2

NAVAL POSTGRADUATE SCHOOL
Monterey, California

THESIS

COMPUTER AIDED THERMAL ANALYSIS OF A MICROCIRCUIT STRUCTURE

by

Joseph Arthur Willhelm, Jr.

December 1990

Thesis Advisor: Allan D. Kraus

Approved for public release; distribution is unlimited.

Unclassified
Security Classification of this page

REPORT DOCUMENTATION PAGE

1a Report Security Classification Unclassified	1b Restrictive Markings
2a Security Classification Authority 2b Declassification/Downgrading Schedule	3 Distribution Availability of Report Approved for public release; distribution is unlimited.
4 Performing Organization Report Number(s)	5 Monitoring Organization Report Number(s)

6a Name of Performing Organization Naval Postgraduate School	6b Office Symbol *(If Applicable)* 39	7a Name of Monitoring Organization Naval Postgraduate School
6c Address *(city, state, and ZIP code)* Monterey, CA 93943-5000		7b Address *(city, state, and ZIP code)* Monterey, CA 93943-5000
8a Name of Funding/Sponsoring Organization	8b Office Symbol *(If Applicable)*	9 Procurement Instrument Identification Number

8c Address *(city, state, and ZIP code)*	10 Source of Funding Numbers Program Element Number	Project No	Task No	Work Unit Accession No

11 Title *(Include Security Classification)* COMPUTER AIDED THERMAL ANALYSIS OF MICROCIRCUIT STRUCTURE

12 Personal Author(s) Joseph A. Willhelm, Jr.

13a Type of Report Master's Thesis	13b Time Covered From To	14 Date of Report *(year, month,day)* December 1990	15 Page Count 65

16 Supplementary Notation The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.

17 Cosati Codes			18 Subject Terms *(continue on reverse if necessary and identify by block number)*
Field	Group	Subgroup	Thermal Analysis; Computer Aided; Microcircuit Structure

19 Abstract *(continue on reverse if necessary and identify by block number*

The Naval Post Graduate School has obtained software which can be used for the thermal analysis of an electronic component. This software includes two versions, one for steady state analysis and the other for transient analysis. Each version consists of two programs, a model builder and a thermal analyzer. This thesis describes a user friendly, menu driven specific model builder which may be used to rapidly generate a thermal model, containing up to 750 nodes, for a microcircuit die. This model builder is an improvement over the existing model builder in that the only pertinent input will be the die physical dimensions and heat transfer data. The main feature of this model builder is the accomodation of the marked variation of silicon thermal conductivity with temperature.

20 Distribution/Availability of Abstract ☒ unclassified/unlimited ☐ same as report ☐ DTIC users	21 Abstract Security Classification Unclassified	
22a Name of Responsible Individual Allan D. Kraus	22b Telephone *(Include Area code)* (408) 646-2730	22c Office Symbol EC/KS

DD FORM 1473, 84 MAR 83 APR edition may be used until exhausted security classification of this page
All other editions are obsolete Unclassified

Computer Aided Thermal Analysis of a Microcircuit Structure

by

Joseph Arthur Willhelm, Jr.
Lieutenant Commander, United States Navy
B.S., Texas A&M University, 1974

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN ELECTRICAL ENGINEERING

from the

NAVAL POSTGRADUATE SCHOOL
December 1990

Author: Joseph A Willhelm, Jr.
Joseph A. Willhelm, Jr.

Approved By: Allan D Kraus
Allan D. Kraus, Thesis Advisor

Yogendra Joshi
Yogendra Joshi, Second Reader

Michael A. Morgan
Michael A. Morgan, Chairman, Department of Electrical and
Computer Engineering

ABSTRACT

The Naval Post Graduate School has obtained software which can be used for the thermal analysis of an electronic component. This software includes two versions, one for steady state analysis and the other for transient analysis. Each version consists of two programs, a model builder and a thermal analyzer. This thesis describes a user friendly, menu driven specific model builder which may be used to rapidly generate a thermal model, containing up to 750 nodes, for a microcircuit die. This model builder is an improvement over the existing model builder in that the only pertinent input will be the physical dimensions and heat transfer data. The main feature of this model builder is the accomodation of the marked variation of silicon thermal conductivity with temperature.

TABLE OF CONTENTS

I. INTRODUCTION

Microcircuit chips have become commonplace items in all types of electronic equipment, both military and commercial. The capabilities of these chips continue to increase as improvements in design and manufacturing are incorporated. However, the design process becomes more difficult as the ability to place more and more circuits on these chips is realized. One area of immediate concern is in thermal control. Chips containing more than one million components in a 60 mm^2 area are known to exist [Ref. 1]. Heat dissipation from components contained in the chip as well as from any outside heat sources needs to be thoroughly analyzed. The reasons for conducting a thermal analysis on a microcircuit structure concern the impact of high temperature on reliability, bias stabilization, manufacturing costs, and thermal runaway.

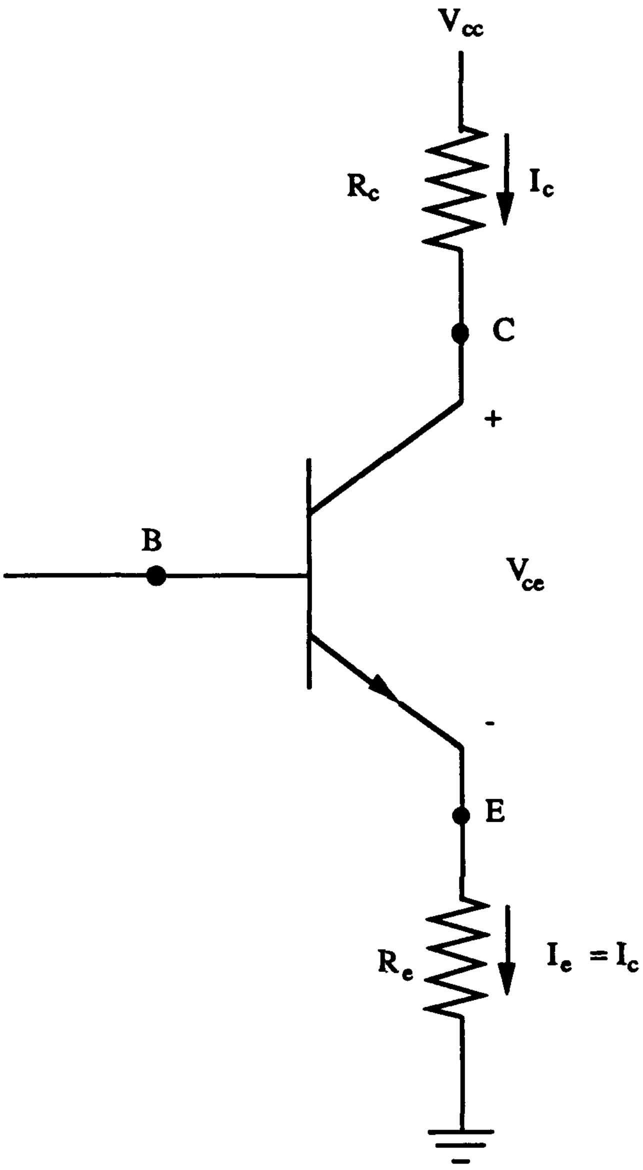
The reliability of a microcircuit is directly related to its junction temperature. It is now common knowledge that failure rate is proportional to junction temperature and designers plan for the microcircuit to operate within a specified temperature range. If this range is exceeded, the operating capability of the device may be severely reduced or it may fail completely. Because the failure rate increases exponentially as the temperature increases, the effects of high junction temperature can be drastic.

It is necessary to bias an electronic circuit in order to obtain a stable and predictable operating point. As the junction temperature changes, the impact on this operating point will be directly impacted. Consider Figure 1 and observe that by Kirchhoff's voltage law,

$$-V_{cc} + R_c I_c + V_{ce} + R_e I_c = 0 \tag{1}$$

so that the collector to emitter voltage will be

$$V_{ce} = V_{cc} - I_c (R_c + R_e) \tag{2}$$



V_{cc} = power supply voltage to collector
B = base
C = collector
E = emitter
V_{ce} = voltage across collector and emitter
R_e = emitter resistance
R_c = collector resistance
I_e = emitter current
I_c = collector current

Figure 1

It is a fact that, the collector current, I_c, is directly proportional to the junction temperature. As the junction temperature increases, the voltage drop across R_c and R_e increases and as a result, V_{ce} is quite likely to decrease to an intolerably low level.

During manufacturing, the chip, at some point, must undergo a soldering process in which connections are made from chip to chip or from one component to another. A particular soldering compound must be selected which will accomodate the expected operating temperature range without failure. The soldering compound cost is based on it's composition and, as general rule of thumb, the higher the melting point, the higher the cost. An increased cost incurred by a manufacturer for a high temperature solder may be very minimal on a per unit basis. But any manufacturer dealing with microcircuit chips may be handling millions of them and these costs could conceivably reach the million dollar mark which is probably not recoverable.

Hot spots anywhere in the microcircuit chip could result in thermal runaway. Because the temperature increases as the collector current increases, a hot spot near the transistor will cause an increase in the collector current. This then causes an increase in power dissipation ($P = I_c V_{ce}$) which in turn, causes an increase in temperature. This increase in temperature causes an additional increment of collector current to flow and leads to yet another increase in power dissipation. This regenerative process is known as thermal runaway and as the cycle continues it could lead to drastic and complete device destruction. [Ref. 1]

The Naval Post Graduate School has obtained software which can be used for the thermal analysis of an electronic component. This software includes two versions, one for steady state analysis and the other for transient analysis. Each version consists of two programs, a model builder and a thermal analyzer. The model builder is designed to provide the user with the means to model a physical configuration in order to provide the thermal analyzer with an input file. This file is taken by the thermal analyzer as its input and an output file containing a summary of the temperatures within the configuration will be generated.

The generation of the thermal model is the biggest hurdle in the actual analysis and the analyst is powerless in the absence of a model builder program. However, the model building process begins with a drawing of the configuration and a subdivision of it into small but finite subvolumes. Each subvolume is presumed isothermal and the centers of each subvolume are then representative of the entire subvolume. These centers (centroids) are called node points or merely nodes and thermal analysis involves the writing of n node equations in n unknown temperatures where the nodes are connected by thermal conductances.

The very laborious and time consuming process of writing the node equations can be avoided through the use of a model builder which will write them automatically. Yet, there are drawbacks in the use of a general model builder in that, while it can be used for a specific geometry and set of material conditions, many hours can be spent on input in front of a computer terminal and, before using any model builder, careful consideration must be given to whether or not the configuration under analysis will be sufficiently well represented by the model generated.

This thesis describes a specific model builder which may be used to rapidly generate a thermal model containing up to 750 nodes for a microcircuit die. The main feature of this model builder is the accomodation of the marked variation of silicon thermal conductivity with temperature.

The specific model builder has additional features. These will be described in this thesis and are as follows:

1) The capability of working in SI or English units.
2) The user has five aspect ratios from which to choose.
3) The provision of up to 750 nodes for the die model.
4) The ability to input heat dissipation using several methods.
5) The automatic calculation of conductance values based on user input dimensions.
6) The automatic correction for variations in the thermal conductivity values of silicon with temperature and location.
7) The provision of automatic linearization of radiation.

II. A PROBLEM IN THERMAL ANALYSIS

The provision of a solution to a simple problem in heat transfer analysis will show that a thermal analyzer is required for serious, large scale, thermal analysis.

Conduction is the heat flow mechanism whereby heat is transfered from one part of a homogeneous medium under the influence of a temperature gradient without appreciable displacement of the particles that compose the medium. It was Fourier who proposed that the heat flow is directly proportional to the area of the heat flow path and the temperature gradient along the path,

$$q \propto A\frac{dT}{dx} \qquad (3)$$

Insertion of a proportionality constant yields:

$$q = -kA\frac{dT}{dx} \qquad (4)$$

where

A = area of the heat flow path

k = thermal conductivity of the material

$\frac{dT}{dx}$ = change in temperature per unit path length (temperature gradient)

where the minus sign assures a positive heat flow in the presence of the required negative temperature gradient. [Ref. 2]

Equation (4) serves to define the thermal conductivity of the material

$$k = -\frac{q}{A\frac{dT}{dx}} \ \text{W/m-}^{\circ}\text{K} \qquad (5)$$

and it must be noted that the simplicity of this development quickly changes when *k* is a function of temperature, as in the case of silicon.

Equation (4) is a simple differential equation which can be solved using the boundary conditions in Figure 2. Separation of the variables gives:

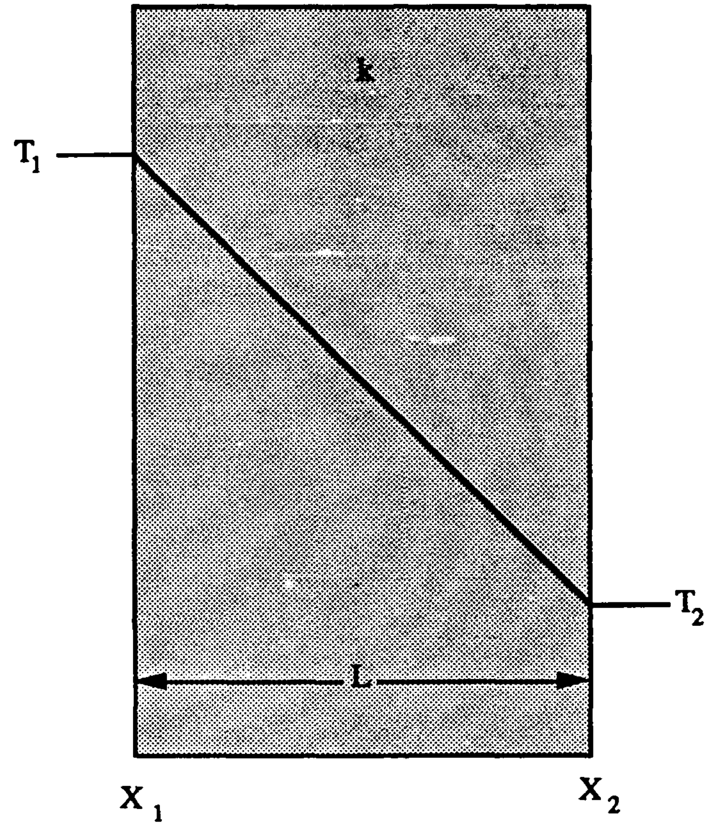


Figure 2

$$-\frac{q}{kA}\,dx = dT$$

and the integration between the limits:

$$-\frac{q}{kA}\int_{x_1}^{x_2} dx = \int_{T_1}^{T_2} dT$$

gives:

$$-\frac{q}{kA}(x_2 - x_1) = T_2 - T_1$$

With $L = x_2 - x_1$, it is seen that:

$$q = \frac{kA}{L}(T_1 - T_2) \tag{6}$$

which is called Fourier's law.

Consider, Ohm's law which governs the flow of current in an electrical resistor:

$$I = \frac{\Delta V}{R} \tag{7}$$

and note the similiarity between the forms of equations (6) and (7). An analogy may be proposed where the analogous quantities are:

$$q \Leftrightarrow I \tag{8a}$$

$$\Delta T \Leftrightarrow \Delta V \tag{8b}$$

$$\frac{L}{kA} \Leftrightarrow R \tag{8c}$$

In particular, equation (8c), defines the thermal resistance for the conduction process and one observes that, for the slab in Figure 2, if T_1 and T_2 are given, then q can be determined if the thermal resistance of the slab is known. On the other hand, if T_1 and q are known, T_2 can be calculated using $R = \frac{L}{kA}$:

$$T_2 = T_1 - R\,q$$

Convection is a fluid flow process and, if it applies in heat transfer, it is the transfer of heat from or to a confining surface by a flowing fluid. The fluid flow may be induced by buoyancy or density gradients within the fluid and this phenomenon is called natural or free convection. If the fluid flow is induced by a fan, a pump, or a blower, it is termed forced convection. [Ref. 2]

Heat flow by convection is directly proportional to the temperature difference between the confining surface and fluid and the surface area over which the process takes place:

$$q \propto A\,\Delta T \tag{9}$$

and a proportionality factor may be inserted:

$$q = h\,A\,\Delta T \tag{10}$$

Equation (10) is the Newton law of cooling and *h* is called the coefficient of heat transfer defined by:

$$h = \frac{q}{A\,\Delta T}\ \text{W/m}^{2}\text{-}^{\circ}\text{K} \tag{11}$$

Notice that the concept of thermal resistance can be extended to the convective case where:

$$\frac{1}{hA} \Leftrightarrow R \tag{12}$$

If convection exists on both faces of the slab in Figure 2, the configuration of Figure 3 exists and the electric analog is shown in Figure 4.Here the total resistance is:

$$R = \frac{1}{h_1A} + \frac{L}{kA} + \frac{1}{h_2A}$$

$$= \frac{1}{A}\left[\frac{1}{h_1} + \frac{L}{k} + \frac{1}{h_2}\right]$$

and the heat flow is seen to be:

$$q = \frac{\Delta T}{R} = \frac{T_1 - T_2}{\frac{1}{A}\left[\frac{1}{h_1} + \frac{L}{k} + \frac{1}{h_2}\right]} \tag{13}$$

Thus far, no difficulty has been encountered in a calculation procedure. The picture changes dramatically when radiation is considered.

Radiation is electromagnetic in nature and is the means for heat communication in a vacuum. It is beyond the scope of this thesis to derive the general radiation equation:

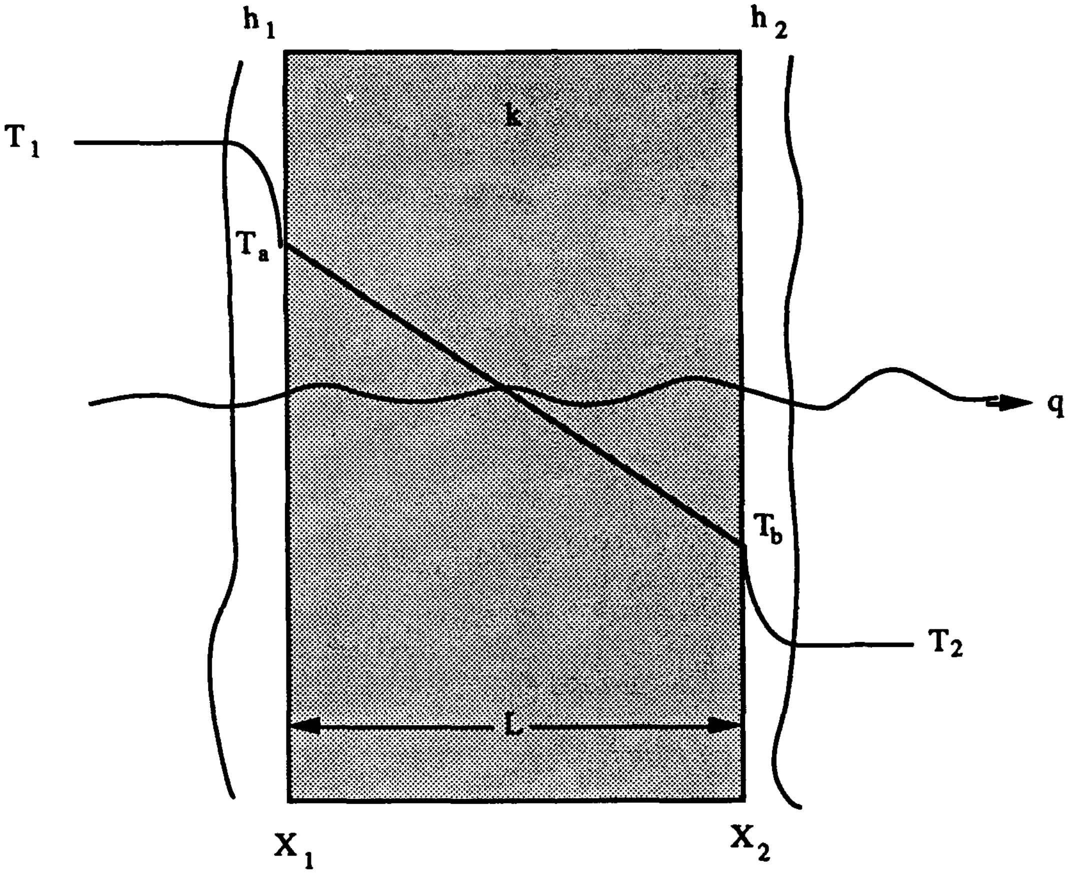


Figure 3

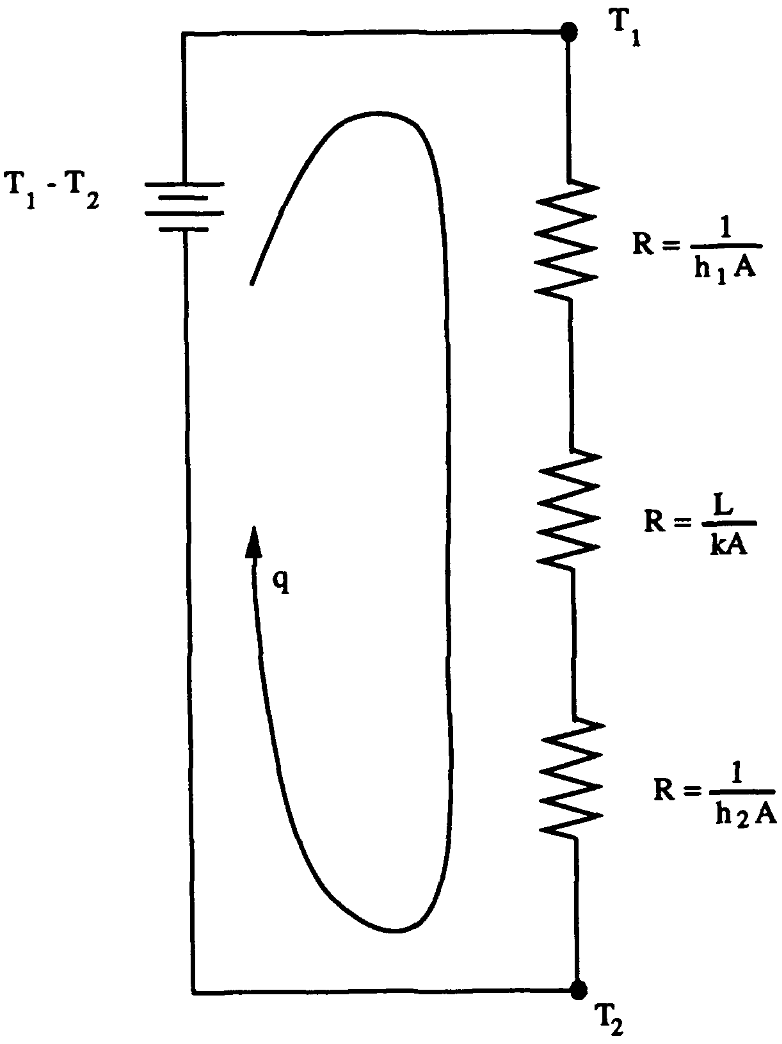


Figure 4

$$q = \sigma F_A F_\varepsilon A (T_s^4 - T_r^4) \tag{14}$$

where

σ is the Stefan-Boltzmann constant = 5.67(10^{-8}) W/m^2-K^4

F_A is a shape factor that accounts for the arrangement of the radiating source and the absorbing receiver

F_ε is the emissivity factor that accounts for the ability of the surfaces to absorb or emit radiation

T_s is the temperature of the source, Kelvin

T_r is the temperature of the receiver, Kelvin

A is the surface area, m^2

In order to put the radiation on a $q = K\,\Delta T$ basis where K is the thermal conductance, consider that:

$$T_s^4 - T_r^4 = (T_s^2 + T_r^2)(T_s^2 - T_r^2)$$

and:

$$T_s^4 - T_r^4 = (T_s^2 + T_r^2)(T_s + T_r)(T_s - T_r)$$

Equation (14) may then be written as:

$$q = \sigma F_A F_\varepsilon A (T_s^2 + T_r^2)(T_s + T_r)(T_s - T_r) \tag{15}$$

and a radiative heat transfer coefficient may be defined:

$$q = h_r A (T_s - T_r) \tag{16}$$

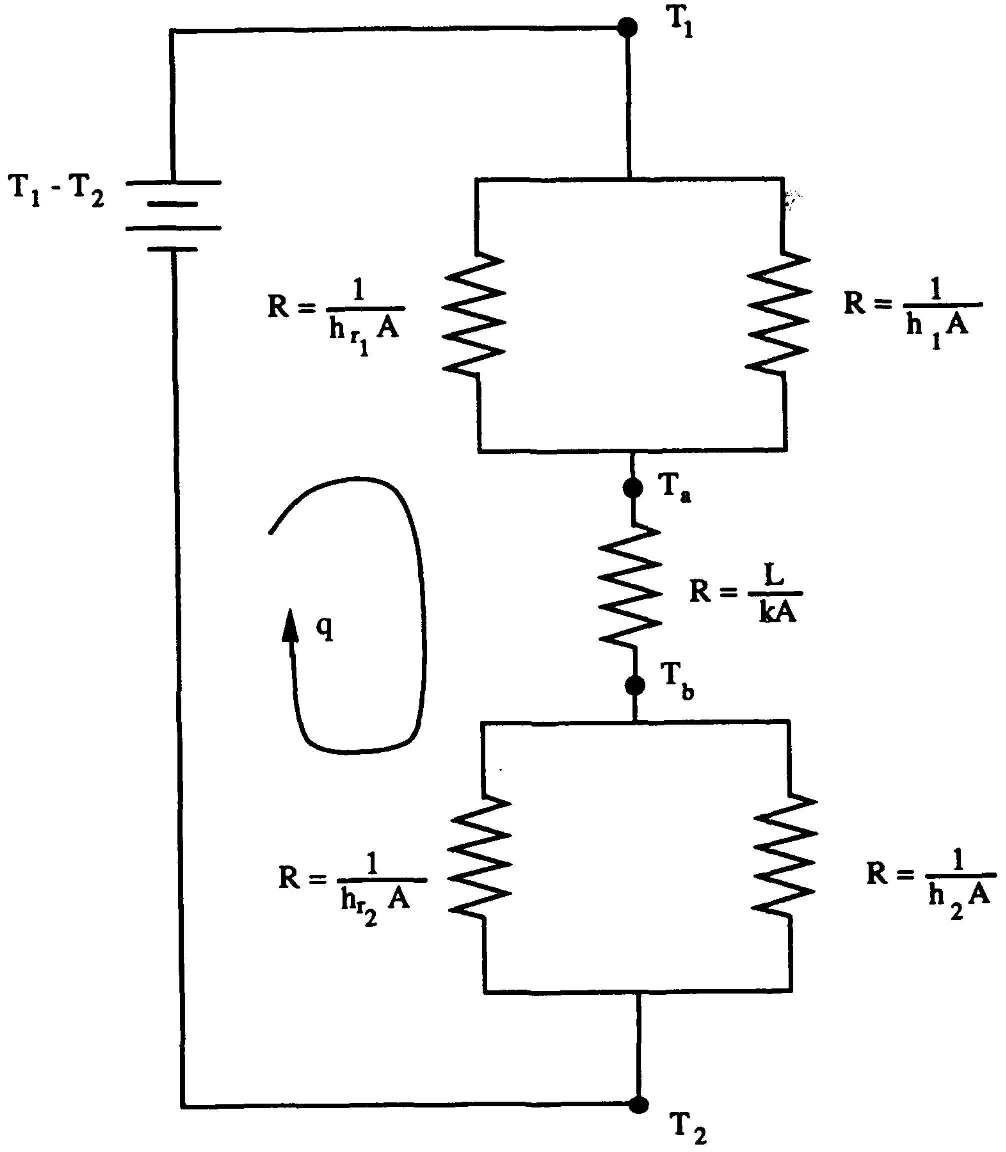
where

$$h_r = \sigma F_A F_\varepsilon (T_s^2 + T_r^2)(T_s + T_r) \tag{17}$$

A thermal resistance in radiation can then be proposed as:

$$R = \frac{1}{h_r A} \tag{18}$$

and, as shown in Figure 5, this resistance is in parallel with the convective resistance.



$$h_{r_1} = \sigma F_A F_\varepsilon (T_1^2 + T_a^2)(T_1 + T_a)$$
$$h_{r_2} = \sigma F_A F_\varepsilon (T_b^2 + T_2^2)(T_b + T_2)$$

Figure 5

A solution procedure for the thermal network in Figure 5 must be iterative because of the form of h_r given by equation (17). This is obviously no longer a simple problem and, at this point, one must turn to the computer for help with more complicated configurations.

III. FINITE DIFFERENCES AND NODAL ANALYSIS

It is the purpose of this section to provide the assurance that the method of modelling will yield accurate results and to show how the *n* node equations in the *n* unknown temperatures are formulated.

Equation (4) is but a one dimensional simplification of the more general equation of heat conduction [Ref. 3]:

$$\frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right)+q_i=\rho c\frac{\partial T}{\partial t} \tag{19}$$

where

T = temperature, °F or °C

t = time, hrs.

q_i = rate of internal heat generation, Btu/hr or Watts

k = thermal conductivity, Btu/hr-ft-°F or Watts/m-°C

ρ = specific weight, lbm/ft^3 or kg/m^3

x, y, z = coordinate system distances, ft or m

c = specific heat, Btu/lbm-°F or Watt-hr/kg-°C

We note that if we wish to formulate a problem that deals in discrete Δx, Δy, Δz, and ΔT's, we must be able to accurately approximate the first and second derivatives.

In general we must be able to determine the slope of a line tangent to the point of interest on the plot of the temperature as a function of *x*, *y*, or *z*. (Figure 6). Using *x* as the spacial coordinate, we observe that the slope of the line (m), if it exists, will be:

$$m=\lim_{\Delta x\to 0}\frac{f(x_o+\Delta x)-f(x_o)}{\Delta x} \tag{20}$$

The term, $[f(x_o+\Delta x)-f(x_o)]/\Delta x$, is called the difference quotient and is the ratio of the change in the value of the function at x_o and $x_o+\Delta x$ to the change in *x* . The limit of the difference quotient is called the derivative of the function at x_o:

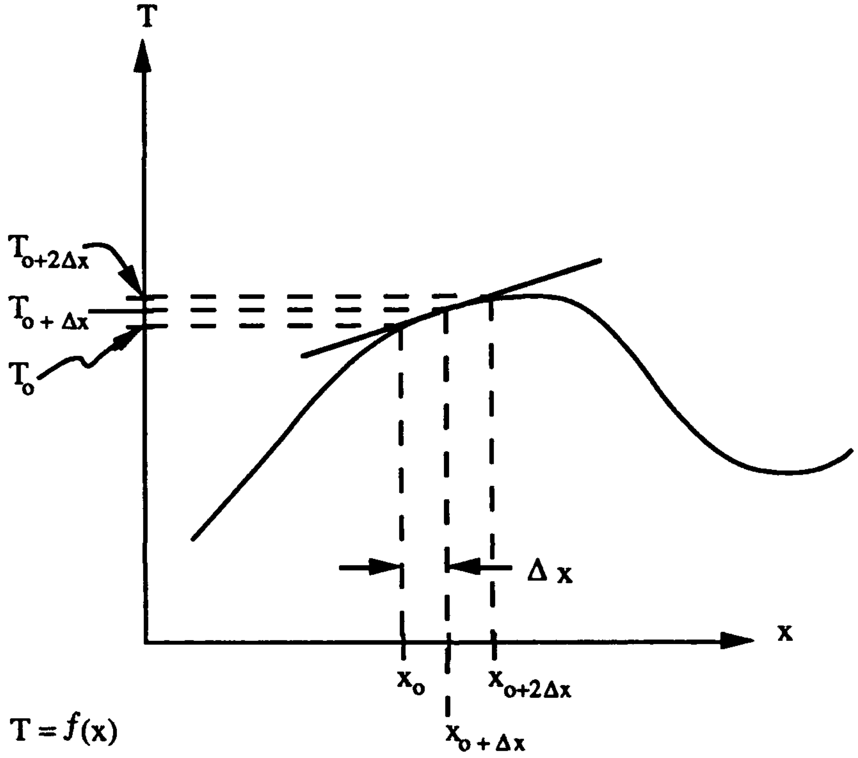


Figure 6

$$f'(x_o) = \lim_{\Delta x \to 0} \frac{f(x_o+\Delta x) - f(x_o)}{\Delta x} \tag{21}$$

In examining Figure 6 we can derive the derivative for this particular curve at the point x_o by letting $f(x) = T(x)$ and noting that:

$$f(x_o+\Delta x) = T(x_o+\Delta x)$$

$$f(x_o) = T(x_o)$$

$$f'(x_o) = \lim_{\Delta x \to 0} \frac{T(x_o+\Delta x) - T(x_o)}{\Delta x} \tag{22}$$

and when $\Delta x \rightarrow 0$ we observe that the expression for the first derivative becomes:

$$f'(x_o) = \frac{T(x_o+\Delta x) - T(x_o)}{\Delta x} \tag{23}$$

and we note that:

$$f'(x_o) = \frac{\Delta T}{\Delta x} \tag{24}$$

as long as Δx is small as required by the limiting process. [Ref. 4]

The second derivative, using the defintion of a derivative, will be the ratio of the change in the value of the first derivative to the change in Δx. Thus, the second derivative in Figure 6 becomes:

$$f'(x_o) = \frac{T(x_o+\Delta x) - T(x_o)}{\Delta x}$$

$$f'(x_o+\Delta x) = \frac{T(x_o+2\Delta x) - T(x_o+\Delta x)}{\Delta x}$$

$$f''(x_o) = \lim_{\Delta x \to 0} \frac{f'(x_o+\Delta x) - f'(x_o)}{\Delta x}$$

$$f''(x_o) = \frac{\frac{T(x_o+2\Delta x) - T(x_o+\Delta x)}{\Delta x} - \frac{T(x_o+\Delta x) - T(x_o)}{\Delta x}}{\Delta x}$$

$$f''(x_o) = \frac{T(x_o+2\Delta x) - 2T(x_o+\Delta x) + T(x_o)}{\Delta x^2} \tag{25}$$

As in the case of the first derivative, the second derivative given by equation (25) is a valid approximation as long as Δx is small. The use of a Taylor series expansion will confirm the validity of equation (25). Taylor's theorem states that a function can be approximated by a polynomial of the form:

$$f(x) = f(a) + f'(a)(x-a) + \frac{f''(a)}{2}(x-a)^2 + \ldots + \frac{f^{(n)}(a)}{n!}(x-a)^n \qquad (26)$$

where the polynomial is for the function expanded about x = a [Ref. 4]. Using our example the Taylor series for the function T(x) at $T(x_o+2\Delta x)$ is:

$$T(x_o+2\Delta x) = T(x_o+\Delta x) + \frac{dT(x_o+\Delta x)}{dx}\Delta x + \frac{1}{2}\frac{d^2T(x_o+\Delta x)}{dx^2}\Delta x^2 +$$

$$\frac{1}{6}\frac{d^3T(x_o+\Delta x)}{dx^3}\Delta x^3 + \ldots + \frac{1}{n!}\frac{d^nT(x_o+\Delta x)}{dx^n}\Delta x^n \qquad (27)$$

and for the function T(x) at $T(x_o)$:

$$T(x_o) = T(x_o+\Delta x) - \frac{dT(x_o+\Delta x)}{dx}\Delta x + \frac{1}{2}\frac{d^2T(x_o+\Delta x)}{dx^2}\Delta x^2 -$$

$$\frac{1}{6}\frac{d^3T(x_o+\Delta x)}{dx^3}\Delta x^3 + \ldots + \frac{1}{n!}\frac{d^nT(x_o+\Delta x)}{dx^n}\Delta x^n \qquad (28)$$

If we keep Δx very small then the terms smaller than Δx^2 become negligble. If equations (27) and (28) are added we can obtain an expression for the second derivative:

$$T(x_o+2\Delta x) + T(x_o) = 2T(x_o+\Delta x) + \frac{d^2T(x_o+\Delta x)}{dx^2}\Delta x^2 \qquad (29)$$

$$\frac{d^2T(x_o+\Delta x)}{dx^2} = \frac{T(x_o+2\Delta x) - 2T(x_o+\Delta x) + T(x_o)}{\Delta x^2} \qquad (30)$$

which confirms our earlier result.

Thus, as long as Δx is kept very small, the following are valid representations and can be used in the analysis process:

$$\frac{dT}{dx} = \frac{T(x_o+\Delta x) - T(x_o)}{\Delta x} = \frac{\Delta T}{\Delta x} \qquad (31)$$

$$\frac{d^2T}{dx^2} = \frac{T(x_o+2\Delta x) - 2T(x_o+\Delta x) + T(x_o)}{\Delta x^2} \qquad (32)$$

As stated in section I, the configuration to be analyzed can be divided into small but finite volumes which are considered to be isothermal. The geometric center of each subvolume is designated as a node and the node can be representative of the entire subvolume. These nodes may be connected to each other through thermal resistances and the nodal analysis for the node temperatures lends itself to solution on the computer.

The first law of thermodynamics (the law of the conservation of energy) states that energy cannot be created nor destroyed, but can be transformed from one form to another. One may therefore form an energy balance on the typical node shown in Figure 7. For ease of explanation, the environment will be considered to be a single node, node 100 (Figure 8). Examination of node 5, shows that it is connected to nodes 2, 4, 6, 8, 14, and 100. If any energy is directly applied to or removed from this node, we would also include it in the equation. The node equation for node 5, with rate of heat input (q_i), becomes:

$$q_2 + q_4 + q_6 + q_8 + q_{14} + q_{100} - q_i = 0 \tag{33}$$

where each one of the q's with a numerical subscript represents the rate of heat flow from node 5 to the node indicated by the subscript.

Equation (33) is a continuity relationship and it does not show the items of interest, the node temperatures. But $q = \frac{\Delta T}{R}$ and the terms in equation (33) can be given by:

$$q_2 = \frac{kA}{L}\Delta T = \frac{k\,\Delta x\,\Delta z}{\Delta y}(T_5 - T_2) \tag{34a}$$

$$q_4 = \frac{kA}{L}\Delta T = \frac{k\,\Delta y\,\Delta z}{\Delta x}(T_5 - T_4) \tag{34b}$$

$$q_6 = \frac{kA}{L}\Delta T = \frac{k\,\Delta y\,\Delta z}{\Delta x}(T_5 - T_6) \tag{34c}$$

$$q_8 = \frac{kA}{L}\Delta T = \frac{k\,\Delta x\,\Delta z}{\Delta y}(T_5 - T_8) \tag{34d}$$

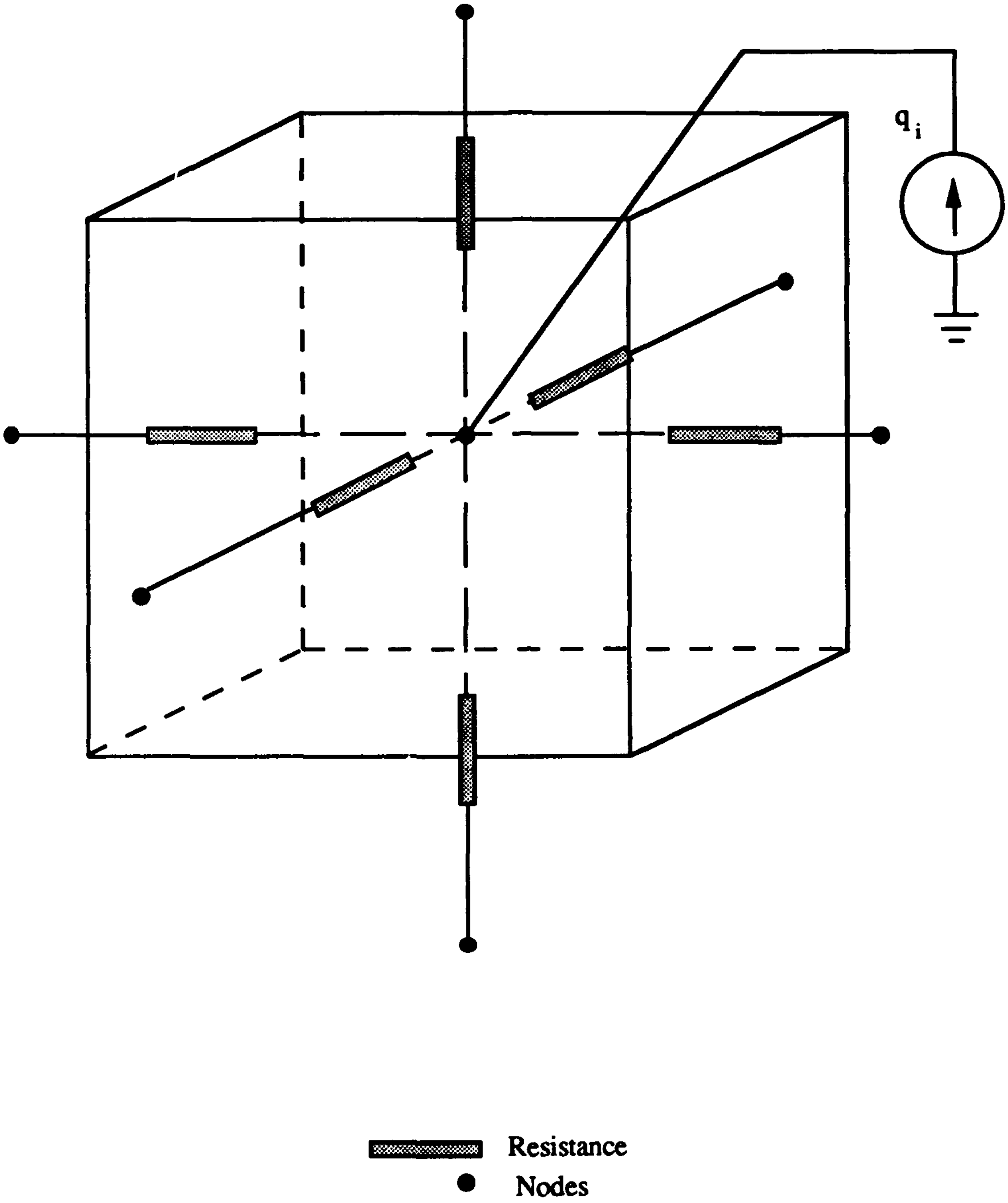


Figure 7

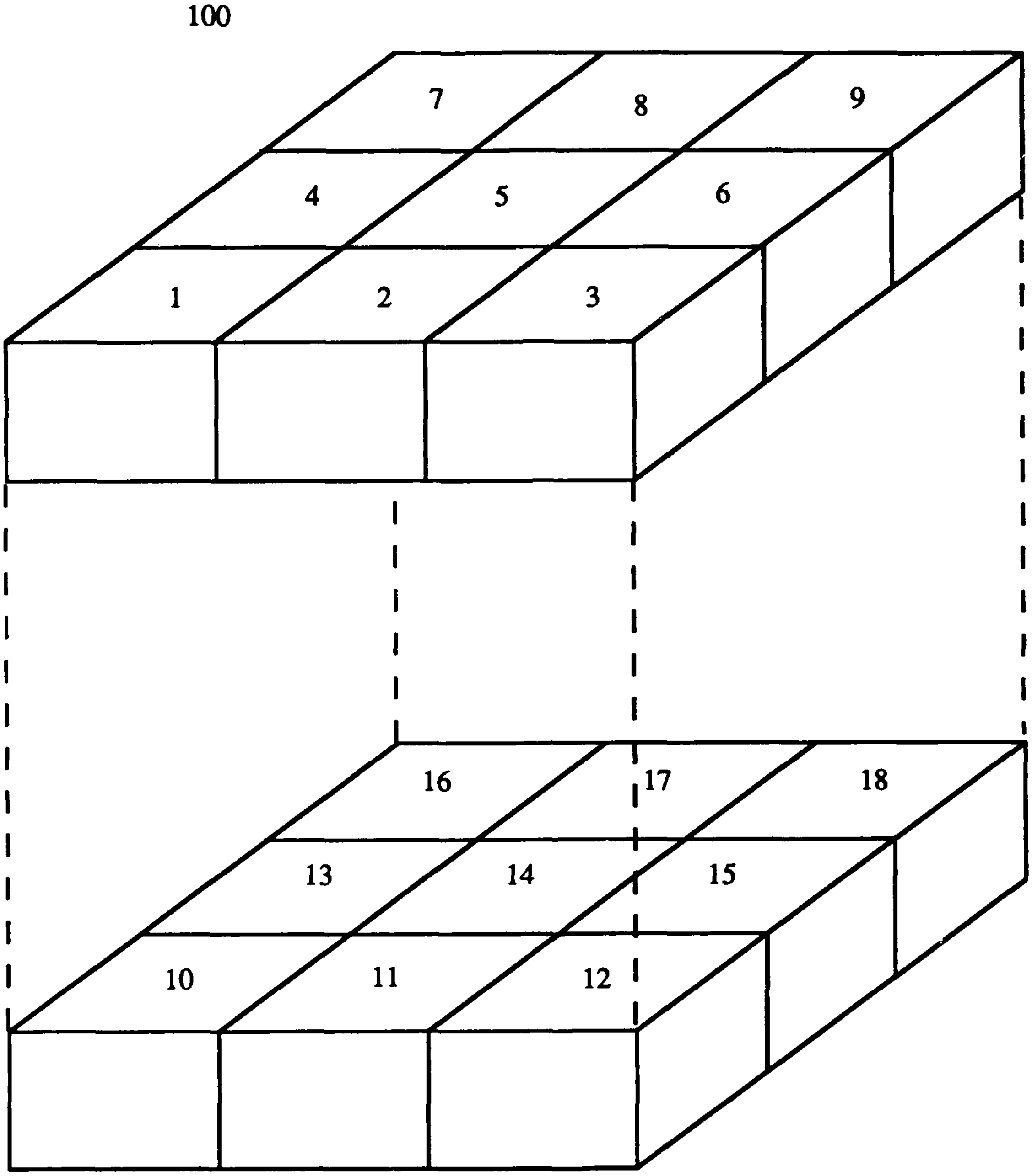


Figure 8

$$q_{14} = \frac{kA}{L} \Delta T = \frac{k\ \Delta x\ \Delta y}{\Delta z} (T_5 - T_{14}) \tag{34e}$$

$$q_{100} = \frac{kA}{L} \Delta T = \frac{k\ \Delta x\ \Delta y}{\frac{\Delta z}{2}} (T_5 - T_{100}) \tag{34f}$$

where

T_{100} is on the top face of node 5 and,

$\Delta x, \Delta y, \Delta z$ = the distance between nodes in the *x*, *y*, and *z* directions respectively

If we assume that $\Delta x = \Delta y = \Delta z = 1$ the node equation becomes:

$$K(T_5-T_2)+K(T_5-T_4)+K(T_5-T_6)+K(T_5-T_8)+K(T_5-T_{14})+2K(T_5-T_{100}) = q_i \tag{35}$$

or

$$-T_2 - T_4 + 7T_5 - T_6 - T_8 - T_{14} = \frac{q_i}{K} + 2T_{100} \tag{36}$$

where the terms on the right hand side of equations (35) and (36) should be known values.

A node equation can be written for each node in the configuration and in Figure 8 which contains 18 nodes, 18 node equations would be required to obtain the 18 unknown node temperatures. To make maximum use of the thermal analysis software, the generation of 750 nodes with 750 node equations similar to the one just derived would be required. There are a number of methods that can be utilized to solve these equations. It is not our purpose to solve these equations at present but to input them into a computer program which will solve them for us.

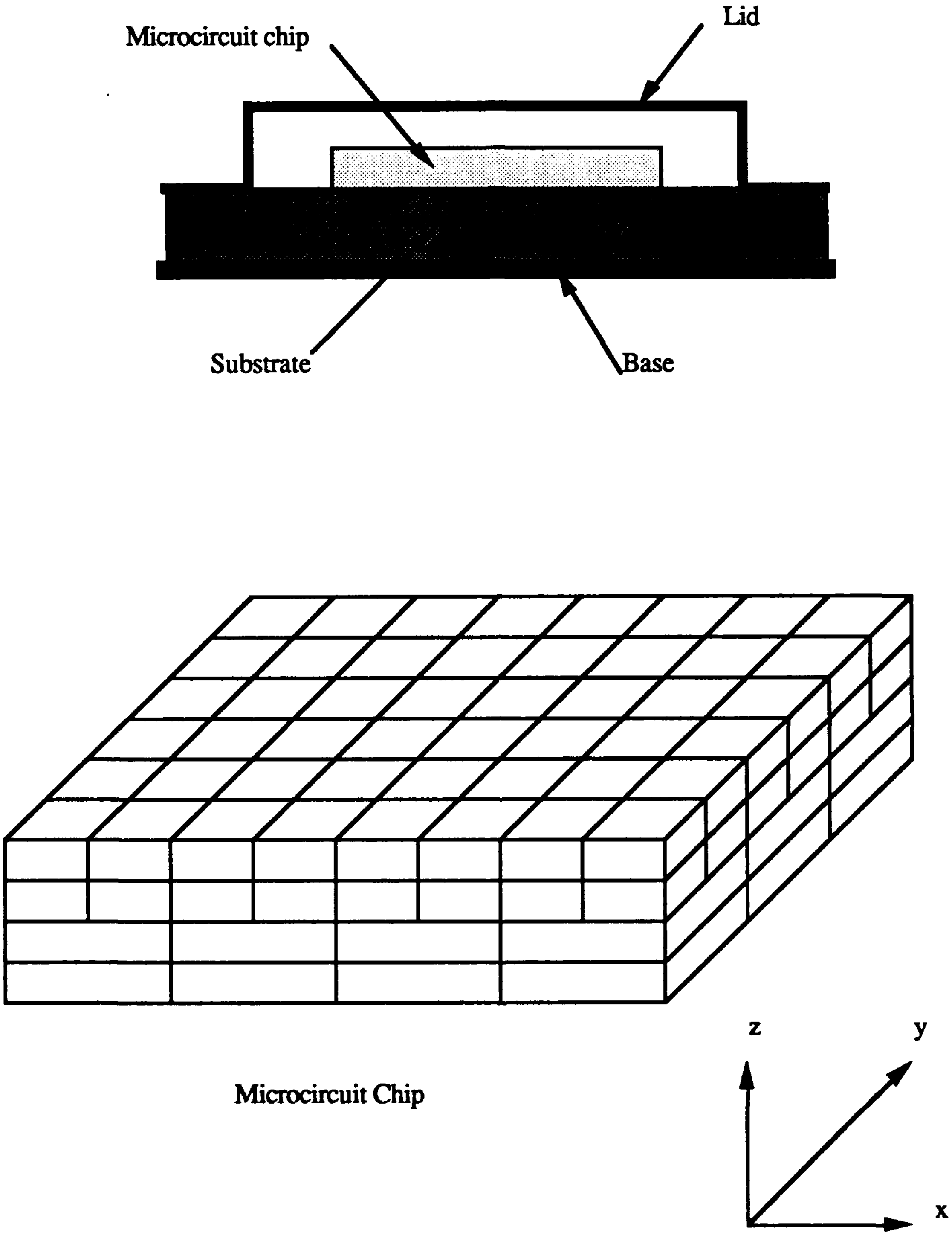
IV. MICCKT AND THE THERMAL ANALYZER

The model builder program which will become part of the thermal analyzer software package is MICCKT. MICCKT is for the specific microcircuit configuration shown in Figure 9, specifically, the microcircuit is covered by a lid and supported by a base. The gap between the chip and the lid is assumed to be air filled. Once the physical properties of the microcircuit are entered MICCKT will generate an output file in the correct format for use in the thermal analysis software.

A. MICROCIRCUIT MODELLING PROCEDURE

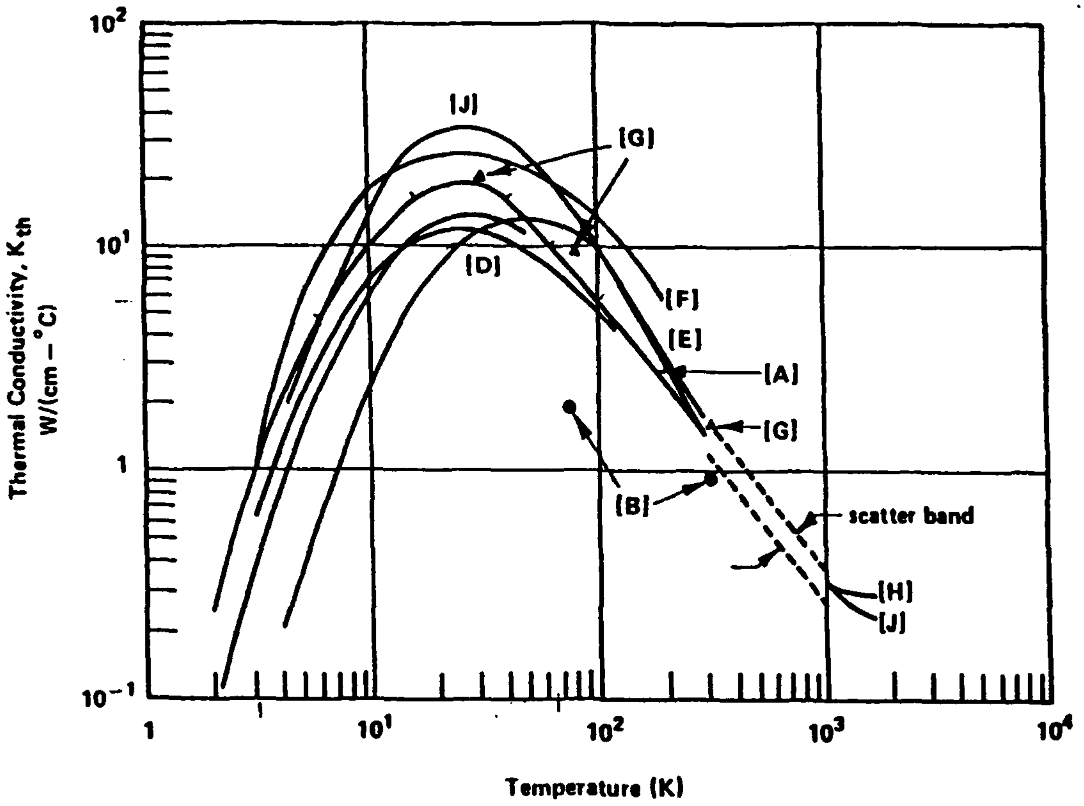
Recalling the idea that Δx, Δy, and Δz must be kept small to enable the use of the finite difference approach, we divide the microcircuit into subvolumes. The model builder will divide the chip into four layers with the top and second layers containing four times as many subvolumes as the bottom layers. (Figure 9) The top layer, containing the circuitry, is preset at 0.002 inches (0.00508 cm) and the thicknesses of each of the next three layers are one third the overall thickness less 0.002 inches. The reason for this is that heat injection will occur in the top layer and accuracy is assisted when the spatial increment is smaller. In accordance with the procedures already discussed, the node will be placed in the geometric center of the subvolume and will be representative of the physical properties of that subvolume.

The microcircuit structure is made of pure silicon. This presents a significant challenge as the thermal conductivity of silicon varies widely with temperature. (Figure 10) In order to determine the internodal conductances it is necessary to modify this curve for use in the thermal analyzer. The thermal conductance is function of the area of the path of transfer, the path length, and the thermal conductivity. Because the area and path length are



Microcircuit Chip

Figure 9



CURVE	IMPURITY	IMPURITY CONTENT (cm^{-3})	CROSS SECTION (mm X mm)
A	no added impurity	5×10^{14}	2.15 x 1.98
B	As	2.5×10^{19}	unknown
C	Au	10^{15}	2.36 x 2.21
D	unknown	7×10^{14}	1.75 x 1.5
E	B	5×10^{14}	3 x 3
F	B	2×10^{12}	3 x 3
G	unknown	4.8×10^{14}	unknown
J	p-Type	7×10^{12}	unknown

Figure 10 [From Ref. 5]

established by the internodal distances, the thermal conductivity at a given temperature is simply multiplied by a scalar value (A/L). It is the selection of the thermal conductivity for the desired temperature that poses a significant problem.

One of the features of the thermal analyzer is its ability to generate a limited facsimile of a temperature dependent curve based on user inputs. This temperature dependent curve may be specified using eight straight line segments between nine data points. Each data point represents a temperature and the corresponding conductance for the physical and thermal characteristics of the chip. Because the physical dimensions of each subvolume may change from location to location, several curves may be required to completely analyze the configuration.

It was determined that eight curves representing the conduction mode of transfer within the structure were required for the model. The top layer required two curves, designated curves 1101 and 1102, to represent the north-south and east-west node connections and a third curve, 1103, to connect the nodes in layer one and layer two. The second, third, and fourth layers use the same curves, 1104 and 1105, for the north-south and east-west connections. The Δx and Δy distances in the bottom two layers are twice that in the second layer but because either Δx or Δy will represent the path length, the curves are identical. Curve 1106 is used to connect layer two to layer three and curve 1107 to connect layer three to layer four. Curve 1108 is used to connect the fourth layer nodes to the heat sink.

The generation of each curve requires the establishment of the thermal conductivity at specific temperatures. Since there is a nine point limitation, the temperatures were selected to correspond to the expected operating range of the chip. The points selected were:

°C	Thermal conductivity W/cm-°C
0.0	1.68
25.0	1.49
60.0	1.27
85.0	1.14
120.0	1.01
160.0	0.88
205.0	0.77
255.0	0.66
310.0	0.55

These points were selected because they yield a piecewise continuous curve that closely resembles the original curve.

The thermal interaction between the top of the chip and the lid of the container must be addressed. The modes of heat transfer involved are, conduction and radiation across the air layer. The linearization of radiation by the analyzer leads to excessive running time. Thus, it would be beneficial to eliminate the non linear effect of the radiation if at all possible. A comparision of the heat transferred by conduction to that transferred by radiation will provide additional information to assist in justifying an alternate approach to the inclusion of radiation.

The rate of heat per unit area for conduction through the air gap is:

$$\frac{q}{A}\Big|_{cond} = \frac{k}{L}(T_s - T_r) \tag{37}$$

and for radiation:

$$\frac{q}{A}\Big|_{rad} = \sigma F_A F_\varepsilon (T_s^2 + T_r^2)(T_s + T_r)(T_s - T_r) \tag{38}$$

and a comparison of these for a typical case leads to a means for the determination of the relative importance of each in the heat transfer process. For example, using the values:

T_s = temperature of the chip = 400 K

T_r = temperature of the lid = 300 K

k = thermal conductivity of air at 350 K $\approx 2.97(10^{-4})$ W/cm-K

L = path length (air gap distance) = 0.254 cm

F_A = shape arrangement = 1.0

F_ε = emissivity factor, for parallel plates = $\dfrac{1}{\left[\dfrac{1}{\varepsilon_C} + \dfrac{1}{\varepsilon_L} - 1 \right]}$

where

ε_C = emissivity of the chip = 0.7

ε_L = emissivity of the lid = 0.8

the rate of heat per unit area for conduction becomes:

$$\frac{q}{A}\Big|_{cond} = 1.17(10^{-1}) \text{ W/cm}^2$$

and for radiation:

$$\frac{q}{A}\Big|_{rad} = 5.9(10^{-2}) \text{ W/cm}^2$$

For the selected conditions, the value for conduction transfer is approximately twice that for the radiation transfer. The difference between the heat transferred through the silicon and the heat transferred across the air layer will be on the order of several magnitudes. In this example, for a chip 0.05 cm thick at 400 K, the heat transfer into the second layer of the chip would be 109.75 W/cm^2. Therefore the vast majority of heat transfer occurs downward into the chip. Due to it's poor heat transfer characteristics, air essentially performs as an insulator. Because radiation is even less effective as a heat transfer mechanism the impact on the final solution is minimal.

Although radiation effects are a small percentage of the total heat transferred, these effects will not be neglected in the model builder. It will be incorporated into the thermal conductivity of air through the use of a correction factor. The correction factor will be a ratio of the magnitudes of the heat per unit area for radiation to the heat per unit area of conduction across the air layer. This correction factor can be used to derive a thermal conductance for heat flow across the air gap at a given temperature difference that involves both modes of heat transfer:

$$K = \frac{k\,A}{L}\,(\text{Ratio})$$

Bearing in mind that the thermal transfer across the air gap by conduction and radiation is significantly smaller than that through silicon, and the desire to limit the running time of the thermal analyzer, we choose to linearize the radiative transfer mechanism in this manner. Conduction, with the correction factor added, will represent the entire heat transfer mechanism between the chip and the lid.

Because the thermal conductivity of air is temperature dependent, an additional curve must be incorporated into the model builder. This curve will be designated as curve 1109 and will be implemented in the same fashion as the silicon conductance curves. The correction factor will, of course, automatically be entered into this curve.

B. FEATURES OF THE THERMAL ANALYZER

The purpose of the model builder is to provide input data to the thermal analyzer. This data must be organized in a format which is consistent with the format of the thermal analyzer. The input file will consist of five data lines and as many as seven data sets. Detailed information regarding the input data file may be obtained in the user's manual. In this section we describe features of specific interest as they pertain to the model builder. This will help the reader gain an understanding of the features of the thermal analyzer .

Line 1 is a title line which may contain as many as 79 alphanumeric characters. This title will be used to identify the output files.

Line 2 is the problem data line and will describe inputs pertaining to the problem at hand. Of the items in this line, the user will control the number of nodes under consideration and the units used. Other items identify the capabilities of the thermal analyzer to handle situations involving heaters, modes of heat transfer with unique exponents, nodes which receive secondary heat inputs, nodes controlling fast heat, and the number of temperature dependent heat input curves. These entries are not applicable to this model builder. The number of constant temperature values and number of temperature dependent curves are applicable and will be set by the model builder.

Line 3 is beyond the user's control and is part of the thermal analysis software; all entries in this line are automatic.

Line 4 is the problem capability line. This line defines the maximum values that may be used for each item in line 2. Of particular interest are the maximum number of nodes to be considered, 750, the maximum number of temperature dependent curves, 15, and the maximum number of constant temperatures, 50. The significance of entering the 750 node maximum becomes clearer when we look at the node assignments to the constant temperature inputs. The first constant temperature will be assigned to node 751 and subsequent constant temperatures will be assigned in order up to node 800.

Line 5 items place certain controls on the computational processes of the thermal analyzer. These items are automatically entered by the model builder. Item 1 describes the accuracy between iterations. The thermal analyzer uses an iterative method to arrive at a solution. As soon as the variation of every temperature computed does not differ from its previously computed value by the error criterion specified here, computation stops. There is a trade off between accuracy and computer time involved in selecting this number. Item 2 is a damping value which is used to prevent temperature oscillations between iterations. Item 3 is the maximum number of iterations to be performed by the computer. This number is specified to prevent long computer runs in the event of faulty data. Item 4 is a convergence factor. Excessive run times may be induced by the damping factors if there is a slow convergence of either overdamped or underdamped temperature values. If it has been determined that this is occurring, the convergence factor will increase the convergence due to damping in order to reduce computer time. Item 5 specifies the initial temperature estimate for use in the iteration process.

Input data set 1 contains the temperature dependent coefficients for as many as 15 curves. These curves and their structure have been previously described in the microcircuit modelling section.

Input data set 2 contains up to 50 constant temperatures.

Input data set 3 involves heaters for fast warm up and is not used in this model.

Input data set 4 contains the information for the construction of the *n* node equations. For each node there will be two lines of data. The odd numbered lines specify which nodes are connected to the node in question and the mode of heat transfer. Each mode of heat transfer is assigned a numerical value from 1 to 10. Our model builder is concerned only with conduction which has been designated by the number one (1). For example, if node 25 was connected to node 2 by conduction, in line 3 of data set 4 an entry of 251 would appear. The even numbered lines specify the internodal conductances. For the model builder this line will contain the curve number specified in data set 1 corresponding to the connecting nodes.

Input data set 5 specifies the use of unique exponents and is not used in this model.

Input data set 6 specifies the initial temperature guesses corresponding to the number of nodes receiving secondary heat and is not used in this model. All initial temperature guesses are equal and are set in line 5.

Input data set 7 specifies the number of temperature dependent heat input curves and is not used in this model.

C. FEATURES OF MICCKT

The MICCKT program will generate a file which can be read by the thermal analysis software in order to provide the thermal analysis. The program is user friendly and will save numerous man hours in the analysis process. Through the use of MICCKT reaching the 750 node capability of the analyzer is now possible with a minimum of effort.

The program is interactive and will provide prompts for the required inputs. After the prompt for a title for the output file there will be a list of options to produce the number of nodes for analysis. These options are:

1) 16 by 16, (640 nodes)
2) 12 by 24, (720 nodes)
3) 10 by 30, (750 nodes)
4) 8 by 32, (640 nodes)
5) 12 by 18, (540 nodes)

The options were selected to provide the user with several aspect ratios to approximate the microcircuit structure. Option 1 provides the user with a 1:1 aspect ratio while options 2 through 5 provide the aspect ratios of 1:2, 1:3, 1:4, and 2:3 respectively.

After selecting the number of nodes for analysis the user must specify the use of either English or SI units. Once this selection is made all subsequent inputs will conform to the chosen units. The next several inputs are concerned with the physical size of the chip and with initial conditions. The user will input the length, width, and overall thickness of the chip, the initial temperatures of the lid and sink, and the air gap distance between the chip and the lid. As a reminder, the user is limited to an air gap thickness of 0.254 centimeters (0.10 inches) maximum.

It is at this point that any heat inputs to the chip may be entered. The user may select from four options. The first option is total rate of heat applied to the chip. The total rate of heat will be divided by the number of nodes in the top layer and evenly distributed to each node as an average input. The second option is average rate of heat per unit area, this will be either in Btu/hr-in^2 or Watts/cm^2. This average rate of heat per area will be multiplied by the area of the chip and evenly distributed to each node. The third option allows the user to select specific nodes for individual heat rate inputs. The fourth option is for no external heat input to the chip.

Once these selections are made a summary of the user's inputs is displayed for verification. The user can review these inputs and make necessary changes before continuing. If all entries are satisfactory the run will continue and produce an output file.

This output file will be in the the proper format for use in the thermal analyzer. All data input lines and data input sets will be automatically generated. In particular, for input data set 4, each node will be connected to its neighboring nodes by the mode of heat transfer and appropiate temperature dependent curve.

```
C                              APPENDIX A
C
C
C     THIS PROGRAM IS DESIGNED TO PROVIDE AN OUTPUT FILE WHICH WILL BE
C  READ BY THE THERMAL ANALYSIS SOFTWARE. IT IS A MODEL BUILDER FOR A
C  MICROCIRCUIT STRUCTURE OF PURE SILICON AND WILL TAKE INTO
C  CONSIDERATION THE VARIATIONS IN THERMAL CONDUCTIVITY EXHIBITED BY
C  SILICON. THE STRUCTURE IS DIVIDED INTO FOUR LAYERS WITH THE TOP TWO
C  LAYERS CONTAINING FOUR TIMES AS MANY NODES AS THE BOTTOM TWO LAYERS.
C  THE STRUCTURE IS COVERED WITH A LID AND THE GAP BETWEEN THE LID AND
C  CHIP IS AIR FILLED.
C     COMMENTS ARE ENTERED THROUGHOUT THIS PROGRAM IN ORDER TO EXPLAIN
C  THE DEFINITION OF SYMBOLS USED OR TO EXPLAIN THE LOGIC INVOLVED.
C  THIS PROGRAM WAS DEVELOPED AS PART OF A THESIS BY LCDR JOSEPH A.
C  WILLHELM, "COMPUTER AIDED THERMAL ANALYSIS OF A MICROCIRCUIT
C  STRUCTURE", DEC. 1990. FURTHER INFORMATION CAN BE OBTAINED IN THIS
C  THESIS.
C
C
      CHARACTER * 79 TITLE
      CHARACTER * 1 RESP, YES, ANS, CHANS
C
C     THE TITLE ALLOWS FOR UP TO 79 ALPHANUMERIC CHARACTERS TO BE
C  ENTERED TO DESCRIBE THE OUTPUT FILE. RESP IS THE RESPONSE TO MAKING
C  ANY CHANGES TO THE SUMMARY WHEN IT APPEARS. YES IS THE RESPONSE TO
C  DIFFERENT QUESTIONS AS THEY OCCUR, ANY OTHER RESPONSE WILL RESULT IN
C  CONTINUATION. ANS IS THE RESPONSE TO MAKING ANY CHANGES TO THE HEAT
C  INPUTS. CHANS IS THE RESPONSE TO ALL CHANGES MADE IN THE HEAT INPUTS.
C
C
      INTEGER R, COUNT, CNTR, NODE, I, J, XROW, YROW, SELECT, NDE,
     +CHNODE, LVL, COUNTER, NX, NY, NR, NL, CTR, KNTR,
     +ALPHA, BETA, GAMMA, DELTA, NP, N
C
      INTEGER CONST, HTR, EXP, SECHT, COEFCV, FASTHT, HTCV,
     +CONTROL1, CONTROL2, CONTROL3, NODES, KMAX, NMAX, XP, SHT, EFCV,
     +TCV, STHT, MAXITS, DNN, UNK, UNIT, LIDN, SNKN
C
C
C     THE FOLLOWING ARE A LIST OF THE ABBREVIATIONS USED IN THE INTEGER
C  LISTING:
C                COUNT, CNTR, COUNTER, CTR, AND KNTR = COUNTERS
C                NODE, NDE = NODE NUMBERS OF THE STRUCTURE
C                I, J, AND N = USED IN DO LOOPS, COUNTERS
C                XROW = NUMBER OF NODES IN THE X DIRECTION
C                YROW = NUMBER OF NODES IN THE Y DIRECTION
C                NX = XROW/2, NUMBER OF NODES IN THE X DIRECTION OF THE
C                     BOTTOM TWO LAYERS
C                NY = YROW/2, NUMBER OF NODES IN THE Y DIRECTION OF THE
C                     BOTTOM TWO LAYERS
C                NR = NEXT ROW, TO DETERMINE THE NODE ADJACENT TO THE
C                     NODE UNDER CONSIDERATION, + OR - Y DIRECTION
C                NL = NEXT LAYER, TO DETERMINE THE NODE ADJACENT TO THE
C                     NODE UNDER CONSIDERATION, ABOVE OR BELOW
C                R = TOTAL NUMBER OF NODES SELECTED
C                NP = NEXT POINT, COUNTER
C                X, Y, AND Z = THREE DIMENSION COORDINATE SYSTEM
C                SELECT = NUMBER OF THE OPTION SELECTED FOR NUMBER OF
C                     NODES TO BE USED
C                CHNODE = CHANGE NODE, TO CHANGE THE NODE SELECTED FOR
C                     HEAT INPUT
C                LVL = LEVEL, IN THIS CASE SET TO 4, ALTHOUGH NOT
C                     SPECIFICALLY USED IN THIS PROGRAM IF FUTURE
C                     APPLICATIONS REQUIRE A VARIABLE LAYER SELECTION THE
C                     BASIS FOR THIS PURPOSE ARE IMBEDDED IN THIS PROGRAM
C                ALPHA, BETA, GAMMA, AND DELTA = ALGORITHMS USED TO
C                     CONNECT THE NODES IN LAYER TWO TO THE NODES IN LAYER
C                     THREE DUE TO THE 4:1 RATIO BETWEEN THE LAYERS
C                UNIT = RESPONSE TO SI OR ENGLISH UNITS
C                SNKN = NUMBER OF SINK NODES
C                LIDN = NUMBER OF NODES TO THE LID AND AIR GAP
C           ALL OTHER INTEGER ENTRIES INVOLVE NECESSARY INPUTS FOR THE
```

```
C        THERMAL ANALYZER AND ARE USED HERE FOR ACCOUNTING PURPOSES.
C
C
      INTEGER B(750,800), TMP(10), KOUNTER(750), SUB1(9)
C
C
C              B ARRAY = NODE NUMBER ARRAY
C              TMP AND SUB1 ARRAYS = TEMPORARY ARRAYS USED FOR COUNTING
C              KOUNTER ARRAY = USED AS A COUNTER
C
C
      REAL WATTS, TOTHT, HTPAR, AVG, AVG1, LENGTH, WIDTH, EPSL, EPSD,
     +EMS, TX, TAV, HGAP, HRAD, FE, LID, SINK, CHOICE, LINE, CHWATT,
     +THICK, TH1, TH2, DELX, DELY, DELZ1, DELZ2, RAT, FACTOR,
     +DELZ3, DELZ4, GAP, TEMP1, TEMP2, TEMP3, TEMP4, TEMP5, TEMP6,
     +TEMP7, TEMP8, TEMP9, ANSW, KAIR, LIDK,
     +K1, K2, K3, K4, K5, K6, K7, K8, ACC, DAMP, CONVFAC, INTEMP
C
C
C              WATTS = HEAT INPUT TO THE NODES, CAN REPRESENT HEAT INPUT
C                   IN EITHER WATTS OR BTU/HR
C              TOTHT = TOTAL HEAT APPLIED TO THE CHIP
C              HTPAR = HEAT PER UNIT AREA APPLIED TO THE CHIP
C              AVG = TOTAL HEAT DIVIDED BY THE NUMBER OF NODES IN THE
C                   FIRST LAYER, PROVIDES EQUAL DISTRIBUTION OF HEAT
C              AVG1 = HEAT PER AREA TIMES THE AREA DIVIDED BY THE NUMBER
C                   OF NODES IN THE FIRST LAYER
C              LENGTH = LENGTH OF THE CHIP, X DIRECTION
C              WIDTH = WIDTH OF THE CHIP, Y DIRECTION
C              EPSL = EMISSIVITY OF THE LID
C              EPSD = EMISSIVITY OF THE CHIP (DIE)
C              EMS = EMISSIVITY EQUIVALENCE, 1/EPSD + 1/EPSL - 1
C              FE = INVERSE OF EMS, EMISSIVITY FACTOR
C              HRAD = RADIATION CONSTANT OF PROPORTIONALITY FOR AIR
C              HGAP = CONDUCTION CONSTANT OF PROPORTIONALITY FOR AIR
C              RAT = RATIO OF HRAD TO HGAP, CORRECTION FACTOR
C              FACTOR = 1+RAT, MULTIPLIER TO PUT CORRECTION INTO THE
C                   THERMAL CONDUCTIVITY CURVE FOR AIR
C              TX = STARTING TEMPERATURE TO CALCULATE THERMAL
C                   CONDUCTIVITY OF AIR TO GENERATE CURVE 1109
C              TAV = AVERAGE TEMPERATURE OF THE LID AND TX
C              K1 THROUGH K8 = THERMAL CONDUCTIVITY CURVES OF SILICON
C                   REFER TO THESIS FOR MORE DETAILED EXPLANATION
C              KAIR = THERMAL CONDUCTIVITY CURVE OF AIR (1109)
C              LID = TEMPERATURE OF THE LID
C              SINK = TEMPERATURE OF THE SINK
C              CHOICE = CHOICE OF THE METHOD OF HEAT INPUT
C              LINE = LINE NUMBER THAT WILL BE CHANGED AFTER SUMMARY
C              CHWATT = CHANGE THE VALUE OF THE HEAT INPUT
C              THICK = OVERALL THICKNESS OF THE CHIP
C              TH1 = THICKNESS OF THE TOP LAYER, PRESET AT 0.002 IN
C                   (0.00508 CM)
C              TH2 = THICKNESS OF THE SECOND, THIRD, AND FOURTH LAYERS
C                   (THICK-TH1)/3
C              DELX = LENGTH DIVIDED BY THE NUMBER OF NODES IN THE X
C                   DIRECTION TO DETERMINE SEPARATION DISTANCE
C              DELY = WIDTH DIVIDED BY THE NUMBER OF NODES IN THE Y
C                   DIRECTION TO DETERMINE SEPARATION DISTANCE
C              DELZ1 = NODE SEPARATION IN THE Z DIRECTION, LEVEL 1
C              DELZ2 = NODE SEPARATION IN THE Z DIRECTION, LEVELS 2-4
C              DELZ3 = NODE SEPARATION IN THE Z DIRECTION, BETWEEN
C                   LAYERS 2 AND 3
C              DELZ4 = NODE SEPARATION IN THE Z DIRECTION, BETWEEN
C                   LAYER 4 AND THE SINK
C              GAP = DISTANCE BETWEEN THE TOP OF THE CHIP AND THE LID
C                   PRESET TO A MAXIMUM OF 0.10 IN (0.254 CM)
C              TEMP1 THROUGH TEMP9 = TEMPERATURES SELECTED FROM THE
C                   SILICON THERMAL CONDUCTIVITY CURVE TO ESTABLISH THE
C                   CURVES FOR USE IN THE THERMAL ANALYZER
C              ANSW = RESPONSE TO THE OPTIONS OFFERED FOR NUMBER OF
C                   NODES TO BE USED
C              LIDK = LID TEMPERATURE IN KELVIN
```

```
C          ALL OTHER REAL ENTRIES INVOLVE NECESSARY INPUTS FOR THE
C          THERMAL ANALYZER AND ARE USED HERE FOR ACCOUNTING PURPOSES.
C
C
      REAL A(750,800), TEMP(10), LIDT(30), SINKT(4),
     +THCOND(9), CURVE(8,9), C(8), SUB(9), THAIR(9), KAR(9)
C
C
C              A ARRAY = HEAT INPUT ARRAY
C              TEMP AND SUB ARRAYS = TEMPORARY ARRAYS FOR COUNTING
C              LIDT ARRAY = INPUTS CONSTANT TEMPERATURE OF THE LID
C                   FOR THE THERMAL ANALYZER BASED ON REQUIREMENTS
C              SINKT ARRAY = INPUTS CONSTANT TEMPERATURE OF THE SINK
C                   FOR THE THERMAL ANALYZER BASED ON REQUIREMENTS
C              THCOND ARRAY = THERMAL CONDUCIVITY OF SILICON AT THE
C                   TEMPERATURES SELECTED IN TEMP1 - TEMP9
C              C ARRAY = AREA DIVIDED BY THE PATH LENGTH BASED ON INPUTS
C              CURVE ARRAY = C ARRAY TIMES THE THCOND ARRARY
C                   THE TEMP1 - TEMP9 POINTS IN CONJUNCTION WITH THE
C                   CURVE ARRAY PROVIDE THE THERMAL ANALYZER WITH THE
C                   DATA TO GENERATE THE 1101 - 1108 CURVES
C              THAIR ARRAY = EQUATION TO GENERATE THERMAL CONDUCTIVITY
C                   OF AIR GIVEN A TEMPERATURE
C              KAR ARRAY = THE K VALUES FOR THE CURVE 1109
C
C
      PARAMETER (YES='Y')
C
C
      PRINT *,'ENTER THE NAME OF YOUR FILE.'
      READ *, TITLE
C
      PRINT *,'YOU MAY SELECT ONE OF THE FOLLOWING OPTIONS.'
30    PRINT *,'1.) 16 BY 16, YIELDS 640 NODES'
      PRINT *,'2.) 12 BY 24, YIELDS 720 NODES'
      PRINT *,'3.) 10 BY 30, YIELDS 750 NODES'
      PRINT *,'4.) 8 BY 32, YIELDS 640 NODES'
      PRINT *,'5.) 12 BY 18, YIELDS 540 NODES'
      READ *, ANSW
C
C
C        THESE OPTIONS WILL ALLOW THE USER TO SELECT THE NUMBER OF NODES
C     FOR ANALYSIS. THESE OPTIONS WERE DESIGNED TO ALLOW THE USER TO
C     SELECT FROM A LENGTH TO WIDTH RATIO OF 1:1, 1:2, 1:3, 1:4, OR 2:3.
C
C
      IF (ANSW.NE.1.AND.ANSW.NE.2.AND.ANSW.NE.3.AND.ANSW.NE.4.AND.
     +ANSW.NE.5) THEN
          PRINT *,'ONLY OPTIONS 1.,2.,3.,4.,OR 5. ARE ALLOWED.'
          GOTO 30
       ELSEIF (ANSW.EQ.1) THEN
          XROW=16
          YROW=16
          CONST=18
       ELSEIF (ANSW.EQ.2) THEN
          XROW=12
          YROW=24
          CONST=20
       ELSEIF (ANSW.EQ.3) THEN
          XROW=10
          YROW=30
          CONST=20
       ELSEIF (ANSW.EQ.4) THEN
          XROW=8
          YROW=32
          CONST=18
       ELSEIF (ANSW.EQ.5) THEN
          XROW=12
          YROW=18
          CONST=15
       ENDIF
C
```

```
10    PRINT *,'ENTER 1.) FOR SI OR 2.) FOR ENGLISH
     +UNITS.'
      READ *, UNIT
C
C
C     THE UNITS USED FOR INPUTS IN THIS PROGRAM WILL BE:
C             SI; CENTIMETERS, WATTS, DEG CENTIGRADE
C             ENGLISH; INCHES, BTU/HR, DEG FAHRENHEIT
C  OTHER PARAMETERS USED IN THIS PROGRAM WILL AUTOMATICALLY CONFORM
C  TO THE CHOSEN UNITS.
C
C
      IF (UNIT.NE.1.AND.UNIT.NE.2)THEN
         PRINT *,'TRY AGAIN'
         GOTO 10
      ELSE
         CONTINUE
      ENDIF
C
      IF (UNIT.EQ.1) THEN
         PRINT *,'INPUT CHIP DIMENSIONS IN CENTIMETERS'
      ELSE
         PRINT *,'INPUT CHIP DIMENSIONS IN INCHES'
      ENDIF
C
      PRINT *,'ENTER LENGTH:'
      READ *, LENGTH
C
      PRINT *,'ENTER WIDTH:'
      READ *, WIDTH
C
      PRINT *,'ENTER THICKNESS:'
      READ *, THICK
C
120   PRINT *,'ENTER THE THICKNESS OF THE AIR LAYER BETWEEN THE LID'
      PRINT *,'AND THE TOP OF THE DIE:'
      READ *, GAP
C
      IF (UNIT.EQ.1.AND.GAP.GT.0.254) THEN
         PRINT *,'AIR LAYER THICKNESS EXCEEDS MAXIMUM ALLOWED (0.254CM)'
         GOTO 120
      ELSEIF (UNIT.EQ.2.AND.GAP.GT.0.10) THEN
         PRINT *,'AIR LAYER THICKNESS EXCEEDS MAXIMUM ALLOWED (0.10 IN)'
         GOTO 120
      ELSE
         CONTINUE
      ENDIF
C
      PRINT *,'ENTER THE TEMPERATURE OF THE LID.'
      READ *, LID
C
      PRINT *,'ENTER THE TEMPERATURE OF THE SINK.'
      READ *, SINK
C
      PRINT *,'ENTER THE EMISSIVITY OF THE LID.'
      READ *, EPSL
C
      PRINT *,'ENTER THE EMISSIVITY OF THE DIE.'
      READ *, EPSD
C
C
      NX=XROW/2
      NY=YROW/2
      LVL=4
      NR=XROW
      NL=XROW*YROW
      R=XROW*YROW*2.5
      COUNTER=1
C
      DO 26 I=1,R
         DO 27 J=1,800
            A(I,J)=0.0
```

```
            B(I,J)=0
27        CONTINUE
26      CONTINUE
C
C
C       INITIALIZES THE MATRICES WITH ZEROES. THIS IS DONE AS THE SIZE OF
C     THESE MATRICES COULD CAUSE EXCESS COMPUTER TIME IF NOT DONE IN THIS
C     FASHION.
C
C
110     DO 11 I=1,R
              A(I,770)=0.0
              B(I,770)=0
11      CONTINUE
C
C
C       IN THE EVENT THE USER WISHES TO MAKE SIGNIFICANT CHANGES TO THE
C     NODE HEAT INPUTS THIS DO LOOP WILL RESET THE NODES AND HEAT INPUTS
C     TO ZERO. THIS IS DONE IN THE EVENT THAT THE MODE OF APPLICATION HAS
C     CHANGED OR IF ONE OR MORE NODES ARE TO BE ELIMINATED.
C
C
        IF (UNIT.EQ.1) THEN
           PRINT *,'HEAT INPUTS WILL BE IN WATTS.'
           TH1=0.00508
           INTEMP=100
        ELSE
           PRINT *,'HEAT INPUTS WILL BE IN BTU/HR.'
           TH1=0.002
           INTEMP=212
        ENDIF
C
C
C       BASED ON THE UNITS SELECTED THIS STATEMENT SERVES AS A PROMPT AND
C     TO SET THE THICKNESS OF THE TOP LAYER AND INITIAL TEMPERATURE FOR
C     THE THERMAL ANALYZER IN THE PROPER UNITS.
C
C
        PRINT *,'HEAT INPUT TO THE MICROCIRCUIT CAN BE ENTERED IN THE'
        PRINT *,'FOLLOWING MANNER. CHOOSE 1.) TO ENTER AS TOTAL HEAT'
        PRINT *,'APPLIED TO THE CHIP, 2.) TO ENTER AS THE AVERAGE HEAT'
        PRINT *,'PER AREA, 3.) TO ENTER NODE BY NODE, OR 4.) FOR NO HEAT'
        PRINT *,'INPUT.'
        READ *, CHOICE
C
        IF (CHOICE.EQ.1) THEN
           PRINT *,'ENTER TOTAL HEAT APPLIED TO THE CHIP'
           READ *, TOTHT
           AVG=TOTHT/NL
           DO 12 N=1,NL
              A(N,770)=AVG
              B(N,770)=9991
12         CONTINUE
        ELSEIF (CHOICE.EQ.2) THEN
           PRINT *,'ENTER AVERAGE HEAT PER UNIT AREA'
           READ *, HTPAR
           AVG1=(HTPAR*LENGTH*WIDTH)/NL
           DO 13 N=1,NL
              A(N,770)=AVG1
              B(N,770)=9991
13         CONTINUE
C
C
C       THE NUMBER 9991 IS RECOGNIZED BY THE THERMAL ANALYZER TO BE A
C     CONDUCTIVE HEAT INPUT FROM AN EXTERNAL SOURCE. THE NODE NUMBER 770
C     IS ASSIGNED TO TRACK THIS HEAT INPUT.
C
C
        ELSEIF (CHOICE.EQ.3) THEN
        PRINT *,'YOU MAY SELECT HEAT INPUTS TO THE INDIVIDUAL NODES.'
111     PRINT *,'YOU ARE LIMITED TO A MAXIMUM OF 256 INPUTS FOR THE'
        PRINT *,'640 NODE MODELS, 288 INPUTS FOR THE 720 NODE MODEL,'
```

```
      PRINT *,'300 INPUTS FOR THE 750 NODE MODEL, OR 216 INPUTS'
      PRINT *,'FOR THE 540 NODE MODEL.'
      PRINT *,'SELECT THE NUMBER OF NODES THAT HAVE HEAT INPUTS.'
      READ *, SELECT
C
C
C     THE REASON FOR THESE OPTIONS IS THAT THEY REPRESENT THE NUMBER OF
C  NODES IN THE TOP LAYER. THESE ARE THE ONLY NODES ALLOWED TO HAVE AN
C  EXTERNAL HEAT INPUT BY THIS PROGRAM.
C
C
      IF (SELECT.GT.NL) THEN
        PRINT *,'NUMBER OF NODES SELECTED EXCEEDS MAXIMUM ALLOWED.'
        GOTO 111
      ELSE
        CONTINUE
      ENDIF
C
      DO 14 I=1,SELECT
      PRINT *,'SELECT THE NODE TO BE INPUTTED.'
        READ *, NODE
      PRINT *,'ENTER THE HEAT INPUT AT THAT NODE.'
        READ *, WATTS
      A(NODE,770)=WATTS
      B(NODE,770)=9991
      KOUNTER(I)=I

 14   CONTINUE
C
      ELSEIF (CHOICE.EQ.4) THEN
        GOTO 17
      ELSEIF (CHOICE.NE.1.AND.CHOICE.NE.2.AND.CHOICE.NE.3.AND.
     +CHOICE.NE.4) THEN
        PRINT *,'TRY AGAIN'
        GOTO 110
      ENDIF
 17   CONTINUE
C
 112  PRINT *,'SUMMARY OF INPUT DATA.'
      IF (UNIT.EQ.1) THEN
      PRINT '(A,G12.4)',' 1.) LENGTH OF THE CHIP IS (CM):               ',
     +LENGTH
      PRINT '(A,G12.4)',' 2.) WIDTH OF THE CHIP IS (CM):                ',
     +WIDTH
      PRINT '(A,G12.4)',' 3.) THICKNESS OF THE CHIP IS (CM):            ',
     +THICK
      PRINT '(A,G12.4)',' 4.) THICKNESS OF THE AIR LAYER (CM):          ',
     +GAP
      PRINT '(A,G12.4)',' 5.) TEMPERATURE OF THE LID IS (DEG C):        ',
     +LID
      PRINT '(A,G12.4)',' 6.) TEMPERATURE OF THE SINK IS (DEG C):       ',
     +SINK
      PRINT '(A,G12.4)',' 7.) THE EMISSIVITY OF THE LID IS:             ',
     +EPSL
      PRINT '(A,G12.4)',' 8.) THE EMISSIVITY OF THE DIE IS:             ',
     +EPSD
      PRINT *,'9.) THE HEAT INPUTS TO THE NODES ARE:'
C
      IF (CHOICE.EQ.1) THEN
        PRINT '(A,G12.4,A)',' AVERAGE HEAT APPLIED TO EACH NODE IS:   ',
     +AVG,' WATTS'
      ELSEIF (CHOICE.EQ.2) THEN
        PRINT '(A,G12.4,A)',' HEAT APPLIED TO EACH NODE IS:           ',
     +AVG1,' WATTS'
      ELSEIF (CHOICE.EQ.3) THEN
        DO 15 I=1,NL
          IF (B(I,770).EQ.0) THEN
            GOTO 15
          ELSE
            NDE=I
            PRINT '(A,I3)', ' NODE    ',NDE
            PRINT '(A,G12.4,/)', ' WATTS',A(I,770)
```

```
            ENDIF
15       CONTINUE
      ELSEIF (CHOICE.EQ.4) THEN
         PRINT *,'NO HEAT INPUTS WERE DESIGNATED.'
      ENDIF
      ELSE
      PRINT '(A,G12.4)',' 1.) LENGTH OF THE CHIP IS (IN):            ',
     +LENGTH
      PRINT '(A,G12.4)',' 2.) WIDTH OF THE CHIP IS (IN):             ',
     +WIDTH
      PRINT '(A,G12.4)',' 3.) THICKNESS OF THE CHIP IS (IN):         ',
     +THICK
      PRINT '(A,G12.4)',' 4.) THICKNESS OF THE AIR LAYER (IN):       ',
     +GAP
      PRINT '(A,G12.4)',' 5.) TEMPERATURE OF THE LID IS (DEG F):     ',
     +LID
      PRINT '(A,G12.4)',' 6.) TEMPERATURE OF THE SINK IS (DEG F):    ',
     +SINK
      PRINT '(A,G12.4)',' 7.) THE EMISSIVITY OF THE LID IS:          ',
     +EPSL
      PRINT '(A,G12.4)',' 8.) THE EMISSIVITY OF THE DIE IS:          ',
     +EPSD
      PRINT *,'9.) THE HEAT INPUTS TO THE NODES ARE:'
C
      IF (CHOICE.EQ.1) THEN
         PRINT '(A,G12.4,A)',' AVERAGE HEAT APPLIED TO EACH NODE IS:  ',
     +AVG,' BTU/HR'
      ELSEIF (CHOICE.EQ.2) THEN
         PRINT '(A,G12.4,A)',' HEAT APPLIED TO EACH NODE IS:          ',
     +AVG1,' BTU/HR'
      ELSEIF (CHOICE.EQ.3) THEN
         DO 22 I=1,NL
            IF (B(I,770).EQ.0) THEN
              GOTO 22
            ELSE
              NDE=I
              PRINT '(A,I3)', ' NODE     ',NDE
              PRINT '(A,G12.4,/)', ' BTU/HR',A(I,770)
            ENDIF
22       CONTINUE
      ELSEIF (CHOICE.EQ.4) THEN
         PRINT *,'NO HEAT INPUTS WERE DESIGNATED.'
      ENDIF
C
      ENDIF
C
      PRINT *,'DO YOU WISH TO MAKE ANY CHANGES, Y OR N?'
      READ (*,5) RESP
5     FORMAT (A1)
C
      IF (RESP.EQ.YES) THEN
         PRINT *,'WHICH LINE ITEM DO YOU WISH TO CHANGE?'
         READ *, LINE
      ELSE
         GOTO 113
      ENDIF
C
         IF (LINE.EQ.1) THEN
            PRINT *,'ENTER THE LENGTH OF THE CHIP.'
            READ *,LENGTH
            GOTO 112
C
         ELSEIF (LINE.EQ.2) THEN
            PRINT *,'ENTER THE WIDTH OF THE CHIP.'
            READ *,WIDTH
            GOTO 112
C
         ELSEIF (LINE.EQ.3) THEN
            PRINT *,'ENTER THE THICKNESS OF THE CHIP.'
            READ *,THICK
            GOTO 112
C
```

```
              ELSEIF (LINE.EQ.4) THEN
                 PRINT *,'ENTER THE THICKNESS OF THE AIR LAYER.'
                 READ *,GAP
                 GOTO 112
C
              ELSEIF (LINE.EQ.5) THEN
                 PRINT *,'ENTER THE LID TEMPERATURE.'
                 READ *,LID
                 GOTO 112
C
              ELSEIF (LINE.EQ.6) THEN
                 PRINT *,'ENTER THE TEMPERATURE OF THE SINK.'
                 READ *,SINK
                 GOTO 112
C
              ELSEIF (LINE.EQ.7) THEN
                 PRINT *,'ENTER THE EMISSIVITY OF THE LID.'
                 READ *, EPSL
                 GOTO 112
C
              ELSEIF (LINE.EQ.8) THEN
                 PRINT *,'ENTER THE EMISSIVITY OF THE DIE.'
                 READ *, EPSD
                 GOTO 112
C
              ELSEIF (LINE.EQ.9) THEN
                 PRINT *,'DO YOU WISH TO CHANGE YOUR CHOICE OF HEAT INPUT?'
                 READ (*,4) ANS
4                FORMAT (A1)
                 IF (ANS.EQ.YES) THEN
                 GOTO 110
                 ELSE
114              PRINT *,'ENTER NODE AND HEAT INPUT TO BE CHANGED:'
                 READ *, CHNODE, CHNATT
                 B(CHNODE,770)=9991
                 A(CHNODE,770)=CHNATT
                 PRINT *,'ALL CHANGES COMPLETED?'
                 READ (*,6) CHANS
6                FORMAT (A1)
                 IF (CHANS.EQ.YES) THEN
                    CHOICE=3.0
                    GOTO 112
                 ELSE
                    GOTO 114
                 ENDIF
                 ENDIF
C
           ELSEIF (LINE.NE.1.AND.LINE.NE.2.AND.LINE.NE.3.AND.LINE.NE.4.AND.
          +LINE.NE.5.AND.LINE.NE.6.AND.LINE.NE.7.AND.LINE.NE.8.AND.
          +LINE.NE.9) THEN
                 PRINT *,'TRY AGAIN'
                 GOTO 112
              ELSE
                 CONTINUE
              ENDIF
C
C
           K1=1101.
           K2=1102.
           K3=1103.
           K4=1104.
           K5=1105.
           K6=1106.
           K7=1107.
           K8=1108.
C
C
C          K1 - K8 ASSIGN THE CURVES 1101 - 1108 TO SPECIFIC NODES FOR USE
C       IN THE THERMAL ANALYZER.
C
C
C          THE FOLLOWING SETS OF ALGORITHMS ESTABLISH THE NODE AND THE
```

```
C  NODES WHICH ARE CONNECTED TO IT. THEY ALSO ESTABLISH THE CURVE TO BE
C  USED IN THE ANALYSIS.
C
C
113       DO 31 Y=1,YROW
            DO 32 X=1,XROW
C
        I=COUNTER
C
        IF (X-1.EQ.0.AND.Y-1.EQ.0) THEN
           A(I,I+1)= K1
           A(I,I+NR)= K2
           B(I,I+1)= 10*(I+1)+1
           B(I,I+NR)= 10*(I+NR)+1
C
        ELSEIF (X+1.GT.XROW.AND.Y-1.EQ.0) THEN
           A(I,I-1)= K1
           A(I,I+NR)= K2
           B(I,I-1)= 10*(I-1)+1
           B(I,I+NR)= 10*(I+NR)+1
C
        ELSEIF (Y-1.EQ.0) THEN
           A(I,I-1)= K1
           A(I,I+1)= K1
           A(I,I+NR)= K2
           B(I,I-1)= 10*(I-1)+1
           B(I,I+1)= 10*(I+1)+1
           B(I,I+NR)= 10*(I+NR)+1
C
        ELSEIF (X-1.EQ.0.AND.Y+1.GT.YROW) THEN
           A(I,I+1)= K1
           A(I,I-NR)= K2
           B(I,I+1)= 10*(I+1)+1
           B(I,I-NR)= 10*(I-NR)+1
C
        ELSEIF (X+1.GT.XROW.AND.Y+1.GT.YROW) THEN
           A(I,I-1)= K1
           A(I,I-NR)= K2
           B(I,I-1)= 10*(I-1)+1
           B(I,I-NR)= 10*(I-NR)+1
C
        ELSEIF (X-1.EQ.0) THEN
           A(I,I+1)= K1
           A(I,I-NR)= K2
           A(I,I+NR)= K2
           B(I,I+1)= 10*(I+1)+1
           B(I,I-NR)= 10*(I-NR)+1
           B(I,I+NR)= 10*(I+NR)+1
C
        ELSEIF (X+1.GT.XROW) THEN
           A(I,I-1)= K1
           A(I,I-NR)= K2
           A(I,I+NR)= K2
           B(I,I-1)= 10*(I-1)+1
           B(I,I-NR)= 10*(I-NR)+1
           B(I,I+NR)= 10*(I+NR)+1
C
        ELSEIF (Y+1.GT.YROW) THEN
           A(I,I-1)= K1
           A(I,I+1)= K1
           A(I,I-NR)= K2
           B(I,I-1)= 10*(I-1)+1
           B(I,I+1)= 10*(I+1)+1
           B(I,I-NR)= 10*(I-NR)+1
C
        ELSE
           A(I,I-1)= K1
           A(I,I+1)= K1
           A(I,I-NR)= K2
           A(I,I+NR)= K2
           B(I,I-1)= 10*(I-1)+1
           B(I,I+1)= 10*(I+1)+1
```

```
           B(I,I-NR)= 10*(I-NR)+1
           B(I,I+NR)= 10*(I+NR)+1
C
        ENDIF
C
           A(I,I+NL)= K3
           B(I,I+NL)= 10*(I+NL)+1
C
        COUNTER=COUNTER+1
C
32      CONTINUE
31      CONTINUE
C
C
        KNTR=NL+1
          DO 33 Y=1,YROW
             DO 34 X=1,XROW
C
        I=KNTR
C
        IF (X-1.EQ.0.AND.Y-1.EQ.0) THEN
           A(I,I+1)= K4
           A(I,I+NR)= K5
           B(I,I+1)= 10*(I+1)+1
           B(I,I+NR)= 10*(I+NR)+1
C
        ELSEIF (X-1.EQ.0.AND.Y+1.GT.YROW) THEN
           A(I,I+1)= K4
           A(I,I-NR)= K5
           B(I,I+1)= 10*(I+1)+1
           B(I,I-NR)= 10*(I-NR)+1
C
        ELSEIF (X+1.GT.XROW.AND.Y-1.EQ.0) THEN
           A(I,I-1)= K4
           A(I,I+NR)= K5
           B(I,I-1)= 10*(I-1)+1
           B(I,I+NR)= 10*(I+NR)+1
C
        ELSEIF (X+1.GT.XROW.AND.Y+1.GT.YROW) THEN
           A(I,I-1)= K4
           A(I,I-NR)= K5
           B(I,I-1)= 10*(I-1)+1
           B(I,I-NR)= 10*(I-NR)+1
C
        ELSEIF (X-1.EQ.0) THEN
           A(I,I+1)= K4
           A(I,I-NR)= K5
           A(I,I+NR)= K5
           B(I,I+1)= 10*(I+1)+1
           B(I,I-NR)= 10*(I-NR)+1
           B(I,I+NR)= 10*(I+NR)+1
C
        ELSEIF (X+1.GT.XROW) THEN
           A(I,I-1)= K4
           A(I,I-NR)= K5
           A(I,I+NR)= K5
           B(I,I-1)= 10*(I-1)+1
           B(I,I-NR)= 10*(I-NR)+1
           B(I,I+NR)= 10*(I+NR)+1
C
        ELSEIF (Y-1.EQ.0) THEN
           A(I,I-1)= K4
           A(I,I+1)= K4
           A(I,I+NR)= K5
           B(I,I-1)= 10*(I-1)+1
           B(I,I+1)= 10*(I+1)+1
           B(I,I+NR)= 10*(I+NR)+1
C
        ELSEIF (Y+1.GT.YROW) THEN
           A(I,I-1)= K4
           A(I,I+1)= K4
           A(I,I-NR)= K5
```

```
         B(I,I-1)= 10*(I-1)+1
         B(I,I+1)= 10*(I+1)+1
         B(I,I-NR)= 10*(I-NR)+1
C
      ELSE
         A(I,I-1)= K4
         A(I,I+1)= K4
         A(I,I-NR)= K5
         A(I,I+NR)= K5
         B(I,I-1)= 10*(I-1)+1
         B(I,I+1)= 10*(I+1)+1
         B(I,I-NR)= 10*(I-NR)+1
         B(I,I+NR)= 10*(I+NR)+1
      ENDIF
C
         A(I,I-NL)= K3
         B(I,I-NL)=10*(I-NL)+1
C
      KNTR=KNTR+1
C
34    CONTINUE
33    CONTINUE
C
C
      CNTR=2*NL+1
      NP=NL+1
         DO 35 Y=1,NY
           DO 36 X=1,NX
C
      I=CNTR
C
      IF (X-1.EQ.0.AND.Y-1.EQ.0) THEN
         A(I,I+1)= K4
         A(I,I+NX)= K5
         B(I,I+1)= 10*(I+1)+1
         B(I,I+NX)= 10*(I+NX)+1
C
      ELSEIF (X-1.EQ.0.AND.Y+1.GT.NY) THEN
         A(I,I+1)= K4
         A(I,I-NX)= K5
         B(I,I+1)= 10*(I+1)+1
         B(I,I-NX)= 10*(I-NX)+1
C
      ELSEIF (X+1.GT.NX.AND.Y-1.EQ.0) THEN
         A(I,I-1)= K4
         A(I,I+NX)= K5
         B(I,I-1)= 10*(I-1)+1
         B(I,I+NX)= 10*(I+NX)+1
C
      ELSEIF (X+1.GT.NX.AND.Y+1.GT.NY) THEN
         A(I,I-1)= K4
         A(I,I-NX)= K5
         B(I,I-1)= 10*(I-1)+1
         B(I,I-NX)= 10*(I-NX)+1
C
      ELSEIF (X-1.EQ.0) THEN
         A(I,I+1)= K4
         A(I,I-NX)= K5
         A(I,I+NX)= K5
         B(I,I+1)= 10*(I+1)+1
         B(I,I-NX)= 10*(I-NX)+1
         B(I,I+NX)= 10*(I+NX)+1
C
      ELSEIF (X+1.GT.NX) THEN
         A(I,I-1)= K4
         A(I,I-NX)= K5
         A(I,I+NX)= K5
         B(I,I-1)= 10*(I-1)+1
         B(I,I-NX)= 10*(I-NX)+1
         B(I,I+NX)= 10*(I+NX)+1
C
      ELSEIF (Y-1.EQ.0) THEN
```

```
          A(I,I-1)= K4
          A(I,I+1)= K4
          A(I,I+NX)= K5
          B(I,I-1)= 10*(I-1)+1
          B(I,I+1)= 10*(I+1)+1
          B(I,I+NX)= 10*(I+NX)+1
C
       ELSEIF (Y+1.GT.NY) THEN
          A(I,I-1)= K4
          A(I,I+1)= K4
          A(I,I-NX)= K5
          B(I,I-1)= 10*(I-1)+1
          B(I,I+1)= 10*(I+1)+1
          B(I,I-NX)= 10*(I-NX)+1
C
       ELSE
          A(I,I-1)= K4
          A(I,I+1)= K4
          A(I,I-NX)= K5
          A(I,I+NX)= K5
          B(I,I-1)= 10*(I-1)+1
          B(I,I+1)= 10*(I+1)+1
          B(I,I-NX)= 10*(I-NX)+1
          B(I,I+NX)= 10*(I+NX)+1
       ENDIF
C
       ALPHA=-NP+X+(Y-1)*(NR+NX)
       BETA=-NL+X+(Y-1)*(NR+NX)
       GAMMA=-NP+X+(Y-1)*(NR+NX)+NR
       DELTA=-NL+X+(Y-1)*(NR+NX)+NR
C
          A(I,I+ALPHA)= K6
          A(I,I+BETA)= K6
          A(I,I+GAMMA)= K6
          A(I,I+DELTA)= K6
          A(I,I+NL/4)= K7
          A(I+ALPHA,I)= K6
          A(I+BETA,I)= K6
          A(I+GAMMA,I)= K6
          A(I+DELTA,I)= K6
          B(I,I+ALPHA)= 10*(I+ALPHA)+1
          B(I,I+BETA)= 10*(I+BETA)+1
          B(I,I+GAMMA)= 10*(I+GAMMA)+1
          B(I,I+DELTA)= 10*(I+DELTA)+1
          B(I,I+NL/4)= 10*(I+NL/4)+1
          B(I+ALPHA,I)= 10*I+1
          B(I+BETA,I)= 10*I+1
          B(I+GAMMA,I)= 10*I+1
          B(I+DELTA,I)= 10*I+1
C
       CNTR=CNTR+1
C
36     CONTINUE
35     CONTINUE
C
C
       CTR=2*NL+NL/4+1
          DO 37 Y=1,NY
             DO 38 X=1,NX
C
       I=CTR
C
       IF (X-1.EQ.0.AND.Y-1.EQ.0) THEN
          A(I,I+1)= K4
          A(I,I+NX)= K5
          B(I,I+1)= 10*(I+1)+1
          B(I,I+NX)= 10*(I+NX)+1
C
       ELSEIF (X-1.EQ.0.AND.Y+1.GT.NY) THEN
          A(I,I+1)= K4
          A(I,I-NX)= K5
          B(I,I+1)= 10*(I+1)+1
```

```
          B(I,I-NX)= 10*(I-NX)+1
C
      ELSEIF (X+1.GT.NX.AND.Y-1.EQ.0) THEN
          A(I,I-1)= K4
          A(I,I+NX)= K5
          B(I,I-1)= 10*(I-1)+1
          B(I,I+NX)= 10*(I+NX)+1
C
      ELSEIF (X+1.GT.NX.AND.Y+1.GT.NY) THEN
          A(I,I-1)= K4
          A(I,I-NX)= K5
          B(I,I-1)= 10*(I-1)+1
          B(I,I-NX)= 10*(I-NX)+1
C
      ELSEIF (X-1.EQ.0) THEN
          A(I,I+1)= K4
          A(I,I-NX)= K5
          A(I,I+NX)= K5
          B(I,I+1)= 10*(I+1)+1
          B(I,I-NX)= 10*(I-NX)+1
          B(I,I+NX)= 10*(I+NX)+1
C
      ELSEIF (X+1.GT.NX) THEN
          A(I,I-1)= K4
          A(I,I-NX)= K5
          A(I,I+NX)= K5
          B(I,I-1)= 10*(I-1)+1
          B(I,I-NX)= 10*(I-NX)+1
          B(I,I+NX)= 10*(I+NX)+1
C
      ELSEIF (Y-1.EQ.0) THEN
          A(I,I-1)= K4
          A(I,I+1)= K4
          A(I,I+NX)= K5
          B(I,I-1)= 10*(I-1)+1
          B(I,I+1)= 10*(I+1)+1
          B(I,I+NX)= 10*(I+NX)+1
C
      ELSEIF (Y+1.GT.NY) THEN
          A(I,I-1)= K4
          A(I,I+1)= K4
          A(I,I-NX)= K5
          B(I,I-1)= 10*(I-1)+1
          B(I,I+1)= 10*(I+1)+1
          B(I,I-NX)= 10*(I-NX)+1
C
      ELSE
          A(I,I-1)= K4
          A(I,I+1)= K4
          A(I,I-NX)= K5
          A(I,I+NX)= K5
          B(I,I-1)= 10*(I-1)+1
          B(I,I+1)= 10*(I+1)+1
          B(I,I-NX)= 10*(I-NX)+1
          B(I,I+NX)= 10*(I+NX)+1
C
      ENDIF
C
          A(I,I-NL/4)= K7
          B(I,I-NL/4)= 10*(I-NL/4)+1
C
      CTR=CTR+1
C
38    CONTINUE
37    CONTINUE
C
C
      TH2=(THICK-TH1)/(LVL-1)
      DELX=LENGTH/XROW
      DELY=WIDTH/YROW
      DELZ1=TH1
      DELZ2=TH2
```

```
      DELZ3=(TH1+TH2)/2
      DELZ4=TH2/2
      KAIR=1109.
C
C
C  THE FOLLOWING ALGORITHM WILL CALCULATE A CORRECTION FACTOR FOR THE
C  THERMAL CONDUCTIVITY OF AIR TO INCLUDE RADIATION EFFECTS. THIS IS
C  DONE TO SAVE ON COMPUTER RUN TIME IN THE THERMAL ANALYZER. SEE
C  THESIS FOR GREATER DETAILS.
C
C
      IF (UNIT.EQ.1) THEN
         LIDK=LID+273.15
      ELSE
         LIDK=(5/9)*(LID-32)+273.15
      ENDIF
C
      EMS=(1/EPSL)+(1/EPSD)-1
      FE=1/EMS
      TX=250.0
      DO 200 N=1,9
         TAV=0.5*(LIDK+TX)
         THAIR(N)=7.76E-5*TAV+2.87E-3
         HGAP=THAIR(N)/GAP
         HRAD=5.669E-8*FE*(LIDK**2+TX**2)*(LIDK+TX)
         RAT=HRAD/HGAP
         FACTOR=1+RAT
         KAR(N)=THAIR(N)*DELX*DELY*FACTOR*0.0001/GAP
         TX=TX+50
200   CONTINUE
C
C
C     THE FOLLOWING GROUP OF ALGORITHMS CONNECT THE TOP LAYER NODES TO
C  THE LID NODES (NODES 751-765).
C  THE THERMAL ANALYZER IS LIMITED TO A MAXIMUM OF 27 CONNECTIONS.
C  THEREFORE BY CONNECTING THE TOP LAYER NODES IN GROUPS OF TWENTY THIS
C  LIMITATION CAN BE BYPASSED. THE SAME ANALOGY IS APPLIED TO
C  CONNECTING THE BOTTOM LAYER NODES TO THE SINK NODES (NODES 766-769).
C
C
      DO 62 I=1,20
         A(I,751)=KAIR
         B(I,751)=7511
62    CONTINUE
C
      DO 63 I=21,40
         A(I,752)=KAIR
         B(I,752)=7521
63    CONTINUE
C
      DO 64 I=41,60
         A(I,753)=KAIR
         B(I,753)=7531
64    CONTINUE
C
      DO 65 I=61,80
         A(I,754)=KAIR
         B(I,754)=7541
65    CONTINUE
C
      DO 66 I=81,100
         A(I,755)=KAIR
         B(I,755)=7551
66    CONTINUE
C
      DO 67 I=101,120
         A(I,756)=KAIR
         B(I,756)=7561
67    CONTINUE
C
      DO 68 I=121,140
         A(I,757)=KAIR
```

```
         B(I,757)=7571
68    CONTINUE
C
      DO 69 I=141,160
         A(I,758)=KAIR
         B(I,758)=7581
69    CONTINUE
C
      DO 70 I=161,180
         A(I,759)=KAIR
         B(I,759)=7591
70    CONTINUE
C
      DO 71 I=181,200
         A(I,760)=KAIR
         B(I,760)=7601
71    CONTINUE
C
      DMM=2*NL+NL/4+1
C
      DO 83 I=DMM,DMM+20
         A(I,766)=K7
         B(I,766)=7661
83    CONTINUE
C
      DO 84 I=DMM+21,DMM+40
         A(I,767)=K7
         B(I,767)=7671
84    CONTINUE
C
      IF (ANSH.EQ.1.AND.ANSH.EQ.4) THEN
         LIDN=13
         SNKN=4
      DO 72 I=201,220
         A(I,761)=KAIR
         B(I,761)=7611
72    CONTINUE
C
      DO 73 I=221,240
         A(I,762)=KAIR
         B(I,762)=7621
73    CONTINUE
C
      DO 74 I=241,256
         A(I,763)=KAIR
         B(I,763)=7631
74    CONTINUE
C
      DO 85 I=DMM+41,DMM+60
         A(I,768)=K7
         B(I,768)=7681
85    CONTINUE
C
      DO 86 I=DMM+61,DMM+64
         A(I,769)=K7
         B(I,769)=7691
86    CONTINUE
C
      ELSEIF (ANSH.EQ.2) THEN
         LIDN=15
         SNKN=4
      DO 75 I=201,220
         A(I,761)=KAIR
         B(I,761)=7611
75    CONTINUE
C
      DO 76 I=221,240
         A(I,762)=KAIR
         B(I,762)=7621
76    CONTINUE
C
      DO 92 I=241,260
```

```
         A(I,763)=KAIR
         B(I,763)=7631
92    CONTINUE
C
      DO 93 I=261,280
         A(I,764)=KAIR
         B(I,764)=7641
93    CONTINUE
C
      DO 94 I=281,288
         A(I,765)=KAIR
         B(I,765)=7651
94    CONTINUE
C
      DO 87 I=DMM+41,DMM+60
         A(I,768)=K7
         B(I,768)=7681
87    CONTINUE
C
      DO 88 I=DMM+61,DMM+72
         A(I,769)=K7
         B(I,769)=7691
88    CONTINUE
C
      ELSEIF (ANSH.EQ.3) THEN
         LIDN=15
         SNKN=4
      DO 77 I=201,220
         A(I,761)=KAIR
         B(I,761)=7611
77    CONTINUE
C
      DO 78 I=221,240
         A(I,762)=KAIR
         B(I,762)=7621
78    CONTINUE
C
      DO 79 I=241,260
         A(I,763)=KAIR
         B(I,763)=7631
79    CONTINUE
C
      DO 80 I=261,280
         A(I,764)=KAIR
         B(I,764)=7641
80    CONTINUE
C
      DO 81 I=281,300
         A(I,765)=KAIR
         B(I,765)=7651
81    CONTINUE
C
      DO 89 I=DMM+41,DMM+60
         A(I,768)=K7
         B(I,768)=7681
89    CONTINUE
C
      DO 90 I=DMM+61,DMM+75
         A(I,769)=K7
         B(I,769)=7691
90    CONTINUE
C
      ELSEIF (ANSH.EQ.5) THEN
         LIDN=11
         SNKN=3
      DO 82 I=200,216
         A(I,761)=KAIR
         B(I,761)=7611
82    CONTINUE
C
      DO 91 I=DMM+41,DMM+54
         A(I,768)=K7
```

```
         B(I,768)=7681
91    CONTINUE
C
      ENDIF
C
C
      DO 16 I=1,LIDN
         LIDI(I)=LID
16    CONTINUE
C
      DO 19 I=1,SNKN
         SINKT(I)=SINK
19    CONTINUE
C
C
C     INITIAL SETTINGS FOR THE THERMAL ANALYZER
C
C
      HTR=0
      EXP=0
      SECHT=0
      COEFCV=9
      FASTHT=0
      HTCV=0
      UNK=0
      CONTROL1=0
      CONTROL2=0
      CONTROL3=0
      NODES=300
      KMAX=50
      HMAX=6
      XP=1
      SHT=2
      EFCV=15
      SINT=5
      TCV=8
      ACC=.05000
      DAMP=.6667
      MAXITS=12
      CONVFAC=.8000
C
C
      C(1)=(DELY*DELZ1)/DELX
      C(2)=(DELX*DELZ1)/DELY
      C(3)=(DELX*DELY)/DELZ3
      C(4)=(DELY*DELZ2)/DELX
      C(5)=(DELX*DELZ2)/DELY
      C(6)=(DELX*DELY)/DELZ2
      C(7)=(4*DELX*DELY)/DELZ2
      C(8)=(DELX*DELY)/DELZ4
C
C
C      THE TEMPERATURES SELECTED FROM THE SILICON THERMAL CONDUCTIVITY
C   CURVE. THE FIRST GROUP IS IN DEG CENTIGRADE, THE SECOND IN
C   FAHRENHEIT. EACH TEMPERATURE GROUP IS FOLLOWED BY THE THERMAL
C   CONDUCTIVITY OF SILICON AT THAT TEMPERATURE IN EITHER WATTS/CM-C
C   OR BTU/HR-IN-F.
C
C
      IF (UNIT.EQ.1) THEN
      TEMP1=-271.2
      TEMP2=-267.2
      TEMP3=-263.2
      TEMP4=-255.2
      TEMP5=-243.2
      TEMP6=-228.2
      TEMP7=-208.2
      TEMP8=-173.2
      TEMP9=26.85
      THCOND(1)=0.25
      THCOND(2)=4.5
      THCOND(3)=10.0
```

```
      THCOND(4)=17.0
      THCOND(5)=19.0
      THCOND(6)=17.0
      THCOND(7)=10.0
      THCOND(8)=5.5
      THCOND(9)=1.5486
      ELSE
      TEMP1=-456.07
      TEMP2=-448.87
      TEMP3=-441.67
      TEMP4=-427.27
      TEMP5=-405.67
      TEMP6=-378.67
      TEMP7=-342.67
      TEMP8=-279.67
      TEMP9=80.33
      THCOND(1)=1.20
      THCOND(2)=21.67
      THCOND(3)=48.15
      THCOND(4)=81.85
      THCOND(5)=91.48
      THCOND(6)=81.85
      THCOND(7)=48.15
      THCOND(8)=26.48
      THCOND(9)=7.46
      ENDIF
C
C
      DO 23 I=1,8
         DO 24 J=1,9
            CURVE(I,J)=C(I)*THCOND(J)
24    CONTINUE
23    CONTINUE
C
      DO 39 I=1,9
         SUB1(I)=0
         SUB(I)=0
39    CONTINUE
C
C
C      OPEN A FILE FOR THE OUTPUT. THIS FILE WILL BE IN THE CORRECT
C   FORMAT TO BE READ BY THE THERMAL ANALYZER.
C
C
      OPEN (3,FILE='MICCKT',FORM='FORMATTED',ACCESS='DIRECT',
     +RECL=108,STATUS='NEW')
C
      WRITE (3,701) TITLE
701   FORMAT (1X,A79)
      WRITE (3,702) R, CONST, HTR, EXP, SECHT, COEFCV, FASTHT, HTCV,
     +UNK, UNIT
702   FORMAT (13I6)
      WRITE (3,703) CONTROL1, CONTROL2, CONTROL3
703   FORMAT (3I6)
      WRITE (3,704) NODES, KMAX, HMAX, XP, SHT, EFCV, STHT, TCV, UNK,
     +UNIT
704   FORMAT (13I6)
      WRITE (3,705) ACC, DAMP, MAXITS, CONVFAC, INTEMP
705   FORMAT (2G12.4,I12,2G12.4)
C
      DO 25 I=1,8
      WRITE (3,706) TEMP1, CURVE(I,1), TEMP2, CURVE(I,2),
     +TEMP3,CURVE(I,3), TEMP4, CURVE(I,4), TEMP5, CURVE(I,5), TEMP6,
     +CURVE(I,6), TEMP7, CURVE(I,7), TEMP8, CURVE(I,8), TEMP9,
     +CURVE(I,9)
706   FORMAT (9G12.4)
25    CONTINUE
C
      DO 201 N=1,9
      WRITE (3,710) THAIR(N), KAR(N)
710   FORMAT (9G12.4)
201   CONTINUE
```

```
      WRITE (3,707) (LIDT(N),N=1,12), (SINKT(N),N=1,2)
 707  FORMAT (9G12.4)
C
      DO 50 I=1,R
            COUNT=0
            COUNTER=0
         DO 51 J=1,800
              IF (A(I,J).EQ.0) THEN
                GOTO 51
              ELSE
                COUNT=COUNT+1
                TEMP(COUNT)=A(I,J)
              ENDIF
51         CONTINUE
         DO 52 J=1,800
              IF (B(I,J).EQ.0) THEN
                GOTO 52
              ELSE
                COUNTER=COUNTER+1
                TMP(COUNTER)=B(I,J)
              ENDIF
52         CONTINUE
C
       WRITE (3,708) COUNT, (TMP(N),N=1,COUNTER), (SUB1(N),N=COUNT+1,9)
  708  FORMAT (I5,I7,8I12)
       WRITE (3,709) (TEMP(N),N=1,COUNT), (SUB(N),N=COUNT+1,9)
  709  FORMAT (9G12.4)
50     CONTINUE
C
C
       ENDFILE (3)
       CLOSE (3)
C
C
       STOP
       END
```

APPENDIX B

The following will demonstrate a typical run using MICCKT. On screen prompts will be indicated within brackets (< >), responses (Resp) will be directly afterwards. Comments will be inserted for clarity.

< Enter the name of your file >

Resp: This is an alphanumeric string with a maximum of 76 characters.

< You may select one of the following options:

1.) 16 by 16, yields 640 nodes
2.) 12 by 24, yields 720 nodes
3.) 10 by 30, yieds 750 nodes
4.) 8 by 32, yields 640 nodes
5.) 12 by 18, yields 540 nodes >

Resp: 3

< Enter 1.) for SI or 2.) for English.

Resp: 1

< Input chip dimensions in centimeters.
Enter length: >

Resp: 0.75

If the English system of measurement was chosen the dimension prompt would be in inches.

< Enter width: >

Resp: 0.5

< Enter thickness: >

Resp: 0.05

This will be the overall thickness of the chip. The top layer is automatically set at 0.002 inches or 0.00508 centimeters. Subsequent layer thicknesses are derived as follows: (overall thickness - first layer thickness)/3.

< Enter the thickness of the air layer between the lid and the top of the die.>

Resp: 0.2

The maximum allowable thickness is 0.254 cm (0.10 in).

< Enter the temperature of the lid: >

Resp: 40

Temperatures will be in Centigrade or Fahrenheit depending on the users choice of dimensions.

< Enter the temperature of the sink: >

Resp: 15

< Enter the emissivity of the lid:>

Resp: 0.7

<Enter the emissivity of the chip:>

Resp: 0.8

< Heat inputs will be in watts.>

This prompt is a reminder of the units the user is working in. Heat inputs will be in Btu/hr if in the English system.

< Heat input to the microcircuit can be entered in the
following manner. Choose 1.) to enter as total heat
applied to the chip, 2.) to enter as the average heat
per area, 3.) to enter node by node, or 4.) for no heat
input.

Resp: 2

< Enter the average heat per unit area:>

This will be in either Watts/cm^2 or Btu/hr-in^2.

Resp: 5

< Summary of input data.

1.) Length of the chip is (cm): 0.7500
2.) Width of the chip is (cm): 0.5000
3.) Thickness of the chip is (cm): 0.5000E-01
4.) Thickness of the air layer (cm): 0.2000
5.) Temperature of the lid is (deg C): 40.00
6.) Temperature of the sink is (deg C): 15.00
7.) The emissivity of the lid is: 0.7000
8.) The emissivity of the chip is: 0.8000

```
9.) The heat inputs to the node are:
Heat applied to each node is:          0.6250E-04 Watts >
```

Heat applied was 5 Watts/cm^2, this was multiplied by the area of the chip and then divided by the number of nodes in the top layer to produce an average heat input to each node. If option 1 had been chosen the total heat applied to the chip would be divided by the number of nodes in the top layer to get an average input to each node.

```
< Do you wish to make any changes, y or n?>
Resp: y

< Which line item do you wish to change?>
Resp: 4

< Enter the thickness of the air layer between the lid and the top of the die.>
Resp: 0..25

< Summary of input data.
  1.) Length of the chip is (cm):          0.7500
  2.) Width of the chip is (cm):           0.5000
  3.) Thickness of the chip is (cm):       0.5000E-01
  4.) Thickness of the air layer (cm):     0.2500
  5.) Temperature of the lid is (deg C):   40.00
  6.) Temperature of the sink is (deg C):  15.00
  7.) The emissivity of the lid is:        0.7000
  8.) The emissivity of the chip is:       0.8000
```

9.) The heat inputs to the node are:

Heat applied to each node is: 0.6250E-04 Watts >

Do you wish to make any changes, y or n?>

Resp: n

With a no response the program will generate an output file for use with the thermal analyzer.

LIST OF REFERENCES

1. Sedra, A.S., and Smith, K.C., *Microelectronic Circuits*, pp. 1 - 17, 564 - 591,Holt, Rinehart and Winston, Inc., 1987.

2. Kraus, A.D., and Bar-Cohen, A., *Thermal Analysis and Control of Electronic Equipment*, pp. 53 - 83, 115 - 147, Hemisphere Publishing Corporation, 1983.

3. Croft, D.R., and Lilley, D.G., *Heat Transfer Calculations Using Finite Difference Equations*, pp. 14 - 38, Applied Science Publishers, Ltd., 1977.

4. Berkey, D.D., *Calculus*, 2d ed., pp. 93 - 229, 561 - 577, Saunders College Publishing, 1988.

5. Beadle, W.E., Tsai, J.C.C., and Plummer, R.D., *Quick Reference Manual for Silicon Integrated Circuit Technology*, pp. 2.64 - 2.66, John Wiley & Sons, 1985.

INITIAL DISTRIBUTION LIST

1.	Defense Technical Information Center Cameron Station Alexandria, Virginia 22304-6145	2
2.	Library, Code 52 Naval Postgraduate School Monterey, California 93943-5002	2
3.	Commander Naval Space Command Attn: Code N152 Dahlgren, Virginia 22448	1
4.	United States Space Command Attn: Technical Library Peterson AFB, Colorado 80914	1
5.	Director Navy Space Systems Division (OP-943) Washington, DC 20350-2000	1
6.	Space Systems Academic Group, Code SP Naval Postgraduate School Monterey, California 93943-5000	1
7.	Department Chairman, Code EC Naval Postgraduate School Monterey, California 93943-5000	1
8.	Prof. Allan D. Kraus, Code EC/KS Department of Electrical & Computer Engineering Naval Postgraduate School Monterey, California 93943-5000	1
9.	Prof. Sherif Michael, Code EC/MI Department of Electrical & Computer Engineering Naval Postgraduate School Monterey, California 93943-5000	1
10.	Prof. Yogendra Joshi, Code ME/JI Department of Mechanical Engineering Naval Postgraduate School Monterey, California 93943-5000	1

11. Joseph A. Willhelm 1
Route 3 Box 247
Dickinson, Texas 77539