done more than once or twice for an entire project.

SECTION 5

THE OVERALL OPTIMIZATION STRATEGY

With the mathematics and the computational steps now defined, we can turn our attention to the work the designer must do. He must:

1. Develop thermal models of the vehicle.

   1.1 A baseline model with the nominal values of the conductances

   1.2 Alternative models with off-nominal values

2. Specify the coatings and coating properties to be used.

   2.1 The nominal values at the beginning and end of the mission

   2.2 The uncertainties at the beginning and end of the mission

3. Specify the external-surfaces

   3.1 External surface areas

   3.2 Solar and infrared heat fluxes on each surface for each mission

   3.3 The coatings that can be applied to each surface

4. Specify the temperature-controlled nodes

   4.1 The allowable range in temperature differences

   4.2 The allowable range in the average temperature of groups of nodes

   4.3 The allowable range in differences in average temperatures of groups of nodes

5. Specify the weight penalties for the beginning and the end of of the mission.

   5.1 Allow for decreasing voltage with time due to power-system degradation

   5.2 Weight penalty per watt of peak heater power

5.3 Weight penalty per watt of average heater power

6. Specify the optimization parameters for CONMIN

   The maximum step size, the number of steps, etc.

The coating configuration will be optimized according to the theory described in the previous sections and shown schematically in Figure 2 (see also Table II). However, the designer uses the optimization procedure only as an aid. He must still exercise his judgment:

- He must select appropriate time periods. In most cases, the time period would be one orbit because all sensitive equipment would be well enclosed by structure and insulation. Optimization for external equipment, such as star trackers and special instruments, might be conducted in a second pass using time averages that were close to the time constants of this externally mounted equipment.

- He must select the final heater configuration. The program will assume the heaters are applied to every node for which the temperature must be controlled. If the heater layout or installation can be simplified, the user must perform the simplification. If the heaters cannot be placed on the temperature-controlled element (such as a mirror), he must adapt the procedure results. For example, he can design a heated plate next to the temperature-controlled element. He can then re-run one optimization iteration with the heated-plate configuration to test his manual modification. For control of temperature differences, he can imitate what will be done in the hardware. For example, if the temperature difference is sensed, heat could be applied to the colder node. Alternatively, the designer can select the node to which heat would be applied, with the temperature of the other node floating.

- He must optimize the less tangible aspects of the thermal design. For example, he must consider the reliability of the design and the appropriate design margins, the non-orbital aspects of the missions, design flexibility for future changes in requirements or power dissipations, system manufacturability, system predictability, the costs and schedule requirements for the

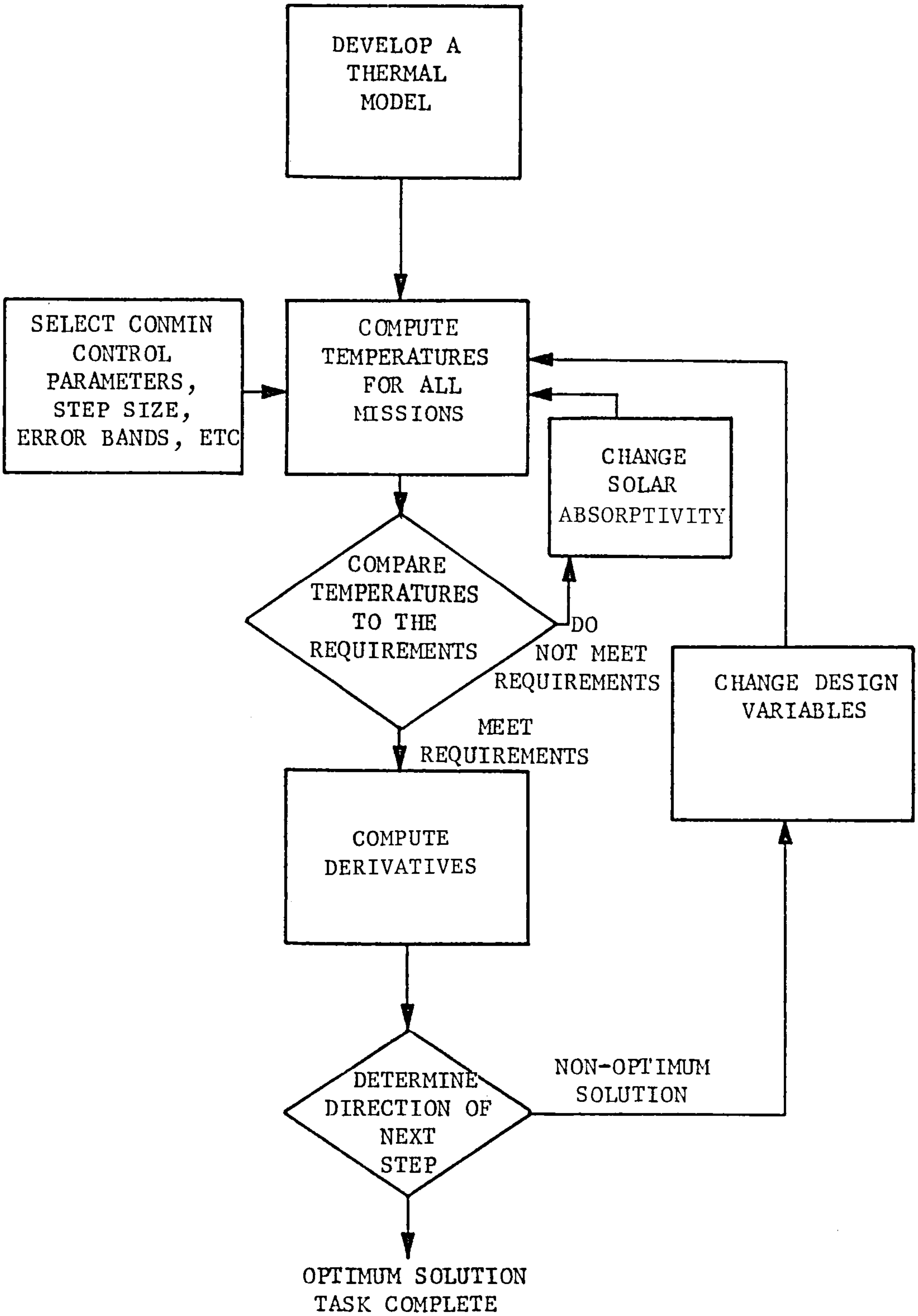


Figure 2. Flow Chart of Optimization Strategy

TABLE II
POSSIBLE FLOW SCHEMATIC FOR OPTIMIZATION PROCEDURE

1. Read input data
   - Include all of the missions, alternative models, etc.
   - Include initial values for the coating patterns
2. Read input data for the CONMIN computations
   - Step size, error bands, etc.
3. Compute a feasible solution
   - For initial set of design variables, compute the temperatures and heater powers for the beginning and end of each mission. Determine the temperature uncertainties
   - Compare the temperatures (with uncertainties) to the requirements
   - If solution is not feasible, reduce the solar absorptances and try again
4. Compute the direction of the next set of design variables:
   - Weight penalty
   - Derivatives of objective function with respect to design variables
   - Derivatives of active constraints with respect to design variables
   - Direction of next step using CONMIN
5. Compute the new temperatures and heater powers
   - For the new set of design variables, compute the temperatures and heater powers for the beginning and end of each mission and determine the temperature uncertainties
   - Compare the temperatures (with uncertainties) to the requirements
   - If solution is not feasible, reduce the solar absorptances and try again
   - If solution is feasible, go to Step 4

thermal-control equipment and the system development, and the costs of testing the thermal-control system.

- Therefore, the optimization strategy, even when implemented on the computer, is a design aid -- not a complete design solution. However, because it is a systematic search among alternatives, it is an aid that can eliminate many of the intuitive decisions that must be made in the design process.

SECTION 6

DEMONSTRATION PROGRAM

A pilot computer program was developed to validate some of the techniques needed for the subsequent optimization:

- Specifying the coatings and their tolerances
- Finding a feasible solution
- Computing the nominal temperatures and uncertainties in temperatures
- Computing the heater power to exactly meet the temperature requirements for all nodes simultaneously
- Computing the derivatives of the temperatures with respect to the design variables.

Because the purpose of the current work was only to define the optimization strategy, the pilot program does not include all of the steps. For example, it does not include an algorithm for selecting the next set of design variables. The steps of the logic are selected manually, rather than automatically. The program runs interactively. A menu appears on the screen and the user selects the next step. The steps include: computing the nominal case, computing the effects of uncertainties, selecting the thermostat set points, computing the heater-power required and computing the derivatives.

The pilot program, presented in Appendix A, was written in Microsoft BASIC. It probably will require modification for other forms of BASIC, because there is no industry standard on this language.

The pilot program was successfully applied to the three-node sample problem presented in Section 3. The details of the application (see Appendix A) confirmed the practicality of each step. Although the program tests only selected parts of the computational procedure, it does include enough of the steps that we are confident that the entire process can be developed and implemented successfully.

SECTION 7

PLAN FOR IMPLEMENTING THE OPTIMIZATION PROCEDURE

Development of a computer program to implement the entire optimization strategy would involve a significant effort. The major steps are defined below.

1. Design the input and preprocessor to accept a SINDA thermal model (Ref. 4) of the vehicle.

   We cite SINDA for use in representing the thermal models because of its extensive use in the aerospace industry. Other thermal modeling programs could also be used; however, SINDA seems to have significant advantages. It is widely used and accepted. It is frequently updated and improved; new computational routines can be easily added. And it is applicable to almost any thermal problem, including problems with fluid flow (most conveniently in a version called SINFLO). On the other hand, if we developed a new thermal-analysis subroutine, the user of the optimization process would need to learn a new set of input procedures and formats. In addition, he would need to have one model for the optimization process and another for the detailed SINDA analyses he might conduct later.

2. Improve the SINDA computational efficiency for multiple-mission analyses.

   SINDA does not have a matrix-inversion solution of the type described in Section 4.1. Therefore, such a routine would need to be added. This can be accomplished by writing a SINDA subroutine. The capability to accept new routines is a standard feature of SINDA.

3. Compute the derivatives of the temperatures with respect to coating properties and coating areas.

A tradeoff between numerical and analytical differentiation must be made, but we anticipate that the analytical differentiation will be faster. Therefore, SINDA must be modified to compute the derivatives. Some versions of SINDA have subroutines for computing sensitivities; these may be suitable. A tradeoff is required to determine if the derivatives need to be evaluated for all constraints or only for the active constraints.

4. Modify SINDA to compute the required heater powers.

   A computational subroutine must be added to SINDA for computing the required heater powers. Some study is needed to determine which heaters should be activated and when all are not needed to meet the constraints. The heater power was computed in the pilot program by re-inverting the rows of the matrix (Eq. 8) corresponding to the nodes with heaters. A similar process can be followed with SINDA, as described in Section 5; however, the non-linear radiation terms may make this linear technique unsuitable. For example, an approximate inverse may be too inaccurate. An iteration scheme may be required.

   The computed heater power required to bring the node back into the specified range can also be used to compute the gradients needed in CONMIN. The matrix of derivatives of the temperatures with respect to heater powers can be inverted to give the derivatives of the heater power with respect to temperature. Therefore, the temperature derivatives obtained in Step 3 can be multiplied by the heater power derivatives to yield the heater power derivatives required in the next step.

5. Modify SINDA to compute the objective function and derivatives of the objective function.

   The objective function is computed from Eq. (2). Derivatives are obtained from Steps 3 and 4.

6. Modify CONMIN to call SINDA for all of the needed information.

   CONMIN, as currently written, would call for the temperatures and the derivatives separately. Because many of the computations associated with the derivatives are the same as or similar to those associated with the temperature computations, CONMIN should probably call SINDA once for all of the data: the temperatures (constraints), fraction of the area of each external node that is covered by each coating (the design variables), the weight penalty (objective function), and the derivatives of the weight penalty with respect to the design variables. SINDA will be called twice for each mission and for each set of internal conductances so that these values can be computed for the beginning and the end of the mission for all possible internal conductances.

   The user-selected option in CONMIN to compute all or only the active constraints should be utilized. (See the discussion under Step 3.) Note that CONMIN permits constraining each design variable independently. Our problem also constrains the sum of the fractions of each external area to be 1.0. It will probably be efficient to analytically eliminate one of the independent variables with this constraint. For example, the optimization program could be designed to assume that the remainder of the surface is coated with a diffuse white surface.

7. Combine SINDA and CONMIN into a single program.

   The currently separate programs, SINDA and CONMIN, must be combined into a single program. It is not clear at present whether SINDA should be a subroutine to CONMIN; CONMIN, to SINDA; or both to a new main program. We have assumed that a new main program would be used. Much will depend on the complexity of the various preprocessors. In any case, the resultant combination should probably look like SINDA because the program will be used by SINDA users. Extra input data will be required for the CONMIN computations.

SECTION 8

PLAN FOR APPLICATION OF PROCEDURE TO SPACE TELESCOPE

The pilot program gives us considerable confidence that the optimization strategy can be implemented in the form of a computer program. Although many of the computational steps need development, we show in this section how the computational process may be used to optimize the thermal control system of the Space Telescope (ST).

The Space Telescope was chosen for the demonstration because it embodies most of the constraints found in a scientific satellite, and its design maturity provides a body of data for input to the optimization. The overall plan is to optimize the Space Telescope using Perkin Elmer's Space Telescope Systems Thermal Model and a modified set of temperature constraints.

The Space Telescope is a stellar observatory comprised of three major subassemblies: the Support Systems Module (SSM), the Optical Telescope Assembly (OTA) and the Scientific Instruments (SI) (see Figure 3). There are two major thermal design constraints:

1. maintain all subassemblies within temperature limits that will assure that damage does not occur due to high or low temperatures, and

2. maintain the change in temperatures between components, within a sub-assembly, within limits that assure optical alignment during any twenty-four hour period.

Maximum/minimum temperature limits must be maintained over all phases of the ST mission (launch, deployment, scientific operation, etc.) while optical alignment must only be maintained during the scientific operations which occur when the ST is in the orbit shown in Figure 4. During scientific operations the solar line of sight can fall within the 135 degree envelope shown in Figure 4. As the vehicle moves relative to the

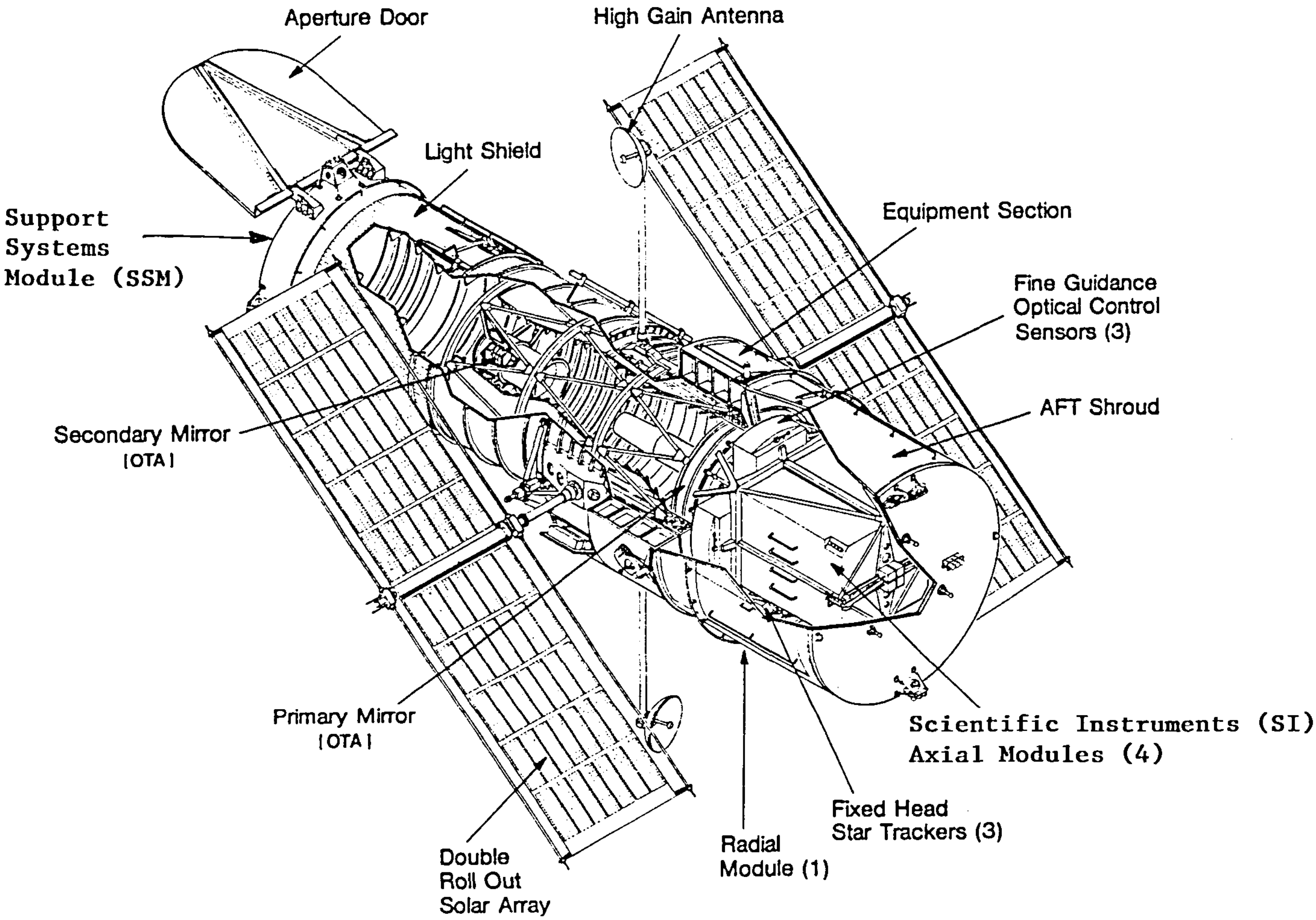
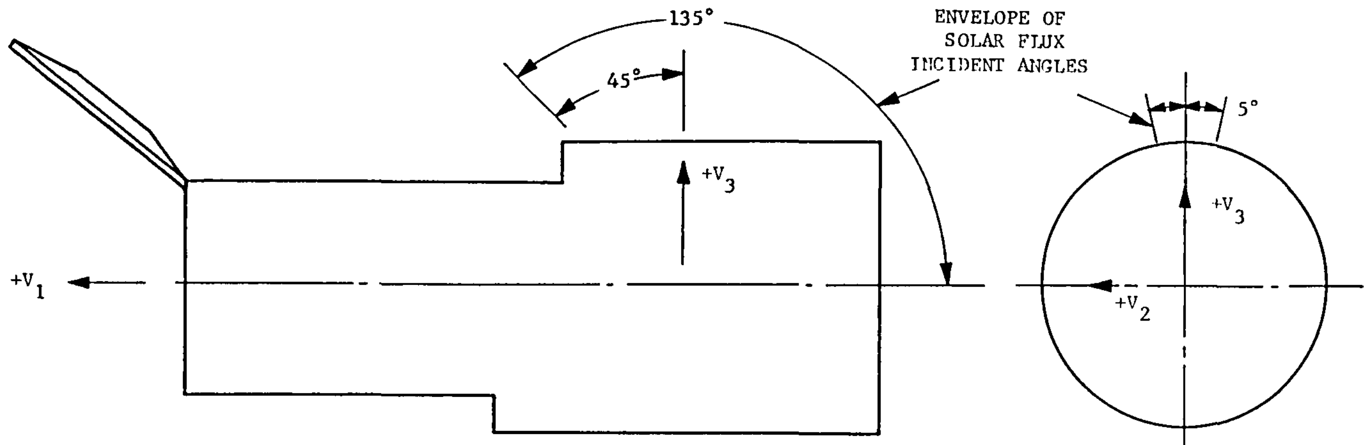


Figure 3. Schematic of Space Telescope



ORBIT PLANE TO (β) SUN ANGLE	-52.3 < β 52.3
ORBIT ALTITUDE (A)	215 < A < 321 MILES
SOLAR FLUX LINE OF SIGHT	WITHIN THE ENVELOPE SHOWN ABOVE
THERMAL CONTROL REQUIREMENTS	MAINTAIN THE ST COMPONENTS AT THE LEVELS SHOWN IN THE FOLLOWING TABLES FOR 24 HOURS FOLLOWING A VEHICLE ORIENTATION CHANGE

Figure 4. Space Telescope Orbit Parameters

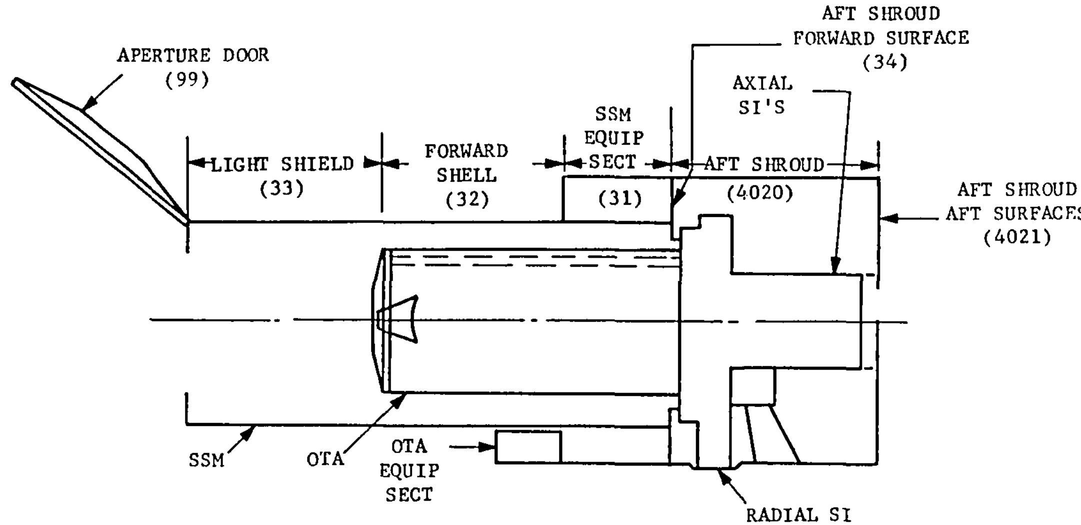
sun, the change in solar viewing angle will cause the Space Telescope to heat or cool by as much as 20°F. Since the major driver in any design is the scientific portion of the mission, the temperature level design should only be optimized for the operational phase of the mission. The resulting design should then be compared to the launch and deployment requirements so that the specific design changes required to meet the nonoperational constraints can be developed.

The SSM provides the overall enclosure, power, power control, guidance and position stability. Its thermal control requirements and nodal breakdown are presented in Figures 5 and 6. Because it does not provide a structure for any of the optical components, the allowed temperature ranges and levels for the SSM are significantly greater than those for either the OTA or the SIs. The OTA provides both the structure to hold the optical components (i.e., primary mirror, etc.) and the SIs. Because of the optical requirements the allowed temperature variations are small. These requirements also tend to limit the choice of materials to those which have a low thermal coefficient of expansion (Graphite Epoxy) and sometimes require the use of resistance heaters to maintain alignment. These all tend to minimize a component's allowed operational temperature range. The SI provides the structure that holds the experiment and its required optics and electronics. While not as massive as the OTA its structural and resulting thermal requirements are similar to the OTA'S. Both the thermal requirements and a nodal breakdown for the the OTA and a typical SI are given in Figures 7 through 12.

A significant aspect of the optimization problem is the uncertainty in the specified coating properties. This is included by utilizing the thermal properties and the uncertainties presented in Table III.

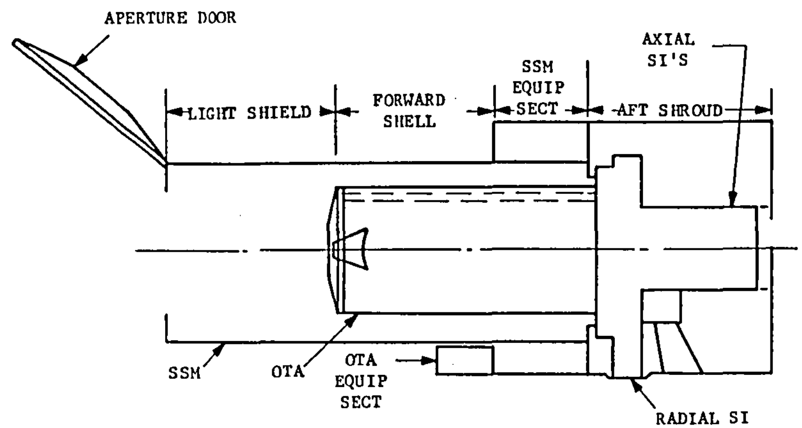
The optimization strategy is to minimize the spacecraft's weight (Eq. 2). For cold bias systems that are maintained by resistance heaters, this requires knowledge of the relationship of weight to power (see Table IV). Three relationships derived from ST data are used to determine the weighting factors ab, ae, bb, and be:

- AVERAGE POWER - This is the penalty for the average power required to maintain the spacecraft. The size of the solar array, battery, power distribution and control etc., weights are accounted for in this term.



Component	Node Number	Thermal Capacitance BTU/°F	Surface Area FT^2	Temperature Requirements °F	Surface Inner	Finish Outer	Power Dissipation Watts
Aperture Door	99	11	75	None	To Be Determined	To Be Determined	None
Light Shield	33	57	390	None	To Be Determined	To Be Determined	None
Forward Shell	32	38	260	None	To Be Determined	To Be Determined	None
SSM Equipment Sect	31	36	244	None	To Be Determined	To Be Determined	None
Aft Shroud	4020	72	493	None	To Be Determined	To Be Determined	None
Aft Shroud Aft Surface	4021	22	193	None	To Be Determined	To Be Determined	None
Aft Shroud Fwd Surface	34	13	88	None	To Be Determined	To Be Determined	None

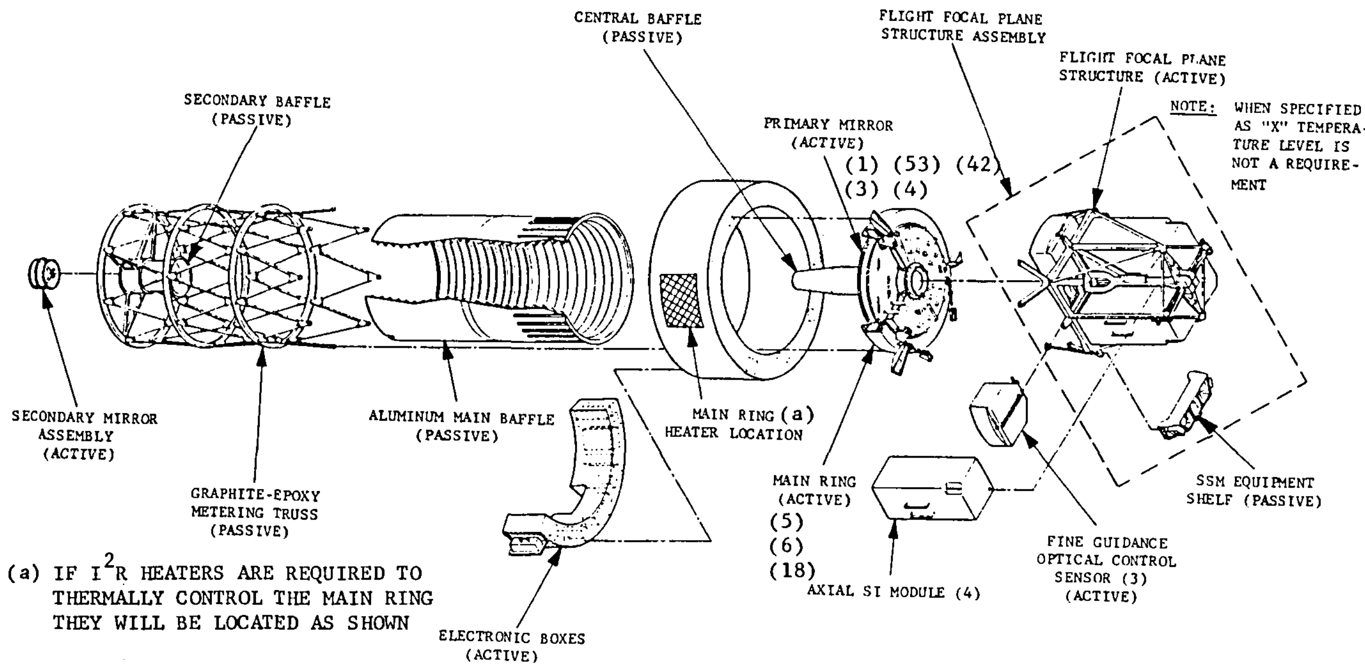
Figure 5. Space Telescope Support Systems Module (SSM) Thermal Node Definition



Component	Minimum Temperature °F	Maximum Temperature °F
SSM	-125	+125
OTA - w/o Electronics	-125	+125
OTA - with Electronics	-40	+95
OTA - Optical Surfaces	+50	+90
SI - w/o Electronics	-125	+125
SI - with Electronics	-40	+95
SI - Optical Surfaces	+50	+90

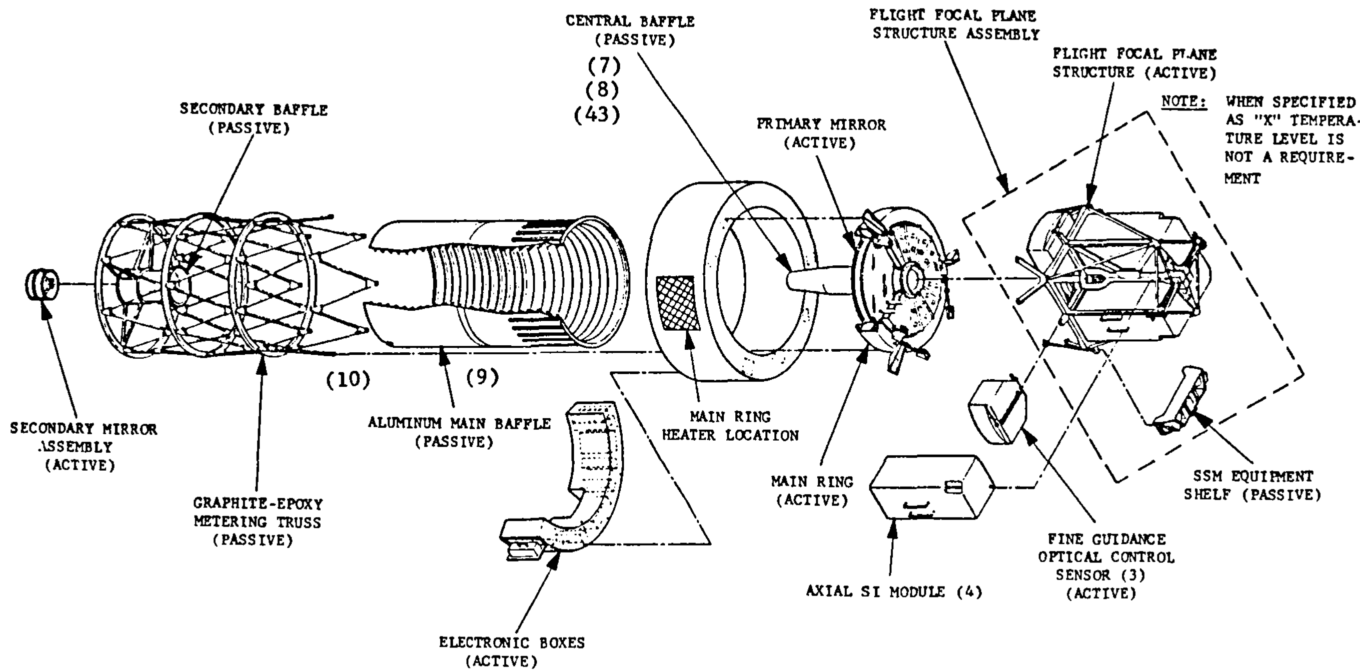
NOTE: These temperature limits are representative of Optical System hardware and are not, in all cases, the final requirements for ST.

Figure 6. Space Telescope Survival Temperature Limits



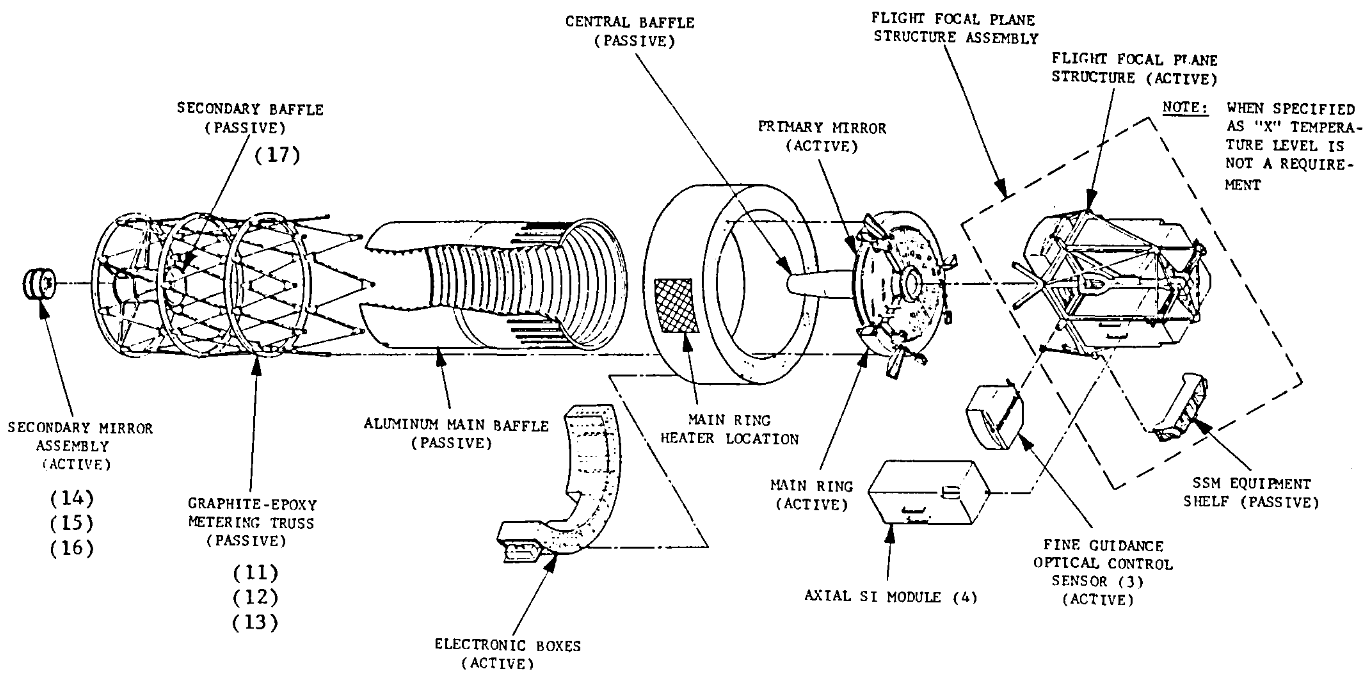
Component	Node Number	Thermal Capacitance BTU/°F	Surface Area FT²	Temperature Requirements °F	Surface Inner	Finish Outer	Power Dissipation
Primary Mirror (PM)							
Front Surface	1	Ø	67	70 ±1	Glass	Mirror	None
PM Aft Surface	3	Ø	67	70 ±1	Glass	Glass	None
PM Central	53	310	None	70 ±1	None	None	None
Reaction Plate	4	18	67	None	Black Paint	MLI2	None
Main Ring Inner	5	104	52	X ±.6	None	MLI2	None
Main Ring Outer	6	30	34	X ±.6	None	MLI2	None
PM Inner Guard Htr	18	Ø	None	None	MLI2	Black Paint	None
PM Attachments	42	Ø	None	None	None	None	None

Figure 7. Space Telescope, Optical Telescope Assembly - Forward Section Thermal Node Description



Component	Node Number	Thermal Capacitance BTU/°F	Surface Area FT^2	Temperature Requirements °F	Surface Inner	Finish Outer	Power Dissipation
Central Baffle (CB) Aft	7	1.55	14	None	Black Paint	Black Paint	None
CB Forward	8	5.25	36	None	Black Paint	Black Paint	None
CB Aft of Reaction	43	0.43	4	None	Black Paint	Black Paint	None
Main Baffle (Aft)	9	38.3	484	None	Black Paint	Black Paint	None
Main Baffle (Fwd)	10	38.3	484	None	Black Paint	Black Paint	None

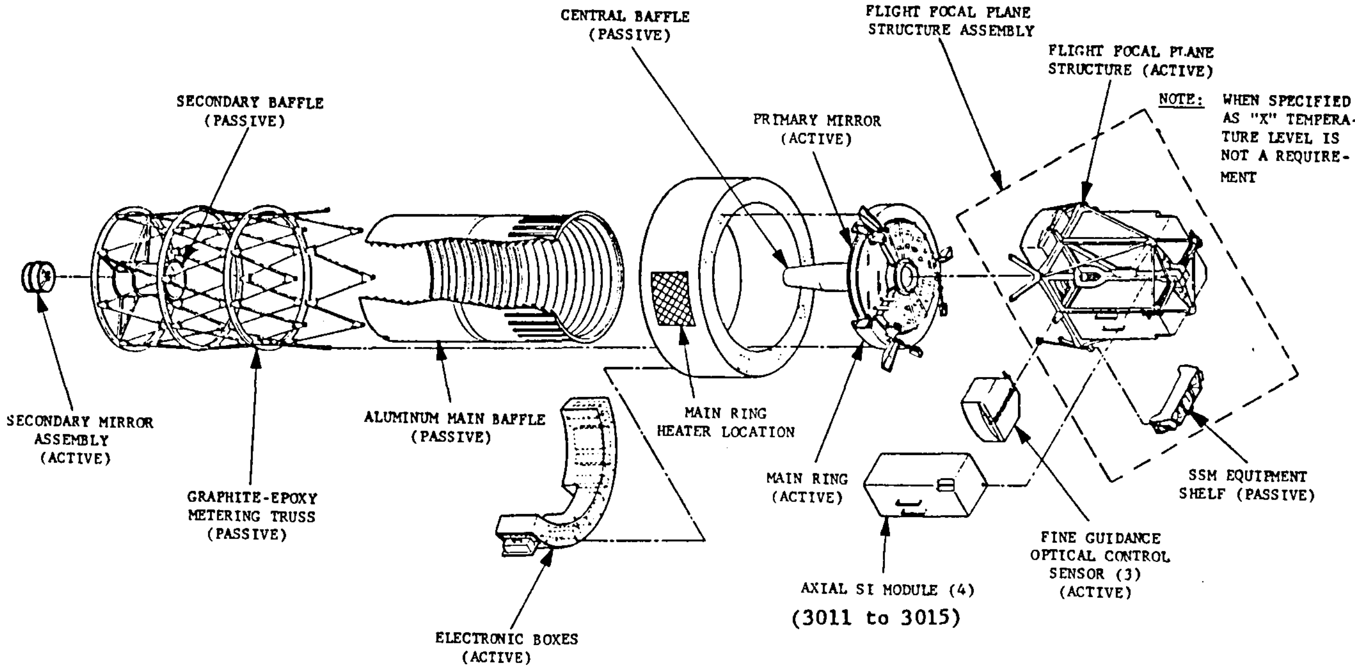
Figure 8. Space Telescope, Optical Telescope Assembly - Central and Main Baffle Thermal Node Description



Component	Node Number	Thermal Capacitance BTU/°F	Surface Area FT^2	Temperature Requirements °F	Surface Inner	Finish Outer	Power Dissipation
Metering Truss (Mid)	11	41	194	16(1)	MLI2	MLI2	None
Metering Truss (Fwd)	12	5	34	16(1)	MLI2	MLI2	None
Metering Truss Spiders	13	6	18	None	Black Paint	Black Paint	None
Secondary Mirror Heater	14	9	3.4	None	Black Paint	MLI2	None
Secondary Mirror Housing	15	3	19	X ± 2	Black Paint	Black Paint	None
Secondary Mirror	16	6	3.4	None	Glass	Mirror	None
Secondary Mirror Baffle	17	2	24	None	Black Paint	Black Paint	None

(1) Change in gradient between Mid (Node 11) and Fwd (Node 12) is less than 16°F.

Figure 9. Space Telescope, Optical Telescope Assembly - Metering Truss and Secondary Mirror Thermal Node Description

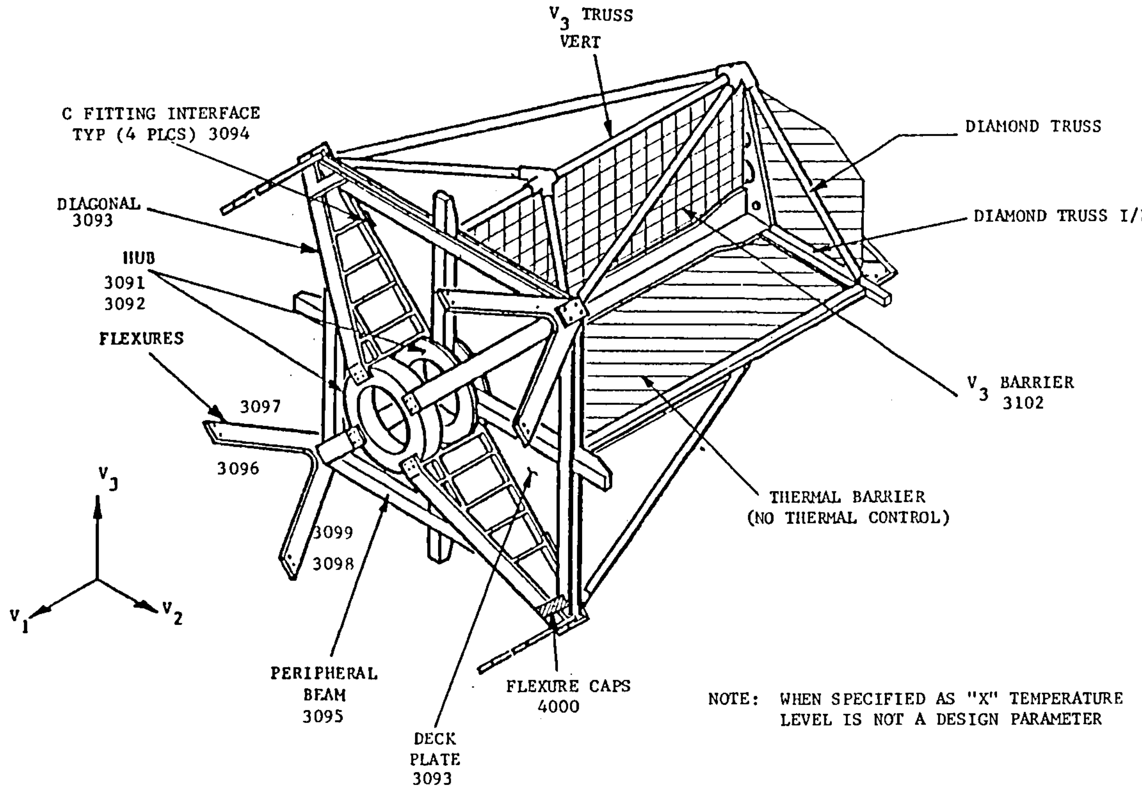


Component	Node Number	Thermal Capacitance BTU/°F	Surface Area FT^2	Temperature Requirements °F	Surface Inner	Finish Outer	Power Dissipation
Typical Axial(1)							
SI Module							
Optical Bench	3011	74	111	X ±1	None	MLI2	150/58(2)
Radiator	3012	18	44	None	Black Paint	Black Paint	None
Interior	3013	16	44	None	Black Paint	MLI2	None
$\pm V_1$ Ends	3014	6	11	None	Black Paint	MLI2	None
"B" Interface	3015	∅	∅	None	None	None	None

NOTE: (1) One of eight axial and radial modules.

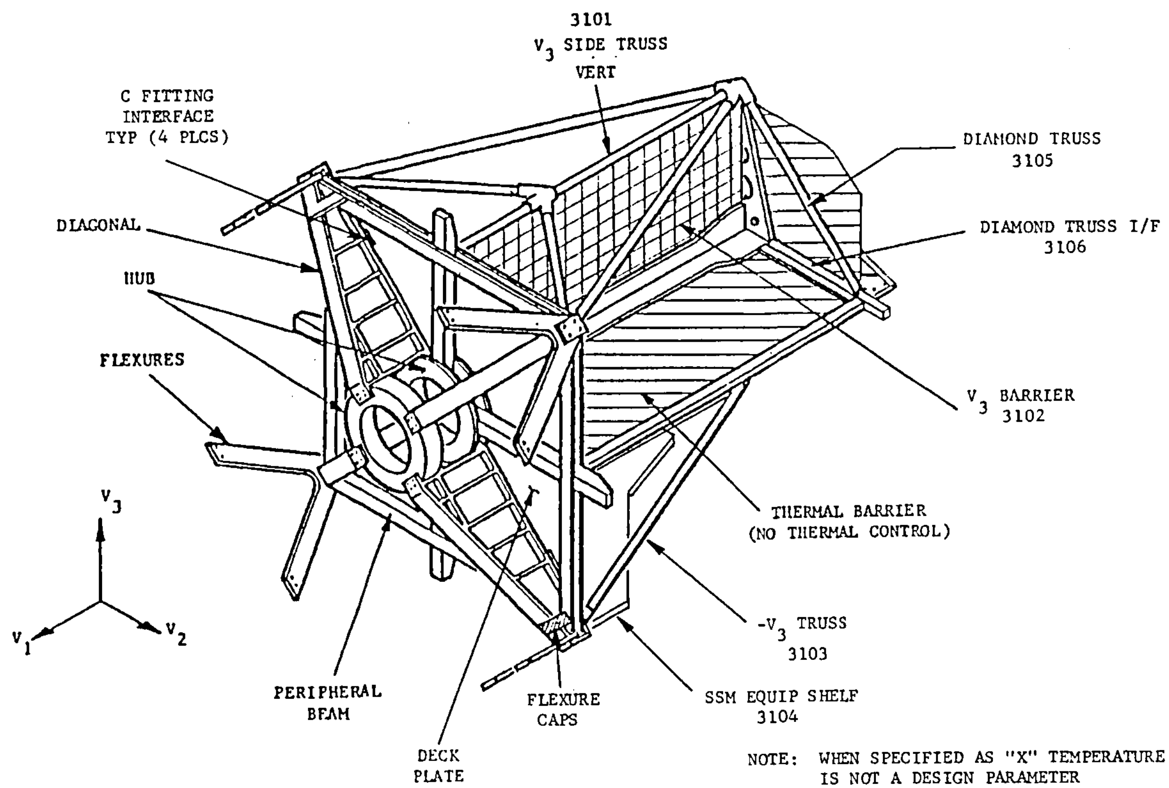
(2) The optical bench power dissipation will range from 58 to 150 Watts.

Figure 10. Space Telescope, Optical Telescope Assembly - Scientific Instruments Thermal Node Description



Component	Node Number	Thermal Capacitance BTU/°F	Surface Area FT^2	Temperature Requirements °F	Surface Inner	Finish Outer	Power Dissipation
Forward Hub	3091	8	10	X ±.50	MAX ORB	MAX ORB	None
Aft Hub	3092	15	11	X ±.50	MAX ORB	MAX ORB	None
Deck Plate and Diagonal Beams	3093	9	128	X ±1.5	None	MLI2	None
"C" Fitting I/F	3094	9	2	X ±1.5	None	MLI2	None
Peripheral Beams	3095	30	42	X ±1.5	None	MLI2	None
Flexures	3096	1.6	8	X ±1.5	None	MLI2	None
Flexures	3097	1.6	8	X ±1.5	None	MLI2	None
Flexures	3098	1.6	8	X ±1.5	None	MLI2	None
Flexures	3099	1.6	8	X ±1.5	None	MLI2	None
Flexure Caps	4000	1.5	6	X ±1.5	None	MLI2	None

Figure 11. Space Telescope, Optical Telescope Assembly - Forward Focal Plane Thermal Node Description



Component	Node Number	Thermal Capacitance BTU/°F	Surface Area FT^2	Temperature Requirements °F	Surface Inner	Finish Outer	Power Dissipation
+V3 Truss	3101	14	43	X $\pm$1.5	None	MLI2	None
V3 Barrier	3102	16	99	X $\pm$1.5	None	MLI2	None
-V3 Truss	3103	14	43	X $\pm$1.5	None	MLI2	None
SSM Equipment Shelf	3104	19	11	None	MLI2	MLI2	None
Diamond Truss	3105	8	95	X $\pm$1.5	None	MLI2	None
Diamond Truss Interface	3106	1	None	X $\pm$1.5	None	None	None

Figure 12. Space Telescope, Optical Telescope Assembly - Aft Focal Plane Thermal Node Description

TABLE III
PROPERTIES OF AVAILABLE THERMAL COATINGS

No.	Description	Alpha Mean	Alpha Variation	Epsilon Mean	Epsilon Variation
1	FOSR	0.1	±0.05	0.85	±0.05
2	Aluminum	0.2	±0.05	0.10	±0.01
3	Max Orb	0.95	±0.05	0.1	±0.01
4	Black Paint	0.95	±0.02	0.95	±0.02
5	Gold	0.25	±0.03	0.03	±0.01
6	Multi-Layer Insulation (high α)	0.95	±0.05	0.01	+0.0 -0.005
7	Multi-Layer Insulation (low α)	0.1	±0.01	0.01	+0.000 -0.005
8	Optical Surface	0.10	±0.02	0.02	±0.01
9	Glass	0.1	±0.05	0.9	±0.05

TABLE IV
POWER PENALTIES

Parameter	Penalties	
Peak Power	0.15	lbm/watt
Average Power	0.7	lbm/watt
Life Cycle(1)	0.56	$\frac{\text{watts end of mission}}{\text{watts start of mission}}$

(1) Based on a 32 to 24 supply voltage variation (start to end) and resistance heaters

- PEAK POWER - This is the penalty for the peak power required to maintain the spacecraft. The number of heaters and their duty cycle has a significant bearing on the weight of a thermal control system and this is accounted for in this term.

- LIFE CYCLE - As the solar arrays age their output and the corresponding supply voltage decreases. This results in a change in both the average and the peak power availability with time. The weight penalty for power vs spacecraft life is accounted for in this term.

The factors given above are combined as shown below to determine the power weighting factors:

ab = average power

ae = average power/life cycle

bb = peak power

be = peak power/life cycle

After the model and weighting factors are defined, the model is put in the form to be optimized as given in Table V.

The ST will be optimized for two missions, each with the solar vector at opposite ends of the allowable envelope shown in Figure 4. During this process the coating on the SSM will be optimized to meet the temperature requirements listed in Figures 5 through 10. If the absolute level is not specified the upper and lower bounds for these components will be set at 70°F plus or minus the prescribed temperature tolerance. For example, the limits for node five in Figure 7 are:

$L_5 = 70 - 0.6 = 69.4°F$

$U_5 = 70 + 0.6 = 70.6°F$

When the analysis for the average temperature of 70°F is complete, other average component temperatures will be tried to assess the impact of temperature level on the optimal design. During this process we will not vary the coatings on nodes other than the exterior surface since these are generally set by requirements other than thermal.

TABLE V

OPTIMIZATION MODEL

• Model size	84 Nodes
• Nodes for coating optimization (f_{nc} varied)	7 SSM Nodes (Figure 5)
• Nodes with temperature requirement constraints	29 [a] OTA and SI Nodes
• Nodes with weighted - average temperature constraints	none
• Nodes with temperature difference constraints	2 difference between the metering truss (Mid) and metering truss (Fwd)
• Nodes with a weighted average temperature difference constraints	none

a The twenty-nine nodes requiring temperature level control are shown in Figures 7 through 12. The optical benches of the 3 axial SI modules and 4 radial modules (not shown) also require thermal control.

However, the program will determine the optimal placement of heaters, and their location will not be fixed by their locations in the ST design.

REMARKS ON ST THERMAL DESIGN PROBLEM

During its design, the ST spacecraft was partitioned into three major subsystems. Each subsystem's contractor tried to optimize that subsystem within that subsystem's constraints. For example, the SSM designer had a wide latitude in temperature excursion during an observational period and over the entire life of the mission. This led to a passive SSM shell design. On the other hand, faced with a varying environment, both the OTA designer and the SI designer were led to active systems to maintain both level and change over any period. Additionally, because of the problems of maintaining the figure of a mirror at temperatures other than the temperature at which it was figured, a significant portion of the OTA is maintained at a single temperature of 70°F. Optimization could change parts of this. Since the entire ST would be optimized as an entity, it is possible that maintaining the SSM at a fixed temperature (plus control tolerance) may be a lower weight solution than the current design. Additionally it would be of interest to modify the OTA criteria from one that requires a 70°F structure to one that only maintains the mirrors at that temperature and finds the optimum temperature for the remaining structure. This may result in a telescope with a 70°F Primary Mirror and a different temperature Focal Plane Assembly.

The accepted thermal control procedure is to find the maximum temperature of a component and then maintain it using heaters and a single set point thermistor controller. This assures that all temperature and gradient constraints are met for all phases of the mission. However a more power-efficient method of control may be to maintain the temperature difference between components by using the temperature of one component as the set point temperature of the other. This type of control is possible with presently available micro-computers and may result in a significant power (thus weight) savings for the optimized spacecraft.

SECTION 9

CONCLUSION

The purpose of the work reported here was to develop a strategy by which thermal designers for spacecraft could devise an optimal thermal control system to maintain the required temperatures, temperature differences, changes in temperatures and changes in temperature differences for specified equipment and elements of the spacecraft's structure. Thermal control would be maintained by the optical coating pattern chosen for the external surfaces and the heaters chosen to supplement the coatings. A strategy appropriate to computer-aided design was anticipated.

We focused on the development of a practical tool for the designer: an optimization program compatible with his present analytical tools and useful in the conceptual-design phase. We initially examined the general problem of spacecraft temperature control, including all phases of the mission and all phases of the design process. To aide in conceptualizing the problem, we set up a simple three node spacecraft to optimize. This provided us with insight into the problem without the confusion of a complex model. From this exercise we learned that two major problems needed to be overcome: (1) how to optimize both power and weight, and (2) how to include coating uncertainties. These were solved by expressing both power and weight as cost functions to be minimized and including both variable properties and uncertainties in the properties of the coating.

We then reviewed the methods available for computation. The optimization requires a considerable amount of computer time to solve a complex problem. However, with estimated run times of 0.5 to 10 hours, the solution times are not considered a significant driver in the problem. This is especially true considering the potential for savings in the development of a space system when optimization is used.

The next task was to develop the overall optimization strategy. The strategy developed does not eliminate the need for a thermal designer, but is a design tool that eliminates many of the intuitive decisions that must be made. While the work to this point demonstrated the feasibility of the proposed optimization procedure, a pilot program was developed to validate some of the techniques needed for the optimization. The pilot program was successfully applied to the three-node sample problem presented in Section 3. The details of the application (see Appendix) confirmed the practicality of each step. Although the program tests only selected parts of the computational procedure, it does include enough of the steps so that we are confident that the entire algorithm can be developed. We performed one additional test on the optimization process by conceptually applying it to the Space Telescope. The work remaining is detailed in Section 7.

In developing the optimization strategy, we have included all of the elements normally considered by the designer: vehicle orientations, equipment power dissipations, coating-property uncertainties, uncertainties in the internal thermal conductances, and coating-property changes. The method uses the same thermal model data the designer develops for his analyses; there is no extra work. He can use his intuition to speed the optimization process and to simplify the resultant heater arrangement, but he can also use the process as a "black box." We have demonstrated how the optimization process can be cast in computer form; the results will be in the form of a specification of the coating pattern to be used on each external surface, the heater capacities required for each node, the average power required for each mission, and the maximum and minimum temperatures expected for each node. The method is limited, however, to quasi-steady-state temperatures; therefore, the designer must select time periods over which steady-state temperatures are representative of the mission temperatures. Because most sensitive equipment is located well inside the vehicle, his selection is usually not difficult: the orbital period is adequate.

Three of the four steps to having an operational optimization program have been accomplished:

- The governing equations have been developed
- The theory has been developed for solving the equations
- The methods have been demonstrated.

The last but largest step - developing the production program, including making the final tradeoffs and determining how to integrate the theory with existing analysis and optimization programs - still must be accomplished.

SECTION 10

NOMENCLATURE

A	surface area
B	black body radiation factors
C	heater capacity
D	electronic power
E	earth flux
G	weight average temperature
G_{nj}	$K_{nj} + RL_{nj}$
K	thermal conductance
K_{nj}	conductance between nodes n and j
L	lower temperature limit
M	mission
N	total number of nodes
P	model version
Q	the heater energy required for the most severe environment; maximum total power demand
Q_{nm}	orbital average power demand for node (n) in mission (m)
R	radiation interchange factor
RL_{njm}	linearized radiation term (Eq. 8) evaluated for temperatures in mission m
RL_{nj}	Linearized radiation term (Eq. 8) evaluated for maximum temperatures
S	solar flux

NOMENCLATURE (Continued)

T_{jm}	temperature of node j in mission m
T_{nm}	temperature of node n in mission m
U	upper temperature
V_{nm}	residual in heat balance equation
W	weight
a	solar absorptance
ab	weight per unit of power, beginning of life
ae	weight per unit of power, end of life
bb	weight per unit of power (capacity) beginning of life
be	weight per unit of power (capacity) end of life
c	coating
ca	changes in absorptance, beginning to end of mission
ce	changes in emissivity, beginning to end of mission
c_n	heater capacity of node (n)
da	range of uncertainty in solar absorptance, beginning to end of mission
de	range of uncertainty in emissivity, beginning to end of mission
δa_c	uncertainty in solar absorptance
δe_c	uncertainty in emittance
δT_{nm}	uncertainty in temperature
e	emissivity; infrared emittance
f_{nc}	fractions of the area of node (n) that are covered with coating (c)
j	node j
m	mission number
n	node n

SECTION 11

REFERENCES

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APPENDIX A

PILOT PROGRAM

APPENDIX A

PILOT PROGRAM

In developing the optimization strategy presented in Sections 3 and 4, we were careful to test the practicality of each step. The testing was done with a pilot program that used selected parts of the technique. In particular, we selected those parts that demonstrated computing the nominal case, computing the effects of uncertainties, selecting the thermostat set points, computing the heater-power required, and computing the derivatives.

The pilot program was tested with the three-node satellite used as an example in Section 3 (see Fig. A-1). Two of the nodes are external, one facing toward the earth and the other facing away from the earth. The third node is internal. Each node is connected to the other two. To minimize computation time, all of the radiation terms were linearized.

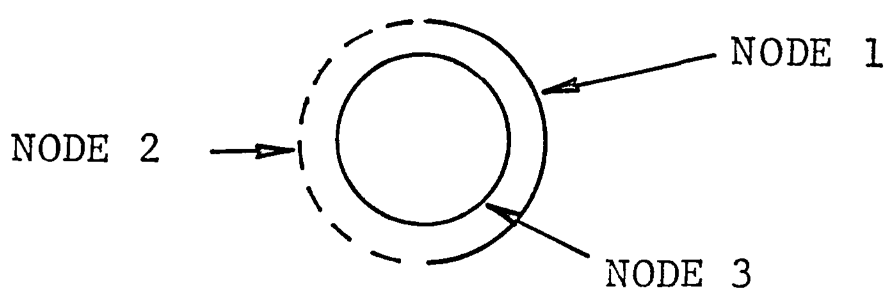

Figure A-1. Three-Node Problem

The input data for the three-node vehicle are listed in Table A-1. In response to prompts from the program, the user specifies the number of nodes, number of missions, and the coating properties. The coating properties were assumed to be known to within plus or minus 0.03. The user also specifies the areas of the external nodes and the starting values of the f_{nc}'s, the fractions of external node areas covered by each of the coatings. The input calls for an initial guess at the temperature, in anticipation of an iterative solution technique. Because a matrix-inversion technique is used, this initial temperature does not enter the solution for the pilot program. The internode conductances are assumed to be symmetric. The missions are described by the electrical heat input to each node from the electronic equipment, the solar flux impinging on each node, and the infrared flux emitted by the earth that impinges on each node. Only two missions were included in the sample case. All of the values used in the sample case were the default values; therefore, there are no entries in response to the prompt asking if there is a change to be made. The computed conductance matrix is listed at the bottom of the input.

The output data for the three-node vehicle are listed in Table A-2. As a check, the residual of the conductance matrix after inversion and the inverted matrix are listed. The residual is seen to be the identity matrix, so the error in the inversion process was insignificant. The pilot program calculates the nominal temperatures with no heater input immediately. The temperatures are listed after the inverted matrix. For example, the temperature of the internal node, Node 3, is 64.7°F for Mission 1. The chart of temperature data includes the area ratios for the various coatings and the effective solar absorptance and an infrared emittance (0.337 and 0.421, respectively, for Node 1). Because there are no heaters for this nominal case, there is no weight penalty, as indicated in the output below the temperature chart.

In response to a list of options displayed on the CRT screen, but not shown in the output data, we chose to compute next the effects of the coating uncertainties (called tolerances in the output data). The temperatures with the uncertainties included are tabulated under the heading, "IF COATING TOLERANCES ARE INCLUDED." The MIN temperature, for example, is the nominal temperature less the three-sigma temperature uncertainty. For Node 3, the temperatures will be between 38.3°F and 91.1°F in Mission 1 and between 38.6°F and 87.9°F in Mission 2, if no heaters are used and this coating pattern is chosen.

TABLE A-1

INPUT DATA FOR THE DEMONSTRATION CASE

```
NUMBER OF NODES                                      3       CHANGE TO?
          YOU CAN HAVE UP TO 51.1404  MISSIONS
NUMBER OF MISSIONS:                                  2       CHANGE TO?

THE FOLLOWING COATINGS ARE AVAILABLE:
  NO. DESCRIPTION   ALPHA     EPSILON
   1   FOSR          .1        .85
   2   ALUMINUM      .2        .1
   3   MAXORB        .95       .1
   4   BLACK PAINT   .95       .95


NODE PROPERTIES:
FOR NODE NO. 1 :
     EXTERNAL AREA, A:                               300     CHANGE TO?
     INITIAL TEMPERATURE, T IN DEG F:                70      CHANGE TO?
     AREA FRACTION WITH AL= .1 ,EP= .85 :            .36     CHANGE TO?
     AREA FRACTION WITH AL= .2 ,EP= .1 :             .41     CHANGE TO?
     AREA FRACTION WITH AL= .95 ,EP= .1 :            .17     CHANGE TO?
     AREA FRACTION WITH AL= .95 ,EP= .95 :           .06     CHANGE TO?
FOR NODE NO. 2 :
     EXTERNAL AREA, A:                               300     CHANGE TO?
     INITIAL TEMPERATURE, T IN DEG F:                70      CHANGE TO?
     AREA FRACTION WITH AL= .1 ,EP= .85 :            .36     CHANGE TO?
     AREA FRACTION WITH AL= .2 ,EP= .1 :             .32     CHANGE TO?
     AREA FRACTION WITH AL= .95 ,EP= .1 :            .17     CHANGE TO?
     AREA FRACTION WITH AL= .95 ,EP= .95 :           .15     CHANGE TO?
FOR NODE NO. 3 :
     EXTERNAL AREA, A:                               0       CHANGE TO?
     INITIAL TEMPERATURE, T IN DEG F:                70      CHANGE TO?

CONDUCTION MATRIX:
                           C( 1 , 2 ) =              125     CHANGE TO?
                           C( 1 , 3 ) =              125     CHANGE TO?
                           C( 2 , 3 ) =              125     CHANGE TO?

MISSION CHARACTERISTICS:
MISSION   NODE     ELEC INPUT     SOLAR FLUX     EARTH FLUX
                   BTU/HR         BTU/HR-SF      BTU/HR-SF
 1         1        0              266.667        7.33333   CHANGE (Y/N)?
 1         2        0              16.6667        41        CHANGE (Y/N)?
 1         3        0              0              0         CHANGE (Y/N)?
MISSION   NODE     ELEC INPUT     SOLAR FLUX     EARTH FLUX
                   BTU/HR         BTU/HR-SF      BTU/HR-SF
 2         1        0              133.333        23.3333   CHANGE (Y/N)?
 2         2        0              133.333        23.3333   CHANGE (Y/N)?
 2         3        0              0              0         CHANGE (Y/N)?

COMBINED CONDUCTANCE MATRIX:
   -281.58    125.00     125.00
    125.00   -287.31     125.00
    125.00    125.00    -250.00
```

TABLE A-2

OUTPUT DATA FOR THE DEMONSTRATION CASE

```
THE RESIDUAL IN THE MATRIX THAT WAS INVERTED:
  1.000000  0.000000  0.000000
  0.000000  1.000000  0.000000
  0.000000  0.000000  1.000000

INVERSE MATRIX:
 -0.015950 -0.013303 -0.014627
 -0.013303 -0.015543 -0.014423
 -0.014627 -0.014423 -0.018525

MISSION:   1
NODE   TEMPERATURE   HEATER PWR   HEATER CAP   ALPH   EP    AREA RATIO BY COATING NO.
        MIN (F) MAX    BTU/HR       BTU/HR                  1     2     3     4
 1       92.4  92.4   0            0
 2       36.9  36.9   0            0           .337 .421   0.360 0.410 0.170 0.060
 3       64.7  64.7   0            0           .404 .498   0.360 0.320 0.170 0.150

MISSION:   2
NODE   TEMPERATURE   HEATER PWR   HEATER CAP   ALPH   EP    AREA RATIO BY COATING NO.
        MIN (F) MAX    BTU/HR       BTU/HR                  1     2     3     4
 1       63.0  63.0   0            0
 2       63.6  63.6   0            0           .337 .421   0.360 0.410 0.170 0.060
 3       63.3  63.3   0            0           .404 .498   0.360 0.320 0.170 0.150

PREVIOUS WEIGHT FUNCTION WAS    0        BTU/HR EQUIV AVERAGE HEATER POWER
THE NEW WEIGHT FUNCTION IS      0


                        IF COATING TOLERANCES ARE INCLUDED
MISSION:   1
NODE   TEMPERATURE   HEATER PWR   HEATER CAP   ALPH   EP    AREA RATIO BY COATING NO.
        MIN (F) MAX    BTU/HR       BTU/HR                  1     2     3     4
 1       64.4 120.5   0            0
 2       12.2  61.7   0            0           .337 .421   0.360 0.410 0.170 0.060
 3       38.3  91.1   0            0           .404 .498   0.360 0.320 0.170 0.150

MISSION:   2
NODE   TEMPERATURE   HEATER PWR   HEATER CAP   ALPH   EP    AREA RATIO BY COATING NO.
        MIN (F) MAX    BTU/HR       BTU/HR                  1     2     3     4
 1       38.1  87.9   0            0
 2       39.2  88.0   0            0           .337 .421   0.360 0.410 0.170 0.060
 3       38.6  87.9   0            0           .404 .498   0.360 0.320 0.170 0.150

PREVIOUS WEIGHT FUNCTION WAS    0        BTU/HR EQUIV AVERAGE HEATER POWER
THE NEW WEIGHT FUNCTION IS      0


ENTER THE THERMOSTAT SET POINTS:
NODE        SET POINT (F)   (SP=-999 => NO THERMOSTAT OR HEATER)
 1          -999            CHANGE TO?
 2          -999            CHANGE TO?
 3          -999            CHANGE TO? 70
```

In running the demonstration case, we next wanted to determine the heater power required to hold the internal temperature (Node 3) to 70°F. The thermostat set points were entered and the program calculated the required heater power (including the effects of the uncertainties) and the resultant nominal temperatures. Notice that the heater power for Mission 1 is 1710.42 Btu/hr. If this power were dissipated and the coating properties were their nominal values, Node 3 would be at 96.4°F for Mission 1. Of course, the thermostatic control would take effect, so this much power would not be dissipated. From the previous data, we saw that with no heat input, Node 3 would be at 64.7°F with the nominal coating properties. Therefore, if the coating properties were the nominal values, a slight amount of heat would be required to maintain 70°F. However, we also saw that, with no heater power and the upper limit of the coating uncertainties, Node 3 could be as high as 91.1F. If this were unacceptable, a new set of coatings would be selected.

If we return to the system performance with the heaters on, but we add the coating uncertainties (tolerances), the last set of temperature output shows that 69.5°F can be maintained at Node 3 for Mission 1 and 69.4°F, for Mission 2. These results are not exactly 70°F because the pilot program does not include the method presented in Section 4 by which the sensitivity of the temperature uncertainty to the coating properties can be computed.

Finally, in running the pilot program, we selected the option of having the derivatives calculated, as shown in the last set of output data. These are the derivatives of the temperatures with respect to the f_{nc}'s, the fractions of nodes 1 and 2 that are covered by each coating. These derivatives could be combined with the derivatives of the heater powers with respect to temperature (dq/dt) and the derivatives of the weight penalty with respect to the heater powers (dw/dq) to estimate the next best set of f_{nc}'s. However this logic was not included in the pilot program.

Again, the purpose of the pilot program was not to demonstrate the complete logic but to test the ideas. It kept the development of the optimization strategy firmly implanted in reality. The success of the pilot program is indicative of the success we can expect in the total implementation of the method.

The complete listing of the pilot program, in Microsoft BASIC, is presented in Table A-3.

TABLE A-3

THERMAL OPTIMIZATION PILOT PROGRAM

```
00010  'PROGRAM              EXAMPLE/OPT       ON PERKINEL AND MINDISK2
00020  '                     JUNE 2, 1983   8:52 PM
00030  'THIS PROGRAM TAKES A SMALL SATELLITE THERMAL MODEL AND OPTIMIZES THE
00040  'ALPHA, EPSILON AND HEATER CAPACITY FOR THE NODES SELECTED.
00050  'TO INVERT A 10-NODE MATRIX REQUIRES 27 SECONDS
00060  DEFINT I-N
00070  L$="OFF"
00080  INPUT "DO YOU WANT TO USE AN EXISTING DATA FILE (Y/N)";SI$
00090  IF SI$  "Y" THEN SI$="N":GOTO 130ELSE INPUT "WHAT IS THE FILE NAME";SI$
00100  OPEN "I",1,SI$
00110  INPUT#1,N,M,NC
00120  NS=N:MS=M
00130  INPUT "WILL YOU WANT TO SAVE THE INPUT DATA ON DISK (Y/N)";S$
00140  IF S$  "Y" THEN S$="N":GOTO 150ELSE INPUT "UNDER WHAT FILE NAME";S$
00150  C$="N":INPUT "DO YOU WANT TO TURN THE LINE PRINTER ON (Y/N)";C$:PRINT
00160  IF C$  "Y" THEN 190
00170  INPUT "WHAT TITLE DO YOU WANT";C$
00180  PRINT CHR$(14);TAB(40-LEN(C$)/2);C$:L$="ON":PRINT:PRINT
00190  IF SI$="N" THEN N=3:M=2:NC=4 'DEFAULT VALUES
00200  N1=45:N2=55:CH$="CHANGE TO"
00210  PRINT "NUMBER OF.NODES";TAB(N1);N;TAB(N2);CH$;:INPUT N
00220  IF N= NS THEN 240
00230  PRINT"CAN'T HAVE NEW CASE WITH FEWER NODES THAN STORED FILE:"NS:GOTO 210
00240  DIM C(N,N),A(N),AL(NC),EP(NC),NC$(NC),H(N),CI(N,N),SP(N),HC(N)
00250  DIM CT(N,N),CN(N,N),AR(N,NC)
00255  I=2975
00260  PRINT TAB(10);"YOU CAN HAVE UP TO";(I-4*N*N-8*N)/(4*N*N+7*N);"MISSIONS"
00270  PRINT "NUMBER OF MISSIONS:";TAB(N1);M;TAB(N2);CH$;:INPUT M
00280  IF M= MS THEN 300
00290  PRINT"CAN'T HAVE NEW CASE WITH FEWER MISS'S THAN STORED FILE:"MS:GOTO 2
00300  DIM T(N,M),Q(N,M),S(N,M),E(N,M),QH(N,M),NH(N,M),TU(N,M),DE(N,M,N,NC)
00305  'THE ARRAYS TAKE 8*N+(4*M+4)*N*N+7*N*M STORAGE LOCATIONS
00310  IF SI$="N" THEN 400
00320  'READ THE DATA FROM THE DISK
00330  FOR I=1 TO NC:INPUT#1,NC$(I),AL(I),EP(I):NEXT
00340  FOR I=1 TO NS-1:FOR J=I+1 TO NS:INPUT#1,C(I,J):NEXT:NEXT
00350  FOR I=1 TO NS:INPUT#1,A(I),T(I,1):IF A(I)=0 THEN 370
00360  FOR J=1 TO NC:INPUT#1,AR(I,J):NEXT
00370  NEXT
00380  FOR I=1 TO MS:FOR J=1 TO NS:INPUT#1,Q(J,I),S(J,I),E(J,I):NEXT:NEXT
00390  FOR I=1 TO NS:INPUT#1,SP(I):NEXT:CLOSE:GOTO 550
00400  IF N  3 OR M  2 THEN 550
00410  FOR J=1 TO NC:READ NC$(J),AL(J),EP(J):NEXT
00420  DATA FOSR,0.1,0.85,ALUM,0.2,0.1,MAXORB,0.95,0.1,BLACK PAINT,0.95,0.95
00430  C(1,2)=125:C(1,3)=125:C(2,3)=125  'DEFAULT VALUES
00440  T(1,1)=70:T(2,1)=70:T(3,1)=70
00450  AR(1,1)=.36:AR(1,2)=.41:AR(1,3)=.17:AR(1,4)=.06
00451  AR(2,1)=.36:AR(2,2)=.32:AR(2,3)=.17:AR(2,4)=.15
00460  A(1)=300:A(2)=300
00470  S(1,1)=80000/300:S(2,1)=5000/300:E(1,1)=2200/300:E(2,1)=12300/300
```

TABLE A-3 (Continued)

THERMAL OPTIMIZATION PILOT PROGRAM

```
00480   S(1,2)=40000/300:S(2,2)=40000/300:E(1,2)=7000/300:E(2,2)=7000/300
00490   FOR I=1 TO N:SP(I)=-999+460:HC(I)=0:FOR J=1 TO M:QH(I,J)=0:NEXT:NEXT
00500   '1. ENTER THE PROPERTIES OF THE EXTERNAL SURFACES
00510   PRINT:PRINT "THE FOLLOWING COATINGS ARE AVAILABLE:"
00520   PRINT "  NO. ";TAB(5);"DESCRIPTION";TAB(20);"ALPHA";TAB(30);"EPSILON"
00530   FOR I=1 TO NC:PRINT TAB(2);I;TAB(7);NC$(I);TAB(20);AL(I);TAB(30);EP(I):NE
00540   PRINT
00550   PRINT:PRINT "NODE PROPERTIES:"
00560   FOR I=1 TO N
00570   PRINT "FOR NODE NO.";I;":"
00580   PRINT TAB(5);"EXTERNAL AREA, A:";TAB(N1);A(I);TAB(N2);CH$;:INPUT A(I)
00590   PRINT TAB(5);"INITIAL TEMPERATURE, T  DEG F:";TAB(N1);T(I,1);TAB(N2);CH
00600   INPUT T(I,1):IF A(I)=0 THEN 630ELSE FOR J=1 TO NC
00610   PRINT TAB(5);"AREA FRACTION WITH AL=";AL(J);",EP=";EP(J);":";TAB(N1);
00620   PRINT AR(I,J);TAB(N2);CH$;:INPUT AR(I,J):NEXT
00630   NEXT
00640   FOR I=1 TO N:FOR J=1 TO NC:IF A(I)*AR(I,J) 0 THEN 680ELSE NEXT J:NEXT I
00650   PRINT "FOR THERE TO BE A SOLUTION, AT LEAST ONE";
00660   PRINT " NODE MUST HAVE AN EXTERNAL AREA.":GOTO 560
00670   '2. ENTER THE CONDUCTION MATRIX
00680   PRINT:PRINT "CONDUCTION MATRIX:"
00690   FOR I=1 TO N-1:FOR J=I+1 TO N
00700   PRINT TAB(20);"C(";I;",";J;") = ";TAB(N1);C(I,J);TAB(N2);CH$;:INPUT C(I,J
00710   C(J,I)=C(I,J)
00720   NEXT:NEXT
00730   '3. ENTER THE INTERNAL HEATING RATES AND ENVIRONMENTAL FLUXES
00740   PRINT:PRINT "MISSION CHARACTERISTICS:":FOR I=1 TO M
00750   PRINT "MISSION";TAB(10);"NODE";TAB(20);"ELEC INPUT";TAB(35);"SOLAR FLUX";
00760   PRINT TAB(50);"EARTH FLUX"
00770   PRINT TAB(20);"BTU/HR";TAB(35);"BTU/HR-SF";TAB(50);"BTU/HR-SF"
00780   FOR J=1 TO N
00790   PRINT I;TAB(10);J;TAB(20);Q(J,I);TAB(35);S(J,I);TAB(50);E(J,I);TAB(60);
00800   C$="N":INPUT "CHANGE (Y/N)";C$:IF C$="N" THEN 820
00810   PRINT TAB(20);:INPUT Q(J,I),S(J,I),E(J,I)
00820   NEXT:NEXT
00830   '4. SET UP THE CONDUCTANCE MATRIX
00840   FOR I=1 TO N:C(I,I)=0:FOR J=1 TO N:IF J=I THEN 860
00850   C(I,I)=C(I,I)-C(I,J)
00860   NEXT J
00870   H(I)=.001713*((T(I,1)+459.67)/100) 3
00880   H(I)=.25 'TEMPORARY FOR CHECKOUT
00890   NEXT I
00900   '5. FOR THE GIVEN AL,EP, FINISH THE CONDUCTANCE MATRIX
00910   FOR I=1 TO N:FOR J=1 TO NC:C(I,I)=C(I,I)-H(I)*A(I)*AR(I,J)*EP(J):NEXT:NEX
00920   FOR I=1 TO N:FOR J=1 TO N:CT(I,J)=C(I,J):NEXT:NEXT
00930   PRINT:PRINT "COMBINED CONDUCTANCE MATRIX:"
00940   FOR I=1 TO N:FOR J=1 TO N:PRINT USING "#######.##";C(I,J);:NEXT:PRINT:NEX
00950   '6. INVERT THE CONDUCTANCE MATRIX
00960   FOR I=1 TO N-1:FOR J=I+1 TO N:CI(I,J)=0:CI(J,I)=0:NEXT:CI(I,I)=1:NEXT
00970   CI(N,N)=1
00980   '6.1. FIND THE LARGEST DIAGONAL
00990   CX=0:FOR I=1 TO N:IF CT(I,I) CX THEN CX=CT(I,I):K(1)=I
01000   NEXT
01010   '6.2. PERFORM THE INVERSION USING THE LARGEST DIAGONAL FIRST
```

TABLE A-3 (Continued)

THERMAL OPTIMIZATION PILOT PROGRAM

```
01020   'DEFER SEARCH FOR LARGEST DIAGONAL TO A LATER VERSION OF THIS PROGRAM
01030   FOR K=1 TO N-1:FOR I=K+1 TO N
01040   R=CT(I,K)/CT(K,K):FOR J=1 TO N:CT(I,J)=CT(I,J)-R*CT(K,J)
01050   CI(I,J)=CI(I,J)-R*CI(K,J)
01060   NEXT:NEXT:NEXT
01070   FOR K=N TO 2 STEP -1:FOR I=K-1 TO 1 STEP -1:R=CT(I,K)/CT(K,K)
01080   FOR J=N TO 1 STEP -1:CT(I,J)=CT(I,J)-R*CT(K,J)
01090   CI(I,J)=CI(I,J)-R*CI(K,J):NEXT:NEXT:NEXT
01100   FOR K=1 TO N:D=CT(K,K)
01110   FOR I=1 TO N:CT(K,I)=CT(K,I)/D:CI(K,I)=CI(K,I)/D:NEXT:NEXT
01120   PRINT:PRINT "THE RESIDUAL IN THE MATRIX THAT WAS INVERTED:"
01130   FOR I=1 TO N:FOR J=1 TO N:PRINT USING "###.######";CT(I,J);:NEXT:PRINT:NE
01140   PRINT:PRINT "INVERSE MATRIX:"
01150   FOR I=1 TO N:FOR J=1 TO N:PRINT USING "###.######";CI(I,J);:NEXT:PRINT:NE
01160   PRINT
01170   '7. COMPUTE THE TEMPERATURES FOR THE VARIOUS RIGHT-HAND SIDES
01180   '7.1.  COMPUTE THE RHS
01190   'ON THE FIRST PASS, ALL HEATERS ARE OFF
01200   FOR I=1 TO N:FOR K=1 TO M:NH(I,K)=1:NEXT:NEXT
01210   FOR K=1 TO M:FOR J=1 TO N:EP=0:AL=0:IF A(J)=0 THEN 1230
01220   FOR I=1 TO NC:EP=EP+AR(J,I)*EP(I):AL=AL+AR(J,I)*AL(I):NEXT
01230   R(J)=-QH(J,K)-Q(J,K)-EP*A(J)*E(J,K)-AL*A(J)*S(J,K):NEXT
01240   '7.2.  COMPUTE THE TEMPERATURES
01250   FOR I=1 TO N:T(I,K)=0:TU(I,K)=0:FOR J=1 TO N:T(I,K)=T(I,K)+CI(I,J)*R(J)
01260   NEXT:NEXT:NEXT:IF C$="2" THEN C$="3":GOTO 2170   'TO RECOMPUTE THE HTRS
01270   WO=W
01280   W=0:FOR K=1 TO M:R=0:FOR I=1 TO N:R=R+QH(I,K):NEXT:IF R W THEN W=R
01290   NEXT:FOR I=1 TO N:W=W+.1*HC(I):NEXT
01300   FOR K=1 TO M:PRINT "MISSION:  ";K
01310   PRINT "NODE";TAB(6);"TEMPERATURE";TAB(19);"HEATER PWR";
01320   PRINT TAB(31);"HEATER CAP";TAB(43);"ALPH";TAB(49);"EP";TAB(54);
01330   PRINT "AREA RATIO BY COATING NO."
01340   PRINT TAB(6);"MIN (F) MAX";TAB(21);"BTU/HR";TAB(33);"BTU/HR";TAB(54);
01350   PRINT "1";TAB(60);"2";TAB(66);"3";TAB(72);"4"
01360   FOR I=1 TO N:PRINT I;TAB(6);
01370   PRINT USING "###.# ";T(I,K)-TU(I,K)-460;T(I,K)+TU(I,K)-460;
01380   PRINT TAB(19);QH(I,K);TAB(31);HC(I);
01390   IF A(I) =0 THEN PRINT:GOTO 1440
01400   EP=0:AL=0:FOR J=1 TO NC:EP=EP+AR(I,J)*EP(J):AL=AL+AR(I,J)*AL(J):NEXT
01410   PRINT TAB(43);:PRINT USING ".###";AL;:PRINT TAB(48);
01420   PRINT USING ".###";EP;:PRINT TAB(54);
01430   FOR J=1 TO NC:PRINT USING "#.### ";AR(I,J);:NEXT:PRINT
01440   NEXT:PRINT:NEXT K
01450   PRINT "PREVIOUS WEIGHT FUNCTION WAS";TAB(30);WO;
01460   PRINT TAB(40);"BTU/HR EQUIV AVERAGE HEATER POWER
01470   PRINT "THE NEW WEIGHT FUNCTION IS";TAB(30);W:PRINT
01480   '8. SELECT NEW SURFACE PROPERTIES OR NEW HEATER CAPACITIES
01490   IF L$="ON" THEN PRINT CHR$(15)
01500   PRINT "ENTER THE OPTION NUMBER TO BE EXERCISED:"
01510   PRINT "  1. ALTER THE HEATER CAPACITIES (COMPUTES REQ'D HEATER POWERS)
01520   PRINT "  2. ALTER THE SURFACE PROPERTIES (RESETS HEATERS TO ZERO)
01530   PRINT "  3. ALTER THERMOSTAT SET POINTS (COMPUTES REQ'D HEATER POWERS)
01540   PRINT "  4. COMPUTE THE DERIVATIVES
01550   PRINT "  5. TOGGLE LINE PRINTER
```

TABLE A-3 (Continued)

THERMAL OPTIMIZATION PILOT PROGRAM

```
01560   PRINT "  6. STORE THE INPUT DATA ON DISK
01570   PRINT "  7. LIST THE TEMPERATURE DATA AGAIN
01580   PRINT "  8. INCLUDE THE TOLERANCES
01590   PRINT "  9. END
01600   INPUT "WHICH";C$:IF C$="2" THEN 1970
01610   IF C$="7" THEN 1300
01620   IF C$="9" THEN END
01630   IF L$="ON" THEN PRINT CHR$(14)
01640   IF C$  "6" THEN 1770
01650   PRINT "THE DATA WILL BE STORED IN FILE NAME ";S$;:INPUT "  OK (Y/N)";C$
01660   IF C$="Y"THEN 1680ELSE INPUT "DO YOU WANT TO RETURN TO THE MENU (Y/N)";C$
01670   IF C$="N" THEN INPUT "WHAT SHOULD THE FILE NAME BE";S$ ELSE 1490
01680   IF S$="N" THEN PRINT "CAN'T USE  N  FOR A FILE NAME":GOTO 1490
01690   OPEN "O",1,S$
01700   PRINT#1,N,M,NC
01710   FOR I=1 TO NC:PRINT#1,NC$(I),AL(I),EP(I):NEXT
01720   FOR I=1 TO N-1:FOR J=I+1 TO N:PRINT#1,C(I,J):NEXT:NEXT
01730   FOR I=1 TO N:PRINT#1,A(I),T(I,1):IF A(I)=0 THEN 1750
01740   FOR J=1 TO NC:PRINT#1,AR(I,J):NEXT
01750   NEXT:FOR I=1 TO M:FOR J=1 TO N:PRINT#1,Q(J,I),S(J,I),E(J,I):NEXT:NEXT
01760   FOR I=1 TO N:PRINT#1,SP(I):NEXT:CLOSE:GOTO 1490
01770   IF L$="OFF" AND C$="5" THEN L$="ON":PRINT CHR$(14):GOTO 1490
01780   IF L$="ON" AND C$="5" THEN L$="OFF":PRINT CHR$(15):GOTO 1490
01790   IF C$="3" THEN 2090
01800   IF C$="8" THEN 2575
01810   IF C$="4" THEN 2760
01820   IF C$  "1" THEN PRINT "OPTION NOT YET AVAILABLE":GOTO 1490
01830   '8.1. SELECT THE HEATER CAPACITIES
01840   PRINT:PRINT "ENTER THE HEATER CAPACITIES:"
01850   IH=0
01860   PRINT "NODE";TAB(10);"SET POINT (F)";TAB(25);"BTU/HR CAPACITY"
01870   C$="N":FOR I=1 TO N:PRINT I;TAB(10);SP(I);TAB(25);HC(I);TAB(35);CH$;
01880   R=HC(I):INPUT HC(I):IF HC(I)= R THEN HC(I)=0:IH=IH+1:IH(IH)=I:GOTO 1910
01890   FOR K=1 TO M:NH(I,K)=2:IF QH(I,K) HC(I) THEN QH(I,K)=HC(I)
01900   NEXT
01910   NEXT
01920   FOR K=1 TO M:FOR J=1 TO N:IF A(J)=0 THEN EP=0:AL=0:GOTO 1940
01930   EP=0:AL=0:FOR I=1 TO NC:EP=EP+AR(J,I)*EP(I):AL=AL+AR(J,I)*AL(I):NEXT
01940   FOR J=1 TO N:R(J)=-QH(J,K)-Q(J,K)-EP*A(J)*E(J,K)-AL*A(J)*S(J,K):NEXT
01950   FOR I=1 TO N:T(I,K)=0:FOR J=1 TO N:T(I,K)=T(I,K)+CI(I,J)*R(J):NEXT:NEXT
01960   NEXT:GOTO 2220
01970   '8.2. SELECT THE NEW SURFACE PROPERTIES
01980   PRINT "NODE";TAB(6);"ALPHA";TAB(13);"EPSILON";TAB(25);"AREA FRACTION FOR"
01990   PRINT " COATINGS":PRINT TAB(25);
02000   FOR J=1 TO NC:PRINT USING ".###    ";AL(J);:NEXT:PRINT "(ALPHA)":PRINT TAB
02010   FOR J=1 TO NC:PRINT USING ".###    ";EP(J);:NEXT:PRINT "(EPSILON)"
02020   FOR I=1 TO N:IF A(I)=0 THEN 2070
02030   PRINT I;TAB(6);AL;TAB(13);EP;TAB(25);:FOR J=1 TO NC
02040   PRINT USING "#.###  ";AR(I,J);:NEXT:PRINT " CHANGE (Y/N)";
02050   X$="N":INPUT X$:IF X$  "Y" THEN 2080
02060   PRINT TAB(25);:INPUT AR(I,1),AR(I,2),AR(I,3),AR(I,4)
02070   HC(I)=0:FOR K=1 TO M:QH(I,K)=0:NEXT
02080   NEXT:GOTO 840'BECAUSE THE DIAGONAL (VIA EP) IS CHANGED
02090   '8.3. COMPUTE THE REQUIRED HEATER CAPACITIES
```

TABLE A-3 (Continued)

THERMAL OPTIMIZATION PILOT PROGRAM

```
02100   'BECAUSE THE TEMP UNCERTAINTIES ARE NOT LINEAR BUT RSS, THE HEATER WILL
02110   'NOT MAKE THE TEMPS EXACTLY MEET THE THERMOSTAT SET POINT, AT LEAST AS
02120   'WE NOW SOLVE THE PROBLEM.  WE TREAT THE UNCERTAINTY AS A LINEAR EFFECT.
02130   PRINT "ENTER THE THERMOSTAT SET POINTS:":IH=0:FOR I=1 TO N:HC(I)=0:NEXT
02140   PRINT "NODE";TAB(10);"SET POINT (F)  (SP=-999 =  NO THERMOSTAT OR HEATER)
02150   FOR I=1 TO N:SP(I)=SP(I)-460:PRINT I;TAB(10);SP(I);TAB(25);CH$;:INPUTSP(I
02155   SP(I)=SP(I)+460:NEXT
02160   PRINT
02170   FOR I=1 TO N:IF SP(I)  -999 THEN FOR K=1 TO M:NH(I,K)=0:NEXT
02180   NEXT
02190   FOR I=1 TO N:HC(I)=0:NEXT
02200   'TO INCORPORATE THE EFFECTS OF EACH HEATER ON ALL OF THE TEMPERATURES,
02210   'WE MUST SOLVE A MATRIX EQUATION FOR EACH NEW HEATER POWER (BY MISSION)
02220   FOR K=1 TO M
02230   IH=0:FOR I=1 TO N:IF NH(I,K) 0 THEN 2250
02240   IH=IH+1:IH(IH)=I
02250   NEXT
02260   IF IH=0 THEN 2440
02270   IF IH=1 THEN I=IH(1):CN(1,1)=1/CI(I,I):GOTO 2370
02280   FOR J=1 TO IH:JH=IH(J):FOR L=1 TO IH:LH=IH(L):CT(J,L)=CI(JH,LH)
02290   CN(J,L)=0:NEXT:CN(J,J)=1:NEXT
02300   FOR KK=1 TO IH-1:FOR II=KK+1 TO IH:R=CT(II,KK)/CT(KK,KK):FOR JJ=1 TO IH
02310   CT(II,JJ)=CT(II,JJ)-R*CT(KK,JJ):CN(II,JJ)=CN(II,JJ)-R*CN(KK,JJ):NEXT:NEXT
02320   NEXT:FOR KK=IH TO 2 STEP -1:FOR II=KK-1 TO 1 STEP -1:R=CT(II,KK)/CT(KK,KK
02330   FOR JJ=IH TO 1 STEP -1:CT(II,JJ)=CT(II,JJ)-R*CT(KK,JJ)
02340   CN(II,JJ)=CN(II,JJ)-R*CN(KK,JJ):NEXT:NEXT:NEXT
02350   FOR KK=1 TO IH:D=CT(KK,KK):FOR II=1 TO IH
02360   CT(KK,II)=CT(KK,II)/D:CN(KK,II)=CN(KK,II)/D:NEXT:NEXT
02370   FOR II=1 TO IH:I=IH(II):R(II)=0:FOR J=1 TO IH:JH=IH(J)
02380   R(II)=R(II)-CN(II,J)*(SP(JH)-T(JH,K)+TU(JH,K)):NEXT
02390   IF QH(I,K)+R(II)= 0 THEN 2410
02400   QH(I,K)=0:R(II)=0:NH(I,K)=1:GOTO 2230
02410   NEXT:FOR II=1 TO IH:I=IH(II):QH(I,K)=QH(I,K)+R(II)
02420   IF QH(I,K) HC(I) THEN HC(I)=QH(I,K)
02430   NEXT
02440   NEXT K
02450   GOTO 1210'BECAUSE T'S NEED TO BE RECALCULATED BEFORE ANY OTHER CHANGES
02460   'WE NEED TO EXAMINE HOW TO INCORPORATE TOLERANCES
02470   'PROBABLY WE SHOULD USE THE RMS ERROR AND GIVE THE TEMP OR HTR RANGE
02480   'THE USER COULD SPECIFY THE NUMBER OF SIGMAS TO CONSIDER, WITH THE
02490   'INPUT BEING ENTERED AS 3 SIGMA.  THE SET POINTS ENTERED BY THE USER
02500   'SHOULD BE TREATED AS THE AVG - N*SIGMA WHEN COMPUTING THE HEATER
02510   'POWER.  IN PRACTICE, WE MAY NOT ALWAYS BE ABLE TO PUT THE HEATER ON
02520   'THE CRITICAL NODE.  WE HAVE NOT ALLOWED FOR THAT IN THE OPTIMIZATION.
02530   'WE SHOULD PROBABLY ADD FIXED-TEMP NODES TO THE PROBLEM STATEMENT,
02540   'ALTHOUGH IT IS DIFFICULT TO CONCEIVE OF THE PHYSICAL SITUATION.
02550   '8. INCLUDE THE TOLERANCES
02560   'FOR NOW, WE ASSUME THAT THE COATING PROPERTIES ARE KNOWN TO WITHIN
02570   '0.03, REGARDLESS OF THE COATING.  THE TOLERANCES ARE DESIGNATED AU,EU
02575   PRINT:C$="IF COATING TOLERANCES ARE INCLUDED":PRINT TAB(40-LEN(C$)/2);C$
02580   FOR J=1 TO NC:AU(J)=.03:EU(J)=.03:NEXT
02590   FOR K=1 TO M:FOR J=1 TO N:TU(J,K)=0:NEXT:FOR JC=1 TO NC:L=0:FOR J=1 TO N
02600   IF A(J)=0 OR AR(J,JC)=0 THEN R(J)=0:GOTO 2630
02610   R(J)=AR(J,JC)*A(J)*(E(J,K)-H(J)*T(J,K))*EU(JC)
```

TABLE A-3 (Continued)

THERMAL OPTIMIZATION PILOT PROGRAM

```
02620   L=1
02630   NEXT J
02640   IF L=0 THEN 2740
02650   'SOLVE FOR ALL OF THE TEMPERATURE UNCERTAINTIES FIRST, AS IF NONLINEAR
02660   FOR J=1 TO N:CT(J,1)=0:FOR I=1 TO N:CT(J,1)=CT(J,1)+CI(J,I)*R(I):NEXT:NEX
02670   FOR J=1 TO N:TU(J,K)=TU(J,K)+CT(J,1)*CT(J,1):NEXT
02680   'NOW INCLUDE THE EFFECTS OF ALPHA
02690   FOR J=1 TO N:IF A(J)=0 OR AR(J,JC)=0 THEN R(J)=0:GOTO 2710
02700   R(J)=AR(J,JC)*A(J)*S(J,K)*AU(JC)
02710   NEXT
02720   FOR J=1 TO N:CT(J,1)=0:FOR I=1 TO N:CT(J,1)=CT(J,1)+CI(J,I)*R(I):NEXT:NEX
02730   FOR J=1 TO N:TU(J,K)=TU(J,K)+CT(J,1)*CT(J,1):NEXT
02740   NEXT JC:FOR J=1 TO N:TU(J,K)=SQR(TU(J,K)):NEXT:NEXT K:GOTO 1300
02750   'COMPUTE THE DERVIATIVES WITH RESPECT TO THE AREA RATIOS
02760   FOR K=1 TO M 'DE(J,K,I,L) = D(T(J,K))/D(AR(I,L))
02770   FOR I=1 TO N:IF A(I)=0 THEN 2900
02780   FOR L=1 TO NC
02790   R(I)=A(I)*(AL(L)*S(I,K)+EP(L)*(E(I,K)-H(I)*T(I,K)))
02800   FOR J=1 TO N:DE(J,K,I,L)=CI(J,I)*R(I):NEXT
02810   NEXT L
02820   C$="MISSION"+STR$(K)
02830   PRINT:PRINT TAB(40-LEN(C$)/2);C$
02840   PRINT "DERVIATIVES OF ALL NODE TEMPERATURES WITH RESPECT TO THE AREA RATI
02850   PRINT "ON NODE";I;"FOR COATING:";TAB(27);"1";TAB(37);"2";TAB(47);"3";
02860   PRINT TAB(57);"4"
02870   PRINT TAB(10);"AFFECTED NODE";TAB(32);"D E R I V A T I V E S"
02880   FOR J=1 TO N:PRINTTAB(15);J;:FOR L=1 TO NC:PRINT TAB(17+L*10);DE(J,K,I,L)
02890   NEXT:PRINT:NEXT
02900   NEXT I:PRINT:NEXT K
02910   GOTO 1490
```

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16. Abstract

A study was conducted to develop a strategy by which thermal designers for spacecraft could devise an optimal thermal control system to maintain the required temperatures, temperature differences, changes in temperature, and changes in temperature differences for specified equipment and elements of the spacecraft's structure. Thermal control is to be maintained by the coating pattern chosen for the external surfaces and I^2R heaters chosen to supplement the coatings. The approach is to minimize the thermal control power, thereby minimizing the weight of the thermal control system. Because there are so many complex computations involved in determining the optimal coating design a computerized approach was contemplated. An optimization strategy including all the elements considered by the thermal designer for use in the early stages of design, where impact on the mission is greatest, and a plan for implementing the strategy were successfully developed. Additionally, a demonstration of how the optimization process may be used to optimize the design of the Space Telescope as a test case is included.

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