Thermoelectric Device Application to Spacecraft Thermal Control

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Active thermal control systems for long duration missions of spacecrafts such as planetary probes and space stations require an inherently reliable design that can be provided by thermoelectric devices (TEDs). Thermoelectric devices used in conjunction with a spacecraft radiator/absorber can provide direct thermal control capability. This paper discusses this application of TEDs to spacecraft thermal control, outlines performance equations, develops an iterative computerized modeling technique, and presents analytical results. The analytical methods outlined are general and involve the use of a thermal analyzer program. Steady-state and transient verification analyses are included for representative spacecraft designs. These analyses utilize the performance characteristics of CAMBION module 801-3958-01. The results demonstrate qualitatively and quantitatively the feasibility of applying TEDs to direct thermal control of spacecrafts. These studies are of particular interest to the analysis of light-weight "thin-film" thermoelectric devices that are currently in the research phases of development.

Nomenclature

a = net Seebeck coefficient for two dissimilar materials
A_m = thermoelectric module average Seebeck coefficient
G = thermal conductance between i and j
G_{TED} = thermoelectric module average thermal conductance
i = thermoelectric junction/node
I = electric current
j = thermoelectric junction/node
k = thermal conductivity
q = thermoelectric couple heat flow
Q = heat flow
Q_S = radiator/absorber heat rejection per unit area
Q_{TED} = thermoelectric module power input
r = electrical resistance
R_m = thermoelectric module average electrical resistance
T = absolute temperature
V = voltage
X, Y, Z = spacecraft coordinate system
α = solar absorptivity
ε = emissivity
τ = Thomson coefficient

Subscripts

E = environmental
F = Fourier
J = Joule
P = Peltier
S = spacecraft
SP = space
T = Thomson

Introduction

ACTIVE thermal control systems for long duration spacecraft missions such as planetary probes and space stations require an inherently reliable design. Such reliability can be achieved by utilization of thermoelectric devices (TEDs). TEDs are low-voltage, high-current, active thermal control modules that provide heating or cooling between two surfaces (junctions) by varying the input current. The TED provides direct thermal control capability by coupling the internal spacecraft to an external radiator/absorber. This direct application of TEDs to spacecraft thermal control is illustrated in Fig. 1. Unfortunately, low TED performance efficiency in conjunction with high weight has prevented spacecraft application as a prime active thermal control system.

The recent application of semiconductor materials to TED design results in higher efficiencies and has caused a resurgence of interest in thermoelectric phenomena. Recently, NASA has awarded a contract to develop techniques to reduce TED weight and to formulate large-scale manufacturing procedures to permit direct application of TEDs to spacecraft thermal control.[1] These research studies have concentrated on "thin-film" active thermal control coatings that utilize vacuum-deposited semiconductor materials. These thin-film devices are not currently available on a production basis.

To date, limited analyses have been performed to determine the advantages/disadvantages of TED spacecraft application. This paper describes the possible application of thermoelectrics to spacecraft thermal control, derives TED performance equations, develops computerized modeling techniques and presents preliminary verification analyses.

Analysis

Thermoelectric phenomenon is the result of five distinct effects (Seebeck, Peltier, Thomson, Joule, and Fourier) that act concurrently. A rigorous description of the thermoelectric phenomenon is beyond the scope of this paper and is dealt with in the literature.[2-6] What follows is a summary of the analytical

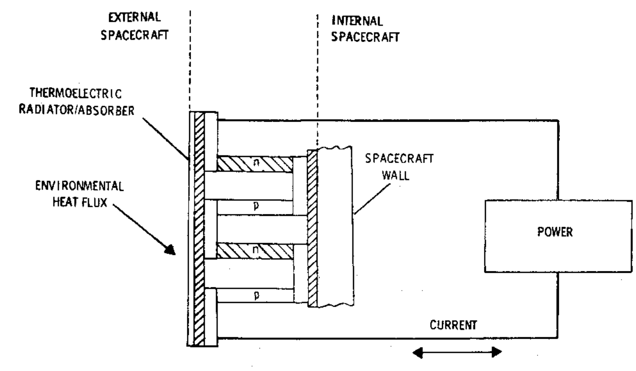

Fig. 1 Spacecraft thermal control using thermoelectric devices.

Received July 10, 1973; presented as Paper 73-722 at the AIAA 8th Thermophysics Conference, Palm Springs, Calif., July 16–18, 1973; revision received October 12, 1973.

Index category: Thermal Modeling and Experimental Thermal Stimulation.

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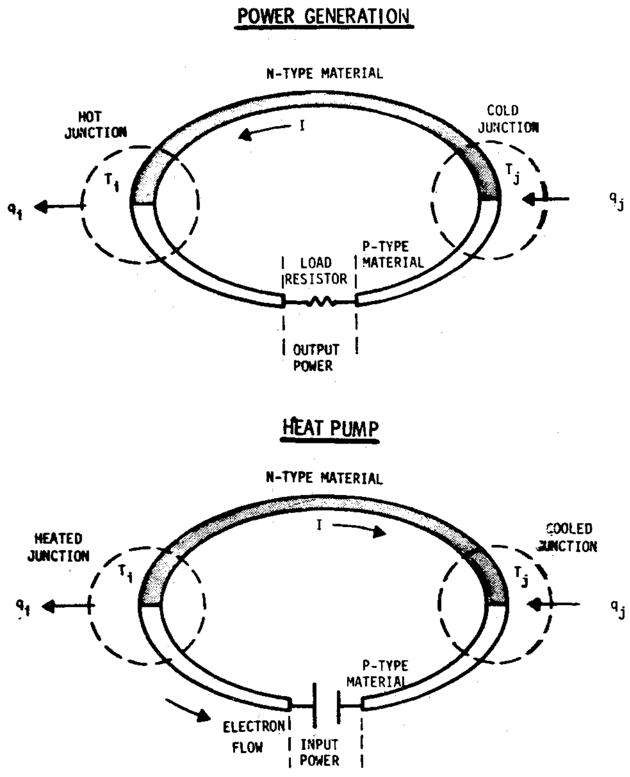

Fig. 2 **Thermoelectric power generation and heat pumping.**

methods of thermoelectrics and how the governing equations are developed.

A thermoelectric couple is an electrical circuit consisting of two different materials connected as illustrated in Fig. 2. These materials are referred to as *n*-type and *p*-type. An *n*-type material has an excess of electrons and is classified as having negative thermoelectric power. The *p*-type material has a deficiency of electrons and is classified as having positive thermoelectric power.

Thermoelectric power generation is the result of the Seebeck effect. As shown in the upper circuit of Fig. 2, when the two junctions formed by the dissimilar materials are maintained at different temperatures a voltage is created resulting in the flow of current. The open circuit potential difference is expressed as

$$\Delta V = a(T_i - T_j) \tag{1}$$

where "a" is the net Seebeck coefficient of the two materials.

Thermoelectric heat pumping, the effect of interest and application in this paper, makes use of the reverse phenomenon known as the Peltier effect. When an electrical current passes through a junction between an *n*-type and a *p*-type material, as shown in the lower circuit of Fig. 2, there is absorption or generation of heat depending on the direction of the current. As an electron passes across the junction from a *p*-type to *n*-type material, it must raise its energy level (heat absorbed). Conversely, as the electron goes from *n*-type to *p*-type material heat is liberated. The quantity of heat absorbed or liberated at the thermoelectric junction (Peltier heat) is

$$q_P = aTI \tag{2}$$

where T is the absolute temperature at the junction and I is the electrical current.

The Thomson effect results in heating or cooling in a homogeneous conductor when an electrical current flows in the direction of a temperature gradient. The Thomson effect per unit of conductor length is

$$q_T = \tau I\, dT/dx \tag{3}$$

where τ is the Thomson coefficient. If q_T is the heat absorbed when the directions of I and dT/dx coincide, then τ is positive. If q_T is the heat liberated for the same conditions, τ is negative.

Heat generation within a conductor (Joule heat) is given by

$$q_J = I^2 r \tag{4}$$

Conductive heat transfer (Fourier effect) is represented as

$$q_F = -k\, dT/dx \tag{5}$$

where k is the thermal conductivity of the material.

Thermal analysis of the thermoelectric heat pump requires a relationship between the net heat absorbed at the cooled junction and the net heat liberated at the heated junction. A heat balance is performed (assuming cooling) on junction j as shown in Fig. 2.

$$q_j = -q_P - q_T + q_J + q_F \tag{6}$$

By evaluating Seebeck coefficient at T_j and using average couple properties ($\bar r$, $\bar k$, $\bar\tau$), Eq. 6 can be rewritten using Eqs. 2–5.

$$q_j = -aT_jI - \tfrac{1}{2}\bar\tau I(T_i - T_j) + \tfrac{1}{2}I^2\bar r + \bar k(T_i - T_j) \tag{7}$$

Typical thermoelectric modules contain a number of thermoelectric couples connected electrically in series and thermally in parallel to provide useful heat pumping capabilities. As an approximation, the Peltier and Thomson heats in Eq. (7) can be combined[6] and the equation rewritten using average module properties as

$$Q_j = -A_m T_j I + \tfrac{1}{2}I^2 R_m + G_{\text{TED}}(T_i - T_j) \tag{8}$$

The total input power for a module is given by

$$Q_{\text{TED}} = A_m(T_i - T_j)I + I^2 R_m \tag{9}$$

where $A_m(T_i - T_j)$ is the Seebeck voltage [Eq. (1)] which tends to generate a current from the *n*-type to the *p*-type material at the hot junction as shown in Fig. 2.

Thermoelectric heating and cooling modes are illustrated in Fig. 3 for the junctions i and j, along with the two temperature relationships that can exist in each case. For each case the heat transferred to junction i is equal to the difference in the TED input power and the heat input to junction j.

$$Q_i = Q_{\text{TED}} - Q_j \tag{10}$$

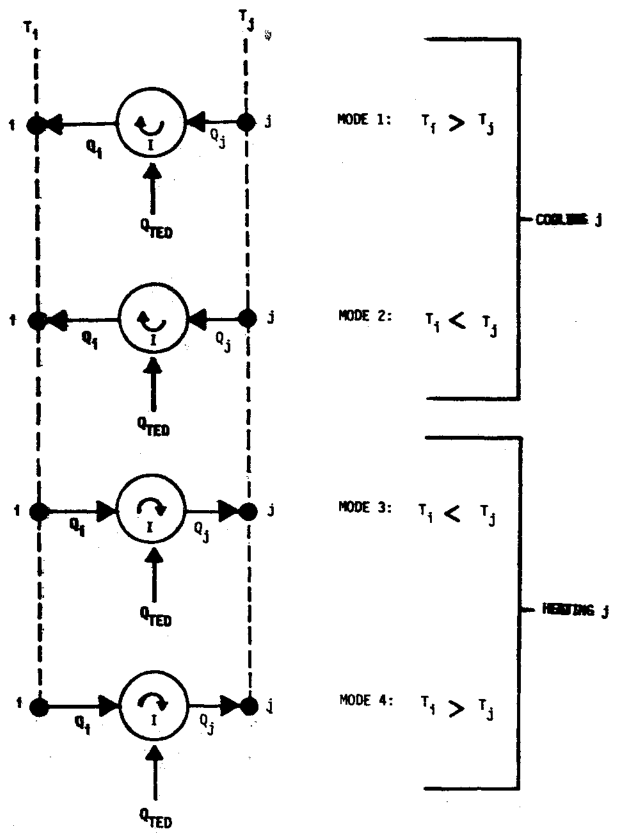

Fig. 3 **Thermoelectric device heat pumping modes.**

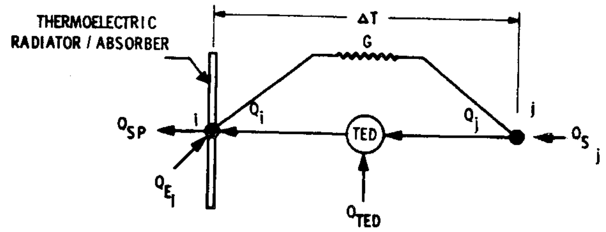

Fig. 4 TED spacecraft modeling concept.

Spacecraft Application

Consider the use of a thermoelectric device to control a spacecraft temperature as illustrated in Fig. 4. The TED links the internal spacecraft (node j) to an external radiator/absorber (node i). In addition, there are other thermal paths (conductive and radiative) such as through insulation and standoffs, as represented by the conductance G.

There are two conditions of interest: 1) given the TED current, determine the spacecraft and radiator/absorber temperatures, and 2) given a constant spacecraft temperature, determine the current and radiator/absorber temperatures. Both cases require consideration of the impressed heat (Q_{S_j}) and varying levels of absorbed heat (Q_{E_i}) and radiated heat (Q_{SP}) as shown in Fig. 4.

A heat balance on j is

$$Q_j = -Q_{S_j} - G(T_i - T_j) \tag{11}$$

Similarly, a heat balance on i gives

$$Q_i = -G(T_j - T_i) - Q_{E_i} - Q_{SP} \tag{12}$$

Using Eqs. (11) and (12) in conjunction with Eqs. (8–10) results in three nonlinear simultaneous equations in T_i, T_j and I, involving temperature dependent module properties (A_m, R_m, G_{TED}). Solutions for these equations can be determined using a straightforward, though tedious, approach. However, problem solution is conveniently obtained with a computerized iterative procedure.

Computer Techniques

Computerized techniques have been developed for TED analyses in a lumped-parameter thermal network for use with the Martin Marietta Thermal Analyzer System (MITAS).[7] However, the methods are general and can be applied to other thermal analysis programs.

Calculation of spacecraft temperatures for constant TED currents uses Eqs. (8–10) with the spacecraft and radiator/absorber represented by floating nodes. At each iteration Q_j and Q_i are determined and control is transferred to thermal analyzer logic to determine temperatures. This procedure is repeated until solution criteria tolerances are met.

The prime concern of this paper is the development of techniques that can be used to determine the required TED current given a constant spacecraft temperature and heat load. For this application a boundary node is used to represent the TED junction at the internal spacecraft wall or coldplate which is to be controlled at a fixed temperature. A floating node is used to represent the other TED junction at the radiator/absorber that acts as a heat source or sink. For transient analysis it is assumed that TED heat pumping can be instantaneously adjusted to maintain the constant internal spacecraft temperature requirements. Figure 5 presents a simplified flow diagram of the computerized computational procedure.

The analyst defines the spacecraft geometry and specifies the thermoelectric boundary junction temperature and heat load. Subroutine TEDX has been developed to calculate the heat pumping required to maintain node j at T_j and the corresponding heat load on the radiator/absorber, node i. At each iteration

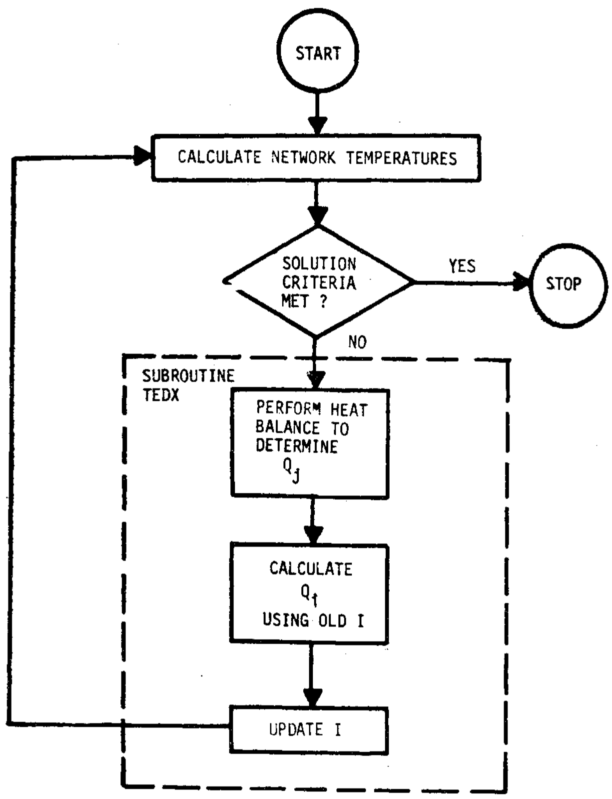

Fig. 5 Simplified flow diagram for TED computerized analysis using MITAS.

TEDX performs a heat balance on j to determine Q_j. Equation (8) is then solved for I using Newton's method. The $n+1$ approximation to I is given by

$$I_{n+1} = I_n - [\tfrac{1}{2}R_m I_n^2 - A_m T_j I_n + G_{\text{TED}}(T_i - T_j) - Q_j]/(R_m I_n - A_m T_j) \tag{13}$$

The TED power is then determined using Eq. (9), and finally Q_i using Eq. (10).

Thermal Networks

Two thermal networks have been developed to assist in verification analysis of TED analysis methodology. The simplified network is utilized to provide analysis to aid in the

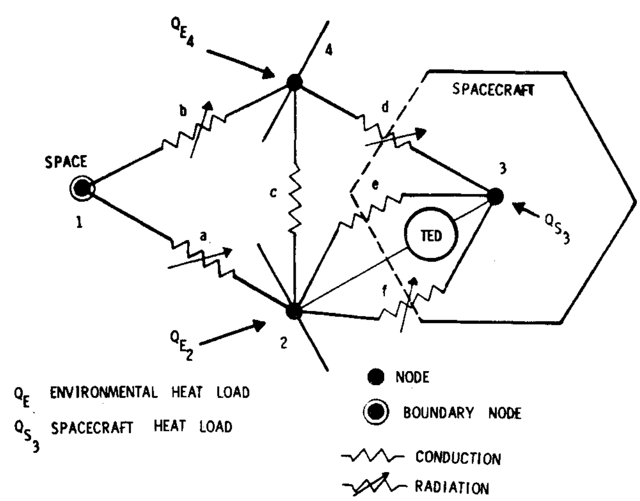

Fig. 6 TED simplified spacecraft model.

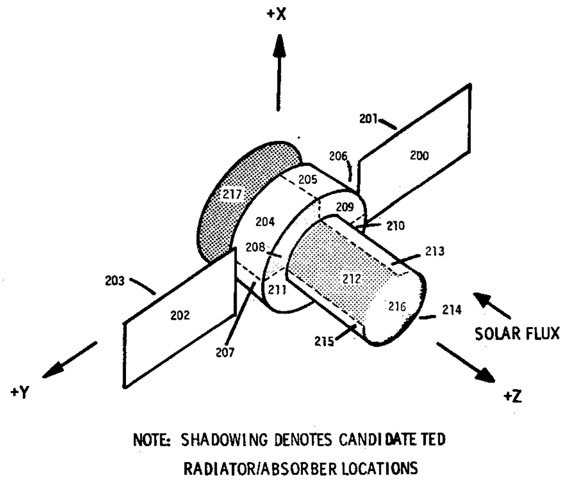

Fig. 7 Spacecraft nodal diagram.

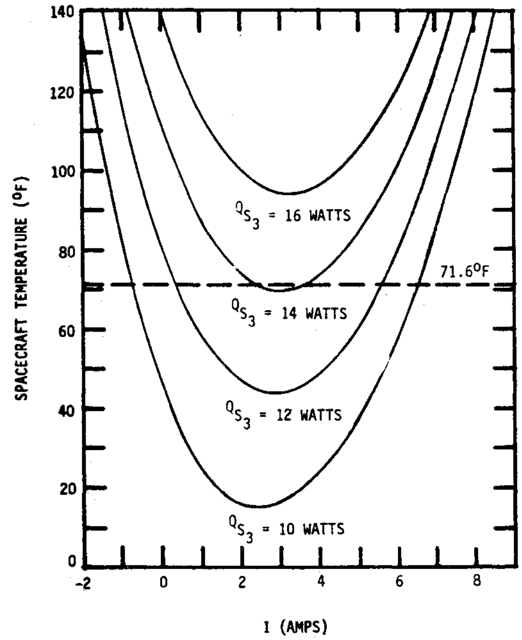

Fig. 8 Simplified model spacecraft temperatures as a function of TED current (CAMBION module 801-3958-01).

selection of TED configurations that can be used in the more realistic spacecraft model. The typical spacecraft model has been developed to provide realistic TED analysis capability.

Simplified Model

The simplified spacecraft model is illustrated in Fig. 6. Two forms of this model are in use: 1) with a floating spacecraft node for constant I analyses, and 2) with a boundary spacecraft node for constant spacecraft temperature analyses.

Both the TED radiator/absorber (node 2) and the spacecraft thermal shield (node 4) have an area of 0.5 ft^2 and an external emissivity of 0.9. Representative conductive and radiative couplings between the TED and the spacecraft have been included.

The model utilizes the performance characteristics of CAMBION module 801-3958-01.[6] This module has been chosen for analyses because detailed performance data are available over a wide range of temperatures. The module properties are evaluated by the program at the mean module temperature.

Typical Spacecraft Model

This model has been developed to provide realistic TED analysis capability for a typical earth orbiting satellite. Figure 7 depicts the spacecraft nodal arrangement. With the $+Z$ axis directed toward the sun, earth orbital environmental heat fluxes have been determined for a circular 300-mile orbit with an inclination of 28°. These transient fluxes have been used to determine the applicability of TEDs to satellite thermal control.

The model can be used to provide a basis for evaluation of TED performance for several candidate radiator/absorber locations. Radiator/absorber location may vary as a result of internal temperature and heat load requirements and potential radiator/absorber nodal locations are indicated in Fig. 7. Nodes 216 and 208 are relatively hot locations as they are solar oriented. In contrast nodes 212 and 217 are relatively cold.

Each radiator/absorber node has an independent corresponding internal node controlled by the CAMBION module as shown in Fig. 4. As an aid to parametric analyses the analyst may specify the number of modules used per square foot of radiator/absorber. Steady-state and transient analyses have been completed using the simplified and typical spacecraft models, respectively.

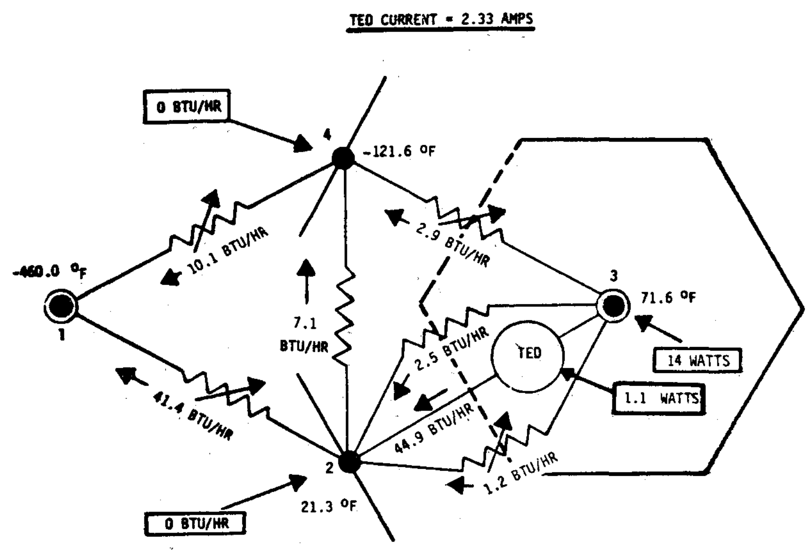

Fig. 9 Simplified model results for a constant spacecraft temperature with TED cooling (CAMBION module 801-3958-01).

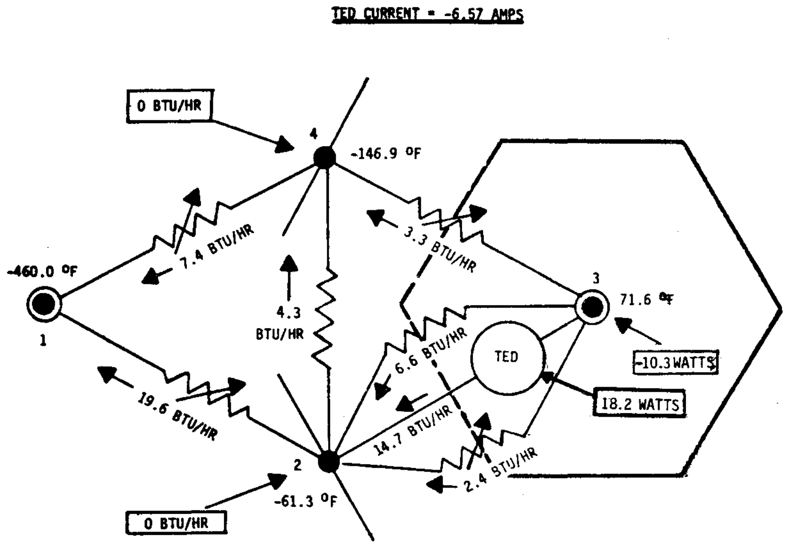

Fig. 10 Simplified model results for a constant spacecraft temperature with TED heating (CAMBION module 801-3958-01).

Results

Simplified Model

Typical steady-state temperatures for the floating spacecraft node model are presented in Fig. 8. Zero environmental heat loads have been assumed for these studies. The same spacecraft temperature is obtained for two values of TED current because the equation relating thermoelectric pumped heat and current is quadratic.

A 71.6°F spacecraft temperature with a heat load of 14 w can be maintained with either 2.5 or 3.5 amp current. The lower current would be selected because it corresponds to minimum power. It should be noted that a 71.6°F temperature cannot be maintained for spacecraft heat loads greater than 14 w, with a single CAMBION module.

Typical steady-state temperatures and heat fluxes for a constant spacecraft temperature requirement are presented in Fig. 9 for cooling, and Fig. 10 for heating. Figure 9 illustrates that a current of 2.33 amps is required to maintain the spacecraft at 71.6°F with a 14 w spacecraft heat load. These results are directly comparable to those depicted in Fig. 8. Spacecraft heating analyses presented in Fig. 10 indicate that a current of −6.57 amps yields a spacecraft temperature of 71.6°F with a spacecraft heat load of −10.3 w. These findings illustrate the flexibility of TEDs to provide both heating and cooling by reversing the current direction.

Typical Spacecraft Model

The results of the analysis performed with this model verify the analytical methods and provide a preliminary evaluation of the CAMBION module 801-3958-01. These results are for the TED radiator/absorber (node 217) located in the $-Z$ axis as shown in Fig. 7. This radiator location is suitable for a spacecraft in solar inertial attitude, since it receives only albedo and earth-emitted heat fluxes. Mission requirements may dictate other locations for the radiator/absorber.

Figure 11 shows the current required to maintain the internal spacecraft temperature at 71.6°F during one earth orbit. For the analysis two CAMBION modules per sq. ft of radiator/absorber have been selected. A radiator/absorber coating with an α/ε of 0.2/0.9 or 0.5/0.9 requires both thermoelectric heating and cooling during an orbit. Corresponding electrical powers and radiator/absorber temperatures are shown in Figs. 12 and 13, respectively.

Consider the application of the preceding studies to a hypothetical earth satellite. An internal temperature requirement of 70°F with a total internal heat load of 100 w would require a

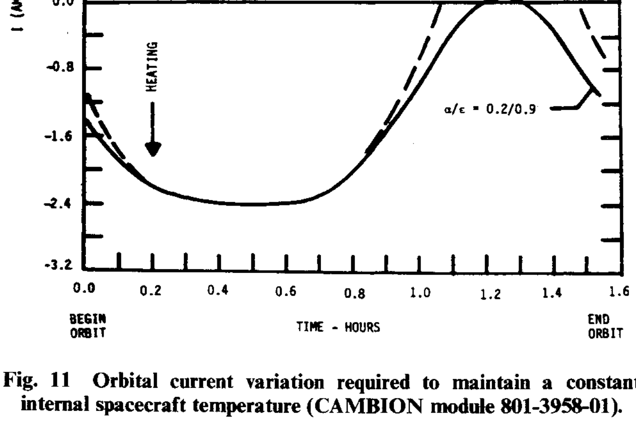

Fig. 11 Orbital current variation required to maintain a constant internal spacecraft temperature (CAMBION module 801-3958-01).

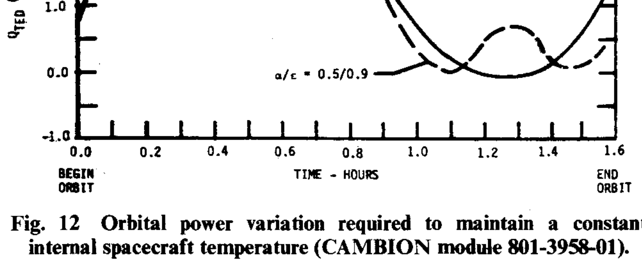

Fig. 12 Orbital power variation required to maintain a constant internal spacecraft temperature (CAMBION module 801-3958-01).

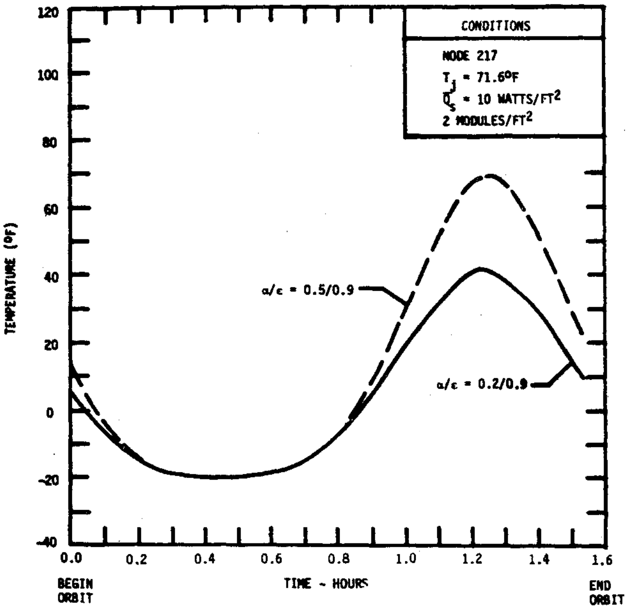

Fig. 13 Orbital TED radiator/absorber temperature variation required to maintain a constant internal spacecraft temperature (CAMBION module 801-3958-01).

10-sq. ft radiator. A total of 20 CAMBION TEDs would require an average power of approximately 30 w. It should be noted that the objective of these studies was to demonstrate the conceptual feasibility of spacecraft thermal control using TEDs as the prime active system. Therefore, no attempt was made to optimize power requirements.

Conclusions

Analytical methods have been developed to enable simulation of thermoelectric module performance in conventional lumped-parameter thermal networks. Analyses using characteristics of an available module have demonstrated that the application of TEDs to direct spacecraft thermal control is feasible. The techniques and analytical procedures outlined in this paper can be utilized to perform system trade-off studies to fully assess the advantages/disadvantages of TEDs when compared to more conventional thermal control techniques.

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