To the Graduate Council:

I am submitting herewith a thesis written by Jeffery K. Little entitled "Thermal Investigation of a Signal Chopping Device within a Cryogenic Test Chamber." I have examined the final copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Mechanical Engineering.

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THERMAL INVESTIGATION OF A SIGNAL CHOPPING DEVICE WITHIN A CRYOGENIC TEST CHAMBER

A Thesis

Presented for the

Master of Science

Degree

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Jeffery K. Little

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ABSTRACT

This paper details the development of a computational model used to investigate the transient thermal response of an infrared signal filtering device located in a cryogenic test chamber. The device, a revolving disk called a chopper, is used to differentiate a blackbody radiation source from the "noise level" of chamber radiation. When the temperature of the disk rises due to radiation exchange with the blackbody source and frictional heating from the support bearings, it begins to radiate energy which contaminates the sensor reading. When this occurs, the test run must be terminated and a cool down period allowed.

The computational model is formulated in standard transient finite-difference equations and a computer program developed to solve the resulting algorithms. The chopper system, consisting of a disk, a shaft, and the enclosure front plate, is represented by finite elements, and three main thermal loads, which are the blackbody radiation source, support bearing frictional heat, and convective helium cooling, are applied at the appropriate elements. The computer program allows modeling of a variety of configurations and can provide guidance toward optimal chopper designs. Several short runs verified capabilities and options found in the program algorithms. Initial investigation runs are also included in this study and reveal some general guidelines.

With a radiation source of $300^{\circ}K$ the major contributor to thermal loading in a typical chopper system is the bearing frictional heat.

The helium coolant applied to the enclosure front plate readily maintains chamber conditions on the plate, and the effect of thermal expansion of the shaft on the bearings is insignificant up to bearing temperatures of $50^{o}K$. The results of initial runs tend to support the validity of the model since the resultant thermal profiles agree with reports from actual operations. Incorporating experimental data into the program could enhance accuracy, however. An initial parametric study reveals the significance of the proper use of materials in the chopper design as an aluminum disk mounted to a stainless steel shaft operates with a lower chopper blade temperature than systems made entirely of either material.

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LIST OF FIGURES

LIST OF SYMBOLS

A	area, cm^2
ΔA	finite-element area, cm^2
B	finite-difference equation variable
C	finite-difference equation constant
c_f	coefficient of friction
c_p	specific heat, $J/gm^{o}K$
D	diameter, cm
D_{bg}	outer radius minus bore in a bearing, cm
E	modulus of elasticity, $dynes/cm^2$
e	small length, cm
$F_{i \rightarrow j}$	shape factor from element i to element j
g	gravitational constant, cm/sec^2
h	convection coefficient, $watts/cm^{2}K$
J	radiosity, $watts/cm^2$
k	thermal conductivity, $watts/cm^{o}K$
L_b	length of a bearing, cm
Δl_b	length of bearing influence on a finite-element, cm
M	mass, gm
$\dot{m}$	mass flowrate, gm/sec
Nu	Nusselt number
P	force load, dynes
Pr	Prandtl number
q	heat transfer rate, watts
Re	Reynolds number
r	radius, cm

Δr	finite-element radial grid dimension, cm
T	temperature, ^{o}K
ΔT	incremental change in temperature, ^{o}K
Δt	incremental change in time, sec
V	velocity, cm/sec
ΔV	finite-element volume, cm^3
W	weight, dynes
w	work, joules
x_b, y_b, z_b	coordinates of blackbody source aperture, cm
x_p, y_p, z_p	coordinates of front plate finite-element, cm
Δz	finite-element grid dimension on the shaft, cm

Greek

α	finite-difference radiation boundary effects variable
β	angle of revolution on chopper disk, rad
γ	finite-difference radiation boundary effects variable
δ	thickness dimension, cm
ϵ	emissivity; strain
θ	circumferential position coordinate, rad
$\Delta\theta$	finite-element circumferential grid dimension, rad
μ	viscosity, g/cm sec
ρ	density, gm/cm^3
Σ	summation symbol
σ	Stefan-Boltzmann constant, $watts/cm^2K^4$
τ	torque, joules
ϕ	circumferential position coordinate, rad

$\Delta\phi$	finite-element circumferential grid dimension, rad
Ω	rotational speed, rad/sec

Subscripts

bf	chopper disk back face
bg	bearing
c	chopper disk; contact point; chopper connector; cooling
cc	chopper connector
cond	conduction
cs	chopper disk and the shaft
f	fin on the chopper disk
ff	chopper disk front face
He	helium coolant
ir	bearing inner race
i1	within the radius of the strengthened disk section
i2	within the radius of the chopper solid disk section
m	shaft drive motor
n	pertaining to the previous finite-difference time
n+1	pertaining to the next finite-difference time
o	outer boundary of the bearing
or	bearing outer race
p	front plate
rad	radiation
s	shaft
stored	energy storage
th	thermal expansion

Ω	rotation
0	pertaining to the finite-element node
1,2,3,4,5	pertaining to the surrounding finite-element nodes

CHAPTER I

INTRODUCTION

An infrared signal chopping device is used in cryogenic test chambers to differentiate directed beam radiation impinging on infrared (IR) test sensors from other background chamber radiation. Due to a number of thermal loads imposed on the chopper system (such as bearing friction heating) the chopper temperature increases with test run time. This temperature increase is detected by the IR sensor and thus confounds the calibration procedure. To understand the magnitude of this effect and to identify the significant thermal loads a computational model of the transient heating of the chopper system is developed. The computational model is formulated in standard transient finite-difference equations and a computer program developed to solve the resulting algorithms.

The development of the computational model is described in Chapters II, III, IV, and V. Chapter II introduces this development while Chapters III, IV, and V describe the finite-difference development, the thermal load models, and a matrix solution technique respectively. Chapter VI presents a general flowchart of the computer program and describes various options available in the computer code. Results of initial investigations are provided to verify and demonstrate the capabilities of the computer program in Chapter VII. Chapter VIII completes the thesis with conclusions. Background on a typical cryogenic test chamber and chopper system with additional details on the transient heating problem are given in the remainder of this chapter.

Background

Cryogenic test chambers are used to simulate space environments for testing space based sensors. Temperatures of $20^{\circ}K$ in the chambers are generally established by jackets of liquid hydrogen and gaseous helium which also produce a 10^{-7} torr vacuum by cryogenic pumping of residual gases. Figure 1 is a schematic representation of a typical chamber. Here an IR radiation beam, generated by a blackbody source (generally at $300^{\circ}K$), emits from a small blackbody source aperture housed within a radiation "black" container. The box is cryogenically cooled with helium tube bundles to approximately $20^{\circ}K$. The signal emitted from this box reflects from a mirror at the front of the chamber to a test sensor in the rear. The sensor performance is monitored and compared with the known radiation level from the blackbody source.

If a perfect cryogenic environment absent of any radiation besides the blackbody source existed, the sensor performance could be easily verified. However, cryogenic test chambers are not perfect, and the sensor reading must be corrected for stray radiation. The imperfections in a chamber consist mainly of radiation leaking in through external seals, and heat loads due to internal mechanisms. An undesired baseline radiation level thus exists. The sensor reads a combination of this baseline radiation and the intended radiation source beam. To accurately monitor the sensor performance, this baseline radiation must be removed from the reading.

A simple and effective method of separating the baseline and test source radiation levels involves a chopper which is a small rotating disk that periodically chops the signal emitted from the blackbody.

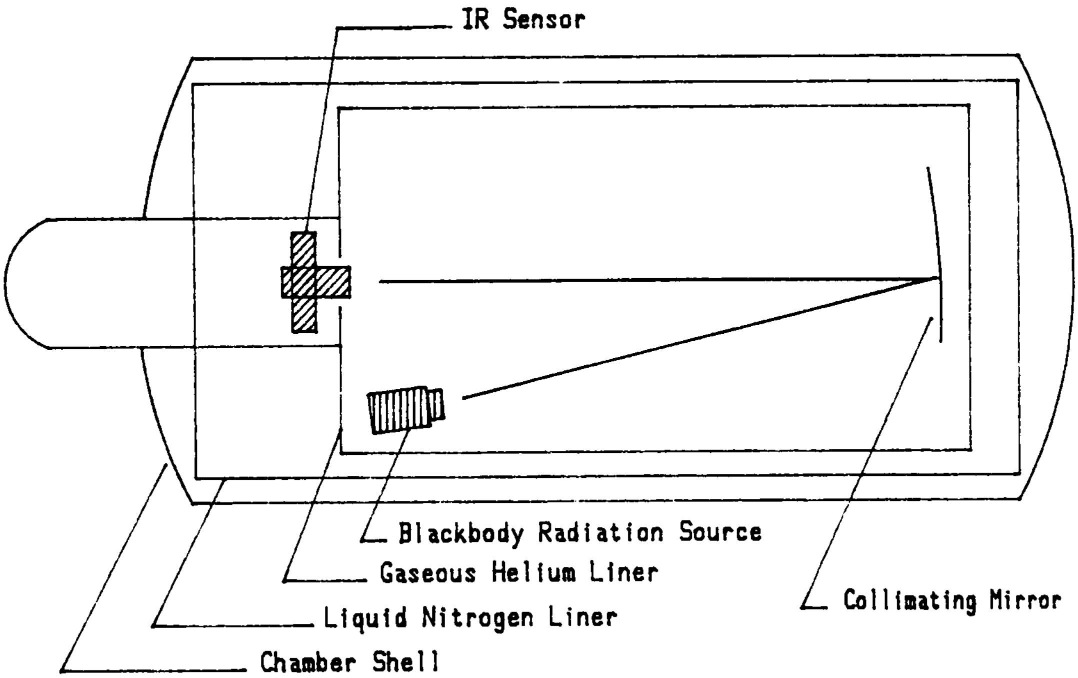
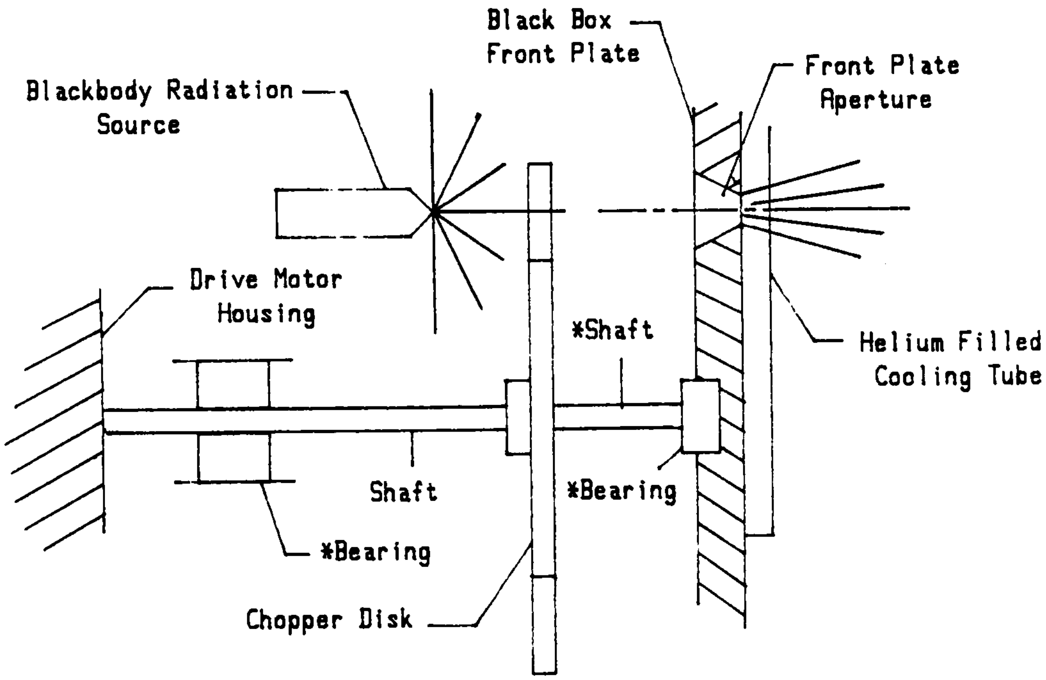


Figure 1. Schematic of a Cryogenic Test Chamber

A schematic of the chopper within the black box is shown in Figure 2, and a typical disk is depicted in Figure 3. The number of disk fins and location of support bearings varies depending on the desired application, but each disk is mounted so as to rotate directly in front of the blackbody source aperture. The disk rotates at a constant velocity creating a "square wave" radiation signal at the sensor. The resulting sensor reading is depicted in Figure 4. The valleys of the plot are not zero and represent the background or baseline radiation level due to the chamber environment. This radiation level is always present but is inundated by the source signal when the chopper is not blocking the source. The peaks are thus the combination of radiation effects generated when the disk rotates out of the signal path. Moving the horizontal axis up to the level of the valleys removes the radiation baseline from the plotted sensor signal output. The result is the calibrated sensor response to the test signal.

Problem Statement

The chopper represents a simple and effective solution for removing undesired background radiation in a cryogenic chamber. Like many solutions, however, the chopper has an undesired side effect. Effective performance of the chopper requires that the temperature of the disk face remain very close to the effective temperature of the test chamber. When the chopper blocks the blackbody signal, it must not radiate at a level higher than the baseline radiation in the cell. If the disk temperature rises above the 20°K test chamber environment, the disk face



*Configuration depends on
system application

Figure 2. Chopper System Schematic

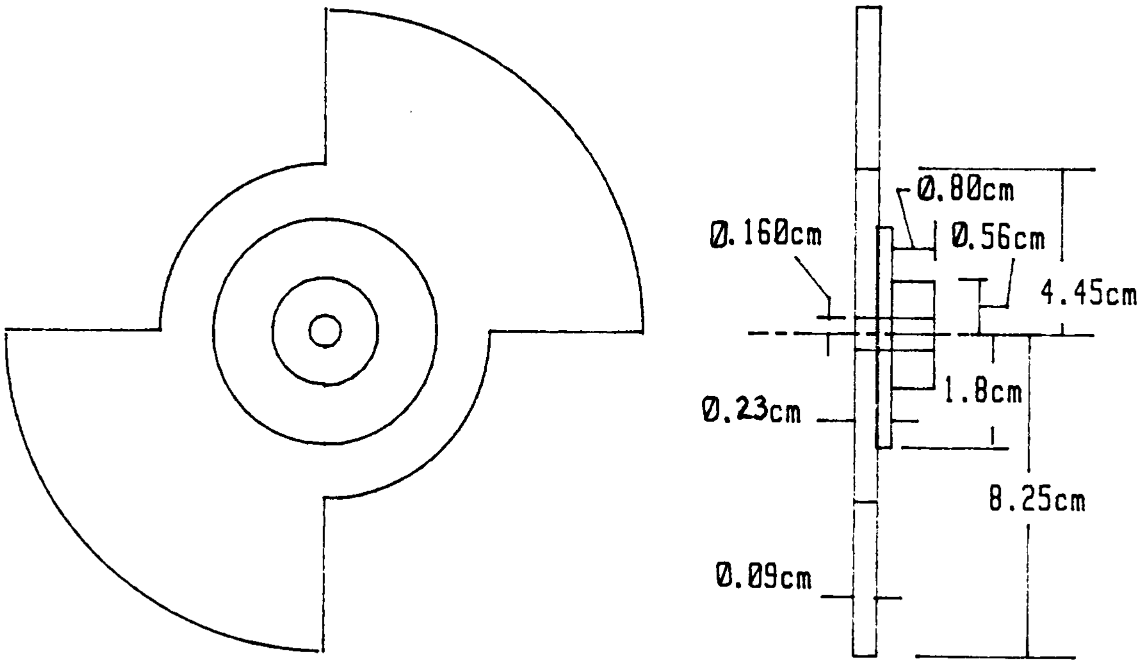


Figure 3. Typical Chopper Disk

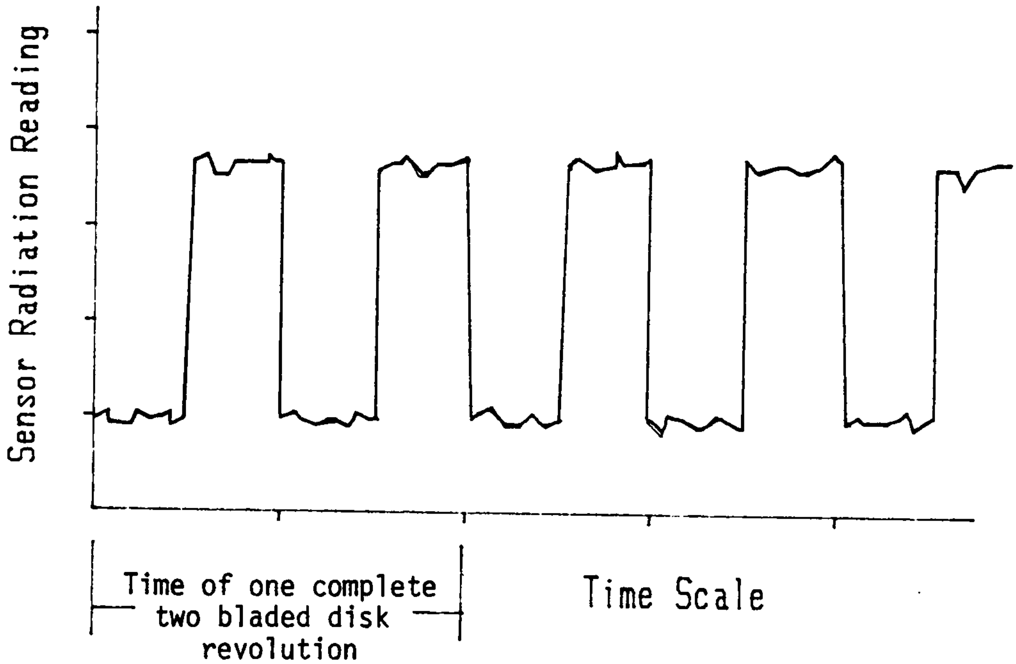


Figure 4. Chopped Sensor Reading Representation

becomes a source of radiation to the sensor. The chopper itself then clouds the mechanism for discriminating between the baseline and source radiations.

The chopper and its drive mechanism are located within the same housing as the blackbody source. The support bearings, which must run unlubricated due to the 20°K environment, and the radiation source contribute small but significant heat loads to the chopper disk and cause it to rise in temperature. The effect of the increasing disk temperature on the radiation monitored by the sensor is illustrated conceptually in Figure 5. The baseline radiation becomes progressively indeterminate as the disk temperature rises. Eventually the data becomes unacceptable and a cooling period is required to bring the chopper back to chamber conditions.

The cooling period requirement is significant. The temperature of the disk face will create unacceptable conditions at approximately 35°K. This results in a 9:1 ratio of cool down period to useful test time.

Purpose of the Study

Many test engineers in the field of cryogenics feel that a significant source of disk heating is from the friction of the bearings supporting the disk shaft. Often bearing designs are investigated to find an optimum bearing for low heat load generations. Theoretically, this optimum bearing design will allow choppers to be constructed which will operate for longer periods without significant heating. A perfectly cooled or designed bearing, however, may achieve only

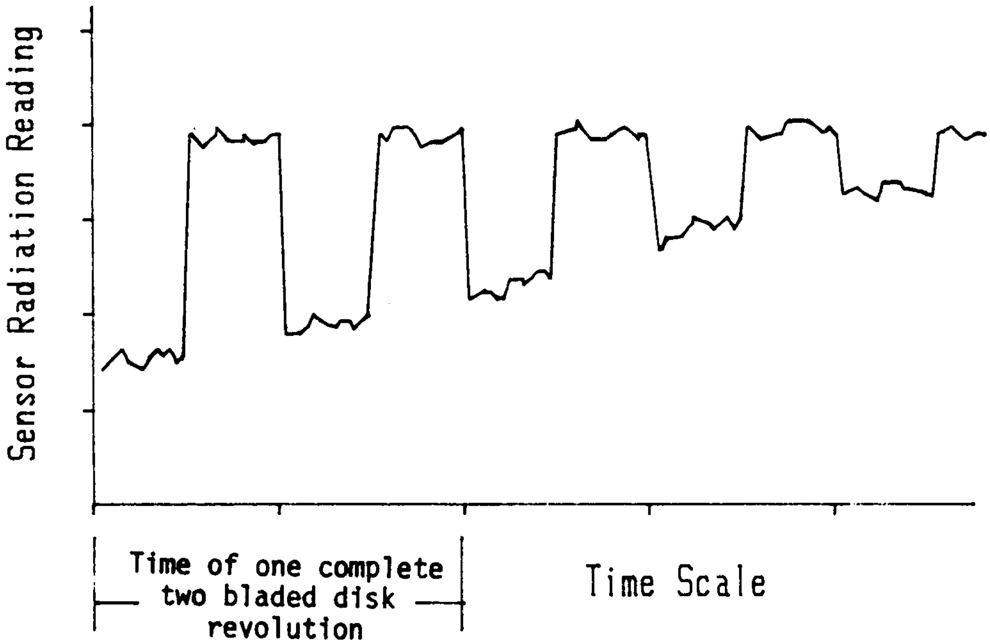


Figure 5. Schematic Illustration of the Sensor Reading with Increasing Chopper Disk Radiation

minimal positive results if the predominant mechanism driving the chopper disk temperature is the interaction of the blade with the blackbody radiation source.

The study detailed within this paper does not attempt to differentiate the performance of various bearing types. Its purpose is to establish an analytical model for investigating the transient thermal response of the entire chopper apparatus. Of particular importance to the model are the abnormal heat transfer characteristics due to the strong variation of thermal properties at cryogenic temperatures. The analytical model must also be formulated to study the effect of the magnitude and location of all heat sources on the transient temperature response. By isolating individual heat sources, their individual effects on the degradation of the sensor readings can be independently studied. Thus the benefits of reduced individual bearing heat loads can be quantified relative to other loads.

The analytical model is designed to allow investigations of a wide range of chopper configurations and operational procedures. The insight gained from the model output can help optimize chopper design. Limited model results are provided in this document. Their specific purpose is to verify the model performance. Further parametric runs are suggested to enhance design understanding.

CHAPTER II

MODEL CONCEPT

The chopper apparatus model is formulated as a composite of the major components of the chopper system. A finite-difference algorithm is written and programmed in Fortran. The program is developed to provide flexibility in modeling unique shapes and boundary conditions. This chapter is the first of four which detail the development of the program. It describes the model concept in general terms. The next three chapters follow with the specific developments of the chopper finite-difference formulas, the analytical representations of the major thermal loads on the system, and the associated solution procedure.

The chopper system (Figure 2, page 5) is composed of three major structural components which significantly participate in the heat exchange and three main sources of thermal energy. The chopper disk, the support shaft, and the system enclosure front plate are the structural components, while the blackbody radiation source, bearing frictional heat, and helium cooling are the thermal energy sources and sinks.

In operation, the shaft and disk rotate at speeds, Ω, around twenty revolutions per second. The disk fins thus interrupt the radiation source beam at $n\Omega$ (where n is the number of fins) creating a periodic chopping of the signal. The cryogenic environment destroys lubricant properties and causes the "dry" running of the shaft support bearings. These bearings therefore generate heat due to friction. The bearings heat the shaft, and along with the source beam, contribute to the thermal loading of the rotating disk. The front plate is cooled by thermal energy transfer to helium circulated through the cooling tubes. In turn the front plate is heated by radiation from the source and, if front plate mounted, by frictional heating from the shaft bearing. Finally, the front plate and the chopper disk exchange thermal energy by radiation. Except for the helium filled tubing, convective cooling is negligible. That is the vacuum environment does not have enough free air molecules for convective heat transfer to take place.

The significant variables in the analytical model for transient heat transfer in the chopper are the system dimensions, the rotational speed of the disk, and the temperatures of the radiation source and the circulated helium. Using equations developed later in Chapter IV, the program calculates the levels of the thermal loads and incorporates them at the respective locations in the modeled system. The preceding paragraph, however, describes how the chopper disk, the shaft, and the front plate are all impacted either directly or indirectly by each of the thermal loads. The resulting interaction is transient, and thus to properly model the situation analytically requires interactive calculations. The finite-difference approach is well suited for such a task and is used for the thermal analysis of the chopper system.

The finite-difference analysis is actually a fairly simple approach in heat transfer studies. One technique (Incropera and DeWitt[1]) utilizes the first law of thermodynamics in combination with basic heat transfer laws to generate energy balances on individual volume elements into

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[1] Incropera, F.P., and DeWitt, D.P., Fundamentals of Heat Transfer, John Wiley and Sons, Inc., 1981.

which the sytem is divided. Each balance results in a single equation for the instantaneous temperature of a volume element as a function of the instantaneous temperatures of all the surrounding elements and any boundary heat fluxes which might occur. By this procedure, N equations for the N unknown volume element temperatures are generated. Simultaneous solution of these equations by matrix or other methods gives the temperature distribution in the overall system at each time step of the analysis.

Figures 6 and 7 show a typical element in the network and how it interacts with its surrounding elements. A point, called a node, is established at a specific location in each volume element. A node is considered the location where the average temperature of the volume element is assigned. The location and size of the volume elements cannot be completely arbitrary, because the governing equations are derived based on differential areas. The dimensions of the grid network and associated nodal spacing must be relatively small. The equations are based on a small but finite increment of time. The solution proceeds by stepping formard in time with each solution of the N temperature equations. The finite-difference approach is shown in more detail in the section on equation development in Chapter III.

The thermal model of the chopper as noted breaks the system into three physical sections and three applied thermal loads. A computer program has been written which solves the finite-difference algorithm. Inputs to the program are menu driven and call for the system dimensions and other values. From these inputs the thermal loads are calculated and applied to the finite-element networks of the three sections. The

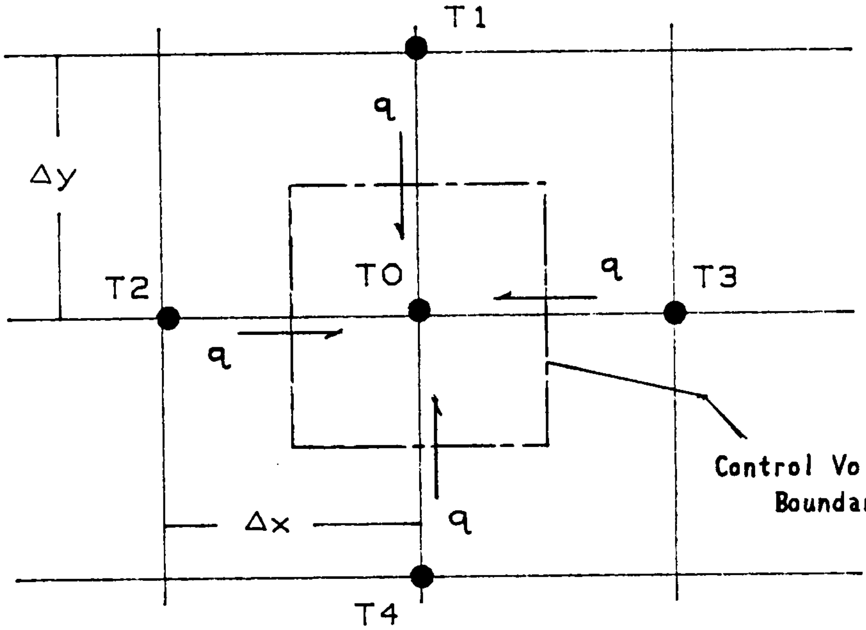
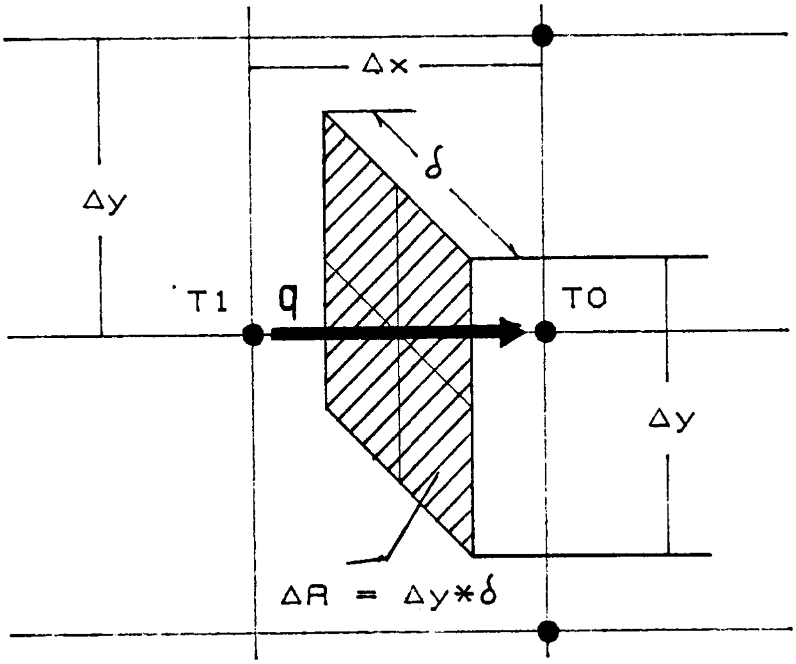


Figure 6. Typical Finite-Difference Nodal Configuration



$$q = k\,\Delta A\,\frac{T1 - T0}{\Delta x}$$

Figure 7. Schematic of Heat Flux Across the Volume Element Interface

finite-element equations are then solved for the temperature distribution in the system at that instant of time. The time-wise stepping of the solution generates the transient temperature response throughout the system. Specific details of the equation developments and finite-difference formulation are given in the next three chapters, and the computer program capabilities and required inputs are summarized in Chapter VI.

CHAPTER III

FINITE-DIFFERENCE EQUATIONS

The basic approach and associated assumptions involved with the finite-difference technique were introduced in Chapter II. In this chapter, the specific form of the finite-difference equations as applied to the chopper thermal model are developed. The chapter begins with a detailed development of the equations, including a thorough review of the finite-difference grid networks. The derivation of the equations for the chopper disk, the shaft, and the front plate are described in detail.

Development of the Finite-Difference Equations

The system of finite-difference equations for the chopper involves twenty-nine nodal configurations with their associated boundary conditions. A general grid network description is given, and a general form of the difference equation for an internal node is developed for each of the three physical chopper sections. The specific equations for individual nodes are listed separately in Appendices A, B, and C. Incropera and DeWitt[2] and Arpaci[3] provide references for the general development.

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[2] Incropera, F.P., and DeWitt, D.P., Fundamentals of Heat Transfer, John Wiley and Sons, Inc., 1981, pgs 146-165,214-229.

[3] Arpaci, V.S., Conduction Heat Transfer, Addison-Wesley Publishing Co., 1966, pgs 483-518.

The volume element network used for the chopper apparatus is displayed in Figure 8. As shown, the grids within the chopper and plate are two-dimensional and cylindrical while the grid for the shaft is one dimensional. The size of the radial and circumferential dimensions of the chopper and plate volume elements are left as program variables limited only by computer capacity and desired speed of calculations. The length of the shaft elements is also a program variable. The remaining volume dimensions, which are the thickness of the front plate and chopper disk and the cross sectional area of the shaft, are dependent on the physical dimensions of the system under investigation. Therefore, a major assumption in the system model is that the chopper disk, front plate, and connecting shaft are all thin with respect to their other dimensions.

As previously mentioned, the entire apparatus is contained within an enclosure cooled with gaseous helium. Although the system includes a 300^{o}K radiation source, the thermal analysis assumes that the background radiation impinging on the chopper components comes from a blackbody at the chamber temperature of 20^{o}K, with one area of exception. The chopper and plate surfaces which face each other are assumed to radiate at their instantaneous nodal temperatures.

The radiation of the 300^{o}K blackbody source, although having negligible influence on ambient conditions, can play an important role in heating the chopper disk and the front plate of the black box. The calculations of the radiation exchange to these surfaces are described in the next chapter. The equations developed in this chapter simply

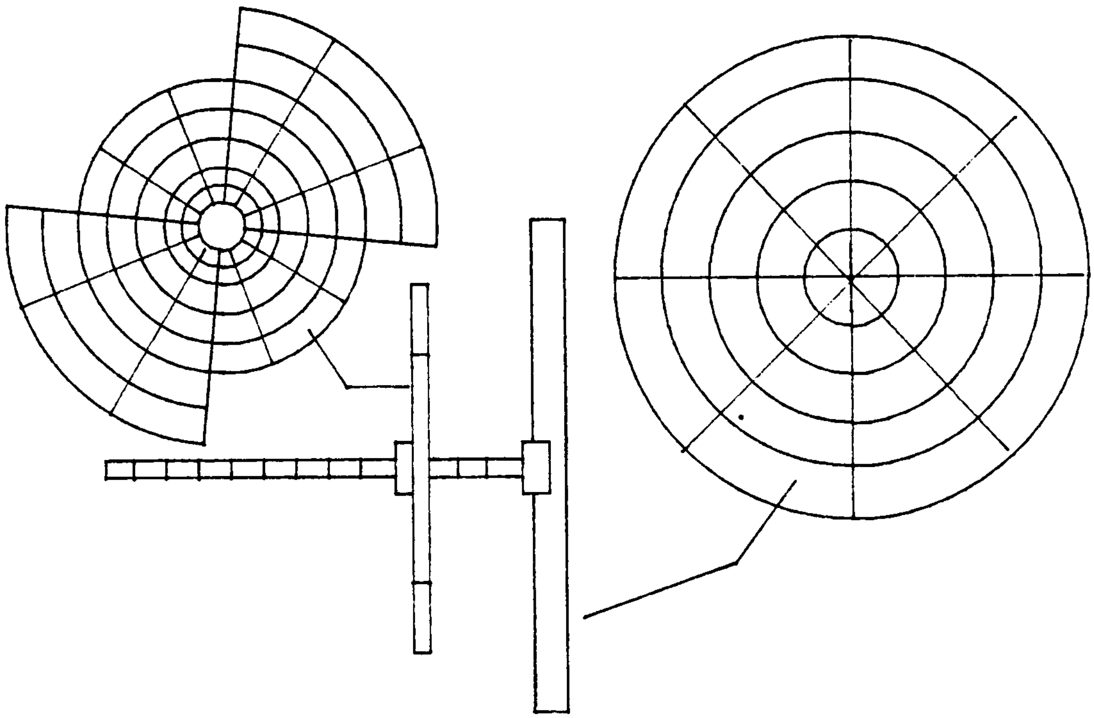

Figure 8. Chopper System Volume Element Network

express the radiation as a constant boundary heat flux. Radiation heating of the shaft is assumed negligible and not included in the model. The emissivities of the different surfaces making up the system are variable inputs to the model and computer program.

Thermal contact resistances are also variable inputs. The three areas which use such a value are the interfaces of the chopper and the shaft, the shaft and the bearing inner race, and the bearing outer race and the system support structure. Since the shaft is the single avenue of energy conduction to the chopper, modeling the thermal resistance is very important. At the bearings the contact resistance values also allow the modeling of a variety of bearing configurations. The details of these configurations are provided in the next chapter.

To this point, the bearing heat calculations have not been addressed. They are based on establishing each bearing as one of the finite-element nodes. This development will not be shown in this chapter. Instead, it will be added to the finite difference equations after it is developed in the next chapter.

The geometry of the helium cooling tube on the front face actually most resembles a three sided square surrounding the chopper shaft mount. In the model this path is represented by a circular arc with its center at the chopper shaft centerline. The subsequent computer program does, however, allow the user to input the arc radius and width of the path, and the average temperature and flow rate of the coolant.

With the overall descriptions of the system components now complete, the detailed derivations will begin with the chopper disk. The chopper grid network is shown in Figure 9. The grid is cylindrical

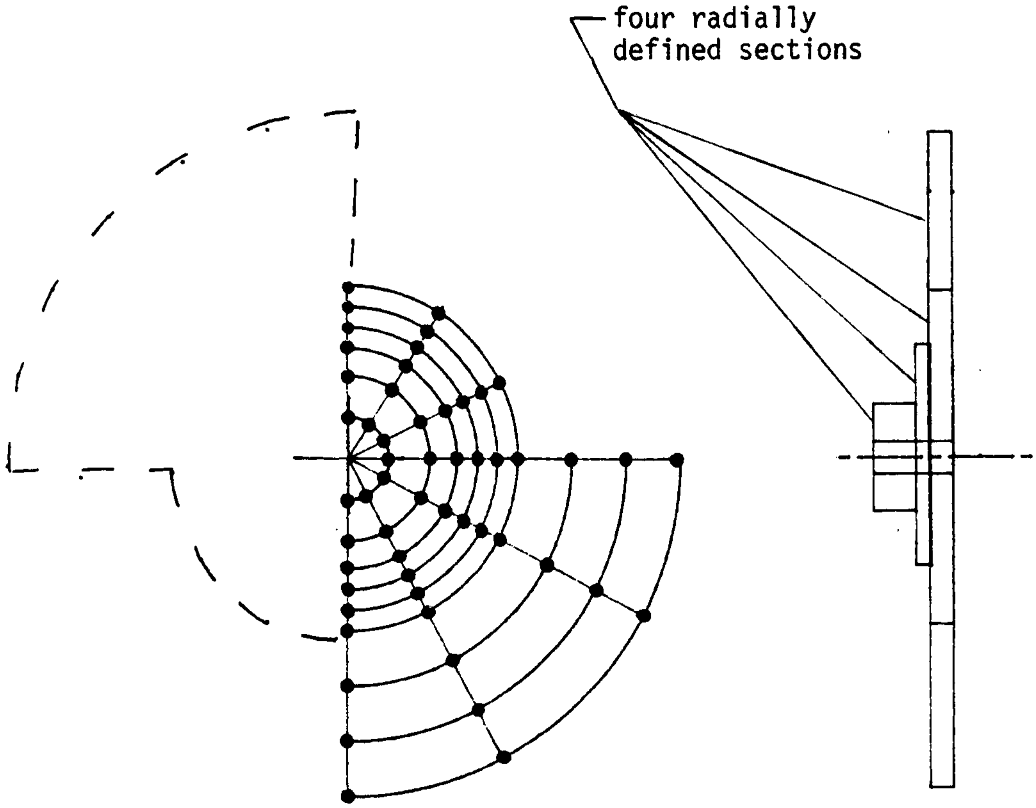

Figure 9. Chopper Disk Finite-Element Grid Network

with many unique shapes and regions. Four regions, the fin, the thin inner section, the strengthened inner section, and the connector, are all modeled with independent radial dimensions. This yields a more accurate representation of the chopper shape and also allows variability in control volume sizes. An additional node dimension is used in the shaft connector region. This is one of the few sections in the model which goes beyond two dimensional networks. The additional nodes are used to ensure an accurate heat flow representation at the critical chopper interface to the shaft.

As a final note in the chopper grid description, the model is simplified by taking advantage of symmetry. The next chapter details the averaging of heat loads on the spinning disk. This averaging process models an equivalent thermal loading on the chopper surfaces at a given radius. The only potential for circumferential heat transfer is due to the geometry of the disk. The heat from the chopper blade conducts circumferentially at the connection with the inner section of the disk. But since the loads on each fin are modeled identically, a repeating thermal profile is established for each fin and associated inner section. The repeating thermal symmetry is represented in Figure 9. The program sets a reaction between the beginning and ending circumferential nodes in the section instead of modeling the entire disk. This is a proper model because the repeating symmetry shows that the temperatures of the last column of nodes in the last section are equivalent to the last column of nodes in any section.

A representative internal node on the chopper disk is shown in Figure 10. The energy balance for this node is

$$q_{stored} = \Sigma q_{cond} + \Sigma q_{rad} \qquad \text{(III-1)}$$

In this equation, Σq_{rad} is the sum of the radiation heat fluxes from the ambient walls and the blackbody heat source. The heat conduction from the neighboring nodes is represented by Σq_{cond}, and q_{stored} is the rate of thermal energy storage. The thermal energy storage is represented by

$$q_{stored} = \rho c_p \Delta V[\Delta T]/\Delta t \qquad \text{(III-2)}$$

where

$$\Delta V = \delta \ \Delta A \qquad \text{(III-3)}$$

and

$$\Delta T = T_0^{n+1} - T_0^{n} \qquad \text{(III-4)}$$

Here "n" represents the time dimension in the transient equation. The term ΔA is, of course, the cross sectional area of the volume element and for cylindrical dimensions is represented by

$$\Delta A = r\Delta r\Delta\phi \qquad \text{(III-5)}$$

The heat conduction is given by

$$\Sigma q_{cond} = -2B_1(T_1-T_0) - 2B_2(T_2-T_0) -2B_3(T_3-T_0) - 2B_4(T_4-T_0) \qquad \text{(III-6)}$$

where B_1 and B_4, for heat conduction in the radial direction, are from Fourier's Law and written as

$$B_1 = -\tfrac{1}{2}k\delta[(r+\tfrac{1}{2}\Delta r)\Delta\phi/\Delta r] \qquad \text{(III-7)}$$

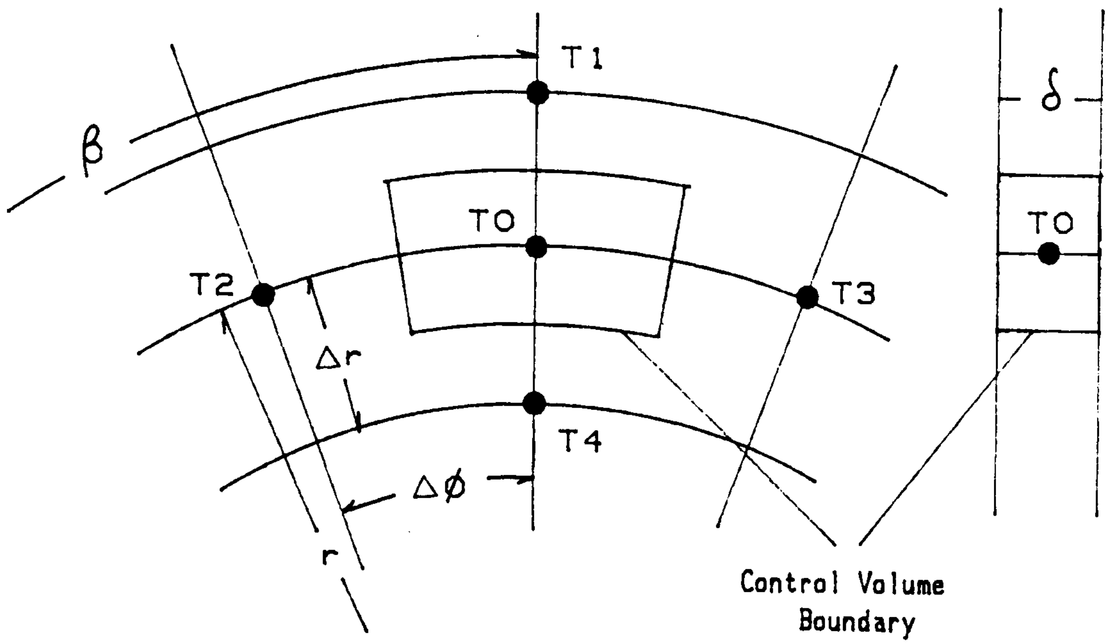

Figure 10. Chopper Internal Node Development

$$B_4 = -\tfrac{1}{2}k\delta[(r-\tfrac{1}{2}\Delta r)\Delta\phi/\Delta r] \tag{III-8}$$

and B_2 and B_3, for heat conduction along the circumference, as

$$B_2 = B_3 = -\tfrac{1}{2}k\delta[\Delta r/(r\Delta\phi)] \tag{III-9}$$

The conduction contribution equation is completed by including the time averaged temperature representation of

$$T_x = \tfrac{1}{2}(T_x^{n+1}+T_x^{n}) \tag{III-10}$$

where T_x stands for each of the temperatures in the equation. The conduction equation can now be written as

$$\begin{aligned}\Sigma q_{cond} = &-B_1[(T_1^{n+1}-T_0^{n+1})+(T_1^{n}-T_0^{n})] \\ &-B_2[(T_2^{n+1}-T_0^{n+1})+(T_2^{n}-T_0^{n})] \\ &-B_3[(T_3^{n+1}-T_0^{n+1})+(T_3^{n}-T_0^{n})] \\ &-B_4[(T_4^{n+1}-T_0^{n+1})+(T_4^{n}-T_0^{n})]\end{aligned} \tag{III-11}$$

where B_1, B_2, B_3, and B_4 remain as previously listed.

The only term left to develop now is Σq_{rad}. Letting q_{bb} represent the source radiation effect and using a standard radiation exchange formula, the radiation term is written

$$\Sigma q_{rad} = \sigma\Delta A[\epsilon_{bf}(T_\infty^{4}-T_0^{4})+\epsilon_{ff}(T_p^{4}-T_0^{4}] + q_{bb} \tag{III-12}$$

To linearize the equation with respect to T_0, the fourth order temperature difference terms are represented in the model by

$$[T_\infty^{4}-T_0^{4}] = [T_\infty^{4}-T_0^{n+1}(T_0^{n})^3] \tag{III-13}$$

and

$$[T_p^{4}-T_0^{4}] = [T_p^{4}-T_0^{n+1}(T_0^{n})^3] \tag{III-14}$$

Combining the three heat contribution effects, Equations III-2, 11, and 12, into the energy balance, Equation III-1, yields

$$B_0(T_0)^{n+1} + B_1(T_1)^{n+1} + B_2(T_2)^{n+1} + B_3(T_3)^{n+1} + B_4(T_4)^{n+1} = C \quad \text{(III-15)}$$

where $$B_0 = (\delta\rho c_p/\Delta t)\Delta A - B_1 - B_2 - B_3 - B_4 + \gamma(T_0{}^n)^3 + \alpha(T_0{}^n)^3 \quad \text{(III-16)}$$

$$\gamma = \epsilon_{bf}\sigma\Delta A \quad \text{(III-17)}$$

$$\alpha = \epsilon_{ff}\sigma\Delta A \quad \text{(III-18)}$$

and $$C = \{[\delta\rho c_p/\Delta t]\Delta A + B_1 + B_2 + B_3 + B_4\}(T_0)^n - B_1(T_1)^n - B_2(T_2)^n - B_3(T_3)^n - B_4(T_4)^n + \gamma(T_\infty)^4 + \alpha(T_p{}^n)^4 + q_{bb} \quad \text{(III-19)}$$

Again, the B_1, B_2, B_3, and B_4 terms remain as originally developed.

This equation is the finite-difference equation for an internal chopper node. Adjustments are made to the equations for boundary nodes. These equations are shown in Appendix A.

A schematic of the shaft grid node network is shown in Figure 11. Note, all boundaries on the shaft are perpendicular to the shaft centerline. Two shaft nodes are defined in their size by the chopper dimensions. These two nodes are located in a three dimensional structure because three dimensional conduction effects are important at the joint. The rest of the shaft nodes assume one dimension conduction and are variable in size. Some special areas on the shaft are the areas of bearing heating, which are addressed in the next chapter, and an area where radiation between the shaft end and the front plate takes place.

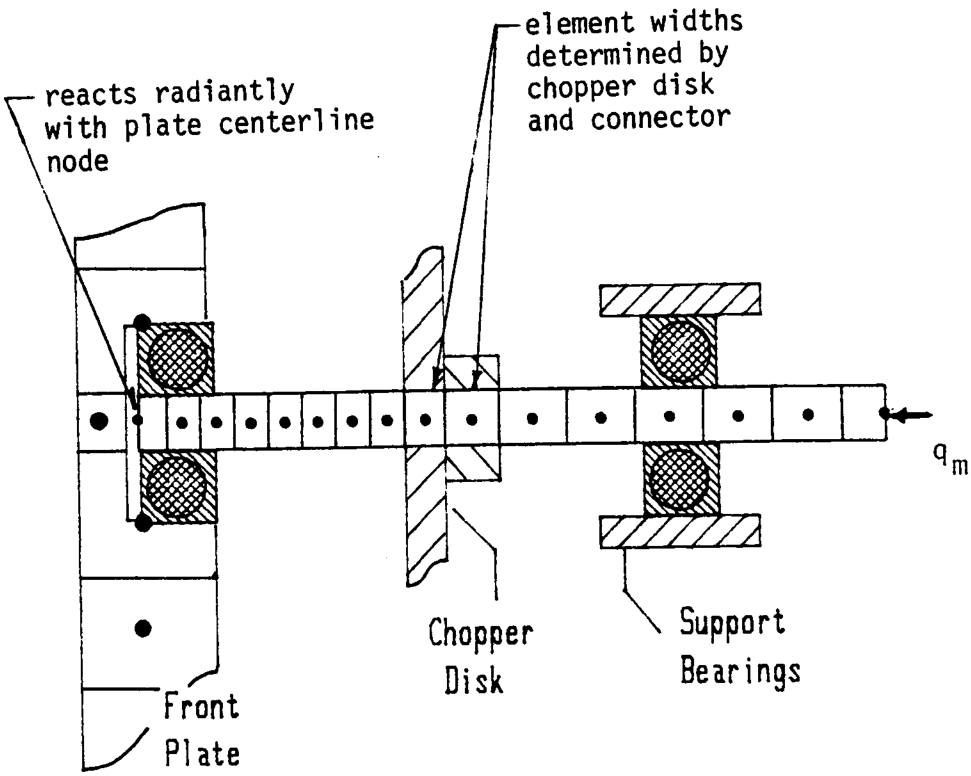

Figure 11. Shaft Finite-Element Grid Network

Figure 12 shows a typical internal node representation for the shaft. The nodes at the bearing sites will be described later.

An energy balance for the shaft control volume is again given by Equation III-1. Identical to the chopper disk derivation, the storage term is represented by Equation III-2, but for this application

$$\Delta V = (\Delta z)\Delta A = (\Delta z)\pi(r_s)^2 \qquad \text{(III-20)}$$

The resultant representation for Σq_{cond} is

$$\begin{aligned}\Sigma q_{cond} = & -B_1[(T_1^{n+1}-T_0^{n+1})+(T_1^{n}-T_0^{n})] \\ & -B_2[(T_2^{n+1}-T_0^{n+1})+(T_2^{n}-T_0^{n})]\end{aligned} \qquad \text{(III-21)}$$

where

$$B_1 = B_2 = -\tfrac{1}{2}k(\Delta A/\Delta z) \qquad \text{(III-22)}$$

The radiation effect for an internal node on the shaft consists only of the interaction with the chamber walls at ambient temperatures. The potential of a bearing covering all or part of the surface area, and thus shielding it from radiation, requires a special modification in the radiation formula. The resultant expression is

$$\Sigma q_{rad} = \gamma[T_\infty^{\,4}-T_0^{n+1}(T_0^{\,n})^3] \qquad \text{(III-23)}$$

$$\gamma = \epsilon_s\sigma(2\pi r_s)(\Delta z-\Delta l_b) \qquad \text{(III-24)}$$

where Δl_b is the length of the node volume which is covered by a bearing. If the volume is completely covered, then the difference between Δz and Δl_b is zero. This results in zeroing the value of Σq_{rad} as desired.

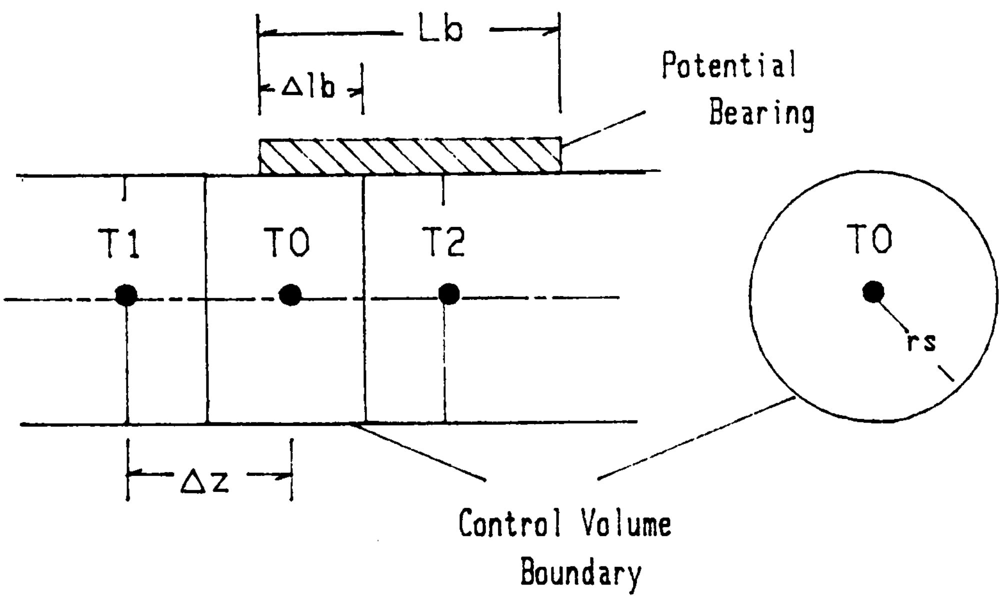

Figure 12. Shaft Internal Node Development

Combining the heat load values into the energy balance equation yields

$$B_0(T_0)^{n+1} + B_1(T_1)^{n+1} + B_2(T_2)^{n+1} = C \qquad \text{(III-25)}$$

where

$$B_0 = [\Delta z \rho c_p/\Delta t]\Delta A - B_1 - B_2 + \gamma(T_0{}^n)^3 \qquad \text{(III-26)}$$

and

$$C = \{[\Delta z \rho c_p/\Delta t]\Delta A + B_1 + B_2\}(T_0)^n - B_1(T_1)^n - B_2(T_2)^n + \gamma(T_\infty)^4 + (\Delta l_b/L_b)q_b \qquad \text{(III-27)}$$

This is the finite-difference representation for an internal shaft node.

Now consider the front plate grid network is detailed in Figure 13. Similar to the chopper, the plate network utilizes symmetry to reduce the computations. The circumferential averaging of effects from the chopper disk face, the representation of the helium tube as a circle about the shaft centerline, and the blackbody source aperture being centered on the front plate aperture establishes this symmetry. The flow of thermal energy due to the helium tube, the chopper disk face, and the shaft bearings is symmetric about the shaft centerline, while the energy from the blackbody is symmetric about the center of the plate aperture. The combination of these effects is symmetry about the line from the shaft centerline to the plate aperture. This symmetry allows modeling the plate as a semicircle (Figure 13) since no heat flows across the line.

Again, like the chopper grid, the front plate has many unique elements. The bearing, the helium cooling tube, the outer boundary of the model, and the plate aperture are these unique areas.

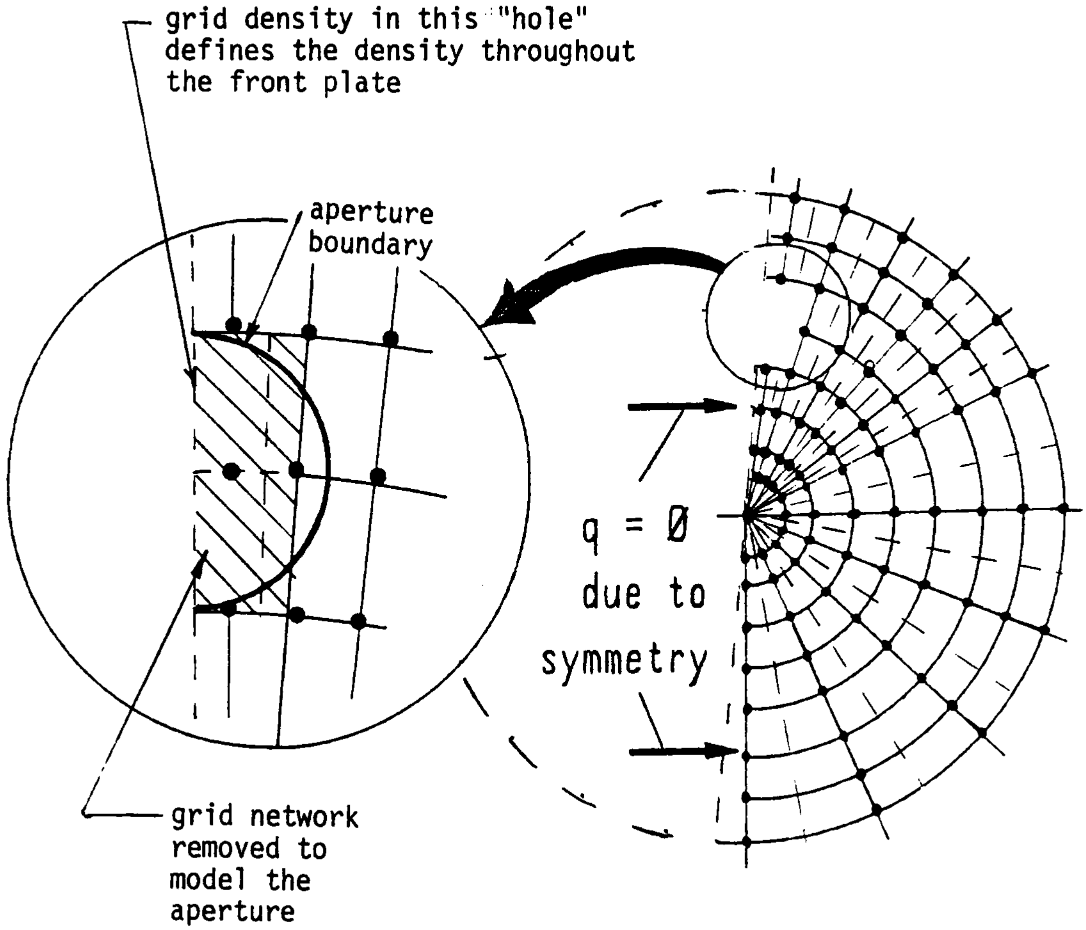

Figure 13. Front Plate Finite-Element Grid Network

Figure 11 (pg 27) shows that with a shaft bearing on the plate, the model program defaults to include a centerline node and one set of nodes at the bearing radius. The centerline node reacts radiantly with the end of the shaft, and the bearing radius nodes are specialized to model the countersinking of the bearing. The helium filled tubes are modeled with a minimal starting point of just outside this bearing radius. This is simply a limitation of the program software. The outer boundary of the plate is specified at a constant ambient temperature. This assumes the temperature gradient decays to zero far from the heated sections.

The plate aperture is modeled, as shown in Figure 13, as a gap in the cylindrical network. Equal in area to the actual aperture, this representation is quite accurate. Standard shape factor calculations for a representative configuration give a shape factor of 0.22 from the source to the aperture. The model, for this same configuration, calculates a shape factor of 0.20. This aperture model also forms the basis for the entire plate nodal dimensions. The radial increment in the section is used throughout the plate. To reduce unnecessary computations two circumferential increments are used. The elements close to the aperture use smaller increments, while the other half of the plate nodes fill the rest of the semicircle with larger increments.

The finite-difference equation for a typical node on the front plate is given by:

$$\begin{aligned} B_0(T_0)^{n+1} + B_1(T_1)^{n+1} + B_2(T_2)^{n+1} \\ + B_3(T_3)^{n+1} + B_4(T_4)^{n+1} = C \end{aligned} \qquad \text{(III-28)}$$

where $$B_0 = [\delta\rho c_p/\Delta t]\Delta A - B_1 - B_2 - B_3 - B_4 + (\gamma+\alpha)(T_0^{\,n})^3 \qquad \text{(III-29)}$$

$$\gamma = \alpha = \epsilon_p \sigma \Delta A \qquad \text{(III-30)}$$

and $$C = \{[\delta\rho c_p/\Delta t]\Delta A + B_1 + B_2 + B_3 + B_4\}(T_0)^n \qquad \text{(III-31)}$$
$$-B_1(T_1)^n - B_2(T_2)^n - B_3(T_3)^n - B_4(T_4)^n$$
$$+ \gamma(T_\infty)^4 + \alpha(T_c)^4 + q_{bb} + q_{He}$$

The symbols q_{bb} and q_{He} represent the radiant heat transfer from the blackbody source and the heat transfer to the helium cooling coils.

Material Property Values

All of the equations developed in this chapter involve material properties. The first chapter of this study mentioned the important impact of cryogenic conditions on such properties. Because the properties vary significantly with temperature at 20°K, the computer program reads the properties for each node at every time step. The program includes three options, aluminum, stainless steel, and copper, as material choices for any of the chopper system components. These are used because they are both common and considered suitable for mechanisms in cryogenic environments.[4] The model represents the property values of these materials through three program subroutines.

[4] Sittig, M., Cryogenics, Research and Applications, D. Van Nostrand Co., Inc., 1963, pg 63.

The first subroutine simply lists the standard density values of the materials[5] as this property is not significantly temperature dependent. The specific heats and thermal conductivities, as mentioned in Chapter I, however, are very much temperature dependent and are listed as functions of temperature in the second subroutine. These functions reflect second and third order regression analyses performed on tabulated data. This was done using a modification of a program by Poole and Borches.[6] A listing of this program is provided in Appendix D. The specific heat values for aluminum and copper are from Corruccini and Gniewek,[7] and the data for stainless steel is from Gopal.[8] The thermal conductivity data comes from three separate sources: Sittig[9] for aluminum, Scurlock[10] for stainless steel, and Berman[11] for copper. The functions within the program are accurate

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[5]Baumeister, T., Avallone, A.E., and Baumeister III, T., Marks' Standard Handbook for Mechanical Engineers, Eighth Edition, McGraw-Hill Inc., 1978, pgs 6 & 7.

[6]Poole, L., and Borchers, M., Some Common Basic Programs, Adam Osborne & Associates, Inc., Berkeley, CA, 1978, pgs 151-153.

[7]Corruccini, R.J., and Gniewek, J.J., Specific Heats and Enthalpies of Technical Solids at Low Temperatures, National Bureau of Standards Monograph 21, U.S. Department of Commerce, Oct 3, 1960, pgs 7 & 8.

[8]Gopal, E.S.R., Specific Heats at Low Temperatures, Plenum Press, New York, 1966, pg 193.

[9]Settig, M., Cryogenics, Research and Applications, D. Van Nostrand Co., Inc., 1963, pg 30.

[10]Scurlock, R.G., Low Temperature Behavior of Solids, Dover Publications, Inc., N.Y., 1966, pg 50.

[11]Berman, R., "Heat Transfer in Solids," Heat Flow below 100oK and Its Technical Applications, Pure and Applied Cryogenics, Vol 4, Pergamon Press, 1966, pg 30.

within single digit percentiles from the range of 10°K to 300°K. The third subroutine utilizes thermal expansion coefficients in calculating the bearing expansion load. These coefficients, also from tabulated data,[12] are, again, accurate from 10°K to 300°K.

This chapter detailed the development of the finite-difference equations for the chopper model. It also described some of the important associated assumptions, and the means by which the property values are represented in the model. The complete development of the finite-difference equations was not performed, however. The blackbody and bearing thermal loads, and the helium thermal sink, are all developed in the next chapter so as to incorporate their effects in the finite-difference equations.

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[12] Baumeister, T., Avallone, A.E., and Baumeister III, T., Marks' Standard Handbook for Mechanical Engineers, Eighth Edition, McGraw-Hill Inc., 1978, pgs 19-29.

CHAPTER IV

THERMAL LOADS AND EFFECTS

The preceding chapter has defined the grid system and developed the finite-difference equations for a typical node on the chopper disk, the shaft, and the front plate, respectively. This chapter details the approaches used to model the three main thermal loads within the chopper apparatus: The blackbody radiation source, the bearing heating, and the front plate cooling. The drive motor for the apparatus is also a heat source, but, mounted to a cooled base plate, its contribution is assumed less significant. Analytically verifying this assumption is beyond the scope of this study.

Blackbody Radiation

The representation of the 300°K blackbody radiation source effect on the chopper and front plate utilizes a basic formula detailed by Incropera and DeWitt.[13] The portion of the blackbody radiant energy which will fall on a typical node is given by

$$q_{i\rightarrow j} = F_{i\rightarrow j}\Delta A_i(\sigma T_i^{\,4}) \tag{IV-1}$$

where $F_{i\rightarrow j}$ is the shape factor between the aperture, ΔA_i, and the typical node area, ΔA_j. T_i is the blackbody source temperature. In

[13] Incropera, F.P., and DeWitt, D.P., Fundamentals of Heat Transfer, John Wiley and Sons, Inc., 1981, pgs. 630-632.

equation form, $F_{i\rightarrow j}$ is

$$F_{i\rightarrow j} = (q_{i\rightarrow j})/(\Delta A_i J_i) = (\cos\theta_i \cos\theta_j/\pi R^2)\Delta A_j \qquad \text{(IV-2)}$$

where the terms in the equation are depicted in Figure 14.

The relation of the source aperture to the chopper back face is shown in Figure 15. The source aperture area, ΔA_i, is typically between 0.008 and 0.018 cm^2, and the finite-difference grid network centered around the jth node on the chopper, ΔA_j, can be adjusted according to grid size selection. A major simplification results from the realization that all of the areas on the chopper are parallel with the facing of the source aperture. The theorem of equal alternate interior angles shows that θ_i and θ_j for the chopper alignment are equal. The view factor can therefore be written as

$$F_{i\rightarrow j} = (\cos^2\theta/\pi R^2)\Delta A_j \qquad \text{(IV-3)}$$

The values of θ and R are a function of the grid spacing and separation distance between the source aperture and the chopper disk surface.

Figure 16 defines the coordinate system employed in the model. The center of the aperture is in a plane aligned along the shaft axis and the verticle axis. As shown, this position is represented by the cartesian coordinates of y_b and z_b (x_b is defined as 0). The node within ΔA_j is located at

$$[r(\sin\beta), r(\cos\beta), 0] \qquad \text{(IV-4)}$$

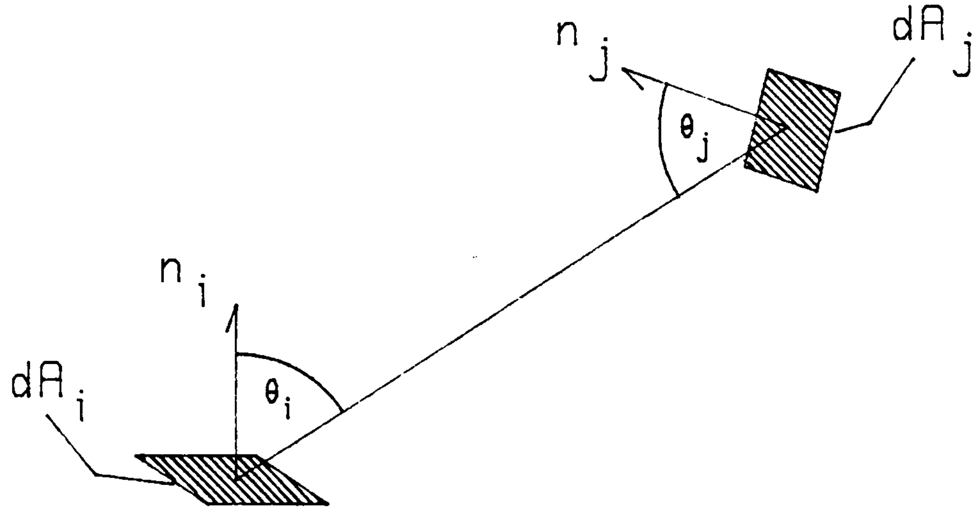

Figure 14. Shape Factor Between Differential Areas

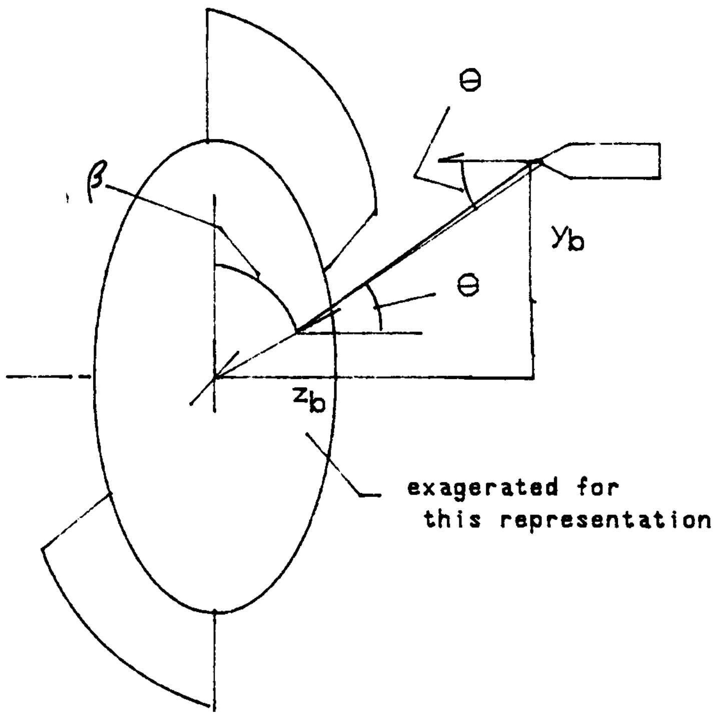

Figure 15. Relation of the Source Aperture to the Chopper

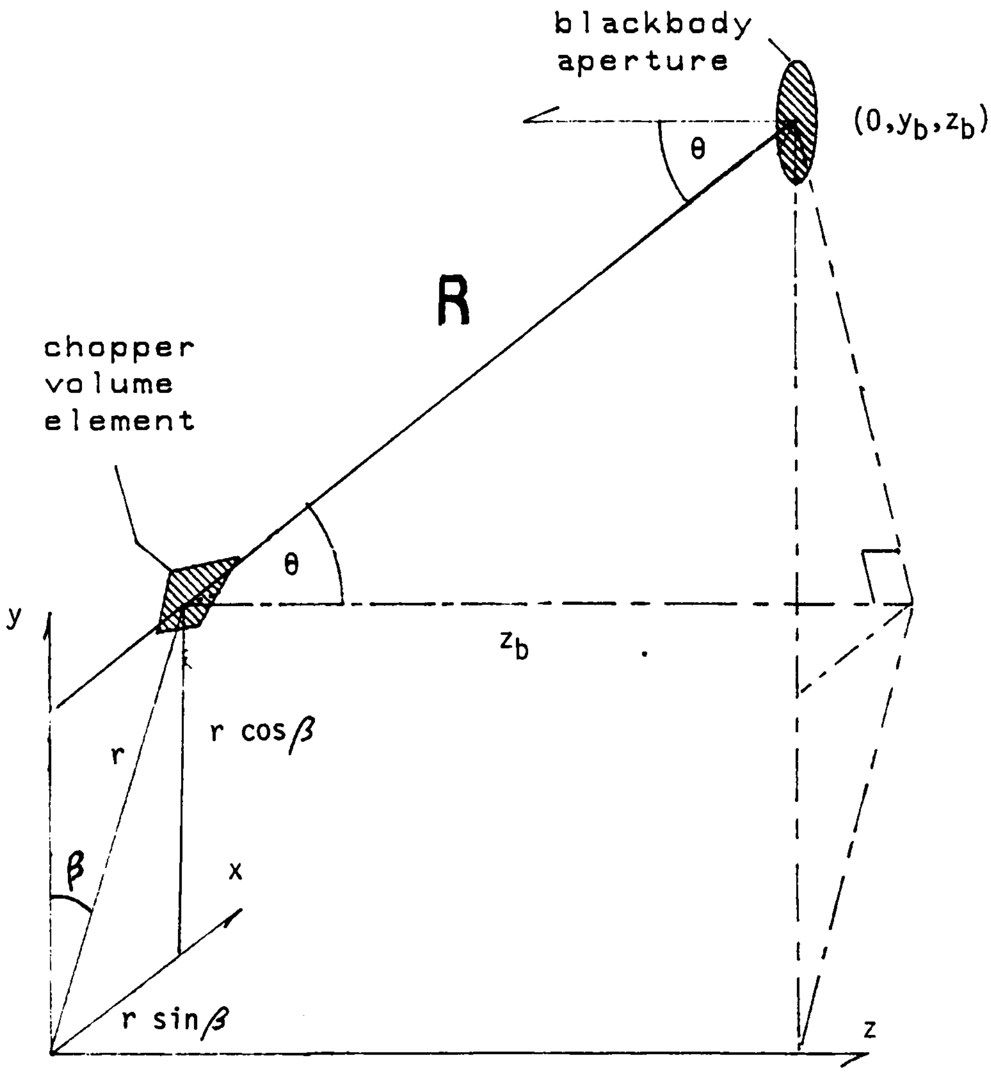

Figure 16. Chopper Node / Source Aperture Alignment

The vector between ΔA_j and ΔA_i, **R**, is then represented by

$$\mathbf{R} = (0-r\sin\beta, y_b-r\cos\beta, z_b) \qquad \text{(IV-5)}$$

The magnitude of **R** is

$$R = [(r\sin\beta)^2+(y_b-r\cos\beta)^2+z_b{}^2]^{1/2} \qquad \text{(IV-6)}$$

From Figure 16, the cosθ term in Equation IV-3 is determined from

$$\cos\theta = (z_b/R) \qquad \text{(IV-7)}$$

The view factor is determined by combining equations IV-7 and IV-6 into IV-3. The radiation heat flux on the ΔA_i element is then given by

$$q_{bb\to0} = F_{bb\to0}\Delta A_{bb}(\sigma T_{bb}{}^4) \qquad \text{(IV-8)}$$

where
$$F_{bb\to0} = (z_b{}^2/\pi R^4)\Delta A_0 \qquad \text{(IV-9)}$$

and
$$R^4 = [(r\sin\beta)^2+(y_b-r\cos\beta)^2+z_b{}^2]^2 \qquad \text{(IV-10)}$$

The subscript 'bb' refers to the blackbody aperture and the subscript '0' refers to the chopper element.

Since the chopper disk is rotating, the position of the element volume is changing with time. A simplifying assumption is utilized to avoid the axcessive bookkeeping required to rigorously account for this transient factor. A typical chopper spin rate is 20 rev/sec. This spin rate is considered high enough to create essentially a steady 'blur' with respect to the heat transfer phenomena. Therefore, the spin effect is modeled by assuming the disk is quasi stationary ("frozen at a point") for any time step. The blackbody radiation effect at a given radial position on the chopper is calculated in advance of the transient thermal investigation by averaging the blackbody thermal load over the circumference. This gives the desired quasi stationary representation because it is the same value as averaging the thermal load "seen" by a single element over one complete revolution. The averaged blackbody radiation is then taken as uniform at the average value for each node at that radial position throughout the transient calculations.

Equation IV-8 also applies to the source radiation on the front plate. As the chopper rotates, however, it blocks a significant portion of the wall from "seeing" the heat source thus creating a shadow on the plate. This shadow is included in the model by calculating the straight line Equation between the source and each plate node (Figure 17) as

$$x/x_p = (y-y_b)/(y_p-y_b) = (z-z_b)/(z_p-z_b) \qquad \text{(IV-11)}$$

Setting z to zero and solving for x and y gives the position of the point of intersection with the chopper disk plane. If this point falls below the chopper inner radius, no heat load is calculated. If the line intersects within the fin section, the heat loads are adjusted by the ratio of the open arc lengths over 2π. This ratio calculation reflects how "often" the line is blocked by the chopper disk (Figure 18). When the intersection point falls outside of the fin radius, the equations are applied directly.

The radiant heat loads calculated in the preceding section are contained in the constant "C" terms appearing in the finite-difference equations of Chapter III. The radiation from the chopper disk and the

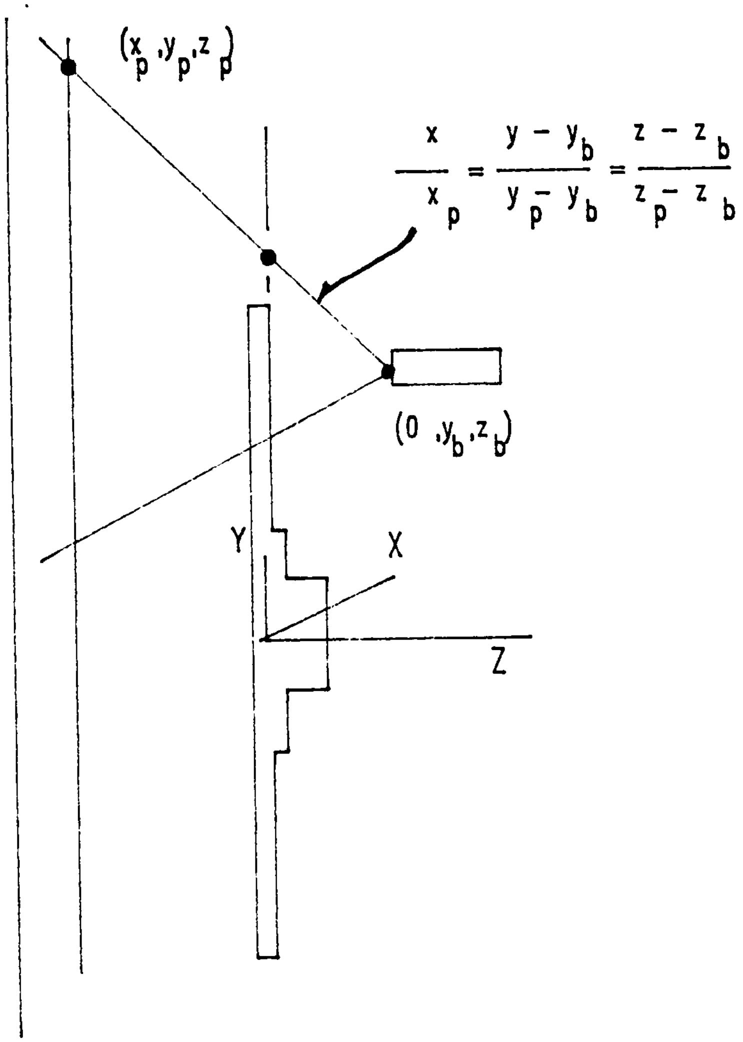

Figure 17. Radiation Source Shadow on the Front Plate

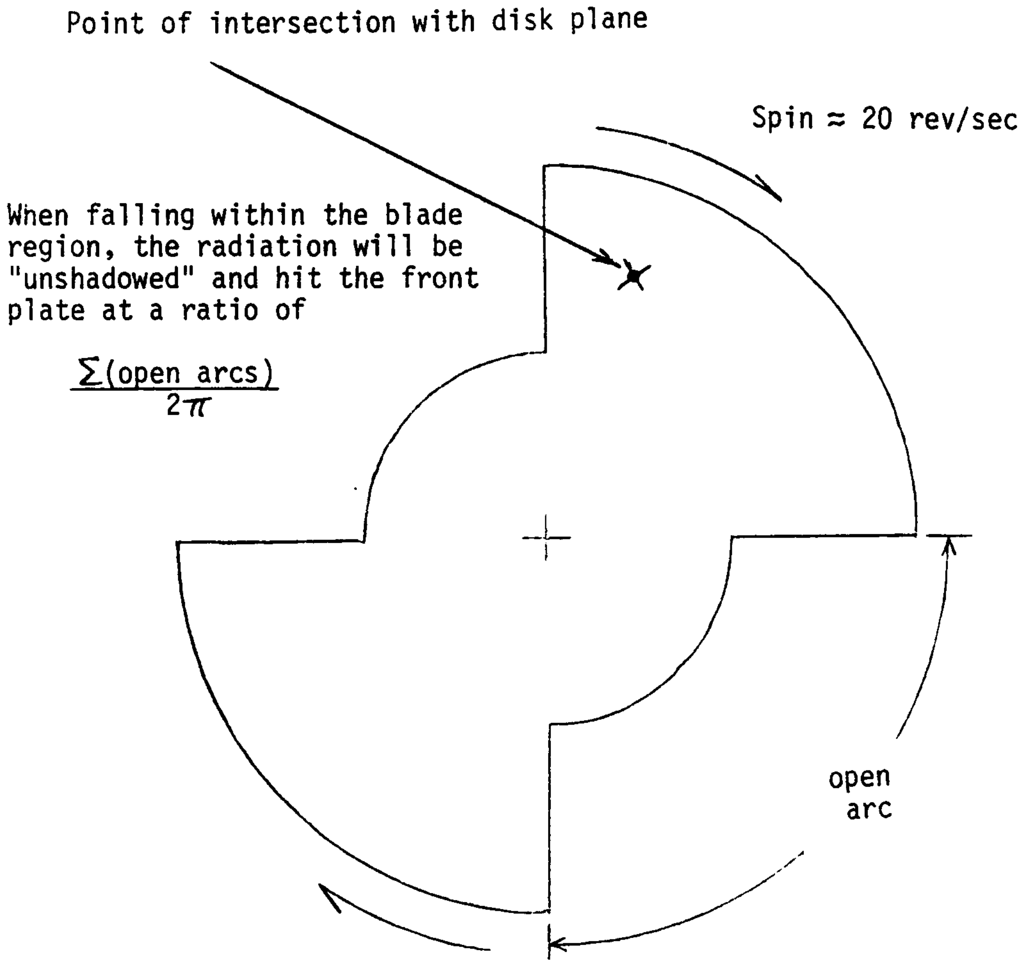

Figure 18. Periodic Shadow Representation

front plate back into the aperture is considered negligible. Therefore, the average radiation from the aperture is not influenced by the transient rise in temperature of the system.

Bearings

A valid model for bearing heating should be based on results from bearing experiments. However, due to the absence of such results an analytical estimate of the heat rate is developed.

The typical bearing used within the chopper apparatus is a standard stainless steel ball bearing. The present model assumes this type of bearing. The Bearing Manual Cyclopedia[14] gives the average coefficient of friction, c_f, of a typical ball bearing under radial load and normal operating conditions as 0.0015. Two factors make this c_f unsuitable for the chopper bearing model, however. First, the 20°K cryogenic environment requires the bearings to run without lubrication, and second, the size of the chopper shaft requires considerably smaller bearings than the "typical" bearing. Marks' Handbook[15] shows a 14.5:1 ratio between dry and lubricated friction in high strength steels. This value is therfore used to approximately correct the referenced c_f for cryogenic chamber conditions. This same reference also describes how the coefficient of rolling friction is inversely proportional to the

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[14] Bearing Manual Cyclopedia, 19th Edition, Vols 1 & 2, No. 104, Industrial Information Headquarters, Inc., 1981, pg 1091.

[15] Baumeister, T., Avallone, A.E., and Baumeister III, T., Marks' Standard Handbook for Mechanical Engineers, 8th Edition, McGraw-Hill, Inc., 1978, pgs 3-26 and 3-28.

radius of the rolling element. Since the typical bearing depth in the literature is 11.8 mm, and the depth used for the chopper bearing is 3.2 mm, a factor of 3.7 is also applied to the referenced c_f. The estimated value for the friction factor is thus 0.080.

This c_f value is important in determining the bearing heat load, q_b. The first law of thermodynamics shows

$$q_b = w_f \qquad \text{(IV-12)}$$

and

$$w_f = \tau_b \Omega \qquad \text{(IV-13)}$$

where w_f is the work performed against friction, τ_b is the bearing torque at the shaft radius, and Ω is the rotational speed. The bearing torque is given in the bearing manual as

$$\tau_b = c_f \; P \; r_s \qquad \text{(IV-14)}$$

where P is the radial load on the bearing and r_s the shaft radius. Combining equations IV-12, 13, and 14, including the previously developed value for c_f, yields

$$q_b = 8.0\text{x}10^{-9} \; P \; r_s \; \Omega \qquad \text{(IV-15)}$$

where the load, P, is given in dynes; the radius, r_s, in centimeters; and the speed, Ω, in radians per second. The resulting value of q_b is then given in watts.

Evaluating the load on the bearing once again involves several significant assumptions relative to values of the input variables. The theory is based upon fundamental concepts of dynamics and mechanics, but some of the required inputs, such as the contact area, must be based on estimation.

The radial load is assumed to consist of a combination of two effects: the weight of the shaft and disk, and shaft expansion under heating. Centripetal forces are assumed zero based on a perfectly balanced shaft and chopper disk. The weight effect on the bearing occurs instantaneously with the chopper run, while the expansion evolves with subsequent run time as the shaft is heated. Each of the effects is handled as a separate item in the present development and summed for the final evaluation.

The weight of the shaft and disk is calculated in the resulting computer program based on the specified chopper disk dimensions and on density values of selected materials chosen from the users menu. The program calculates mass in grams and the shaft and chopper combined weight is calculated from

$$W_{cs} = g\, M_{cs} = 981.\, M_{cs} \qquad \text{(IV-16)}$$

where the acceleration of gravity, g, in cm/sec^2, gives the value of weight in dynes. Fundamental moment equations are used in the program to calculate the resultant load at each of the support bearings.

The load due to thermal expansion is calculated by assuming a loaded column between the shaft and the bearing as illustrated in Figure 19. Theoretically the contact between the bearing and its race is a point contact. Any stress in the system, however, will create deformation of the ball element resulting in a finite contact area.

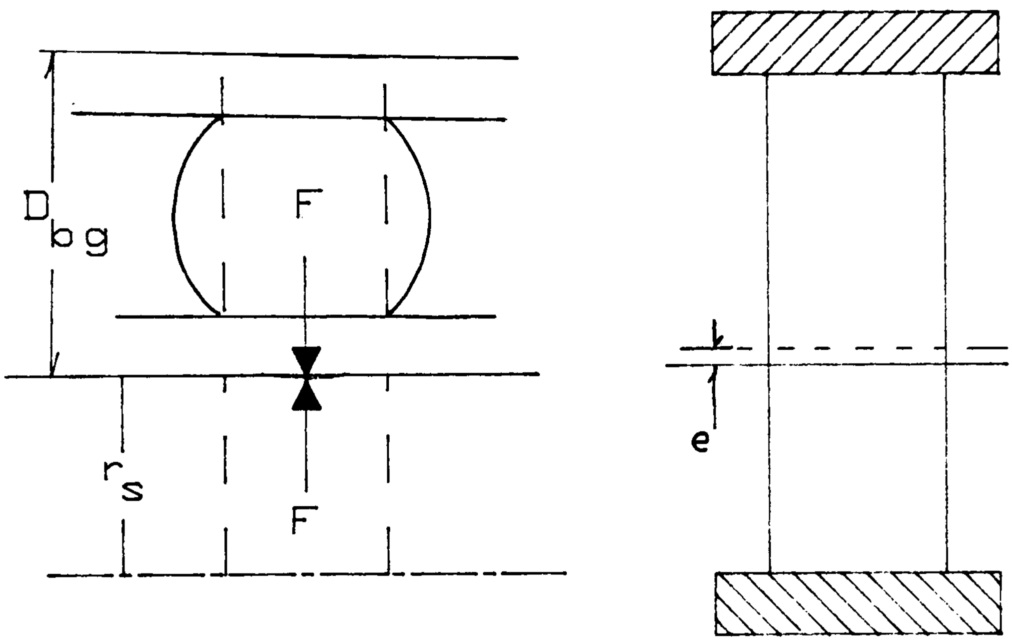

Figure 19. Thermal Expansion of the Shaft on a Bearing

By assuming the contact area exists, and further assuming the stress reaction of the shaft on the bearing can be estimated from a column loading model, the load due to thermal expansion becomes

$$P_{th} = E_{bg} \epsilon_{bg} A_c \tag{IV-17}$$

This equation utilizes the standard stress and strain relationship where E_{bg} is the modulus of elasicity, ϵ_{bg} is the thermal bearing strain, and A_c is the contact area. The modulus is a constant, but the strain and the contact area both vary with temperature and must be calculated.

Using standard strain representations, the strains in the bearing and the shaft are respectively represented by

$$\epsilon_{bg} = [(L_{T.bg}+e)-L_{20.bg}]/L_{20.bg} \tag{IV-18}$$

and

$$\epsilon_{s} = [(L_{T.s}+e)-L_{20.s}]/L_{20.s} \tag{IV-19}$$

Here $L_{T.x}$ is the length which the section would extend given free expansion at the temperature, T, and the subscripts 'bg', 's', and '20' refer to the bearing, the shaft, and 20°K, respectively. The strain, in this presentation, is simply the comparison of the unrestrained thermal growth to original lengths. In the computer program, therefore, the values of $L_{20.bg}$ and $L_{20.s}$ are the bearing depth and shaft radius, respectively (Figure 19).

Baumeister, Avallone, and Baumeister[16] provide a plot of values which allow the direct calculation of

$$(L_{T.x}-L_{528.x})/L_{528.x} \tag{IV-20}$$

as a function of temperatures down to $20^{o}K$. These values were curve fit by the relationship

$$(L_{T.x}-L_{20.x})/L_{20.x} = (C-y_{528}) \text{ X } 10^{-5} \tag{IV-21}$$

where y_{528} is determined from curvefits of the referenced plots at T, and C is a dimensionless constant equal to 412 for aluminum, 315 for copper, and 288 for stainless.

Using a simple balance equation, the bearing and shaft contact forces are:

$$F_{bg} = F_{s} = P_{th} \tag{IV-22}$$

Introducing the relation of stress to strain results in

$$E_{bg}\epsilon_{bg}A_{c} = E_{s}\epsilon_{s}A_{c} = P_{th} \tag{IV-23}$$

Utilizing the first two parts of Equation IV-23, the previously derived strain formulas, and letting

$$y_{bg} = (L_{T.bg}-L_{20.bg})/L_{20.bg} \tag{IV-24}$$

and

$$y_{s} = (L_{T.s}-L_{20.s})/L_{20.s} \tag{IV-25}$$

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[16] Baumeister, T., Avallone, A.E., and Baumeister III, T., Marks' Standard Handbook for Mechanical Engineers, 8^{th} Edition, McGraw-Hill, Inc., 1978, pg 19-29.

gives the value of e as:

$$e = (y_{bg}E_{bg}-y_sE_s)/(E_{bg}/D_{bg}+E_s/r_s) \qquad (IV-26)$$

The bearing strain is then given by:

$$\epsilon_{bg} = y_{bg} + e/D_{bg} \qquad (IV-27)$$

Only the contact area remains unresolved in the basic formula for the thermal expansion given in the preceeding section. This can be estimated by utilizing the bearing strain value. The difference between the radius of the ball element in an unrestrained and a loaded bearing is

$$\Delta r_{bg} = r_{bg}\epsilon_{bg} \qquad (IV-28)$$

Adding this value to the original ball element radius yields the unrestrained value as

$$r_{ur} = r_{bg} + \Delta r_{bg} = r_{bg}(1+\epsilon_{bg}) \qquad (IV-29)$$

Figure 20 shows that the resultant estimate of the contact area is

$$A_c = \pi(r_c)^2 = \pi[(r_{ur})^2-(r_{bg})^2] \qquad (IV-30)$$

Removing second order strain values, Equation IV-30 becomes

$$A_c = 2\pi(r_{bg})^2\epsilon_{bg} \qquad (IV-31)$$

Once again the load due to thermal expansion is calculated using

$$P_{th} = E_{bg}\epsilon_{bg}A_c \qquad (IV-32)$$

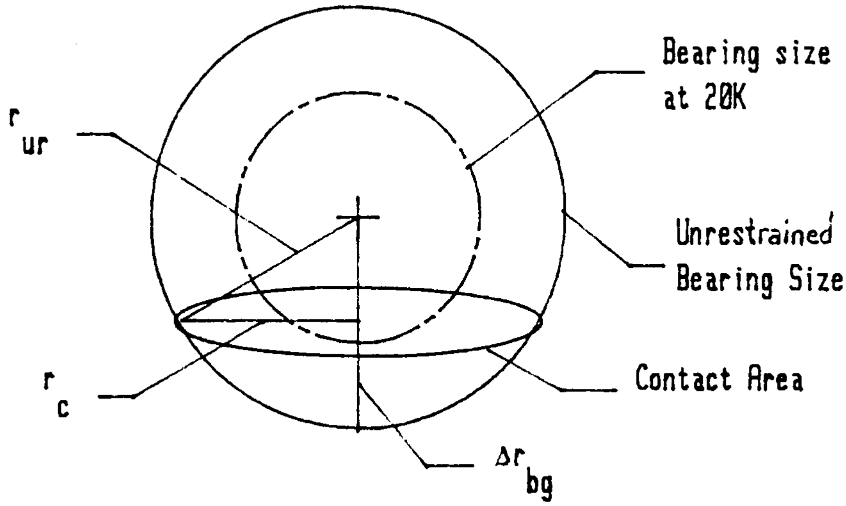

Figure 20. Bearing Contact Area

This is the other element of the shaft load on the bearings and is added to the weight in Equation IV-15. All strain and stress information is found internally within the computer program.

In summary, the heat load generated by a bearing is computed in the program from:

$$q_b = 8.0 \times 10^{-9} \; P \; r_s \; \Omega \qquad \text{(IV-33)}$$

where

$$P = P_w + P_\Omega + P_{th} \qquad \text{(IV-34)}$$

The program user should note that the bearing heat load generation will cease if Ω is changed to zero during the run. This effect is an appropriate representation and allows modeling of the cool down process. The user should also recognize limitations of the model due to the major assumptions utilized in calculating the heat load. An empirical bearing test would be very beneficial in checking the details of this approach, as well as providing accurate bearing heat information.

Like the source heating effect, the bearing heat is included in the finite-element model by adding it to the "C" term of specific nodes in the system. The node which receives this heat is a node in the bearing itself. The finite-element equations for this node are now developed.

The finite-element model of the bearing is shown in Figure 21. It is based on the assumption that the thermal resistance across the ball is zero when rolling and infinite when at rest. This is based on the very small contact area present for conduction across the ball if at rest, and the very high effective contact area due to the rolling of the ball elements when the shaft is rotating. The nodes with which the

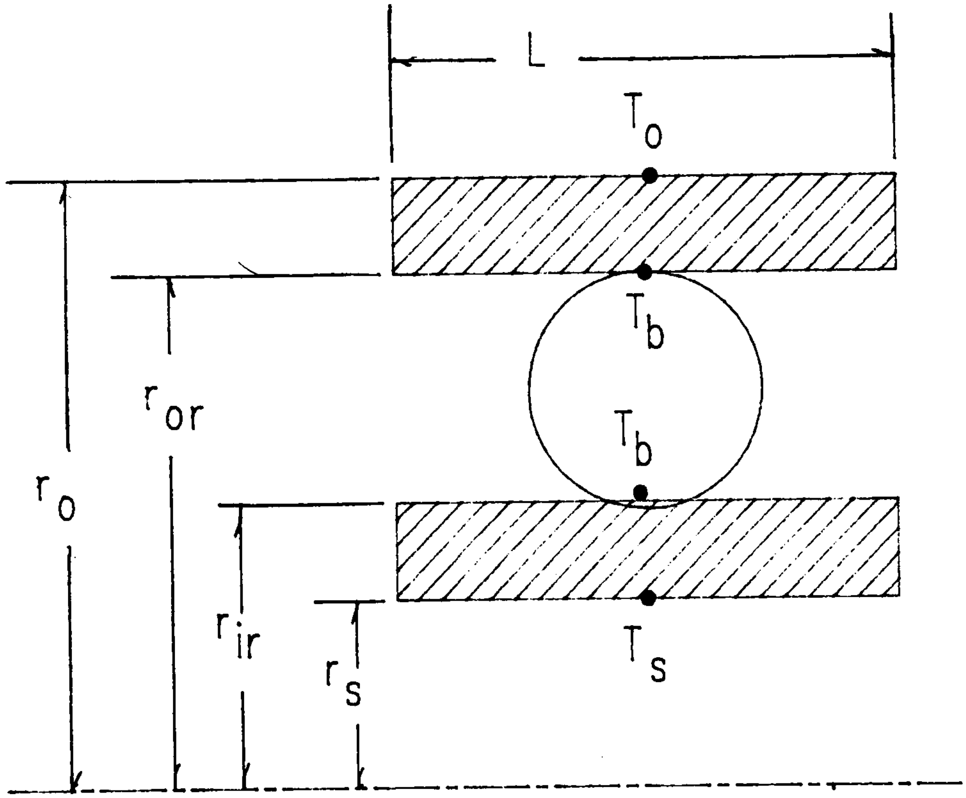

Figure 21. The Bearing as a Node

bearing element reacts are the shaft node, T_s, and a support structure node, T_o. The computer program allows the support node to either be set equal to the shaft node or to the ambient conditions in the chamber. When the node is set equal to the shaft temperature, the bearing heat is distributed based on the ratio of the shaft contact area to the outer race/housing contact area. Alternatively, with the node set at the chamber temperature, the maximum possible bearing cooling situation is modeled. The contact resistance values are difficult to determine, but trends in the heat transfer process can be investigated by varying these values computationally.

The finite-difference formula for T_b assumes the shaft temperature at the outer edge of the shaft and the support temperature just beyond the outer race of the bearing. Also, because of the very small areas exposed to radiant cooling, radiation effects are assumed negligible. Using a standard annulus representation for the thermal resistances,[17] the finite difference formula is

$$B_b(T_b)^{n+1} + B_s(T_s)^{n+1} + B_o(T_o)^{n+1} = C \qquad \text{(IV-35)}$$

where

$$B_b = [\rho c_p V/\Delta t] - B_s - B_o \qquad \text{(IV-36)}$$

$$B_s = -\tfrac{1}{2}[\ln(r_{ir}/r_s)/2\pi L k_b + R_{ci}] \qquad \text{(IV-37)}$$

$$B_o = -\tfrac{1}{2}[\ln(r_o/r_{or})/2\pi L k_b + R_{co}] \qquad \text{(IV-38)}$$

$$C = [(\rho c_p \Delta V/\Delta t) + B_1 + B_2](T_b)^n - B_s(T_s)^n - B_o(T_o)^n \qquad \text{(IV-39)}$$

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[17] Incropera, F.P., and DeWitt, D.P., Fundamentals of Heat Transfer, John Wiley and Sons, Inc., 1981, pg 81.

The dimensions of the bearing are estimated in the program based on the bore and outer diameter. The bore is simply the diameter of the opening of the bearing. For the purpose of this development, the thickness of the bearing is one half of the difference between the outer diameter and the bore. In the computer program the ball radius is arbitrarily set at half of the thickness of the bearing while the inner and outer races are one quarter of the thickness each. The number of balls is computed using a standard formula for circles in an annulus. This value is used in the bearing volume calculation. If desired, actual bearing dimensions can be hard coded in the computer program data list.

The B_s value, Equation IV-37, along with the T_b variable are also used in the finite-difference equations at the shaft nodes where the bearing is mounted. This is required to fulfill Equation IV-35 since the finite-difference equations must be interdependent.

Plate Cooling

The front plate cooling effect is modeled by a standard convective boundary condition. For each finite-difference node on the plate in direct contact with the helium cooling tube, q_c is given by:

$$q_c = h\ \Delta A_{He}(T_0 - T_{He}) \qquad \text{(IV-40)}$$

This is used to represent a heat sink in the finite-difference formulation. This approach is simple and effective but does involve some assumptions.

Convection is a surface effect. For a completely proper representation, T_0, used in calculating q_c, must be the inner surface temperature of the cooling tube. However, the plate is thin and the assumption that the node temperature is constant throughout the plate width is realistic. In turn the computational algorithm assigns a constant temperature of T_{He} to the coolant as it transverses the tube passage. This assumption is justified on the basis of test operations information which documents that the helium temperature drop throughout the entire cooling passage is only a few degrees. Finally, the value of ΔA_{He} is simply the area of the plate nodal point within the defined cooling passage path.

The convective heat transfer coefficient is computed from the correlation for fully developed turbulent flow in a tube (Kays and Crawford[18]) ie:

$$Nu = 0.022\ Pr^{0.5} Re^{0.8} \qquad \begin{array}{l} 2300 < Re < 100{,}000 \\ 0.5 < Pr < 1.0 \end{array} \tag{IV-41}$$

where

$$Re = D\rho V/\mu \tag{IV-42}$$

The Nusselt number, Nu, is a dimensionless parameter defined as

$$Nu = hD/k \tag{IV-43}$$

Therefore, the convective heat transfer coefficient for turbulent flow

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[18] Kays, W.M., Crawford, M.E., Convective Heat and Mass Transfer, 2nd Edition, McGraw-Hill Book Company, 1980, pg 243.

is given by

$$h = 0.022(k/D)Pr^{0.5}Re^{0.8} \qquad \text{(IV-44)}$$

Turbulent flow probably prevails in operations. As a precaution, however, the convective heat transfer coefficient for laminar flow in tubes given by

$$h = 4.364\ k/D \qquad Re < 2300 \qquad \text{(IV-45)}$$

(Kays and Crawford), is included in the computer program as well.

The program initially calculates Re, compares its value to the 2300 limit, and selects the coefficient accordingly. To streamline the Reynolds equation, the mass flowrate through a tube of diameter D,

$$\dot{m} = \rho A_c V = \rho(\pi D^2/4)V \qquad \text{(IV-46)}$$

is used to represent the flow velocity as

$$V = \dot{m}/\rho(\pi D^2/4) \qquad \text{(IV-47)}$$

Substituting this into the Reynolds equation yields

$$Re = 4\dot{m}/(\pi D\mu) \qquad \text{(IV-48)}$$

The program assumes the width of the cooling area as the cooling tube diameter and the value of $\dot{m}$ is prompted on the input menu.

To evaluate Equations IV-44 and 48, the thermal properties of helium at cryogenic temperatures must be evaluated. The normal operating temperature of helium in the chopper apparatus is $15^{\circ}K$.

Keesom[19] gives the thermal conductivity for helium at $20^{\circ}K$ and at $60^{\circ}K$ as

$$k = 2.093 \text{ X } 10^{-4} \text{ watts/cm}^{\circ}\text{K} \tag{IV-49}$$

and

$$k = 4.772 \text{ X } 10^{-4} \text{ watts/cm}^{\circ}\text{K} \tag{IV-50}$$

respectively. Extrapolating these data to $15^{\circ}K$ yields

$$k = 1.76 \times 10^{-4} \text{ watts/cm}^{\circ}\text{K} \tag{IV-51}$$

This extrapolation should be fairly accurate as the conductivity curve from experimental data is nearly linear. Keesom also provides the viscosity of helium at $15^{\circ}K$ as

$$\mu = 28.0 \times 10^{-6} \text{ g/cm sec} \tag{IV-52}$$

Edwards, Denny, and Mills[20] show very little variability in the Prandtl number for helium from 0.72, at $1000^{\circ}K$, to 0.70, at $150^{\circ}K$, to 0.73, at $50^{\circ}K$. Simply assuming the same value at $20^{\circ}K$ is risky. Many fluid properties change significantly between $50^{\circ}K$ and $20^{\circ}K$. Therefore, since the Prandtl number is defined as

$$Pr = c_p \mu / k \tag{IV-53}$$

a calculation is performed to provide an estimated value for $15^{\circ}K$ applications.

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[19] Keesom, W.H., <u>Helium</u>, Elsevier Publishing Co., Amsterdam, 1942, pgs 99-106.

[20] Edwards, D.K., Denny, V.E., and Mills, A.F., <u>Transfer Processes</u>, 2nd Edition, Hemisphere Publishing Corp., 1979, pg. 379.

Keesom gives the values of specific heat and the viscosity at $20.5^{\circ}K$ as

$$c_p = (c_p/c_v)c_v = (1.673)(0.753) = 1.26 \text{ cal/g}^{\circ}\text{K} \quad \text{(IV-54)}$$

$$\mu = 35 \times 10^{-6} \text{ g/cm sec} \quad \text{(IV-55)}$$

and the thermal conductivity at $20.9^{\circ}K$ as

$$k = 51.8 \times 10^{-6} \text{ cal/sec/cm}^{\circ}\text{K} \quad \text{(IV-56)}$$

Combining these values gives the Prandtl number for helium at $20^{\circ}K$ as

$$Pr = c_p\mu/k = 0.85 \quad \text{(IV-57)}$$

This is not a major change from the quoted value at $50^{\circ}K$. It is therefore assumed to be a good estimate for the Prandtl number at $15^{\circ}K$.

Introducing the physical property values into the respective equations; the Reynolds number becomes

$$Re = 4.55\text{x}10^{4}\dot{m}/D \quad \text{(IV-58)}$$

and the convective heat transfer coefficient becomes

$$h = 3.57\text{x}10^{-6}Re^{0.8}/D \quad \text{(IV-59)}$$

for turbulent flow, and

$$h = 7.68\text{x}10^{-4}/D \quad \text{(IV-60)}$$

for laminar flow. For the equations listed above, with $\dot{m}$ in g/sec, and D in cm the value of h is in $\text{watts/cm}^2\text{K}$. These equations are contained in the computer algorithm and used to model the coolant reaction based on the appropriate input variables. Repeating the convective heat transfer coefficient calculation in this section for $20^{o}K$ showed less than a 1% change in the value. The model is, therefore, considered good for all ranges of coolant temperatures in a typical $20^{o}K$ cryogenic chamber.

CHAPTER V

MATRIX SOLUTION TECHNIQUE

The matrix generated by the compilation of the finite-difference equations has a number of unique qualities which drive the selection of the solution technique. These drivers, as well as the solution technique itself, are both detailed within this chapter.

The mathematical representation of the chopper model matrix is simply

$$[B][T] = [C] \tag{V-1}$$

In this equation, [B] is the large n x n matrix of nodal influence values, [T] is the one dimensional matrix of n temperature values, and [C] represents the finite-difference equation constants, also a one dimensional matrix. An example of the matrix is shown schematically in Figure 22. As shown the matrix has a large number of zero elements, but is also quite large. Burden, Faires, and Reynolds[21] suggest utilizing an iterative technique for such a matrix. There are numerous applicable iteration methods, but a close investigation into the matrix geometry and element values drives a very specific choice.

Burden, Faires, and Reynolds also show that if an n x n matrix, [A], has elements where

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[21] Burden, R.L., Faires, J.D., and Reynolds, A.C., Numerical Analysis, 2nd Edition, Prindle, Weber, and Schmidt, Boston, MA, 1981, pgs. 299, 386-387, & 389.

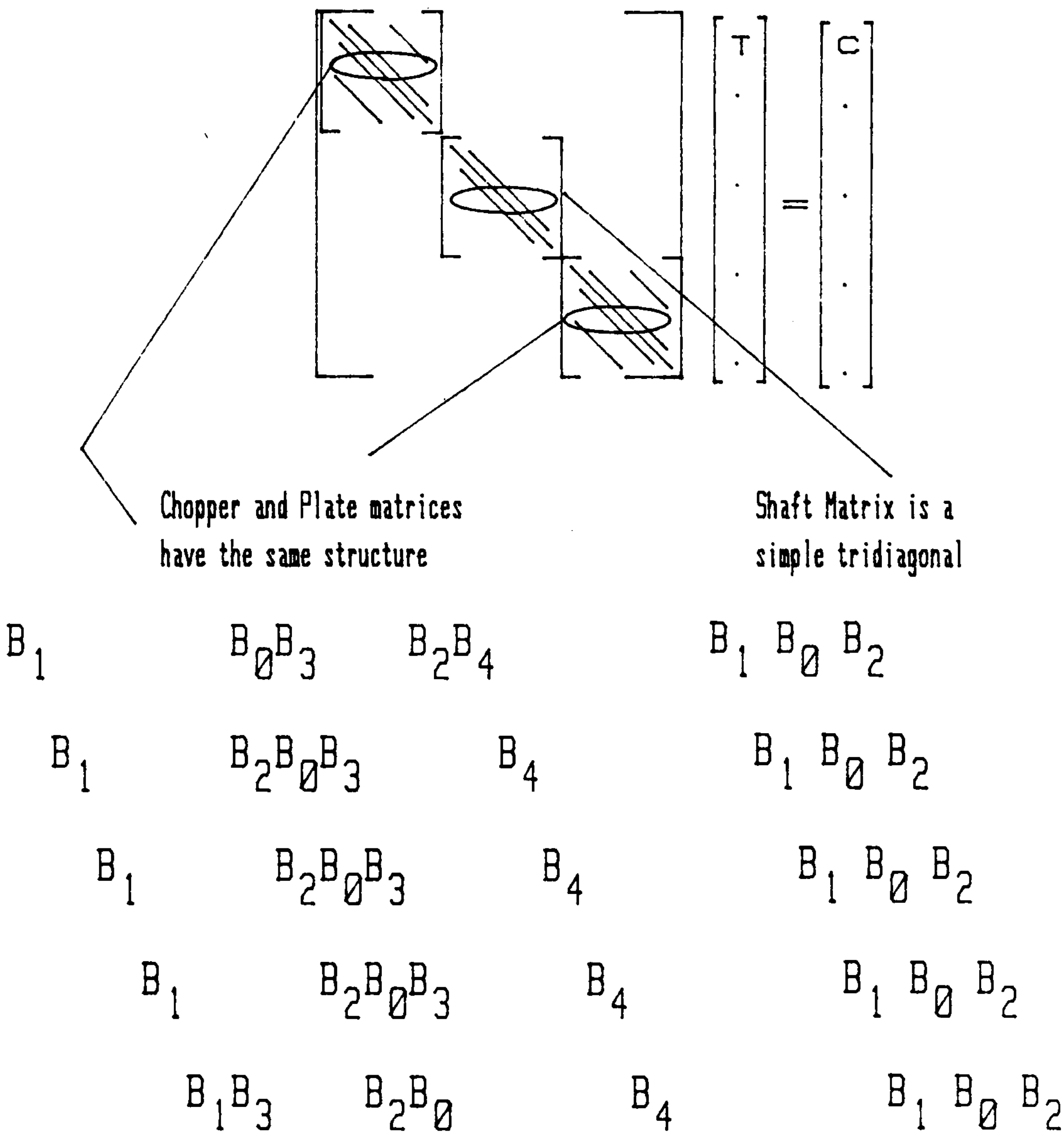

Figure 22. Chopper Model Matrix Representation

$$|a_{ii}| > \sum_{\substack{j=1 \\ j \neq i}}^{n} |a_{ij}| \tag{V-2}$$

then this matrix is classified as "strictly diagonally dominant". The [B] chopper matrix fits this requirement. This is easily recognized since the diagonal elements are the B_0 values outlined in the finite-difference equations of the last section. As previously detailed, the equation for this value with respect to any of the nodes is simply

$$B_0 = \rho c_p \Delta V/\Delta t - \Sigma B_i + (\gamma+\alpha)(T_0^{\,n})^3 \tag{V-3}$$

The values of the B_i elements are always negative, and γ and α are always positive. Therefore, the B_0 values are always positive and greater than the absolute sum of the other row elements.

Utilizing Burden, Faires, and Reynolds once again, a strictly diagonal matrix will converge for any initial guess in either the Jacobi or the Gauss-Seidel iterative methods. In addition, if the non-diagonal elements in the matrix are negative while the diagonal elements are positive, the Gauss-Seidel method will give the faster convergence. Since the chopper matrix fits this description, Gauss-Seidel is used in the computer program.

Gauss-Seidel is a standard routine in numerical analysis and is actually a simple concept. It is based on rearranging the standard finite-difference equations to set $T_0^{\,n+1}$ as a function of the other elements. An initial temperature profile is set, and each of the $T_0^{\,n+1}$ values are calculated. Some of the factors in the equations are the unknown temperatures of the surrounding nodes. These values are represented by their value in the initial profile, or if, already calculated, the new value. With each calculation the new temperature value is compared to the initial. If the greatest temperature difference is less than a predefined tolerance value, then the new temperatures are assumed an accurate profile. If this does not occur, the initial profile is replaced by the new values and the technique is repeated. As already discussed, the chopper matrix will converge using this technique; therefore, the tolerance limit will be met eventually.

The description written above, again referenced from Burden, Faires, and Reynolds, is represented in equation form as

$$T_i^{n+1} = [-\sum_{j=1}^{i-1}(b_{ij}T_j^{n+1}) - \sum_{j=i+1}^{n}(b_{ij}TO_j^{n+1}) + C_i] \, / \, b_{ii} \qquad \text{(V-4)}$$

$$\text{if } \|[T]-[TO]\| < TOL \text{ then OUTPUT } (T_1, \ldots, T_n)$$

where TO is the value from the previous calculation loop, and the symbol, $\|[T]-[TO]\|$, represents the greatest elemental difference.

The completion of the iteration technique generates the temperature profile solution for each time increment in the transient model. This can easily require a substantial number of calculations to perform the modeling if the iteration does not quickly converge. Unfortunately, this represents the main limitation of the technique. Although considered the best approach for the application, the Gauss-Seidel iteration method could require extensive computer time for a complete model run.

CHAPTER VI

PROGRAM OPTIONS

The program used to investigate the thermal loading on the chopper apparatus is entitled EJTL. This title has no significant meaning; it is simply a title. While the input prompts are somewhat crude, the Fortran program contains numerous options to allow a variety of chopper configurations and operating conditions to be investigated. This chapter reviews the otions in EJTL and also provides a simple flowchart of the program.

The flowchart is shown in Figure 23. It is simply a general flow of program logic. The program list is provided in Appendix E, and sample run profiles are found in Appendix F. The remainder of this chapter references these sample run profiles and describes the options available in the program menu.

The menu first prompts for the output file name. This can be up to twelve characters long. The program asks at various points in the run if the user wishes to place specified data into this storage file.

Initializing the chopper system configuration is next on the menu. The term configuration refers to whether the bearings are mounted on the plate, further down the shaft, or both. If a shaft mount configuration is chosen, the user can eliminate the plate in the model if desired. This allows significantly faster program execution and is a good system representation if the front plate is properly cooled. This section also allows a material selection for each of the three main chopper

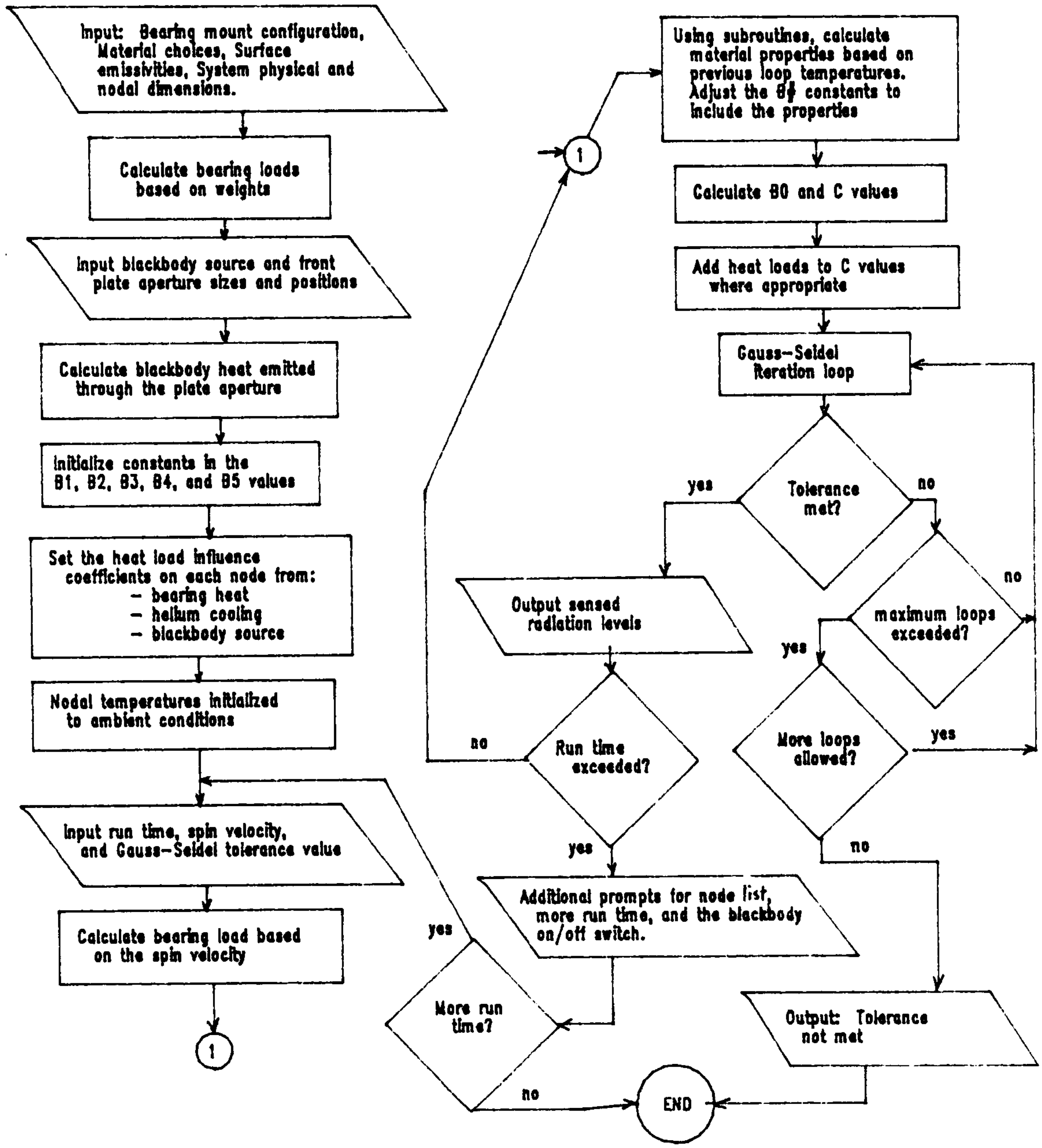

Figure 23. EJTL General Program Flowchart

subsections. Aluminum, copper, and stainless steel are material choices for either the disk, the shaft, or the front plate. The surface emissivities are requested next with a table of suggested values. The remaining material properties required in the analysis for the cryogenic range are built into the computer algorithm and are automatically calculated. If desired, additional materials can be added to the program by expanding the material subroutine. The default material for the bearings is stainless steel. This also can be varied by expanding a subroutine. Note, however, the program does not investigate bearing failure. Another bearing material may appear thermally beneficial, but not withstand the operating stress.

The next several items on the menu are system dimensions. Nearly complete freedom in establishing system dimensions is allowed. All physical dimensions are requested for input, and many of the grid networks sizes for different sections. One restriction is that the chopper fins must be of equivalent size with equal spacing. The program, however, automatically adjusts the physical and circumferential nodal inputs to force equivalent element dimensions. The program notifies the user if his inputs are altered and allows them to be reset if desired.

Included throughout the physical and network dimension menus are the various descriptors of the three thermal loads. The bearings are identified in the shaft section, the helium tube in the plate section, and the blackbody source at the conclusion of the initial menu. Both the helium cooling model and the blackbody source model request position, temperature, and dimension. The bearing input menu also calls for position and size, but include two special descriptors: contact resistances and support structure temperature. A table of optional contact resistances are included in the menu item for the interface between the disk and the shaft and between the bearing and the mounts.[22] Selecting certain combinations of these values determines various bearing operating profiles. As an example, a high value of resistance on the outer race of the bearing will simulate an insulated mounting with the majority of the heat transferring to the shaft. As mentioned earlier, the support structure temperature at the outer race can be set as perfectly cooled (ie $T=20^{o}K$) or at the same temperature as the shaft node. Setting the shaft node condition yields a bearing heat distributed according to contact resistances and bearing dimensions only. The outer race cooling model is effectively "turned off".

As discussed, EJTL has a large number of setup options. This, however, can become tedious for repeated program runs. If a specific design is under investigation, the author suggests hard coding the inputs and re-compiling the program. During this step, the input prompts should be commented, not erased. This allows the original prompt capabilities to be reinstated at anytime.

Once the chopper design is entered into the program there are still some very useful options available. The run time, disk spin speed, and data output -- content and location -- are all options. After the run is completed, a full listing of the network temperatures can be

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[22] Rohsenow, W.M., Hartnett, J.P., Handbook of Heat Transfer, McGraw-Hill Book Co., 1973, pgs 3-14 - 3-16.

placed in the storage file. Also, additional run time can be input, as well as changes in the spin speed, calculation time increment, or the Gauss-Seidel tolerance value. A negative value for the spin speed will turn off the bearing heat. The blackbody source effect can also be removed by yet another program run time prompt. The combination of all options allows modeling of a chopper through the thermal load cycle and cool down periods. They also allow each heat source to be turned on or off and thus their individual impacts studied.

In summary, EJTL is a flexible chopper design tool. The limitations of the program concerning run time requirements are discussed in the next chapter.

CHAPTER VII

INVESTIGATIONS AND RESULTS

This chapter presents the results of numerous program runs of EJTL. They consist of two categories: verification and investigation. The verification runs were all short and very specific to identify program operations. The investigation runs generally modeled thirty minutes of chopper operation under a $300^{\circ}K$ blackbody source. These runs provide examples to compare against typical operations to verify the bearing heat model. A limited parametric study of the significance of the chopper materials is included as well.

Many of the verification runs, and all of the investigation runs, were configured dimensionally from a sample design. The dimensions of the design are listed in the example run profiles in Appendix F. The design is basically a sixteen centimeter chopper disk mounted two centimeters from the blackbody source and one centimeter from the front plate. The connecting shaft to the drive motor is five centimeters long. The system material is aluminum, and the chopper rotates twenty revolutions every second. Again, the full design details are referenced in Appendix F.

Program Verification

Numerous runs were performed during the program development to verify capabilities. This consisted of exercising all of the menu options and checking results against hand calculations. In areas where hand calculations were not feasible, extreme conditions were modeled to verify the code. An example of this is the setting of a high source temperature and zero plate cooling to check the shadow effect calculations on the front plate.

One significant point was brought forth during the verification exercise. The impact on the bearing heat due to shaft thermal expansion is minimal until a shaft temperature of $50^{\circ}K$ is reached. Remember, bearing heat is directly proportional to the load on the bearing. This load consists of the system weight and thermal expansion forces. For a typical chopper design with bearings at $50^{\circ}K$, the load on the bearings was increased only 3% due to thermal expansion. At $100^{\circ}K$, thermal expansion accounts for over 50% of the load on the bearings. This high value is unlikely to occur in actual operations, however.

Program efficiency was also checked during these runs. Using the sample design dimensions, and a network of 60 nodes on the chopper disk, 15 nodes on the shaft, and 72 nodes on the front plate, reasonable accuracy was obtained with a time increment and Gauss-Seidel tolerance of 1.0 second and $1x10^{-5}K$ respectively. This conclusion is based on a number of comparisons with more and less dense grid networks, and higher and lower time increments and tolerance values. The values calculated with this grid for Aluminum should be computationally accurate within 10%. An investigation of a stainless steel system revealed that a 30% denser grid network is required to achieve the same accuracy as the aluminum system studies. For all of these configurations, the optimum time increment and Gauss-Seidel tolerance remained at 1 second and $1x10^{-5}K$. The variance of the accuracy in the stainless steel investigation shows that the run profile should be re-checked for any new design exercise. This "re-checking" should consist of comparing various grid structures, time increments, and tolerance values to ensure a proper system model and complete matrix solutions are obtained.

On a VAX system, the ratio of CPU time to modeled time for the network used on the aluminum configuration is 2:1. With a $300^{\circ}K$ blackbody source heat and only shaft mounted bearings, the helium cooling maintained the entire front plate at ambient conditions. A front plate removal option was exercised and the ratio of CPU to modeled time reduced to 1:2.

Investigation

Ten program runs were carried out to investigate performance of the model and to provide some initial design information. All but one run investigate 30 minutes of chopper operations under a $300^{\circ}K$ blackbody heat source. Eight of these nine runs were "shaft mount" configured. This means they did not have a support bearing mounted to the front plate. The other run in this group was "combination mounted" with one support bearing on the plate and another further down the shaft. The tenth run, also a "combination mount" configuration, looks at the effects of a $2500^{\circ}K$ source. Because of the increased network density required and the greater heat loads for this case, only five minutes of operation were modeled.

Under the $300^{\circ}K$ source, the thermal loading of the chopper system was clearly dominated by the bearing heat and helium cooling. The blackbody source emitted only 9.0×10^{-4} watts while the average heat from two bearings was 1.8×10^{-2} watts. The convective coefficient for the helium cooling was 0.058 watts/cm^{2}K, and the cooling tube contact area was 119 cm^2. This provided the front plate with 6.9 watts/$^\circ$K of cooling. As a result, the front plate effectively maintained chamber conditions at the plate throughout the 300°K runs. The eight "shaft mount" runs performed in the investigation utilized this conclusion and replaced the plate network in the model with a constant chamber condition.

The 2500°K blackbody heat source was modeled to further check the capabilities of the helium cooling. The blackbody generated 4.3 watts of energy and was clearly the dominant source of heat in the system. The run revealed at five minutes that a 17°K coolant could maintain the region around the tube at 21°K. The front plate cooling also handled the direct "unshadowed" radiation from the source, but the plate bearing heated the interior of the plate. The plate bearing was heated by the chopper disk and shaft to a temperature of 67°K. This, in turn, set the plate temperatures around the bearing to 45°K. Overall, however, the helium coolant seemed adequate in cooling the plate even for this extreme case.

The remaining runs performed in this investigation consist of varying contact resistances and boundary temperatures at the bearings and recording the resultant chopper blade and bearing temperatures over the run period. Remember Chapter IV described the bearing model , and Chapter VI described the use of the contact resistances and boundary temperature selections. Test engineers who utilize chopper systems give widely varying opinions on the "typical" thermal responses of chopper systems. Some feel they have no thermal problems with the chopper system, others mention a general figure of two hours of operation before reaching a critical $35^{\circ}K$ on the chopper blade. Plotting this $35^{\circ}K$ rise linearly gives an anticipated blade temperature of $23.75^{\circ}K$ at thirty minutes. The actual growth should be more exponential and therefore somewhat higher than this value.

Figures 24 and 25 show the results from the first set of program runs. Plot 1 is from a model where the frictional bearing heat is distributed evenly through the inner and outer bearing races with no contact resistances. A blade temperature of $26^{\circ}K$ was reached at the thirty minute mark, and the curve continues to rise at this point. Comparing the blade temperature profile in Figure 24 to the bearing profile in Figure 25 shows that the temperatures at these points in the system are very close to each other due to the high conductivity of the aluminum. Plot 2 was generated by effectively "insulating" the back side of the bearings with a contact resistance of 10^6 $(\text{watts/cm}^2\text{K})^{-1}$. This worst case condition gave a blade temperature of $31^{\circ}K$ at 30 minutes. Again the high conductivity effect is presented. The same blade temperature profile was approximately obtained when realistic contact resistances were applied to both sides of the bearing. Plot 3 is from a model with both contact resistances at 100 $(\text{watts/cm}^2\text{K})^{-1}$, while Plot 4 is from one with 1000 $(\text{watts/cm}^2\text{K})^{-1}$. The bearing temperatures greatly varied but the blade temperatures remained close to those of the insulated condition in plot 2.

The second set of plots in Figures 26 and 27 show the effects of cooling the backside of the bearings. Plot 1 is the same plot as Plot 1 in Figures 24 and 25. This is shown for comparative purposes. Plot 2

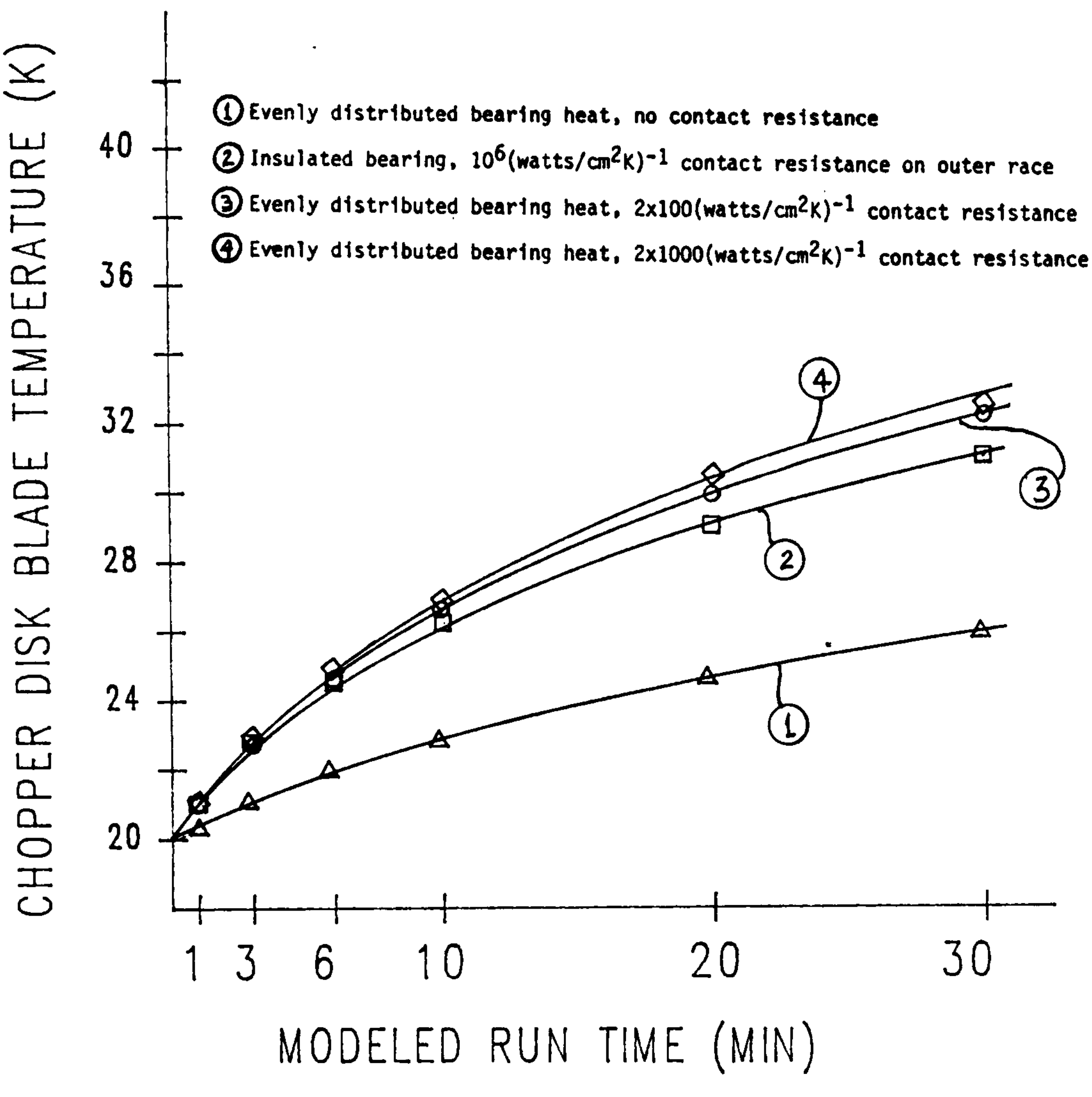

Figure 24. Chopper Blade Temperatures
with Distributed Bearing Heat

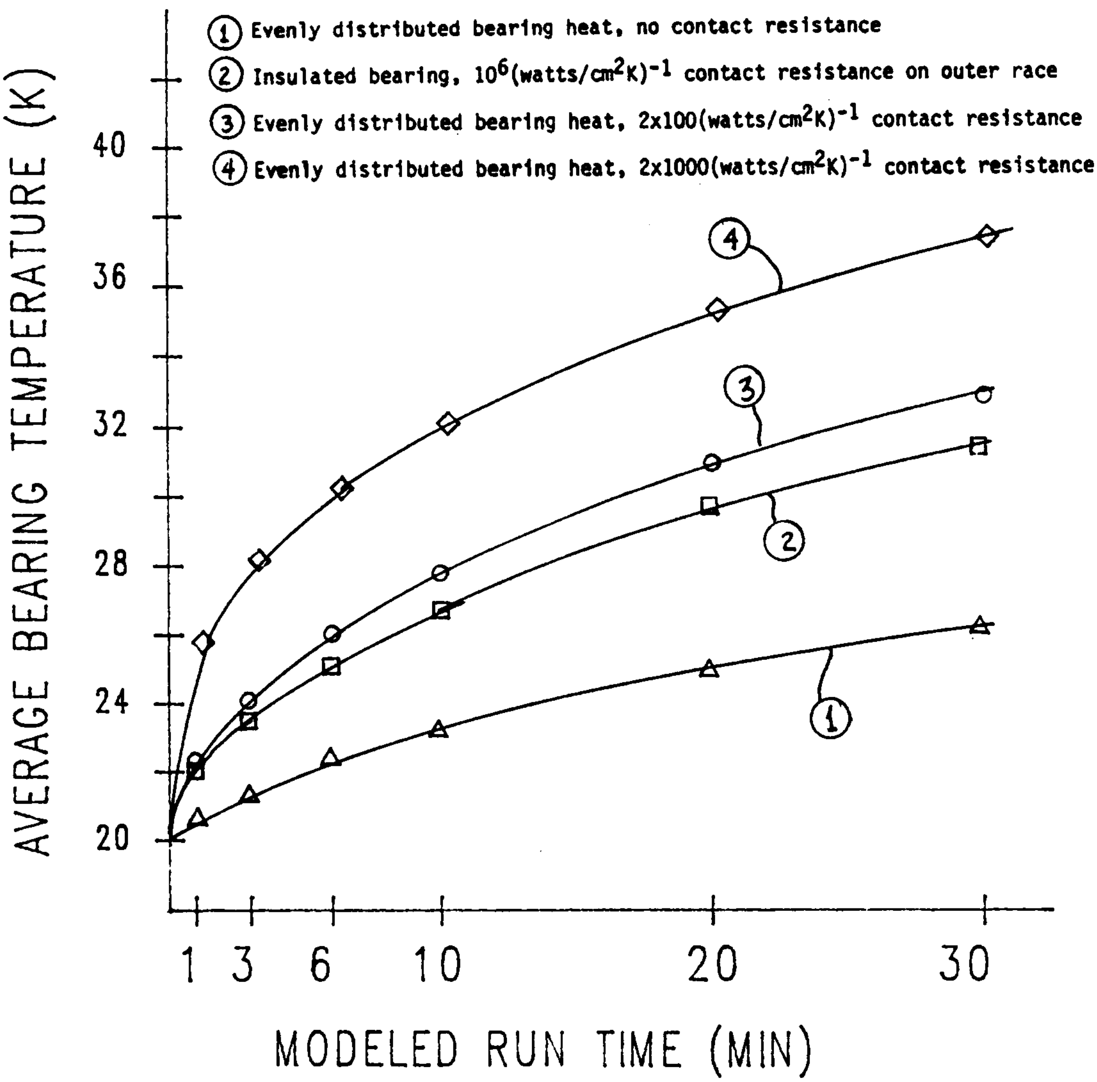

Figure 25. Bearing Temperatures with
Distributed Bearing Heat

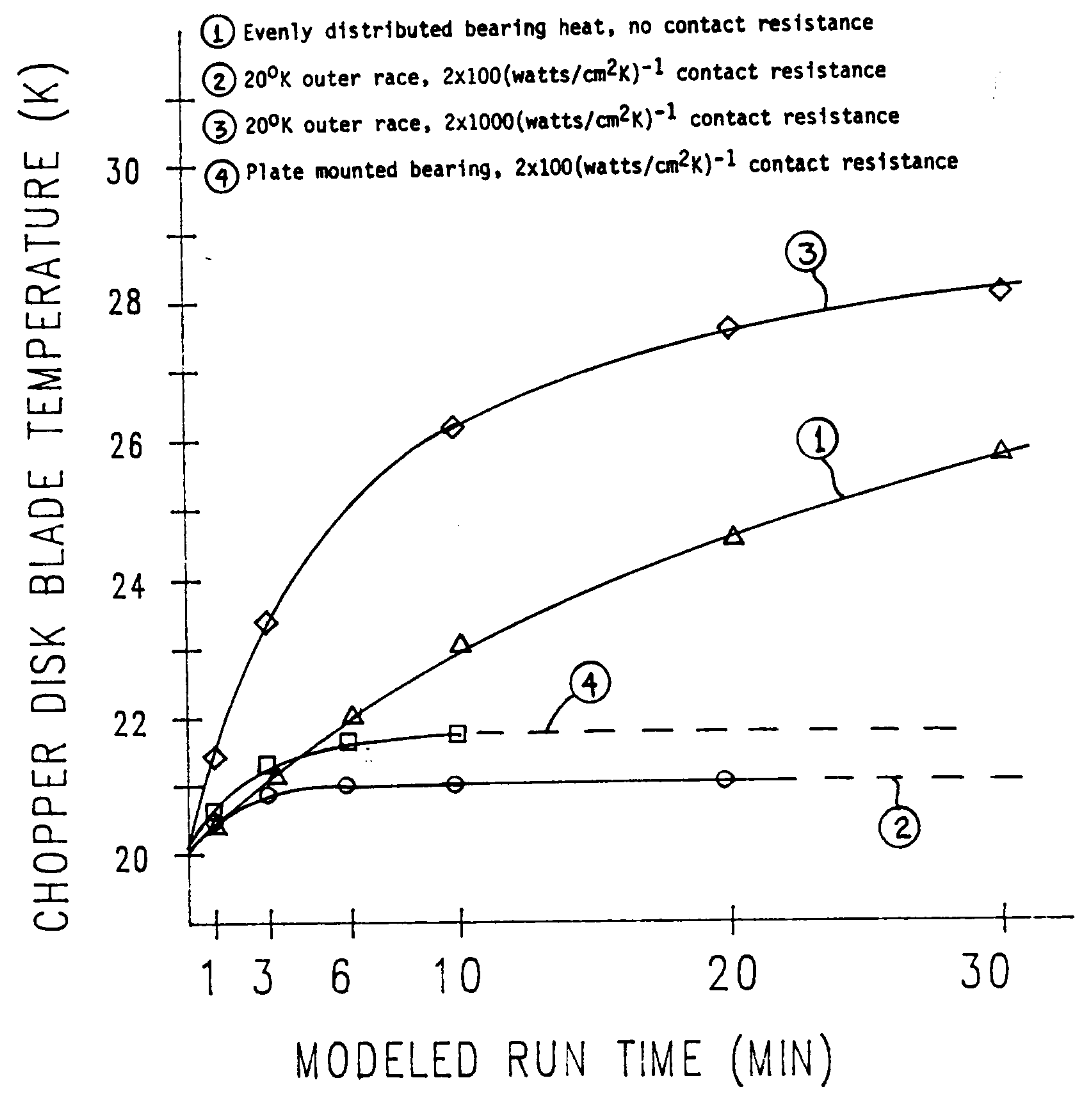

Figure 26. Chopper Blade Temperatures
with Cooled Bearings

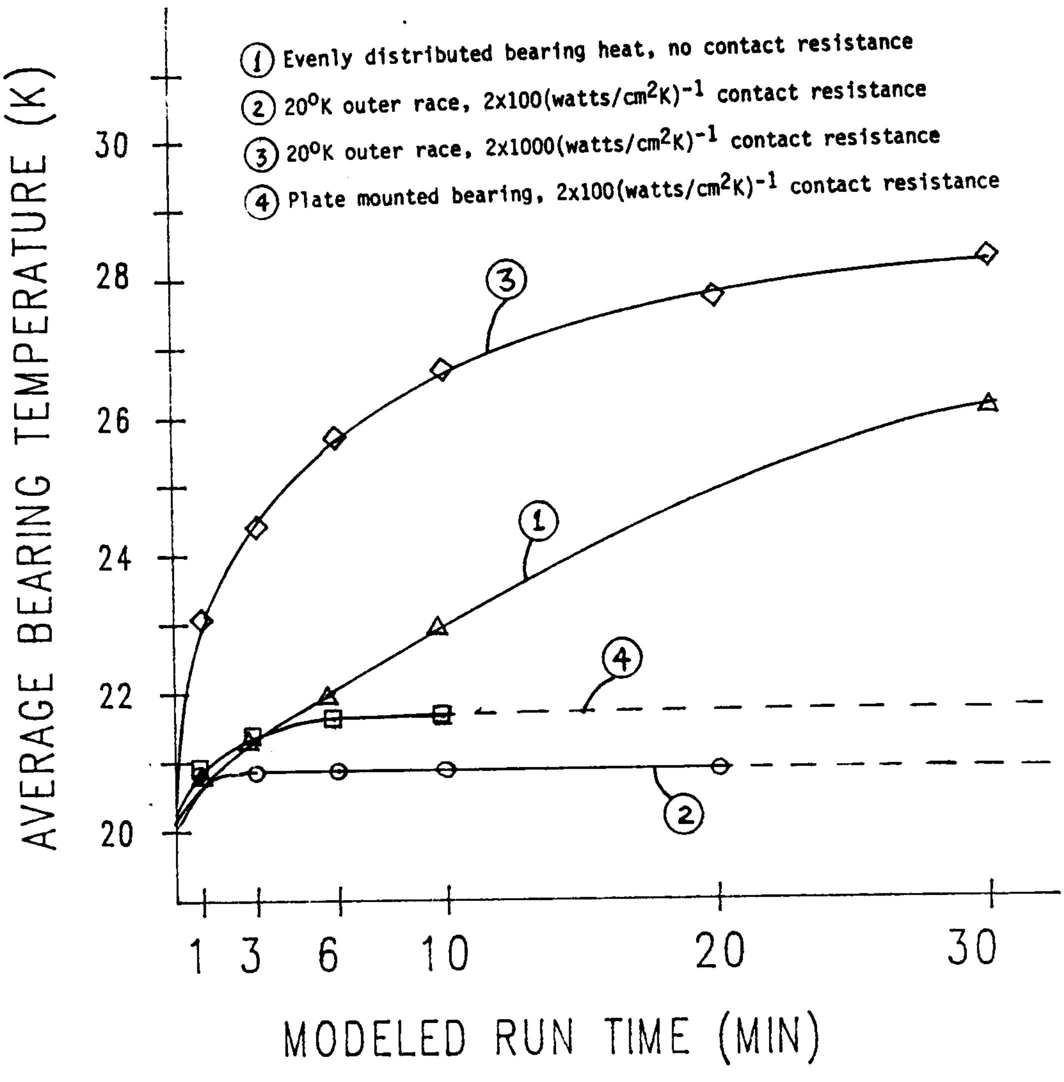

Figure 27. Cooled Bearing Temperatures

shows the result of maintaining ambient conditions and a contact resistance of 100 $(\text{watts/cm}^2\text{K})^{-1}$ at the back of the bearings. Steady state conditions at 21°K are quickly met. The run detailed in Plot 3 raises the contact resistance to 1000 $(\text{watts/cm}^2\text{K})^{-1}$. While the blade heats to 28°K, the slope of the curve is approaching steady state. To check the validity of ambient conditions modeled on the outside of the bearing, a run was performed with a front plate bearing mount. In this configuration the temperatures around the bearing are calculated as part of the network rather than arbitrarily chosen. The temperature of the helium coolant was conservatively set at 20°K and both the plate and the other support bearing were set with 100 $(\text{watts/cm}^2\text{K})^{-1}$ resistances on both sides of the bearings. Steady state conditions at 21.5°K were reached quickly.

All of these investigative runs support the validity of the bearing heat model. The blade temperatures are all within the range reported by test engineers. Since the bearing frictional heat is the main driver of the blade temperature, the bearing model appears to give a proper order of magnitude for the thermal load. A bearing test could be used to "calibrate" the actual contact resistance and coefficient of friction values for the model. This would enhance the accuracy for design applications.

The next set of plots summarizes parametric runs of the program to show some trends which are useful guidelines for designing choppers. Initial short runs of copper and stainless steel systems revealed a tripling of bearing heats over aluminum systems due to the increased weight of the shaft and disk. Copper has a very high conductivity at the cryogenic temperatures and quickly transferred this increased heat to the chopper disk. Remember, aluminum also conducts the bearing heat readily to the blade of the chopper. Stainless steel, on the other hand, has a lower conductivity than aluminum, and the runs with stainless steel showed promise in maintaining system temperature gradients.

Plot 1 (Figures 28 and 29) is a plot of results from the modeling of an aluminum system with 100 $(\text{watts}/\text{cm}^2\text{K})^{-1}$ resistances at both sides of the bearings. Plot 2 shows results of the identical run with stainless steel. The average bearing heat of 0.028 watts (compared to 0.009 watts for the aluminum system) very quickly raises the bearing temperature considerably. The lower thermal conductivity in the system, however, allows the blade temperature to be lower by over 3°K at the thirty minute mark. The stainless steel system appears better, but the high bearing heat might cause increased wear and friction since thermal expansion starts to be significant at 50°K. Plot 3 shows the compromise solution. An aluminum disk mounted to a stainless steel shaft generates only a 1½% increase in heat over an all aluminum design, and the shaft's conductive properties allow a 4.2°K lower blade temperature at the end of the run. Also, while the initial reaction is increased bearing temperatures, the bearings appear to reach steady state temperatures more quickly and by thirty minutes are actually cooler than in the all aluminum chopper.

This example parametric study shows that even if the exact levels of bearing heat are not precisely known, the model can provide insight which supports design decisions. EJTL is therefore believed to be a

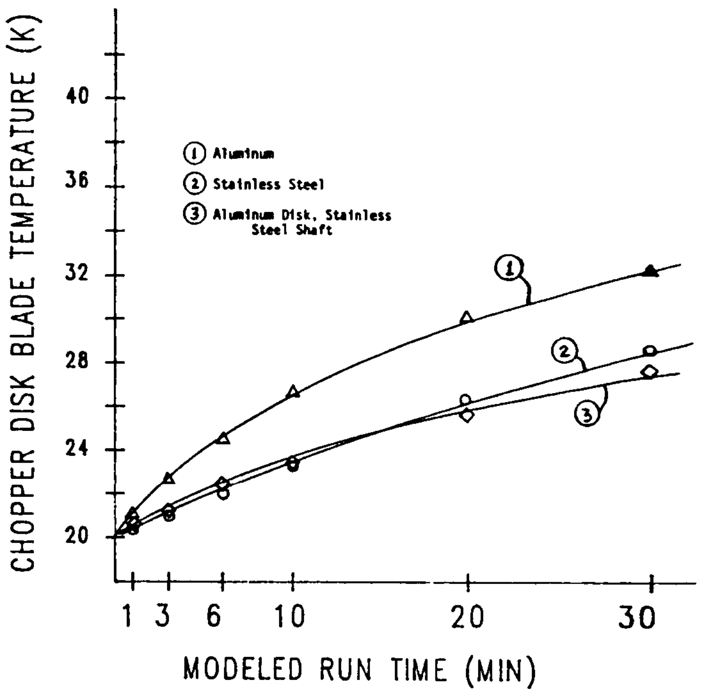

Figure 28. Chopper Blade Temperatures in Aluminum and Stainless Steel Designs

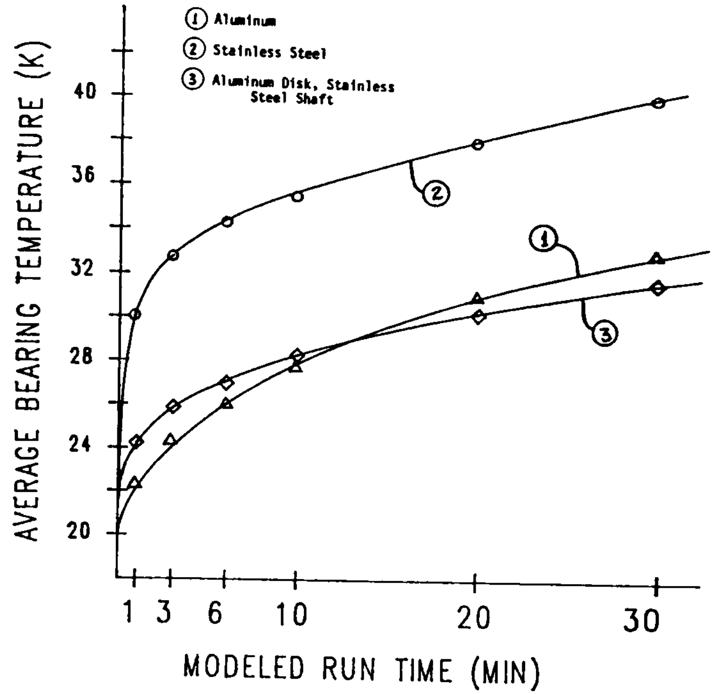

Figure 29. Bearing Temperatures in Aluminum and Stainless Steel Designs

useful tool for investigating the transient thermal response of a chopper system. Including experimental bearing data will increase its accuracy, but in its present form EJTL is a good tool for comparative design studies.

CHAPTER VIII

CONCLUSIONS

This document represents the successful completion of the main goal of the study. A tool is provided which can help optimize chopper system designs.

A meaningful model of the transient response of an infrared chopper in a $20^{o}K$ cryogenic environment has been developed. The system components are established with finite-element networks, and the main thermal loads on the system are applied at the appropriate locations. These thermal loads, the blackbody radiation, the bearing frictional heat, and the convective helium cooling on the front plate, are all fundamentally studied and established in equation form for the model. The insignificance of shaft thermal expansion up to $50^{o}K$ was realized during this development.

A computer algorithm of this model has been programmed and its operation verified. The program has many options which are menu driven making it easy to use and a viable design tool. The physical and nodal dimensions of the chopper system and the critical attributes of the thermal loads are all readily adjusted through this menu.

Preliminary runs of the program have been carried out which provide physically realistic results based on verbal descriptions of operations in cryogenic chambers. These runs revealed that the major source of heating in chopper systems is the friction at the bearings. Further verification and fine tuning of the model is possible when better experimental data on bearings is available.

A preliminary parametric study revealed that an aluminum disk mounted to a stainless steel shaft reduces the heat transferred to the chopper blade compared to a design entirely composed of either material. This study clearly demonstrates that the appropriate selections of materials for different chopper components can reduce thermal heating and hence extend run time of a cryogenic chamber test.

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APPENDICES

APPENDIX A

NODAL FINITE-DIFFERENCE EQUATIONS

FOR THE CHOPPER DISK

A1. Chopper Interior Node

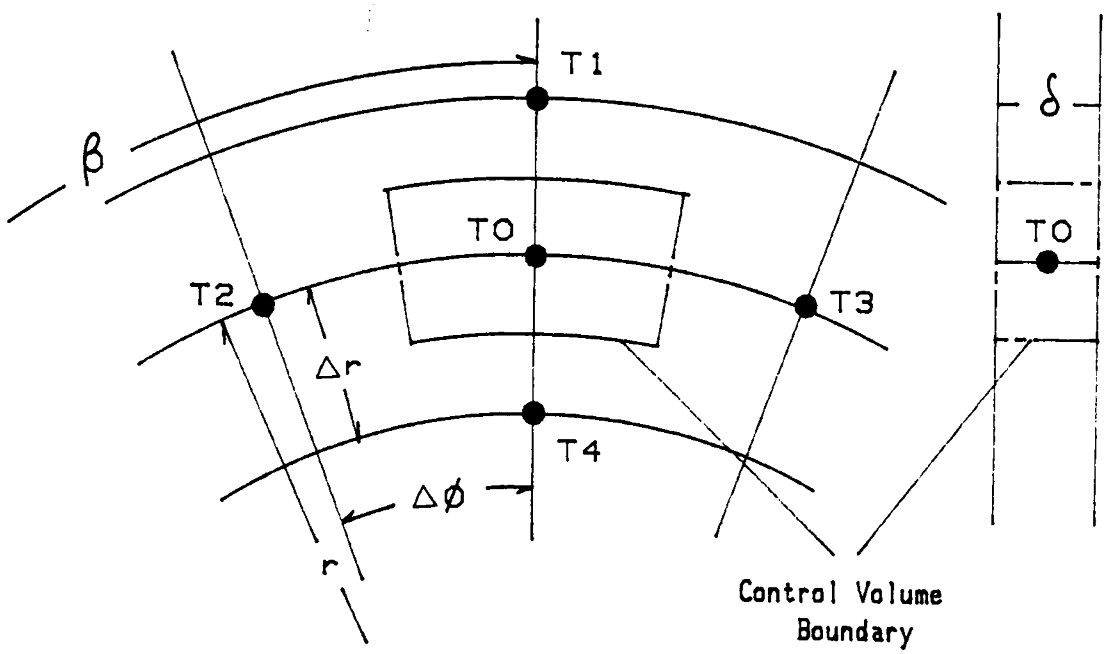

Figure A1. Chopper Interior Node

$$B_0(T_0)^{n+1} + B_1(T_1)^{n+1} + B_2(T_2)^{n+1} + B_3(T_3)^{n+1} + B_4(T_4)^{n+1} = C$$

$$B_0 = [\delta\rho c_p/\Delta t]\Delta A - B_1 - B_2 - B_3 - B_4 + (\gamma+\alpha)(T_0{}^n)^3$$

$$\Delta A = r(\Delta\phi)\Delta r \qquad \gamma = \epsilon_{bf}\sigma\Delta A \qquad \alpha = \epsilon_{ff}\sigma\Delta A$$

$$B_1 = -\tfrac{1}{2}k\delta[(r+\tfrac{1}{2}\Delta r)\Delta\phi/\Delta r] \qquad B_2 = -\tfrac{1}{2}k\delta[\Delta r/(r\Delta\phi)]$$

$$B_3 = -\tfrac{1}{2}k\delta[\Delta r/(r\Delta\phi)] \qquad B_4 = -\tfrac{1}{2}k\delta[(r-\tfrac{1}{2}\Delta r)\Delta\phi/\Delta r]$$

$$C = \{[\delta\rho c_p/\Delta t]\Delta A + B_1 + B_2 + B_3 + B_4\}(T_0)^n - B_1(T_1)^n - B_2(T_2)^n$$
$$- B_3(T_3)^n - B_4(T_4)^n + \gamma(T_\infty)^4 + \alpha(T_p)^4 + \epsilon_{bf}\sigma A_{bb}F_{bb\to 0}(T_{bb})^4$$

$$F_{bb\to 0} = [(z_b)^2/(\pi R^4)]\Delta A$$

$$R^4 = \{[r(\sin\beta)]^2+[y_b-r(\cos\beta)]^2+(z_b)^2\}^2$$

A2. Chopper Outer Boundary Node

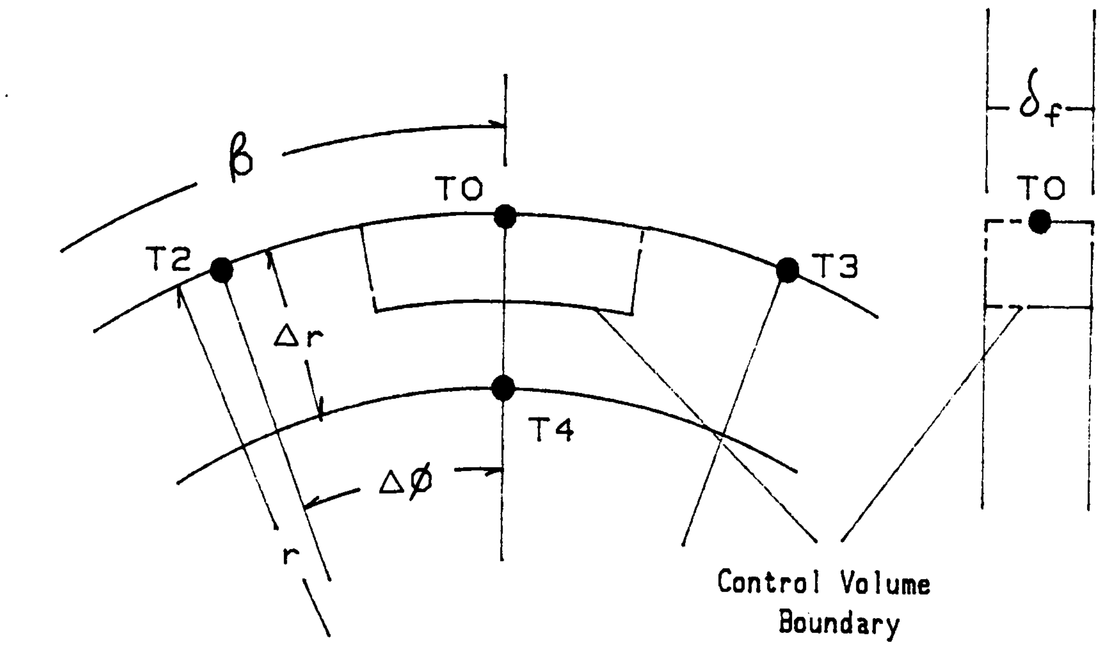

Figure A2. Chopper Outer Boundary Node

$$B_0(T_0)^{n+1} + B_2(T_2)^{n+1} + B_3(T_3)^{n+1} + B_4(T_4)^{n+1} = C$$

$$B_0 = [\delta_f \rho c_p/\Delta t]\Delta A - B_2 - B_3 - B_4 + (\gamma+\alpha)(T_0^{\,n})^3$$

$$\Delta A = (r-\tfrac{1}{4}\Delta r)\Delta\phi(\tfrac{1}{2}\Delta r) \qquad \gamma = \epsilon_{bf}\sigma\Delta A + \epsilon_{ce}\sigma[\delta_f(r\Delta\phi)]$$

$$B_2 = -\tfrac{1}{4}k\delta_f[\Delta r/(r\Delta\phi)] \qquad \alpha = \epsilon_{ff}\sigma\Delta A$$

$$B_4 = -\tfrac{1}{2}k\delta_f[(r-\tfrac{1}{2}\Delta r)\Delta\phi/\Delta r] \qquad B_3 = -\tfrac{1}{4}k\delta_f[\Delta r/(r\Delta\phi)]$$

$$C = \{[\delta_f \rho c_p/\Delta t]\Delta A + B_2 + B_3 + B_4\}(T_0)^n - B_2(T_2)^n - B_3(T_3)^n$$
$$- B_4(T_4)^n + \gamma(T_\infty)^4 + \alpha(T_p)^4 + \epsilon_{bf}\sigma A_{bb}F_{bb\to 0}(T_{bb})^4$$

$$F_{bb\to 0} = [(z_b)^2/(\pi R^4)]\Delta A$$

$$R^4 = \{[r(\sin\beta)]^2 + [y_b - r(\cos\beta)]^2 + (z_b)^2\}^2$$

A3. Chopper Left Edge Node

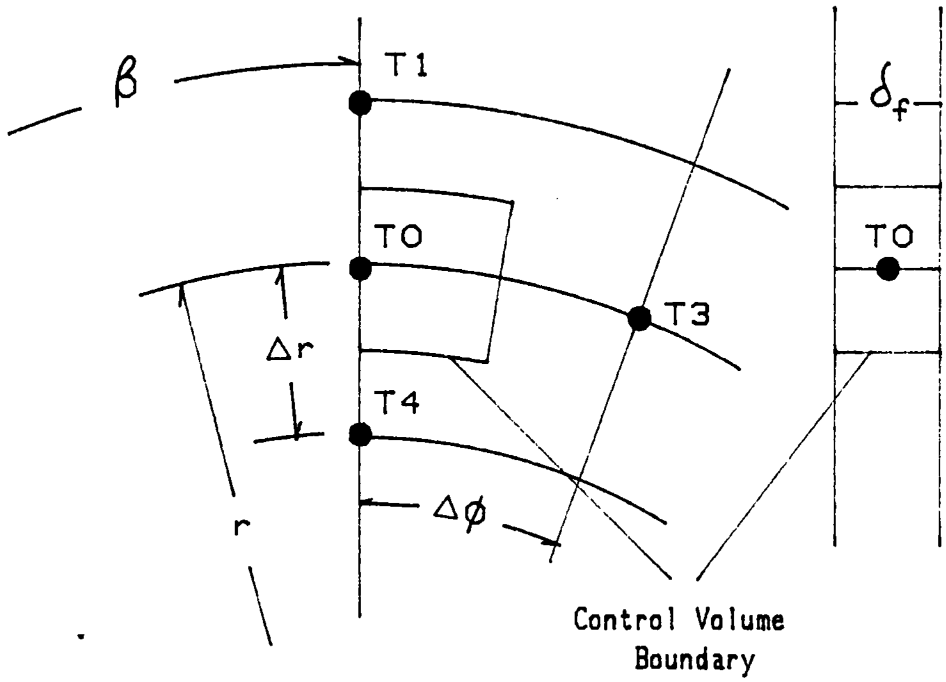

Figure A3. Chopper Left Edge Node

$$B_0(T_0)^{n+1} + B_1(T_1)^{n+1} + B_3(T_3)^{n+1} + B_4(T_4)^{n+1} = C$$

$$B_0 = [\delta_f \rho c_p/\Delta t]\Delta A - B_1 - B_3 - B_4 + (\gamma+\alpha)(T_0{}^n)^3$$

$$\Delta A = \tfrac{1}{2}r(\Delta\phi)\Delta r \qquad \gamma = \epsilon_{bf}\sigma\Delta A + \epsilon_{ce}\sigma\delta_f(\Delta r)$$

$$B_1 = -\tfrac{1}{4}k\delta_f[(r+\tfrac{1}{2}\Delta r)\Delta\phi/\Delta r] \qquad \alpha = \epsilon_{ff}\sigma\Delta A$$

$$B_4 = -\tfrac{1}{4}k\delta_f[(r-\tfrac{1}{2}\Delta r)\Delta\phi/\Delta r] \qquad B_3 = -\tfrac{1}{2}k\delta_f[\Delta r/(r\Delta\phi)]$$

$$C = \{[\delta_f \rho c_p/\Delta t]\Delta A + B_1 + B_3 + B_4\}(T_0)^n - B_1(T_1)^n - B_3(T_3)^n$$
$$- B_4(T_4)^n + \gamma(T_\infty)^4 + \alpha(T_p)^4 + \epsilon_{bf}\sigma A_{bb}F_{bb\to 0}(T_{bb})^4$$

$$F_{bb\to 0} = [(z_b)^2/(\pi R^4)]\Delta A$$

$$R^4 = \{[r(\sin\beta)]^2 + [y_b - r(\cos\beta)]^2 + (z_b)^2\}^2$$

A4. Chopper Right Edge Node

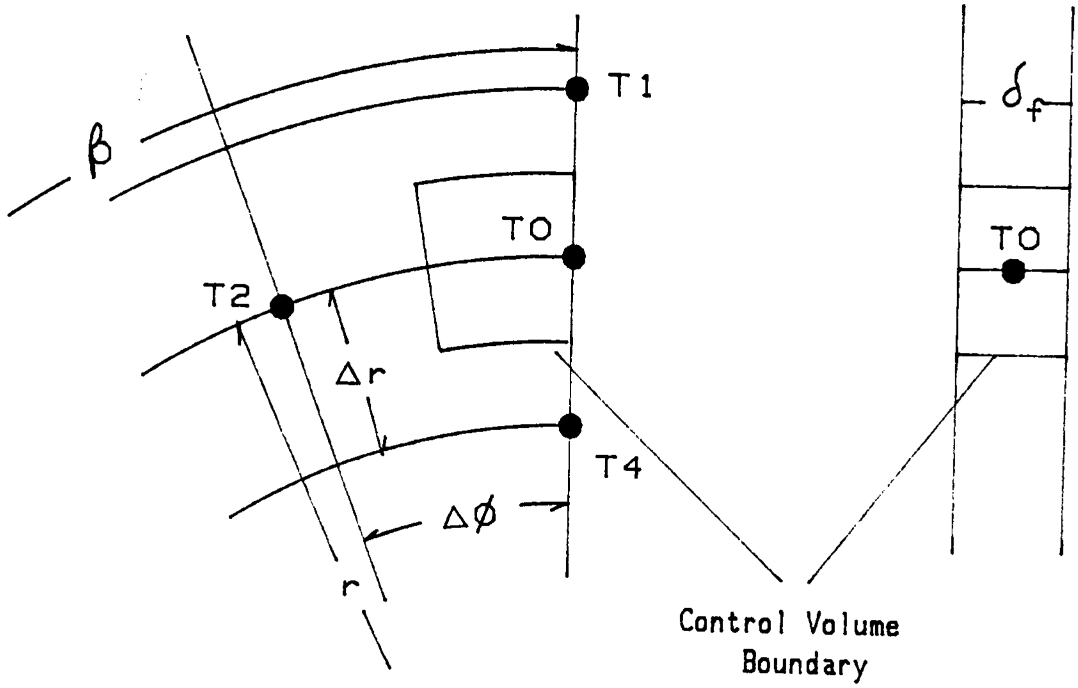

Figure A4. Chopper Right Edge Node

$$B_0(T_0)^{n+1} + B_1(T_1)^{n+1} + B_2(T_2)^{n+1} + B_4(T_4)^{n+1} = C$$

$$B_0 = [\delta_f \rho c_p/\Delta t]\Delta A - B_1 - B_2 - B_4 + (\gamma+\alpha)(T_0{}^n)^3$$

$$\Delta A = \tfrac{1}{2} r(\Delta\phi)\Delta r \qquad \gamma = \epsilon_{bf}\sigma\Delta A + \epsilon_{ce}\sigma\delta_f(\Delta r)$$

$$B_1 = -\tfrac{1}{4}k\delta_f[(r+\tfrac{1}{2}\Delta r)\Delta\phi/\Delta r] \qquad \alpha = \epsilon_{ff}\sigma\Delta A$$

$$B_4 = -\tfrac{1}{4}k\delta_f[(r-\tfrac{1}{2}\Delta r)\Delta\phi/\Delta r] \qquad B_2 = -\tfrac{1}{2}k\delta_f[\Delta r/(r\Delta\phi)]$$

$$C = \{[\delta_f\rho c_p/\Delta t]\Delta A + B_1 + B_2 + B_4\}(T_0)^n - B_1(T_1)^n - B_2(T_2)^n - B_4(T_4)^n + \gamma(T_\infty)^4 + \alpha(T_p)^4 + \epsilon_{bf}\sigma A_{bb}F_{bb\to 0}(T_{bb})^4$$

$$F_{bb\to 0} = [(z_b)^2/(\pi R^4)]\Delta A$$

$$R^4 = \{[r(\sin\beta)]^2 + [y_b - r(\cos\beta)]^2 + (z_b)^2\}^2$$

A5. Chopper Upper Left Corner Node

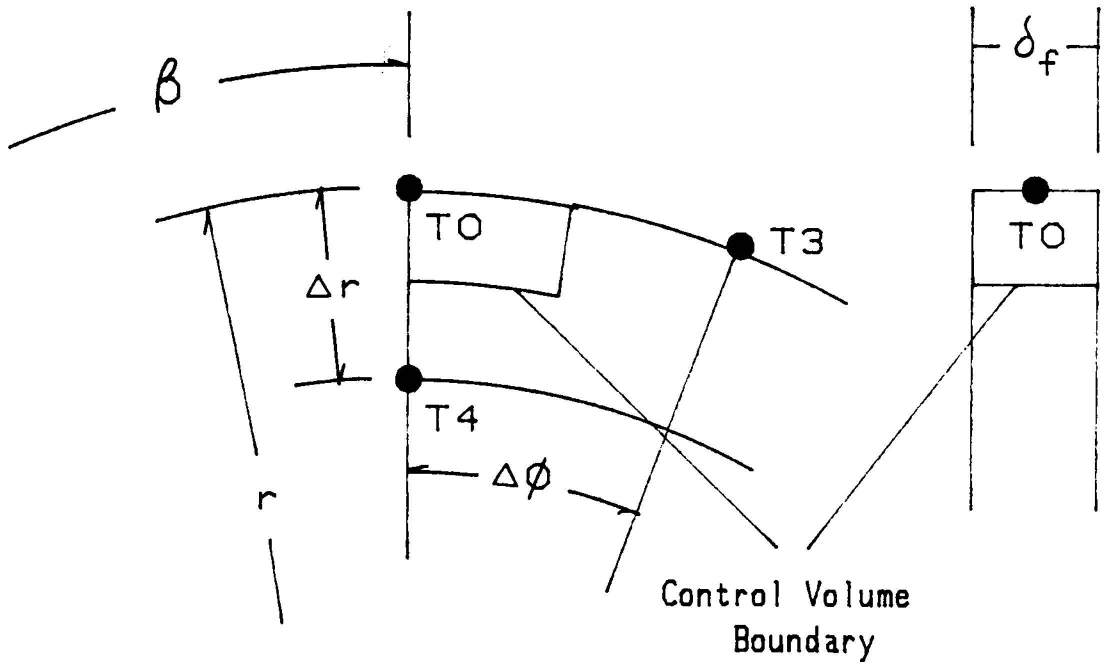

Figure A5. Chopper Upper Left Corner Node

$$B_0(T_0)^{n+1} + B_3(T_3)^{n+1} + B_4(T_4)^{n+1} = C$$

$$B_0 = [\delta_f \rho c_p/\Delta t]\Delta A - B_3 - B_4 + (\gamma+\alpha)(T_0{}^n)^3$$

$$\Delta A = \tfrac{1}{4}(r-\tfrac{1}{4}\Delta r)\Delta\phi(\Delta r)$$

$$\gamma = \epsilon_{bf}\sigma\Delta A + \epsilon_{ce}\sigma\delta_f[\tfrac{1}{2}(r\Delta\phi+\Delta r)] \qquad \alpha = \epsilon_{ff}\sigma\Delta A$$

$$B_3 = -\tfrac{1}{4}k\delta_f[\Delta r/(r\Delta\phi)] \qquad B_4 = -\tfrac{1}{4}k\delta_f[(r-\tfrac{1}{2}\Delta r)\Delta\phi/\Delta r]$$

$$C = \{[\delta_f \rho c_p/dt]\Delta A + B_3 + B_4\}(T_0)^n$$
$$- B_3(T_3)^n - B_4(T_4)^n + \gamma(T_\infty)^4 + \alpha(T_p)^4 + \epsilon_{bf}\sigma A_{bb}F_{bb\to0}(T_{bb})^4$$

$$F_{bb\to0} = [(z_b)^2/(\pi R^4)]\Delta A$$

$$R^4 = \{[r(\sin\beta)]^2+[y_b-r(\cos\beta)]^2+(z_b)^2\}^2$$

A6. Chopper Upper Right Corner Node

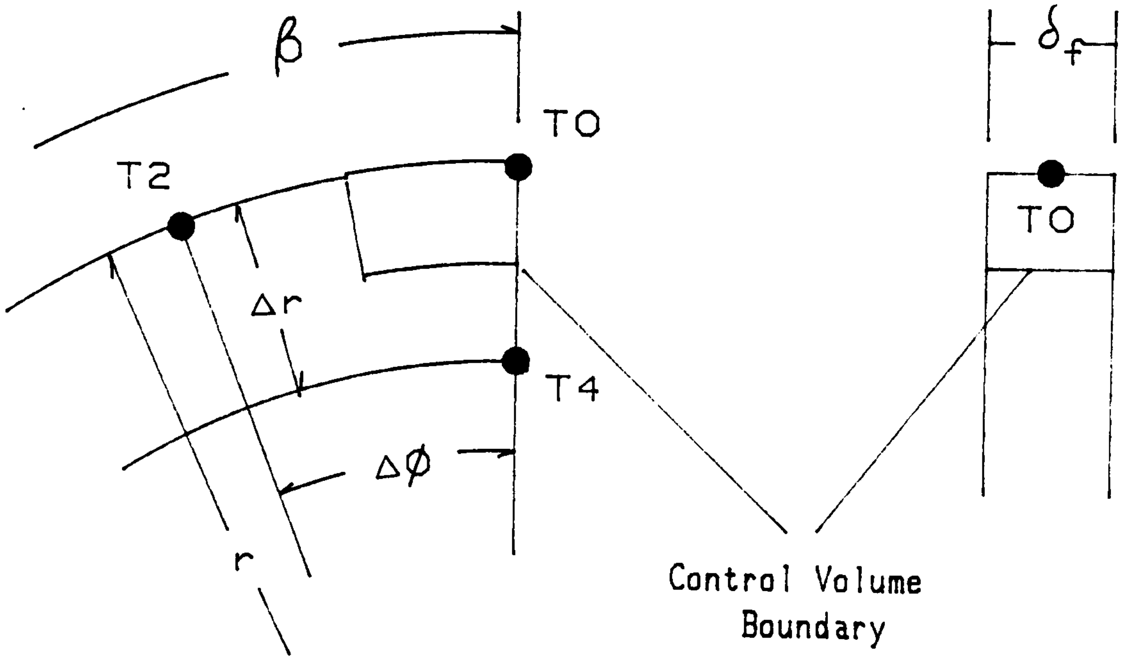

Figure A6. Chopper Upper Right Corner Node

$$B_0(T_0)^{n+1} + B_2(T_2)^{n+1} + B_4(T_4)^{n+1} = C$$

$$B_0 = [\delta_f \rho c_p/\Delta t]\Delta A - B_2 - B_4 + (\gamma+\alpha)(T_0{}^n)^3$$

$$\Delta A = \tfrac{1}{4}(r-\tfrac{1}{4}\Delta r)\Delta\phi(\Delta r)$$

$$\gamma = \epsilon_{bf}\sigma dA + \epsilon_{ce}\sigma\delta_f[\tfrac{1}{2}(r\Delta\phi+\Delta r)] \qquad \alpha = \epsilon_{ff}\sigma\Delta A$$

$$B_2 = -\tfrac{1}{4}k\delta_f[\Delta r/(r\Delta\phi)] \qquad B_4 = -\tfrac{1}{4}k\delta_f[(r-\tfrac{1}{2}\Delta r)\Delta\phi/\Delta r]$$

$$C = \{[\delta_f \rho c_p/\Delta t]\Delta A + B_2 + B_4\}(T_0)^n - B_2(T_2)^n$$

$$- B_4(T_4)^n + \gamma(T_\infty)^4 + \alpha(T_p)^4 + \epsilon_{bf}\sigma A_{bb}F_{bb\rightarrow 0}(T_{bb})^4$$

$$F_{bb\rightarrow 0} = [(z_b)^2/(\pi R^4)]\Delta A$$

$$R^4 = \{[r(\sin\beta)]^2+[y_b-r(\cos\beta)]^2+(z_b)^2\}^2$$

A7. Chopper Lower Left Corner Node

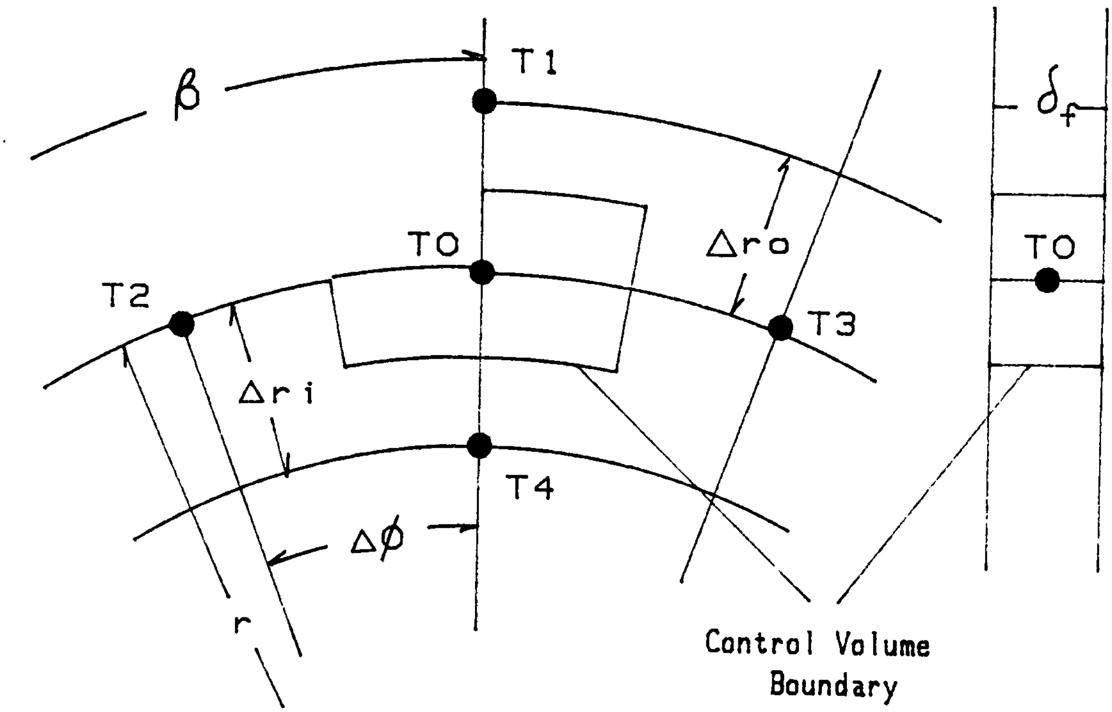

Figure A7. Chopper Lower Left Corner Node

$$B_0(T_0)^{n+1} + B_1(T_1)^{n+1} + B_2(T_2)^{n+1} + B_3(T_3)^{n+1} + B_4(T_4)^{n+1} = C$$

$$B_0 = [\delta_f \rho c_p/\Delta t]\Delta A - B_1 - B_2 - B_3 - B_4 + (\gamma+\alpha)(T_0{}^n)^3$$

$$\Delta A_o = \tfrac{1}{4}(r+\tfrac{1}{4}\Delta r_o)\Delta r_o \Delta\phi \qquad \Delta A_i = \tfrac{1}{2}(r-\tfrac{1}{4}\Delta r_i)\Delta r_i \Delta\phi$$

$$\Delta A = \Delta A_o + \Delta A_i$$

$$\gamma = \epsilon_{bf}\sigma\Delta A + \epsilon_{ce}\sigma\delta_f[\tfrac{1}{2}(r\Delta\phi+\Delta r_o)] \qquad \alpha = \epsilon_{ff}\sigma\Delta A$$

$$B_1 = -\tfrac{1}{4}k\delta_f[(r+\tfrac{1}{2}\Delta r_o)\Delta\phi/\Delta r_o] \qquad B_2 = -\tfrac{1}{4}k\delta_f[\Delta r_i/(r\Delta\phi)]$$

$$B_3 = -\tfrac{1}{4}k\delta_f[(\Delta r_o+\Delta r_i)/(r\Delta\phi)] \qquad B_4 = -\tfrac{1}{2}k\delta_f[(r-\tfrac{1}{2}\Delta r_i)\Delta\phi/\Delta r_i]$$

$$C = \{[\delta_f\rho c_p/\Delta t]\Delta A + B_1 + B_2 + B_3 + B_4\}(T_0)^n - B_1(T_1)^n - B_2(T_2)^n$$
$$- B_3(T_3)^n - B_4(T_4)^n + \gamma(T_\infty)^4 + \alpha(T_p)^4 + \epsilon_{bf}\sigma A_{bb}F_{bb\to 0}(T_{bb})^4$$

$$F_{bb\to 0} = [(z_b)^2/(\pi R^4)]\Delta A$$

$$R^4 = \{[r(\sin\beta)]^2+[y_b-r(\cos\beta)]^2+(z_b)^2\}^2$$

A8. Chopper Lower Right Corner Node

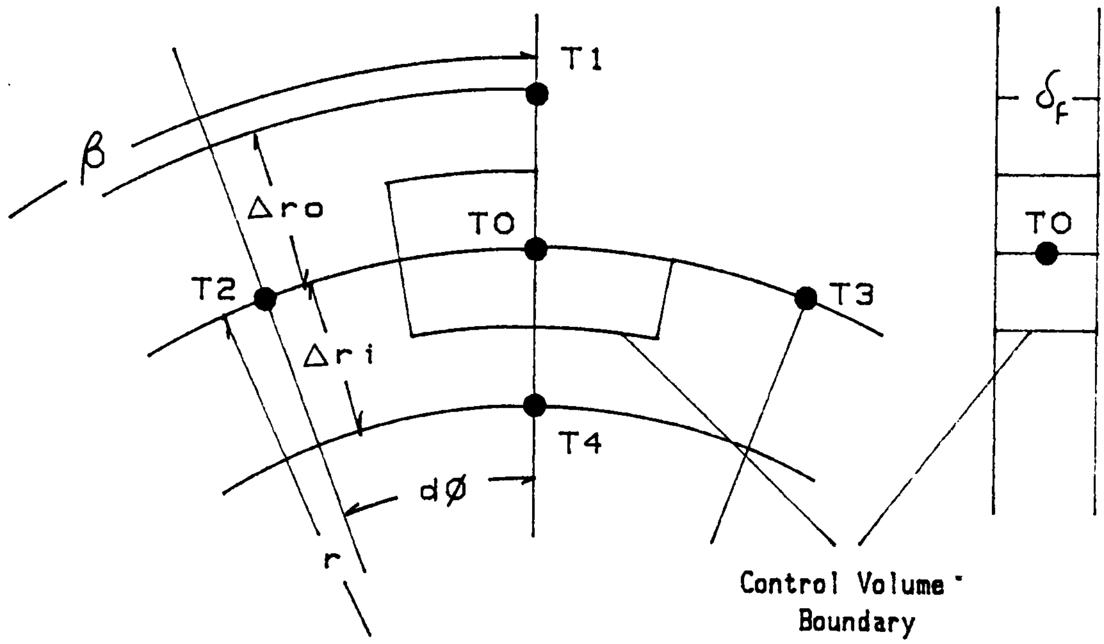

Figure A8. Chopper Lower Right Corner Node

$$B_0(T_0)^{n+1} + B_1(T_1)^{n+1} + B_2(T_2)^{n+1} + B_3(T_3)^{n+1} + B_4(T_4)^{n+1} = C$$

$$B_0 = [\delta_f \rho c_p/\Delta t]\Delta A - B_1 - B_2 - B_3 - B_4 + (\gamma+\alpha)(T_0{}^n)^3$$

$$\Delta A_o = ¼(r+¼\Delta r_o)\Delta r_o \Delta \phi \qquad \Delta A_i = ½(r-¼\Delta r_i)\Delta r_i \Delta \phi$$

$$\Delta A = \Delta A_o + \Delta A_i$$

$$\gamma = \epsilon_{bf}\sigma\Delta A + \epsilon_{ce}\sigma\delta_f[½(r\Delta\phi+\Delta r_o)] \qquad \alpha = \epsilon_{ff}\sigma\Delta A$$

$$B_1 = -¼k\delta_f[(r+½\Delta r_o)\Delta\phi/\Delta r_o] \qquad B_2 = -¼k\delta_f[(\Delta r_o+\Delta r_i)/(r\Delta\phi)]$$

$$B_3 = -¼k\delta_f[\Delta r_i/(r\Delta\phi)] \qquad B_4 = -½k\delta_f[(r-½\Delta r_i)\Delta\phi/\Delta r_i]$$

$$C = \{[\delta_f\rho c_p/\Delta t]\Delta A + B_1 + B_2 + B_3 + B_4\}(T_0)^n - B_1(T_1)^n - B_2(T_2)^n$$
$$- B_3(T_3)^n - B_4(T_4)^n + \gamma(T_\infty)^4 + \alpha(T_p)^4 + \epsilon_{bf}\sigma A_{bb}F_{bb\to 0}(T_{bb})^4$$

$$F_{bb\to 0} = [(z_b)^2/(\pi R^4)]\Delta A$$

$$R^4 = \{[r(\sin\beta)]^2+[y_b-r(\cos\beta)]^2+(z_b)^2\}^2$$

A9. R_{i2} Interface Node

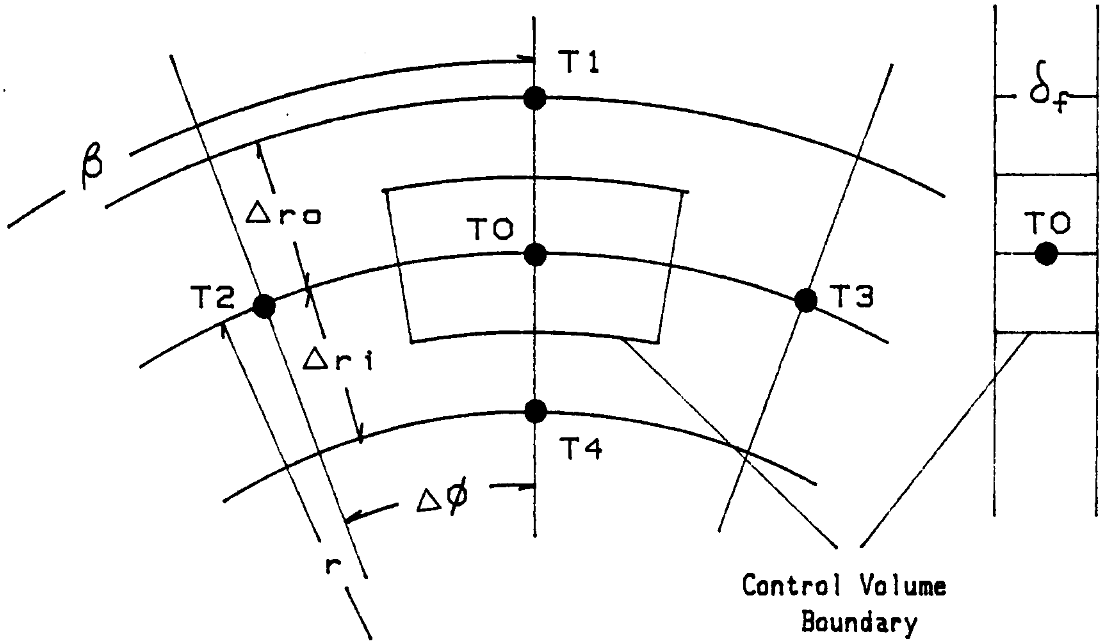

Figure A9. R_{i2} Interface Node

$$B_0(T_0)^{n+1} + B_1(T_1)^{n+1} + B_2(T_2)^{n+1} + B_3(T_3)^{n+1} + B_4(T_4)^{n+1} = C$$

$$B_0 = [\delta_f \rho c_p/\Delta t]\Delta A - B_1 - B_2 - B_3 - B_4 + (\gamma+\alpha)(T_0{}^n)^3$$

$$\Delta A_o = \tfrac{1}{2}(r+\tfrac{1}{4}\Delta r_o)\Delta r_o \Delta\phi \qquad \Delta A_{i2} = \tfrac{1}{2}(r-\tfrac{1}{4}\Delta r_{i2})\Delta r_{i2}\Delta\phi$$

$$\Delta A = \Delta A_o + \Delta A_{i2} \qquad \gamma = \epsilon_{bf}\sigma\Delta A \qquad \alpha = \epsilon_{ff}\sigma\Delta A$$

$$B_1 = -\tfrac{1}{2}k\delta_f[(r+\tfrac{1}{2}\Delta r_o)\Delta\phi/\Delta r_o] \qquad B_2 = -\tfrac{1}{4}k\delta_f[(\Delta r_o+\Delta r_{i2})/(r\Delta\phi)]$$

$$B_3 = -\tfrac{1}{4}k\delta_f[(\Delta r_o+\Delta r_{i2})/(r\Delta\phi)] \qquad B_4 = -\tfrac{1}{2}k\delta_f[(r-\tfrac{1}{2}\Delta r_{i2})\Delta\phi/\Delta r_{i2}]$$

$$C = \{[\delta_f \rho c_p/\Delta t]\Delta A + B_1 + B_2 + B_3 + B_4\}(T_0)^n - B_1(T_1)^n - B_2(T_2)^n$$
$$- B_3(T_3)^n - B_4(T_4)^n + \gamma(T_\infty)^4 + \alpha(T_p)^4 + \epsilon_{bf}\sigma A_{bb}F_{bb\to 0}(T_{bb})^4$$

$$F_{bb\to 0} = [(z_b)^2/(\pi R^4)]\Delta A$$

$$R^4 = \{[r(\sin\beta)]^2+[y_b-r(\cos\beta)]^2+(z_b)^2\}^2$$

A10. R_{i1} Interface Node

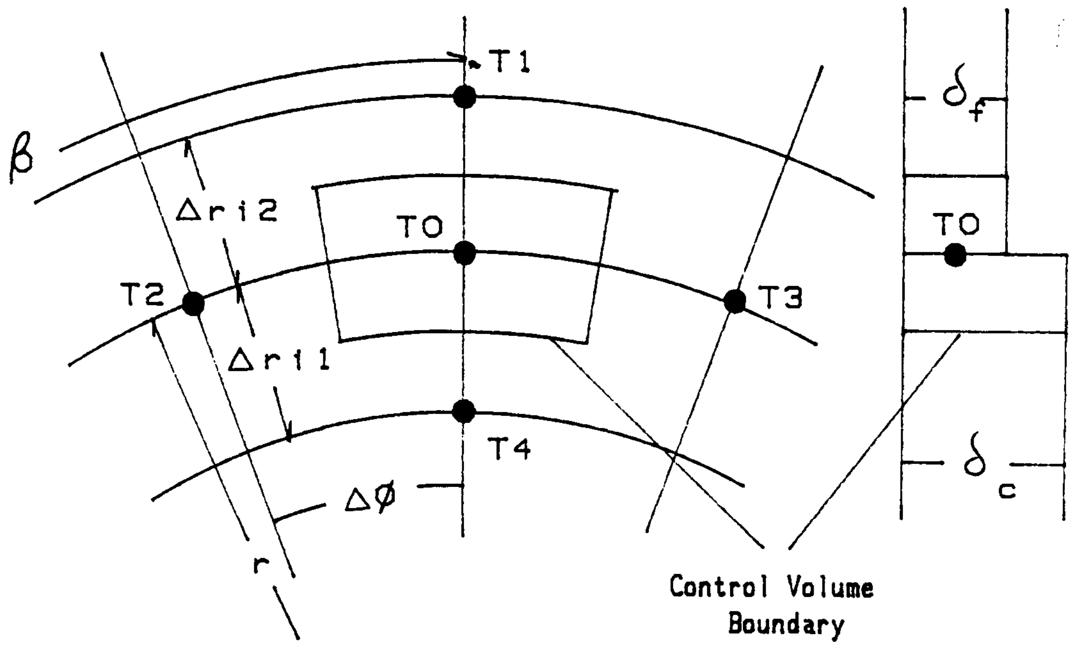

Figure A10. R_{i1} Interface Node

$$B_0(T_0)^{n+1} + B_1(T_1)^{n+1} + B_2(T_2)^{n+1} + B_3(T_3)^{n+1} + B_4(T_4)^{n+1} = C$$

$$B_0 = (\delta_c \Delta A_{i2} + \delta_f \Delta A_{i1})[\rho c_p/\Delta t] - B_1 - B_2 - B_3 - B_4 + (\gamma+\alpha)(T_0{}^n)^3$$

$$\Delta A_{i2} = \tfrac{1}{2}(r+\tfrac{1}{4}\Delta r_{i2})\Delta r_{i2}\Delta\phi \qquad \Delta A_{i1} = \tfrac{1}{2}(r-\tfrac{1}{4}\Delta r_{i1})\Delta r_{i1}\Delta\phi$$

$$\Delta A = \Delta A_{i1} + \Delta A_{i2} \qquad \gamma = \epsilon_{bf}\sigma\Delta A \qquad \alpha = \epsilon_{ff}\sigma\Delta A$$

$$B_1 = -\tfrac{1}{2}k\delta_f[(r+\tfrac{1}{2}\Delta r_{i2})\Delta\phi/\Delta r_{i2}] \qquad B_2 = -\tfrac{1}{4}k[(\delta_f\Delta r_{i2}+\delta_c\Delta r_{i1})/(r\Delta\phi)]$$

$$B_3 = -\tfrac{1}{4}k[(\delta_f\Delta r_{i2}+\delta_c\Delta r_{i1})/(r\Delta\phi)] \qquad B_4 = -\tfrac{1}{2}k\delta_c[(r-\tfrac{1}{2}\Delta r_{i1})\Delta\phi/\Delta r_{i1}]$$

$$C = \{(\delta_c \Delta A_{i2} + \delta_f \Delta A_{i1})[\rho c_p/\Delta t] + B_1 + B_2 + B_3 + B_4\}(T_0)^n - B_1(T_1)^n$$
$$- B_2(T_2)^n - B_3(T_3)^n - B_4(T_4)^n + \gamma(T_\infty)^4 + \alpha(T_p)^4 + \epsilon_{bf}\sigma A_{bb}F_{bb\to 0}(T_{bb})^4$$

$$F_{bb\to 0} = [(z_b)^2/(\pi R^4)]\Delta A$$

$$R^4 = \{[r(\sin\beta)]^2 + [y_b - r(\cos\beta)]^2 + (z_b)^2\}^2$$

A11. R_c Interface Node

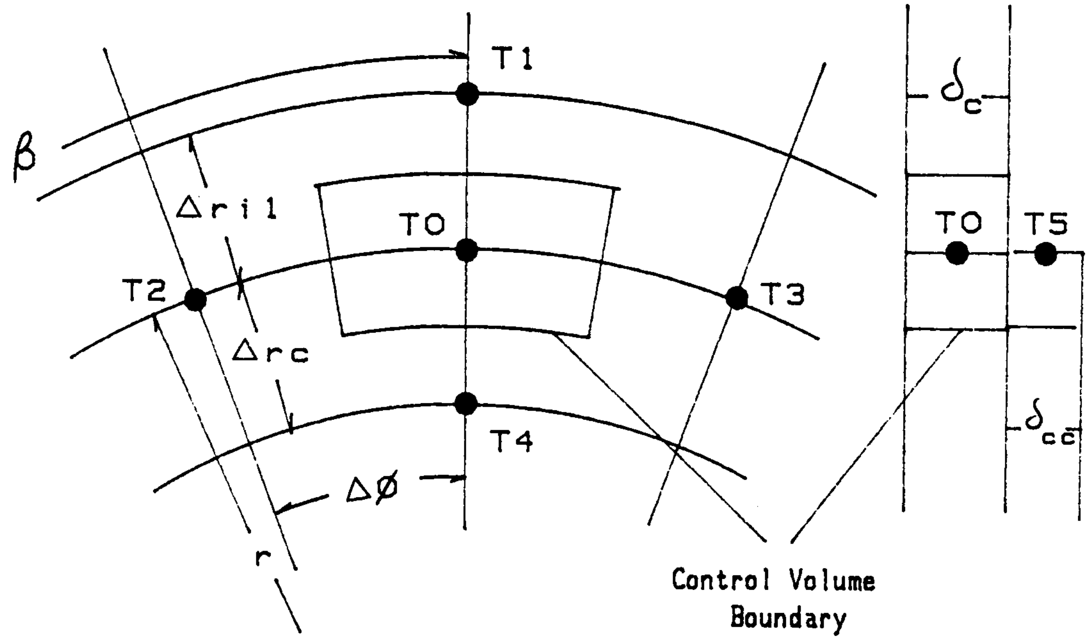

Figure A11. R_c Interface Node

$$B_0(T_0)^{n+1} + B_1(T_1)^{n+1} + B_2(T_2)^{n+1} + B_3(T_3)^{n+1} + B_4(T_4)^{n+1} + B_5(T_5)^{n+1} = C$$

$$B_0 = [\delta_c \rho c_p/\Delta t]\Delta A - B_1 - B_2 - B_3 - B_4 - B_5 + (\gamma+\alpha)(T_0{}^n)^3$$

$$\Delta A_{i1} = \tfrac{1}{2}(r+2\Delta r_{i1})\Delta r_{i1}\Delta\phi \qquad \Delta A_c = \tfrac{1}{2}(r-\tfrac{1}{4}\Delta r_c)\Delta r_c\Delta\phi$$

$$\Delta A = \Delta A_{i1} + \Delta A_c \qquad \gamma = \epsilon_{bf}\sigma\Delta A_{i1} \qquad \alpha = \epsilon_{ff}\sigma\Delta A$$

$$B_1 = -\tfrac{1}{2}k\delta_c[(r+\tfrac{1}{2}\Delta r_{i1})\Delta\phi/\Delta r_{i1}] \qquad B_2 = -\tfrac{1}{4}k\delta_c[(\Delta r_{i1}+\Delta r_c)/(r\Delta\phi)]$$

$$B_3 = -\tfrac{1}{4}k\delta_c[(\Delta r_{i1}+\Delta r_c)/(r\Delta\phi)] \qquad B_4 = -\tfrac{1}{2}k\delta_c[(r-\tfrac{1}{2}\Delta r_c)\Delta\phi/\Delta r_c]$$

$$B_5 = -k\Delta A_c/(\delta_c+\delta_{cc})$$

$$C = ([\delta_c \rho c_p/\Delta t]\Delta A + B_1 + B_2 + B_3 + B_4 + B_5)(T_0)^n - B_1(T_1)^n - B_2(T_2)^n - B_3(T_3)^n - B_4(T_4)^n + \gamma(T_\infty)^4 + \alpha(T_p)^4$$

A12. R_c Connector Node

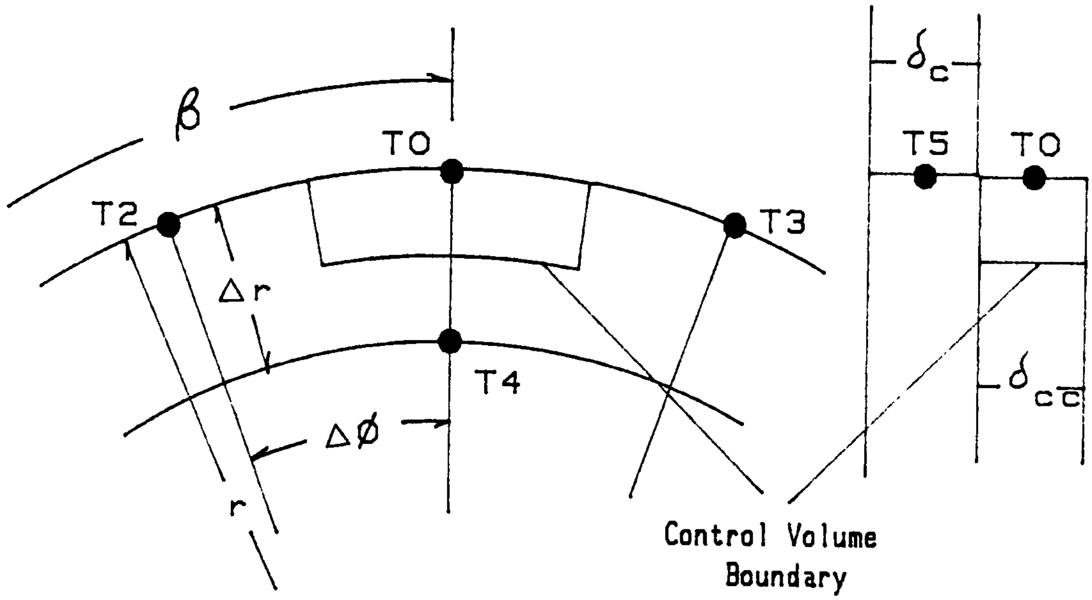

Figure A12. R_c Connector Node

$$B_0(T_0)^{n+1} + B_2(T_2)^{n+1} + B_3(T_3)^{n+1} + B_4(T_4)^{n+1} + B_5(T_5)^{n+1} = C$$

$$B_0 = [\delta_{cc}\rho c_p/\Delta t]\Delta A - B_2 - B_3 - B_4 - B_5 + \gamma(T_0{}^n)^3$$

$$\Delta A = \tfrac{1}{2}\Delta r(r-2\Delta r)\Delta\phi \qquad \gamma = \epsilon_{cc}\sigma(\Delta A+\delta_{cc}r\Delta\phi)$$

$$B_2 = -\tfrac{1}{4}k\delta_{cc}[\Delta r/(r\Delta\phi)] \qquad B_3 = -\tfrac{1}{4}k\delta_{cc}[\Delta r/(r\Delta\phi)]$$

$$B_4 = -\tfrac{1}{2}k\delta_{cc}[(r-\tfrac{1}{2}\Delta r)\Delta\phi/\Delta r] \qquad B_5 = -k(\Delta A)/(\delta_c+\delta_{cc})$$

$$C = \{[\delta_{cc}\rho c_p/\Delta t]\Delta A + B_2 + B_3 + B_4 + B_5\}(T_0)^n - B_2(T_2)^n$$
$$- B_3(T_3)^n - B_4(T_4)^n - B_5(T_5)^n + \gamma(T_\infty)^4$$

A13. Chopper Interior Node within R_c

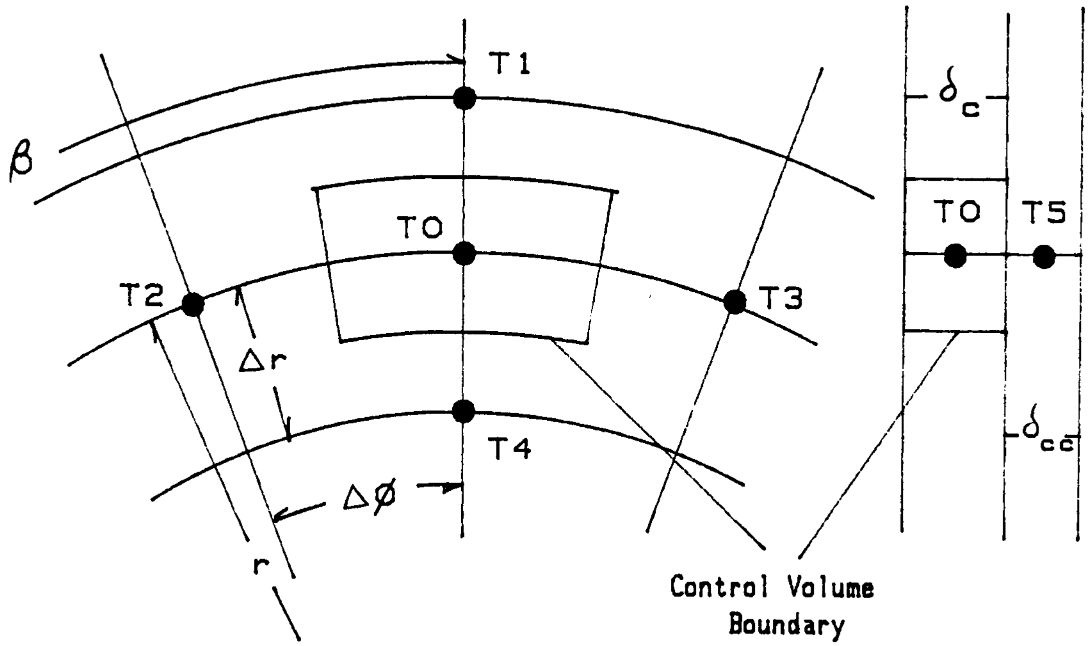

Figure A13. Chopper Interior Node within R_c

$$B_0(T_0)^{n+1} + B_1(T_1)^{n+1} + B_2(T_2)^{n+1} + B_3(T_3)^{n+1} + B_4(T_4)^{n+1} + B_5(T_5)^{n+1} = C$$

$$B_0 = [\delta_c \rho c_p/\Delta t]\Delta A - B_1 - B_2 - B_3 - B_4 - B_5 + \alpha(T_0{}^n)^3$$

$$\Delta A = r(\Delta\phi)\Delta r \qquad \alpha = \epsilon_{ff}\sigma\Delta A$$

$$B_1 = -\tfrac{1}{2}k\delta_c[(r+\tfrac{1}{2}\Delta r)\Delta\phi/\Delta r] \qquad B_2 = -\tfrac{1}{2}k\delta_c[\Delta r/(r\Delta\phi)]$$

$$B_3 = -\tfrac{1}{2}k\delta_c[\Delta r/(r\Delta\phi)] \qquad B_4 = -\tfrac{1}{2}k\delta_c[(r-\tfrac{1}{2}\Delta r)\Delta\phi/\Delta r]$$

$$B_5 = -k(\Delta A)/(\delta_c+\delta_{cc})$$

$$C = \{[\delta_c \rho c_p/\Delta t]\Delta A + B_1 + B_2 + B_3 + B_4 + B_5\}(T_0)^n - B_1(T_1)^n$$
$$- B_2(T_2)^n - B_3(T_3)^n - B_4(T_4)^n - B_5(T_5)^n + \alpha(T_p)^4$$

A14. Chopper Connector Interior Node

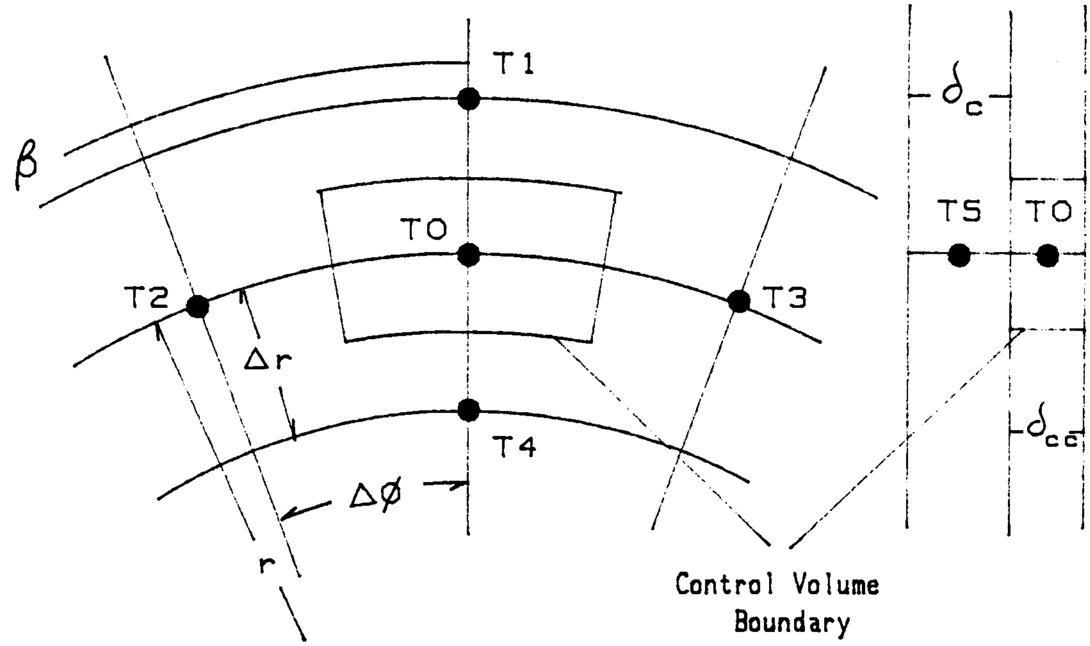

Figure A14. Chopper Connector Interior Node

$$B_0(T_0)^{n+1} + B_1(T_1)^{n+1} + B_2(T_2)^{n+1} + B_3(T_3)^{n+1} + B_4(T_4)^{n+1} + B_5(T_5)^{n+1} = C$$

$$B_0 = [\delta_{cc}\rho c_p/\Delta t]\Delta A - B_1 - B_2 - B_3 - B_4 - B_5 + \gamma(T_0{}^n)^3$$

$$\Delta A = r(\Delta\phi)\Delta r \qquad \gamma = \epsilon_{cc}\sigma\Delta A$$

$$B_1 = -\tfrac{1}{2}k\delta_{cc}[(r+3\Delta r)\Delta\phi/\Delta r] \qquad B_2 = -\tfrac{1}{2}k\delta_{cc}[\Delta r/(r\Delta\phi)]$$

$$B_3 = -\tfrac{1}{2}k\delta_{cc}[\Delta r/(r\Delta\phi)] \qquad B_4 = -\tfrac{1}{2}k\delta_{cc}[(r-\tfrac{1}{2}\Delta r)\Delta\phi/\Delta r]$$

$$B_5 = -k(\Delta A)/(\delta_c+\delta_{cc})$$

$$C = \{[\delta_{cc}\rho c_p/\Delta t]\Delta A + B_1 + B_2 + B_3 + B_4 + B_5\}(T_0)^n - B_1(T_1)^n - B_2(T_2)^n - B_3(T_3)^n - B_4(T_4)^n - B_5(T_5)^n + \gamma(T_\infty)^4$$

A15. Chopper Node at the Shaft Radius

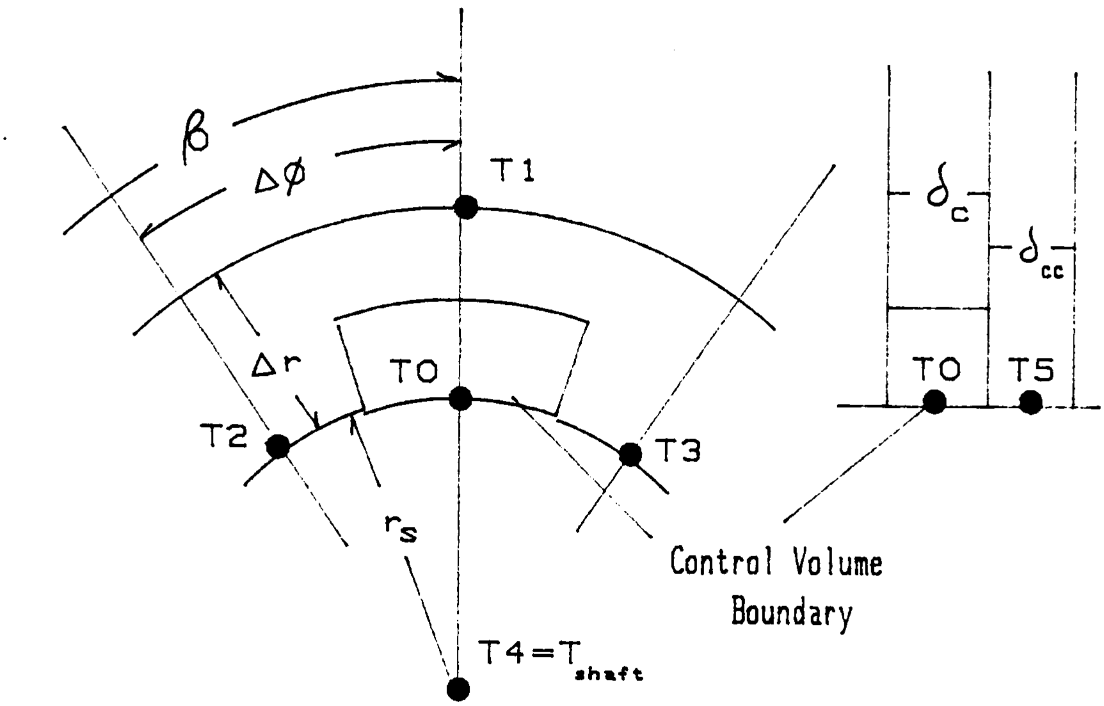

Figure A15. Chopper Node at the Shaft Radius

$$B_0(T_0)^{n+1} + B_1(T_1)^{n+1} + B_2(T_2)^{n+1} + B_3(T_3)^{n+1} + B_4(T_4)^{n+1} + B_5(T_5)^{n+1} = C$$

$$B_0 = [\delta_c \rho c_p/\Delta t]\Delta A - B_1 - B_2 - B_3 - B_4 - B_5 + \alpha(T_0{}^n)^3$$

$$\Delta A = \tfrac{1}{2}\Delta r(r + \tfrac{1}{4}\Delta r)\Delta\phi \qquad \alpha = \epsilon_{ff}\sigma\Delta A$$

$$B_1 = -\tfrac{1}{2}k_c\delta_c[(r+\tfrac{1}{2}\Delta r)\Delta\phi/\Delta r] \qquad B_2 = -\tfrac{1}{4}k_c\delta_c[\Delta r/(r\Delta\phi)]$$

$$B_3 = -\tfrac{1}{4}k_c\delta_c[\Delta r/(r\Delta\phi)] \qquad B_4 = -\tfrac{1}{2}\delta_c\Delta\phi r_s/(r_s/k_s + C_R)$$

$$B_5 = -k(\Delta A)/(\delta_c + \delta_{cc})$$

$$C = \{[\delta_c\rho c_p/\Delta t]\Delta A + B_1 + B_2 + B_3 + B_4 + B_5\}(T_0)^n - B_1(T_1)^n - B_2(T_2)^n - B_3(T_3)^n - B_4(T_4)^n - B_5(T_5)^n + \alpha(T_p)^4$$

A16. Connector Node at the Shaft Radius

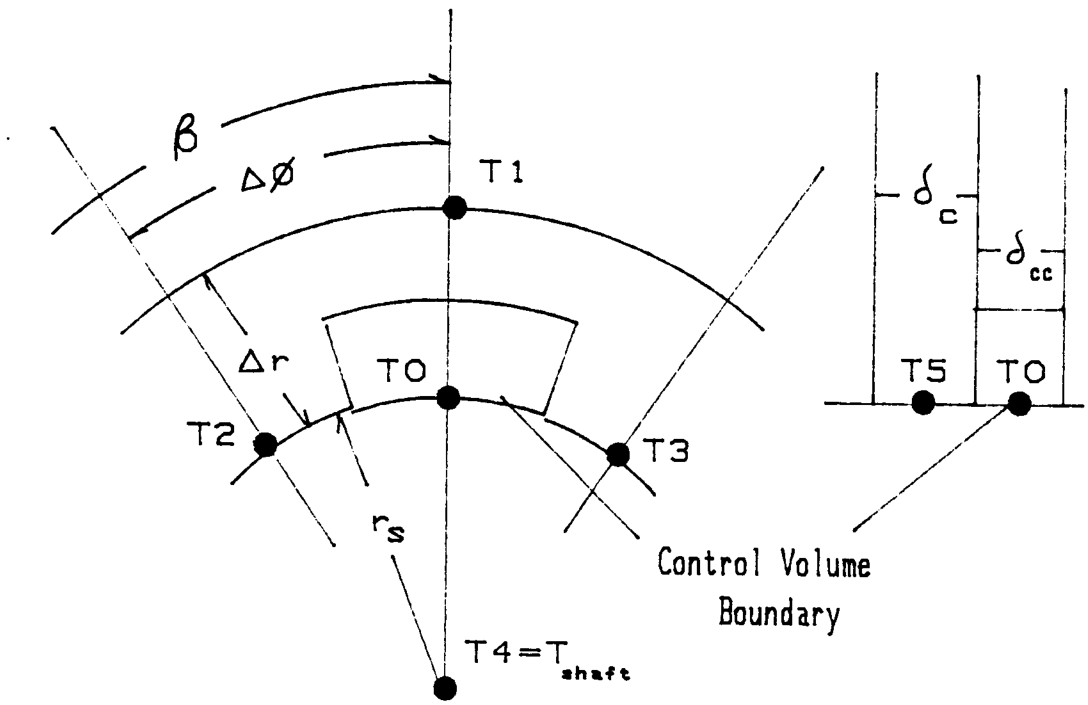

Figure A16. Connector Node at the Shaft Radius

$$B_0(T_0)^{n+1} + B_1(T_1)^{n+1} + B_2(T_2)^{n+1} + B_3(T_3)^{n+1} + B_4(T_4)^{n+1} + B_5(T_5)^{n+1} = C$$

$$B_0 = [\delta_{cc}\rho c_p/\Delta t]\Delta A - B_1 - B_2 - B_3 - B_4 - B_5 + \gamma(T_0{}^n)^3$$

$$\Delta A = \tfrac{1}{2}\Delta r(r+\tfrac{1}{4}\Delta r)\Delta\phi \qquad \gamma = \epsilon_{cc}\sigma\Delta A$$

$$B_1 = -\tfrac{1}{2}k_c\delta_{cc}[(r+\tfrac{1}{2}\Delta r)\Delta\phi/\Delta r] \qquad B_2 = -\tfrac{1}{4}k_c\delta_{cc}[\Delta r/(r\Delta\phi)]$$

$$B_3 = -\tfrac{1}{4}k_c\delta_{cc}[\Delta r/(r\Delta\phi)] \qquad B_4 = -\tfrac{1}{2}\delta_{cc}\Delta\phi r_s/(r_s/k_s+C_R)$$

$$B_5 = -k(\Delta A)/(\delta_c+\delta_{cc})$$

$$C = \{[\delta_{cc}\rho c_p/\Delta t]\Delta A + B_1 + B_2 + B_3 + B_4 + B_5\}(T_0)^n - B_1(T_1)^n$$
$$- B_2(T_2)^n - B_3(T_3)^n - B_4(T_4)^n - B_5(T_5)^n + \gamma(T_\infty)^4$$

APPENDIX B

NODAL FINITE-DIFFERENCE EQUATIONS

FOR THE SHAFT

B1. Shaft Interior Node

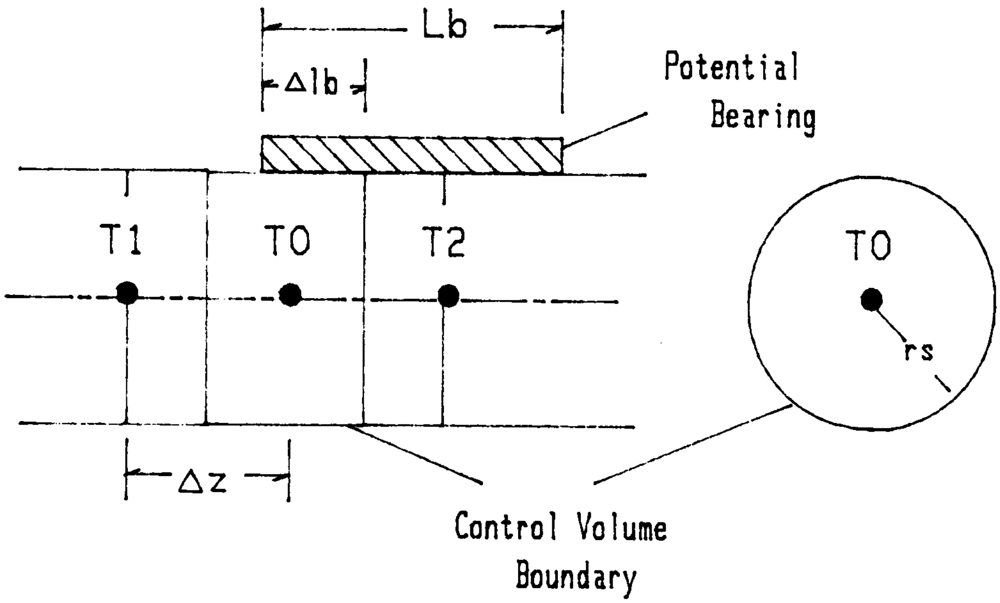

Figure B1. Shaft Interior Node

$$B_0(T_0)^{n+1} + B_1(T_1)^{n+1} + B_2(T_2)^{n+1} + B_b(T_b)^{n+1} = C$$

$$B_0 = [\Delta z \rho c_p/\Delta t]\Delta A - B_1 - B_2 - B_b + \gamma(T_0{}^n)^3$$

$$\Delta A = \pi(r_s)^2 \qquad \gamma = 2\epsilon_s \sigma \pi r_s(\Delta z - \Delta l_b)$$

$$B_1 = -\tfrac{1}{2}k(\Delta A/\Delta z) \qquad B_2 = -\tfrac{1}{2}k(\Delta A/\Delta z)$$

$$B_b = -\tfrac{1}{2}(\Delta l_b/L_b)[\ln(r_{ir}/r_s)/(2\pi L_b k) + C_R]^{-1}$$

$$C = \{[\Delta z \rho c_p/\Delta t]\Delta A + B_1 + B_2 + B_b\}(T_0)^n - B_1(T_1)^n - B_2(T_2)^n - B_b(T_b)^n + \gamma(T_\infty)^4$$

B2. Shaft Node at the Chopper without the Plate Modeled

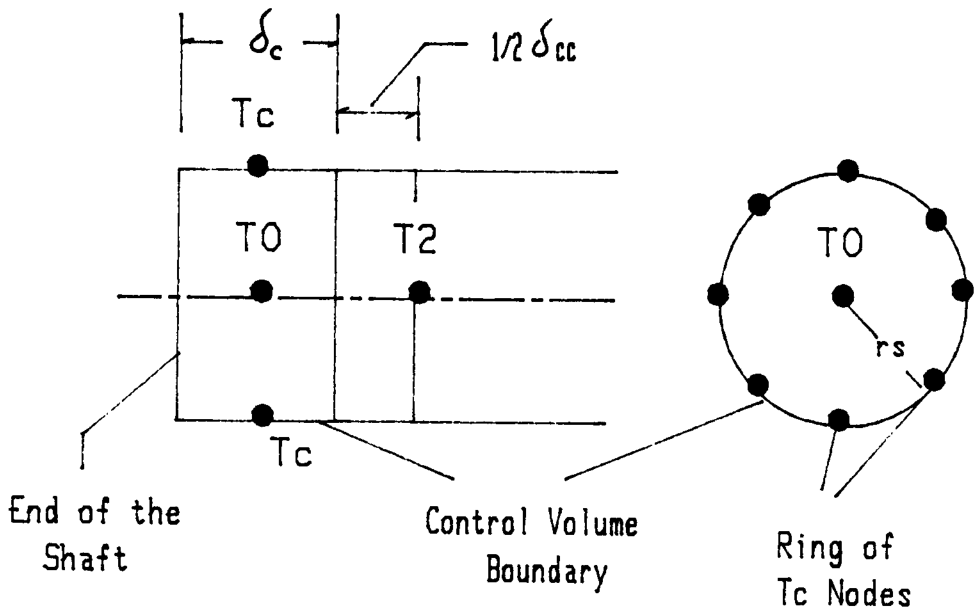

Figure B2. Shaft Node at the Chopper without the Plate Modeled

$$B_0(T_0)^{n+1} + B_2(T_2)^{n+1} + \Sigma[B_C(T_C)^{n+1}] = C$$

$$B_0 = [\delta_c \rho c_p/\Delta t]\Delta A - B_2 - \Sigma B_C + \gamma(T_0{}^n)^3$$

$$\Delta A = \pi(r_s)^2 \qquad \gamma = \epsilon_{se}\sigma\Delta A$$

$$B_2 = -k[\Delta A/(\delta_c+\delta_{cc})]$$

$$B_C = -\tfrac{1}{2}\delta_c d\phi r_s/(r_s/k+C_R) \qquad \Sigma B_C = -\pi\delta_c r_s/(r_s/k+C_R)$$

$$C = \{[\delta_c \rho c_p/\Delta t]\Delta A + B_2 + \Sigma B_C\}(T_0)^n$$
$$- B_2(T_2)^n - \Sigma[B_C(T_C)^n] + \gamma(T_\infty)^4$$

B3. Shaft Node at the Chopper with the Plate Modeled

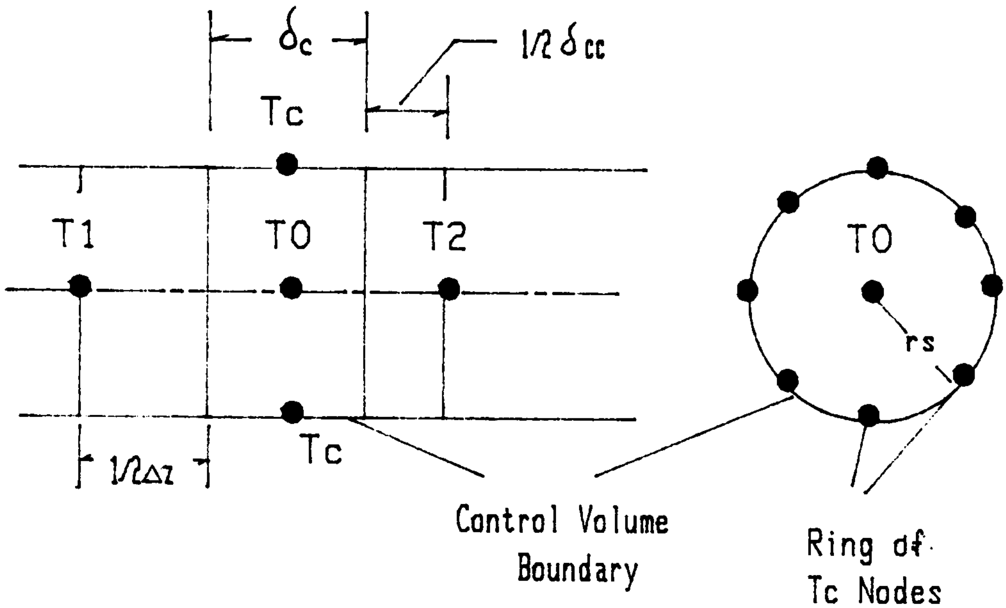

Figure B3. Shaft Node at the Chopper with the Plate Modeled

$$B_0(T_0)^{n+1} + B_1(T_1)^{n+1} + B_2(T_2)^{n+1} + \Sigma[B_C(T_C)^{n+1}] = C$$

$$B_0 = [\delta_c \rho c_p/\Delta t]\Delta A - B_1 - B_2 - \Sigma B_C$$

$$\Delta A = \pi(r_s)^2$$

$$B_1 = -k[\Delta A/(\Delta z+\delta_c)] \qquad B_2 = -k[\Delta A/(\delta_c+\delta_{cc})]$$

$$B_C = -\tfrac{1}{2}\delta_c d\phi r_s/(r_s/k+C_R) \qquad \Sigma B_C = -\pi\delta_c r_s/(r_s/k+C_R)$$

$$C = \{[\delta_c \rho c_p/\Delta t]\Delta A + B_1 + B_2 + \Sigma B_C\}(T_0)^n$$
$$- B_1(T_1)^n - B_2(T_2)^n - \Sigma[B_C(T_C)^n]$$

B4. Shaft Node at the Chopper Connector

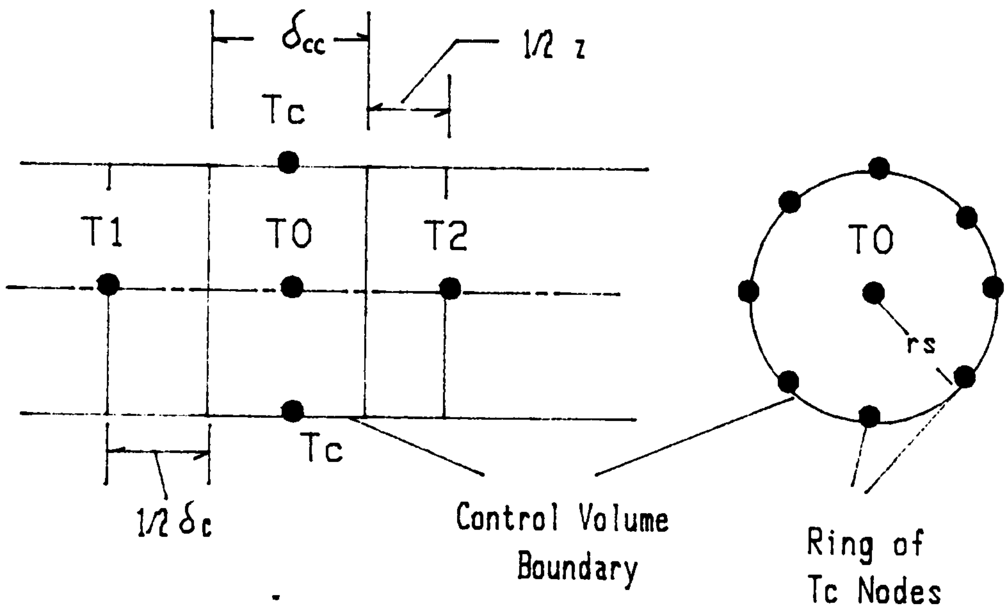

Figure B4. Shaft Node at the Chopper Connector

$$B_0(T_0)^{n+1} + B_1(T_1)^{n+1} + B_2(T_2)^{n+1} + \Sigma[B_C(T_C)^{n+1}] = C$$

$$B_0 = [\delta_c\rho c_p/\Delta t]\Delta A - B_1 - B_2 - \Sigma B_C$$

$$dA = \pi(r_s)^2$$

$$B_1 = -k[\Delta A/(\delta_{cc}+\delta_c)] \qquad B_2 = -k[\Delta A/(\Delta z+\delta_{cc})]$$

$$B_C = -\tfrac{1}{2}\delta_{cc}\Delta\phi r_s/(r_s/k+C_R) \qquad \Sigma B_C = -\pi\delta_{cc}r_s/(r_s/k+C_R)$$

$$C = \{[\delta_c\rho c_p/\Delta t]\Delta A + B_1 + B_2 + \Sigma B_C\} (T_0)^n$$

$$- B_1(T_1)^n - B_2(T_2)^n - \Sigma[B_C(T_C)^n]$$

B5. Shaft Node at the Motor Housing

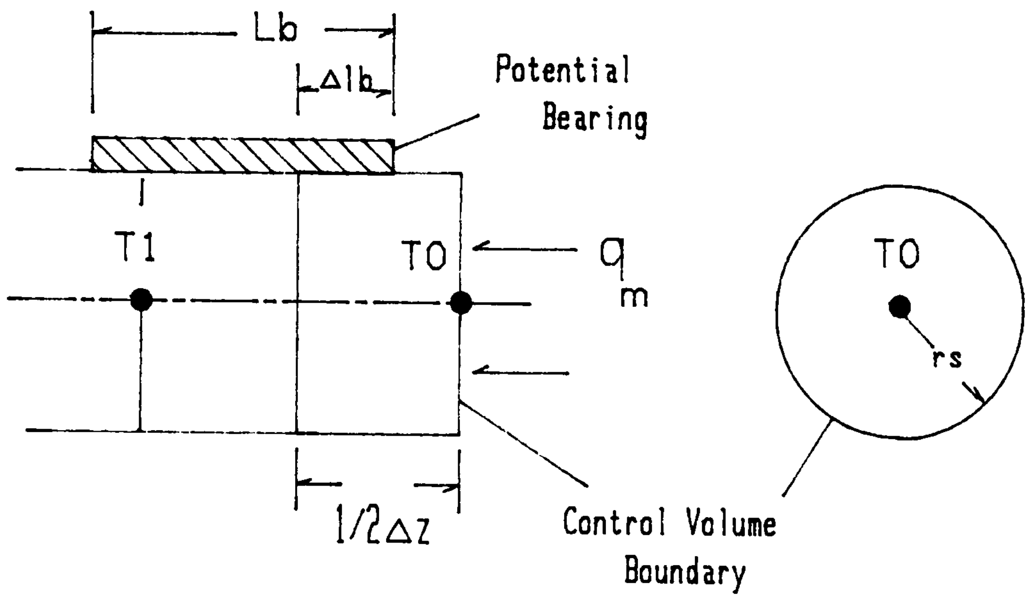

Figure B5. Shaft Node at the Motor Housing

$$B_0(T_0)^{n+1} + B_1(T_1)^{n+1} = C$$

$$B_0 = [\tfrac{1}{2}\Delta z\rho c_p/\Delta t]\Delta A - B_1 + \gamma(T_0{}^n)^3$$

$$\Delta A = \pi(r_s)^2 \qquad \gamma = 2\epsilon_s\sigma\pi r_s(\tfrac{1}{2}\Delta z-\Delta l_b)$$

$$B_1 = -\tfrac{1}{2}k(\Delta A/\Delta z)$$

$$C = \{[\tfrac{1}{2}\Delta z\rho c_p/\Delta t]\Delta A + B_1\}\ (T_0)^n - B_1(T_1)^n + \gamma(T_\infty)^4 + q_m$$

B6. Shaft Node at the Front Plate

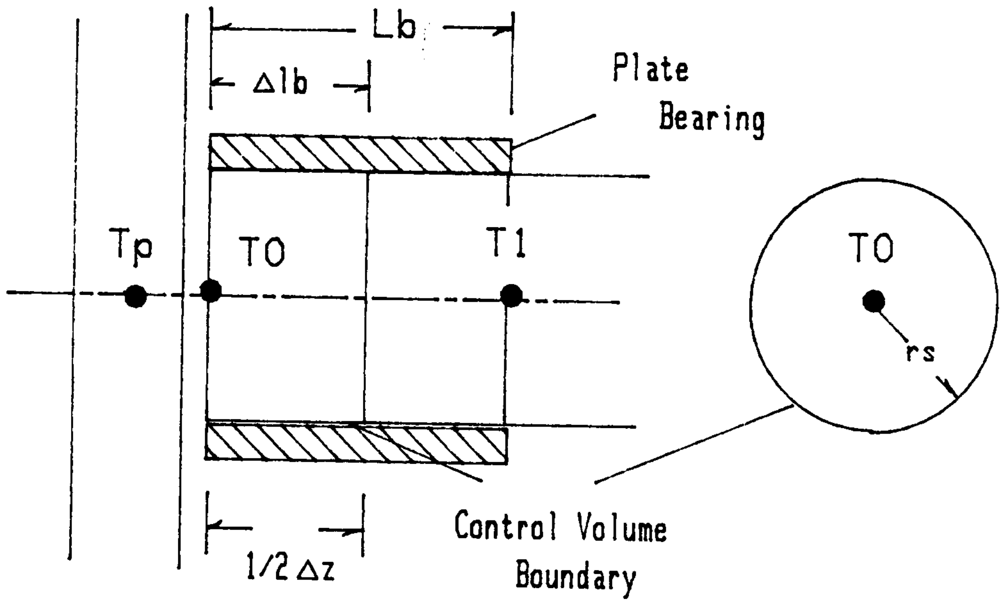

Figure B6. Shaft Node at the Front Plate

$$B_0(T_0)^{n+1} + B_1(T_1)^{n+1} + B_b(T_b)^{n+1} = C$$

$$B_0 = [\tfrac{1}{2}\Delta z \rho c_p/\Delta t]\Delta A - B_1 - B_b + \gamma(T_0{}^n)^3$$

$$\Delta A = \pi(r_s)^2 \qquad \gamma = \gamma_1 + \gamma_2$$

$$\text{if } [\tfrac{1}{2}\Delta z.\mathrm{GT}.L_b] \text{ then } \quad \gamma_1 = \epsilon_s \sigma [2\pi r_s(\tfrac{1}{2}\Delta z - L_b)]$$

$$\text{if } [\tfrac{1}{2}\Delta z.\mathrm{LE}.L_b] \text{ then } \quad \gamma_1 = 0$$

$$B_1 = -\tfrac{1}{2}k(\Delta A/\Delta z) \qquad \gamma_2 = \epsilon_{se}\sigma\Delta A$$

$$B_b = -\tfrac{1}{2}(\Delta l_b/L_b)[\ln(r_{ir}/r_s)/(2\pi L_b k) + C_R]^{-1}$$

$$C = ([\tfrac{1}{2}\Delta z \rho c_p/\Delta t]\Delta A + B_1)\ (T_0)^n - B_1(T_1)^n - B_b(T_b)^n + \gamma_1(T_\infty)^4$$

APPENDIX C

NODAL FINITE-DIFFERENCE EQUATIONS

FOR THE FRONT PLATE

C1. Front Plate Interior Node

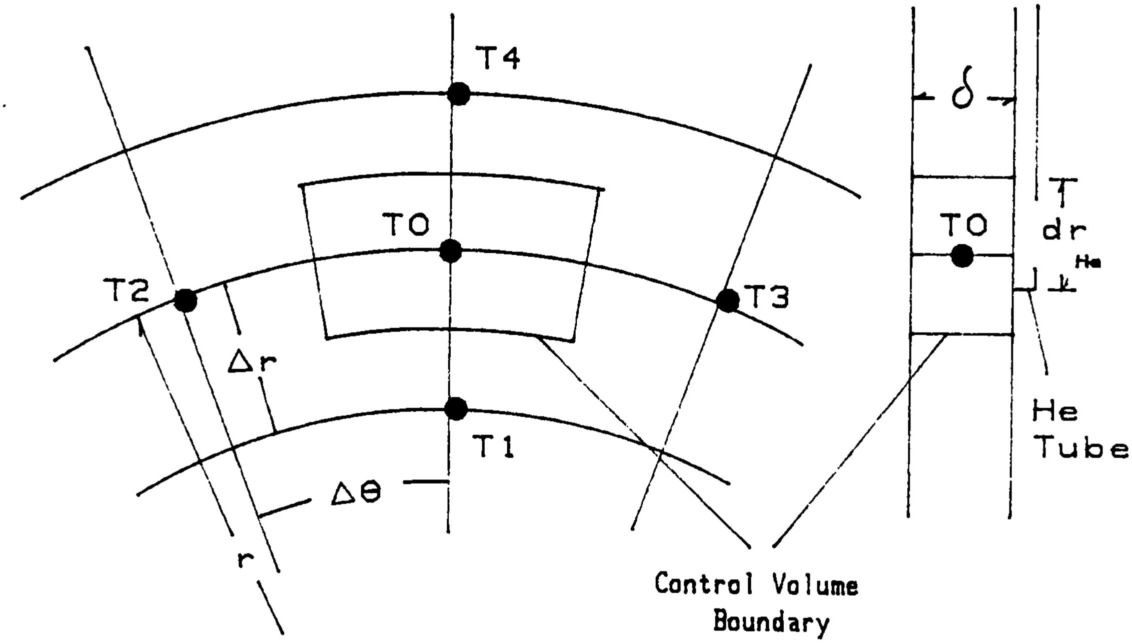

Figure C1. Front Plate Interior Node

$$B_0(T_0)^{n+1} + B_1(T_1)^{n+1} + B_2(T_2)^{n+1} + B_3(T_3)^{n+1} + B_4(T_4)^{n+1} = C$$

$$B_0 = [\delta\rho c_p/\Delta t]\Delta A - B_1 - B_2 - B_3 - B_4 + (\gamma+\alpha)(T_0{}^n)^3$$

$$\Delta A = r(\Delta\Theta)\Delta r \qquad \gamma = \alpha = \epsilon_p\sigma\Delta A$$

$$B_1 = -\tfrac{1}{2}k\delta[(r+\tfrac{1}{2}\Delta r)\Delta\Theta/\Delta r] \qquad B_2 = -\tfrac{1}{2}k\delta[\Delta r/(r\Delta\Theta)]$$

$$B_3 = -\tfrac{1}{2}k\delta[\Delta r/(r\Delta\Theta)] \qquad B_4 = -\tfrac{1}{2}k\delta[(r-\tfrac{1}{2}\Delta r)\Delta\Theta/\Delta r]$$

$$C = \{[\delta\rho c_p/\Delta t]\Delta A + B_1 + B_2 + B_3 + B_4\}(T_0)^n - B_1(T_1)^n - B_2(T_2)^n - B_3T_3)^n - B_4(T_4)^n$$

$$+\gamma(T_\infty)^4 + \alpha(T_c)^4 + \epsilon_{bf}\sigma A_{bb}F_{bb\to 0}(T_{bb})^4 + h_{He}\Delta A(\Delta r_{He}/\Delta r)(T_{He} - T_0{}^n)$$

$$F_{bb\to 0} = [(z_b)^2/(\pi R^4)]\Delta A$$

$$R^4 = \{[r(\sin\Theta)]^2 + [y_b - r(\cos\Theta)]^2 + (z_{b\to p})^2\}^2$$

C2. Front Plate Centerline Node

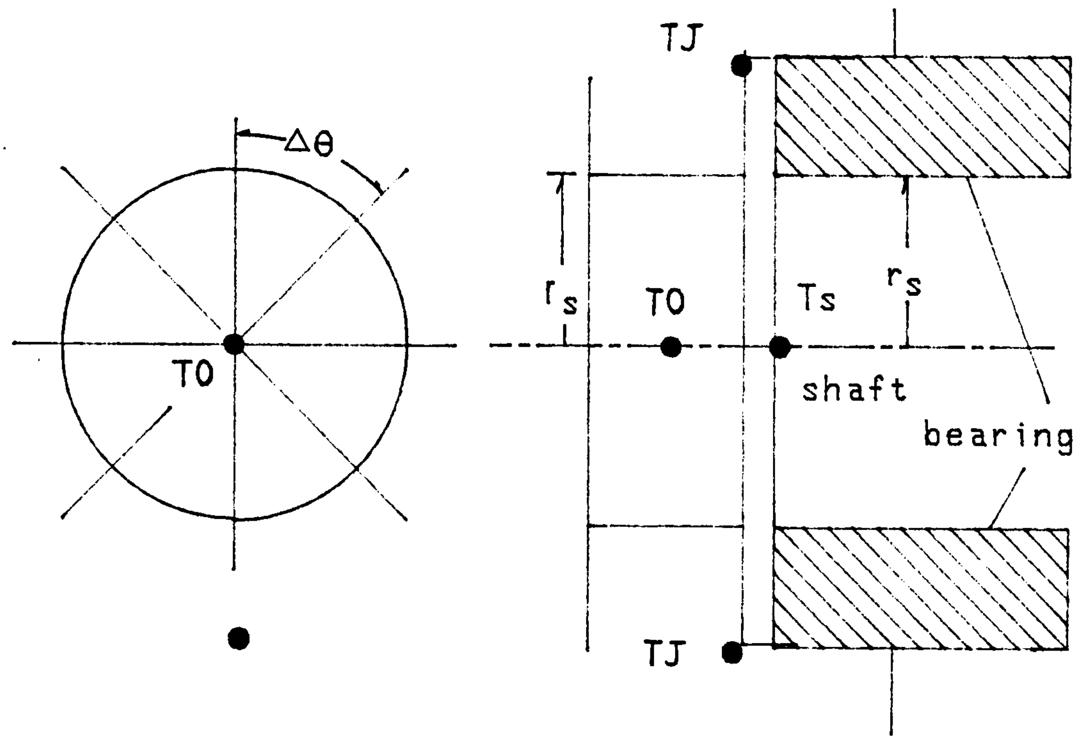

Figure C2. Front Plate Centerline Node

$$B_0(T_0)^{n+1} + 2\Sigma[B_j(T_j)^{n+1}] = C$$

$$B_0 = [\delta_{pb}\rho c_p/dt]dA - \Sigma B_j + (\gamma+\alpha)(T_0^{\,n})^3$$

$$\Delta A = \pi(r_s)^2 \qquad \alpha = \gamma = \epsilon_p\sigma\Delta A$$

$$B_j = -\tfrac{1}{2}k\delta_{pb}r_s\Delta\theta/r_b \qquad \Sigma B_j = -\pi k\delta_{pb}(r_s/r_b)$$

$$C = \{[\delta_{pb}\rho c_p/\Delta t]\Delta A + \Sigma B_j\}\,(T_0)^n - 2\Sigma[B_j(T_j)^n]$$

$$+ \gamma[(T_\infty)^4 + (T_S^{\,n})^4]$$

C3. Front Plate Node at Bearing Radius

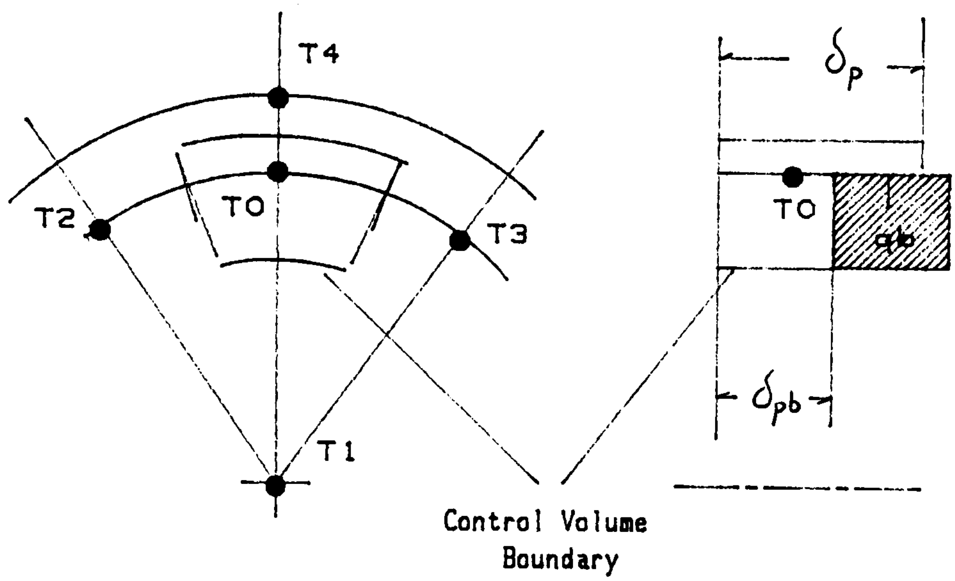

Figure C3. Front Plate Node at Bearing Radius

$$B_0(T_0)^{n+1} + B_1(T_1)^{n+1} + B_2(T_2)^{n+1} + B_3(T_3)^{n+1} + B_4(T_4)^{n+1} + B_b(T_b)^{n+1} = C$$

$$B_0 = [\rho c_p/\Delta t](\delta_p \Delta A_p + \delta_{pb} \Delta A_b) - B_1 - B_2 - B_3 - B_4 - B_b + (\gamma + \alpha)(T_0{}^n)^3$$

$$\Delta A_b = ½(r_b{}^2 - r_s{}^2)\Delta\theta \qquad \Delta A_p = ½(r_b + ¼\Delta r_{pb})\Delta r_{pb}\Delta\theta$$

$$\Delta A = \Delta A_b + \Delta A_p \qquad \gamma = \epsilon_p \sigma \Delta A \qquad \alpha = \epsilon_p \sigma \Delta A_p$$

$$B_1 = -½k\delta_{pb}(r_s\Delta\theta/r_b) \qquad B_2 = -½k[(\delta_{pb}(r_b - r_s) + ½\delta_p \Delta r_{pb})/(r_b\Delta\theta)]$$

$$B_3 = B_2 \qquad B_4 = -½k\delta_p[(r + ½\Delta r_{pb})\Delta\theta/\Delta r_{pb}]$$

$$B_b = -½(\Delta\theta/2\pi)[\ln(r_b/r_{or})/(2\pi k(\delta_p - \delta_{pb})) + C_R]^{-1}$$

$$C = [(\rho c_p/\Delta t)(\delta_p \Delta A_p + \delta_{pb} \Delta A_{pb}) + B_1 + B_2 + B_3 + B_4 + B_b](T_0)^n$$
$$- B_1(T_1)^n - B_2(T_2)^n - B_3(T_3)^n - B_4(T_4)^n - B_b(T_b)^n + \gamma(T_\infty)^4 + \alpha(T_c)^4$$

C4. Nodes at Δr_{pb}

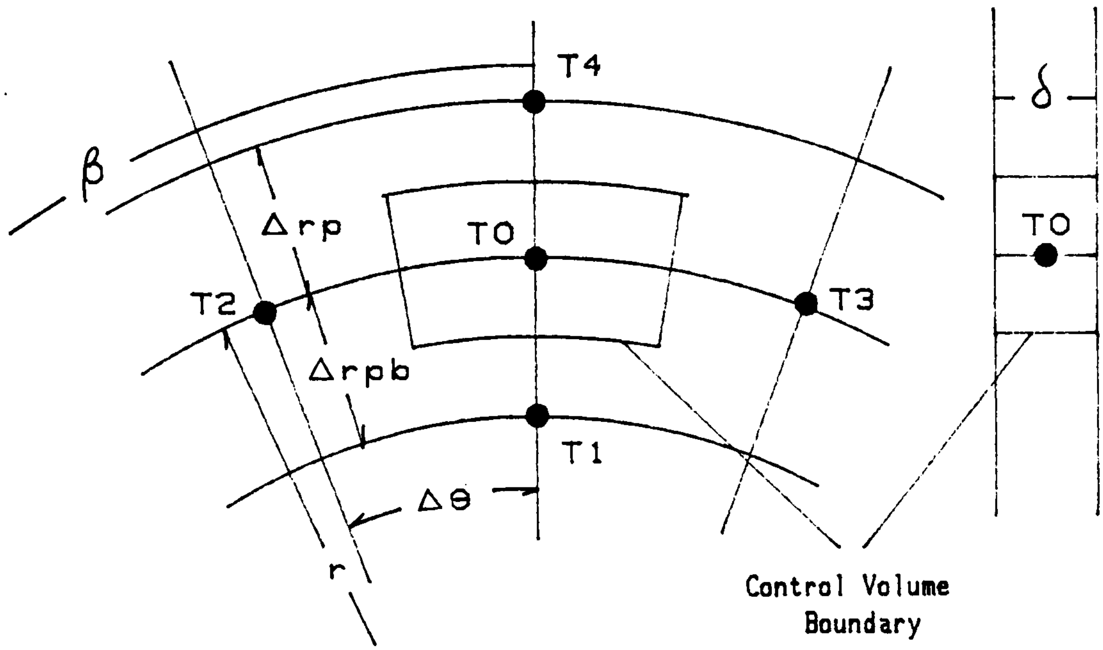

Figure C4. Nodes at Δr_{pb}

$$B_0(T_0)^{n+1} + B_1(T_1)^{n+1} + B_2(T_2)^{n+1} + B_3(T_3)^{n+1} + B_4(T_4)^{n+1} = C$$

$$B_0 = [\delta_f \rho c_p/\Delta t]\Delta A - B_1 - B_2 - B_3 - B_4 + (\gamma+\alpha)(T_0{}^n)^3$$

$$\Delta A_p = \tfrac{1}{2}(r+\tfrac{1}{4}\Delta r_p)\Delta r_p \Delta\theta \qquad \Delta A_{pb} = \tfrac{1}{2}(r-\tfrac{1}{4}\Delta r_{pb})\Delta r_{pb}\Delta\theta$$

$$\Delta A = \Delta A_p + \Delta A_{pb} \qquad \gamma = \alpha = \epsilon_p \sigma \Delta A$$

$$B_1 = -\tfrac{1}{2}k\delta_p[(r+\tfrac{1}{2}\Delta r_p)\Delta\theta/\Delta r_p] \qquad B_2 = -\tfrac{1}{4}k\delta_p[(\Delta r_p+\Delta r_{pb})/(r\Delta\theta)]$$

$$B_3 = -\tfrac{1}{4}k\delta_p[(\Delta r_p+\Delta r_{pb})/(r\Delta\theta)] \qquad B_4 = -\tfrac{1}{2}k\delta_p[(r-\tfrac{1}{2}\Delta r_{pb})\Delta\theta/\Delta r_{pb}]$$

$$C = \{[\delta_f\rho c_p/\Delta t]\Delta A + B_1 + B_2 + B_3 + B_4\}(T_0)^n - B_1(T_1)^n - B_2(T_2)^n - B_3(T_3)^n - B_4(T_4)^n + \gamma(T_\infty)^4 + \alpha(T_c)^4 + q_{He} + q_{bb}$$

C5. Nodes at $\Delta\theta_1$ / $\Delta\theta_2$ Interface

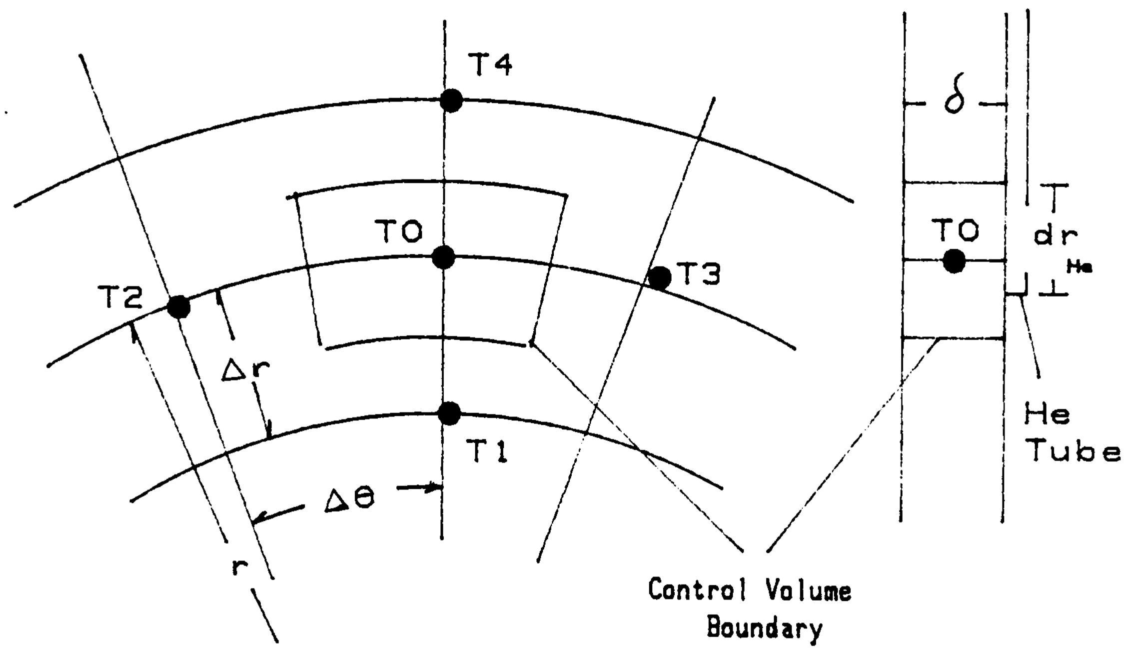

Figure C5. Nodes at $\Delta\theta_1$ / $\Delta\theta_2$ Interface

$$B_0(T_0)^{n+1} + B_1(T_1)^{n+1} + B_2(T_2)^{n+1} + B_3(T_3)^{n+1} + B_4(T_4)^{n+1} = C$$

$$B_0 = [\delta_p \rho c_p/\Delta t]\Delta A - B_1 - B_2 - B_3 - B_4 + (\gamma+\alpha)(T_0{}^n)^3$$

$$\Delta\theta = \tfrac{1}{2}(\Delta\theta_1+\Delta\theta_2)$$

$$\Delta A = r(\Delta\theta)\Delta r \qquad \gamma = \alpha = \epsilon_p \sigma \Delta A$$

$$B_1 = -\tfrac{1}{2}k\delta_p[(r-\tfrac{1}{2}\Delta r)\Delta\theta/\Delta r] \qquad B_2 = -\tfrac{1}{2}k\delta_p[\Delta r/(r\Delta\theta)]$$

$$B_3 = -\tfrac{1}{2}k\delta_p[\Delta r/(r\Delta\theta)] \qquad B_4 = -\tfrac{1}{2}k\delta_p[(r+\tfrac{1}{2}\Delta r)\Delta\theta/\Delta r]$$

$$C = [(\delta_p \rho c_p/\Delta t)\Delta A + B_1 + B_2 + B_3 + B_4](T_0)^n - B_1(T_1)^n - B_2(T_2)^n$$
$$- B_3(T_3)^n - 2B_4(T_\infty) + \gamma(T_\infty)^4 + \alpha(T_c{}^n)^4 + q_{He} + q_{bb}$$

C6. Front Plate Outer Boundary Nodes

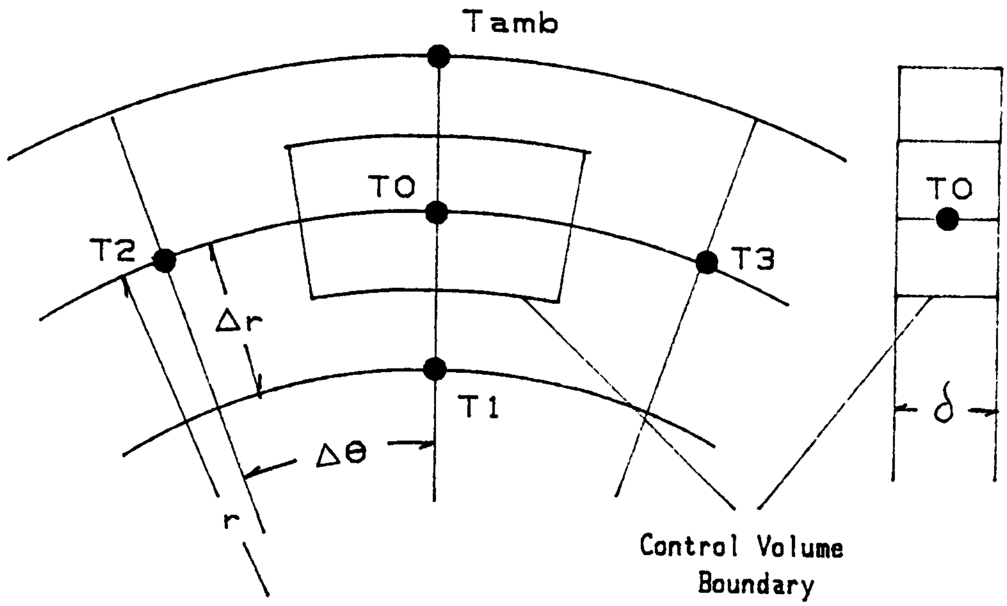

Figure C6. Front Plate Outer Boundary Nodes

$$B_0(T_0)^{n+1} + B_1(T_1)^{n+1} + B_2(T_2)^{n+1} + B_3(T_3)^{n+1} = C$$

$$B_0 = [\delta p \rho c_p/\Delta t]\Delta A - B_1 - B_2 - B_3 - B_4 + (\gamma+\alpha)(T_0{}^n)^3$$

$$\Delta A = r(\Delta\theta)\Delta r \qquad \gamma = \alpha = \epsilon_p \sigma \Delta A$$

$$B_1 = -\tfrac{1}{2}k\delta_p[(r-\tfrac{1}{2}\Delta r)\Delta\theta/\Delta r] \qquad B_2 = -\tfrac{1}{2}k\delta_p[\Delta r/(r\Delta\theta)]$$

$$B_3 = -\tfrac{1}{2}k\delta_p[\Delta r/(r\Delta\theta)] \qquad B_4 = -\tfrac{1}{2}k\delta_p[(r+\tfrac{1}{2}\Delta r)\Delta\theta/\Delta r]$$

$$C = [(\delta_p \rho c_p/\Delta t)\Delta A + B_1 + B_2 + B_3 + B_4](T_0)^n - B_1(T_1)^n - B_2(T_2)^n$$
$$- B_3(T_3)^n - 2B_4(T_\infty) + \gamma(T_\infty)^4 + \alpha(T_c{}^n)^4 + q_{He} + q_{bb}$$

APPENDIX D

N^{th} ORDER REGRESSION

PROGRAM LIST

```
C
C     ================================================
C     - CVFIT - Nth ORDER REGRESSION 'CURVEFIT' PROGRAM -
C     ================================================
C
C     --------------------------------------------------------
C     - NOTE:  DIMENSION STATEMENT LIMITS DEGREE OF EQUATION
C                AND THE MAXIMUM NUMBER OF COORDINATE INPUTS -
C     --------------------------------------------------------
C           - DEGREE OF EQUATION IS A(2D+1), R(D+1,D+2), &
C             T(D+2), WHERE D = MAXIMUM DEGREE OF EQUATION -
C     --------------------------------------------------------
C           - FOR THIS LISTING D=6, & 20 INPUT PTS ALLOWED -
C     --------------------------------------------------------
C
      DIMENSION  A(21), R(11,12), T(12), X(20), Y(20)
      WRITE (*,1010)
 90   WRITE (*,1020)
      READ (*,2020) N
      DO 100  I = 1,N
      WRITE (*,1030) I
      READ (*,2030) X(I),Y(I)
 100  CONTINUE
 200  WRITE (*,1040)
      READ (*,2040) KD
C
C     ------------------------------------------------------
C     - POPULATING MATRICES WITH A SYSTEM OF EQUATIONS -
C     ------------------------------------------------------
C
      A(1) = N
      KDP1 = KD + 1
      KDP2 = KD + 2
      KTWDP1 = 2*KD + 1
      DO 300  I = 1,N
      DO 310  J = 2,KTWDP1
      A(J) = A(J) + X(I)**(J-1)
 310  CONTINUE
      DO 320  K = 1,KDP1
      R(K,KDP2) = T(K) + Y(I)*(X(I)**(K-1))
      T(K) = T(K) + Y(I)*(X(I)**(K-1))
 320  CONTINUE
      T(KDP2) = T(KDP2) + Y(I)**2
 300  CONTINUE
C
C     ------------------------------------------------
C     - SOLVING SYSTEM OF EQUATIONS IN THE MATRICES -
C     ------------------------------------------------
C
      DO 400  J = 1,KDP1
      DO 410  K = 1,KDP1
      JPKM1 = J + K - 1
```

```
      R(J,K) = A(JPKM1)
  410 CONTINUE
  400 CONTINUE
      DO 420  J = 1,KDP1
      DO 430  K = J,KDP1
      IF (R(K,J).NE.0.)  GO TO 425
  430 CONTINUE
      WRITE (*,1050)
      GO TO 3000
  425 CONTINUE
      DO 440  I = 1,KDP2
      S = R(J,I)
      R(J,I) = R(K,I)
      R(K,I) = S
  440 CONTINUE
      Z = 1./R(J,J)
      DO 450  I = 1,KDP2
      R(J,I) = Z*R(J,I)
  450 CONTINUE
      DO 460  K = 1,KDP1
      IF (K.EQ.J)  GO TO 460
      Z = -1.*R(K,J)
      DO 470  I = 1,KDP2
      R(K,I) = R(K,I) + Z*R(J,I)
  470 CONTINUE
  460 CONTINUE
  420 CONTINUE
C
C     ------------------------------
C     - PRINT EQUATION COEFFICIENTS -
C     ------------------------------
C
      WRITE (*,1060)  R(1,KDP2)
      DO 500  J = 1,KD
      JP1 = J+1
      WRITE (*,1070) J,R(JP1,KDP2)
  500 CONTINUE
C
C     ------------------------------
C     - COMPUTE REGRESSION ANALYSIS -
C     ------------------------------
C
      P = 0.
      DO 600  J = 2,KDP1
      P = P + R(J,KDP2)*(T(J)-A(J)*T(1)/N)
  600 CONTINUE
      Q = T(KDP2) - T(1)**2./FLOAT(N)
      Z = Q-P
      I = N-KD-1
      IF (Q.EQ.0.)  GO TO 610
      XJ = P/Q
      WRITE (*,1080) XJ
```

```
      IF (XJ.LT.0.)  GO TO 610
      SQRJ = SQRT(XJ)
      WRITE (*,1090) SQRJ
 610  IF (I.EQ.0) GO TO 700
      ZQI = Z/FLOAT(I)
      IF (ZQI.LT.0.) GO TO 700
      SQRZQI = SQRT(ZQI)
      WRITE (*,1100) SQRZQI
C
C     ----------------------------------------------------
C     - COMPUTING Y-COORDINATE FROM ENTERED X-COORDINATE -
C     ----------------------------------------------------
C
 700  WRITE (*,1110)
      READ (*,2110) XI
      IF (XI.EQ.0.) GO TO 3000
      P = R(1,KDP2)
      DO 710  J = 1,KD
      JP1 = J + 1
      P = P + R(JP1,KDP2)*(XI**J)
 710  CONTINUE
      WRITE (*,1120) P
      GO TO 700
C
C     -------------------------------
C     - PROMPTS FOR ADDITIONAL RUNS -
C     -------------------------------
C           -----------------------------------
C           - & ZEROING OUT VALUES FOR RERUNS -
C           -----------------------------------
C
 3000 DO 225  J = 1,KTWDP1
      A(J) = 0.
 225  CONTINUE
      DO 235  K = 1,KDP2
      T(K) = 0.
 235  CONTINUE
      WRITE (*,1130)
      READ (*,2130) LOOP
      IF (LOOP.EQ.1)  GO TO 200
      IF (LOOP.EQ.2)  GO TO 90
C
C     -----------------
C     - WRITE FORMATS -
C     -----------------
C
 1010 FORMAT (/,1X,'N''TH-ORDER REGRESSION')
 1020 FORMAT (/,1X,'ENTER NUMBER OF KNOWN COORDINATE POINTS',/
     &          ,1X,'XX')
 1030 FORMAT (1X,'ENTER X,Y OF POINT #',I2,/,1X,'S#.###ES##',
     &          ,1X,'S#.###ES##')
 1040 FORMAT (/,1X,'ENTER THE DESIRED EQUATION DEGREE',/,1X,'X')
```

```
 1050 FORMAT (/,1X,'NO UNIQUE SOLUTION')
 1060 FORMAT (/,26X,'CONSTANT =',E15.8)
 1070 FORMAT (13X,'#',I1,' DEGREE COEFFICIENT =',E15.8)
 1080 FORMAT (/,13X,'COEFFICIENT OF DETERMINATION (R**2) =',E15.8)
 1090 FORMAT (13X,'COEFFICIENT OF CORRELATION =',E15.8)
 1100 FORMAT (13X,'STANDARD ERROR OF ESTIMATE =',E15.8,/)
 1110 FORMAT (/,1X,'INTERPOLATION: (ENTER 0. TO END SESSION)',/,/
     &            1X,'ENTER X-COORDINATE',/,1X,'S#.###ES##')
 1120 FORMAT (1X,'Y = ',E15.8)
 1130 FORMAT (/,/,1X,'ENTER ''1'' TO PROCESS ANOTHER EQUATION ',
     &            'WITH THE SAME',/,3X,'DATA BUT DIFFERENT DEGREE, OR',
     &            ' ENTER ''2'' TO PROCESS',/,3X,'AN EQUATION FROM NEW',
     &            ' DATA.',/,7X,'(DEFAULT TO END PROGRAM)',/,1X,'X')
C
C     ----------------
C     - READ FORMATS -
C     ----------------
C
 2020 FORMAT (I2)
 2030 FORMAT (E10.3,1X,E10.3)
 2040 FORMAT (I1)
 2110 FORMAT (E10.3)
 2130 FORMAT (I1)
C
C
C
      STOP
      END
```

APPENDIX E

CHOPPER MODEL PROGRAM

LIST

```
C
C     - EJTL.FOR -
C
C     - INITIAL SET-UP VALUES FOR THE PROGRAM -
C
      CHARACTER*12 FNAME
      DIMENSION TN(0:400), C(0:400), GAM(400), FBB(400), ANG(400),
     & B0(400), B1(400), B2(400), B3(400), B4(400), B5(300), DV(400),
     & B1QK(400), B2QK(400), B3QK(400), B4QK(400), B5QK(300),ND(8),
     & J1(400),J2(400),J3(400),J4(400),J5(300),JR(400),NSKIP(200),
     & RADIUS(400),TCR4(0:30),TPR4(0:30),BBRAD(400),PERQBS(0:30),
     & PERQB1(0:20),PERQB2(0:20),PERQBP(0:20),HHEDA(200),ALPH(400)
      WRITE (5,6005)
      PI = 3.141592654
      TWOPI = 2.*PI
C           - UNITS FOR SIGMA ARE (WATTS/CM**2 K**4) -
      SIGMA = 5.668 E-12
C           - STORAGE FILES FOR DATA -
      WRITE(5,'(A)') ' INPUT THE NEW FILE NAME FOR DATA STORAGE:  '
      READ (5,'(A)') FNAME
      OPEN (7,FILE=FNAME,STATUS='NEW')
      WRITE (7,6000)  FNAME
C     ----------------------------------------------
C     - ESTABLISHING SCOPE OF REQUESTED INVESTIGATION -
C     ----------------------------------------------
 50   WRITE (5,6001)
      READ (5,7001) KPLMT,KSHMT,KCOMB
      IF (KSHMT.EQ.1) THEN
      WRITE (5,6002)
      READ (5,7002) NPLATE
      ENDIF
C     --------------------
C     - MATERIAL CHOICES -
C     --------------------
      WRITE (5,6051)
      READ (5,7051) MATC,MATS,MATP
      MATB = 2
      CALL RHOVAL(MATB,RHOB)
      CALL RHOVAL(MATC,RHOC)
      CALL RHOVAL(MATS,RHOS)
      CALL RHOVAL(MATP,RHOP)
C     ----------------
C     - EMMISSIVITIES -
C     ----------------
      WRITE (5,6061)
      READ (5,7061) EPSCC,EPSCF,EPSCB,EPSCE,EPSS,EPSSE,EPSP
      EPSCC = EPSCC*SIGMA
      EPSCF = EPSCF*SIGMA
      EPSCB = EPSCB*SIGMA
      EPSCE = EPSCE*SIGMA
      EPSS  = EPSS *SIGMA
      EPSSE = EPSSE*SIGMA
```

```
      EPSP  = EPSP*SIGMA
C     -----------------------------------------------------
C     - SETTING CHOPPER DIMENSIONS & RESULTANT CONSTANTS -
C     -----------------------------------------------------
 101  WRITE (5,6011)
      READ (5,7011) RS,RC,RI1,RI2,RO
      WRITE (5,6012)
      READ (5,7012) DLCC,DLC,DLF
      WRITE (5,6013)
      READ (5,7013) KFNPHI,NUMFIN
      FINPHI = FLOAT(KFNPHI)*PI/180.
      SECPHI = TWOPI/FLOAT(NUMFIN)
      WRITE (5,6014)
      READ (5,7014) NDSSEC,NDSRC,NDSRI1,NDSRI2,NDSRO
C
C           - TWEEKING INPUT VALUES TO MAKE A MODEL ALONG PHI -
C
      DPHI = SECPHI / FLOAT(NDSSEC)
      NDSPHI = NUMFIN*NDSSEC
      X = (FINPHI/DPHI) + .5
      NDSFIN = INT(X) + 1
      NX = NDSFIN-1
      FNPHI = DPHI*FLOAT(NX)
      NDSGAP = NDSSEC - NDSFIN
      IF (FNPHI.EQ.FINPHI) GO TO 102
C
C           - RELATING THE MODIFIED INPUTS FOR THE MODEL -
C
      FNPHID = FNPHI*180./PI
      WRITE (5,6015) FNPHID,NDSSEC
      READ (5,7015) KDCAGN
      IF (KDCAGN.EQ.1) GO TO 101
C
C           - OTHER CHOPPER CONSTANTS -
C
      FINPHI = FNPHI
 102  GAPPHI = SECPHI - FINPHI
      DRC = (RC-RS)/FLOAT(NDSRC)
      DRI1 = (RI1-RC)/FLOAT(NDSRI1)
      DRI2 = (RI2-RI1)/FLOAT(NDSRI2)
      DRO = (RO-RI2)/FLOAT(NDSRO)
      DPHQ2 = DPHI/2.
      NDSRIC = NDSRI1 + NDSRI2 + 2*NDSRC + 2
C
C                 -CHOPPER MASS AND WEIGHT -
C
      PMFIN = RHOC*PI*DLF*(RO**2-RI2**2)*FINPHI/TWOPI
      PMFINS = PMFIN*NUMFIN
      PMRI2 = RHOC*PI*DLF*(RI2**2-RS**2)
      PMRI1 = RHOC*PI*(DLC-DLF)*(RI1**2-RS**2)
      PMRC = RHOC*PI*DLCC*(RC**2-RS**2)
      PMC = PMFINS + PMRI2 + PMRI1 + PMRC
```

```
      CMC = ((PMFINS+PMRI2)*DLF/2. + PMRI1*(DLF+DLC)/2.
     &            + PMRC*(DLC+DLCC/2.))/PMC
      WC = 981.*PMC
C     ---------------------------------------------------
C     - SETTING SHAFT DIMENSIONS & RESULTANT CONSTANTS -
C     ---------------------------------------------------
      IF (KSHMT.EQ.1) GO TO 210
      WRITE (5,6025)
      READ (5,7025) ZLA,ZLB
      WRITE (5,6026)
      READ (5,7026) NDSA,NDSB,QM
      DZA = ZLA/(FLOAT(NDSA)-.5)
      DZB = ZLB/(FLOAT(NDSB)-.5)
C           - SHAFT MASS & WEIGHT (W/PLATE MOUNT) -
      ZLS = ZLB + DLC + DLCC
      PMS = RHOS*PI*(RS**2)*(ZLS+ZLA)
      CMS = (ZLS-ZLA)/2.
      WS = 981.*PMS
      GO TO 215
C ------------------------------------------------
 210  WRITE (5,6027)
      READ (5,7027) ZLS,NDSB,QM
      ZLB = ZLS-(DLC+DLCC)
      DZB = ZLB/(FLOAT(NDSB)-.5)
C           - SHAFT MASS & WEIGHT (W/O PLATE MOUNT) -
      PMS = RHOS*PI*(RS**2)*ZLS
      CMS = ZLS/2.
      WS = 981.*PMS
C ------------------------------------------------
 215  WRITE (5,6063)
      READ (5,7063) CRC
C ------------------------------------------------
      IF (KPLMT.EQ.1) GO TO 301
C ------------------------------------------------
C           - SHAFT BEARINGS SIZE & LOCATION -
      IF (KCOMB.EQ.1) GO TO 231
      WRITE (5,6021)
      READ (5,7021) NUMBG
 231  IF (NUMBG.EQ.2) THEN
      WRITE (5,6023)
      N=1
      WRITE (5,6024) N
      READ (5,7024) ZLSB1,POSB1,ODB1,CRI1,CRO1
      ELSE
      WRITE (5,6022)
      READ (5,7022) ZLSB1,POSB1,ODB1,CRI1,CRO1
      ENDIF
      ZLB11 = POSB1-.5*ZLSB1
      ZLB21 = POSB1+.5*ZLSB1
      DB1 = (ODB1-RS)/2.
      RB1 = .5*DB1
      DRIR1 = .25*DB1
```

```
      DROR1 = .25*DB1
      NB1 = INT(PI/ASIN(RB1/(RS+DRIR1+RB1)))
      VBB1 = 4.19*(RB1**3)*FLOAT(NB1)
      VB1 = ZLSB1*TWOPI*((RS+.5*DRIR1)*DRIR1
     &            +(RS+DB1-.5*DROR1)*DROR1) + VBB1
      RO1 = ODB1/2
      ROR1 = RO1 - DROR1
      RIR1 = RS + DRIR1
      RIB1K = ALOG(RIR1/RS)/(TWOPI*ZLSB1)
      ROB1K = ALOG(RO1/ROR1)/(TWOPI*ZLSB1)
      IF (NUMBG.NE.2) GO TO 301
      N = 2
      WRITE (5,6024) N
      READ (5,7024) ZLSB2,POSB2,ODB2,CRI2,CRO2
      ZLB12 = POSB2-.5*ZLSB2
      ZLB22 = POSB2+.5*ZLSB2
      DB2 = (ODB2-RS)/2.
      RB2 = .5*DB2
      DRIR2 = .25*DB2
      DROR2 = .25*DB2
      NB2 = INT(PI/ASIN(RB2/(RS+DRIR2+DR2)))
      VBB2 = 4.19*(RB2**3)*FLOAT(NB2)
      VB2 = ZLSB2*TWOPI*((RS+.5*DRIR2)*DRIR2
     &                +(RS+DB2-.5*DROR2)*DROR2) + VBB2
      RO2 = ODB2/2
      ROR2 = RO2 - DROR2
      RIR2 = RS + DRIR2
      RIB2K = ALOG(RIR2/RS)/(TWOPI*ZLSB2)
      ROB2K = ALOG(RO2/ROR2)/(TWOPI*ZLSB2)
C           - BEARING LOADS BASED ON C/S WEIGHTS -
 301  WCS = WC + WS
      PMCS = WCS/981.
      IF (KPLMT.EQ.1) THEN
      PWBP = ((ZLS-CMC)*WC+(ZLS-CMS)*WS)/(ZLS+ZLA)
      ELSEIF (KCOMB.EQ.1) THEN
      PWB1 = ((ZLA+CMC)*WC+(ZLA+CMS)*WS)/(ZLA+DLC+DLCC+POSB1)
      PWBP = WCS - PWB1
      ELSEIF (NUMBG.EQ.1) THEN
      PWB1 = ((ZLS-CMC)*WC+(ZLS-CMS)*WS)/(ZLS-POSB1)
      ELSEIF (NUMBG.EQ.2) THEN
      PWB1 = ((POSB2+DLC+DLCC-CMC)*WC+(POSB2+DLC+DLCC-CMS)*WS)
     &           /(POSB2-POSB1)
      PWB2 = WCS - PWB1
      PWB1 = ABS(PWB1)
      PWB2 = ABS(PWB2)
      ENDIF
      IF (KPLMT.NE.1) THEN
      WRITE (5,6041)
      READ (5,7041) NBQ
      ENDIF
```

```
C     -------------------------------------------------
C     - SETTING PLATE DIMENSIONS & RESULTANT CONSTANTS -
C     -------------------------------------------------
      IF (NPLATE.EQ.1) GO TO 401
      IF (KSHMT.EQ.1) THEN
      RB = 0.
      NCL = 1
      WRITE (5,6030)
      READ (5,7030) DLP
      ELSE
      NCL = 2
      WRITE (5,6031)
      READ (5,7031) DLP,RB,DLPB,ZLBP
      WRITE (5,6032)
      READ (5,7032) CRIP,CROP
      DBP = RB - RS
      RBP = .5*DBP
      DRIRP = .25*DBP
      DRORP = .25*DBP
      NBP = INT(PI/ASIN(RBP/(RS+DRIRP+RBP)))
      VBBP = 4.19*(RBP**3)*FLOAT(NBP)
      VBP = ZLBP*TWOPI*((RS+.5*DRIRP)*DRIRP
     &              +(RS+DBP-.5*DRORP)*DRORP) + VBBP
      RIRP = RS + DRIRP
      RORP = RB - DRORP
      RIBPK = ALOG(RIRP/RS)/(TWOPI*ZLBP)
      ROBPK = ALOG(RB/RORP)/(TWOPI*ZLBP)
      ENDIF
      WRITE (5,6033)
      READ (5,7033) RHE,DHE,DMDTHE,TCOOL
      RHEI = RHE - 0.5*DHE
      RHEO = RHE + 0.5*DHE
      RE = (4.55E4)*DMDTHE/DHE
      IF (RE.LE.2300.) THEN
      HHE = (7.68E-4)/DHE
      ELSE
      HHE = (3.57E-6)*(RE**.8)/DHE
      ENDIF
      WRITE (5,6035)
      READ (5,7035)  NDRSPA, NDSPAT, NTHEQ2
      IF (NTHEQ2.LE.NDSPAT)  NTHEQ2 = NDSPAT + 1
C     ------------------------------------
C     - BLACKBODY POSITION AND INTENSITY -
C     ------------------------------------
 401  WRITE (5,6071)
      READ (5,7071) RBB,ZB,ZBBTP
      WRITE (5,6072)
      READ (5,7072) TBB,TAMB,DBBA,DPA
      APA = PI*(DPA**2)/4.
      ABBA = PI*(DBBA**2)/4.
      X = (RO-RBB)/DRO + .5
      Y = FLOAT(NDSFIN)/2. + .5
```

```
      KRAD = INT(X)*NDSFIN + INT(Y)
      RPA = DPA/2.
      RBBA = DBBA/2.
      EF = RPA/ZBBTP
      DF = ZBBTP/RBBA
      XF = 1. + (DF**2)*(1.+(EF**2))
      X = XF**2 - 4.*(EF**2)*(DF**2)
      FBBTH = .5*(XF-SQRT(X))
      TAMB4 = TAMB**4
      RADBB = FBBTH*SIGMA*ABBA*(TBB**4-TAMB4)
      EATB4C = EPSCB*ABBA*(TBB**4)
      EATB4P = EPSP*ABBA*(TBB**4)
      ZBSQD = ZB**2
      ZBBSQD = ZBBTP**2
      APSGMA = APA*SIGMA
      MUBB = 1
C -----------------------------------------------
      IF (NPLATE.EQ.1) GO TO 1001
      NDSPAR = NDRSPA + 1
      DRP = DPA/FLOAT(NDRSPA)
      K1 = 1 + 2*(NDSPAT-1)
      DTHE1 = .25*PI*DPA/(FLOAT(K1)*RBB)
      DTHE2 = (PI-(FLOAT(NTHEQ2)-.5)*DTHE1)/(FLOAT(NTHEQ2)+.5)
      NDSTHE = 2*NTHEQ2
      X = (RBB-.5*DPA-RB)/DRP - .25
      NDRPA1 = INT(X)
      NDRPA2 = NDRPA1 + NDRSPA
      NPA2M1 = NDRPA2 - 1
      DRPB = (RBB-.5*DPA-RB) - DRP*NDRPA1
      RPBND = RB + DRPB + DRP*FLOAT(NDRPA2+NDRPA1)
      RHEOP3 = RHEO + 3.*DRP
      IF (RPBND.GE.RHEOP3) THEN
      NDSRP = NCL + NDRPA2 + NDRPA1
      ELSE
      X = (RHEOP3-RB-DRPB)/DRP + .5
      NDSRP = INT(X) + NCL
      ENDIF
      DRPBQ2 = DRPB/2.
      RSQ2 = RS/2.
      RBPQ2 = RB + DRPBQ2
C     -------------------------------
C     - INITIALIZING CONSTANT ARRAYS -
C     -------------------------------
 1001 CONTINUE
C           -------------------
C           - FOR THE CHOPPER -
C           -------------------
C                 --------------
C                 - FIN SECTION -
C                 --------------
      I = 1
      DR = DRO
```

```
      DO 1021  J = NDSRO,1,-1
      R = RI2 + DR*FLOAT(J)
      IF (J.EQ.NDSRO)  THEN
      DA = (R-.25*DR)*DPHI*(.5*DR)
      GAMM = EPSCB*DA + EPSCE*DLF*R*DPHI
      GAME = .5*GAMM + EPSCE*DLF*DR/2.
      ALPHA = EPSCF*DA
      ALPHE = .5*ALPHA
      B1X = 0.
      BX = -.25*DLF*DR/(R*DPHI)
      ELSE
      DA = R*DPHI*DR
      GAMM = EPSCB*DA
      GAME = .5*GAMM + EPSCE*DLF*DR
      ALPHA = EPSCF*DA
      ALPHE = .5*ALPHA
      B1X = -.5*DLF*((R+.5*DR)*DPHI/DR)
      BX = -.5*DLF*(DR/(R*DPHI))
      ENDIF
      B4X = -.5*DLF*((R-.5*DR)*DPHI/DR)
      DO 1023  L = 1,NDSFIN
      B2QK(I) = BX
      B3QK(I) = BX
      IF (J.NE.NDSRO)  J1(I) = I-NDSFIN
      J2(I) = I-1
      J3(I) = I+1
      J4(I) = I+NDSFIN
      IF (L.EQ.1)  B2QK(I) = 0.
      IF (L.EQ.NDSFIN)  B3QK(I) = 0.
      IF ((L.GT.1).AND.(L.LT.NDSFIN)) THEN
      B1QK(I) = B1X
      B4QK(I) = B4X
      GAM(I) = GAMM
      ALPH(I) = ALPHA
      DA0 = DA
      ELSE
      B1QK(I) = .5*B1X
      B4QK(I) = .5*B4X
      GAM(I) = GAME
      ALPH(I) = ALPHE
      DA0 = .5*DA
      ENDIF
      DV(I) = DA0*DLF
      RADIUS(I) = R
      ANG(I) = DPHI*(FLOAT(L)-1.)
      FBB(I) = ZBSQD*DA0/PI
      I = I+1
 1023 CONTINUE
 1021 CONTINUE
```

```
C ----------------------------------------------
      NFEND = I-1
      NRI2ST = I
C ----------------------------------------------
C                 ----------
C                 - AT RI2 -
C                 ----------
      R = RI2
      DAO = .5*(R+.25*DRO)*DRO*DPHI
      DAI = .5*(R-.25*DRI2)*DRI2*DPHI
      DA = DAO + DAI
      DAC = .5*DAO + DAI
      GAMM = EPSCB*DA
      GAME = EPSCB*DAI + EPSCE*DLF*R*DPHI
      GAMC = EPSCB*DAC + EPSCE*DLF*.5*(R*DPHI+DRO)
      ALPHA = EPSCF*DA
      ALPHE = EPSCF*DAI
      ALPHC = EPSCF*DAC
      B1X = -.5*DLF*((R+.5*DRO)*DPHI/DRO)
      BF = -.25*DLF*((DRO+DRI2)/(R*DPHI))
      BE = -.25*DLF*(DRI2/(R*DPHI))
      B4X = -.5*DLF*((R-.5*DRI2)*DPHI/DRI2)
      DO 1032  L = 1,NDSSEC
      B2QK(I) = BF
      B3QK(I) = BF
      B4QK(I) = B4X
      J1(I) = I - NDSFIN
      J2(I) = I-1
      IF (L.EQ.1)  J2(I) = I+(NDSSEC-1)
      J3(I) = I+1
      IF (L.EQ.NDSSEC)  J3(I) = I-(NDSSEC-1)
      J4(I) = I+NDSSEC
      IF ((L.EQ.1).OR.(L.GT.NDSFIN))  B2QK(I) = BE
      IF (L.GE.NDSFIN)  B3QK(I) = BE
      IF ((L.EQ.1).OR.(L.EQ.NDSFIN)) THEN
      B1QK(I) = .5*B1X
      GAM(I) = GAMC
      ALPH(I) = ALPHC
      DA0 = DAC
      ELSEIF (L.GT.NDSFIN) THEN
      B1QK(I) = 0.
      GAM(I) = GAME
      ALPH(I) = ALPHE
      DA0 = DAI
      ELSE
      B1QK(I) = B1X
      GAM(I) = GAMM
      ALPH(I) = ALPHA
      DA0 = DA
      ENDIF
      DV(I) = DA0*DLF
      RADIUS(I) = R
```

```
      ANG(I) = DPHI*(FLOAT(L)-1.)
      FBB(I) = ZBSQD*DAO/PI
      I = I+1
 1032 CONTINUE
C                    ---------------------
C                    - BETWEEN RI2 AND RC -
C                    ---------------------
      NDSRI = NDSRI1 + NDSRI2
      NRIM1 = NDSRI - 1
      DO 1041  J = NRIM1,1,-1
      IF (J.EQ.NDSRI1)  THEN
      NI2LST = I-1
      R = RI1
      DAI2 = 0.5*(R+.25*DRI2)*DRI2*DPHI
      DAI1 = 0.5*(R-.25*DRI1)*DRI1*DPHI
      DA = DAI1 + DAI2
      B1X = -.5*DLF*((R+.5*DRI2)*DPHI/DRI2)
      BX = -.25*((DLF*DRI2+DLC*DRI1)/(R*DPHI))
      B4X = -.5*DLC*((R-.5*DRI1)*DPHI/DRI1)
      DVX = DLC*DAI1 + DLF*DAI2
      ELSE
      IF (J.GT.NDSRI1) THEN
      DR = DRI2
      R = RI1 + DR*FLOAT(J-NDSRI1)
      DLV = DLF
      ELSEIF (J.LT.NDSRI1) THEN
      DR = DRI1
      R = RC + DR*FLOAT(J)
      DLV = DLC
      ENDIF
      DA = R*DPHI*DR
      B1X = -.5*DLV*(R+.5*DR)*DPHI/DR
      BX = -.5*DLV*DR/(R*DPHI)
      B4X = -.5*DLV*(R-.5*DR)*DPHI/DR
      DVX = DLV*DA
      ENDIF
      GAMM = EPSCB*DA
      ALPHA = EPSCF*DA
      DO 1042  L = 1,NDSSEC
      B1QK(I) = B1X
      B2QK(I) = BX
      B3QK(I) = BX
      B4QK(I) = B4X
      J1(I) = I-NDSSEC
      J2(I) = I-1
      IF (L.EQ.1)  J2(I) = I+(NDSSEC-1)
      J3(I) = I+1
      IF (L.EQ.NDSSEC)  J3(I) = I-(NDSSEC-1)
      J4(I) = I+NDSSEC
      GAM(I) = GAMM
      ALPH(I) = ALPHA
      DV(I) = DVX
```

```
      RADIUS(I) = R
      ANG(I) = DPHI*(FLOAT(L)-1.)
      FBB(I) = ZBSQD*DA/PI
      I = I+1
 1042 CONTINUE
 1041 CONTINUE
C                      --------------
C                      - NODES AT RC -
C                      --------------
      NCCST = I
      NI1LST = I-1
C ----------------------------------------------
      R = RC
      DAI = .5*(R+.25*DRI1)*DRI1*DPHI
      DAC = .5*(R-.25*DRC)*DRC*DPHI
      DA = DAI + DAC
      DO 1051  K = 1,2
      IF (K.EQ.1)  THEN
      GAMM = EPSCB*DAI
      ALPHA = EPSCF*DA
      B1X = -.5*DLC*((R+.5*DRI1)*DPHI/DRI1)
      BX = -.25*DLC*((DRI1+DRC)/(R*DPHI))
      DLCV = DLC
      ELSE
C ----------------------------------------------
      NBBEND = I-1
C ----------------------------------------------
      GAMM = EPSCC*(DAC+DLCC*R*DPHI)
      ALPHA = 0.
      B1X = 0.
      BX = -.25*DLCC*DRC/(R*DPHI)
      DLCV = DLCC
      ENDIF
      B4X = -.5*DLCV*((R-.5*DRC)*DPHI/DRC)
      DO 1061  L = 1,NDSSEC
      B1QK(I) = B1X
      B2QK(I) = BX
      B3QK(I) = BX
      B4QK(I) = B4X
      B5QK(I) = B5X
      J2(I) = I-1
      IF (L.EQ.1)  J2(I) = I+(NDSSEC-1)
      J3(I) = I+1
      IF (L.EQ.NDSSEC)  J3(I) = I-(NDSSEC-1)
      J4(I) = I + 2*NDSSEC
      IF (K.EQ.1)  THEN
      J1(I) = I-NDSSEC
      J5(I) = I+NDSSEC
      FBB(I) = ZBSQD*DAI/PI
      ELSE .
      J1(I) = 0
      J5(I) = I-NDSSEC
```

```
      ENDIF
      GAM(I) = GAMM
      ALPH(I) = ALPHA
      DV(I) = DAC*DLCV
      RADIUS(I) = R
      ANG(I) = DPHI*(FLOAT(L)-1.)
      I = I+1
 1061 CONTINUE
 1051 CONTINUE
C                  ------------------------------------
C                  - NODES WITHIN THE CONNECTOR REGION -
C                  ------------------------------------
      DR = DRC
      DO 1071  J = NDSRC,1,-1
      R = RS + DR*FLOAT(J-1)
      IF (J.EQ.1) DA = .5*DR*(R+.25*DR)*DPHI
      B5X = -1.*DA/(DLC+DLCC)
      DO 1072  K = 1,2
      IF (K.EQ.1) THEN
      GAMM = 0.
      ALPHA = EPSCF*DA
      DLCV = DLC
      ELSE
      GAMM = EPSCC*DA
      ALPHA = 0.
      DLCV = DLCC
      ENDIF
      B1X = -.5*DLCV*((R+.5*DR)*DPHI/DR)
      BX = -.5*DLCV*DR/(R*DPHI)
      IF (J.EQ.1) THEN
      B4X = -.5*DLCV*DPHI*RS
      ELSE
      B4X = -.5*DLCV*((R-.5*DR)*DPHI/DR)
      ENDIF
      DO 1073  L = 1,NDSSEC
      B1QK(I) = B1X
      B2QK(I) = BX
      B3QK(I) = BX
      B4QK(I) = B4X
      B5QK(I) = B5X
      J1(I) = I - 2*NDSSEC
      J2(I) = I-1
      IF (L.EQ.1)  J2(I) = I+(NDSSEC-1)
      J3(I) = I+1
      IF (L.EQ.NDSSEC)  J3(I) = I-(NDSSEC-1)
      IF ((J.EQ.1).AND.(K.EQ.1)) THEN
      J4(I) = I + 2*NDSSEC - (L-1)
      ELSEIF ((J.EQ.1).AND.(K.EQ.2)) THEN
      J4(I) = I + NDSSEC + 2 - L
      ELSE
      J4(I) = I + 2*NDSSEC
      ENDIF
```

```
      IF (K.EQ.1)  J5(I) = I+NDSSEC
      IF (K.EQ.2)  J5(I) = I-NDSSEC
      GAM(I) = GAMM
      ALPH(I) = ALPHA
      DV(I) = DA*DLCV
      RADIUS(I) = R
      ANG(I) = DPHI*(FLOAT(L)-1.)
      I = I+1
 1073 CONTINUE
 1072 CONTINUE
 1071 CONTINUE
C -----------------------------------------------
C     - CHOPPER COMPLETED, THEREFORE,
      NDCTL = I-1
      NSATC = I
      NSATCC = I+1
C -----------------------------------------------
C           -------------------------
C           - FOR THE SHAFT SECTIONS -
C           -------------------------
      DA = PI*(RS**2)
C                 --------------
C                 - FIRST NODE -
C                 --------------
      BCQK1 = -.5*DLC*DPHI*RS
      IF (KSHMT.EQ.1) THEN
      ICCL = I
      B1QK(I) = 0.
      J1(I) = 0
      ALPH(I) = EPSSE*DA
      ELSE
      B1QK(I) = -1.*DA/(DZA+DLC)
      J1(I) = I+2 + NDSB
      ENDIF
      B2QK(I) = -1.*DA/(DLC+DLCC)
      JC1ST = I - 2*NDSSEC
      J2(I) = I+1
      DV(I) = DA*DLC
      I = I+1
C                 ---------------
C                 - SECOND NODE -
C                 ---------------
      BCQK2 = -.5*DLCC*DPHI*RS
      B1QK(I) = -1.*DA/(DLC+DLCC)
      B2QK(I) = -1.*DA/(DZB+DLCC)
      JC2ST = I - NDSSEC - 1
      J1(I) = I-1
      J2(I) = I+1
      DV(I) = DA*DLCC
      I = I+1
```

```
C                      ---------------------------------
C                      - FROM CHOPPER TO MOTOR HOUSING -
C                      ---------------------------------
      DZ = DZB
      BX = -.5*DA/DZ
      GAMM = 2.*EPSS*PI*RS*DZ
      GAME = EPSS*PI*RS*DZ
      DO 1121  J = 1,NDSB
      B1QK(I) = BX
      J1(I) = I-1
      IF (J.EQ.NDSB) THEN
      ISATM = I
      B2QK(I) = 0.
      J2(I) = 0
      GAM(I) = GAME
      DV(I) = .5*DZ*DA
      ELSE
      B2QK(I) = BX
      J2(I) = I+1
      GAM(I) = GAMM
      DV(I) = DZ*DA
      ENDIF
      RADIUS(I) = .5*DZ + DZ*FLOAT(J-1)
      I = I+1
 1121 CONTINUE
C ------------------------------------------------
      IF (KSHMT.EQ.1)  GO TO 1126
C ------------------------------------------------
C                      -------------------------------
C                      - FROM CHOPPER TO FRONT PLATE -
C                      -------------------------------
      DZ = DZA
      BX = -.5*DA/DZ
      GAMM = 2.*EPSS*PI*RS*DZ
      ALPHE = EPSSE*DA
      DO 1131  J = 1,NDSA
      IF (J.EQ.1) THEN
      J1(I) = I-2 - NDSB
      B1QK(I) = -1.*DA/(DZA+DLC)
      ELSE
      B1QK(I) = BX
      J1(I) = I-1
      ENDIF
      IF (J.EQ.NDSA) THEN
      ICCL = I
      B2QK(I) = 0.
      J2(I) = 0
      GAM(I) = .5*GAMM
      ALPH(I) = ALPHE
      DV(I) = .5*DZ*DA
      ELSE
      B2QK(I) = BX
```

```
      J2(I) = I+1
      GAM(I) = GAMM
      DV(I) = DZ*DA
      ENDIF
      RADIUS(I) = .5*DZ + DZ*FLOAT(J-1)
      I = I+1
 1131 CONTINUE
C ------------------------------------------------
C     - SHAFT COMPLETED, THEREFORE,
 1126 NDSLST = I-1
      IF (NPLATE.EQ.1) THEN
      NDTL = I - 1
      GO TO 1320
      ENDIF
      NDPFST = I
      JTB = I+1
C ------------------------------------------------
C            -----------------
C            - FOR THE PLATE -
C            -----------------
C                  -------------------
C                  - CENTERLINE NODE -
C                  -------------------
      IF (KSHMT.EQ.1)  THEN
      DA = .25*PI*(DRPB**2)
      DV(I) = DLP*DA
      BJQK1 = -.25*DLP*DTHE1
      BJQKX = -.25*DLP*(DTHE1+DTHE2)/2.
      BJQK2 = -.25*DLP*DTHE2
      SBJQK = -.5*PI*DLP
      ELSE
      DA = PI*(RS**2)
      DV(I) = DLPB*DA
      BJQK1 = -.5*DLPB*DTHE1*RS/RB
      BJQKX = -.25*DLPB*(DTHE1+DTHE2)*RS/RB
      BJQK2 = -.5*DLPB*DTHE2*RS/RB
      SBJQK = -1.*PI*DLPB*RS/RB
      ENDIF
      B1QK(I) = 0.
      B2QK(I) = 0.
      B3QK(I) = 0.
      B4QK(I) = 0.
      GAM(I) = EPSP*DA
      ALPH(I) = EPSP*DA
      RADIUS(I) = 0.
      ANG(I) = 0.
      I = I+1
      IF (KSHMT.EQ.1)  GO TO 1220
```

```
C                    ------------------------
C                    - AT THE BEARING RADIUS -
C                    ------------------------
      IPB1 = I
      IPB2 = I + NDSTHE - 1
      R = RB
      DO 1210  J = 1,NDSTHE
C ---------------------------------------------------
      IF (J.LT.NTHEQ2) THEN
      DTHEVX = DTHE1
      DTHEV2 = DTHE1
      DTHEV3 = DTHE1
      ELSEIF (J.EQ.NTHEQ2) THEN
      DTHEVX = .5*(DTHE1+DTHE2)
      DTHEV2 = DTHE1
      DTHEV3 = DTHE2
      ELSE
      DTHEVX = DTHE2
      DTHEV2 = DTHE2
      DTHEV3 = DTHE2
      ENDIF
C ---------------------------------------------------
      DAPB = .5*(RB**2-RS**2)*DTHEVX
      DAP = .5*(R+.25*DRPB)*DRPB*DTHEVX
      B1QK(I) = -.5*DLPB*RS*DTHEVX/RB
      B2QK(I) = -.5*(DLPB*(RB-RS)+.5*DLP*DRPB)/(RB*DTHEV2)
      B3QK(I) = -.5*(DLPB*(RB-RS)+.5*DLP*DRPB)/(RB*DTHEV3)
      B4QK(I) = -.5*DLP*(R+.5*DRPB)*DTHEVX/DRPB
      IF (J.EQ.1)  B2QK(I) = 0.
      IF (J.EQ.NDSTHE)  B3QK(I) = 0.
      J1(I) = NDPFST
      J2(I) = I-1
      J3(I) = I+1
      J4(I) = I+NDSTHE
      GAM(I) = EPSP*(DAPB+DAP)
      ALPH(I) = EPSP*DAP
      DV(I) = DLPB*DAPB + DLP*DAP
      RADIUS(I) = R
      IF (J.LE.NTHEQ2)  ANG(I) = .5*DTHE1 + FLOAT(J-1)*DTHE1
      IF (J.GT.NTHEQ2)  ANG(I) = NTHEQ2*DTHE1 - .5*DTHE1
     &                             + FLOAT(J-NTHEQ2)*DTHE2
      I = I+1
 1210 CONTINUE
C                    ----------------
C                    - NODES AT DRPB -
C                    ----------------
 1220 R = RB + DRPB
      DO 1221  J = 1,NDSTHE
      IF (J.LT.NTHEQ2) THEN
      DTHEVX = DTHE1
      DTHEV2 = DTHE1
      DTHEV3 = DTHE1
```

```
      ELSEIF (J.EQ.NTHEQ2) THEN
      DTHEVX = .5*(DTHE1+DTHE2)
      DTHEV2 = DTHE1
      DTHEV3 = DTHE2
      ELSE
      DTHEVX = DTHE2
      DTHEV2 = DTHE2
      DTHEV3 = DTHE2
      ENDIF
      DA = (R+.5*(DRP-DRPB))*(.5*(DRP+DRPB))*DTHEVX
      B1QK(I) = -.5*DLP*(R-.5*DRPB)*DTHEVX/DRPB
      B2QK(I) = -.25*DLP*(DRP+DRPB)/(R*DTHEV2)
      B3QK(I) = -.25*DLP*(DRP+DRPB)/(R*DTHEV3)
      B4QK(I) = -.5*DLP*(R+.5*DRP)*DTHEVX/DRP
      IF (J.EQ.1)  B2QK(I) = 0.
      IF (J.EQ.NDSTHE)  B3QK(I) = 0.
      IF (KSHMT.EQ.1)  J1(I) = NDPFST
      IF (KSHMT.NE.1)  J1(I) = I - NDSTHE
      J2(I) = I-1
      J3(I) = I+1
      J4(I) = I + NDSTHE
      GAM(I) = EPSP*DA
      ALPH(I) = EPSP*DA
      DV(I) = DLP*DA
      RADIUS(I) = R
      IF (J.LE.NTHEQ2)  ANG(I) = .5*DTHE1 + FLOAT(J-1)*DTHE1
      IF (J.GT.NTHEQ2)  ANG(I) = NTHEQ2*DTHE1 - .5*DTHE1
     &                               + FLOAT(J-NTHEQ2)*DTHE2
      I = I+1
 1221 CONTINUE
C                  ------------------------------
C                  - THE REST OF THE FRONT PLATE -
C                  ------------------------------
      K1 = 0
      K2 = 0
      DR = DRP
      IMIP = I-1
      IP = 1
      DO 1231  K = 1,NDSRP
      R = RB + DRPB + DRP*FLOAT(K)
C -------------------------------------------------
      DO 1232  J = 1,NDSTHE
      IF ((K.GT.NDRPA1).AND.(K.LT.NDRPA2).AND.(J.LT.NDSPAT)) THEN
      NSKIP(IP) = 1
      GO TO 1233
      ENDIF
      IF (J.LT.NTHEQ2) THEN
      DTHEVX = DTHE1
      DTHEV2 = DTHE1
      DTHEV3 = DTHE1
      ELSEIF (J.EQ.NTHEQ2) THEN
      DTHEVX = .5*(DTHE1+DTHE2)
```

```
      DTHEV2 = DTHE1
      DTHEV3 = DTHE2
      ELSE
      DTHEVX = DTHE2
      DTHEV2 = DTHE2
      DTHEV3 = DTHE2
      ENDIF
      DA = R*DTHEVX*DR
      B1QK(I) = -.5*DLP*(R-.5*DR)*DTHEVX/DR
      B2QK(I) = -.5*DLP*DR/(R*DTHEV2)
      B3QK(I) = -.5*DLP*DR/(R*DTHEV3)
      B4QK(I) = -.5*DLP*(R+.5*DR)*DTHEVX/DR
      IF (J.EQ.1)  B2QK(I) = 0.
      IF (J.EQ.NDSTHE)  B3QK(I) = 0.
      J1(I) = I - NDSTHE
      J2(I) = I-1
      J3(I) = I+1
      J4(I) = I + NDSTHE
C -----------------------------------------------
      IF (K.EQ.NDRPA1) THEN
C -----------------------------------------------
      IF (J.LT.NDSPAT) THEN
      DA = .5*DRP*(R-.25*DRP)*DTHE1
      B2QK(I) = .5*B2QK(I)
      B3QK(I) = .5*B3QK(I)
      B4QK(I) = 0.
      ELSEIF (J.EQ.NDSPAT) THEN
      DA = DA - .25*DRP*(R+.25*DRP)*DTHE1
      B2QK(I) = .5*B2QK(I)
      B4QK(I) = .5*B4QK(I)
      ENDIF
C -----------------------------------------------
      ELSEIF ((K.GT.NDRPA1).AND.(K.LT.NDRPA2)) THEN
C -----------------------------------------------
      IF (J.EQ.NDSPAT) THEN
      DA = .5*DA
      B1QK(I) = .5*B1QK(I)
      B2QK(I) = 0.
      B4QK(I) = .5*B4QK(I)
      ENDIF
C -----------------------------------------------
      ELSEIF (K.EQ.NDRPA2) THEN
C -----------------------------------------------
      IF (J.LT.NDSPAT) THEN
      DA = .5*DRP*(R+.25*DRP)*DTHE1
      B1QK(I) = 0.
      B2QK(I) = .5*B2QK(I)
      B3QK(I) = .5*B3QK(I)
      ELSEIF (J.EQ.NDSPAT) THEN
      DA = DA - .25*DRP*(R-.25*DRP)*DTHE1
      B1QK(I) = .5*B1QK(I)
      B2QK(I) = .5*B2QK(I)
```

```
      ENDIF
C ------------------------------------------------
      ENDIF
C ------------------------------------------------
      GAM(I) = EPSP*DA
      ALPH(I) = EPSP*DA
      DV(I) = DLP*DA
      FBB(I) = ZBBSQD*DA/PI
C -------------------------------------------------
      RNDI = R - DR/2.
      RNDO = R + DR/2.
      IF ((RNDO.GT.RHEI).AND.(RNDI.LT.RHEO))  THEN
      K1 = K1 + 1
      IF (K1.EQ.1)  NHE1 = I
      IF ((RNDI.GE.RHEI).AND.(RNDO.LE.RHEO))  THEN
      HHEDA(IP) = DA*HHE
      GAM(I) = 0.
      ELSEIF ((RNDI.LE.RHEI).AND.(RNDO.GE.RHEO)) THEN
      HHEDA(IP) = R*DHE*DTHEVX*HHE
      GAM(I) = GAM(I) - EPSP*R*DHE*DTHE
      ELSEIF (RNDI.LE.RHEI)  THEN
      HHEDA(IP) = R*(RNDO-RHEI)*DTHEVX*HHE
      GAM(I) = GAM(I) - EPSP*R*(RNDO-RHEI)*DTHEVX*HHE
      ELSEIF (RNDO.GE.RHEO)  THEN
      HHEDA(IP) = R*(RHEO-RNDI)*DTHEVX*HHE
      GAM(I) = GAM(I) - EPSP*R*(RHEO-RNDI)*DTHEVX*HHE
      ENDIF
      ENDIF
      IF ((RNDO.GE.RHEO).AND.(J.EQ.NDSTHE))  K2 = K2+1
      IF (K2.EQ.1)  NHE2 = I
      IF (K2.EQ.1)  K2 = K2+1
 1233 RADIUS(I) = R
      IF (J.LE.NTHEQ2)  ANG(I) = .5*DTHE1 + FLOAT(J-1)*DTHE1
      IF (J.GT.NTHEQ2)  ANG(I) = NTHEQ2*DTHE1 - .5*DTHE1
     &                            + FLOAT(J-NTHEQ2)*DTHE2
      I = I+1
      IP = IP+1
 1232 CONTINUE
C ------------------------------------------------
 1231 CONTINUE
C ------------------------------------------------
      NDPLST = I-1
      NDTL = I-1
C ------------------------------------------------
      DO 1301  J = 1,NDSTHE
      RADIUS(I) = R + DRP
      IF (J.LE.NTHEQ2)  ANG(I) = .5*DTHE1 + FLOAT(J-1)*DTHE1
      IF (J.GT.NTHEQ2)  ANG(I) = NTHEQ2*DTHE1 - .5*DTHE1
     &                            + FLOAT(J-NTHEQ2)*DTHE2
      TN(I) = TAMB
      I = I+1
 1301 CONTINUE
```

```
C          -------------------------------------------
C          -SETTING CHOPPER RADIATION EFFECTS ON THE PLATE -
C          -------------------------------------------
      DO 1305  I = NDPFST,NDPLST
      R = RADIUS(I)
      IF (R.GT.RO)  THEN
      JR(I) = 0
      ELSEIF (R.GT.RI2) THEN
      NPSEEC = I
      X = (RO-R)/DRO + .5
      JR(I) = INT(X) + 1
      ELSEIF (R.GT.RI1) THEN
      X = (RI2-R)/DRI2 + .5
      JR(I) = NDSRO + INT(X) + 1
      ELSEIF (R.GT.RC) THEN
      X = (RI1-R)/DRI1 + .5
      JR(I) = NDSRO + NDSRI2 + INT(X) + 1
      ELSEIF (R.GE.RS) THEN
      X = (RC-R)/DRC + .5
      JR(I) = NDSRO + NDSRI2 + NDSRI1 + 2*INT(X) + 1
      ELSE
      JR(I) = 0
      ENDIF
 1305 CONTINUE
C          -------------------------------------------
C          - SETTING PLATE RADIATION EFFECTS ON THE CHOPPER -
C          -------------------------------------------
      DO 1310  I = 1,NDCTL
      R = RADIUS(I)
      IF (KSHMT.EQ.1) THEN
      IF (R.LE.DRPBQ2)  JR(I) = 0
      IF (R.GT.DRPBQ2)  THEN
      X = (R-DRPB)/DRP + .5
      JR(I) = INT(X) + 1
      ENDIF
      ELSEIF (KSHMT.NE.1) THEN
      IF (R.LE.RSQ2) THEN
      JR(I) = 0
      ELSEIF (R.LE.RBPQ2) THEN
      JR(I) = 1
      ELSEIF (R.GT.RBPQ2) THEN
      X = (R-RB)/DRP + .5
      JR(I) = INT(X) + 1
      ENDIF
      ENDIF
      IF (I.EQ.1)  LASTPR = JR(I)
 1310 CONTINUE
```

```
C     --------------------------------
C     - HEAT LOAD VALUES AND LOCATIONS -
C     --------------------------------
 1320 CONTINUE
C           ----------------
C           - SHAFT BEARINGS -
C           ----------------
      IF (KPLMT.EQ.1)  GO TO 1410
      DLBZ = ZLB21-ZLB11
      XNBZ1 = 1.+ZLB11/DZB
      XNBZ2 = 1.+ZLB21/DZB
      NBZ11 = INT(XNBZ1)
      NBZ21 = INT(XNBZ2)
      IBZ11 = NSATCC + NBZ11
      IBZ21 = NSATCC + NBZ21
      X = FLOAT(NBZ11+NBZ21)/2.
      IB1 = NSATCC + INT(X)
      I = NBZ11 + NSATCC
      IF (NBZ11.NE.NBZ21) GO TO 1402
      PERQB1(NBZ11) = 1.0
      GAM(I) = GAM(I) - (XNBZ2-XNBZ1)*DZB*TWOPI*RS*EPSS
      GO TO 1401
 1402 NBZ = NBZ11
      NX = NBZ + 1
      PERQB1(NBZ) = (FLOAT(NX)-XNBZ1)*DZB/DLBZ
      GAM(I) = GAM(I) - (FLOAT(NX)-XNBZ1)*DZB*TWOPI*RS*EPSS
 1404 NBZ = NBZ + 1
      I = NBZ + NSATCC
      IF (NBZ.EQ.NBZ21) GO TO 1403
      GAM(I) = 0.
      PERQB1(NBZ) = (DZB/DLBZ)
      GO TO 1404
 1403 PERQB1(NBZ) = (XNBZ2-FLOAT(NBZ))*DZB/DLBZ
      GAM(I) = GAM(I) - (XNBZ2-FLOAT(NBZ))*DZB*TWOPI*RS*EPSS
 1401 CONTINUE
C ------------------------------------------------
      IF (KCOMB.EQ.1) GO TO 1410
      IF (NUMBG.NE.2) GO TO 1415
C ------------------------------------------------
      DLBZ = ZLB22-ZLB12
      XNBZ1 = 1.+ZLB12/DZB
      XNBZ2 = 1.+ZLB22/DZB
      NBZ12 = INT(XNBZ1)
      NBZ22 = INT(XNBZ2)
      IBZ12 = NSATCC + NBZ12
      IBZ22 = NSATCC + NBZ22
      X = FLOAT(NBZ12+NBZ22)/2.
      IB2 = NSATCC + INT(X)
      I = NBZ12 + NSATCC
      IF (NBZ12.NE.NBZ22) GO TO 1406
      PERQB2(NBZ12) = 1.0
      GAM(I) = GAM(I) - (XNBZ2-XNBZ1)*DZB*TWOPI*RS*EPSS
```

```
      GO TO 1405
 1406 NBZ = NBZ12
      NX = NBZ + 1
      PERQB2(NBZ) = (FLOAT(NX)-XNBZ1)*DZB/DLBZ
      GAM(I) = GAM(I) - (FLOAT(NX)-XNBZ1)*DZB*TWOPI*RS*EPSS
 1408 NBZ = NBZ + 1
      I = NBZ + NSATCC
      IF (NBZ.EQ.NBZ22) GO TO 1407
      GAM(I) = 0.
      PERQB2(NBZ) = (DZB/DLBZ)
      GO TO 1408
 1407 PERQB2(NBZ) = (XNBZ2-FLOAT(NBZ))*DZB/DLBZ
      GAM(I) = GAM(I) - (XNBZ2-FLOAT(NBZ))*DZB*TWOPI*RS*EPSS
 1405 CONTINUE
C -----------------------------------------------
      GO TO 1415
C -----------------------------------------------
C           -----------------
C           - PLATE BEARING -
C           -----------------
 1410 ZLPB1 = ZLA - ZLBP
      XNBZ1 = 1. + ZLPB1/DZA + FLOAT(NDSB)
      NBZ1P = INT(XNBZ1)
      NBZ2P = NDSLST - NSATCC
      IBZ1P = NBZ1P + NSATCC
      X = FLOAT(NBZ1P+NBZ2P)/2.
      IBP = NSATCC + INT(X)
      I = NBZ1P + NSATCC
      IF (NBZ1P.NE.NBZ2P) GO TO 1412
      PERQBS(NBZ1P) = 1.0
      GAM(I) = GAM(I) - (FLOAT(NBZ1P)+.5-XNBZ1)*DZA*TWOPI*RS*EPSS
      GO TO 1411
 1412 NX = NBZ1P + 1
      PERQBS(NBZ1P) = (FLOAT(NX)-XNBZ1)*DZA/ZLBP
      GAM(I) = GAM(I)-(FLOAT(NX)-XNBZ1)*DZA*TWOPI*RS*EPSS
      DO 1413  N = NX,NBZ2P
      I = N + NSATCC
      PERQBS(N) = DZA/ZLBP
      IF (N.EQ.NBZ2P)  PERQBS(N) = .5*PERQBS(N)
      GAM(I) = 0.
 1413 CONTINUE
 1411 CONTINUE
      DO 1414  J = 1,NDSTHE
      I = NDPFST + J
      IF (J.LT.NTHEQ2) DTHE = DTHE1
      IF (J.EQ.NTHEQ2) DTHE = .5*(DTHE1+DTHE2)
      IF (J.GT.NTHEQ2) DTHE = DTHE2
      PERQBP(J) = TWOPI/DTHE
 1414 CONTINUE
 1415 CONTINUE
```

```
C ----------------------------------------------
      IF (NBQ.EQ.1) THEN
      IBO1 = IB1
      IBO2 = IB2
      ELSEIF (NBQ.EQ.2) THEN
      IBO1 = 0
      IBO2 = 0
      ENDIF
C           -----------------------------------------------
C           - FRONT PLATE HELIUM COOLING IS COVERED
C             IN THE LAST PLATE INITIALIZATIONS SECTION -
C           -----------------------------------------------
C           -------------------------------
C           - BLACKBODY RADIATION EFFECTS -
C           -------------------------------
C                 - ON THE CHOPPER -
      DO 1450  K = 1,NDSPHI
      OMEGA = DPHI*FLOAT(K-1)
      DO 1451  I = 1,NBBEND
      BETA = ANG(I) + OMEGA
      IF (BETA.GE.TWOPI)  BETA = BETA-TWOPI
      R4 = ((RADIUS(I)*SIN(BETA))**2
     &            +(RBB-RADIUS(I)*COS(BETA))**2+ZBSQD)**2
      BBRAD(I) = BBRAD(I) + EATB4C*(FBB(I)/R4)
 1451 CONTINUE
 1450 CONTINUE
      DO 1455  I = 1,NBBEND
      BBRAD(I) = BBRAD(I)/FLOAT(NDSPHI)
 1455 CONTINUE
C                 - ON THE FRONT PLATE -
      IF (NPLATE.EQ.1) GO TO 1500
      K = 0
      DO 1460  I = NDPFST,NDPLST
      THETA = ANG(I)
      XT = RADIUS(I)*SIN(THETA)
      YT = RADIUS(I)*COS(THETA)
      XQ = XT*(ZB/ZBBTP)
      YQ = RBB + (YT-RBB)*(ZB/ZBBTP)
      RQ = SQRT(XQ**2+YQ**2)
      IF (RQ.GE.RI2) THEN
      K = K+1
      IF (K.EQ.1)  NBBSTP = I
      R4 = ((RADIUS(I)*SIN(THETA))**2
     &            +(RBB-RADIUS(I)*COS(THETA))**2+ZBBSQD)**2
      BBRAD(I) = BBRAD(I) + EATB4P*(FBB(I)/R4)*GAPPHI*NUMFIN/TWOPI
      ELSEIF (RQ.GE.RO) THEN
      R4 = ((RADIUS(I)*SIN(THETA))**2
     &            +(RBB-RADIUS(I)*COS(THETA))**2+ZBBSQD)**2
      BBRAD(I) = BBRAD(I) + EATB4P*(FBB(I)/R4)
      ENDIF
 1460 CONTINUE
```

```
C     ------------------------------------------
C     -INITIALIZING THE MODEL TEMPERATURE PROFILE -
C     ------------------------------------------
 1500 DO 1510  I = 0,NDTL
      TN(I) = TAMB
 1510 CONTINUE
      TNB1 = TAMB
      TNB2 = TAMB
      TNBP = TAMB
C     -----------------------------------------------------
C     - RUN TIME, TIME INCREMENTS & CHOPPER SPIN SIMULATION -
C     -----------------------------------------------------
      WRITE (5,6091)
      READ (5,7091) KTMXMN,TMXSEC,DT,REVPS,TOL
      TIMMAX = 60.*FLOAT(KTMXMN) + TMXSEC
 1999 WRITE (5,6400)
      READ (5,7400)  KOUT
      IF ((KOUT.EQ.1).OR.(KOUT.EQ.3)) THEN
      WRITE (5,6401) RADBB
      IF (NUMBG.EQ.2) WRITE(5,6402)
      IF (KCOMB.EQ.1) WRITE(5,6403)
      WRITE (5,6405)
      ENDIF
      IF ((KOUT.EQ.2).OR.(KOUT.EQ.3)) THEN
      WRITE (7,6401) RADBB
      IF (NUMBG.EQ.2) WRITE(7,6402)
      IF (KCOMB.EQ.1) WRITE(7,6403)
      WRITE (7,6405)
      ENDIF
C     -----------------------
C     - SETTING SPIN VELOCITY -
C     -----------------------
      OMEGA = REVPS*TWOPI
C
C     ===================
C     - CALCULATION LOOP -
C     ===================
C     ------------------------------------------
C     - SETTING CONSTANTS DEPENDENT ON NODE TEMPS -
C     ------------------------------------------
 2000 CONTINUE
C           ---------------------------------
C           - RADIATION BETWEEN DISK AND PLATE -
C           ---------------------------------
      IF (NPLATE.EQ.1) GO TO 2007
      I = 1
      DO 2001  K=1,NDSRO
      ST4 = 0.
      DO 2002  J = 1,NDSFIN
      IF ((J.EQ.1).OR.(J.EQ.NDSFIN))  THEN
      ST4 = ST4 + (TN(I)**4)*DPHI/2.
      ELSE
```

```
      ST4 = ST4 + (TN(I)**4)*DPHI
      ENDIF
      I = I+1
 2002 CONTINUE
      TCR4(K) = (ST4+TAMB4*GAPPHI)/SECPHI
 2001 CONTINUE
      DO 2003  K2 = 1,NDSRIC
      K = NDSRO + K2
      ST4 = 0.
      DO 2004  J = 1,NDSSEC
      ST4 = ST4 + TN(I)**4
      I = I+1
 2004 CONTINUE
      TCR4(K) = ST4/NDSSEC
 2003 CONTINUE
      TCR4(0) = TN(ICCL)**4
C ----------------------------------------------
      TPR4(0) = TN(NDPFST)**4
      I = JTB
      DO 2005  K = 1,LASTPR
      ST4 = 0.
      DO 2006  J = 1,NDSTHE
      IF (J.LT.DTHEQ2)  ST4 = ST4 + (TN(I)**4)*DTHE1
      IF (J.EQ.DTHEQ2)  ST4 = ST4 + (TN(I)**4)*(DTHE1+DTHE2)/2.
      IF (J.GT.DTHEQ2)  ST4 = ST4 + (TN(I)**4)*DTHE2
      I = I+1
 2006 CONTINUE
      TPR4(K) = ST4/PI
 2005 CONTINUE
C          ------------
C          - BEARINGS -
C          ------------
 2007 IF (KPLMT.EQ.1) GO TO 2225
      TNBO1 = TN(IBO1)
      TNBI = TN(IB1)
      IF (TNBI.GT.50) CALL THREXP(MATS,TNB1,TNBI,RS,DB1,PTH)
      IF (TNBI.LE.50) PTH = 0.
      QB1 = (8.00E-9)*(PWB1+PTH)*RS*OMEGA
      TNI = TNB1
      CALL MATVAL(MATB,TNI,SPHT,XK)
      RCDT = RHOB*SPHT*VB1/DT
      BBI1 = -.5/(RIB1K/XK+CRI1)
      BBO1 = -.5/(ROB1K/XK+CRO1)
      IF (OMEGA.EQ.0.) BBO1 = 0.
      B10 = RCDT - BBI1 - BBO1
      CB1 = (RCDT+BBI1+BBO1)*TNI - BBI1*TNBI - BBO1*TNBO1 + QB1
      IF (NUMBG.EQ.2) THEN
      TNBO2 = TN(IBO2)
      TNBI = TN(IB2)
      IF (TNBI.GT.50) CALL THREXP(MATS,TNB2,TNBI,RS,DB2,PTH)
      IF (TNBI.LE.50) PTH = 0.
      QB2 = (8.00E-9)*(PWB2+PTH)*RS*OMEGA
```

```
      TNI = TNB2
      CALL MATVAL(MATB,TNI,SPHT,XK)
      RCDT = RHOB*SPHT*VB2/DT
      BBI2 = -.5/(RIB2K/XK+CRI2)
      BBO2 = -.5/(ROB2K/XK+CRO2)
      IF (OMEGA.EQ.0.) BBO2 = 0.
      B20 = RCDT - BBI2 - BBO2
      CB2 = (RCDT+BBI2+BBO2)*TNI - BBI2*TNBI - BBO2*TNBO2 + QB2
      ENDIF
 2225 IF ((KPLMT.EQ.1).OR.(KCOMB.EQ.1)) THEN
      TNBOP = TN(JTB)
      TNBI = TN(IBP)
      IF (TNBI.GT.50) CALL THREXP(MATS,TNBP,TNBI,RS,DBP,PTH)
      IF (TNBI.LE.50) PTH = 0.
      QBP = (8.00E-9)*(PWBP+PTH)*RS*OMEGA
      TNI = TNBP
      CALL MATVAL(MATB,TNI,SPHT,XK)
      RCDT = RHOB*SPHT*VBP/DT
      BBIP = -.5/(RIBPK/XK+CRIP)
      BBOP = -.5/(ROBPK/XK+CROP)
      IF (OMEGA.EQ.0.) BBOP = 0.
      BP0 = RCDT - BBIP - BBOP
      CBP = (RCDT+BBIP+BBOP)*TNI - BBIP*TNBI - BBOP*TNBOP + QBP
      ENDIF
C            ------------------
C            - FOR THE CHOPPER -
C            ------------------
      DO 2010  I = 1,NDCTL
      TNI = TN(I)
      CALL MATVAL(MATC,TNI,SPHT,XK)
      RCDT = RHOC*SPHT*DV(I)/DT
      B1(I) = XK*B1QK(I)
      B2(I) = XK*B2QK(I)
      B3(I) = XK*B3QK(I)
      IF (I.GE.JC1ST)  THEN
      CALL MATVAL(MATS,TNI,SPHTS,XKS)
      B4(I) = (1./(RS/XKS+CRC))*B4QK(I)
      ELSE
      B4(I) = XK*B4QK(I)
      ENDIF
      B0(I) = RCDT-B1(I)-B2(I)-B3(I)-B4(I)+(GAM(I)+ALPH(I))*(TNI**3)
      J1X = J1(I)
      J2X = J2(I)
      J3X = J3(I)
      J4X = J4(I)
      K = JR(I)
      C(I) = (RCDT+B1(I)+B2(I)+B3(I)+B4(I))*TNI - B1(I)*TN(J1X)
     &          - B2(I)*TN(J2X) - B3(I)*TN(J3X) - B4(I)*TN(J4X)
     &          + GAM(I)*TAMB4 + ALPH(I)*TPR4(K)
      IF (I.GE.NCCST)  THEN
      B5(I) = XK*B5QK(I)
      B0(I) = B0(I) - B5(I)
```

```
      J5X = J5(I)
      C(I) = C(I) + B5(I)*(TNI-TN(J5X))
      ENDIF
 2010 CONTINUE
C           -----------------
C           - FOR THE SHAFT -
C           -----------------
      DO 2020  I = NSATC,NDSLST
      TNI = TN(I)
      CALL MATVAL(MATS,TNI,SPHT,XK)
      RCDT = RHOS*SPHT*DV(I)/DT
      B1(I) = XK*B1QK(I)
      B2(I) = XK*B2QK(I)
      B0(I) = RCDT-B1(I)-B2(I)+GAM(I)*(TNI**3)
      J1X = J1(I)
      J2X = J2(I)
      C(I) = (RCDT+B1(I)+B2(I))*TNI - B1(I)*TN(J1X)
     &         -B2(I)*TN(J2X) + GAM(I)*TAMB4
      IF (I.EQ.NSATC)  THEN
      BC1 = (1./(RS/XKS+CRC))*BCQK1
      SBC1 = BC1*FLOAT(NDSPHI)
      B0(I) = B0(I) - SBC1
      SUMBT = 0.
      DO 2021  L = 1,NDSSEC
      JX = JC1ST + L - 1
      SUMBT = SUMBT + BC1*TN(JX)
 2021 CONTINUE
      C(I) = C(I) + SBC1*TNI - NUMFIN*SUMBT
      ELSEIF (I.EQ.NSATCC)  THEN
      BC2 = (1./(RS/XKS+CRC))*BCQK2
      SBC2 = BC2*FLOAT(NDSPHI)
      B0(I) = B0(I) - SBC2
      SUMBT = 0.
      DO 2022  L = 1,NDSSEC
      JX = JC2ST + L - 1
      SUMBT = SUMBT + BC2*TN(JX)
 2022 CONTINUE
      C(I) = C(I) + SBC2*TNI - NUMFIN*SUMBT
      ENDIF
      IF (I.EQ.ICCL) THEN
      B0(I) = B0(I) + ALPH(I)*(TNI**3)
      C(I) = C(I) + ALPH(I)*TPR4(0)
      ENDIF
      IF (I.EQ.ISATM) C(I) = C(I) + QM
      IF ((I.GE.IBZ11).AND.(I.LE.IBZ21)) THEN
      J = I - NSATCC
      B0(I) = B0(I) - BBI1*PERQB1(J)
      C(I) = C(I) + PERQB1(J)*BBI1*(TNI-TNB1)
      ENDIF
      IF ((I.GE.IBZ12).AND.(I.LE.IBZ22)) THEN
      J = I - NSATCC
      B0(I) = B0(I) - BBI2*PERQB2(J)
```

```
      C(I) = C(I) + PERQB2(J)*BBI2*(TNI-TNB2)
      ENDIF
      IF (I.GE.IBZ1P) THEN
      J = I - NSATCC
      B0(I) = B0(I) - BBIP*PERQBS(J)
      C(I) = C(I) + PERQBS(J)*BBIP*(TNI-TNBP)
      ENDIF
 2020 CONTINUE
C           ----------------------
C           - FOR THE FRONT PLATE -
C           ----------------------
      IF (NPLATE.EQ.1) GO TO 2031
      DO 2030  I = NDPFST,NDPLST
      IP = I - IMIP
      NSKP = NSKIP(IP)
      IF (NSKP.EQ.1)  GO TO 2030
      TNI = TN(I)
      CALL MATVAL(MATP,TNI,SPHT,XK)
      RCDT = RHOC*SPHT*DV(I)/DT
      B1(I) = XK*B1QK(I)
      B2(I) = XK*B2QK(I)
      B3(I) = XK*B3QK(I)
      B4(I) = XK*B4QK(I)
      B0(I) = RCDT-B1(I)-B2(I)-B3(I)-B4(I)+(GAM(I)+ALPH(I))*(TNI**3)
      J1X = J1(I)
      J2X = J2(I)
      J3X = J3(I)
      J4X = J4(I)
      C(I) = (RCDT+B1(I)+B2(I)+B3(I)+B4(I))*TNI - B1(I)*TN(J1X)
     &          -B2(I)*TN(J2X)-B3(I)*TN(J3X)-B4(I)*TN(J4X) + GAM(I)*TAMB4
      IF (I.EQ.NDPFST) THEN
      BJ1 = XK*BJQK1
      BJX = XK*BJQKX
      BJ2 = XK*BJQK2
      SBJ = XK*SBJQK
      B0(I) = B0(I) - SBJ
      SUMBT = 0.
      DO 2025  K = 1,NDSTHE
      J = NDPFST + K
      IF (K.LT.NTHEQ2) SUMBT = SUMBT + BJ1*TN(J)
      IF (K.EQ.NTHEQ2) SUMBT = SUMBT + BJX*TN(J)
      IF (K.GT.NTHEQ2) SUMBT = SUMBT + BJ2*TN(J)
 2025 CONTINUE
      C(I) = C(I) + SBJ*TNI - 2.*SUMBT
      ENDIF
      IF (I.LE.NPSEEC) THEN
      K = JR(I)
      C(I) = C(I) + ALPH(I)*TCR4(K)
      ELSE
      C(I) = C(I) + ALPH(I)*TAMB4
      ENDIF
      IF ((I.GE.IPB1).AND.(I.LE.IPB2)) THEN
```

```
      J = I - NDPFST
      BO(I) = BO(I) - BBOP*PERQBP(J)
      C(I) = C(I) + PERQBP(J)*BBOP*(TNI-TNBP)
      ENDIF
 2030 CONTINUE
C     -------------------------
C     - ADDING HEAT LOAD VALUES -
C     -------------------------
 2031 CONTINUE
C           -----------------
C           - BLACKBODY HEAT -
C           -----------------
      IF (MUBB.EQ.0)  GO TO 2200
      DO 2150  I = 1,NBBEND
      C(I) = C(I) + BBRAD(I)
 2150 CONTINUE
      IF (NPLATE.EQ.1) GO TO 3000
      DO 2155  I = NBBSTP,NDPLST
      C(I) = C(I) + BBRAD(I)
 2155 CONTINUE
 2200 CONTINUE
C           -----------------
C           - HELIUM COOLING -
C           -----------------
      DO 2310  I = NHE1,NHE2
      IP = I - IMIP
      C(I) = C(I) - (TN(I)-TCOOL)*HHEDA(IP)
 2310 CONTINUE
C     ------------------------
C     - GAUSS-SEIDEL ITERATION -
C     ------------------------
 3000 LOOP = 0
 3001 LOOP = LOOP + 1
      DTNMAX = 0.
C ----------------------------------------------
      IF (NBZ11.GT.0) THEN
      TNB1P1 = (CB1-(BBI1*TN(IB1)+BBO1*TNBO1))/B1O
      DX = TNB1P1 - TNB1
      DTN = ABS(DX)
      IF (DTN.GT.DTNMAX) DTNMAX = DTN
      TNB1 = TNB1P1
      ENDIF
C ----------------------------------------------
      IF (NBZ22.GT.0) THEN
      TNB2P1 = (CB2-(BBI2*TN(IB2)+BBO2*TNBO2))/B2O
      DX = TNB2P1 - TNB2
      DTN = ABS(DX)
      IF (DTN.GT.DTNMAX) DTNMAX = DTN
      TNB2 = TNB2P1
      ENDIF
C ----------------------------------------------
      IF (KSHMT.NE.1) THEN
```

```
      TNBPP1 = (CBP-(BBIP*TN(IBP)+BBOP*TN(JTB)))/BPO
      DX = TNBPP1 - TNBP
      DTN = ABS(DX)
      IF (DTN.GT.DTNMAX) DTNMAX = DTN
      TNBP = TNBPP1
      ENDIF
C ---------------------------------------------
      DO 3100  I = 1,NDCTL
      J1X = J1(I)
      J2X = J2(I)
      J3X = J3(I)
      J4X = J4(I)
      TNP1 = (C(I)-(B1(I)*TN(J1X)+B2(I)*TN(J2X)
     &               +B3(I)*TN(J3X)+B4(I)*TN(J4X))) / B0(I)
      IF (I.GE.NCCST) THEN
      J5X = J5(I)
      TNP1 = TNP1 - B5(I)*TN(J5X)/B0(I)
      ENDIF
      DX = TNP1 - TN(I)
      DTN = ABS(DX)
      IF (DTN.GT.DTNMAX)  DTNMAX = DTN
      TN(I) = TNP1
 3100 CONTINUE
C ---------------------------------------------
      DO 3200  I = NSATC,NDSLST
      J1X = J1(I)
      J2X = J2(I)
      TNP1 = (C(I)-(B1(I)*TN(J1X)+B2(I)*TN(J2X))) / B0(I)
      IF (I.EQ.NSATC)  THEN
      SUMBT = 0.
      DO 3210  L = 1,NDSSEC
      JX = JC1ST + L - 1
      SUMBT = SUMBT + BC1*TN(JX)
 3210 CONTINUE
      TNP1 = TNP1 - NUMFIN*SUMBT/B0(I)
      ELSEIF (I.EQ.NSATCC)  THEN
      SUMBT = 0.
      DO 3220  L = 1,NDSSEC
      JX = JC2ST + L - 1
      SUMBT = SUMBT + BC2*TN(JX)
 3220 CONTINUE
      TNP1 = TNP1 - NUMFIN*SUMBT/B0(I)
      ENDIF
      IF ((I.GE.IBZ11).AND.(I.LE.IBZ21)) THEN
      J = I-NSATCC
      TNP1 = TNP1 - BBI1*TNB1*PERQB1(J)/B0(I)
      ENDIF
      IF ((I.GE.IBZ12).AND.(I.LE.IBZ22)) THEN
      J = I-NSATCC
      TNP1 = TNP1 - BBI2*TNB2*PERQB2(J)/B0(I)
      ENDIF
      IF (I.GE.IBZ1P) THEN
```

```
      J = I-NSATCC
      TNP1 = TNP1 - BBIP*TNBP*PERQBS(J)/BO(I)
      ENDIF
      DX = TNP1 - TN(I)
      DTN = ABS(DX)
      IF (DTN.GT.DTNMAX)  DTNMAX = DTN
      TN(I) = TNP1
 3200 CONTINUE
C -----------------------------------------------
      IF (NPLATE.EQ.1) GO TO 3500
      DO 3300  I = NDPFST,NDPLST
      IP = I - IMIP
      NSKP = NSKIP(IP)
      IF (NSKP.EQ.1)  GO TO 3300
      J1X = J1(I)
      J2X = J2(I)
      J3X = J3(I)
      J4X = J4(I)
      TNP1 = (C(I)-(B1(I)*TN(J1X)+B2(I)*TN(J2X)
     &               +B3(I)*TN(J3X)+B4(I)*TN(J4X))) / BO(I)
      IF (I.EQ.NDPFST) THEN
      SUMBT = 0.
      DO 3310  K = 1,NDSTHE
      J = NDPFST + K
      IF (K.LT.NTHEQ2) SUMBT = SUMBT + BJ1*TN(J)
      IF (K.EQ.NTHEQ2) SUMBT = SUMBT + BJX*TN(J)
      IF (K.GT.NTHEQ2) SUMBT = SUMBT + BJ2*TN(J)
 3310 CONTINUE
      TNP1 = TNP1 - 2.*SUMBT/BO(I)
      ENDIF
      IF ((I.GE.IPB1).AND.(I.LE.IPB2)) THEN
      J = I - NDPFST
      TNP1 = TNP1 - BBOP*TNBP*PERQBP(J)/BO(I)
      ENDIF
      DX = TNP1 - TN(I)
      DTN = ABS(DX)
      IF (DTN.GT.DTNMAX)  DTNMAX = DTN
      TN(I) = TNP1
 3300 CONTINUE
C -----------------------------------------------
 3500 IF (DTNMAX.LE.TOL)  GO TO 4000
C -----------------------------------------------
      IF (LOOP.LT.10000)  GO TO 3001
      WRITE (5,6600)
      READ (5,7600)  LPAGN,TOL2
      IF (LPAGN.EQ.1)  THEN
      LOOP = 0
      IF (TOL2.GT.0.)  TOL = TOL2
      GO TO 3001
      ENDIF
      WRITE (5,6610)
      GO TO 4200
```

```
C     ---------------------------------------------------------------
C     - OUTPUT OF SENSED RADIATION LEVEL FOR EACH TIME INCREMENT -
C     ---------------------------------------------------------------
 4000 TIME = TIME + DT
      IF ((KOUT.NE.1).AND.(KOUT.NE.2).AND.(KOUT.NE.3))  GO TO 4100
      KTIMMN = INT(TIME/60.)
      TIMSC = TIME - FLOAT(KTIMMN*60)
      RAD = APSGMA*(TN(KRAD)**4-TAMB4)
C ------------------------------------------------
      IF ((KOUT.EQ.1).OR.(KOUT.EQ.3)) THEN
      IF (KPLMT.EQ.1) THEN
      WRITE (5,6411) KTIMMN,TIMSC,RAD,TN(KRAD),TNBP
      ELSEIF (KCOMB.EQ.1) THEN
      WRITE (5,6412) KTIMMN,TIMSC,RAD,TN(KRAD),TNBP,TNB1
      ELSEIF (NUMBG.EQ.1) THEN
      WRITE (5,6411) KTIMMN,TIMSC,RAD,TN(KRAD),TNB1
      ELSEIF (NUMBG.EQ.2) THEN
      WRITE (5,6412) KTIMMN,TIMSC,RAD,TN(KRAD),TNB1,TNB2
      ENDIF
      ENDIF
C ------------------------------------------------
      IF ((KOUT.EQ.2).OR.(KOUT.EQ.3)) THEN
      IF (KPLMT.EQ.1) THEN
      WRITE (7,6411) KTIMMN,TIMSC,RAD,TN(KRAD),TNBP
      ELSEIF (KCOMB.EQ.1) THEN
      WRITE (7,6412) KTIMMN,TIMSC,RAD,TN(KRAD),TNBP,TNB1
      ELSEIF (NUMBG.EQ.1) THEN
      WRITE (7,6411) KTIMMN,TIMSC,RAD,TN(KRAD),TNB1
      ELSEIF (NUMBG.EQ.2) THEN
      WRITE (7,6412) KTIMMN,TIMSC,RAD,TN(KRAD),TNB1,TNB2
      ENDIF
      ENDIF
C ------------------------------------------------
C     -------------------------------------------
C     - CHECKING REQUESTED RUN TIME OF PROGRAM -
C     -------------------------------------------
 4100 IF (TIME.GE.TIMMAX)  GO TO 4200
      GO TO 2000
C     ---------------------
C     - ADDITIONAL PROMPTS -
C     ---------------------
 4200 TIMMAX = TIME
      KTIMMN = INT(TIME/60.)
      TIMSC = TIME - 60.*FLOAT(KTIMMN)
      WRITE (5,6501) KTIMMN,TIMSC
      READ (5,7501) NDLST,MRNTM,KBBSW
C           -------------
C           - NODE LIST -
C           -------------
      IF ((KOUT.NE.2).AND.(KOUT.NE.3)) THEN
      WRITE (7,6401) RADBB
      IF (NUMBG.EQ.2) WRITE(7,6402)
```

```
      IF (KCOMB.EQ.1) WRITE(7,6403)
      WRITE (7,6405)
      IF (KPLMT.EQ.1) THEN
      WRITE (7,6411) KTIMMN,TIMSC,RAD,TN(KRAD),TNBP
      ELSEIF (KCOMB.EQ.1) THEN
      WRITE (7,6412) KTIMMN,TIMSC,RAD,TN(KRAD),TNBP,TNB1
      ELSEIF (NUMBG.EQ.1) THEN
      WRITE (7,6411) KTIMMN,TIMSC,RAD,TN(KRAD),TNB1
      ELSEIF (NUMBG.EQ.2) THEN
      WRITE (7,6412) KTIMMN,TIMSC,RAD,TN(KRAD),TNB1,TNB2
      ENDIF
      ENDIF
      IF (NDLST.NE.1)  GO TO 4300
      WRITE (7,8000)  KTIMMN,TIMSC
      IF (KSHMT.EQ.1) THEN
      IF (NUMBG.EQ.1) WRITE(7,8511) QB1
      IF (NUMBG.EQ.1) WRITE(7,8501) TNB1
      IF (NUMBG.EQ.2) WRITE(7,8512) QB1,QB2
      IF (NUMBG.EQ.2) WRITE(7,8502) TNB1,TNB2
      ELSEIF (KPLMT.EQ.1) THEN
      WRITE(7,8511) QBP
      WRITE(7,8501) TNBP
      ELSEIF (KCOMB.EQ.1) THEN
      WRITE(7,8513) QBP,QB1
      WRITE(7,8503) TNBP,TNB1
      ENDIF
C -----------------------------------------------
      DO 5000  N = 1,5
      IF (N.EQ.1)  THEN
      WRITE (7,8010)
      NWIDE = NDSFIN
      NBFOR = 0
      NLONG = NDSRO
      ELSEIF (N.EQ.2)  THEN
      WRITE (7,8100)
      NWIDE = NDSSEC
      NBFOR = NFEND
      NLONG = NDSRIC
      ELSEIF (N.EQ.3)  THEN
      WRITE (7,8200)  TN(NSATC), TN(NSATCC)
      WRITE (7,8210)
      WRITE (7,8230)
      NWIDE = NDSB
      NBFOR = NSATCC
      ELSEIF (N.EQ.4)  THEN
      IF (KSHMT.EQ.1)  GO TO 5000
      WRITE (7,8220)
      WRITE (7,8230)
      NWIDE = NDSA
      NBFOR = NSATCC + NDSB
      ELSEIF (N.EQ.5)  THEN
      IF (NPLATE.EQ.1) GO TO 5000
```

```
      WRITE (7,8401) TN(NDPFST)
      NWIDE = NDSTHE
      NBFOR = NDPFST
      IF (KSHMT.EQ.1) NLONG = NDSRP + 2
      IF (KSHMT.NE.1) NLONG = NDSRP + 3
      ENDIF
      NCOUNT = 0
C ------------------------------------------------
 5100 NDEND = NCOUNT + 8
      NX = NWIDE - NDEND
      IF (NX.LT.0)  THEN
      NDGRP = NWIDE - NCOUNT
      NSTOP = 1
      ELSEIF (NX.EQ.0)  THEN
      NDGRP = 8
      NSTOP = 1
      ELSE
      NDGRP = 8
      NSTOP = 0
      ENDIF
C ------------------------------------------------
      DO 5150  K = 1,NDGRP
      ND(K) = NBFOR + NCOUNT + K
      IF (K.EQ.1)  THEN
      N1 = ND(K)
      IF ((N.LE.2).OR.(N.EQ.5))  NG1 = INT((ANG(N1)*180./PI)+.5)
      IF ((N.EQ.3).OR.(N.EQ.4))   Z1 = RADIUS(N1)
      ELSEIF (K.EQ.2)  THEN
      N2 = ND(K)
      IF ((N.LE.2).OR.(N.EQ.5))  NG2 = INT((ANG(N2)*180./PI)+.5)
      IF ((N.EQ.3).OR.(N.EQ.4))   Z2 = RADIUS(N2)
      ELSEIF (K.EQ.3)  THEN
      N3 = ND(K)
      IF ((N.LE.2).OR.(N.EQ.5))  NG3 = INT((ANG(N3)*180./PI)+.5)
      IF ((N.EQ.3).OR.(N.EQ.4))   Z3 = RADIUS(N3)
      ELSEIF (K.EQ.4)  THEN
      N4 = ND(K)
      IF ((N.LE.2).OR.(N.EQ.5))  NG4 = INT((ANG(N4)*180./PI)+.5)
      IF ((N.EQ.3).OR.(N.EQ.4))   Z4 = RADIUS(N4)
      ELSEIF (K.EQ.5)  THEN
      N5 = ND(K)
      IF ((N.LE.2).OR.(N.EQ.5))  NG5 = INT((ANG(N5)*180./PI)+.5)
      IF ((N.EQ.3).OR.(N.EQ.4))   Z5 = RADIUS(N5)
      ELSEIF (K.EQ.6)  THEN
      N6 = ND(K)
      IF ((N.LE.2).OR.(N.EQ.5))  NG6 = INT((ANG(N6)*180./PI)+.5)
      IF ((N.EQ.3).OR.(N.EQ.4))   Z6 = RADIUS(N6)
      ELSEIF (K.EQ.7)  THEN
      N7 = ND(K)
      IF ((N.LE.2).OR.(N.EQ.5))  NG7 = INT((ANG(N7)*180./PI)+.5)
      IF ((N.EQ.3).OR.(N.EQ.4))   Z7 = RADIUS(N7)
      ELSEIF (K.EQ.8)  THEN
```

```
      N8 = ND(K)
      IF ((N.LE.2).OR.(N.EQ.5))  NG8 = INT((ANG(N8)*180./PI)+.5)
      IF ((N.EQ.3).OR.(N.EQ.4))   Z8 = RADIUS(N8)
      ENDIF
 5150 CONTINUE
C -----------------------------------------------
      IF ((N.EQ.3).OR.(N.EQ.4))  THEN
      IF (NDGRP.EQ.1) WRITE(7,8201)  Z1,TN(N1)
      IF (NDGRP.EQ.2) WRITE(7,8202)  Z1,Z2,TN(N1),TN(N2)
      IF (NDGRP.EQ.3) WRITE(7,8203)  Z1,Z2,Z3,TN(N1),TN(N2),TN(N3)
      IF (NDGRP.EQ.4) WRITE(7,8204)  Z1,Z2,Z3,Z4,TN(N1),TN(N2),TN(N3),
     &      TN(N4)
      IF (NDGRP.EQ.5) WRITE(7,8205)  Z1,Z2,Z3,Z4,Z5,TN(N1),TN(N2),
     &      TN(N3),TN(N4),TN(N5)
      IF (NDGRP.EQ.6) WRITE(7,8206)  Z1,Z2,Z3,Z4,Z5,Z6,TN(N1),TN(N2),
     &      TN(N3),TN(N4),TN(N5),TN(N6)
      IF (NDGRP.EQ.7) WRITE(7,8207)  Z1,Z2,Z3,Z4,Z5,Z6,Z7,TN(N1),TN(N2),
     &      TN(N3),TN(N4),TN(N5),TN(N6),TN(N7)
      IF (NDGRP.EQ.8) WRITE(7,8208)  Z1,Z2,Z3,Z4,Z5,Z6,Z7,Z8,
     &      TN(N1),TN(N2),TN(N3),TN(N4),TN(N5),TN(N6),TN(N7),TN(N8)
C -----------------------------------------------
      ELSE
      IF(NDGRP.EQ.1)  WRITE(7,8001) NG1
      IF(NDGRP.EQ.2)  WRITE(7,8002) NG1,NG2
      IF(NDGRP.EQ.3)  WRITE(7,8003) NG1,NG2,NG3
      IF(NDGRP.EQ.4)  WRITE(7,8004) NG1,NG2,NG3,NG4
      IF(NDGRP.EQ.5)  WRITE(7,8005) NG1,NG2,NG3,NG4,NG5
      IF(NDGRP.EQ.6)  WRITE(7,8006) NG1,NG2,NG3,NG4,NG5,NG6
      IF(NDGRP.EQ.7)  WRITE(7,8007) NG1,NG2,NG3,NG4,NG5,NG6,NG7
      IF(NDGRP.EQ.8)  WRITE(7,8008) NG1,NG2,NG3,NG4,NG5,NG6,NG7,NG8
      DO 5200  J = 1,NLONG
      DO 5300  K = 1,NDGRP
      ND(K) = NBFOR + (J-1)*NWIDE + NCOUNT + K
      IF (K.EQ.1)  N1 = ND(K)
      IF (K.EQ.2)  N2 = ND(K)
      IF (K.EQ.3)  N3 = ND(K)
      IF (K.EQ.4)  N4 = ND(K)
      IF (K.EQ.5)  N5 = ND(K)
      IF (K.EQ.6)  N6 = ND(K)
      IF (K.EQ.7)  N7 = ND(K)
      IF (K.EQ.8)  N8 = ND(K)
 5300 CONTINUE
      IF (NDGRP.EQ.1)  WRITE(7,8011)  RADIUS(N1),TN(N1)
      IF (NDGRP.EQ.2)  WRITE(7,8012)  RADIUS(N1),TN(N1),TN(N2)
      IF (NDGRP.EQ.3)  WRITE(7,8013)  RADIUS(N1),TN(N1),TN(N2),TN(N3)
      IF (NDGRP.EQ.4)  WRITE(7,8014)  RADIUS(N1),TN(N1),TN(N2),TN(N3),
     &                                TN(N4)
      IF (NDGRP.EQ.5)  WRITE(7,8015)  RADIUS(N1),TN(N1),TN(N2),TN(N3),
     &                                TN(N4),TN(N5)
      IF (NDGRP.EQ.6)  WRITE(7,8016)  RADIUS(N1),TN(N1),TN(N2),TN(N3),
     &                                TN(N4),TN(N5),TN(N6)
      IF (NDGRP.EQ.7)  WRITE(7,8017)  RADIUS(N1),TN(N1),TN(N2),TN(N3),
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     &                                        TN(N4),TN(N5),TN(N6),TN(N7)
      IF (NDGRP.EQ.8)  WRITE(7,8018)  RADIUS(N1),TN(N1),TN(N2),TN(N3),
     &                                        TN(N4),TN(N5),TN(N6),TN(N7),TN(N8)
 5200 CONTINUE
      ENDIF
C -----------------------------------------------
 5400 IF (NSTOP.EQ.1) GO TO 5000
      NCOUNT = NCOUNT + 8
      GO TO 5100
 5000 CONTINUE
C           ---------------------------
C           - BLACKBODY ON/OFF SWITCH -
C           ---------------------------
 4300 IF (KBBSW.NE.1) GO TO 4400
      IF (MUBB.EQ.1) THEN
      MUBB = 0
      ELSEIF (MUBB.EQ.0) THEN
      MUBB = 1
      ENDIF
C           - ADDITIONAL RUN TIME -
 4400 IF (MRNTM.EQ.1) THEN
      WRITE (5,6092)
      READ (5,7092) KTMXMN,TMXSEC,DT2,REVPS2,TOL2
      IF (DT2.GT.0.)  DT = DT2
      IF (TOL2.GT.0.)  TOL = TOL2
      IF(REVPS2.GT.0.)  REVPS = REVPS2
      IF(REVPS2.LT.0.)  REVPS = 0.
      TIMMAX = TIMMAX + 60.*FLOAT(KTMXMN) + TMXSEC
      GO TO 1999
      ENDIF
```

```
C     -----------------
C     - WRITE FORMATS -
C     -----------------
 6000 FORMAT (/,/,1X,'DATA FILE:  ',A12)
 6001 FORMAT (/,/,1X,'CHOOSE FROM THE FOLLOWING BEARING CONFIGURATIONS',
     &           /,1X,'(ENTER ''1'' UNDER YOUR CHOICE)',/,1X,'PLATE MOU'
     &           ,'NT',5X,'SHAFT MOUNT',5X,'OR COMBINATION',/,1X,'X',15X
     &           ,'X',15X,'X')
 6002 FORMAT (/,/,1X,'ENTER "1" IF YOU DO NOT WANT THE PLATE MODELED',
     &          /,1X,'X')
 6005 FORMAT (/,/,1X,'EJTL - A PROGRAM TO EVALUATE THE THERMAL PERFORMA'
     &           ,'NCE OF A',/,8X,'CHOPPER DEVICE IN THE  7V  CRYOGENIC'
     &           ,' TEST CHAMBER AT',/,8X,'THE ARNOLD ENGINEERING DEVEL'
     &           ,'OPMENT CENTER, TENNESSEE.'
     &           ,/,/,1X,'NOTE - DIMENSIONS USED IN THIS PROGRAM:',/,
     &           6X,'LENGTHS................CENTIMETERS',/,
     &           6X,'ANGLES.................DEGREES',/,
     &           6X,'AREAS..................CENTIMETERS**2',/,
     &           6X,'TEMPERATURES...........KELVIN DEGREES',/,
     &           6X,'MASS...................GRAMS',/,
     &           6X,'TIME...................SECONDS',/,
     &           6X,'HEAT TRANSFER..........WATTS')
 6011 FORMAT (/,/,1X,'INPUT THE SHAFT AND CHOPPER RADIAL DIMENSIONS',
     &           /,1X,'S.RADIUS',5X,'C.RADIUS',5X,'I1.RDIUS',5X,
     &           'I2.RDIUS',5X,'O.RADIUS',/,1X,5('XX.XXXX',6X))
 6012 FORMAT (/,/,1X,'INPUT THE CHOPPER DEPTHS',/,1X,'CONNECTOR DEPTH',
     &        3X,'INNER DISK D.',5X,'FIN DEPTH',/,1X,3('X.XXXX',12X))
 6013 FORMAT (/,/,1X,'INPUT THE FIN DIMENSIONS',/,1X,'RAD''L FIN WIDTH',
     &            5X,'# OF FINS',/,1X,'XXX',17X,'XX')
 6014 FORMAT (/,/,1X,'INPUT # OF NODES ALONG CHOPPER DIMENSIONS',/,1X,
     &           'SECTION WIDTH',5X,'C.RADIUS',5X,'I1.RDIUS',5X,'I2.RDI'
     &           ,'US',5X,'O.RADIUS',/,1X,'XX',16X,3('XX',11X),'XX')
 6015 FORMAT (/,/,1X,'THE MODEL WILL USE ',F5.1,' DEGREES FOR THE FIN W'
     &           ,'IDTH AND',/,1X,I3,' NODES ALONG THE SECTION CIRCUMFE'
     &           ,'RENCE.',/,/,1X,'INPUT ''1'' IF YOU WISH TO REDIMENSI'
     &           ,'ON THE CHOPPER',/,1X,'X')
 6021 FORMAT (/,/,1X,'ONE OR TWO BEARINGS MOUNTED ON THE SHAFT?',/,1X,
     &           'X')
 6022 FORMAT (/,/,1X,'INPUT THE WIDTH OF THE SHAFT BEARING, THE POSI'
     &     ,'TION OF ITS',/,1X,'CENTROID (MEASURED FROM THE BACK OF '
     &     ,'THE CHOPPER CONNECTOR),',/,1X,'THE OUTER DIAMETER, AND '
     & ,'THE CONTACT RESISTANCES',/,1X,'B''RING WIDTH',5X,'POSITION',5X
     & ,'O. DIA',5X,'INNER CR',4X,'OUTER CR',/,
     & 1X,'XX.XXXX',10X,'XXX.XXXX',5X,'X.XXXX',2(4X,'XXXXXX.X'))
 6023 FORMAT (/,/,1X,'INPUT THE WIDTHS OF THE SHAFT BEARINGS, THE PO'
     & ,'SITIONS OF THEIR',/,1X,'CENTROIDS (MEASURED FROM THE BACK O'
     & ,'F THE CHOPPER CONNECTOR),',/,1X,'THE OUTER DIAMETERS, '
     & ,'AND THE CONTACT RESISTANCES')
 6024 FORMAT (1X,'B''RING #',I1,' WIDTH',5X,'POSITION',5X,'O. DIA',
     &    5X,'INNER CR',4X,'OUTER CR',/,1X,'XX.XXXX',13X,'XXX.XXXX',
     &    5X,'X.XXXX',2(4X,'XXXXXX.X'))
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6025 FORMAT (/,/,1X,'INPUT THE SHAFT LENGTHS',/,1X,'PLATE TO CHOPPER',
   &     5X,'CHOPPER TO MOTOR',/,1X,'XX.XXXX',14X,'XX.XXXX')
6026 FORMAT (/,/,1X,'INPUT THE DESIRED # OF NODES ON THE SHAFT (IN ADD'
   &           ,'ITION TO',/,1X,'THE TWO NODES SET AT THE CHOPPER), A'
   &           ,'ND INPUT THE HEAT',/,1X,'LOAD GENERATED TO THE SHAFT'
   &          ,' FROM THE MOTOR HOUSING.',/,1X,'FROM PLATE TO CHOPPER'
   &           ,5X,'FROM CHOPPER TO MOTOR HOUSING',5X,'HEAT LOAD (WAT'
   &           ,'TS',/,1X,'XX',24X,'XX',32X,'SX.XXXESYY')
6027 FORMAT (/,/,1X,'INPUT THE SHAFT LENGTH, THE DESIRED # OF NODES',
   &           ' ON THE SHAFT,',/,1X,'(IN ADDITION TO THE TWO NODES',
   &           ' SET AT THE CHOPPER), AND THE HEAT',/,1X,'LOAD',
   &           ' GENERATED TO THE SHAFT FROM THE MOTOR HOUSING.',/,1X,
   &           'LENGTH',5X,'# OF NODES',5X,'HEAT LOAD',/,1X
   &           ,'XXX.XXX',4X,'XX',13X,'SX.XXXESYY')
6030 FORMAT (/,/,1X,'INPUT THE FRONT PLATE DEPTH',/,1X,'X.XXXX')
6031 FORMAT (/,/,1X,'INPUT THE FOLLOWING PLATE DIMENSIONS',/,1X,'DEPTH'
   &    ,5X,'B''RING O.R.',5X,'DEPTH AT B''RING',5X,'LENGTH OF B''RING'
   &    ,/,1X,'X.XXXX',4X,'X.XXXX',10X,'X.XXXX',14X,'X.XXXX')
6032 FORMAT (/,/,1X,'INPUT THE PLATE BEARING CONTACT RESISTANCES',/,
   &     1X,'CR AT SHAFT',5X,'CR AT PLATE',/,1X,2('XXXXXX.X',8X))
6033 FORMAT (/,/,1X,'INPUT THE PLATE COOLING STRIP DIMENSIONS, THE HE',
   &       'LIUM FLOWRATE',/,1X,'AND THE AVERAGE COOLANT TEMPERATURE'
   &       ,/,1X,'RADIAL POSITION',5X,'DIAMETER',5X,'DM/DT (GM/SEC)'
   &       ,5X,'AVG HE TEMP',/,1X,'XX.XXX',14X,'X.XXX',8X,'XX.XXX'
   &       ,13X,'XX.XXX')
6035 FORMAT (/,/,1X,'INPUT NODAL DENSITIES OF PLATE APERTURE MODEL',/,
   &           3X,'(NOTE:  NUMBER OF NODES ALONG THE APERTURE SETS',
   &           ' THE ENTIRE PLATE)',/,1X,'RADIAL',5X,'CIRCUMFERENCE',
   &      5X,'# OF NODES ALONG THETA * 1/2',/,1X,'X',10X,'X',17X,'XX')
6041 FORMAT (/,/,1X,'SHAFT BEARING SUPPORT TEMPERATURE',/,3X,'(ENTER ',
   &       '"1" FOR SHAFT VALUE OR "2" FOR AMBIENT)',/,1X,'X')
6051 FORMAT(/,/,1X,'SELECT THE MATERIAL # FROM THE LIST BELOW FOR EACH'
   &       ,' OF',/,1X,'THE MODEL SECTIONS.',/,
   &       /,11X,'#',6X,'MATERIAL',/,10X,'---',5X,'--------',
   &       /,11X,'1......ALUMINUM',
   &       /,11X,'2......STAINLESS STEEL',
   &       /,11X,'3......COPPER',
   &       /,/,1X,'CHOPPER',5X,'SHAFT',5X,'FRONT PLATE',
   &       /,1X,'X',11X,'X',13X,'X')
6061 FORMAT(/,/,1X,'INPUT THE EMMISSIVITY VALUES FOR THE VARIOUS SURFA'
   &       ,'CES.',/,/,6X,'SOME TYPICAL VALUES ARE (FROM POLISHED TO',
   &       ' HEAVILY OXIDIZED):',
   &             /,12X,'ALUMINUM............  .04 TO .20',
   &             /,12X,'STAINLESS STEEL.....  .07 TO .50',
   &             /,12X,'COPPER..............  .02 TO .76',
   &             /,12X,'BLACK GLOSS PAINT...  .90',
   &       /,/,1X,'CHOPPER (BACK FACES BLACK BODY)',6X,'SHAFT',13X,
   &       'PLATE',/,1X,'CONNECTOR',3X,'FRONT',3X,'BACK',4X,'EDGE',5X,
   &       'SURFACE',3X,'END',5X,'SURFACE',
   &       /,1X,'X.XXX',7X,'X.XXX',3X,'X.XXX',3X,'X.XXX',4X,'X.XXX',5X,
   &       'X.XXX',5X,'X.XXX')
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6063 FORMAT(/,/,1X,'INPUT THE CONTACT RESISTANCE BETWEEN THE CHOPPER A'
   &      ,'ND THE SHAFT.',/,/,6X,'SOME TYPICAL VALUES AT 50K ARE:',
   &      /,11X,'--------   -----------------   ----------------',
   &      /,11X,'MATERIAL      CONTACT RES      CONTACT PRESSURE',
   &      /,11X,'            1/(WATTS/CM**2 K)  (DYNES/CM**2)E-5',
   &      /,11X,'--------   -----------------   ----------------',
   &      /,11X,' AL/AL         500 - 110            2 - 30',
   &      /,11X,'S.S./S.S.      330 -  12            5 - 700',
   &      /,11X,' CU/CU         0.6 - 0.3            6 - 700',
   &      /,11X,' AL/S.S.        17 -  12            4 - 270',
   &      /,/,1X,'CONTACT RESISTANCE',/,1X,'XXXXXX.X')
6071 FORMAT (/,/,1X,'INPUT THE RADIAL DISTANCE OF THE BLACKBODY (BB) '
   &           ,'SOURCE FROM THE',/,1X,'SHAFT CENTERLINE.  ALSO GIVE'
   &           ,' DISTANCES TO THE BACK FACES OF THE',/,1X,'CHOPPER '
   &           ,'FIN AND THE FRONT PLATE.',/,1X,'RADIAL POS',5X,
   &           'BB TO FIN',6X,'BB TO PLATE',/,1X,3('XX.XXX',9X))
6072 FORMAT (/,/,1X,'INPUT THE BB TEMPERATURE, THE CHAMBER AMBIENT TEM'
   &           ,'PERATURE, THE',/,1X,'BB APERTURE SIZE, AND THE PLATE'
   &           ,' APERTURE (PA) SIZE',/,1X,'BB TEMP',5X,'AMB TEMP',5X,
   &           'BB DIA',5X,'PA DIA',/,1X,'XXXX.X',6X,'XXX.XX',7X,
   &           2('X.XXXX',5X))
6091 FORMAT (/,/,1X,'INPUT THE DESIRED RUN TIME, TIME INCREMENT, C'
   &           ,'HOPPER SPEED,',/,1X,'AND GAUSS-SEIDEL TOLERANCE.',/,
   & /,1X,'   RUN TIME           INCREMENT     SPEED     TOLERANCE'
   &,/,1X,'(MIN)     (SEC)       (SEC)         (REV/S)   (K)'
   &,/,1X,'XXX',7X,'XX.XX',6X,'X.XXXX',8X,'XXX.X',5X,'X.XXESYY')
6092 FORMAT (/,/,1X,'INPUT ADDITIONAL RUN TIME, TIME INCREMENT, C'
   &           ,'HOPPER SPEED,',/,1X,'AND GAUSS-SEIDEL TOLERANCE.'
   &   ,/,1X,'(NOTE:  DEFAULTS ON LAST 3 LEAVE THE PREVIOUS',/,
   &      1X,'          VALUE, NEGATIVE VALUE SETS SPEED TO ZERO)',/,
   & /,1X,'   RUN TIME           INCREMENT     SPEED     TOLERANCE'
   &,/,1X,'(MIN)     (SEC)       (SEC)         (REV/S)   (K)'
   &,/,1X,'XXX',7X,'XX.XX',6X,'X.XXXX',8X,'XXX.X',5X,'X.XXESYY')
6400 FORMAT (/,/,1X,'RADIATION PRINTS - ENTER ''1'' FOR SCREEN PRINTS',
   &         /,1X,'                          ''2'' FOR FILE PRINTS',
   &         /,1X,'                       OR ''3'' FOR BOTH PRINTS',
   &         /,1X,'(NOTE:  DEFAULT GIVES NEITHER PRINT)',/,1X,'X')
6401 FORMAT (/,/,/,1X,'THE RADITION ''SEEN'' BY THE SENSOR',/,/
   &      ,6X,'NOTE:  SENSOR SEES ',E9.2,' WATTS FROM THE B.B.',/,/,
   & 3X,'TIME',7X,'FIN RAD',4X,'CRIT FIN',10X,'BEARING',/,
   & 1X,'MIN',3X,'SEC',4X,'(WATTS)',6X,'TEMP',12X,'TEMP (K)')
6402 FORMAT (38X,'B''RING #1',2X,'B''RING #2')
6403 FORMAT (38X,'PLATE BRG',2X,'SHAFT BRG')
6405 FORMAT (1X,9('-'),3X,9('-'),3X,8('-'),5X,16('-'))
6411 FORMAT (1X,I3,2X,F4.1,3X,E9.2,4X,F6.2,11X,F6.2)
6412 FORMAT (1X,I3,2X,F4.1,3X,E9.2,4X,F6.2,6X,F6.2,4X,F6.2)
6501 FORMAT (/,/,/,1X,'YOU HAVE REACHED THE END OF YOUR TIME REQUEST'
   & ,/,6X,'AT',I3,' MINUTES,',F4.1,' SECONDS.',/,/,1X,'ADDITIONAL ',
   &  'PROMPTS (USE ''1'' FOR YES):',/,1X,'NODE LIST?',5X,'MORE RU'
   & ,'N TIME?',5X,'TURN BLACKBODY ON/OFF?',/,1X,'X',14X,'X',18X,'X')
```

```
6600 FORMAT (/,/,1X,'EXCEEDED MAX LOOP # IN GAUSS-SEIDEL ITERATION',/,
   &            2X,'ENTER ''1'' FOR ANOTHER ITERATION RUN',/,1X,
   &            'MORE LOOPS?',5X,'NEW TOLERANCE?',/,
   &            1X,'X',15X,'X.XXXXXX')
6610 FORMAT (/,/,1X,'LAST ITERATION SET WAS UNSUCCESSFUL',/)
8000 FORMAT (/,/,/,1X,'MODEL NODE TEMPERATURES AT ',I3,' MIN  ',
   &            F5.2,' SEC')
8010 FORMAT (/,/,/,1X,'.....FOR THE CHOPPER FIN',/)
8008 FORMAT (/,9X,'ANGLE',/,1X,'RADIUS',2X,8(2X,I3,3X),/,1X,6('-'),
   &            2X,8(2X,'---',3X))
8007 FORMAT (/,9X,'ANGLE',/,1X,'RADIUS',2X,7(2X,I3,3X),/,1X,6('-'),
   &            2X,7(2X,'---',3X))
8006 FORMAT (/,9X,'ANGLE',/,1X,'RADIUS',2X,6(2X,I3,3X),/,1X,6('-'),
   &            2X,6(2X,'---',3X))
8005 FORMAT (/,9X,'ANGLE',/,1X,'RADIUS',2X,5(2X,I3,3X),/,1X,6('-'),
   &            2X,5(2X,'---',3X))
8004 FORMAT (/,9X,'ANGLE',/,1X,'RADIUS',2X,4(2X,I3,3X),/,1X,6('-'),
   &            2X,4(2X,'---',3X))
8003 FORMAT (/,9X,'ANGLE',/,1X,'RADIUS',2X,3(2X,I3,3X),/,1X,6('-'),
   &            2X,3(2X,'---',3X))
8002 FORMAT (/,9X,'ANGLE',/,1X,'RADIUS',2X,2(2X,I3,3X),/,1X,6('-'),
   &            2X,2(2X,'---',3X))
8001 FORMAT (/,9X,'ANGLE',/,1X,'RADIUS',4X,I3,3X,/,1X,6('-'),4X,'---')
8018 FORMAT (1X,F6.3,2X,8(F6.2,2X))
8017 FORMAT (1X,F6.3,2X,7(F6.2,2X))
8016 FORMAT (1X,F6.3,2X,6(F6.2,2X))
8015 FORMAT (1X,F6.3,2X,5(F6.2,2X))
8014 FORMAT (1X,F6.3,2X,4(F6.2,2X))
8013 FORMAT (1X,F6.3,2X,3(F6.2,2X))
8012 FORMAT (1X,F6.3,2X,2(F6.2,2X))
8011 FORMAT (1X,F6.3,2X,F6.2,2X)
8100 FORMAT (/,/,/,1X,'.....FOR THE CHOPPER INNER DISK',/,6X,'NOTE:  '
   &          ,'DOUBLE RADIAL VALUES INDICATE CONNECTOR REGION',/,
   &            13X,'WITH (CHOPPER/CONNECTOR) DISPLAYS.',/)
8200 FORMAT (/,/,/,1X,'.....FOR THE SHAFT NODES AT THE CHOPPER',/,/,
   &            1X,'TEMPERATURE AT CHOPPER   = ',F6.2,/,
   &            1X,'TEMPERATURE AT CONNECTOR = ',F6.2)
8208 FORMAT (2X,8(F6.3,3X),/,2X,8(F6.2,3X),/,1X,72('-'))
8207 FORMAT (2X,7(F6.3,3X),/,2X,7(F6.2,3X),/,1X,72('-'))
8206 FORMAT (2X,6(F6.3,3X),/,2X,6(F6.2,3X),/,1X,72('-'))
8205 FORMAT (2X,5(F6.3,3X),/,2X,5(F6.2,3X),/,1X,72('-'))
8204 FORMAT (2X,4(F6.3,3X),/,2X,4(F6.2,3X),/,1X,72('-'))
8203 FORMAT (2X,3(F6.3,3X),/,2X,3(F6.2,3X),/,1X,72('-'))
8202 FORMAT (2X,2(F6.3,3X),/,2X,2(F6.2,3X),/,1X,72('-'))
8201 FORMAT (2X,1(F6.3,3X),/,2X,1(F6.2,3X),/,1X,72('-'))
8210 FORMAT (/,/,1X,'.....FROM THE CHOPPER TO THE MOTOR HOUSING')
8220 FORMAT (/,/,1X,'.....FROM THE CHOPPER TO THE FRONT PLATE')
8230 FORMAT (/,17X,26('-'),/,6X,'.....KEY:  DISTANCE FROM CHOPPER (CM)'
   &          ,/,23X,'TEMPERATURE (K)',/,17X,26('-'),/,/,1X,72('-'))
8401 FORMAT (/,/,/,1X,'.....FOR THE FRONT PLATE',/,/,6X,'.....CENTER',
   &            'LINE NODE TEMPERATURE = ',F6.2)
8501 FORMAT (/,/,1X,'BEARING TEMPERATURE = ',F6.2)
```

```
 8502 FORMAT (/,/,1X,'BEARING TEMPERATURES',/,6X,'BEARING #1 = ',F6.2,
     &           /,6X,'BEARING #2 = ',F6.2)
 8503 FORMAT (/,/,1X,'BEARING TEMPERATURES',/,6X,'PLATE BEARING = ',
     &        F6.2,/,6X,'SHAFT BEARING = ',F6.2)
 8511 FORMAT (/,/,1X,'BEARING HEAT = ',E9.3,' WATTS')
 8512 FORMAT (/,/,1X,'BEARING HEAT LOADS (WATTS)',/,6X,'BEARING #1 = '
     &    ,E9.3,/,6X,'BEARING #2 = ',E9.3)
 8513 FORMAT (/,/,1X,'BEARING HEAT LOADS (WATTS)',/,6X,'PLATE BEARING',
     &    ' = ',E9.3,/,6X,'SHAFT BEARING = ',E9.3)
C     ----------------
C     - READ FORMATS -
C     ----------------
 7001 FORMAT (I1,15X,I1,15X,I1)
 7002 FORMAT (I1)
 7011 FORMAT (5(F7.4,6X))
 7012 FORMAT (F6.4,2(12X,F6.4))
 7013 FORMAT (I3,17X,I2)
 7014 FORMAT (I2,16X,3(I2,11X),I2)
 7015 FORMAT (I1)
 7021 FORMAT (I1)
 7022 FORMAT (F7.4,10X,F8.4,5X,F6.4,2(4X,F8.1))
 7024 FORMAT (F7.4,13X,F8.4,5X,F6.4,2(4X,F8.1))
 7025 FORMAT (F7.4,14X,F7.4)
 7026 FORMAT (I2,24X,I2,32X,E10.3)
 7027 FORMAT (F7.3,4X,I2,13X,E10.3)
 7030 FORMAT (F6.4)
 7031 FORMAT (F6.4,4X,F6.4,10X,F6.4,14X,F6.4)
 7032 FORMAT (2(F8.1,8X))
 7033 FORMAT (F6.3,14X,F5.3,8X,F6.3,13X,F6.3)
 7035 FORMAT (I1,10X,I1,17X,I2)
 7041 FORMAT (I1)
 7051 FORMAT (I1,11X,I1,13X,I1)
 7061 FORMAT (F5.3,7X,F5.3,3X,F5.3,3X,F5.3,4X,F5.3,5X,F5.3,5X,F5.3)
 7063 FORMAT (F8.1)
 7071 FORMAT (3(F6.3,9X))
 7072 FORMAT (F6.1,6X,F6.2,7X,2(F6.4,5X))
 7091 FORMAT (I3,7X,F5.2,6X,F6.4,8X,F5.1,4X,E9.2)
 7092 FORMAT (I3,7X,F5.2,6X,F6.4,8X,F5.1,4X,E9.2)
 7400 FORMAT (I1)
 7501 FORMAT (I1,14X,I1,18X,I1)
 7600 FORMAT (I1,15X,F8.6)
C
      STOP
      END
```

```
C     ==========================================================
C     - 'RHOVAL' ALLOWS CALLING OF DENSITY FOR A GIVEN MATERIAL -
C     ==========================================================
C     ------------------------------------
C     - NOTE:  DIMENSIONS -
C                  RHOM   (=)  GM/(CM**3)
C     ------------------------------------
      SUBROUTINE RHOVAL(MAT,RHOM)
C           - STAINLESS STEEL -
      IF (MAT.EQ.2) THEN
      RHOM = 7.75
C           - COPPER -
      ELSEIF (MAT.EQ.3) THEN
      RHOM = 8.906
C           - ALUMINUM (DEFAULT) -
      ELSE
      RHOM = 2.643
      ENDIF
      RETURN
      END
C     ================================================================
C     - 'MATVAL' CALCULATES THE MATERIAL VALUES AS FUNCTIONS OF TEMP -
C     ================================================================
C     ------------------------------------
C     - NOTE:  DIMENSIONS -
C                  SPHTM  (=)  J/(GM*K)
C                  XKM    (=)  W/(CM*K)
C     ------------------------------------
      SUBROUTINE MATVAL(MAT,TK,SPHTM,XKM)
C           - ALUMINUM -
      IF (MAT.EQ.1) THEN
      SPHTM = 3.189E-2 - (4.479E-3)*TK + (1.768E-4)*(TK**2)
     &            -(8.729E-7)*(TK**3)
      XKM = -4.623E-2 + (1.773E-2)*TK - (7.284E-5)*(TK**2)
C           - STAINLESS STEEL -
      ELSEIF (MAT.EQ.2) THEN
      SPHTM = 7.415E-3 - (1.314E-3)*TK + (6.833E-5)*(TK**2)
     &             - (3.083E-7)*(TK**3)
      XKM = -6.777E-3 + (1.606E-3)*TK - (6.310E-6)*(TK**2)
C           - COPPER -
      ELSEIF (MAT.EQ.3) THEN
      SPHTM = 5.825E-3 - (1.523E-3)*TK + (9.324E-5)*(TK**2)
     &            -(5.341E-7)*(TK**3)
      XKM = 83.67 - 2.263*TK + (1.648E-2)*(TK**2)
C           - DEFAULT -
      ELSE
      SPHTM = .65
      XKM = .142
      ENDIF
      RETURN
      END
```

```
C     ==============================================================
C     - 'THREXP' CALCULATES THE BEARING LOAD DUE TO THERMAL EXPANSION -
C     ==============================================================
C     ------------------------------
C     - NOTE:  DIMENSIONS -
C                 P  (=)  DYNES
C                 E  (=)  DYNES/CM**2
C     ------------------------------
      SUBROUTINE THREXP(MAT,TB,TS,R,DB,P)
      RB = .25*DB
C           - BEARINGS DEFAULTED AS S.S. -
      EB = 2.1E12
      IF (TB.LT.90.)  YB = (3.9-.33794*TB+(6.4109E-3)*TB**2)/1.0E5
      IF (TB.GE.90.)  YB = (-46.2+.63549*TB+(1.7272E-3)*TB**2)/1.0E5
C           - COPPER SHAFT -
      IF (MAT.EQ.3) THEN
      ES = 1.2E12
      IF (TS.LT.90.)  YS = (6.4-.45476*TS+(7.2880E-3)*TS**2)/1.0E5
      IF (TS.GE.90.)  YS = (-21.4+.17426*TS+(3.7878E-3)*TS**2)/1.0E5
C           - S.S. SHAFT -
      ELSEIF (MAT.EQ.2) THEN
      ES = EB
      IF (TS.LT.90.)  YS = (3.9-.33794*TB+(6.4109E-3)*TB**2)/1.0E5
      IF (TS.GE.90.)  YS = (-46.2+.63549*TB+(1.7272E-3)*TB**2)/1.0E5
C           - ALUMINUM SHAFT (DEFAULT SETTING) -
      ELSE
      ES = .77E12
      IF (TS.LT.90.)  YS = (5.2-.43996*TS+(8.8286E-3)*TS**2)/1.0E5
      IF (TS.GE.90.)  YS = (-8.0+.0500*TS+(5.0000E-3)*TS**2)/1.0E5
C ----------------------------------------------
      ENDIF
C ----------------------------------------------
      E = (YB*EB-YS*ES)/(EB/DB+ES/R)
      EPSB = YB + E/DB
      AC = 6.283*(RB**2)*EPSB
      IF (AC.GT.0.) THEN
      P = EB*EPSB*AC
      ELSE
      P = 0.
      ENDIF
C ----------------------------------------------
      RETURN
      END
```

APPENDIX F

SAMPLE PROGRAM

RUNS

F-1A. <u>SAMPLE PROGRAM RUN</u> - <u>SHAFT MOUNT CONFIGURATION</u>

```
EJTL - A PROGRAM TO EVALUATE THE THERMAL PERFORMANCE OF A
       CHOPPER DEVICE IN THE  7V  CRYOGENIC TEST CHAMBER AT
       THE ARNOLD ENGINEERING DEVELOPMENT CENTER, TENNESSEE.

NOTE - DIMENSIONS USED IN THIS PROGRAM:
     LENGTHS................CENTIMETERS
     ANGLES.................DEGREES
     AREAS..................CENTIMETERS**2
     TEMPERATURES...........KELVIN DEGREES
     MASS...................GRAMS
     TIME...................SECONDS
     HEAT TRANSFER..........WATTS


INPUT THE NEW FILE NAME FOR DATA STORAGE:
RUN1.DAT


CHOOSE FROM THE FOLLOWING BEARING CONFIGURATIONS
(ENTER '1' UNDER YOUR CHOICE)
PLATE MOUNT      SHAFT MOUNT      OR COMBINATION
X                X                X
0                1                0


ENTER "1" IF YOU DO NOT WANT THE PLATE MODELED
X
1


SELECT THE MATERIAL # FROM THE LIST BELOW FOR EACH OF
THE MODEL SECTIONS.

           #      MATERIAL
          ---     --------
           1......ALUMINUM
           2......STAINLESS STEEL
           3......COPPER

CHOPPER      SHAFT      FRONT PLATE
X            X              X
1            1
```

```
INPUT THE EMMISSIVITY VALUES FOR THE VARIOUS SURFACES.

     SOME TYPICAL VALUES ARE (FROM POLISHED TO HEAVILY OXIDIZED):
           ALUMINUM............  .04 TO .20
           STAINLESS STEEL.....  .07 TO .50
           COPPER..............  .02 TO .76
           BLACK GLOSS PAINT...  .90

CHOPPER (BACK FACES BLACK BODY)     SHAFT              PLATE
CONNECTOR    FRONT    BACK    EDGE     SURFACE    END     SURFACE
X.XXX        X.XXX    X.XXX   X.XXX    X.XXX      X.XXX   X.XXX
 .900         .900     .900    .900     .900       .900    .900


INPUT THE SHAFT AND CHOPPER RADIAL DIMENSIONS
S.RADIUS      C.RADIUS      I1.RDIUS      I2.RDIUS      O.RADIUS
XX.XXXX       XX.XXXX       XX.XXXX       XX.XXXX       XX.XXXX
  .1600         .5600        1.8000        4.4500        8.2500


INPUT THE CHOPPER DEPTHS
CONNECTOR DEPTH   INNER DISK D.     FIN DEPTH
X.XXXX            X.XXXX            X.XXXX
 .8000             .2300             .0900


INPUT THE FIN DIMENSIONS
RAD'L FIN WIDTH      # OF FINS
XXX                  XX
90                   2


INPUT # OF NODES ALONG CHOPPER DIMENSIONS
SECTION WIDTH      C.RADIUS      I1.RDIUS      I2.RDIUS      O.RADIUS
XX                 XX            XX            XX            XX
 6                  1             2             2             3


INPUT THE SHAFT LENGTH, THE DESIRED # OF NODES ON THE SHAFT,
(IN ADDITION TO THE TWO NODES SET AT THE CHOPPER), AND THE HEAT
LOAD GENERATED TO THE SHAFT FROM THE MOTOR HOUSING.
LENGTH      # OF NODES      HEAT LOAD
XXX.XXX     XX              SX.XXXESYY
  6.120     10                .000E+00
```

INPUT THE CONTACT RESISTANCE BETWEEN THE CHOPPER AND THE SHAFT.

SOME TYPICAL VALUES AT 50K ARE:

MATERIAL	CONTACT RES 1/(WATTS/CM**2 K)	CONTACT PRESSURE (DYNES/CM**2)E-5
AL/AL	500 - 110	2 - 30
S.S./S.S.	330 - 12	5 - 700
CU/CU	0.6 - 0.3	6 - 700
AL/S.S.	17 - 12	4 - 270

CONTACT RESISTANCE
XXXXXX.X
.0

ONE OR TWO BEARINGS MOUNTED ON THE SHAFT?
X
2

INPUT THE WIDTHS OF THE SHAFT BEARINGS, THE POSITIONS OF THEIR CENTROIDS (MEASURED FROM THE BACK OF THE CHOPPER CONNECTOR), THE OUTER DIAMETERS, AND THE CONTACT RESISTANCES

B'RING #1 WIDTH	POSITION	O. DIA	INNER CR	OUTER CR
XX.XXXX	XXX.XXXX	X.XXXX	XXXXXX.X	XXXXXX.X
.4000	1.7500	.9600	.0	.0
B'RING #2 WIDTH	POSITION	O. DIA	INNER CR	OUTER CR
XX.XXXX	XXX.XXXX	X.XXXX	XXXXXX.X	XXXXXX.X
.4000	4.5000	.9600	.0	.0

SHAFT BEARING SUPPORT TEMPERATURE
(ENTER "1" FOR SHAFT VALUE OR "2" FOR AMBIENT)
X
1

INPUT THE RADIAL DISTANCE OF THE BLACKBODY (BB) SOURCE FROM THE SHAFT CENTERLINE. ALSO GIVE DISTANCES TO THE BACK FACES OF THE CHOPPER FIN AND THE FRONT PLATE.

RADIAL POS	BB TO FIN	BB TO PLATE
XX.XXX	XX.XXX	XX.XXX
7.600	2.000	3.000

INPUT THE BB TEMPERATURE, THE CHAMBER AMBIENT TEMPERATURE, THE BB APERTURE SIZE, AND THE PLATE APERTURE (PA) SIZE

BB TEMP	AMB TEMP	BB DIA	PA DIA
XXXX.X	XXX.XX	X.XXXX	X.XXXX
300.0	20.00	.1500	3.2000

INPUT THE DESIRED RUN TIME, TIME INCREMENT, CHOPPER SPEED, AND GAUSS-SEIDEL TOLERANCE.

RUN TIME (MIN)	(SEC)	INCREMENT (SEC)	SPEED (REV/S)	TOLERANCE (K)
XXX	XX.XX	X.XXXX	XXX.X	X.XXESYY
1	.00	1.0000	20.0	.50E-05

RADIATION PRINTS - ENTER '1' FOR SCREEN PRINTS
'2' FOR FILE PRINTS
OR '3' FOR BOTH PRINTS
(NOTE: DEFAULT GIVES NEITHER PRINT)
X
3

THE RADITION 'SEEN' BY THE SENSOR

NOTE: SENSOR SEES 0.18E-03 WATTS FROM THE B.B.

TIME MIN	SEC	FIN RAD (WATTS)	CRIT FIN TEMP	BEARING TEMP (K) B'RING #1	B'RING #2
0	1.0	0.32E-08	20.00	20.06	20.03
0	2.0	0.52E-08	20.00	20.08	20.07
0	3.0	0.74E-08	20.01	20.10	20.10
0	4.0	0.96E-08	20.01	20.11	20.13
0	5.0	0.12E-07	20.01	20.12	20.16
0	6.0	0.14E-07	20.01	20.12	20.18
0	7.0	0.17E-07	20.01	20.13	20.20
0	8.0	0.20E-07	20.01	20.13	20.22
0	9.0	0.22E-07	20.02	20.14	20.23
0	10.0	0.25E-07	20.02	20.14	20.24
:	:	:	:	:	:
0	30.0	0.81E-07	20.06	20.19	20.34
:	:	:	:	:	:
0	45.0	0.12E-06	20.08	20.22	20.37
:	:	:	:	:	:
1	0.0	0.17E-06	20.11	20.25	20.40

YOU HAVE REACHED THE END OF YOUR TIME REQUEST
AT 1 MINUTES, 0.0 SECONDS.

```
ADDITIONAL PROMPTS (USE '1' FOR YES):
NODE LIST?      MORE RUN TIME?      TURN BLACKBODY ON/OFF?
X               X                   X
1               1


INPUT ADDITIONAL RUN TIME, TIME INCREMENT, CHOPPER SPEED,
AND GAUSS-SEIDEL TOLERANCE.
(NOTE:  DEFAULTS ON LAST 3 LEAVE THE PREVIOUS
        VALUE, NEGATIVE VALUE SETS SPEED TO ZERO)

   RUN TIME             INCREMENT      SPEED      TOLERANCE
(MIN)      (SEC)       (SEC)          (REV/S)    (K)
XXX        XX.XX       X.XXXX         XXX.X      X.XXESYY
  4


THE RADITION 'SEEN' BY THE SENSOR

     NOTE:  SENSOR SEES  0.18E-03 WATTS FROM THE B.B.

  TIME        FIN RAD    CRIT FIN          BEARING
MIN   SEC     (WATTS)      TEMP            TEMP (K)
                                      B'RING #1  B'RING #2

---------   ---------   --------     ----------------
  1  30.0    0.25E-06     20.17        20.31      20.45
  :   :         :           :            :          :
  2   0.0    0.33E-06     20.23        20.36      20.51
  :   :         :           :            :          :
  2  30.0    0.42E-06     20.28        20.42      20.56
  :   :         :           :            :          :
  3   0.0    0.50E-06     20.33        20.47      20.61
  :   :         :           :            :          :
  3  30.0    0.58E-06     20.38        20.52      20.67
  :   :         :           :            :          :
  4   0.0    0.66E-06     20.44        20.57      20.72
  :   :         :           :            :          :
  4  30.0    0.74E-06     20.49        20.62      20.77
  :   :         :           :            :          :
  5   0.0    0.81E-06     20.54        20.67      20.82
```

F-1B. SAMPLE NODE LIST - SHAFT MOUNT & NO PLATE

DATA FILE: RUN1.DAT

MODEL NODE TEMPERATURES AT 1 MIN 0.00 SEC

BEARING HEAT LOADS (WATTS)
BEARING #1 = 0.123E-01
BEARING #2 = 0.596E-02

BEARING TEMPERATURES
BEARING #1 = 20.25
BEARING #2 = 20.40

.....FOR THE CHOPPER FIN

RADIUS	ANGLE 0	30	60	90
8.250	20.11	20.11	20.11	20.11
6.983	20.11	20.11	20.11	20.11
5.717	20.11	20.11	20.11	20.11

.....FOR THE CHOPPER INNER DISK
NOTE: DOUBLE RADIAL VALUES INDICATE CONNECTOR REGION
WITH (CHOPPER/CONNECTOR) DISPLAYS.

RADIUS	ANGLE 0	30	60	90	120	150
4.450	20.11	20.11	20.11	20.11	20.11	20.11
3.125	20.11	20.11	20.11	20.11	20.11	20.11
1.800	20.11	20.11	20.11	20.11	20.11	20.11
1.180	20.11	20.11	20.11	20.11	20.11	20.11
0.560	20.11	20.11	20.11	20.11	20.11	20.11
0.560	20.11	20.11	20.11	20.11	20.11	20.11
0.160	20.11	20.11	20.11	20.11	20.11	20.11
0.160	20.11	20.11	20.11	20.11	20.11	20.11

.....FOR THE SHAFT NODES AT THE CHOPPER

TEMPERATURE AT CHOPPER = 20.11
TEMPERATURE AT CONNECTOR = 20.11

.....FROM THE CHOPPER TO THE MOTOR HOUSING

.....KEY: DISTANCE FROM CHOPPER (CM)
TEMPERATURE (K)

0.268	0.804	1.339	1.875	2.411	2.947	3.483	4.018
20.15	20.19	20.22	20.25	20.28	20.30	20.33	20.36
4.554	5.090						
20.38	20.38						

F-2A. SAMPLE PROGRAM RUN - COMBINATION MOUNT CONFIGURATION

```
EJTL - A PROGRAM TO EVALUATE THE THERMAL PERFORMANCE OF A
       CHOPPER DEVICE IN THE  7V  CRYOGENIC TEST CHAMBER AT
       THE ARNOLD ENGINEERING DEVELOPMENT CENTER, TENNESSEE.

NOTE - DIMENSIONS USED IN THIS PROGRAM:
     LENGTHS................CENTIMETERS
     ANGLES.................DEGREES
     AREAS..................CENTIMETERS**2
     TEMPERATURES...........KELVIN DEGREES
     MASS...................GRAMS
     TIME...................SECONDS
     HEAT TRANSFER..........WATTS


INPUT THE NEW FILE NAME FOR DATA STORAGE:
RUN3.DAT


CHOOSE FROM THE FOLLOWING BEARING CONFIGURATIONS
(ENTER '1' UNDER YOUR CHOICE)
PLATE MOUNT      SHAFT MOUNT      OR COMBINATION
X                X                X
                                  1


SELECT THE MATERIAL # FROM THE LIST BELOW FOR EACH OF
THE MODEL SECTIONS.

           #      MATERIAL
          ---     --------
           1......ALUMINUM
           2......STAINLESS STEEL
           3......COPPER

CHOPPER      SHAFT      FRONT PLATE
X            X             X
1            1             1


INPUT THE EMMISSIVITY VALUES FOR THE VARIOUS SURFACES.

     SOME TYPICAL VALUES ARE (FROM POLISHED TO HEAVILY OXIDIZED):
          ALUMINUM...........  .04 TO .20
          STAINLESS STEEL.....  .07 TO .50
          COPPER..............  .02 TO .76
          BLACK GLOSS PAINT...  .90
```

CHOPPER (BACK FACES BLACK BODY)				SHAFT		PLATE
CONNECTOR	FRONT	BACK	EDGE	SURFACE	END	SURFACE
X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX	X.XXX
.900	.900	.900	.900	.900	.900	.900

INPUT THE SHAFT AND CHOPPER RADIAL DIMENSIONS

S.RADIUS	C.RADIUS	I1.RDIUS	I2.RDIUS	O.RADIUS
XX.XXXX	XX.XXXX	XX.XXXX	XX.XXXX	XX.XXXX
.1600	.5600	1.8000	4.4500	8.2500

INPUT THE CHOPPER DEPTHS

CONNECTOR DEPTH	INNER DISK D.	FIN DEPTH
X.XXXX	X.XXXX	X.XXXX
.8000	.2300	.0900

INPUT THE FIN DIMENSIONS

RAD'L FIN WIDTH	# OF FINS
XXX	XX
90	2

INPUT # OF NODES ALONG CHOPPER DIMENSIONS

SECTION WIDTH	C.RADIUS	I1.RDIUS	I2.RDIUS	O.RADIUS
XX	XX	XX	XX	XX
6	1	2	2	3

INPUT THE SHAFT LENGTHS

PLATE TO CHOPPER	CHOPPER TO MOTOR
XX.XXXX	XX.XXXX
.0000	.0000

INPUT THE DESIRED # OF NODES ON THE SHAFT (IN ADDITION TO THE TWO NODES SET AT THE CHOPPER), AND INPUT THE HEAT LOAD GENERATED TO THE SHAFT FROM THE MOTOR HOUSING.

PLATE TO CHOPPER	CHOPPER TO MOTOR HOUSING	HEAT LOAD (WATTS)
XX	XX	SX.XXXESYY
5	10	.000E+00

```
INPUT THE CONTACT RESISTANCE BETWEEN THE CHOPPER AND THE SHAFT.

    SOME TYPICAL VALUES AT 50K ARE:
          --------   -----------------   ----------------
          MATERIAL       CONTACT RES     CONTACT PRESSURE
                     1/(WATTS/CM**2 K)   (DYNES/CM**2)E-5
          --------   -----------------   ----------------
           AL/AL         500 - 110            2 - 30
          S.S./S.S.      330 -  12            5 - 700
           CU/CU         0.6 - 0.3            6 - 700
           AL/S.S.        17 -  12            4 - 270

CONTACT RESISTANCE
XXXXXX.X
      .0


INPUT THE WIDTH OF THE SHAFT BEARING, THE POSITION OF ITS
CENTROID (MEASURED FROM THE BACK OF THE CHOPPER CONNECTOR),
THE OUTER DIAMETER, AND THE CONTACT RESISTANCES
B'RING WIDTH       POSITION      O. DIA     INNER CR     OUTER CR
XX.XXXX            XXX.XXXX      X.XXXX     XXXXXX.X     XXXXXX.X
  .4000              3.0000       .9600           .0           .0


SHAFT BEARING SUPPORT TEMPERATURE
  (ENTER "1" FOR SHAFT VALUE OR "2" FOR AMBIENT)
X
1


INPUT THE FOLLOWING PLATE DIMENSIONS
DEPTH      B'RING O.R.      DEPTH AT B'RING      LENGTH OF B'RING
X.XXXX     X.XXXX           X.XXXX               X.XXXX
1.9000      .4800           1.5000                .4000


INPUT THE PLATE BEARING CONTACT RESISTANCES
CR AT SHAFT      CR AT PLATE
XXXXXX.X         XXXXXX.X
      .0               .0


INPUT THE PLATE COOLING STRIP DIMENSIONS, THE HELIUM FLOWRATE
AND THE AVERAGE COOLANT TEMPERATURE
RADIAL POSITION      DIAMETER     DM/DT (GM/SEC)      AVG HE TEMP
XX.XXX               X.XXX        XX.XXX              XX.XXX
19.000               1.000         4.000              20.000
```

```
INPUT NODAL DENSITIES OF PLATE APERTURE MODEL
  (NOTE:  NUMBER OF NODES ALONG THE APERTURE SETS THE ENTIRE PLATE)
RADIAL      CIRCUMFERENCE      # OF NODES ALONG THETA * 1/2
X           X                  XX
2           2                   4


INPUT THE RADIAL DISTANCE OF THE BLACKBODY (BB) SOURCE FROM THE
SHAFT CENTERLINE.  ALSO GIVE DISTANCES TO THE BACK FACES OF THE
CHOPPER FIN AND THE FRONT PLATE.
RADIAL POS      BB TO FIN      BB TO PLATE
XX.XXX          XX.XXX         XX.XXX
 7.600           2.000          3.000


INPUT THE BB TEMPERATURE, THE CHAMBER AMBIENT TEMPERATURE, THE
BB APERTURE SIZE, AND THE PLATE APERTURE (PA) SIZE
BB TEMP      AMB TEMP     BB DIA      PA DIA
XXXX.X       XXX.XX       X.XXXX      X.XXXX
 300.0        20.00        .1500      3.2000


INPUT THE DESIRED RUN TIME, TIME INCREMENT, CHOPPER SPEED,
AND GAUSS-SEIDEL TOLERANCE.

   RUN TIME             INCREMENT      SPEED      TOLERANCE
(MIN)      (SEC)        (SEC)          (REV/S)    (K)
XXX        XX.XX        X.XXXX         XXX.X      X.XXESYY
  1          .00        1.0000          20.0       .50E-05


RADIATION PRINTS - ENTER '1' FOR SCREEN PRINTS
                         '2' FOR FILE PRINTS
                      OR '3' FOR BOTH PRINTS
(NOTE:  DEFAULT GIVES NEITHER PRINT)
X


YOU HAVE REACHED THE END OF YOUR TIME REQUEST
     AT  0 MINUTES, 1.0 SECONDS.


ADDITIONAL PROMPTS (USE '1' FOR YES):
NODE LIST?     MORE RUN TIME?     TURN BLACKBODY ON/OFF?
X              X                  X
1

- PROGRAM COMPLETED -
```

F-2B. <u>SAMPLE NODE LIST</u> - <u>COMBINATION MOUNT & NO SCREEN PRINTS</u>

DATA FILE: RUN3.DAT

THE RADITION 'SEEN' BY THE SENSOR

NOTE: SENSOR SEES 0.18E-03 WATTS FROM THE B.B.

TIME MIN	SEC	FIN RAD (WATTS)	CRIT FIN TEMP	BEARING TEMP (K) PLATE BRG	SHAFT BRG
1	0.0	0.73E-06	20.48	21.77	22.66

MODEL NODE TEMPERATURES AT 1 MIN 0.00 SEC

BEARING HEAT LOADS (WATTS)
PLATE BEARING = 0.520E-02
SHAFT BEARING = 0.114E-02

BEARING TEMPERATURES
PLATE BEARING = 21.77
SHAFT BEARING = 22.66

.....FOR THE CHOPPER FIN

RADIUS	ANGLE 0	30	60	90
8.250	20.48	20.48	20.48	20.48
6.983	20.48	20.48	20.48	20.48
5.717	20.48	20.48	20.48	20.48

.....FOR THE CHOPPER INNER DISK

NOTE: DOUBLE RADIAL VALUES INDICATE CONNECTOR REGION WITH (CHOPPER/CONNECTOR) DISPLAYS.

RADIUS	ANGLE 0	30	60	90	120	150
4.450	20.49	20.48	20.48	20.49	20.49	20.49
3.125	20.49	20.49	20.49	20.49	20.49	20.49
1.800	20.49	20.49	20.49	20.49	20.49	20.49
1.180	20.49	20.49	20.49	20.49	20.49	20.49
0.560	20.50	20.50	20.50	20.50	20.50	20.50
0.560	20.51	20.51	20.51	20.51	20.51	20.51
0.160	20.50	20.50	20.50	20.50	20.50	20.50
0.160	20.51	20.51	20.51	20.51	20.51	20.51

.....FOR THE SHAFT NODES AT THE CHOPPER

TEMPERATURE AT CHOPPER = 20.51
TEMPERATURE AT CONNECTOR = 20.51

.....FROM THE CHOPPER TO THE MOTOR HOUSING

.....KEY: DISTANCE FROM CHOPPER (CM)
TEMPERATURE (K)

0.263	0.789	1.316	1.842	2.368	2.895	3.421	3.947
20.73	20.94	21.16	21.38	21.60	21.81	22.03	22.25
4.474	5.000						
22.48	22.64						

.....FROM THE CHOPPER TO THE FRONT PLATE

.....KEY: DISTANCE FROM CHOPPER (CM)
TEMPERATURE (K)

0.111	0.333	0.556	0.778	1.000
20.54	20.58	20.61	20.64	20.65

.....FOR THE FRONT PLATE

.....CENTERLINE NODE TEMPERATURE = 20.70

RADIUS	ANGLE 3	9	16	22	57	92	127	162
0.480	20.90	20.89	20.87	20.85	20.73	20.66	20.62	20.60
1.200	20.59	20.59	20.59	20.58	20.55	20.51	20.49	20.48
2.800	20.40	20.40	20.39	20.39	20.37	20.36	20.34	20.34
4.400	20.30	20.30	20.30	20.29	20.28	20.27	20.26	20.25
6.000	20.25	20.24	20.23	20.23	20.21	20.20	20.20	20.19
7.600	20.00	20.17	20.17	20.17	20.16	20.16	20.15	20.15
9.200	20.09	20.11	20.12	20.12	20.12	20.12	20.11	20.11
10.800	20.08	20.08	20.09	20.09	20.09	20.09	20.09	20.09
12.400	20.06	20.07	20.07	20.07	20.07	20.07	20.07	20.07
14.000	20.05	20.05	20.05	20.05	20.05	20.05	20.05	20.05
15.600	20.04	20.04	20.04	20.04	20.04	20.04	20.04	20.04
17.200	20.02	20.02	20.02	20.02	20.02	20.02	20.02	20.02
18.800	20.01	20.01	20.01	20.01	20.01	20.01	20.01	20.01
20.400	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00

VITA

The author, Jeffery K. Little, was born in Kenmore, New York, on July 18, 1960. He graduated from Butler High School in Huntsville, Alabama, in 1978 and was awarded a four year Air Force scholarship. Attending Auburn University, he earned a Bachelor's Degree in Mechanical Engineering in June 1982. That same month, he entered Air Force active duty and received a special assignment as a turbine engine research engineer at the NASA Lewis Research Center in Cleveland, Ohio. He was a supporting author on numerous NASA publications, and the primary author on NASA Technical Memorandum 86940, "Ribbon-Burner Simulation of the T-700 Turbine Shroud Section for Ceramic-Lined Seals Research." During this period he also attended graduate courses at the University of Toledo.

In 1984 the author was reassigned to the Arnold Engineering Development Center, Arnold Air Force Base, Tennessee. In conjunction with working three years in turbine engine testing operations and one year in facilities engineering, he attended the University of Tennessee Space Institute. This thesis represents the culmination of a Masters Degree in Mechanical Engineering from this institution.

The author is married to the former Ellen Turk of Huntsville, Alabama. They have two children and, in the summer of 1988, are moving to Tucson, Arizona. There the author will be a faculty member of the Aerospace Military Studies Department at the University of Arizona.