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GENERALIZED HEAT CONDUCTION CODE FOR THE IBM-704 COMPUTER

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OAK RIDGE NATIONAL LABORATORY
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GENERALIZED HEAT CONDUCTION CODE FOR THE IBM-704 COMPUTER

T. B. Fowler E. R. Volk

ABSTRACT

A generalized heat conduction code, GHT, has been written as an IBM-704 code. This code solves steady-state and/or transient heat conduction problems in three-dimensional geometry. The method used in GHT is numerical integration of the appropriate finite-difference equations. Boundary temperatures and heat generation may be a function of position and/or time. Material properties and film coefficients may be considered as a function of position but are assumed constant with respect to temperature and time. The number of nodal points is limited to 950, which includes internal and boundary points. All boundary points, however, which have the same temperature-time relationship may be considered as one point. The number of neighbors which may affect a given point must be equal to or less than 8.

Two code decks have been prepared which have the following minimum machine requirements:

GHT code deck No. I: IBM-704; 8000-word memory
8 magnetic-tape units
2 drum-storage units

GHT code deck No. II: IBM-704; 16,000- or 32,000-word memory
8 magnetic-tape units

One less tape unit (reserved for input data) is required if all input is from cards.

Use of GHT is illustrated by means of a sample problem.

INTRODUCTION

The solution of heat conduction problems is associated with integration of the appropriate partial differential equations. The calculation presented here is based on the assumption that heat transfer within the material follows Fourier's law of heat conduction.

With an arbitrary source distribution, the analytical solution of the time-dependent equations is available for only the simplest geometrical configurations (such as slabs, cylinders, and spheres). Even for these simple geometries, many boundary conditions either impose intractable analytical difficulties or result in solutions which in practice are unwieldly and time-consuming. To overcome the difficulties encountered in the analytical approach, numerical methods as well as experimental, analog, and graphical methods have been used. Each of these methods has advantages and disadvantages, many of which depend on the type of problem to be solved. Considering problems in which irregular physical boundaries and somewhat complicated boundary conditions are treated, the most practicable integration methods appear to be associated with the use of analog networks and digital computers. If the problems of interest contain heat generation as a function of position and time, and if temperature profiles are desired as a function of time (e.g., as for thermal-stress-analysis purposes), numerical integration by means of a high-speed digital computer appears to be the better method.

The program described here, abbreviated as GHT, was written for the IBM-704 digital computer; it solves transient and/or steady-state heat conduction problems in either one, two, or three dimensions.

The authors wish to express their appreciation to P. R. Kasten (under whose supervision this work was performed), R. D. Cheverton, and J. E. Rowe for their advice and cooperation during the course of this work. Grateful acknowledgment is made to M. P. Lietzke and C. S. Williams for their suggestions and help with the programing, and to M. Tobias and V. E. Anderson for their assistance with the CURE code.

EQUATIONS USED IN GHT

Steady-State Equations

GHT makes use of the "extrapolated Liebmann" method[1] in obtaining the steady-state temperature distribution. The system of equations is written as

$$T_J^{n+1} = T_J^n(1-\beta) + \frac{\beta\left[\sum_M {}_J K_M T_M + Q_J\right]}{\sum_M {}_J K_M} , \qquad 1 \leqq \beta < 2 , \qquad (1)$$

where $T_M = T_M^{n+1}$ for neighbor-point numbers less than J, and $T_M = T_M^n$ for neighbor-point numbers greater than J. Successive iterations are carried out using Eq. (1) until

$$\left|\frac{T_J^n - T_J^{n+1}}{T_J^{n+1}}\right|_{max}$$

is less than the specified convergence criterion.

$$\beta = 2 - 2\left\{1 - \left[\frac{\left(T_J^{n-1} - T_J^n\right)_{max\ at\ n}}{\left(T_J^{n-2} - T_J^{n-1}\right)_{max\ at\ n-1}}\right]^{1/2}\right\}^{1/2} . \qquad (7)$$

To accelerate the steady-state calculation the "Aitken δ^2 process"[2] of extrapolation is used, the temperatures at each point being calculated from

$$T_J^{n+1} = T_J^n + \frac{\left(T_J^n - T_J^{n-1}\right)^2}{\left(T_J^{n-1} - T_J^{n-2}\right) - \left(T_J^n - T_J^{n-1}\right)} . \qquad (2)$$

Before the Aitken δ^2 process [and therefore Eq. (2)] can be applied, the following restrictions must be satisfied:

$$\left|T_J^{n-1} - T_J^{n-2}\right| > \left|T_J^n - T_J^{n-1}\right| , \qquad (3)$$

$$\left(T_J^{n-1} - T_J^{n-2}\right)\left(T_J^n - T_J^{n-1}\right) > 0 . \qquad (4)$$

To minimize excessive extrapolation, the maximum and minimum values of the extrapolated temperatures are limited by the condition

$$\frac{\left(T_J^n - T_J^{n-1}\right)^2}{\left(T_J^{n-1} - T_J^{n-2}\right) - \left(T_J^n - T_J^{n-1}\right)} < \left|T_J^n\right| . \qquad (5)$$

If this criterion is not satisfied, T_J^{n+1} is obtained from the equation

$$T_J^{n+1} = T_J^n \pm T_J^n . \qquad (6)$$

The sign used in the right side of Eq. (6) is the same as that of the second term on the right side of Eq. (2). Ordinarily, no temperatures are extrapolated unless the temperatures at all points satisfy Eqs. (3) and (4); however, the option of having the code extrapolate only the temperatures at those points which meet the above condition is under control of a sense switch (see "Sense-Switch Settings").

When the value of β is computed by GHT (see "β Indicator," columns 58–59 of the input control card, Fig. 1), the equation used is Eq. (7).

If, however, the value of β calculated from Eq. (7) is less than 1.0, the value of β will be set equal to 1.0 by GHT.

Transient Equations

The transient equations used in GHT are similar to those derived and presented by Hellman, Habetler, and Babrov.[3] For unknown temperature

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[1] S. P. Frankel, *Mathematical Tables and Other Aids to Computation*, vol IV, p 65–75, National Research Council, Washington, D.C., 1950.

[2] A. S. Householder, *Principles of Numerical Analysis*, p 126–28, McGraw-Hill, New York, 1953.

[3] S. K. Hellman, G. Habetler, and H. Babrov, *Trans. Am. Soc. Mech. Engrs.* **78**, 1155–61 (1956).

points the equations are written as

$$T_J(\tau+\Delta\tau) = T_J(\tau) + \frac{\Delta\tau}{C_J}\left\{\sum_M {}_JK_M\,[T_M(\tau) - T_J(\tau)] + Q_J + \Delta Q_J\right\} , \quad (8)$$

where

$$\begin{aligned} \Delta Q_J &= B_1\tau , \quad \text{for } 0 < \tau \leqq S_1 , \\ &= B_1S_1 + B_2(\tau - S_1) , \\ &\qquad\qquad \text{for } S_1 < \tau \leqq S_2 , \\ &\qquad \cdots \\ &= \sum_{i=1}^{j-1} B_i(S_i - S_{i-1}) + B_j(\tau - S_{j-1}) , \quad (9) \\ &\qquad\qquad \text{for } S_{j-1} < \tau \leqq S_j , \end{aligned}$$

in which $J \leqq 25$ for each point.

For known temperature points the equations used are of the form

$$T_J(\tau+\Delta\tau) = T_J(\tau) + \Delta T_J , \quad (10)$$

where

$$\begin{aligned} \Delta T_J &= A_1\Delta\tau , \quad \text{for } 0 < \tau \leqq W_1 , \\ &= A_2\Delta\tau , \quad \text{for } W_1 < \tau \leqq W_2 , \\ &\qquad \cdots \\ &= A_i\Delta\tau , \quad \text{for } W_{i-1} < \tau \leqq W_i , \quad (11) \end{aligned}$$

in which $i \leqq 25$ for each point.

Since Eq. (8) is based upon the solution of T_J at time τ, it is necessary that a convergence criterion be satisfied so that a divergent solution is not obtained. It is recommended that the convergence criterion derived in ref 3 be used with GHT. This convergence criterion can be written as

$$\Delta\tau \leqq \left(\frac{C_J}{\sum_M {}_JK_M}\right)_{\text{min for all } J} \quad (12)$$

Equations (9) and (11) may be used to represent constant values, step changes, linear changes, or arbitrary changes (approximated by a series of linear changes) of heat generation and temperature, respectively, with time. Equation (9) may be used to account for convection heat flow by proper evaluation of ${}_JK_M$ and T_M as shown in ref 3. Equation (12) is not included in GHT; hence it must be calculated prior to the solution of a transient problem. The $\Delta\tau$ which satisfies Eq. (12) can quickly be obtained from a small number of points.

There are four types of problems which may be solved by GHT; these are associated with the following conditions: (1) steady-state only, (2) steady-state and transient, (3) transient and steady-state, and (4) transient only.

For the steady-state and transient type of calculation the converged steady-state temperature distribution is used as the initial temperature distribution corresponding to time zero. For the transient and steady-state type of problem the final transient temperature distribution is used as the initial steady-state temperature distribution. All four types of calculations require an initial temperature distribution as an input.

INPUT DATA

General

The nodal-point numbers (points at which temperatures are known or are to be computed) for each problem must be numbered consecutively and must always begin with 1. To obtain the best convergence, it is recommended that nodal points be numbered right to left (or left to right) and by successive rows (or columns). Boundary-temperature point values which follow the same temperature function may be given the same point number. GHT is limited to a maximum of 950 points.

The following types of input data cards are used with GHT (see sample data sheets, Figs. 1–8):

1. control card,
2. initial-time card (not given as a figure),
3. temperature cards,
4. heat generation cards,
5. capacitance cards,
6. point data cards,
7. conductance cards,
8. variable temperature and/or heat generation cards,
9. map output cards.

In the sample problem given in Appendix C, the input data sheets (Tables C-2 through C-9) indicate some of the ways in which each of the different types of input numbers may be written and key-punched; however, certain relaxations are permitted in the number formats for ease in writing or key-punching. The various number formats that are permissible are given below with an explanation of each of the input numbers required for GHT.

Control Card (Fig. 1)

For each problem, one control card must be punched. The manner is indicated below, along with explanatory remarks.

Columns 1–5: Total Number of Points. – The total number of points is equal to the number of nodal points, which have different point numbers assigned. Since point numbers must begin with 1 and since no numbers may be skipped, the total number of points is always equal to the largest point number; one point number can represent more than one physical point if the physical points have the same temperature.

The least significant digit of the number must occupy column 5; column 1 may contain either a plus or be left blank. Columns void of information may be left blank; that is, blank columns following the sign column are read as zeros. For example, the number 157 could be punched as |+|1|0|5|7|, or |+| |1|5|7|, or | | |1|5|7|.

Columns 6–11: Maximum Number of Steady-State Iterations. – For a steady-state and transient type of problem, if the number of steady-state iterations reaches the specified value before the convergence criterion is satisfied, the machine will stop and "ask" whether to go on to the transient calculation or produce the temperature distribution it has. This information plus instructions are printed on-line. If the above occurs for a transient and steady-state calculation, or for a steady-state-only calculation, the machine prints END OF STEADY-STATE, CONV. NOT SATISFIED and proceeds to the next problem, or it stops, depending on the instructions.

This number may be punched in the same way as the total number of points; that is, 150 could be punched as |+|0|0|1|5|0|, or |+| | |1|5|0|, or | | | |1|5|0|. For a transient calculation alone, the entire field may be left blank.

Columns 12–17: Number of Steady-State Iterations Before Calculating β and/or Beginning Extrapolation Cycle. – The use of this information is dependent, in part, upon the β indicator (see columns 58–59, Fig. 1). If the β indicator is +1, the number specified in columns 12–17 will be the number of iterations run prior to the calculation of β by Eq. (7). However, regardless of the β-indicator value, the number in columns 12–17 is used by the code to determine when to start the extrapolation cycle. It has been found by running a series of test cases that 10 is a reasonable value for this number. It is key-punched in the same way as the number in columns 6–11 and affects the steady-state calculation only.

Columns 18–23: Extrapolation Cycle. – This number is key-punched in the same way as the number in columns 6–11 and affects the steady-state calculation only. A value of 5 is recommended for this number.

Once the number of steady-state iterations has reached the value specified in columns 12–17, the code will attempt to extrapolate the temperatures. This is done by using the Aitken δ^2 process (Eq. 2) at every nth iteration, where n is the extrapolation cycle.

Columns 24–27: Type of Problem. – For the four types of problems which may be solved by GHT, columns 24–27 are punched

$+\ 1\ +\ 0$ for steady-state only,

$-\ 1\ +\ 0$ for transient only,

$+\ 0\ +\ 1$ for steady-state and transient,

$+\ 0\ -\ 1$ for transient and steady-state.

Columns 28–29: Type of Output. – GHT has two optional types of output: (1) a sequential listing (by point number) of the temperature distribution and (2) a map output of the temperature distribution (which is controlled by the map output cards). In the sequential listing the temperature values are printed as floating-decimal-point numbers of the form ±X.XXXE±XX, with ten values to a line. The sign of the number and the sign of the power of 10 are left blank if positive. For example, the output number 3.696E – 02 equals $+3.696 \times 10^{-2}$. The map output temperatures are fixed-point numbers with one digit to the right of the decimal point.

In columns 28–29, punch +1 for a sequential listing of output, or –1 for the map output.

Columns 30–33: Transient Output Cycle. – The transient output cycle specifies the number of iterations between the "time-dependent" outputs, that is, the number of passes through the transient-type calculation. For example, if a value of 10 is given for this number, the transient temperature distributions at times $10\Delta\tau$, $20\Delta\tau$, $30\Delta\tau$, etc., will be included in the output answers. (The time increment specified in columns 42–49 is $\Delta\tau$.)

This number is written and key-punched in a manner similar to that for the first four numbers of the control card; that is, 10 could be punched as |+|0|1|0|, or |+| |1|0|, or | | |1|0|. This number affects only the transient calculation and may be left blank for steady-state-only problems.

Columns 34–41:* *Total Time. – The total time (τ) for which a transient calculation is to be run is specified here. The number of iterations for a particular case may be found by dividing the total time by the time increment specified in columns 42–49.

This number may be key-punched either as a floating-decimal-point number or as a fixed-point number; however, the sign of the number (specified in column 34) must contain a plus, a minus, or be left blank (a blank indicates a plus). If the number is written in floating-point notation, the last three columns (columns 39–41) comprise the exponent field, with column 39 containing either a plus or minus, but not a blank. A decimal point may be written if desired; if a decimal point is not written, it is assumed to precede the first digit. Columns void of information may be left blank. For example, if the total specified time is 0.7 hr, this number (written in floating-point notation) could be key-punched as |+|7|0|0|0|+|0|0|, or | |7| | | |+| | |, or |+|7|•|0|0|–|0|1|, or | |7| |•|–| |2|.

With fixed-point notation, 0.7 could be key-punched as

|+|0|•|7|0|0|0|0| or as | | | | |•|7| | | .

Note that in the fixed-point notation the decimal point must be punched and occupies one column.

The total time affects only the transient calculation and need not be specified if a steady-state problem is being run.

Columns 42–49:* *Time Increment. – The time increment ($\Delta\tau$) is the time step taken between successive iterations. The time increment specified must satisfy the convergence criterion [Eq. (12)] for the transient equation.

This number is key-punched in the same way as the total time (columns 34–41) and affects only the transient calculation.

Columns 50–57:* *Convergence Criterion. – The steady-state calculation will continue until

$$\left| \frac{T_J^n}{T_J^{n+1}} (\max) - 1 \right| \leq \epsilon ,$$

where ϵ is the convergence criterion and n is the iteration number. With a value for ϵ of 10^{-5}, the maximum error for several test cases was found to be less than 1%.

This number affects the steady-state type of calculation only and may be left blank for a transient-only problem. It is written and key-punched in the same way as "total time."

Columns 58–59:* β *Indicator. – This number is either +1 or –1 and indicates whether the code is to calculate β or whether the user has inserted a β in columns 60–67 which is to be used throughout the steady-state calculation. If the β indicator is punched +1, the value of β in columns 60–67 *must* be unity, and GHT will calculate β from Eq. (7) when the number of iterations has reached the value specified in columns 12–17. This calculated β will be used on all subsequent steady-state iterations. If the β indicator is punched –1, β will not be calculated by the code. The input value of β (columns 60–67) will then be used on all steady-state iterations regardless of the number in columns 12–17.

Unless the user is familiar with a method of determining β (β is the extrapolated Liebmann coefficient and is such that $1 \leq \beta < 2$), it is recommended that the β indicator be punched +1 so that β is calculated by GHT.

The β indicator affects only the steady-state calculations and may be ignored for the transient-only case.

***Columns 60–67:* β.** – The value of β must not exceed the following limitations:

$$1 \leq \beta < 2 \ .$$

If the β indicator is +1, *β must be specified as 1.0,* since the method of calculating β from Eq. (7) is based upon β being unity for a specified number of iterations.

Beta must be written as a fixed-point number with column 60 punched as a plus or left blank. The decimal point must be punched. For example, 1.0 could be punched as |+|1|•|0|0|0|0|0| or as | |1|•| | | | | |. This number may be ignored except for a steady-state calculation.

Columns 68–72:* *Case Number. – Column 68 is either left blank or punched with a plus or a minus, and columns 69–72 may contain any digits from 0–9 or be left blank. This number is reproduced on the output to identify the case.

Columns 73–80. – These columns are not used by GHT and may contain any desired information, such as a card number.

Initial-Time Card (required for all problems)

This card contains one number (τ_0) occupying columns 1–10 and gives the time at which a transient calculation is to begin. The primary purpose of this card is to facilitate the restarting of a transient case if the calculation has been interrupted (see "Restart and Machine Error Procedure"); in that case the machine will punch the initial-time card to be used. This initial-time card must be present in the input deck even for a steady-state-only calculation; however, a blank card will suffice if $\tau_0 = 0$, which corresponds to a transient calculation.

If a value other than zero is punched in this card, it may be punched either as a floating-point or fixed-point number in the same way as the total time (columns 34–41) is punched on the control card, except that τ_0 occupies a field of ten columns instead of eight. For example, the number 1.2 could be punched, as floating point,

`|+|1|2|0|0|0|0|+|0|1|`

or

`| |1|2|•| | | | |-| |1|` ;

or, as fixed point,

`|+|1|•|2| | | | | | |`

or

`| | | | | | | |1|•|2|` .

No sample-data sheet is included for τ_0.

Temperature Cards (Fig. 2; required for all problems)

A value of temperature must be entered consecutively for each nodal point in the mesh beginning with point No. 1; however, all or any number of the values may be zero. Seven temperature values must be punched in each card, with the possible exception of the last temperature card (i.e., if the number of points is not a multiple of 7); each number occupies a field of ten columns.

These numbers may be either floating point or fixed point and are punched in the same way as explained previously for the initial-time card. Blanks may be left for the entire field of ten columns for zero values of temperature, and a blank card will suffice if all seven temperature values on a card are zero.

Heat Generation Cards (Fig. 3; required for all problems)

A value for the heat generation must be punched consecutively for each nodal point in the mesh beginning with point No. 1; however, all or any number of values may be zero. Each card must contain nine numbers, except the last card; these numbers correspond to the heat generation values at nine different points.

The heat generation values may be key-punched as either floating-point or fixed-point numbers, with each number occupying a field of eight columns. The entire field may be left blank for zero values, and blank cards may be used when all nine numbers are zero. These numbers are punched in the same way as the total time (see control card, columns 34–41).

Capacitance Cards (Fig. 4; required for transient-only problems)

For a steady-state-only calculation these cards are left out of the input deck. For the other three types of problems there must be a value entered consecutively for each nodal point in the mesh beginning with point No. 1. Zeros may be entered for only those boundary points which follow known temperature-time functions.

There are nine capacitance values on each card except possibly the last; the cards are key-punched in the same way as the heat generation cards.

Point Data Cards (Fig. 5; required for all problems)

Each point in the mesh must contain a value, beginning with point No. 1 and proceeding consecutively. There are nine groups of point data information on each card, each group pertaining to one point. Each group of point data consists of the following:

Number of A's $\leqq 25$ per point,

Number of B's $\leqq 25$ per point,

Number of M's $\leqq 8$ per point.

For steady-state problems, only the number of M's is pertinent. If the number of A's, number of B's, and number of M's are all zero for any point, that point is maintained at a constant temperature equal to the input temperature for both the steady-state and transient calculations. For a transient calculation, if the number of A's for a specified point is not equal to zero, the number of B's and the number of M's must be zero, since Eq. (10) is required to calculate the temperatures at that point. For a transient calculation, if the number of B's for a specified point is not zero, the number of M's must not be zero and the number of A's must be zero, since Eqs. (8) and (9) are required to calculate the temperatures at that point.

The number of A's and the number of B's are written and punched in fields of three columns each, with the first column of each field being a plus (or blank) followed by the number of A's or B's. For example, the number 7 might be written either as |+|0|7| or as | | |7|. The number of M's is punched in a field of two columns, with the first column being either a plus or a blank.

Conductance Cards (Fig. 6; required for all problems)

Conductance information must be entered for only those points which correspond to unknown temperatures, that is, those points having an M value different from zero on the point data cards. The conductance cards specify the point number of a neighboring point and also the effective conductance between it and the original point. A maximum of six neighbors can be specified per card. A point with seven or eight neighbors will require two cards. Each point which has one or more neighboring points ($M > 0$ on point data cards) must have its own conductance card or cards; these cards must be placed in the input deck in their point-number order (same order as for point data cards). The order in which neighbor-point numbers are listed is unimportant; however, the information punched in these cards must begin in column 1, and no columns may be skipped between a neighbor-point number and its conductance value, or between a conductance value and the next neighbor-point number.

The neighbor-point numbers are key-punched in the same way as the transient output cycle (columns 30–33 on the control card), and the conductance values are punched in the same manner as the total time (columns 34–41 on the control card).

Variable Temperature and/or Heat Generation Cards (Fig. 7)

The variable temperature and/or heat generation cards are required only for those points which have a nonzero value for the number of A's or the number of B's on the point data cards. (Note: A point *cannot* have A's *and* B's associated with it.) These cards specify A_1 followed by W_1, A_2 followed by W_2, etc., or B_1 followed by S_1, B_2 followed by S_2, etc., for the A's or B's associated with a particular point. A maximum of four pairs of numbers per card and a maximum of 25 pairs of numbers per point are permitted. These cards must be inserted in the input deck such that A_{i+1} (or B_{i+1}) follows A_i (or B_i). Also, these cards must be inserted in point-number order; however, no cards are associated with points having zero A's or B's.

Each of these numbers is a fixed-decimal-point or floating-decimal-point number with a field of eight and is punched in the same manner as total time (columns 34–41 in the control card).

Map Output Cards (Fig. 8)

The map output cards are required only if column 28 of the control card contains a minus. Otherwise, these cards are not used, and all output will be a sequential listing of the temperature distributions by point number.

If the map output is used, the information given on these cards will permit the temperature distributions to be printed in some configuration, or map, which represents the physical configuration associated with the problem. To illustrate this, consider a page consisting of 50 lines (or rows) and 12 temperature points per row (12 columns). Then each map output card, (representing one row) would have 12 numbers representing nodal-point values, and 50 such cards would represent the 50 lines of the page. Hence 50 map output cards will represent a grid of 50 rows and 12 columns. Thus a value of V for a nodal-point number associated with the 6th number on the 30th card will produce the temperature of nodal-point number V in the 30th row and 6th column of the printed output.

One card must precede the first map output card; this card specifies the number of pages of map output desired for each temperature distribution. Furthermore, there must be 50 map output cards for each page specified; blank cards will suffice for any lines that are void of information. Thus, in using the map output for a three-dimensional problem, each page can contain the temperature distribution at a specified cross-sectional area.

To specify the number of pages of map output, a plus (or blank) is placed in column 1 of the first card of the map output; this is followed in columns 2 and 3 by the desired number of pages per temperature distribution. For example, the number |+| |2| specifies two pages of output. Each of the map output cards has point numbers punched in the same manner as the number associated with the maximum number of iterations on the control card (columns 6–11).

Color Code

It is suggested that some sort of color scheme be used for each of the different types of input data cards for ease in handling the input data decks. Columns 73–80 on the input cards are available for punching a card number or other information.

The complete input data deck for each problem, in the order in which it is used by the code, is listed below, along with a suggested color scheme:

1. control card – right-cut pink stripe – required for all problems,
2. initial-time card – red stripe – required for all problems,
3. temperature cards – solid yellow – required for all problems,
4. heat generation cards – solid green – required for all problems,
5. capacitance cards – solid red – required for the transient calculation only,
6. point data cards – solid blue – required for all problems,
7. conductance cards – solid brown – required for all problems,
8. variable temperature and/or heat generation cards – solid orange – required for transient problems only, if A's or $B's$ are specified,
9. map output cards – green stripe – required for map output only.

GENERAL HEAT TRANSFER CODE

Problem Number____________

CONTROL CARD

USE CUT RIGHT PINK STRIPE CARD

I2 Page______ Of______

8F.5

COLUMN NO. 1 5	6 11	12 17	18 23	± 25	± 27	± 29	30 33	34. ± 41	42. ± 49	50. ± 57	± 59	60 67	68 72	73 76	77 80
+	+	+	+	1		1	+	+	+	+	1	+ •	+		

1- 5 Total Number of Points NØPS

6-11 Maximum Number of Iterations NØITX

12-17 Number of Iterations, Before Calculating β or Extrapolation Cycle NEXI

use 0 18-23 Extrapolation Cycle NEX

24-27 Type of Problem IØR1

leave blank 28-29 Type of Output IØR2

30-33 Output Cycle IOUT

34-41 Total Time NDTA

42-49 Time Increment TIME

50-57 Convergence Criteria DELTAT

58-59 β Indicator EPI

60-67 β INDIC

68-72 Problem Number BETA

73-76 Leave Blank NCASE

77-80 Card Number NCARD

+/+0

Figure 1

GENERAL HEAT TRANSFER CODE

TEMPERATURE CARDS - T

Problem Number________________

Page ________ Of ________

USE SOLID YELLOW CARDS

POINT NUMBER	TEMPERATURES							LEAVE BLANK	CARD NUMBER
DO NOT PUNCH	COLUMN NO. ± .2 ± 10	± .12 ± 20	± .22 ± 30	± .32 ± 40	± .42 ± 50	± .52 ± 60	± .62 ± 70	71 76	77 80

GENERAL HEAT TRANSFER CODE

HEAT GENERATION CARDS - Q

Problem Number ________________

Page ________ Of ________

USE SOLID GREEN CARDS

POINT NUMBER	HEAT GENERATION									LEAVE BLANK	CARD NUMBER
DO NOT PUNCH	COLUMN NO. ± .2 ± 8	± .10 ± 16	± .18 ± 24	± .26 ± 32	± .34 ± 40	± .42 ± 48	± .50 ± 56	± .58 ± 64	± .66 ± 72	73 76	77 80

Figure 2 (top) and Figure 3 (bottom)

GENERAL HEAT TRANSFER CODE

CAPACITANCE CARDS - C

Problem Number________________

Page__________Of__________

USE SOLID RED CARDS

POINT NUMBER	CAPACITANCE									LEAVE BLANK	CARD NUMBER
DO NOT PUNCH	COLUMN NO. + .2 ± 8	+ .10 ± 16	+ .18 ± 24	+ .26 ± 32	+ .34 ± 40	+ .42 ± 48	+ .50 ± 56	+ .58 ± 64	+ .66 ± 72	73 76	77 80

GENERAL HEAT TRANSFER CODE

POINT DATA CARDS

Problem Number________________

Page__________Of__________

USE SOLID BLUE CARDS

POINT NUMBER	NO. OF A's	NO. OF B's	NO. OF M's	NO. OF A's	NO. OF B's	NO. OF M's	NO. OF A's	NO. OF B's	NO. OF M's	NO. OF A's	NO. OF B's	NO. OF M's	NO. OF A's	NO. OF B's	NO. OF M's	NO. OF A's	NO. OF B's	NO. OF M's	NO. OF A's	NO. OF B's	NO. OF M's	NO. OF A's	NO. OF B's	NO. OF M's	NO. OF A's	NO. OF B's	NO. OF M's	LEAVE BLANK	CARD NUMBER
DO NOT PUNCH	COLUMN NO. + 2	+ 5	+ 8	+ 10	+ 13	+ 16	+ 18	+ 21	+ 24	+ 26	+ 29	+ 32	+ 34	+ 37	+ 40	+ 42	+ 45	+ 48	+ 50	+ 53	+ 56	+ 58	+ 61	+ 64	+ 66	+ 69	+ 72	73	77 80

Figure 4 (top) and Figure 5 (bottom)

GENERAL HEAT TRANSFER CODE

CONDUCTANCE CARDS

Problem Number________________

USE SOLID BROWN CARDS

Page________ Of________

POINT NUMBER	NEIGHBOR POINT NO.	CONDUCTANCE K	NEIGHBOR POINT NO.	CONDUCTANCE K	NEIGHBOR POINT NO.	CONDUCTANCE K	NEIGHBOR POINT NO.	CONDUCTANCE K	NEIGHBOR POINT NO.	CONDUCTANCE K	NEIGHBOR POINT NO.	CONDUCTANCE K	LEAVE BLANK	CARD NUMBER
DO NOT PUNCH	COLUMN NO. + 2 4	+ .6 ± 12	+ 14 16	+ .18 ± 24	+ 26 28	+ .30 ± 36	+ 38 40	+ .42 ± 48	+ 50 52	+ .54 ± 60	+ 62 64	+ .66 ± 72	73 76	77 80

GENERAL HEAT TRANSFER CODE

VARIABLE TEMPERATURE AND/OR HEAT GENERATION CARDS

Problem Number________________

USE SOLID ORANGE CARDS

Page________ Of________

POINT NUMBER	A OR B	W OR S	A OR B	W OR S	A OR B	W OR S	A OR B	W OR S	LEAVE BLANK	CARD NUMBER
DO NOT PUNCH	COLUMN NO. ± .2 ± 8	± .10 ± 16	± .18 ± 24	± .26 ± 32	± .34 ± 40	± .42 ± 48	± .50 ± 56	± .58 ± 64	65 76	77 80

Figure 6 (top) and Figure 7 (bottom)

GENERAL HEAT TRANSFER CODE

Problem Number________________

MAP OUTPUT CARDS

Page ________ Of ________

USE GREEN STRIPE CARDS

ROW NUMBER	POINT NUMBERS												LEAVE BLANK	CARD NUMBER
DO NOT PUNCH	COLUMN NO. + 2 6	+ 8 12	+ 14 18	+ 20 24	+ 26 30	+ 32 36	+ 38 42	+ 44 48	+ 50 54	+ 56 60	+ 62 66	+ 68 72	73 76	77 80

Figure 8

RUNNING INSTRUCTIONS FOR GHT

Any number of different problems may be run as a series of cases with no machine stops between cases. Three blank cards following the last input data deck cause the code to list the answers that have been specified for the cases in the series.

Given below are the IBM-704 operating instructions, sense-switch settings, tape and drum usage, programed stops, restart procedure (if the calculation has been interrupted), and output information.

IBM-704 Operating Instructions

1. Place the code deck, followed by any number of input data decks, in the card reader. The last data deck must be followed by three blank cards.
2. Select the proper tape units and sense switches.
3. Press "clear" and then press "load cards" on the console; then press "start" on the card reader.

The code deck will be read in, followed by the data cards for the first case (except map output cards, if any), and the machine will begin the calculation of that case. Normal information printed by the on-line printer (other than special information and information called for by sense switches) will begin with

GEN. HEAT TRA. CODE CASE NO. XXXX.

Following this will be

BEGIN STEADY STATE CALCULATION

or

BEGIN TRANSIENT CALCULATION,

as the case may be. If a steady-state-only or a transient-only calculation is being run, the above information is followed by

END OF STEADY STATE

or

END OF TRANSIENT.

If a steady-state and transient, or a transient and steady-state calculation is being run, the code indicates (via the printer) when each type of calculation begins and ends. If the input cards for a second problem are in the card reader following the end of the calculation of the first case, the machine advances the page and prints the above information for this second problem. Following the calculation of the last case, the machine prints

END OF CALCULATION, ANS ON TAPE 1

and halts (see "Programed Stops").

Under certain circumstances additional information may be printed during the course of a calculation. For a steady-state calculation in which β is calculated by the code, the machine prints

β = X.XXXXXXXX

immediately following the calculation of β. Also, following a successful extrapolation of the temperatures, the code prints

EXTRAPOLATION ITERATION NO. = XXXX.

Sense-Switch Settings

Any or all of the sense switches may be used during a calculation. Listed below are the effects of depressing each of the six sense switches.

Sense Switch 1. – If sense switch 1 is in the down position, the convergence (at each steady-state iteration) or the time (at each transient iteration) is monitored via the on-line printer. The format for the steady-state convergence is

ITERATION NO. = XXXX POINT NO. = XXX

T1 – T2 = X.XXXXXXX CONV. = X.XXXXXXXX.

"POINT NO." refers to the point number which gives the maximum temperature difference between two successive iterations. This maximum difference is the $T1 - T2$ above. "CONV." is the maximum value of

$$\left| \frac{T2}{T1} - 1 \right| ,$$

where $T1$ and $T2$ refer to the temperature values for two successive iterations. The point number corresponding to this value is not printed.

The time for a transient calculation is given as

TIME = X.XXXXE ± XX.

Sense Switch 2. – If sense switch 2 is depressed, the output answers will be printed on-line, as well as stored on output tape 1.

Sense Switch 3. – If sense switch 3 is down, the code calls for all input data from tape 7 *except* that from the control card, the time card, the map output cards (if any), and the three blank cards used to end the calculation. Refer to "Tape and Drum Usage" for information on preparing input tape 7.

Sense Switch 4. – As long as sense switch 4 remains down, the temperature distributions for each steady-state or transient iteration will be printed on-line. These distributions will be a sequential listing of the temperatures by point number. For steady-state and transient problems, when the maximum number of steady-state iterations (specified on the control card) is reached before the convergence criterion is satisfied, the machine stops after printing

END OF STEADY STATE – CONV. NOT SAT.,

CONV. = X.XXXXXXXX,

HIT START TO CONT.,

USE S.S. 4 FOR ANS. AND STOP.

At this point if "start" is pressed with sense switch 4 in the up position, the calculation proceeds in the normal way, with the nonconverged steady-state temperature distribution as the initial temperature for the transient calculation. If sense switch 4 is put down before "start" is pressed, the machine proceeds as if a steady-state-only calculation were being run, lists the distribution it has, and calls for the next problem, or it stops.

Sense Switch 5. – If sense switch 5 is in the down position during a steady-state calculation, the converged temperature distribution is punched on cards. Also, if sense switch 5 is down during a transient calculation, the specific time and the temperature distribution at that time are punched on cards. This output is obtained after each time iteration as long as sense switch 5 remains in the down position. These output cards may be used directly as input to GHT, and so the use of sense switch 5 is primarily associated with restarting a calculation which has been interrupted (see "Restart and Machine Error Procedure").

Sense Switch 6. – The use of sense switch 6 can greatly accelerate the convergence of a slowly converging, steady-state problem in which some of the temperatures fail to meet the extrapolation conditions. The extrapolation cycle, specified on the control card, indicates how often the code is to attempt to extrapolate the temperatures. As stated under "Running Times," if the conditions in the extrapolation procedure are met by all points, one or two extrapolations can greatly reduce the number of iterations required for convergence. Ordinarily, however, if one or more points do not meet the extrapolation conditions, then no temperatures are extrapolated.

If sense switch 6 is down during an attempted extrapolation, all those temperatures meeting the conditions are extrapolated, while those failing to meet the conditions are not. It has been found by running a series of test cases that use of this sense switch once or twice during a calculation (i.e., putting sense switch 6 in the down position at some time during the calculation and leaving it in the down position until an extrapolation is performed) reduces the number of iterations required to reach convergence by as much as 50%. However, only with experience with various types of problems can it be determined when and how often to use this switch.

After an extrapolation of the kind discussed above (using sense switch 6), the machine will print

EXTRAPOLATION – SOME PTS. –

IT. NO. = XXXX.

Any of the six sense switches may be put in the up or down position at any time during the calculation.

Tape and Drum Usage

The code uses a minimum of six and a maximum of eight tape units; the actual number is dependent upon the type of problem and whether the input is on cards or tape:

Tape 1 is the BCD output tape and is needed for all types of problems.

Tape 2 is used for storage of the heat generation data and is used for all problems.

Tape 3 is used for storage of the thermal capacitance data, if any. This tape should be selected even for a steady-state-only calculation, since the code selects tape 3 for rewind.

Tape 4 is used for storage of the point data and is needed for all problems.

Tape 5 is used for storage of variable temperature and/or heat generation data and is needed for all problems.

Tape 6 is used for storage of the thermal conductance data and the map output data; it is needed for all problems.

Tape 7 is used for BCD input. This tape need not be selected if input is from cards. If tape 7 is to be used for input, all input cards except the control card, the initial-time card, and the map output cards (if any) are listed on tape 7 on an off-line card-to-tape unit.

Tape 8 is used for storage of binary output data and is needed for all problems.

For an 8000-word machine, two drums are used for intermediate storage of the temperature distribution. No drums are required for a 16,000-word machine.

Programed Stops

The calculation includes automatic stops if certain conditions exist; the cause of a programed stop can be identified by examining the contents of the storage register (not the instruction counter). The list below correlates the contents of the storage register with the cause; the contents contain, in order, the operation, content of the address field, and content of the tag field:

1. HPR, 22222,0 – Steady-state convergence not satisfied. See on-line printer for instructions.
2. HPR, 00000,3 – Tape redundancy information in error due to error introduced through input tape 7. Restart problem from the beginning.
3. HPR, 10101,0 – Tape redundancy information in error due to error introduced through tape 4 during the input calculation. Restart problem from the beginning.
4. HPR, 20202,0 – Tape redundancy information in error due to error introduced through tapes 2, 4, or 6 during steady-state calculation. Press "start" to accept information read, and continue. Refer to "Restart and Machine Error Procedure" to obtain answers that have been calculated up to this point.
5. HPR, 40404,0 – Tape redundancy information in error due to error introduced through tapes 2, 3, 4, 5, or 6 during the transient calculation. Press "start" to accept information read, and continue. Refer to "Restart and Machine Error Procedure" to obtain answers that have been calculated up to this point.
6. HPR, 50505,0 – Tape redundancy information in error due to error introduced through tape 8 during the output calculation. Press "start" to accept information read, and continue.
7. HPR,00000,1 – End file has occurred in reading cards or input tape. Press "start" to continue reading next file. This stop is probably due to input data error.
8. HPR,0000,0 – End file has occurred in reading binary tape. Press "start" to resume reading next file. This stop is probably due to machine error.
9. HPR, 00001,1; HPR, 00002,1; HPR, 00003,1; HPR, 00004,1 – Inappropriate character has occurred in a data field in reading cards or input tape. Press "start" to set character to zero, and continue. This stop is probably due to input data error.
10. HPR, 00000,2 – Non-Hollerith character encountered in reading card. Correct the card in the reader and press "start."
11. HPR, 00000,4 – Echo check has occurred in printing. Press "start" to continue. Press "reset" and "start" to repeat line, and continue.
12. HPR, 77777,0 – End of calculation. Pressing the "start" has no effect. To continue with another case, replace output tape 1 with blank tape, place data cards for next case in card reader, and transfer machine control to octal location 00140.

Restart and Machine Error Procedure

The restart provision in GHT makes it possible to stop a calculation at any stage and restart it at a later time with a minimum of effort on the part of the user. If it is desired to stop a steady-state calculation before the convergence is satisfied for either a steady-state-only type of problem or for a steady-state and transient type of problem, put sense switch 4 down to obtain an on-line listing of the temperature distribution at that point and then simply stop the machine. To continue the calculation at a later time, a new set of temperature cards should be punched from this listing, and these cards should be used for the initial-temperature input cards; all other input cards would remain the same. Following this, the procedure would be the same as though a new problem were being run.

If it is desired to stop any transient calculation before completion, depress sense switch 5 to obtain an initial-time card and also the temperature distribution cards at that time. After these cards have been punched, stop the machine and manually transfer machine control to octal location 03542 for an 8000-word machine, or to octal location 03433 for a 16,000- or 32,000-word machine. This transfer causes the output answers (that have been calculated up to this point) to be listed in the normal manner; the machine then proceeds to the next case, or stops if no more cases are to be run. However, the output answers for the last time interval which are obtained in this manner will be in error, since they have not been calculated correctly. To restart this case at a later time, replace the initial-time card and the temperature cards with the appropriate cards punched by the machine (key-punch a new control card if needed). For instance, if the problem were a steady-state and transient type of calculation, columns 24–27 on the control card would be changed to indicate a transient-only type of problem for the restart. Also, the transient output cycle might need to be changed for this new case.

After a machine-error stop or end-of-calculation stop, a new case can be started (or the case on which the machine has stopped can be restarted) by placing the input data deck in the card reader and doing a manual transfer to octal location 00140 for both code I and code II. (Note: When the end-of-calculation stop occurs, output tape 1 has been rewound. Replace this tape with a blank tape if another case is to be run.) The above manual transfer eliminates the need of reading-in the code deck again. If a machine error occurs during a transient calculation and it is desired to obtain the temperature distributions which have already been computed and stored for output, do a manual transfer to octal location 03542 for code I (8000-word 704) or to 03437 for code II (16,000- or 32,000-word 704). This transfer causes the normal output answer (up to the stop) to be listed, plus one transient distribution in which the calculation was not completed. This latter distribution should be disregarded.

Output

As indicated previously, the output consists of the temperature distribution either in map form or listed sequentially. The headings of each page of output are self-explanatory, indicating which particular distribution is on each page. For the sequential list the temperature values are floating-decimal-point numbers of the form ±X.XXXE ± XX, with blanks left for the plus signs. The map output temperatures are fixed-decimal-point numbers, with one digit to the right of the decimal point. If the number is positive, the sign is not printed. The maximum range of the map output temperature values is ±999,999.9.

RUNNING TIMES

The running times listed below are for GHT code deck No. I (IBM-704 8000-word memory) and are based upon an average of four neighbors per point, with no variable heat generation:

Read-in GHT code deck No. I	0.93 min
Read input data from cards	0.467 sec/point
Calculate transient	0.023 sec/point-iteration
Calculate steady-state	0.021 sec/point-iteration
Arrange map output	5.00 sec/page

The machine time required to calculate the temperatures for a transient heat transfer problem can be estimated by the following relation:

Time required (sec)

$$= \left(\frac{\tau}{\Delta\tau}\right) (0.023)\ (\text{Total number of points}) \ . \qquad (13)$$

The machine time required to calculate a steady-state temperature distribution is dependent upon such things as initial error, convergence criteria, convergence rate, and extrapolation (including the use of sense switch 6). Most of these items vary with each problem, and experience is the only guide for making an estimate of the number of iterations required to reach steady-state.

In regard to test cases which have been run, a brief outline of two of these will be presented in order that a better understanding of the steady-state calculation can be obtained.

Test Case No. 1. – In test case No. 1 a rectangular section was considered that was perfectly insulated on three sides and held at a constant temperature on the fourth side; there were 150 nodal sections. The constant-temperature surface was at 140° F, and the conductivity and heat generation were assumed to be 2 $\text{Btu}\cdot\text{hr}^{-1}\cdot\text{in.}^{-1}\cdot(°\text{F})^{-1}$ and 15 $\text{Btu}\cdot\text{hr}^{-1}\cdot\text{in.}^{-3}$, respectively. With a value of β = 1.0, the problem would not extrapolate without using sense switch 6. A total of 117 iterations was run without satisfying the convergence criteria; it was estimated that 660 iterations would have been necessary. Using β = 1.0 and letting GHT calculate a new β after ten iterations, the problem extrapolated (without using sense switch 6) at the 39th iteration and satisfied the convergence criteria after a total of 72 iterations. The same case required 200 iterations when β was calculated by the machine and no extrapolation was permitted. From the last two runs it should be noted that one extrapolation reduced the number of iterations required to reach steady-state by 128, or 64%.

Test Case No. 2. – Test case No. 2 had the configuration of a nozzle with 160 nodal points. The inside surface of the nozzle was held at constant temperature, while the outside was perfectly insulated. There was no heat generation associated with this problem. Using $\beta = 1.0$ and letting GHT calculate a new value of β after ten iterations, 100 iterations were required to satisfy the convergence criteria (this problem would not extrapolate without use of sense switch 6). By running this problem in the same manner, but putting sense switch 6 down at the 33rd and 51st iterations (one extrapolation each time), only 61 iterations were required to satisfy the convergence criteria. Thus, by using sense switch 6 at these times, the number of iterations was reduced by 39, or 39%.

Appendix A

DERIVATION OF EQUATIONS

The problems considered here consist essentially of solving certain partial differential equations; in all cases the temperature distribution is the desired unknown. For the purpose of illustration, the equations are written in terms of Cartesian coordinates; however, any orthogonal coordinate system (up to three dimensions) can be considered.

For steady-state conditions the conduction equation considered is

$$\frac{\partial}{\partial x}\left[k(x,y,z)\frac{\partial T}{\partial x}\right]+\frac{\partial}{\partial y}\left[k(x,y,z)\frac{\partial T}{\partial y}\right]+\frac{\partial}{\partial z}\; k(x,y,z)\frac{\partial T}{\partial z}\;+q(x,y,z)=0\;, \tag{A-1}$$

where T is temperature, k is the thermal conductivity, and q is the volume-heat-generation rate. As indicated, k and q can be functions of position. At the boundary, specified by subscript b, T is given by either

$$T_b = f(x,y,z) \tag{A-2}$$

or

$$-k\left(\frac{\partial T}{\partial x}\right)_b = h[T_b - f(x,y,z)]\;, \tag{A-3}$$

where f is an arbitrary, but known, function of position, and h is an effective heat transfer coefficient.

For unsteady-state conditions, the mathematical system is

$$\frac{\partial}{\partial x}\left[k(x,y,z)\frac{\partial T}{\partial x}\right]+\frac{\partial}{\partial y}\left[k(x,y,z)\frac{\partial T}{\partial y}\right]+\frac{\partial}{\partial z}\left[k(x,y,z)\frac{\partial T}{\partial z}\right]+q(x,y,z,\tau)=c(x,y,z)\frac{\partial T}{\partial \tau}\;, \tag{A-4}$$

where τ represents time, c is the volume heat capacity, q is an arbitrary function of position and time. At the boundary, T satisfies either

$$T_b = F(x,y,z,\tau) \tag{A-5}$$

or

$$-k\left(\frac{\partial T}{\partial x}\right)_b = h[T_b - F(x,y,z,\tau)]\;, \tag{A-6}$$

where F is a function of position and time. As formulated, the time variation of F at a specified position must be linear in a given time interval; up to 25 such time intervals can be considered. Thus F can be represented by

$$F(x,y,z,\tau)=\sum_{i=1}^{25}\left[a_i(x,y,z)+b_i(x,y,z)\,\tau\right]\;, \tag{A-7}$$

where the a_i's and b_i's are known functions of position and also of the particular time interval.

Derivation of the steady-state and transient equations is done by performing a heat balance about a nodal point which is connected (thermally) to M other nodal points. The resulting equations may also be derived from the appropriate partial-differential equation of heat conduction by writing the latter in difference form. By choosing the mesh size (associated with nodal points) small enough, the numerical results give a practical solution to the appropriate differential equation. The major problem in the numerical calculation is the iteration method used in obtaining the final temperature distribution. The numerical procedure is such that points on the boundary are treated in essentially the same manner as points interior to the boundary, taking into consideration the known information, for example, the appropriate value for the effective conductance.

Steady-State Equation

Consider a specified nodal point, J, which is thermally connected with M adjacent nodal points. Under steady-state conditions the rate at which energy is conducted away from point J must equal the rate of energy generation at that point. Thus, if T_i is the temperature at nodal point i, T_J must satisfy the equation

$$\sum_{i=1}^{M} {}_JK_i(T_i - T_J) + Q_J = 0\;, \tag{A-8}$$

where ${}_JK_i$ is the thermal conductance between points J and i, Q_J is the rate of energy generation at point J, T_J is the temperature at point J, and T_i is the temperature at points i adjacent to J. The value of T_J which satisfies Eq. (A-8) can be obtained only after a number of iterations; it is assumed that the $(n + 1)$th iteration on T_J, termed T_J^{n+1}, satisfies Eq. (A-8), but that the nth iteration gives

$$\sum_{i-1}^{M} {}_JK_i(T_i - T_J^n) + Q_J = \epsilon \ , \qquad \text{(A-9)}$$

where ϵ is a residual term. It follows that

$$\epsilon = \sum_{i-1}^{M} {}_JK_i \left(T_J^{n+1} - T_J^n\right) \ . \qquad \text{(A-10)}$$

Combining Eqs. (A-9) and (A-10) gives

$$\left(T_J^{n+1} - T_J^n\right) \sum_{i-1}^{M} {}_JK_i$$

$$= \sum_{i-1}^{M} {}_JK \left(T_i - T_J^n\right) + Q_J \ . \qquad \text{(A-11)}$$

If the values of T_i are taken at iteration n, this would be the "Richardson method";[4] however, to increase the convergence rate, $T_i = T_i^n$ for values of $i > J$, and $T_i = T_i^{n+1}$ for values of $i < J$. If the points are numbered as recommended in the section, "Input Data," this procedure is called the "Liebmann method."[4]

By use of Eq. (A-11) the temperature unbalance is brought to zero for each nodal point as it is calculated; however, to increase convergence it is desirable to "overrelax" the unbalance. This can be done by multiplying the right side of Eq. (A-11) by a constant, termed β. Thus Eq. (A-11) becomes

$$\left(T_J^{n+1} - T_J^n\right) \sum_M {}_JK_M$$

$$= \beta \left[\sum_M {}_JK_M \left(T_M - T_J^n\right) + Q_J\right] \ ; \qquad \text{(A-12)}$$

upon rearranging, this becomes

$$T_J^{n+1} = T_J^n (1 - \beta) + \frac{\beta \left(\sum_M {}_JK_M T_M + Q_J\right)}{\sum_M {}_JK_M} \ . \qquad \text{(A-13)}$$

[4] S. P. Frankel, *Mathematical Tables and Other Aids to Computation*, vol IV, p 65–75, National Research Council, Washington, D.C., 1950.

Equation (A-13) is commonly called the "extrapolated Liebmann" equation and is used in GHT. The value of β must be in the range $1 \leq \beta < 2$. If $\beta = 1$, Eq. (A-11) should be used.

The value of β which will produce the optimum convergence rate for all points is difficult to obtain analytically for simple geometries and is practically impossible to obtain for complex geometries. However, by combining analytical and empirical results, a method of computing β was developed which has been satisfactory for a wide variety of test cases.

Consider a rectangular array of points (j, k), with p equal divisions in the j direction and q equal divisions in the k direction; let the boundary conditions be $T = C_1$ at $j = 0, p$ and $T = C_1$ at $k = 0, q$; Frankel has shown[4] that

$$K^*_{\text{Lieb.}} \cong \left[1 - \frac{\pi^2 (p^{-2} + q^{-2})}{4}\right]^2 \ , \qquad \text{(A-14)}$$

where

$$K^*_{\text{Lieb.}} = \frac{\epsilon^{n+1}}{\epsilon^n} \ , \qquad \text{(A-15)}$$

and where

$$\epsilon^n = \left(T^n - T_{\text{final}}\right) \ , \qquad \text{(A-16)}$$

$$\epsilon^{n+1} = \left(T^{n+1} - T_{\text{final}}\right) \ . \qquad \text{(A-17)}$$

For the extrapolated Liebmann method, it has been shown[4] that

$$K^*_{\text{ex Lieb.}} \cong 1 - \sqrt{2}\,\pi (p^{-2} + q^{-2})^{1/2} \ , \qquad \text{(A-18)}$$

or

$$K^*_{\text{ex Lieb.}} = 4\alpha - 1 \ , \qquad \text{(A-19)}$$

where $4\alpha \equiv \beta$ of GHT. Assuming that $K^*_{\text{Lieb.}}$ can be determined and that the geometry factor $(p^{-2} + q^{-2})$ is unknown, an equation for β can be obtained in terms of K^*_{Lieb}, namely,

$$\beta = 2 - \sqrt{8}\left(1 - \sqrt{K^*_{\text{Lieb.}}}\right)^{1/2} \ . \qquad \text{(A-20)}$$

The problem is now one of determining the value of $K^*_{\text{Lieb.}}$.

By plotting the results of many test cases, it was found that the nodal point with the slowest convergence rate satisfied equations of the form

$$T^{n+1} - T^n = Ae^{-m(n+1)} \ , \qquad \text{(A-21)}$$

$$T^{n+2} - T^{n+1} = Ae^{-m(n+2)} \quad , \qquad \text{(A-22)}$$

where A and m are parameters. Eliminating the constant A from these two equations gives

$$e^{-m} = \frac{T^{n+2} - T^{n+1}}{T^{n+1} - T^n} \quad . \qquad \text{(A-23)}$$

Also, if Eqs. (A-21) and (A-22) are valid, T_{final} can be obtained from

$$T_{\text{final}} = T^n + \int_{x=n}^{\infty} Ae^{-mx}\,dx \ , \qquad \text{(A-24)}$$

$$T_{\text{final}} = T^{n+1} + \int_{x=n+1}^{\infty} Ae^{-mx}\,dx \ . \qquad \text{(A-25)}$$

Integration gives

$$T_{\text{final}} = T^n + \frac{Ae^{-m(n)}}{m} \ , \qquad \text{(A-26)}$$

$$T_{\text{final}} = T^{n+1} + \frac{Ae^{-m(n+1)}}{m} \ . \qquad \text{(A-27)}$$

It also follows that

$$T_{\text{final}} = T^{n+2} + \frac{Ae^{-m(n+2)}}{m} \ . \qquad \text{(A-28)}$$

Eliminating A from the above equations gives

$$e^{-m} = \frac{T^{n+1} - T_{\text{final}}}{T^n - T_{\text{final}}} \ , \qquad \text{(A-29)}$$

$$e^{-m} = \frac{T^{n+2} - T_{\text{final}}}{T^{n+1} - T_{\text{final}}} \ . \qquad \text{(A-30)}$$

Combining Eqs. (A-15), (A-16), (A-17), (A-23), and (A-29) gives

$$K^*_{\text{Lieb.}} = \frac{T^{n+2} - T^{n+1}}{T^{n+1} - T^n} \ . \qquad \text{(A-31)}$$

Also, from a number of test cases the authors have found that if $\sqrt{8}$ in Eq. (A-20) is replaced by 2, a better value of β is obtained. Therefore the equation used in GHT for calculating β is

$$\beta = 2 - 2\left[1 - \left(\frac{T^{n+2} - T^{n+1}}{T^{n+1} - T^n}\right)^{1/2}\right]^{1/2} \ . \qquad \text{(A-32)}$$

The value of β calculated from Eq. (A-32) will be smaller than the optimum value unless n becomes very large. It is recommended that $n + 2$ be equal to 10 before β is calculated. A small value of β will not seriously slow down the convergence, and in most cases the convergence will exceed that for the optimum value if the Aitken δ^2 process is used for extrapolating the temperatures. This extrapolation process can be obtained by combining Eqs. (A-29) and (A-30), which gives

$$T_{\text{final}} = \frac{(T^n)(T^{n+2}) - (T^{n+1})^2}{T^{n+2} + T^n - 2T^{n+1}} \ . \qquad \text{(A-33)}$$

Adding and subtracting T^{n+2} from the right side of Eq. (A-33) gives

$$T_{\text{final}} = T^{n+2} + \frac{(T^{n+2} - T^{n+1})^2}{(T^{n+1} - T^n) - (T^{n+2} - T^{n+1})} \ . \qquad \text{(A-34)}$$

Due to boundary conditions, geometry factors, β, and initial conditions, the temperatures at certain nodal points for some problems will not converge in accordance with Eqs. (A-21) and (A-22), but will converge in an "oscillating" fashion. To prevent these particular nodal points from extrapolating, the program is written so that Eq. (A-34) cannot be applied unless the following conditions are satisfied:

$$|(T^{n+1} - T^n)| > |(T^{n+2} - T^{n+1})| \ , \qquad \text{(A-35)}$$

$$(T^{n+2} - T^{n+1})(T^{n+1} - T^n) > 0 \ . \qquad \text{(A-36)}$$

Actually, GHT has been programed such that the user may either extrapolate when all nodal points satisfy Eqs. (A-35) and (A-36), or extrapolate only those points which satisfy these equations.

Transient Equation

Consider a specified nodal point, J, which is thermally connected with M adjacent nodal points. Under transient conditions the rate at which energy is conducted away from point J must equal the rate of energy generation plus the rate change of energy storage associated with that point. With the same nomenclature as in Eq. (A-8), the non-steady-state equation is

$$\sum_{i=1}^{M} {}_JK_i[T_i(\tau) - T_J(\tau)] + q_J(\tau) = C_J \frac{\Delta T_J}{\Delta T} \ , \qquad \text{(A-37)}$$

where C_J is the thermal capacitance associated with point J, $q_J(\tau)$ is the rate of heat generation at J as a function of time, and ΔT_J is the change in temperature of point J in the time interval $\Delta\tau$. [Heat transfer by convection into node J can also be considered with GHT by proper evaluation of ${}_JK_i$ and $T_i(\tau)$; this is shown by Hellman, Habetler, and Babrov.[5]] Thus ΔT_J is given by

$$\Delta T_J = T_J(\tau + \Delta\tau) - T_J(\tau) \quad . \qquad \text{(A-38)}$$

In GHT, it is assumed that the time variation of q_J is linear with time in a specified time interval (the number of specified time intervals can be as great as 25). Thus $q_J(\tau)$ is considered to be of the form

$$q_J(\tau) = Q_J + \Delta Q_J(\tau) \quad , \qquad \text{(A-39)}$$

where Q_J is a function of position alone,

$$\Delta Q_J(\tau) = \sum_{i-1}^{j-1} B_i(S_i - S_{i-1}) + B_j(\tau - S_{j-1}) \quad ,$$

for

$$S_{j-1} < \tau \leqq S_j \quad ,$$

$$j \leqq 25 \quad ,$$

B_i, S_i = input parameters .

Combining Eqs. (A-37) and (A-39) gives

$$T_J(\tau + \Delta\tau) = T_J(\tau) + $$

$$+ \frac{\Delta\tau}{C_J}\left\{\sum_{i=1}^{M} {}_JK_M[T_i(\tau) - T_J(\tau)] + Q_J + \Delta Q_J(\tau)\right\} \quad . \qquad \text{(A-40)}$$

The calculation of T_J as a function of time as specified by Eq. (A-40) is straightforward so long as the $\Delta\tau$ associated with each iteration is kept sufficiently small. Thus $\Delta\tau$ should be based on a stability criteria such that the numerical result utilizing Eq. (A-40) does not diverge from the correct solution. The criterion for $\Delta\tau$ derived in ref 5 can be used in GHT; this is written as

$$\Delta\tau \leqq \left(\frac{C_J}{\sum_{i=1}^{M} {}_JK_i}\right) \quad , \qquad \text{(A-41)}$$

where the right side refers to that nodal point which gives the smallest value for $\Delta\tau$.

[5] S. K. Hellman, G. Habetler, and H. Babrov, *Trans. Am. Soc. Mech. Engrs.* **78**, 1155–61 (1956).

Appendix B

CALCULATION OF INPUT CONSTANTS

The input data required for each nodal point are the point heat generation (Q), the thermal capacitance (C), and the thermal conductances (K). The thermal conductance is the reciprocal of the thermal resistance; its value between the point under consideration and each of the neighboring points must be known. The conductance values may be calculated from the basic formulas

$$K = \frac{kA_c}{\Delta x} \quad \text{(conduction)} \ , \qquad \text{(B-1)}$$

$$K = hA_c \quad \text{(film coefficient)} \ , \qquad \text{(B-2)}$$

$$K = C_r A_c \quad \text{(contact coefficient)} \ . \qquad \text{(B-3)}$$

Thermal capacitance is the ability of the node under consideration to store heat and is applicable to transient problems only. This value may be computed from

$$C = \rho C_p V \ , \qquad \text{(B-4)}$$

where ρ is the material density, C_p is the mass heat capacity, and V is the effective volume associated with the particular nodal point.

Heat generation may be positive (heat source) or negative (heat sink). Knowing the heat generation rate per unit volume (q), the input value can be calculated from

$$Q = qV \ . \qquad \text{(B-5)}$$

The values of K and V are by far the most difficult of the input values to calculate by hand. However, the code CURE, which is a generalized two-space-dimension multigroup coding for the IBM-704[6] can calculate these values for X-Y, R-Z, or R-θ geometry. (Neutron diffusion theory leads to equations which can be interpreted as heat conduction equations. Thus CURE can be used to calculate the appropriate K's and V's. This particular application of CURE utilizes only a small fraction of the calculations normally associated with CURE use.) Many heat conduction problems can be formulated in these geometries; thus it is possible to use the CURE code to calculate GHT input values. This procedure may also be used to obtain the constants for a three-dimensional problem, by repeating the two-dimensional CURE calculation for different planes.

Preparation of the input data for calculating GHT constants by use of CURE is quite simple. The following information on the preparation of the CURE code input data explains its use in the sample problem in Appendix C. Most of the information has been taken directly from ref 6, with minor changes in terminology and with deletions of those parts not applicable to this specific use of CURE. The calculation of K and V is but a minor part of CURE. Reference 6 gives an explanation of the operation of CURE as well as a listing of the required input data. The time required to calculate the constants for one point in GHT is about 0.5 sec.

The CURE code requires an IBM-704 with at least an 8000-word memory and six magnetic-tape units; no auxiliary drum storage is required. The basic code mesh is a rectangular array of I (columns) times J (rows) points and so includes all temperature nodal points. The limitations on the mesh size are as listed in Table B-1.

Input for CURE may be written on CURE code input forms, as shown in Table B-2. For each type of input a value is entered in the "location" column; the data type (DEC or BCD) is entered in the "operation" column. The data are entered

[6] E. L. Wachspress, *Cure: A Generalized Two-Space-Dimension Multigroup Coding for the IBM 704*, KAPL-1724 (April 1957).

Table B-1. Limitations on Mesh Size in CURE Code

Memory of Machine	Maximum I, J	Maximum $(I + 1) \times (J + 1)$	Maximum Number of Nodal Points Inside and on Boundary
8,129	50	1400	644
16,258	120	2600	1516
32,519	200	7475	3275

Table B-2. CURE Code Input Form

PROBLEM

CODER | DATE | PAGE OF

H (1)	LOCATION (2–6)	7	OP (8–10)	11	ADDRESS, TAG, DECREMENT (12–)	COMMENTS (–72)	IDENTI-FICATION (73–80)
	1000		DEC		i_{max}	Maximum value of i	
	1001		DEC		i_{max}	Maximum value of j	
	1006		DEC		N	N = 7 for 8,000-word 704	
						N = 4 for 16,000-word 704	
						N = 2 for 32,000-word 704	
	1007		DEC		1	Always enter 1	
	1008		BCD		1 XXXXXX	XXXXXX = six BCD characters (letters or numbers)	
	1010		DEC		δ_1	Geometry designation:	
	1011		DEC		δ_2	X – Y $\delta_1 = \delta_2 = 0$	
						R – Z $\delta_1 = \delta_2 = 1$	
						R – θ $\delta_1 = 1, \delta_2 = 0$	
	1021		DEC		1	Always enter 1	
	1024		DEC		M	M = 644 for 8,000-word 704	
						M = 1516 for 16,000-word 704	
	2000		DEC		990, 0, 0, 0		
			DEC		i_1, 1, Z_1		
			DEC		0, i_1, Z_2		
			DEC		i_2, 0, Z_3	Boundary conditions	
			DEC		.	(see explanation of Table 990)	
			DEC		.		
			DEC		. i_1, 0, Z_1		
			DEC		0, 0, 0, 990		

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Table B-2 (continued)

PROBLEM

CODER | DATE | PAGE | OF

H	LOCATION	7	OP	11	ADDRESS, TAG, DECREMENT	COMMENTS	IDENTIFICATION
			DEC		993, 0, 0, 0		
			DEC		0, 1, i_1, i_2, l_1		
			DEC		i_2, i_3, l_2		
			DEC		.		
			DEC		.		
			DEC		i_m, i_n, l_s	Material regions	
			DEC		0, j, i_1, i_2, l_8	(see explanations of	
			DEC		i_2, i_3, l_9	Table 993)	
			DEC		.		
			DEC		.		
			DEC		i_p, i_q, l_t		
			DEC		0, 0, 0, 993		
			DEC		999		
	3000		DEC		996, 0, 0, 0		
			DEC		1, i_1, Δ_1		
			DEC		i_1, i_2, Δ_2		
			DEC		$\vdots$	Horizontal increments	
			DEC		i_n, i_{n+1}, Δ_{n+1}	(see explanation of	
			DEC		i_{n+1}, i_{n+2}, Δ_{n+2}	Table 996)	
			DEC		$\vdots$		
			DEC		i_m, i_{max}, Δ_{m+1}		
			DEC		0, 0, 0, 996		
			DEC		997, 0, 0, 0		

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Table B-2 (continued)

PROBLEM

CODER | DATE | PAGE | OF

H	LOCATION	OP	ADDRESS, TAG, DECREMENT	COMMENTS	IDENTIFICATION
1	2 6	8 10	12	72	73 80
			$1, i_1, \Delta_1$		
			i_1, i_2, Δ_2		
		DEC	⋮	Vertical increments	
		DEC	$i_n, i_{n+1}, \Delta_{n+1}$	(see explanation of	
		DEC	$i_{m+1}, i_{n+2}, \Delta_{n+2}$	Table 997)	
		DEC	⋮		
		DEC	$i_m, i_{max}, \Delta_{m+1}$		
		DEC	0, 0, 0, 997		
		TRA	2, 4		
	3505	DEC	k_{l_1}, 0, 0, 0, 0, 0		
	3520	DEC	k_{l_2}, 0, 0, 0, 0, 0		
	⋮	DEC	⋮		
	⋮	DEC	⋮	Material properties	
	3490 + 15(n)	DEC	k_{l_n}, 0, 0, 0, 0, 0	(see explanation under	
	⋮	DEC	⋮	"Table of Conductivities")	
	3490 + 15(m)	DEC	k_{l_m}, 0, 0, 0, 0, 0		
	⋮	DEC	⋮		
	4090	DEC	$k_{l_{40}}$, 0, 0, 0, 0, 0		
	5500	BCD	1 XXXXXX	Same as value entered for	
		TRA	2, 4	location 1008	

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in the "address-tag-decrement" column and may extend into the "comments" column up to and including card column No. 72. Each line of data comprises one card. The "identification" column may be used for card numbers if desired. Commas must be used to separate data, but no comma should appear after the last value of data on each card (line).

Table B-2 shows the input to CURE which is required for calculation of GHT constants. In this table the "comments" column is used for explanation only, and such information would not be punched in cards. A description of "tables of conductivities" and "tables 990, 993, 996, 997," referred to in Table B-2, is given below in "Configuration Data."

It should be noted that in $X\text{-}Y$ and $R\text{-}\theta$ geometry the length in the Z direction is taken as unity; in $R\text{-}Z$ geometry the distance in the θ direction is taken as 1 radian. Also, for $R\text{-}Z$ or $R\text{-}\theta$ geometry the $i = 1$ position is at the center line or the vertex, respectively.

Configuration Data

Four tables are necessary to specify the configuration data. Each table starts with a sentinel 99X, 0, 0, 0 and ends with a sentinel 0, 0, 0, 99X, where 99X specifies the table number. Tables 990 and 993 are associated with location counter 2000, while tables 996 and 997 are associated with location counter 3000. Prior to the card containing sentinel 996, 0, 0, 0 is one card with a sentinel 999 (no zeros follow this sentinel).

Table 990: Boundary Specification. – A path is traced clockwise around the boundary. Information is expressed in triplets i, j, z, where i, j are mesh coordinates for point temperatures, and z is the boundary-condition index referring to that portion of the boundary leading up to a point. The first triplet is i_1, 1, z_1, where i_1 is the minimum i value for temperature points on row $j = 1$.

The next triplet is 0, j_1, z_2 (z_2 may equal z_1), where j_1 is the row number of the next boundary corner on the next point for which a new z must be specified. A nonzero i or j value appears only if there is a change from the previous triplet. Only the first triplet has neither i nor j equal to zero.

A triplet is specified for each boundary corner and for each boundary point, for which a new z must be specified. The final triplet (which closes the path) must be i_1, 0, z_1, where i_1 and z_1 must be the same as in the first triplet, since the first triplet and the last triplet correspond to the same point.

The values of z which are applicable to GHT are as follows:

$$z = 41 \text{ (no-heat-flow boundary)} ,$$

$$z = 62 \text{ (constant-temperature boundary)} .$$

Table 993: Material Indexes. – Each row j, along which material indexes (l) are specified, is started on a new card sentinelized by 0, j. The material index (l) is any integer from 1 through 40 which represents a material with a specific conductivity. Each material with a different conductivity should be given a different material index (l). Materials are specified in triplets. Each triplet includes the i values between which the material appears and the l index of that material. Only those indexes which change from their value on the previous row need be specified; all materials must be specified above row 1. For example, row 1 would be written as

$$0,\ 1,\ i_1,\ i_2,\ l_1,\ i_2,\ i_3,\ l_2,\ \ldots\ .$$

In general, row j could be

$$0,\ j,\ i_4,\ i_5,\ l_3,\ i_6,\ i_7,\ l_4\ \ldots\ .$$

For each row the i's are given in increasing order.

Table 996: Horizontal Increments. – Information is in triplets. The triplet specifying Δ, the distance between vertical grid lines, is i_1, i_2, Δ, where i_1 and i_2 are the vertical grid-line numbers between which Δ is constant. These triplets follow each other in increasing i order, that is,

$$1,\ i_1,\ \Delta_1,\ i_1,\ i_2,\ \Delta_2,\ \ldots\ ,\ i_n,\ i_{n+1},\ \Delta_{n+1}\ ,$$

or, in general,

$$1_{n+1},\ i_{n+2},\ \Delta_{n+2},\ \ldots\ ,\ i_m,\ I,\ \Delta_{m+1}\ .$$

For example, if the vertical spacing between $i = 1$ through $i = 6$ is 0.5, and $i = 6$ through $i = 7$ is 1.5, and $i = 7$ through $i = 10$ is 0.75, the specification would be

$$1,\ 6,\ 0.5,\ 6,\ 7,\ 1.5,\ 7,\ 10,\ 0.75\ .$$

Table of Conductivities. – One card is used to specify the conductivity of each material. The location column of each card is specified by the following formula:

$$\text{Location} = 3490 + 15l\ .$$

(For three materials the locations of materials 1, 2, and 3 would be 3505, 3520, and 3535, respectively.)

The conductivity of each material is specified as

$$k, 0, 0, 0, 0, 0 \ .$$

Since k is entered as a fixed-point number, the decimal point must be indicated.

Following the last conductivity card is one BCD card stating the problem number (same as 1008 in table 1000) and location 5500.

Preceding the first conductivity card and after the location 5500 card is a card with TRA 2, 4.

Procedure

The procedure for running the CURE code for calculating GHT constants is as stated in ref 7, except that sense light 1 is used as an indicator to show when the constants have been calculated, and sense switch 5 is down. Sense light 1 will be off when the program starts; however, it will be turned on by the program. When the light is turned off by the code, the constants have been calculated and stored on magnetic-tape-unit No. 6; therefore at this point the machine is manually stopped and an end of file is written on magnetic-tape-unit No. 6. The list obtained from this tape unit will contain the conductances and volumes of all temperature points in the grid network. This tape is printed under program control.

Output

With sense switch 5 down, stopping the program manually with sense light 1 turned off gives the type of output shown in Table B-3. (The specific example is outlined below in example 2.) In terms of GHT significance, the values in the columns titled A, C, D, and E in Table B-3 are as follows:

A = conductance to left neighbor point ,

C = conductance to right neighbor point ,

D = conductance to bottom neighbor point ,

E = conductance to top neighbor point.

The values in the columns titled K_1, K_2, K_3, and K_4 are as follows:

K_1 = volume of top right quadrant ,

K_2 = volume of top left quadrant ,

K_3 = volume of bottom left quadrant ,

K_4 = volume of bottom right quadrant .

The sum of the K columns $\left(\sum_{i=1}^{4} K_i \right)$ is equal to the volume associated with the mesh point under consideration.

The columns headed X and Y give the coordinates of each point in the grid mesh. Negative values of X or Y indicate "flag points" and have no meaning as far as GHT is concerned.

Examples

Two examples are presented to illustrate the CURE code input and output data.

Example 1 considers the configuration shown in Fig. B-1, which represents a nozzle. The boundary conditions are specified on the figure. The CURE input for this problem is shown in Table B-4. Only the CURE code input data sheets are shown; the output sheets are quite lengthy.

Example 2 considers the two-dimensional configuration shown in Fig. B-2; the boundary conditions are specified on the figure. The constants for this problem (K's and V's) can readily be calculated by hand; however, the output for this example is relatively short and is given in Table B-3. The CURE input data sheets are shown in Table B-5.

[7] E. L. Wachspress, *Cure: A Generalized Two-Space-Dimension Multigroup Coding for the IBM 704*, KAPL-1724 (April 1957).

Table B-3. Output Form of CURE Code

CURE OCT.28,-1957
0 CORNER D E A F Z
1

X	Y	A	C	D	E	B	K1	K2	K3	K4
.00000	-1.00000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000
.50000	-1.00000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000
1.00000	-1.00000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000
2.00000	-1.00000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000
3.00000	-1.00000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000
-1.00000	-1.00000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000
X	Y	A	C	D	E	B	K1	K2	K3	K4
.00000	.00000	.0000	.0000	.0000	.0000	.5000	.0000	.0000	.0000	.0000
.50000	.00000	.0000	.0000	.0000	.0000	.5000	.0000	.0000	.0000	.0000
1.00000	.00000	.0000	.0000	.0000	.0000	.5000	.0000	.0000	.0000	.0000
2.00000	.00000	.0000	.0000	.0000	.0000	.5000	.0000	.0000	.0000	.0000
3.00000	.00000	.0000	.0000	.0000	.0000	.5000	.0000	.0000	.0000	.0000
-1.00000	.00000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000
X	Y	A	C	D	E	B	K1	K2	K3	K4
.00000	1.00000	.0000	.0000	.0000	.0000	.5000	.0000	.0000	.0000	.0000
.50000	1.00000	1.5000	1.5000	.5000	1.0000	.0000	.0625	.0625	.1250	.1250
1.00000	1.00000	1.5000	.7500	.7500	1.5000	.0000	.1250	.0625	.1250	.2500
2.00000	1.00000	.7500	.7500	1.0000	2.0000	.0000	.1250	.1250	.2500	.2500
3.00000	1.00000	.7500	-.0000	.5000	1.0000	.0000	.0000	.1250	.2500	.0000
-1.00000	1.00000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000
X	Y	A	C	D	F	B	K1	K2	K3	K4
.00000	1.50000	.0000	.0000	.0000	.0000	.5000	.0000	.0000	.0000	.0000
.50000	1.50000	1.0000	1.5000	1.0000	1.5000	.0000	.0625	.0625	.0625	.0625
1.00000	1.50000	1.5000	.7500	1.5000	3.0000	.0000	.1250	.0625	.0625	.1250
2.00000	1.50000	.7500	.7500	2.0000	4.0000	.0000	.1250	.1250	.1250	.1250
3.00000	1.50000	.7500	-.0000	1.0000	2.0000	.0000	.0000	.1250	.1250	.0000
-1.00000	1.50000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000
X	Y	A	C	D	E	B	K1	K2	K3	K4
.00000	2.00000	.0000	.0000	.0000	.0000	.5000	.0000	.0000	.0000	.0000
.50000	2.00000	1.0000	2.0000	1.5000	1.5000	.0000	.0625	.0625	.0625	.0625
1.00000	2.00000	.0000	.0000	.0000	.0000	.5000	.0000	.0000	.0000	.0000
2.00000	2.00000	.0000	.0000	.0000	.0000	.5000	.0000	.0000	.0000	.0000
3.00000	2.00000	.0000	.0000	.0000	.0000	.5000	.0000	.0000	.0000	.0000
-1.00000	2.00000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000
X	Y	A	C	D	E	B	K1	K2	K3	K4
.00000	2.50000	.0000	.0000	.0000	.0000	.5000	.0000	.0000	.0000	.0000
.50000	2.50000	1.2500	2.5000	1.5000	1.0000	.0000	.0938	.0938	.0625	.0625
1.00000	2.50000	.0000	.0000	.0000	.0000	.5000	.0000	.0000	.0000	.0000
-1.00000	2.50000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000
.00000	3.25000	.0000	.0000	.0000	.0000	.5000	.0000	.0000	.0000	.0000
.50000	3.25000	1.5000	3.0000	1.0000	1.0000	.0000	.0938	.0938	.0938	.0938
X	Y	A	C	D	E	B	K1	K2	K3	K4
1.00000	3.25000	.0000	.0000	.0000	.0000	.5000	.0000	.0000	.0000	.0000
-1.00000	3.25000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000
.00000	4.00000	.0000	.0000	.0000	.0000	.5000	.0000	.0000	.0000	.0000
.50000	4.00000	.7500	1.5000	1.0000	-.0000	.0000	.0000	.0000	.0938	.0938
1.00000	4.00000	.0000	.0000	.0000	.0000	.5000	.0000	.0000	.0000	.0000
-1.00000	4.00000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000

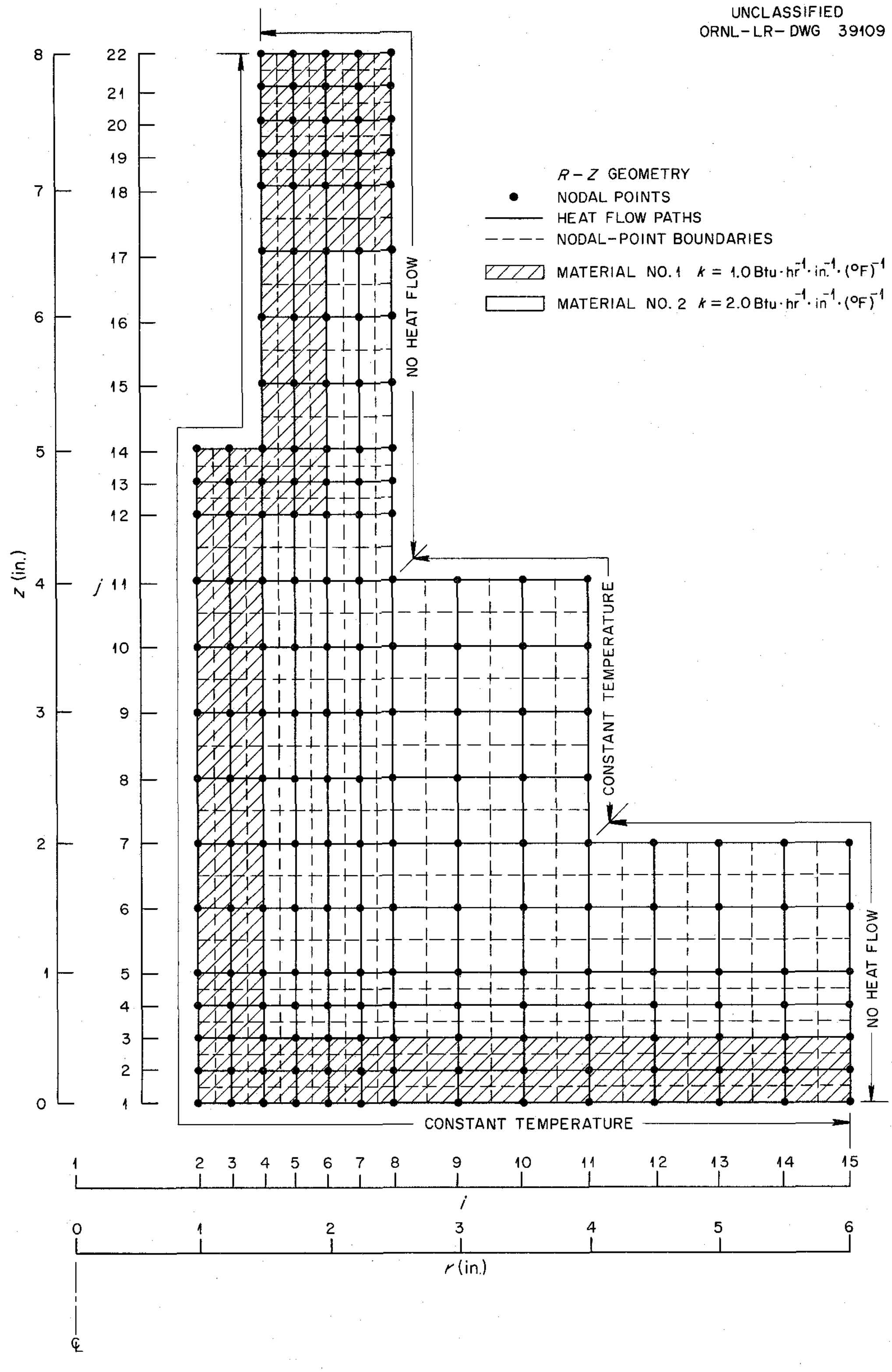

Fig. B-1. Nozzle Configuration Considered in Example 1 for CURE Code.

PROBLEM NOZZLE-CURE CODE EXAMPLE 1

CODER E. R. Volk | DATE 8 July 1958 | PAGE 1 OF 2

H (1)	LOCATION (2–6)	(7)	OP (8–10)	(11)	ADDRESS, TAG, DECREMENT (12–72)	COMMENTS	IDENTIFICATION (73–80)
	1000		DEC		15	Maximum value of i	1
	1001		DEC		22	Maximum value of j	2
	1006		DEC		7	Designation of machine memory	3
	1007		DEC		1		4
	1008		BCD		1 Nozzle	Problem number	5
	1010		DEC		1	Designation of geometry	6
	1011		DEC		1		7
	1021		DEC		1		8
	1024		DEC		644	Maximum allowable No. of mesh points	9
	2000		DEC		990,0,0,0		10
			DEC		2,1,62		11
			DEC		0,14,62		12
			DEC		4,0,62		13
			DEC		0,22,62		14
			DEC		8,0,41		15
			DEC		0,11,41	Boundary conditions	16
			DEC		11,0,62		17
			DEC		0,7,62		18
			DEC		15,0,41		19
			DEC		0,1,41		20
			DEC		2,0,62		21
			DEC		0,0,0,990		22

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Table B-4 (continued)

PROBLEM NOZZLE-CURE CODE EXAMPLE 1

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H	LOCATION	OP	ADDRESS, TAG, DECREMENT	COMMENTS	IDENTIFICATION
		DEC	993,0,0,0		23
		DEC	0,1,2,15,1		24
		DEC	0,3,4,15,2	Material regions	25
		DEC	0,12,4,6,1		26
		DEC	0,17,6,8,1		27
		DEC	0,0,0,993		28
		DEC	999	Sentinel	29
	3000	DEC	996,0,0,0		30
		DEC	1,2,1.0		31
		DEC	2,8,.25	Radial increments	32
		DEC	8,15,.50		33
		DEC	0,0,0,996		34
		DEC	997,0,0,0		35
		DEC	1,5,.25		36
		DEC	5,12,.50		37
		DEC	12,14,.25	Axial increments	38
		DEC	14,18,.50		39
		DEC	18,22,.25		40
		DEC	0,0,0,997		41
		TRA	2,4		42
	3505	DEC	1.0,0,0,0,0,0	Material properties	43
	3520	DEC	2.0,0,0,0,0,0		44
	5500	BCD	1 Nozzle	Problem number	45
		TRA	2,4		46

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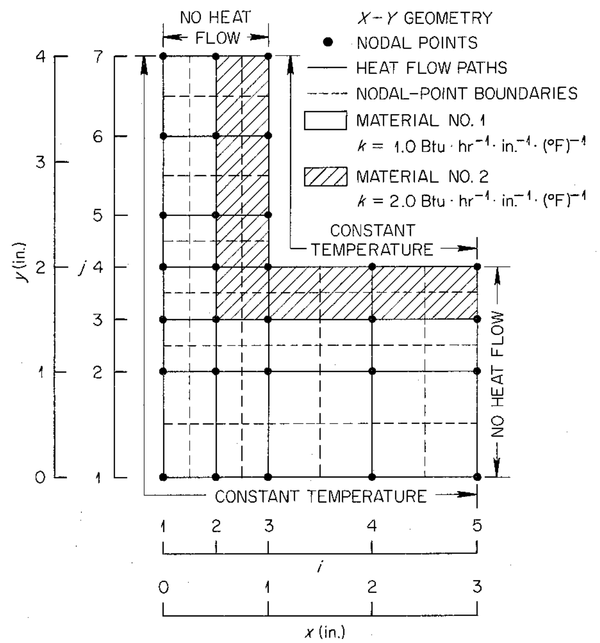

Fig. B-2. Corner Configuration Considered in Example 2 for CURE Code.

Table B-5. Share Symbolic Coding Form for CURE Code, Example 2

PROBLEM CORNER-CURE CODE EXAMPLE 2

CODER E. R. Volk | DATE 8 July 1958 | PAGE 1 OF 2

H (1)	LOCATION (2–6)	(7)	OP (8–10)	(11)	ADDRESS, TAG, DECREMENT (12–)	COMMENTS (–72)	IDENTIFICATION (73–80)
	1000		DEC		5	Maximum value of i	1
	1001		DEC		7	Maximum value of j	2
	1006		DEC		7	Designation of machine memory	3
	1007		DEC		1		4
	1008		BCD		1 Corner	Problem number	5
	1010		DEC		0	Designation of geometry	6
	1011		DEC		0		7
	1021		DEC		1		8
	1024		DEC		644	Maximum allowable No. of mesh points	9
	2000		DEC		990,0,0,0		10
			DEC		1,1,62		11
			DEC		0,7,62		12
			DEC		3,0,41		13
			DEC		0,4,62	Boundary conditions	14
			DEC		5,0,62		15
			DEC		0,1,41		16
			DEC		1,0,62		17
			DEC		0,0,0,990		18
			DEC		993,0,0,0		19
			DEC		0,1,1,5,1	Material regions	20
			DEC		0,3,2,5,2		21
			DEC		0,0,0,993		22
			DEC		999	Sentinel	23

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Table B-5 (continued)

PROBLEM	CORNER-CURE CODE EXAMPLE 2				
CODER	E. R. Volk	DATE	8 July 1958	PAGE 2	OF 2

H	LOCATION	OP	ADDRESS, TAG, DECREMENT	COMMENTS	IDENTI-FICATION
	3000	DEC	996,0,0,0		24
		DEC	1,3,.5	Horizontal increments	25
		DEC	3,5,1.		26
		DEC	0,0,0,996		27
		DEC	997,0,0,0		28
		DEC	1,2,1.		29
		DEC	2,5.5	Vertical increments	30
		DEC	5,7,.75		31
		DEC	0,0,0,997		32
		TRA	2,4		33
	3505	DEC	1.0,0,0,0,0,0	Material properties	34
	3520	DEC	2.0,0,0,0,0,0		35
	5500	BCD	1 Corner	Problem number	36
		TRA	2,4		37

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Appendix C

SAMPLE PROBLEM FOR GHT

The sample problem included in this report is pedagogical and therefore considers many variables in order to illustrate the various input and output forms of GHT. The geometry and boundary conditions are specified; illustrations are given of the temperature distribution which exists at a specific time under nonsteady-state conditions, as well as the distribution under steady-state conditions.

The geometrical configuration associated with the sample problem is shown in Fig. C-1; a unit depth was assumed in the z direction, and the material properties for material No. 1 were

$$k = 1.0 \text{ Btu}\cdot\text{hr}^{-1}\cdot\text{in.}^{-1}\cdot(^\circ\text{F})^{-1} \quad ,$$

$$\rho C_p = 0.05 \text{ Btu}\cdot\text{in.}^{-3}\cdot(^\circ\text{F})^{-1} \quad .$$

For material No. 2 the material properties were

$$k = 2.0 \text{ Btu}\cdot\text{hr}^{-1}\cdot\text{in.}^{-1}\cdot(^\circ\text{F})^{-1} \quad ,$$

$$\rho C_p = 0.05 \text{ Btu}\cdot\text{in.}^{-3}\cdot(^\circ\text{F})^{-1} \quad .$$

The time-independent part of the heat generation rate was assumed to be independent of position and to be equal to 20 $\text{Btu}\cdot\text{hr}^{-1}\cdot\text{in.}^{-3}$.

For the transient part of the problem the temperature at points 1, 2, and 3 (see Fig. C-1) was assumed to vary with time as shown in Fig. C-2. No time dependence was associated with the other points. The time-dependent portion of the heat generation rate was assumed to be independent of position and to vary with time as shown in Fig. C-3.

For the time-dependent portion, calculation of the time interval, $\Delta\tau$, which satisfies Eq. (12) is given in Table C-1. The value of $\Delta\tau$ was calculated for every point only for the purposes of illustration; normally it would have been checked only at obvious points such as points 9, 11, 13, and 14.

Most of the input constants were taken directly from the CURE code output for example 2 given

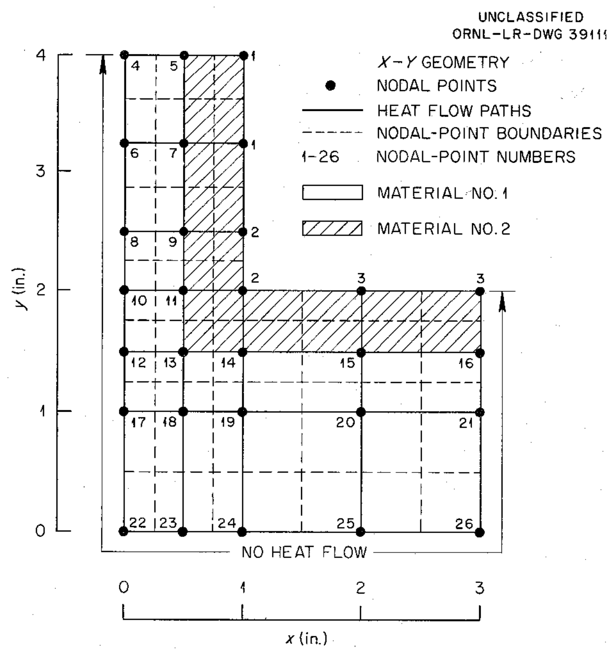

Fig. C-1. Configuration of Sample Problem for GHT.

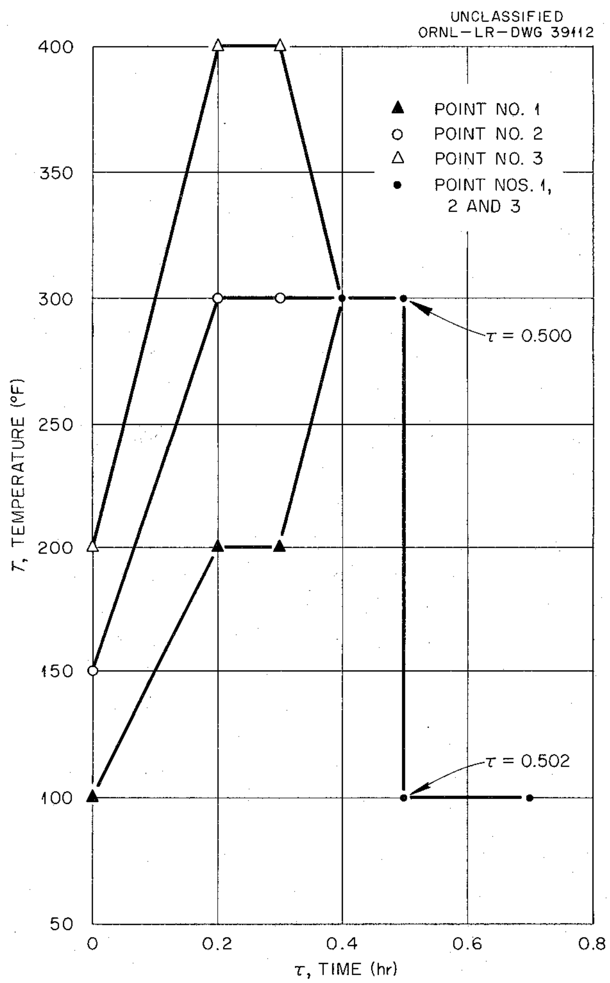

Fig. C-2. Temperature vs Time at Points 1, 2, and 3 in GHT Sample Problem.

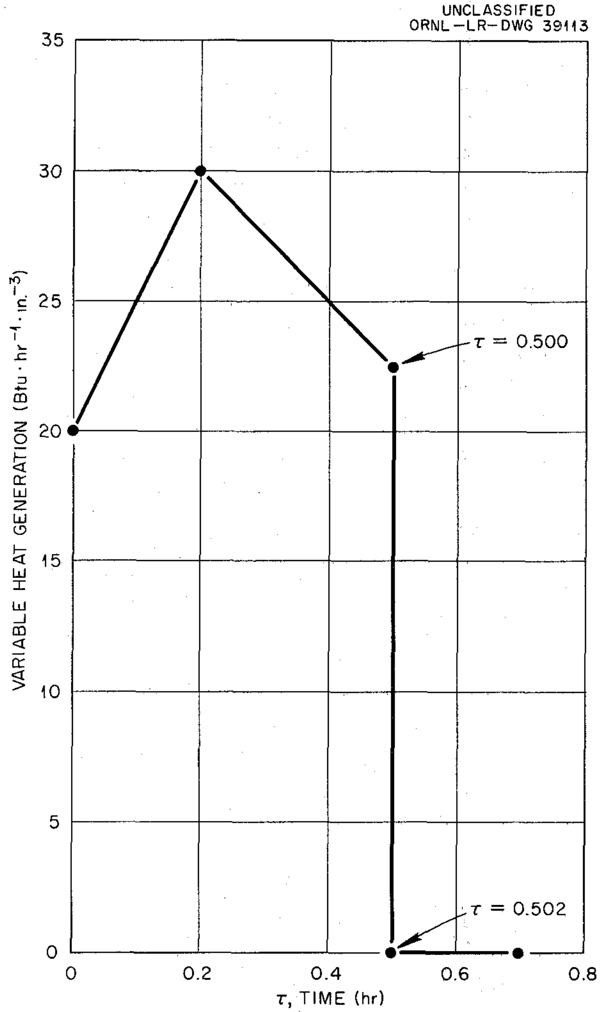

Fig. C-3. Time-Dependent Part of the Heat Generation Rate vs Time for GHT Sample Problem.

in Appendix B (example 2 had the same geometry as the problem here). However, some of the constants were calculated by hand, since the GHT sample problem does not have boundary conditions identical to those in example 2. (The CURE code would have calculated all the constants if the boundary conditions had corresponded.) Tables C-2 through C-9 show the input data sheets for this example.

As required by the input, the steady-state calculation was performed first, followed by the transient calculation. Table C-10 shows the on-line edit obtained. The first portion of Table C-10 shows how the temperatures converged to the steady-state values. Those lines giving the iteration number, point number, $T_1 - T_2$, and convergence would not have appeared if sense switch

Table C-1. Calculation of Transient-Time Criteria for GHT Sample Problem

Point No.	$\sum_M {}_JK_M$	C_J	$\Delta\tau = C_J/\sum_M {}_JK_M$
4	1.083	0.004688	0.00433
5	2.500	0.009380	0.00375
6	2.166	0.009375	0.00433
7	5.500	0.01876	0.00341
8	2.083	0.007813	0.00375
9	5.250	0.01563	0.00297
10	2.000	0.006250	0.00313
11	6.000	0.01250	0.00208*
12	2.000	0.006250	0.00313
13	5.000	0.01250	0.00250
14	6.750	0.01875	0.00277
15	7.500	0.02500	0.00333
16	3.750	0.01250	0.00333
17	2.250	0.009375	0.00417
18	4.500	0.01875	0.00417
19	4.500	0.02813	0.00625
20	4.500	0.03750	0.00833
21	2.250	0.01875	0.00833
22	1.250	0.00625	0.00500
23	2.500	0.01250	0.00500
24	2.250	0.01875	0.00833
25	2.000	0.0250	0.0125
26	1.000	0.01250	0.0125

*Minimum value ($\Delta\tau = 0.00200$).

1 had been up. Also, if sense switch 1 had been in the up position during the transient calculation, the time value would not have appeared (these time values are given in the middle of Table C-10). Leaving sense switch 1 in the down position slows the calculation; however, the down position is useful in conjunction with the use of sense switch 6 to accelerate the convergence rate of a steady-state problem.

The transient temperature distribution listed in Table C-10 is a result of placing sense switch 4 in the down position; this action permits results to be obtained for a time other than that requested by the output cycle on the problem control card.

Tables C-11 through C-13 are the results requested by the input cards; Table C-11 gives the steady-state results, while Tables C-12 and C-13 give the temperature distribution for the specified times. These tables were obtained by printing the contents of output tape 1 on an off-line tape-to-printer unit.

Table C-2. GHT Control-Card Input for Sample Problem

Problem Number 7777

CONTROL CARD

USE CUT RIGHT PINK STRIPE CARD

Page 1 Of 8

COLUMN NO. 1 5	6 11	12 17	18 23	± 25	± 27	± 29	30 33	34. ± 41	42. ± 49	50. ± 57	± 59	60 67	68 72	73 76	77 80
+ 26	+ 100	+ 10	+ 5	+ 0	+ 1	– 1	+ 100	+ 4 +	+ 002 +	+ 1 – 04	+ 1	+ 1 . 0	+ 7777		1

1- 5 Total Number of Points

6-11 Maximum Number of Iterations

12-17 Number of Iterations, Before Calculating β or Extrapolation Cycle

18-23 Extrapolation Cycle

24-27 Type of Problem

28-29 Type of Output

30-33 Output Cycle

34-41 Total Time

42-49 Time Increment

50-57 Convergence Criteria

58-59 β Indicator

60-67 β

68-72 Problem Number

73-76 Leave Blank

77-80 Card Number

Problem Number 7777

TEMPERATURE CARDS - T

USE SOLID YELLOW CARDS

Page 2 Of 8

POINT NUMBER (DO NOT PUNCH)	TEMPERATURES ± .2 … ± 10	± .12 … ± 20	± .22 … ± 30	± .32 … ± 40	± .42 … ± 50	± .52 … ± 60	± .62 … ± 70	LEAVE BLANK 71–76	CARD NUMBER 77–80
1	+100 +03	+150 +03	+200 +03	+100 +03	+100 +03	+100 +03	+100 +03		1
8	+100 +03	+100 +03	+100 +03	+100 +03	+100 +03	+100 +03	+100 +03		2
15	+100 +03	+100 +03	+100 +03	+100 +03	+100 +03	+100 +03	+100 +03		3
22	+100 +03	+100 +03	+100 +03	+100 +03	+100 +03				4

Table C-3. GHT Temperature Input for Sample Problem

Problem Number 7777

HEAT GENERATION CARDS - Q

USE SOLID GREEN CARDS

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POINT NUMBER (DO NOT PUNCH)	HEAT GENERATION ± .2 … ± 8	± .10 … ± 16	± .18 … ± 24	± .26 … ± 32	± .34 … ± 40	± .42 … ± 48	± .50 … ± 56	± .58 … ± 64	± .66 … ± 72	LEAVE BLANK 73–76	CARD NUMBER 77–80
1	0	0	0	+1875 +01	+3752 +01	+3750 +01	+7504 +01	+3125 +01	+6252 +01		1
10	+25 +01	+5 +01	+25 +01	+5 +01	+75 +01	+1 +02	+5 +01	+3750 +01	+75 +01		2
19	+1125 +02	+15 +02	+75 +01	+25 +01	+5 +01	+75 +01	+1 +02	+5 +01			3

Table C-4. GHT Heat Generation Input for Sample Problem

CAPACITANCE CARDS - C

Problem Number 7777

USE SOLID RED CARDS

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POINT NUMBER (DO NOT PUNCH)	CAPACITANCE COLUMN NO. + .2 ± 8	+ .10 ± 16	+ .18 ± 24	+ .26 ± 32	+ .34 ± 40	+ .42 ± 48	+ .50 ± 56	+ .58 ± 64	+ .66 ± 72	LEAVE BLANK 73 76	CARD NUMBER 77 80
1	0	0	0	+4688 -02	+9380 -02	+9375 -02	+1876 -01	+7813 -02	+1563 -01		1
10	+6250 -02	+1250 -01	+6250 -02	+1250 -01	+1875 -01	+25 -01	+1250 -01	+9375 -02	+1875 -01		2
19	+2813 -01	+3750 -01	+1875 -01	+6250 -02	+1250 -01	+1875 -01	+25 -01	+1250 -01			3

Table C-5. GHT Capacitance Input for Sample Problem

POINT DATA CARDS

Problem Number 7777

USE SOLID BLUE CARDS

Page 5 Of 8

POINT NUMBER (DO NOT PUNCH)	NO. OF A's (COLUMN NO. + 2)	NO. OF B's + 5	NO. OF M's + 8	NO. OF A's + 10	NO. OF B's + 13	NO. OF M's + 16	NO. OF A's + 18	NO. OF B's + 21	NO. OF M's + 24	NO. OF A's + 26	NO. OF B's + 29	NO. OF M's + 32	NO. OF A's + 34	NO. OF B's + 37	NO. OF M's + 40	NO. OF A's + 42	NO. OF B's + 45	NO. OF M's + 48	NO. OF A's + 50	NO. OF B's + 53	NO. OF M's + 56	NO. OF A's + 58	NO. OF B's + 61	NO. OF M's + 64	NO. OF A's + 66	NO. OF B's + 69	NO. OF M's + 72	LEAVE BLANK 73	CARD NUMBER 77 80
1	6			4			6				4	2		4	3		4	3		4	4		4	3		4	4		1
10		4	3		4	4		4	3		4	4		4	4		4	4		4	3		4	3		4	4		2
19		4	4		4	4		4	3		4	2		4	3		4	3		4	3		4	2					3

Table C-6. GHT Point Data Input for Sample Problem

Problem Number 7777

CONDUCTANCE CARDS

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USE SOLID BROWN CARDS

POINT NUMBER	NEIGHBOR POINT NO.	CONDUCTANCE K	NEIGHBOR POINT NO.	CONDUCTANCE K	NEIGHBOR POINT NO.	CONDUCTANCE K	NEIGHBOR POINT NO.	CONDUCTANCE K	NEIGHBOR POINT NO.	CONDUCTANCE K	NEIGHBOR POINT NO.	CONDUCTANCE K	LEAVE BLANK	CARD NUMBER
DO NOT PUNCH	COLUMN NO. + 2 4	+ .6 ± 12	+ 14 16	+ .18 ± 24	+ 26 28	+ .30 ± 36	+ 38 40	+ .42 ± 48	+ 50 52	+ .54 ± 60	+ 62 64	+ .66 ± 72	73 76	77 80
4	5	0.75	6	0.333	7	1.0								1
5	4	0.75	1	1.5	4	0.333								2
6	7	1.5	8	0.333	9	1.0								3
7	6	1.5	1	3.0	6	0.333	5	+100 +01						4
8	9	1.25	10	0.5	11	1.5								5
9	8	1.25	2	2.5	8	0.5	7	+1 +01						6
10	11	1.0	12	0.5	13	1.5								7
11	10	1.0	2	2.0	10	0.5	9	+15 +01						8
12	13	1.0	17	0.5	18	1.0								9
13	12	1.0	14	1.5	19	1.5	11	+15 +01						10
14	13	1.5	15	0.75	20	2.0	2	+3 +01						11
15	14	0.75	16	0.75	3	2.0	3	+4 +01						12
16	15	0.75	21	1.0	12	0.5								13
17	18	1.5	22	0.25	23	0.5								14
18	17	1.5	19	1.5	24	0.75	13	+1 +01						15
19	18	1.5	20	0.75	25	1.0	14	+15 +01						16
20	19	0.75	21	0.75	16	1.0	15	+2 +01						17
21	20	0.75	26	0.5										18
22	23	1.0	17	0.25	18	0.5								19
23	22	1.0	24	1.0	19	0.75								20
24	23	1.0	25	0.5	20	1.0								21
25	24	0.5	26	0.5										22
26	25	0.5	21	0.5										23

Table C-7. GHT Conductance Input for Sample Problem

Problem Number 7777

VARIABLE TEMPERATURE AND/OR HEAT GENERATION CARDS

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USE SOLID ORANGE CARDS

POINT NUMBER	A OR B	W OR S	A OR B	W OR S	A OR B	W OR S	A OR B	W OR S	LEAVE BLANK	CARD NUMBER
DO NOT PUNCH	COLUMN NO. ± .2 ± 8	± .10 ± 16	± .18 ± 24	± .26 ± 32	± .34 ± 40	± .42 ± 48	± .50 ± 56	± .58 ± 64	65 76	77 80
1	500.	.2		.3	+1 +4	.4	0	.5		1
1	-1 +06	.502		.7						2
2	750.	.2		.5	-1 +6	.502	0	.7		3
3	1 +04	.2		.3	-1 +4	.4	0	.5		4
3	-1 +6	.502		.7						5
4	4.688	.2	-2.344	.5	-1055.	.502	0	.7		6
5	9.38	.2	-4.69	.5	-2111.	.502	0	.7		7
6	9.375	.2	-4.688	.5	-2109.	.502	0	.7		8
7	18.76	.2	-9.38	.5	-4221.	.502	0	.7		9
8	7.813	.2	-3.906	.5	-1758.	.502	0	.7		10
9	15.63	.2	-7.815	.5	-3517.	.502	0	.7		11
10	6.25	.2	-3.125	.5	-1406.	.502	0	.7		12
11	12.5	.2	-6.25	.5	-2813.	.505	0	.7		13
12	6.25	.2	-3.125	.5	-1406.	.502	0	.7		14
13	12.5	.2	-6.25	.5	-2813.	.502	0	.7		15
14	18.75	.2	-9.375	.5	-4219.	.502	0	.7		16
15	25.	.2	-12.5	.5	-5625.	.502	0	.7		17
16	12.5	.2	-6.25	.5	-2813.	.502	0	.7		18
17	9.375	.2	-4.688	.5	-2109.	.502	0	.7		19
18	18.75	.2	-9.375	.5	-4219.	.502	0	.7		20
19	28.13	.2	-14.06	.5	-6328.	.502	0	.7		21
20	37.5	.2	-18.75	.5	-8438.	.502	0	.7		22
21	18.75	.2	-9.375	.5	-4219.	.502	0	.7		23
22	6.25	.2	-3.125	.5	-1406.	.502	0	.7		24
23	12.5	.2	-6.25	.5	-2813.	.502	0	.7		25
24	18.75	.2	-9.375	.5	-4219.	.502	0	.7		26
25	25.	.2	-12.5	.5	-5625.	.502	0	.7		27
26	12.5	.2	-6.25	.5	-2813.	.502	0	.7		28

Table C-8. GHT Variable Temperature and/or Heat Generation Input for Sample Problem

Problem Number 7777

MAP OUTPUT CARDS

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USE GREEN STRIPE CARDS

ROW NUMBER (DO NOT PUNCH)	POINT NUMBERS — COLUMN NO. + 2 … 6	+ 8 … 12	+ 14 … 18	+ 20 … 24	+ 26 … 30	+ 32 … 36	+ 38 … 42	+ 44 … 48	+ 50 … 54	+ 56 … 60	+ 62 … 66	+ 68 … 72	LEAVE BLANK 73 … 76	CARD NUMBER 77 … 80
	+ 0 1													1
1				4	5	1								2
2				6	7	1								3
3				8	9	2								4
4				1 0	1 1	2	3	3						5
5				1 2	1 3	1 4	1 5	1 6						6
6				1 7	1 8	1 9	2 0	2 1						7
7				2 2	2 3	2 4	2 5	2 6						8
8														
:														
:														
:														
:														
5 0														

Table C-9. GHT Map Output Input for Sample Problem

Table C-10. GHT On-Line Edit for Sample Problem

```
GEN. HEAT TRA. CODE   CASE NO.  7777
 BEGIN STEADY STATE CALCULATION


 ITERATION NO. =     1    POINT NO. =   16    T1-T2 =    66.10353088    CONV. =      0.39796584
 ITERATION NO. =     2    POINT NO. =   25    T1-T2 =    23.41220951    CONV. =      0.16025847
 ITERATION NO. =     3    POINT NO. =   25    T1-T2 =    16.18619728    CONV. =      0.09974455
 ITERATION NO. =     4    POINT NO. =   24    T1-T2 =    11.72174835    CONV. =      0.08493568
 ITERATION NO. =     5    POINT NO. =   22    T1-T2 =    10.76799202    CONV. =      0.08012342
 ITERATION NO. =     6    POINT NO. =   22    T1-T2 =    10.23558044    CONV. =      0.07077170
 ITERATION NO. =     7    POINT NO. =   22    T1-T2 =     9.12749672    CONV. =      0.05936366
 ITERATION NO. =     8    POINT NO. =   22    T1-T2 =     7.88126373    CONV. =      0.04875907
 ITERATION NO. =     9    POINT NO. =   22    T1-T2 =     6.68850708    CONV. =      0.03973558
 ITERATION NO. =    10    POINT NO. =   22    T1-T2 =     5.62172318    CONV. =      0.03231858
 BETA =   1.42307904
 ITERATION NO. =    11    POINT NO. =   24    T1-T2 =     8.47836876    CONV. =      0.04359420
 ITERATION NO. =    12    POINT NO. =   22    T1-T2 =     7.77502823    CONV. =      0.04113514
 ITERATION NO. =    13    POINT NO. =   22    T1-T2 =     6.11061096    CONV. =      0.03131680
 ITERATION NO. =    14    POINT NO. =   17    T1-T2 =     3.26241493    CONV. =      0.01762106
 ITERATION NO. =    15    POINT NO. =   17    T1-T2 =     1.86952591    CONV. =      0.00999680
 ITERATION NO. =    16    POINT NO. =   17    T1-T2 =     1.08417320    CONV. =      0.00576392
 ITERATION NO. =    17    POINT NO. =   12    T1-T2 =     0.54027748    CONV. =      0.00309961
 ITERATION NO. =    18    POINT NO. =   12    T1-T2 =     0.21354485    CONV. =      0.00130318
 ITERATION NO. =    19    POINT NO. =   12    T1-T2 =     0.09942818    CONV. =      0.00056941
 ITERATION NO. =    20    POINT NO. =   12    T1-T2 =     0.04244614    CONV. =      0.00024302
```

Table C-10 (continued)

```
ITERATION NO. =    21    POINT NO. =   17    T1-T2 =     0.01896477    CONV. =     0.00010854
         EXTRAPOLATION      ITERATION NO. =    21
ITERATION NO. =    22    POINT NO. =    8    T1-T2 =    -0.01135826    CONV. =     0.00007707
ITERATION NO. =    23    POINT NO. =   10    T1-T2 =    -0.00348282    CONV. =     0.00002968
ITERATION NO. =    24    POINT NO. =    6    T1-T2 =    -0.00243282    CONV. =     0.00002004
ITERATION NO. =    25    POINT NO. =    4    T1-T2 =    -0.00367546    CONV. =     0.00003208
ITERATION NO. =    26    POINT NO. =    4    T1-T2 =     0.00162697    CONV. =     0.00001421
END OF STEADY STATE CALCULATION
BEGIN TRANSIENT CALCULATION


TIME =  2.0000E-03
TIME =  1.6000E-02
TIME =  1.8000E-02
TIME =  2.0000E-02
TIME =  2.2000E-02
TIME =  2.4000E-02
TIME =  2.6000E-02
TIME =  5.4000E-02
TIME =  5.6000E-02
TIME =  5.8000E-02
TIME =  6.0000E-02
TIME =  6.2000E-02
TIME =  6.4000E-02
TIME =  6.6000E-02
```

Table C-10 (continued)

TRANSIENT TEMP. DISTR.   TIME = 1.6400E-01

1.820E 02	2.730E 02	3.640E 02	1.959E 02	1.909E 02	2.069E 02	2.003E 02	2.483E 02	2.545E 02	2.625E 02
2.665E 02	2.708E 02	2.741E 02	2.830E 02	3.408E 02	3.480E 02	2.753E 02	2.780E 02	2.858E 02	3.182E 02
3.267E 02	2.772E 02	2.791E 02	2.847E 02	3.040E 02	3.111E 02				

TIME = 3.2000E-01

TIME = 3.2200E-01

TIME = 3.2400E-01

TIME = 3.2600E-01

TIME = 3.2800E-01

TIME = 3.3000E-01

TIME = 3.3200E-01

TIME = 3.3400E-01

TIME = 3.3600E-01

TIME = 3.3800E-01

TIME = 6.3400E-01

TIME = 6.3600E-01

END OF TRANSIENT CALCULATION

END OF CALCULATION, ANS ON TAPE 1

Table C-11. GHT Output for Sample Problem; Steady-State Results

STEADY STATE TEMP. DIST. CASE NO. 7777 NO. OF ITERATIONS = 27 CONV. = 0.00000180 SET 1 PAGE 1

0.	0.	0.	114.6	109.0	100.0	0.	0.	0.	0.	0.	0.
0.	0.	0.	121.4	114.6	100.0	0.	0.	0.	0.	0.	0.
0.	0.	0.	147.4	146.6	150.0	0.	0.	0.	0.	0.	0.
0.	0.	0.	160.4	157.3	150.0	200.0	200.0	0.	0.	0.	0.
0.	0.	0.	174.7	172.2	170.8	200.9	204.7	0.	0.	0.	0.
0.	0.	0.	189.0	189.1	191.2	207.5	211.9	0.	0.	0.	0.
0.	0.	0.	201.7	202.4	204.7	214.4	218.2	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.

Table C-12. GHT Transient Output at 0.2 sec for Sample Problem

TRANSIENT TEMP. DISTRIB. CASE NO. 7777 TIME = 2.0000E-01 SET 3 PAGE 1

0.	0.	0.	215.9	210.2	200.0	0.	0.	0.	0.	0.	0.
0.	0.	0.	228.0	220.5	200.0	0.	0.	0.	0.	0.	0.
0.	0.	0.	273.7	280.2	300.0	0.	0.	0.	0.	0.	0.
0.	0.	0.	289.6	293.6	300.0	400.0	400.0	0.	0.	0.	0.
0.	0.	0.	299.2	302.5	311.9	375.4	383.4	0.	0.	0.	0.
0.	0.	0.	304.7	307.5	316.1	351.7	361.2	0.	0.	0.	0.
0.	0.	0.	307.0	309.2	315.4	336.8	344.6	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.

Table C-13. GHT Transient Output at 0.4 sec for Sample Problem

TRANSIENT TEMP. DISTRIB. CASE NO. 7777 TIME = 4.0000E-01 SET 5 PAGE 1

0.	0.	0.	297.1	298.1	300.0	0.	0.	0.	0.	0.	0.
0.	0.	0.	299.7	299.6	300.0	0.	0.	0.	0.	0.	0.
0.	0.	0.	308.4	305.4	300.0	0.	0.	0.	0.	0.	0.
0.	0.	0.	317.9	312.3	300.0	300.0	300.0	0.	0.	0.	0.
0.	0.	0.	333.0	328.2	321.6	323.4	324.4	0.	0.	0.	0.
0.	0.	0.	350.8	349.9	349.2	354.2	356.6	0.	0.	0.	0.
0.	0.	0.	368.5	368.8	370.1	376.7	379.8	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.

Appendix D

NOMENCLATURE

Symbol	Description	Suggested Units
A_i	Rate of temperature change with respect to time	°F/hr
A_c	Cross-sectional area perpendicular to heat flow	in.^{2}
B_i	Rate of heat generation change with respect to time	Btu/hr^2
C	Thermal capacitance ($\rho C_p V$)	Btu/°F
C_p	Specific heat	Btu·lb^{-1}·(°F)$^{-1}$
C_r	Contact coefficient	Btu·hr^{-1}·in.$^{-2}$·(°F)$^{-1}$
h	Film coefficient	Btu·hr^{-1}·in.$^{-2}$·(°F)$^{-1}$
J	Any nodal point	
K^*	Convergence factor	
K	Thermal conductance	Btu·hr^{-1}·(°F)$^{-1}$
k	Thermal conductivity	Btu·hr^{-1}·in.$^{-1}$·(°F)$^{-1}$
M	Number of neighbor points affecting point J	
m	Convergence rate	°F/iteration
n	Iteration number	
Q	Heat generation	Btu/hr
q	Heat generation per unit volume	Btu·hr^{-1}·in.$^{-3}$
S_i	Maximum time over which A_i is applicable	hr
T	Temperature	°F
V	Volume	in.^{3}
W_i	Maximum time over which B_i is applicable	hr
Δx	Length of heat flow path	in.
β	Extrapolated Liebmann coefficient ($1 \leqq \beta < 2$)	
ρ	Density	lb/in.^{3}
τ	Time	hr
$\Delta\tau$	Time increment	hr

Subscripts

b	Boundary temperature point	
J	Any nodal point	
M	Number of neighbor points affecting point J	
i	A neighbor point affecting point J	

Superscript

n	Iteration number (an iteration is defined as a complete recalculation of all the nodal-point temperatures)	

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