464
11/12/82 T.S.

MASTER

**THEORETICAL EVALUATION OF THERMAL IMAGING
FOR DETECTION OF EROSION WEAR OF
INTERNALLY REFRACTORY-LINED TRANSFER LINES**

by

**C. K. Hsieh, W. A. Ellingson,
and K. C. Su**

ARGONNE NATIONAL LABORATORY, ARGONNE, ILLINOIS

**Prepared for the U. S. DEPARTMENT OF ENERGY
under Contract W-31-109-Eng-38**

Argonne National Laboratory is operated by Argonne National Laboratory for the U. S. Department of Energy under Contract W-31-109-Eng-38.

Distribution Categories:
Coal Conversion and Utilization:
Coal Gasification (UC-90c)
Direct Combustion of Coal (UC-90e)
Materials and Components (UC-90h)

ANL-78-82

ARGONNE NATIONAL LABORATORY
9700 South Cass Avenue
Argonne, Illinois 60439

THEORETICAL EVALUATION OF THERMAL IMAGING
FOR DETECTION OF EROSION WEAR OF
INTERNALLY REFRACTORY-LINED TRANSFER LINES

by

C. K. Hsieh,* W. A. Ellingson,
and K. C. Su**

Materials Science Division

May 1980

DISCLAIMER

This book was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

*Department of Mechanical Engineering, University of Florida, Gainesville
**Bell Telephone Laboratories, Member of Technical Staff

21A

TABLE OF CONTENTS

	<u>Page</u>
ABSTRACT	9
I. INTRODUCTION	9
II. BACKGROUND	11
A. Parameters Related to Infrared Scanning Instrument	11
B. Parameters Related to Transmission Path between Scanner and Object.	12
C. Parameters Related to Test Object	12
III. GENERAL STATEMENT OF PROBLEM	13
A. Scope of Project.	13
B. Mathematical Formulation.	13
C. Justification for Boundary Conditions Imposed.	15
IV. DEVELOPMENT OF BASIC HEAT-TRANSFER MODELS	18
A. Finite-difference Formulation	18
B. Development of Basic Two-dimensional Model.	20
C. Development of Basic Three-dimensional Model	22
D. Modeling of Thermal Contact Resistance	23
E. Modeling of Surface-emissivity Effects	25
V. TEST OF COMPUTER PROGRAMS USING LIMITING CASES.	31
VI. RESULTS AND DISCUSSION	34
A. Prediction of Surface Temperatures for a Two-dimensional Model.	34
B. Prediction of Surface Temperatures for a Two-dimensional Model Fitted with a Telltale Rib	37
C. Prediction of Surface Temperatures for a Three-dimensional Model.	38
D. Prediction of Surface Temperatures for a Three-dimensional Model with a Dual-component Wall Lining.	48

TABLE OF CONTENTS

	<u>Page</u>
E. Prediction of Surface Temperatures for a Three-dimensional Model with Contact Resistances	51
F. Study of Distortions of Infrared Images	53
VII. CONCLUSIONS AND RECOMMENDATIONS	57
APPENDIXES	
A. Computer Program for a Two-dimensional System	58
B. Computer Program for a Three-dimensional System	64
C. Computer Program for Evaluating Emissivity Effects	80
D. Derivation of Equations for Estimating Limiting Temperatures.	83
E. Computer Program for a Two-dimensional System Fitted with a Telltale Rib.	84
F. Computer Program for a Three-dimensional System with a Double-layered Refractory Lining	89
G. Computer Program for a Three-dimensional System with Interfacial Contact Resistance.	102
REFERENCES.	125

LIST OF FIGURES

<u>No.</u>	<u>Title</u>	<u>Page</u>
1.	Sectional View of Refractory-lined Transfer Line Used for Analytical Modeling	14
2.	Cylindrical Coordinates Used in Formulation of Mathematical Model	14
3.	Evaluation of Convective Contribution for $\epsilon = 0.2$, $T_{\infty} = 50^{\circ}\text{F}$ (10°C).	16
4.	Evaluation of Convective Contribution for $\epsilon = 0.2$, $T_{\infty} = 80^{\circ}\text{F}$ (26.6°C)	17
5.	Evaluation of Convective Contribution for $\epsilon = 0.8$, $T_{\infty} = 80^{\circ}\text{F}$ (26.6°C)	17
6.	Volume Element in Cylindrical Coordinates	19
7.	Schematic Diagram Showing Locations of Nine Classes of Nodes Used in Difference Formulation	21
8.	Schematic Diagram Showing Notation Used to Relate Polar (θ), Emission (α), and View (β) Angles.	26
9.	Polar- to View-angle Conversion Chart	27
10.	Polar- to Emission-angle Conversion Chart	27
11.	Emission- to View-angle Conversion Chart	27
12.	Directional Emissivity Curve for Metal Surface	29
13.	Directional Emissivity Curve for Nonmetal Surface	29
14.	Emissivity Correction Curve for Data in Figs. 9 and 12	29
15.	Emissivity Correction Curve for Data in Figs. 9 and 13	29
16.	Comparison between Correlated Eq. 46 and Test Data	36
17.	A Two-dimensional System Modified by Installation of a Telltale Rib	37
18.	A Three-dimensional Surface-temperature Plot Using Data in Table VII	40
19.	A Three-dimensional Plot of the Cavity Configuration Reconstructed from the Temperature Data in Fig. 18	40
20.	A Surface Isotherm Map for Data in Table VII.	40
21.	Plot of Areas Enclosed inside Isotherm Loops (Table VIII) vs Temperature.	41
22.	Integrated Energy Equivalents from Table VIII vs Temperature	41
23.	Effect of Cavity Depth on Temperature	43
24.	Effect of Cavity Width on Temperature	44

LIST OF FIGURES

<u>No.</u>	<u>Title</u>	<u>Page</u>
25.	Feature Curves for Cases in Fig. 23	45
26.	Feature Curves for Cases in Fig. 24	46
27.	Chart for Predicting Cavity Configurations	47
28.	Schematic Diagram Showing Construction of a Transfer Line with Double-layered Refractory Lining	48
29.	Feature Data for Case in Table X	49
30.	Feature Data for Case in Table XI	50
31.	Comparison of Three-dimensional Surface-temperature Plots Obtained with Indicated Values of Uniform Interfacial Contact Resistance	52
32.	Comparison of Three-dimensional Surface-temperature Plots Obtained with Various Nonuniform Interfacial Contact Resistances	54
33.	Three-dimensional Plots of Variable Interfacial Resistances Used to Generate Temperature Plots Presented in Fig. 32	55
34.	Distortion of Infrared Images	56
A.1.	Computer Program for Evaluating Surface Temperature in a Two-dimensional System	59
A.2.	Schematic Diagram Showing Nodal Locations in a Two- dimensional System	62
B.1.	Computer Program for Evaluating Surface Temperature in a Three-dimensional System	65
B.2.	Schematic Diagram Showing Nodal Locations in the Axial Direc- tion in a Three-dimensional System	76
C.1.	Computer Program for Correction of Emissivity Effects	81
E.1.	Computer Program for Evaluating Surface Temperature in a Modified Two-dimensional System Containing a "Telltale Rib"	85
F.1.	Computer Program for Evaluating Surface Temperature in a Three-dimensional System Constructed with a Double-layered Refractory Lining	90
F.2.	Schematic Diagram Showing Nodal Locations in Radial Direction in a Modified Three-dimensional System	101
G.1.	Computer Program for Evaluating Surface Temperature in a Three-dimensional System with Constant Contact Resistance	103
G.2.	Computer Program for Evaluating Surface Temperature in a Three-dimensional System with Variable Contact Resistance	114

LIST OF TABLES

<u>No.</u>	<u>Title</u>	<u>Page</u>
I.	Expressions Used to Derive Nodal Equations by Means of Physical Formulation	20
II.	Comparison between Numerical and Analytical Data	32
III.	Test Conditions for Studies of Two-dimensional Model	34
IV.	Computer Data for a Sample Two-dimensional System	35
V.	Computer Data for a Two-dimensional System Fitted with a Telltale Rib.	37
VI.	Test Conditions for Studies of Three-dimensional Model	38
VII.	Sample Output of Surface-temperature Distribution for Study of a Three-dimensional Model	39
VIII.	Features Defined by Data in Table VII	39
IX.	Computer Data Used for Prediction of Cavity Configuration	47
X.	Surface-temperature Data for System Shown in Fig. 28 with a 0.5-in. (12.7-mm)-deep Cavity	48
XI.	Surface-temperature Data for System Shown in Fig. 28 with a 1.5-in. (38.1-mm)-deep Cavity	51
XII.	Test Conditions for Data Presented in Fig. 31	53
XIII.	Test Conditions for Data Presented in Fig. 32	56
A.1.	Definitions of Input Variables for Program in Fig. A.1	62
B.1.	Definitions of Additional Input Variables for Program in Fig. B.1	76

THEORETICAL EVALUATION OF THERMAL IMAGING FOR DETECTION OF EROSIVE WEAR OF INTERNALLY REFRACTORY-LINED TRANSFER LINES

by

C. K. Hsieh, W. A. Ellingson,
and K. C. Su

ABSTRACT

Infrared scanning has potential use in detecting erosive wear (thickness change) of the refractory surface of large-diameter steel pipes internally lined with refractory concrete, which are typical of those used in coal-conversion processes. An analytical study was conducted to determine the viability of this method. Heat-transfer models were developed to predict surface-temperature distributions on the outer metal surface for various erosive-wear conditions on the inner surface, assuming uniform inner-surface temperature. Variables investigated included thermal conductivity of the refractory concrete, thermal contact resistance between the steel shell and the refractory, outer-surface convective coefficient, outer-surface radiative properties, and refractory-lining thickness and composition.

The study used two- and three-dimensional heat-transfer models and various well-defined rectangular cavities on the inner surface. Temperature resolution, and thus calculation of cavity sizes from surface-temperature profiles, is better when the convective coefficient is small and the interfacial contact resistance is uniformly low. The presence of dual refractory-concrete liners using a layer of insulating concrete between the hot-face lining and the steel shell, together with thick steel ($t > 25$ mm), tends to smear temperature patterns and reduce the temperature gradient so that calculation of cavity shapes becomes impractical.

I. INTRODUCTION

One of the many tasks in the development of the nation's coal-conversion program is to improve the reliability of plant operation through the use of non-destructive-evaluation (NDE) methods. NDE methods will be increasingly important for characterizing material performance in situ as second-generation coal-conversion processes push materials of construction close to their operating limits. One area of particular concern in coal-conversion

processes is the need to transfer highly erosive media (e.g., coal, ash, and char) under elevated temperatures ($T \approx 500-1000^\circ\text{C}$) and pressures [$p \approx 60-70$ atm ($0.6-0.7$ Mpa)]. Under these conditions, solid-particle impact erosion (which causes locally thin walls) becomes a serious material-degradation problem. This is particularly true in transfer lines and in regions in which the erosive media flow must change direction. Continuous monitoring of material conditions in critical areas is important to ensure long-term safe operation of coal-conversion processes and to prevent unnecessary plant shutdowns.

Several methods are being developed to detect potential material-failure conditions. Ultrasonic techniques^{1,2} can be used to detect erosive wear of metallic transfer lines. Gamma-radiography methods^{3,4} promise to be useful in detecting erosive wear and refractory degradation in refractory-lined transfer lines. However, the strong radiation sources ($\sim 3.7 \times 10^{12}$ Bq) required for gamma radiography are potentially hazardous to human beings. Furthermore, gamma-radiography methods require experienced and skilled technicians to produce high-quality images. The infrared scanning technique (thermography) is fast and inexpensive, and yields full-field images. With proper development, this technique could be made part of a routine inspection operation and thus enhance plant safety.

The use of thermography in the inspection of industrial plants has received much attention in recent years. Because they can measure the temperature of a body without making physical contact with it, thermographic devices permit a remote sensing capability that is lacking with most other nondestructive testing methods. Equipped with a mechanical scanner, a commercially available state-of-the-art infrared camera can scan a large field of view and present real-time infrared images of scanned objects in a few tenths of milliseconds. The method is thus more powerful than most other nondestructive methods, which rely heavily on sophisticated instrumentation and are handicapped because of their limitation to localized inspections. These advantages have placed infrared scanning in a favorable position for use in plant inspections, as evidenced by the various applications reported in the literature. Thermography techniques have been used to monitor the condition of refractory linings in blast furnaces, stoves, furnace offtakes, and hot-blast mains in the steel industry.⁵ In power plants, thermographic techniques have been applied to check boiler furnaces and stack walls.⁶ In the utility industries, thermographic techniques are easily implemented to locate hot spots in power transmission lines.⁷⁻¹⁰ Probably most important of all is the application of thermography in chemical-processing-plant reaction vessels and material transfer lines, which must be constantly monitored as part of routine plant operation to locate component malfunctions.⁷⁻¹⁰

II. BACKGROUND

The capabilities of thermographic techniques in nondestructive testing have been widely recognized. However, proper data-analysis methods have often been overlooked. The data collected by an infrared scanning system is a function of many parameters, which can be grouped into three categories:

1. Parameters related to the infrared scanning instrument.
2. Parameters related to the transmission path between the scanner and the object.
3. Parameters related to the test object.

These parameters are discussed separately in the following three sections.

A. Parameters Related to Infrared Scanning Instrument

The infrared cameras presently available from commercial sources are equipped with mechanical scanners. The spatial resolution of the temperature gradient that can be detected is a function of the distance between the camera and the object. A larger camera-to-object distance permits a broader field of observation, but at a lower temperature (spatial) resolution.

Infrared scanning cameras differ from other temperature sensors in the method of data presentation. The infrared camera consists of a scanning camera and an electronic display unit. The scanning optics are synchronized with the oscilloscope in the electronic display so that each point in the optical field of view is transformed into a corresponding point on the oscilloscope screen; the intensity of the modulated beam in the oscilloscope tube is a function of the infrared radiation received. The data output from the infrared camera is thus presented in a two-dimensional array, with the light intensity at each point corresponding to the input energy levels. The oscilloscope screen plays much the same role as a conventional TV screen. In its normal black-and-white mode of operation, bright spots represent high temperatures and dark spots represent lower temperatures. This method of data presentation causes a problem that is not experienced in more conventional analog or digital data displays. The problem arises when the temperature selectivity and picture black-level controls on the camera* are not properly adjusted to cover the full range of the input intensities. The result is usually a saturation of the picture gray level. Unfortunately, the human eye is only moderately able to differentiate various shades of gray and, as such, this saturation (brightness) phenomenon could evade detection in operation.

Note that a change of the temperature-sensitivity setting to a larger temperature span could resolve the saturation problem. However, a large temperature range also reduces the temperature resolution of the system.

*These controls, or controls with similar functions, can be found on nearly all commercial infrared cameras.

The best way to alleviate this problem appears to be the use of a second oscilloscope to present the analog data along with the infrared images. The saturation problem can then be detected and corrected in the operation.

B. Parameters Related to Transmission Path between Scanner and Object

Since the infrared camera is sensing the radiation emitted from a distant object, the net radiation received by the camera is a function of the ambient conditions between the object and the detector. Among other factors, atmospheric attenuation affects the energy detected. The water vapor and carbon dioxide in the atmosphere have absorption bands located at $\lambda = 1.9, 2.7, 4.3,$ and $6 \mu\text{m}$, which fall within the sensitivity range of most commercial infrared cameras using indium-antimony (InSb) detectors. The absorption is a function of the partial pressure of water vapor, the total pressure, and the dry-bulb temperature of the atmosphere, as well as the optical-path length. Only for short paths in a dry and nonfoggy atmosphere can the attenuation be neglected.

C. Parameters Related to Test Object

Wind velocity and direction at the test site also affect the temperature distribution on the test object. An increase in the wind velocity or a shift of wind direction toward the test surface tends to increase the convective heat-transfer coefficient, thus diminishing the surface temperature. An analysis of the infrared picture without reference to existing wind conditions could result in an erroneous picture interpretation.

The energy actually received by an infrared camera is the surface radiosity, defined as the total radiation leaving a surface. For an opaque surface, this total energy consists of emitted and reflected energy. Since the emitted part is a function of the surface emissivity, among other factors, the emitted energy is a function of the surface conditions. The emissivity is high for most dull surfaces. Additionally, a rough surface emits more energy than a smooth one. It is also known that long-time exposure of a metallic surface to air tends to oxidize the surface and therefore changes the surface-emissivity behavior. Emissivity also is directionally dependent. Thus, a round surface emits differently from a flat surface. All these conditions add complexity to the problem and must be accounted for in the analysis of infrared pictures.

The surface reflectivity is a function of the same parameters that govern the surface emissivity. In addition, radiators placed in the vicinity of the test object contribute part of their energy through reflections from the test surface. A method commonly used to rectify the surface-reflection problem is to paint the test surface black.¹¹

III. GENERAL STATEMENT OF PROBLEM

A. Scope of Project

The problem under investigation in the present project is the development of appropriate heat-transfer models for a refractory-lined duct such that, given a surface-temperature distribution (obtained by a full-field imaging system such as an infrared camera), the cavity size and shape at the interior surface can be predicted. Because refractory thinning reduces thermal protection of the steel pressure boundary, prediction of cavity depth is of primary importance. The purpose of this investigation is twofold:

1. To develop heat-transfer models which can be used to make parametric studies that include realistic effects of material status changes on the temperature distributions, in order to establish the limits of the technique. Typical parameters to be studied include thermal conductivity, variation of wall construction, thermal-contact resistance, and outer-surface conditions, including the effect of the convective heat-transfer coefficient. In addition, the erosion-prediction capabilities of the new "telltale rib" model will be investigated.

2. To examine various surface-temperature distributions and predict the sizes and shapes of cavities on the inner surface of the refractory linings, on the basis of the above heat-transfer models.

B. Mathematical Formulation

The transfer-line configuration studied in this investigation (see Fig. 1) can be readily fitted to a cylindrical coordinate system as shown in Fig. 2. The general heat-conduction equation can be written for this cylindrical system as

$$\frac{\partial T}{\partial t} = \alpha \left(\frac{\partial^2 T}{\partial r^2} + \frac{1}{r} \frac{\partial T}{\partial r} + \frac{1}{r^2} \frac{\partial^2 T}{\partial \theta^2} + \frac{\partial^2 T}{\partial z^2} \right) + \frac{Q'}{\rho c}, \quad (1)$$

where α is the thermal diffusivity, Q' is the internal heat generation, ρ is the density, and c is the specific heat of the medium. Under steady-state conditions without heat generation, the governing equation becomes

$$\frac{\partial^2 T}{\partial r^2} + \frac{1}{r} \frac{\partial T}{\partial r} + \frac{1}{r^2} \frac{\partial^2 T}{\partial \theta^2} + \frac{\partial^2 T}{\partial z^2} = 0. \quad (2)$$

Fig. 1. Sectional View of Refractory-lined Transfer Line Used for Analytical Modeling. ANL Neg. No. 306-78-528.

Fig. 2. Cylindrical Coordinates Used in Formulation of Mathematical Model. ANL Neg. No. 306-79-1087.

The boundary conditions applicable to the system include a prescribed surface temperature on the inner (hot) refractory surface and a convective boundary on the outer steel surface. In the angular (θ) direction, the boundary conditions selected are based on the necessity that the temperature must be single valued for an angular increment of 2π . In the axial (z) direction, the boundaries are free from edge effects due to either the cavity wall or axial heat transfer remote from the system. Hence, the actual length of the system must be sufficient to ensure that an adiabatic condition prevails at both ends. These boundary conditions can be formulated as follows:

$$T(r_i, \theta, z) = T_i, \quad (3)$$

$$k \frac{\partial T(r_o, \theta, z)}{\partial r} + h[T(r_o, \theta, z) - T_\infty] = 0, \quad (4)$$

$$\frac{\partial T(r, \theta, z)}{\partial \theta} = \frac{\partial T(r, \theta + 2\pi, z)}{\partial \theta}, \quad (5)$$

$$T(r, \theta, z) = T(r, \theta + 2\pi, z), \quad (6)$$

$$\frac{\partial T(r, \theta, -l/2)}{\partial z} = 0, \quad (7)$$

and

$$\frac{\partial T(r, \theta, l/2)}{\partial z} = 0, \quad (8)$$

where h in Eq. 4 represents the convective heat-transfer coefficient.

In practice, the transfer-line wall is composed of a refractory-concrete lining cast inside a steel shell. In the presence of such a composite structure, two sets of governing equations and boundary conditions are needed to describe the system. A formulation suited to this composite system can be derived by reusing the previous equations, with subscripts added to T to differentiate temperatures in different parts of the medium. In addition, if the contact resistance at the interface is ignored, two new boundary conditions are required at the interface:

$$k_r \frac{\partial T_r(r_m, \theta, z)}{\partial r} = k_s \frac{\partial T_s(r_m, \theta, z)}{\partial r} \quad (9)$$

and

$$T_r(r_m, \theta, z) = T_s(r_m, \theta, z). \quad (10)$$

Here, subscripts r , m , and s have been added to designate the refractory concrete, the interface, and the steel shell, respectively.

C. Justification for Boundary Conditions Imposed

The boundary conditions given above are strictly valid only in the angular (θ) and axial (z) directions. In the radial direction, a certain degree of arbitrariness is necessary. The problem lies in the fact that, strictly speaking, the inner refractory surface is not subjected to a prescribed temperature. In coal-conversion processes, the refractory inside the transfer line is exposed to both convection and radiation from two-phase (solid-gas) mixtures. Cavity recesses in the wall can induce secondary vortices which are not amenable to such simple analysis. In fact, the effective heat-transfer coefficient cannot be estimated for such complicated flow conditions using present state-of-the-art methods such as finite elements. The assumption of a prescribed surface temperature is thus made in order to simplify the problem and allow a solution.

The assumption of a convective boundary at the outer surface, however, is a valid one. A point of caution is that, if the heat is dissipated from a highly emissive surface at elevated temperatures, the radiative component must also be considered. An analysis showing the fraction of the convective contribution to the total heat dissipation can be made by separately considering the convective component as

$$q_c = hT_\infty \left(\frac{T_o}{T_\infty} - 1 \right) \quad (11)$$

and the radiative component as

$$q_r = \epsilon \sigma T_\infty^4 \left[\left(\frac{T_o}{T_\infty} \right)^4 - 1 \right], \quad (12)$$

where ϵ is the surface emissivity, σ is the Stefan-Boltzmann constant, T_o is the outer-surface temperature, and T_∞ is the ambient temperature. The fraction of the convective contribution to the total heat dissipation $[q_c/(q_c + q_r)]$ can be evaluated and plotted as a function of the temperature ratio (T_o/T_∞), as shown in Fig. 3. The following observations can be made from this figure: For the emissivity and temperature values chosen for this plot ($\epsilon = 0.2$, $T_\infty = 10^\circ\text{C}$), an increase in the temperature ratio (i.e., T_o) decreases the fraction of the convective contribution. Note that the parameter used in the family of curves shown is the convective coefficient, h . The trends of the curves appear to indicate that the fraction of the convective contribution increases more rapidly for small values of h at low temperature ratios. Such a trend is, nevertheless, reversed when the h values are increased.

Fig. 3

Evaluation of Convective Contribution for $\epsilon = 0.2$, $T_\infty = 50^\circ\text{F}$ (10°C). Conversion factor: $1 \text{ Btu/h}\cdot\text{ft}^2\cdot^\circ\text{F} = 5.68 \times 10^{-6} \text{ W/mm}^2\cdot^\circ\text{C}$. ANL Neg. No. 306-80-148.

When the emissivity is kept constant, but T_∞ is increased from 10°C (50°F) to 26.6°C (80°F), only a slight upward shift of the curves is noted, as shown in Fig. 4. On the other hand, if the ambient temperature remains

constant while the emissivity is raised from 0.2 to 0.8, a downward shift of the curves results (see Fig. 5). This effect is more pronounced at low convection rates under which the fraction of the convective contribution is almost halved over broad temperature ratios.

Fig. 4

Evaluation of Convective Contribution for $\epsilon = 0.2$, $T_\infty = 80^\circ\text{F}$ (26.6°C). Conversion factor: $1 \text{ Btu/h}\cdot\text{ft}^2\cdot^\circ\text{F} = 5.68 \times 10^{-6} \text{ W/mm}^2\cdot^\circ\text{C}$. ANL Neg. No. 306-80-144.

Fig. 5

Evaluation of Convective Contribution for $\epsilon = 0.8$, $T_\infty = 80^\circ\text{F}$ (26.6°C). Conversion factor: $1 \text{ Btu/h}\cdot\text{ft}^2\cdot^\circ\text{F} = 5.68 \times 10^{-6} \text{ W/mm}^2\cdot^\circ\text{C}$. ANL Neg. No. 306-80-153.

Note that, for small temperature differences ($T_0 - T_\infty$), the following approximation holds:

$$(T_0^2 + T_\infty^2)(T_0 + T_\infty) \approx 4 \left(\frac{T_0 + T_\infty}{2} \right)^3. \quad (13)$$

Thus, if the quantity in parentheses on the right of Eq. 13 is denoted as the mean temperature T_m , Eq. 12 can be recast as

$$q_r \approx 4\epsilon\sigma T_m^3 T_\infty \left(\frac{T_0}{T_\infty} - 1 \right). \quad (14)$$

If the coefficient $4\epsilon\sigma T_m^3$ in Eq. 14 is denoted as h_r , the radiative contribution to heat dissipation can be combined with the convective component as

$$q_c + q_r = (h + h_r) T_\infty \left(\frac{T_0}{T_\infty} - 1 \right). \quad (15)$$

Hence, by choosing a suitable value of h , we can account for the radiative contribution in the analysis; a separate consideration of the radiative transfer is thus unnecessary.

IV. DEVELOPMENT OF BASIC HEAT-TRANSFER MODELS

A. Finite-difference Formulation

The formulation given in the preceding section has been idealized in the sense that the transfer line has not been eroded. In the presence of a cavity defect in the wall (erosion), the structural system takes on a more complicated configuration (see Fig. 1). Under this condition, the exact solution becomes difficult and numerical methods must be relied on for solution. The numerical solution can be effected by a reformulation of the problem into finite difference as follows:

According to Taylor's expansion, one can replace the second derivative $\partial^2 T / \partial r^2$ in Eq. 2 by a second central-difference quotient:

$$\frac{\partial^2 T}{\partial r^2} = \frac{T_{i+1,j} - 2T_{i,j} + T_{i-1,j}}{(\Delta r)^2} \quad (16)$$

The truncation error involved in this substitution can be expressed as

$$E_T = -\frac{(\Delta r)^2}{12} \left[D_r^4 + \frac{(\Delta r)^2}{30} D_r^6 + \dots \right] T_{i,j}, \quad (17)$$

where the operator D_r is defined as

$$D_r = \frac{\partial}{\partial r}. \quad (18)$$

Similarly, the first derivatives that appear in the boundary conditions can be replaced by either a forward- or a backward-difference quotient given, respectively, as

$$\frac{\partial T}{\partial r} = \frac{T_{i+1,j} - T_{i,j}}{\Delta r} \quad (19)$$

and

$$\frac{\partial T}{\partial r} = \frac{T_{i,j} - T_{i-1,j}}{\Delta r}. \quad (20)$$

Again, these truncation errors can be expressed in terms of operators as

$$E_T = -\frac{\Delta r}{2} \left[D_r^2 + \frac{(\Delta r)}{3} D_r^3 + \dots \right] T_{i,j}, \quad (21)$$

which is valid for a forward difference. For a backward difference, the negative sign on the right of Eq. 21 must be changed to a positive sign.

The truncation errors given in Eqs. 17 and 21 obviously have different orders of magnitude. Unless an average difference quotient is used for the first partial differential, the error involved in replacing the first partial differential by either a forward- or a backward-difference quotient is of order Δr , while that for the second differential is $(\Delta r)^2$. To rectify this inconsistency, one has to use a refined mesh size at the boundary in order to ensure a uniform truncation error throughout the system. This points to the fact that a simple replacement of differentials by differences might result in a magnitude-nonhomogeneous system that is inherent in this method of formulation.

Fig. 6. Volume Element in Cylindrical Coordinates.
ANL Neg. No. 306-78-526.

A second, and actually better, method to derive a difference formulation is to use a physical analysis. This method is based on the assumption that an energy balance exists at each nodal point in the system. For the cylindrical system under consideration, the entire region is modularized into volume elements as shown in Fig. 6. Ohm's law can be used to derive heat flow to each node (i, j, k) from each neighboring point. Kirchhoff's law can next be used to sum all heat flow to the nodal point and the sum equated to zero to relate a steady-state condition. This process is repeated for each node in the system such that a complete set of finite-difference equations can be derived. To facilitate the formulation, all nodal-resistance expressions are listed in Table I. The thermal-conductivity terms, k , in the expressions have been identified with

subscripts that refer to the temperature level at which these conductivities are evaluated. Hence, for example, $k_{i(1/2)}$ refers to a conductivity evaluated at $(T_{i-1,j,k} + T_{i,j,k})/2$. The temperature dependency in the thermal conductivity can be accounted for in the analysis. Note that the difference formulation derived here on the basis of the physical analysis will result in a magnitude-homogeneous system.¹² For this reason, the physical-analysis approach is used exclusively in the present work to derive all the finite-difference formulations.

TABLE I. Expressions Used to Derive Nodal Equations by Means of Physical Formulation

Quantity	Equivalent Expressions in Cylindrical Coordinate System ^a
ΔV	$r_i \Delta \theta \Delta r \Delta z$
$R_{i-(1/2)}$	$\frac{\Delta r}{(r_i - \Delta r/2) \Delta \theta \Delta z k_{i-(1/2)}}$
$R_{i+(1/2)}$	$\frac{\Delta r}{(r_i + \Delta r/2) \Delta \theta \Delta z k_{i+(1/2)}}$
$R_{j-(1/2)}$	$\frac{r_i \Delta \theta}{\Delta r \Delta z k_{j-(1/2)}}$
$R_{j+(1/2)}$	$\frac{r_i \Delta \theta}{\Delta r \Delta z k_{j+(1/2)}}$
$R_{k-(1/2)}$	$\frac{\Delta z}{\Delta r \Delta \theta r_i k_{k-(1/2)}}$
$R_{k+(1/2)}$	$\frac{\Delta z}{\Delta r \Delta \theta r_i k_{k+(1/2)}}$

^a $r = \Delta r(i)$, $\theta = \Delta \theta(j)$, $z = \Delta z(k)$.

B. Development of Basic Two-dimensional Model

In the two-dimensional model, the temperature is free of z-axis dependency. Hence, the cavity is of infinite length. Finite-difference equations can be derived for this two-dimensional system and summarized as follows:

For interior nodes in the refractory or the steel shell, the temperature can be determined from

$$T_{i,j} = \left\{ \frac{1}{(\Delta r)^2} \left[\left(r_i - \frac{\Delta r}{2} \right) T_{i-1,j} + \left(r_i + \frac{\Delta r}{2} \right) T_{i+1,j} \right] + \frac{1}{r_i (\Delta \theta)^2} (T_{i,j-1} + T_{i,j+1}) \right\} \cdot \left\{ 2 \left[\frac{r_i}{(\Delta r)^2} + \frac{1}{r_i (\Delta \theta)^2} \right] \right\}^{-1} \quad (22)$$

For nodes at the interface between the refractory lining and the steel shell, the temperature can be determined from

$$T_{i,j} = \left\{ \frac{1}{(\Delta r)^2} \left[k_1 \left(r_i - \frac{\Delta r}{2} \right) T_{i-1,j} + k_2 \left(r_i + \frac{\Delta r}{2} \right) T_{i+1,j} \right] + \frac{k_1 + k_2}{2r_i(\Delta \theta)^2} (T_{i,j-1} + T_{i,j+1}) \right\} \cdot \left\{ \frac{1}{(\Delta r)^2} \left[k_1 \left(r_i - \frac{\Delta r}{2} \right) + k_2 \left(r_i + \frac{\Delta r}{2} \right) \right] + \frac{k_1 + k_2}{r_i(\Delta \theta)^2} \right\}^{-1}, \quad (23)$$

where k_1 and k_2 are thermal conductivities for the refractory and the steel shell, respectively.

For nodes at the outer surface of the steel shell, the temperature can be determined from

$$T_{i,j} = \left[\frac{k_2}{(\Delta r)^2} \left(r_i - \frac{\Delta r}{2} \right) T_{i-1,j} + \frac{hr_i}{\Delta r} T_{\infty} + \frac{k_2}{2r_i(\Delta \theta)^2} (T_{i,j-1} + T_{i,j+1}) \right] \cdot \left[\frac{k_2}{(\Delta r)^2} \left(r_i - \frac{\Delta r}{2} \right) + \frac{hr_i}{\Delta r} + \frac{k_2}{r_i(\Delta \theta)^2} \right]^{-1} \quad (24)$$

In applying these equations to nodes at various locations in the system, one should be aware that the temperature distribution is symmetrical with respect to the cavity location in the system. Hence, if the cavity center is set at $\theta = 0$ (see Fig. 7), only the region from $\theta = 0$ to 180° need be considered to reduce the computation cost.

Fig. 7. Schematic Diagram Showing Locations of Nine Classes of Nodes Used in Difference Formulation. ANL Neg. No. 306-80-132.

For nodes located on the plane of symmetry, the nodal equations can be further simplified. Since the temperature gradient vanishes at the plane of symmetry, one can introduce a fictitious node outside the region of investigation. This fictitious node is related to the interior node by

$$T_{i,j+1} = T_{i,j-1}. \quad (25)$$

This equation can be used to further simplify the difference formulation for boundary nodes.

For a two-dimensional system as considered here, nine types of nodal equations appear in the solution. Each of these represent a distinct nodal location that requires a general nodal equation for temperature calculations using DO loops. Figure 7 is a schematic diagram showing these nine locations. The total number of equations to be solved simultaneously in the problem, of course, equals the total number of nodes in the system. These nodal equations written in FORTRAN are compiled in the computer program included as Appendix A to this report.

C. Development of Basic Three-dimensional Model

For the three-dimensional model, the cavity is of finite length. General equations can be derived for this three-dimensional system, again using a physical formulation. For interior nodes in the refractory and the steel shell, the difference equation is developed as

$$\begin{aligned} T_{i,j,k} = & \left\{ \frac{1}{(\Delta r)^2} \left[\left(1 - \frac{\Delta r}{2r_i} \right) T_{i-1,j,k} + \left(1 + \frac{\Delta r}{2r_i} \right) T_{i+1,j,k} \right] \right. \\ & \left. + \frac{1}{r_i^2 (\Delta \theta)^2} (T_{i,j-1,k} + T_{i,j+1,k}) + \frac{1}{(\Delta z)^2} (T_{i,j,k-1} + T_{i,j,k+1}) \right\} \\ & \cdot \left\{ 2 \left[\frac{1}{(\Delta r)^2} + \frac{1}{r_i^2 (\Delta \theta)^2} + \frac{1}{(\Delta z)^2} \right] \right\}^{-1}. \end{aligned} \quad (26)$$

For nodes at the interface between the refractory lining and the steel shell, the difference equation is developed as

$$\begin{aligned} T_{i,j,k} = & \left\{ \frac{1}{(\Delta r)^2} \left[k_1 \left(1 - \frac{\Delta r}{2r_i} \right) T_{i-1,j,k} + k_2 \left(1 + \frac{\Delta r}{2r_i} \right) T_{i+1,j,k} \right] \right. \\ & \left. + \frac{k_1 + k_2}{2r_i^2 (\Delta \theta)^2} (T_{i,j-1,k} + T_{i,j+1,k}) + \frac{k_1 + k_2}{2(\Delta z)^2} (T_{i,j,k-1} + T_{i,j,k+1}) \right\} \\ & \cdot \left\{ \frac{1}{(\Delta r)^2} \left[k_1 \left(1 - \frac{\Delta r}{2r_i} \right) + k_2 \left(1 + \frac{\Delta r}{2r_i} \right) \right] + \frac{k_1 + k_2}{r_i^2 (\Delta \theta)^2} + \frac{k_1 + k_2}{(\Delta z)^2} \right\}^{-1}. \end{aligned} \quad (27)$$

For nodes at the outer surface of the steel shell, the difference equation is given as

$$\begin{aligned}
 T_{i,j,k} = & \left[\frac{k_2}{(\Delta r)^2} \left(1 - \frac{\Delta r}{2r_i} \right) T_{i-1,j,k} + \frac{h}{\Delta r} T_\infty + \frac{k_2}{2r_i^2 (\Delta \theta)^2} (T_{i,j-1,k} + T_{i,j+1,k}) \right. \\
 & \left. + \frac{k_2}{2(\Delta z)^2} (T_{i,j,k-1} + T_{i,j,k+1}) \right] \\
 & \cdot \left[\frac{k_2}{(\Delta r)^2} \left(1 - \frac{\Delta r}{2r_i} \right) + \frac{h}{\Delta r} + \frac{k_2}{r_i^2 (\Delta \theta)^2} + \frac{k_2}{(\Delta z)^2} \right]^{-1}. \quad (28)
 \end{aligned}$$

Again, planes of symmetry can be used to economize the solution. This time, in addition to the plane located at $\theta = 0$, new planes are placed at $z = 0$ and $\ell/2$. The coordinates of the system are also fitted such that the origin lies radially along the center of the cavity $(r, 0, 0)$. This arrangement permits a reduction of the system to one quadrant of the original volume.

For a three-dimensional system, 27 types of nodal equations appear. Since a graphical presentation of these nodal locations is difficult, a verbal accounting is given as follows: Consider that the system under investigation occupies a space of $\pi \geq \theta \geq 0$ and $\ell/2 \geq z \geq 0$, where the z axis is one that penetrates normally into the plane of Fig. 7. In this way, the nine classes of nodes that have previously been shown in the two-dimensional system are still valid. Since these nodes can be located at either the front ($z = 0$) or the rear end ($z = \ell/2$) of the system, they give a combination of 18 nodal locations that require 18 general equations for temperature calculations using DO loops.

In addition, because of the presence of the axial direction as the third dimension, there are nodal points located at (1) $(r, 0^\circ, z)$ and $(r, 180^\circ, z)$, where $r_m > r > r_i$ and $\ell/2 > z > 0$; (2) $(r_m, 0^\circ, z)$ and $(r_m, 180^\circ, z)$, where $\ell/2 > z > 0$; (3) $(r_0, 0^\circ, z)$ and $(r_0, 180^\circ, z)$, where $\ell/2 > z > 0$; (4) interior nodes inside the refractory, i.e., (r, θ, z) , where $r_m > r > r_i$, $180^\circ > \theta > 0$, $\ell/2 > z > 0$; (5) interior nodes on the refractory/steel interface, i.e., (r_m, θ, z) with the ranges of θ and z unchanged from before; and finally, (6) interior nodes on the outer surface of the steel shell, i.e., (r_0, θ, z) . All together, these represent nine additional nodal locations that require nine additional equations in the formulation. A computer program developed for the three-dimensional model is included as Appendix B to this report.

D. Modeling of Thermal Contact Resistance

The thermal resistance at the refractory/steel interface has a marked effect on the heat transfer to the steel shell. Unfortunately, modeling this resistance is difficult because of the lack of data available in the literature.

Most of the data available today have been for metal-to-metal contacts.¹³⁻¹⁶ These data cannot be used to predict a metal-to-ceramic contact, as is necessary for the present study. Experience has shown that, because of the complexity of the contact mechanism present at the interface, analysis using resistance data for metal-to-ceramic contact* may be inaccurate if the data given are not for the same materials. To alleviate this difficulty, the modeling of contact resistance in the present study follows a different approach. The method consists of reorganizing the contact-resistance equation using a dimensionless parameter that is to be incorporated into the neighboring resistances. The method is derived from an effective-resistance concept, which owes its origin to the contact-resistance equation given as¹⁶

$$R_c = \frac{1}{2nakA}, \quad (29)$$

where n is the number of contact spots per unit area, a is the mean radius of the contact spots, k is the thermal conductivity, and A is the apparent area in contact. Since it is a resistance, R_c can now be incorporated into the resistance network.

For the problem at hand, the lumping of the contact resistance to the refractory side of the network appears to be more appropriate, because the magnitude of the contact resistance is comparable to that of the refractory material. As a result, the new resistance at the refractory side takes the form

$$\frac{\Delta r}{k_1 A} + \frac{1}{2nak_1 A} = \frac{\Delta r}{k_1 A} \left[1 + \frac{1}{2na(\Delta r)} \right]. \quad (30)$$

The bracketed quantity on the right of Eq. 30 plays the role of a modified resistance factor that offers the same resistance to heat flow as an interfacial contact resistance. The second term in the brackets is a dimensionless quantity that is always positive in magnitude. The entire bracketed term can thus be designated as f ,

$$f = 1 + \frac{1}{2na(\Delta r)}, \quad (31)$$

in which $f \geq 1$; $f = 1$ when the interfacial resistance is zero. This f factor can be used to model a wide range of interfacial conditions and to analyze the resistance effects. Two conditions are studied below for illustration.

When a uniform resistance occurs at the interface, the contact resistance can be modeled by using a constant f value to modify all the resistances

*Only two references^{17, 18} in the literature report data on metal-to-ceramic contacts.

at the refractory side of the network. The solution to this case is straightforward, and no further discussion is necessary.

A slightly more involved case is one in which the contact resistance is a variable. In this case, the temperature distribution becomes strongly dependent on how the f function is chosen in the analysis. In the absence of actual resistance data for modeling, the f function chosen in the present study was dictated by the consideration that the purpose of the selected f function would give rise to a limiting case so that the surface temperature would be upset because of the resistance. With this in mind, the f function was chosen as

$$\left(\frac{j - J}{J}\right)^2 + \left(\frac{k - K}{J}\right)^2 = \frac{v - f}{v - 1}, \quad (32)$$

where the coordinates have been expressed using indices (j for θ , k for z). The selected f function has a paraboloid variation, with the peak point located at (J, K) , of value v . Since the center of the cavity is also located at (J, K) in the analysis, the large contact resistance occurs where the highest heat flow takes place. Thus, the proposed contact resistance will impede the heat flow and also suppress the temperature of the hot spot appearing on the surface. Adjusting the v value enables a limiting case to be found.

It should be added that the f function developed above (Eq. 31) is indeed of general utility. In the future, when the contact-resistance data become available, one can readily convert them to f values and use them in model studies. The equation to be used in this conversion is

$$f = 1 + \frac{R_c k A}{\Delta r}, \quad (33)$$

which is derived by combining Eqs. 29 and 31.

E. Modeling of Surface-emissivity Effects

Unless a surface is black or is coated with a material of known emissivity, the surface emissivity must be carefully examined before an infrared picture can be analyzed.

The effect of surface emissivity on infrared images was qualitatively discussed in Sec. III.C. In this section, a quantitative prediction of the emissivity will be given to show how the surface-emissivity effect can be incorporated in the model study. Some qualitative data will also be examined in passing in order to support discussions. To facilitate analysis, the surface being investigated is assumed to have a homogeneous structure. That is to say, the surface has neither a peeling-paint appearance, nor nonuniformities of either a physical or chemical nature such as localized smooth or rough

spots, chips, abrasions, dents, etchings, or rust spots. These nonhomogeneities can normally be detected from an infrared image as abnormally hot or cold spots in an otherwise uniform background. Since they can be corrected in the experiment and their appearance is by no means related to the true temperature distributions, an inclusion of these artifacts in the study is meaningless. In the following, the modeling of the emissivity effect will start with a development of the relation between emission and view angles. The surface-emissivity relation will be examined and used to show how the emitted energy will vary in the view field because of the dependence of the emissivity on direction.

The discussion can be facilitated by reference to the schematic shown in Fig. 8, where the infrared camera is at a distance D from the center of

Fig. 8. Schematic Diagram Showing Notation Used to Relate Polar (θ), Emission (α), and View (β) Angles. ANL Neg. No. 306-78-527.

the pipe. For a surface element located at a polar angle θ on the pipe, the emission angle from the element is α , while the view angle at the camera is β . The energy reaching the camera from the center of the view field ($\beta = 0$) is due to surface emission normal to the pipe surface and parallel to the lens axis. Unless the viewed surface is diffuse, the emissivity varies strongly with the emission angle. Hence, a relation between emission and view angles must be developed before a correction can be made for emissivity. The law of cosines can be used to relate θ and β as

$$D^2 + r_0^2 - 2Dr_0 \cos \theta = \frac{r_0^2 \sin^2 \theta}{\sin^2 \beta}. \quad (34)$$

For a given test setup, both D and r_0 are known and the polar and view angles can be found. The emission angle can also be calculated from θ and β , using

$$\alpha = \theta + \beta. \quad (35)$$

The nonlinearity of Eq. 34 yields a relation between θ and β that is difficult to visualize. A computer program was developed to evaluate these angles.

(A computer program evaluating the relations among the angles α , β , and θ and the surface emissivity of both metallic and nonmetallic substances is given in Appendix C.) In a test run using $D = 1.524$ m (60 in.) and $r_0 = 0.1333$ m (5.25 in.) as inputs, the angular relations were calculated and plotted. This

is shown in Figs. 9 and 10. Figure 9 shows that the relation between the view angle and the polar angle (both expressed in radians) is nonlinear. The nonlinearity is quite pronounced toward large angles. Similarly, the relation between the emission angle and the polar angle is also nonlinear, primarily toward large polar angles (see Fig. 10). On the basis of these data, a third figure can be constructed that relates the emission and the view angles (see Fig. 11). Again, a nonlinear relation is found in the figure.

Fig. 9. Polar- to View-angle Conversion Chart. ANL Neg. No. 306-80-146.

Fig. 10. Polar- to Emission-angle Conversion Chart. ANL Neg. No. 306-80-142.

Fig. 11
Emission- to View-angle Conversion Chart. ANL Neg. No. 306-80-131.

The angular relations presented above have significance in studying the distortion of infrared images. As one may recall in the previous modeling using finite differences, the surface-temperature data were evaluated at equal increments of the polar angle (θ), while the instantaneous fields scanned by the infrared camera and presented on the oscilloscope screen were made in equal increments of the view angle (ϕ). In Fig. 9 these two angles are shown to be nonlinear. Hence, a predicted temperature map using the heat-transfer model developed here might not exactly be the one found on the oscilloscope screen, even if the model were perfect. A distortion of the image in the transverse direction is inherent in the method, since the two temperature maps do not share identical angular coordinates.

The problem is further complicated by the fact that the surface emissivity is also a function of the emission angles. In order to evaluate this emissivity effect, the emissivity equations must also be examined. The emissivity can be predicted using electromagnetic theory. If the complex refractive index N is expressed as

$$N = n - ik, \quad (36)$$

where n (index of refraction) and k (extinction coefficient) are known optical constants, the directional spectral emissivity can be calculated using¹⁹

$$\epsilon'_\lambda = \frac{1}{2} \epsilon_\perp(\alpha) \left[1 + \frac{a^2 + b^2 + \sin^2 \alpha}{\cos^2 \alpha (a^2 + b^2 + 2a \sin \alpha \tan \alpha + \sin^2 \alpha \tan^2 \alpha)} \right], \quad (37)$$

where

$$\epsilon_\perp(\alpha) = \frac{4a \cos \alpha}{a^2 + b^2 + 2a \cos \alpha + \cos^2 \alpha}. \quad (38)$$

The parameters a and b in the above equations can be evaluated using the equations

$$2a^2 = \sqrt{(n^2 - k^2 - \sin^2 \alpha)^2 + 4n^2 k^2} + (n^2 - k^2 - \sin^2 \alpha) \quad (39)$$

and

$$2b^2 = \sqrt{(n^2 - k^2 - \sin^2 \alpha)^2 + 4n^2 k^2} - (n^2 - k^2 - \sin^2 \alpha). \quad (40)$$

To illustrate how the emissivity varies with angle, two test runs were made. The first used the optical constants $n = 4$ and $k = 10$, which are representative of metals ($k \neq 0$); hence, the resultant emissivity curve characterizes metal behavior. As shown in Fig. 12, the emissivity increases with polar angle and drops rapidly to zero at 90° . Nonmetal behavior ($n = 4$, $k = 0$) is illustrated in Fig. 13; here, the emissivity is high and holds constant over a wide range of polar angles, then again drops down to zero toward 90° . Because

of the spectral dependency of the optical constants, the emissivity curves given above are strictly valid for a certain wavelength condition. However, because of the spectral insensitivity of most engineering materials in the far infrared, the total emissivity is expected to behave in a like manner.

Fig. 12. Directional Emissivity Curve for Metal Surface

Fig. 13. Directional Emissivity Curve for Nonmetal Surface.
ANL Neg. No. 306-80-150.

The emissivity curves given can be regarded as total emissivities and their values replotted against view angles, as shown in Figs. 14 and 15. These curves can now be used to study the distortion of infrared images due to emissivity effects. Let the transfer line have a cavity at $\theta = 0$ (refer to Fig. 8). Because of the emissivity variation, the anticipated hot spot at the center of the infrared image will not appear as hot as expected if the transfer line has a metallic surface. On the other hand, if the transfer line has a nonmetallic surface, the hot spot tends to cool off rapidly toward the edges.

Fig. 14. Emissivity Correction Curve for Data in Figs. 9 and 12.
ANL Neg. No. 306-80-149.

Fig. 15. Emissivity Correction Curve for Data in Figs. 9 and 13.
ANL Neg. No. 306-80-155.

In conclusion, it is important to note that the analysis given above has concentrated on the surface emissivity effects. For a nonblack surface, the reflectivity also plays a role in the total energy detected. Unfortunately, to include the reflected energy in the analysis is difficult, because the reflected energy is also dependent on the radiosity coming from the surroundings. Because of the infinite variations that can occur in the surroundings, a general analysis cannot be made without going into radiative transfer theory in great depth. For this reason, the reflection studies have been omitted; the interested reader is referred to Refs. 20-23. Here, it suffices to say that the reflection problem can be alleviated by using cooled radiation shields. A method of correcting this reflection effect is proposed in Ref. 24.

V. TEST OF COMPUTER PROGRAMS USING LIMITING CASES

The computer programs developed in the present work invoke an iterative solution. (Because of the large number of nodal equations to be solved in this work, the iterative solution appears to be more economical. However, the method is not without drawbacks, as discussed in Ref. 12.) Instead of solving the nodal equations simultaneously using orthodox techniques such as Gaussian elimination or matrix inversions, the program initializes the temperature at each nodal point. An improved temperature is then calculated and repeatedly corrected until the difference between successive computations converges to a prescribed limit. According to this method, the convergence of the solution and the accuracy of temperatures depend heavily on the mesh size chosen as well as the convergence level selected in the computation. For this reason, the computer program must be pretested to determine these parameters.

The method used for tests consists of comparing the numerical results with analytical solutions. Since the total system cannot be solved exactly because of its configuration and boundary conditions, some limiting cases are used for comparison. For the system under investigation, the surface temperature at the center of the cavity should approach that of a cylindrical shell of the same thickness and inner radius if the cavity has a large cross section. Similarly, the temperature farthest away from the cavity should approach that of the same shell if the cavity width is small. In both cases, the temperature on the cylindrical shell can be predicted analytically using (see Appendix D for derivation)

$$T_s(r_0) = T_\infty - \frac{T_i - T_\infty}{\frac{k_s}{k_r} \ln \frac{r_i}{r_m} + \ln \frac{r_m}{r_0} - \frac{k_s}{hr_0}} \left(\frac{k_s}{hr_0} \right) \quad (41)$$

where T_∞ is the ambient temperature and h is the convective coefficient at the steel surface; other notations are defined in Fig. 2.

The parameters were tested using the following as inputs:

$$T_i = 815^\circ\text{C} (1500^\circ\text{F}),$$

$$T_\infty = 26.6^\circ\text{C} (80^\circ\text{F}),$$

$$k_s = 4.67 \times 10^{-2} \text{ W/mm}\cdot^\circ\text{C} (324 \text{ Btu/h}\cdot\text{ft}^2\cdot^\circ\text{F/in.}),$$

$$k_r = 6.63 \times 10^{-4} \text{ W/mm}\cdot^\circ\text{C} (4.6 \text{ Btu/h}\cdot\text{ft}^2\cdot^\circ\text{F/in.}),$$

$$r_i = 50.8 \text{ mm} (2 \text{ in.}) \text{ and } 63.5 \text{ mm} (2.5 \text{ in.}),$$

$$r_m = 127 \text{ mm} (5 \text{ in.}),$$

$$r_0 = 133.3 \text{ mm (5.25 in.)}$$

and

$$h = 5.68 \times 10^{-5} \text{ W/mm}^2\cdot^\circ\text{C (10 Btu/h}\cdot\text{ft}^2\cdot^\circ\text{F) and}$$

$$1.13 \times 10^{-4} \text{ W/mm}^2\cdot^\circ\text{C (20 Btu/h}\cdot\text{ft}^2\cdot^\circ\text{F).}$$

In the computer program, the mesh size was chosen as follows:

$$\Delta r = 6.35 \text{ mm (0.25 in.)}$$

and

$$\Delta\theta = 15^\circ.$$

Both the computer program and the analytical equation (Eq. 41) were used to test a cavity size of

$$\text{depth} = 127 \text{ mm (0.5 in.)}$$

and

$$\text{angular span} = 120^\circ.$$

The results, listed in Table II, lead to the following conclusions: First, the number of iterations needed for solution increases markedly when the convergence criterion (EPS) is reduced. The increase in CPU time is indicative of this increase. Second, the number of iterations decreases as the value of the convective coefficient increases. A reduction of about 35% of the CPU time is seen for all EPS values tested. Physically, a large increase in the convective coefficient tends to change a convective boundary to that of a prescribed surface temperature, which is often favorable from the iteration point of view. Third, the agreement between the numerical data and the analytical data is satisfactory. This can be seen from the case in which $h = 1.13 \times 10^{-4} \text{ W/mm}^2\cdot^\circ\text{C (20 Btu/h}\cdot\text{ft}^2\cdot^\circ\text{F)}$. The iterative surface temperature at the center of the cavity using $\text{EPS} = 0.00556^\circ\text{C (0.01}^\circ\text{F)}$ is 73.41°C , while that of the analytical solution [for $r_i = 63.5 \text{ mm (2.5 in.)}$] is 73.51°C . The corresponding iterative value farthest away from the cavity is 63.62°C , while the analytical value there [for $r_i = 50.8 \text{ mm (2 in.)}$] is 62.63°C .

TABLE II. Comparison between Numerical and Analytical Data

Convective Coefficient, h		Convergence Criterion (EPS)		Numerical Data				Analytical Data				CPU Time, s
Btu/h-ft ² -°F	W/mm ² -°C	of	°C	TNEW(NI, I)		TNEW(NI, NJ)		r _i = 2.5 in. (63.5 mm)		r _i = 2 in. (50.8 mm)		
				of	°C	of	°C	of	°C	of	°C	
10	5.68 x 10 ⁻⁵	0.1	0.2	257.24	124.13	230.63	110.35	239.21	115.11	203.85	95.47	51
		0.05	0.1	245.97	118.87	218.18	103.43					60
		0.01	0.02	237.08	113.93	208.24	97.91					84
20	1.13 x 10 ⁻⁴	0.1	0.2	174.75	79.30	158.22	70.12	164.33	<u>73.51</u>	144.75	<u>62.63</u>	33
		0.05	0.1	168.81	76.00	151.72	66.51					39
		0.01	0.02	164.14	73.41	146.52	63.62					53

From the above analysis, the selected mesh size appears to be satisfactory for $EPS = 0.005566^\circ\text{C}$ (0.01°F). Because of the given boundary conditions, the accuracy of the temperature cannot be further improved for the iterative solution if the mesh size is unconditionally reduced.¹² In fact, a repeated calculation using $h = 1.13 \times 10^{-4} \text{ W/mm}^2\cdot^\circ\text{C}$ ($20 \text{ Btu/h}\cdot\text{ft}^2\cdot^\circ\text{F}$), with $\Delta r = 3.17 \text{ mm}$ (0.125 in.) and $\Delta\theta = 5^\circ$, results in $T_{NEW}(NII, 1) = 75.33^\circ\text{C}$ (167.61°F), i.e., about 2°C higher, while $T_{NEW}(NII, NJ)$ is 65.86°C (150.55°F) or over 3°C higher than required. Also, the cost of running the program is increased by about 20%. Hence, the selection of a very small mesh size is certainly unnecessary.

A reduction of the convergence to $EPS = 0.001$, while improving the temperature prediction at all nodal points, makes the cost of running the program prohibitively high. In view of the large amount of data to be computed, a further refinement beyond what is presently used [$EPS = 0.01$, $\Delta r = 6.35 \text{ mm}$ (0.25 in.) and $\Delta\theta = 15^\circ$] would be too costly. For this reason, these parameters are used to compute all the data given in the present work.

VI. RESULTS AND DISCUSSION

A. Prediction of Surface Temperatures for a Two-dimensional Model

Thirty-six cases were tested for the two-dimensional model, using the computer program given in Appendix A. The input data to the program are summarized in Table III. This sample run included the following additional inputs:

$$h = 5.68 \times 10^{-5} \text{ W/mm}^2 \cdot ^\circ\text{C} \text{ (10 Btu/h}\cdot\text{ft}^2 \cdot ^\circ\text{F)},$$

$$\text{cavity depth} = 12.7 \text{ mm (0.5 in.)},$$

and

$$\text{cavity angular span (width)} = 120^\circ.$$

TABLE III. Test Conditions for Studies of
Two-dimensional Model

System Dimensions

$$\text{ID} = 101.6 \text{ mm (4 in.)}$$

$$\text{OD} = 266.7 \text{ mm (10.5 in.)}$$

$$\text{Refractory thickness} = 76.2 \text{ mm (3 in.)}$$

Parameters Related to Boundary Conditions

$$T_i = 815^\circ\text{C (1500}^\circ\text{F)}$$

$$T_\infty = 26.6^\circ\text{C (80}^\circ\text{F)}$$

$$h = 5.68 \times 10^{-5} \text{ W/mm}^2 \cdot ^\circ\text{C (10 Btu/h}\cdot\text{ft}^2 \cdot ^\circ\text{F)}$$

$$1.13 \times 10^{-4} \text{ W/mm}^2 \cdot ^\circ\text{C (20 Btu/h}\cdot\text{ft}^2 \cdot ^\circ\text{F)}$$

Parameters Related to Material Properties

$$k_1 = 6.63 \times 10^{-4} \text{ W/mm}\cdot^\circ\text{C (4.6 Btu/h}\cdot\text{ft}^2 \cdot ^\circ\text{F/in.)}$$

$$k_2 = 4.67 \times 10^{-2} \text{ W/mm}\cdot^\circ\text{C (324 Btu/h}\cdot\text{ft}^2 \cdot ^\circ\text{F/in.)}$$

Cavity Sizes Tested

$$\text{Depth} = 1.27 \text{ mm (0.5 in.)}, 19.0 \text{ mm (0.75 in.)}$$

$$25.4 \text{ mm (1.0 in.)}, 31.7 \text{ mm (1.25 in.)}$$

$$38.1 \text{ mm (1.5 in.)}, 44.4 \text{ mm (1.75 in.)}$$

$$\text{Angular span} = 120^\circ$$

$$180^\circ$$

$$240^\circ$$

Mesh Size Used

$$\Delta r = 6.3 \text{ mm (0.25 in.)}$$

$$\Delta \theta = 15^\circ$$

Convergence Criterion Used

$$\text{EPS} = 0.00556^\circ\text{C (0.01}^\circ\text{F)}$$

The data output, a sample of which appears in Table IV, follows the computer instruction

TNEW(NII, J), J = 1, NJ.

As expected, the hot-spot temperature, which is reported as the first data entry in the output array, appears at the center of the surface.

TABLE IV. Computer Data for a Sample Two-dimensional System

0.2572435365D+03	0.2567999024E+03	0.2553947877D+03	0.2528569797D+03	0.2490741300D+03
0.2444027210D+03	0.2399787583D+03	0.2364693550D+03	0.2339727080D+03	0.2323294669D+03
0.2313257487D+03	0.2307934495D+03	0.2306267455D+03		

An attempt was made to correlate the computer data in terms of dimensionless parameters as

$$\theta = \frac{T - T_{\infty}}{T_i - T_{\infty}}, \quad \eta = \frac{d}{D}, \quad \zeta = \frac{\theta}{180}, \quad (42)$$

where d denotes the depth of the cavity and D the outside diameter of the transfer line. For the cases tested, six equations were correlated. The first three are valid for $h = 5.68 \times 10^{-5} \text{ W/mm}^2\cdot^{\circ}\text{C}$ ($10 \text{ Btu/h}\cdot\text{ft}^2\cdot^{\circ}\text{F}$):

1. For cavity angular span of 120° ,

$$\begin{aligned} \theta(\eta, \zeta) = & (0.102 + 1.101\eta^2) + (-0.001 - 0.028\eta + 0.265\eta^2)\zeta - (0.054 \\ & - 0.222\eta + 5.237\eta^2)\zeta^2 + (0.043 - 0.193\eta + 3.966\eta^2)\zeta^3. \end{aligned} \quad (43)$$

2. For cavity angular span of 180° ,

$$\begin{aligned} \theta(\eta, \zeta) = & (0.101 + 0.02\eta + 1.039\eta^2) + (0.02 - 0.163\eta + 1.794\eta^2)\zeta - (0.086 \\ & - 0.437\eta + 6.906\eta^2)\zeta^2 + (0.054 - 0.278\eta + 4.156\eta^2)\zeta^3. \end{aligned} \quad (44)$$

3. For cavity angular span of 240° ,

$$\begin{aligned} \theta(\eta, \zeta) = & (0.101 + 0.025\eta + 1.056\eta^2) + (0.013 - 0.058\eta + 0.959\eta^2)\zeta - (0.04 \\ & - 0.042\eta + 2.558\eta^2)\zeta^2 + (0.015 + 0.045\eta + 0.686\eta^2)\zeta^3. \end{aligned} \quad (45)$$

The second three are valid when the value of the convective coefficient is doubled:

4. For cavity angular span of 120° ,

$$\begin{aligned} \theta(\eta, \zeta) = & (0.056 - 0.027\eta + 0.751\eta^2) + (-0.001 - 0.018\eta + 0.222\eta^2)\zeta \\ & - (0.043 - 0.274\eta + 3.974\eta^2)\zeta^2 + (0.035 - 0.233\eta + 3.059\eta^2)\zeta^3. \end{aligned} \quad (46)$$

5. For cavity angular span of 180° ,

$$\begin{aligned} \theta(\eta, \zeta) = & (0.055 - 0.016\eta + 0.686\eta^2) + (0.018 - 0.16\eta + 1.494\eta^2)\zeta \\ & - (0.072 - 0.51\eta + 5.492\eta^2)\zeta^2 + (0.045 - 0.328\eta + 3.327\eta^2)\zeta^3. \end{aligned} \quad (47)$$

6. For cavity angular span of 240° ,

$$\begin{aligned} \theta(\eta, \zeta) = & (0.055 - 0.018\eta + 0.705\eta^2) + (0.011 - 0.068\eta + 0.753\eta^2)\zeta \\ & - (0.032 - 0.123\eta + 1.859\eta^2)\zeta^2 + (0.011 - 0.006\eta + 0.405\eta^2)\zeta^3. \end{aligned} \quad (48)$$

The correlated equations given above were also checked to see how well they fit the data. Equation 46 was chosen and plotted for a wide range of cavity depths, d , as shown in Fig. 16. The equation appears to correlate fairly well with the computed data for shallow cavities, but to disagree markedly at large angles; for example, a deviation of over 7° is found for the deepest cavity, $d = 44.4$ mm (1.75 in.), at an angle of about 150° .

Fig. 16

Comparison between Correlated
Eq. 46 and Test Data. ANL Neg.
No. 306-80-145.

A further attempt to incorporate the cavity width (angular span) in the correlation did not meet with success. From the experience of exact solutions, one might be tempted to expand $T(r, \theta)$ in a Fourier series. Indeed, a more successful correlation would probably have to use a Fourier series, as is suggested by the trend of the calculated data shown in Fig. 16. Two recent analytical studies^{25,26} also support this proposition.

B. Prediction of Surface Temperatures for a Two-dimensional Model Fitted with a Telltale Rib

The two-dimensional model studied in the preceding section was modified by adding a "telltale rib" penetrating into the refractory lining as shown in Fig. 17. Appendix E provides a computer program for this system. The surface temperature for a two-dimensional system fitted with a telltale rib was calculated for a test case, as shown in Table V. The legend at the top of Table V summarizes the test conditions used in the computation. The four groups of data correspond to four positions of the rib, indexed as NQJ in the output. To permit testing of a wide range of rib locations, the angular mesh size was reduced to 5°. The actual rib location can be found by using the equation

$$\text{Rib Position} = (\text{NQJ} - 1) \times 5. \quad (49)$$

Fig. 17

A Two-dimensional System Modified by Installation of a Telltale Rib. ANL Neg. No. 306-80-147.

TABLE V. Computer Data for a Two-dimensional System Fitted with a Telltale Rib

DIMENSIONS:	ID- 4.00 IN., OD- 10.50 IN. REFRACTORY THICKNESS- 3.00 IN. SHELL THICKNESS 0.25 IN.											
CAVITY SIZE:	DEPTH- 0.50 IN., (HALF) ANGLE- 60.00 DEG.											
MESH SIZE:	RADIAL- 0.125 IN. ANGULAR- 5.00 DEG.											
TEMPERATURES:	INSIDE SURFACE- 1500.00 DEG., AMBIENT- 80.00 DEG.											
PROPERTIES:	K FOR REF.- 4.60, K FOR SHELL- 324.00, K FOR RIB 162.00 BTU IN./HR FT**2 F H- 10.00 BTU/HR FT**2 F											
ITERATION ERROR:	E- 0.01 DEG.											
NQJ- 5												
870.13	878.70	904.61	946.63	968.41	909.37	810.13	723.09	648.94	585.78	531.94	485.97	446.60
413.08	384.31	359.67	338.58	320.52	305.07	291.87	280.60	270.99	262.80	255.85	249.95	244.95
240.74	237.21	234.25	231.81	229.81	228.20	226.93	225.98	225.32	224.93	224.81		
NQJ- 10												
554.53	558.70	571.33	592.78	623.63	664.74	717.26	782.56	859.75	901.30	850.53	759.22	678.91
610.45	552.14	502.46	460.12	424.03	393.28	367.08	344.77	325.79	309.65	295.95	284.34	274.51
266.23	259.27	253.46	248.64	244.70	241.52	239.03	237.15	235.85	235.08	234.83		
NQJ- 15												
365.84	367.46	372.36	380.68	392.64	408.58	428.93	454.26	485.29	522.90	568.15	622.38	687.04
761.50	601.81	758.70	680.00	610.93	552.22	502.38	460.08	424.17	393.71	367.88	346.01	327.52
311.94	298.86	287.93	278.87	271.44	265.46	260.77	257.24	254.78	253.33	252.85		
NQJ- 20												
301.03	301.71	303.80	307.33	312.42	319.19	327.85	338.64	351.86	367.89	387.19	410.31	437.92
470.83	510.00	556.55	611.84	677.34	752.41	793.16	751.30	674.57	607.37	550.42	502.28	461.65
427.42	398.70	374.73	354.85	338.57	325.45	315.15	307.41	302.02	298.83	297.79		

The first two sets of data in Table V ($NQJ = 5, 10$) refer to ribs located inside the eroded region; the other sets ($NQJ = 15, 20$) refer to ribs located outside this region. Surface temperatures at the rib are underlined in the output to facilitate inspection.

Several conclusions can be drawn by examining Table V. In all cases, the hot-spot temperature is located where the rib is installed; this is not unexpected because of the high conductivity of the rib material. If the rib is inside the eroded region, this hot-spot temperature is a strong function of rib location: Thus, a change in the angular position of the rib from 20° ($NQJ = 5$) to 45° ($NQJ = 10$) decreases the hot-spot temperature by about 37°C (67°F). However, such a trend is not found if the rib is located outside the eroded region. When the rib position is moved from 70° ($NQJ = 15$) to 95° ($NQJ = 20$), the hot-spot temperature drops only 4°C (8°F). Also, the hot spot is much cooler outside the eroded region. (Compare hot-spot temperatures for $NQJ = 15$ and $NQJ = 10$.) From this preliminary study it appears that the telltale rib indeed has a high potential to predict the cavity position and location. A more detailed analysis is in order for further substantiation.

C. Prediction of Surface Temperatures for a Three-dimensional Model

Surface temperatures for a three-dimensional model have been calculated using the computer program given in Appendix B. A total of 108 cases were tested, encompassing 54 cavity sizes, with each size tested for two values of convective coefficient. These test conditions are summarized in Table VI. For illustrative purposes, only one set of data output is used; it is shown in Tables VII and VIII and Figs. 18-22.

TABLE VI. Test Conditions
for Studies of Three-
dimensional Model^a

System Dimensions

Height = 508 mm (20 in.)

Cavity Sizes Tested

Cavity height = 50.8 mm (2 in.)

101.6 mm (4 in.)

152.4 mm (6 in.)

^aConditions given in this table are
in addition to those in Table III.

TABLE VII. Sample Output of Surface-temperature Distribution
for Study of a Three-dimensional Model^a

DIMENSION:	ID= 4.00 IN.,OD= 10.50 IN., (TOTAL) HEIGHT= 20.00 IN.
	REFRACTORY THICKNESS= 3.00 IN.,SHELL THICKNESS= 0.25 IN.
CAVITY SIZE:	DEPTH= 1.75 IN., (HALF) ANGLE= 60.00 DEG.
	(HALF) HEIGHT= 4.00 IN.
MESH SIZE:	RADIAL= 0.250 IN.,ANGULAR= 15.00 DEG.,AXIAL= 2.00 IN.
TEMPERATURES:	INSIDE SURFACE= 1500.00 DEG.,AMBIENT= 80.00 DEG.
PROPERTIES:	K FOR REF.= 4.60, K FOR SHELL= 324.00 BTU IN./HR FT**2 F
	H= 10.00 BTU/HR FT**2 F
ITERATION ERROR :	E= 0.10 DEG.

0.3899547520D+03	0.3881871355D+03	0.3822654137D+03	0.3701768897D+03	0.3483212548D+03
0.3141240687D+03	0.2848730100D+03	0.2643068513D+03	0.2510403843D+03	0.2429260096D+03
0.2382365105D+03	0.2358361864D+03	0.2351013763D+03		
0.3830147199D+03	0.3813386428D+03	0.3757178647D+03	0.3642019465D+03	0.3432468166D+03
0.3102067229D+03	0.2821306552D+03	0.2625272120D+03	0.2499457392D+03	0.2422716051D+03
0.2378422950D+03	0.2355750710D+03	0.2348813648D+03		
0.3573585806D+03	0.3559657728D+03	0.3513070999D+03	0.3417781416D+03	0.3243208024D+03
0.2963343464D+03	0.2736110878D+03	0.2569373658D+03	0.2466614960D+03	0.2403795197D+03
0.2367334533D+03	0.2348571229D+03	0.2342805940D+03		
0.3005147367D+03	0.2995436071D+03	0.2964080132D+03	0.2905209480D+03	0.2811652999D+03
0.2686376391D+03	0.2570412304D+03	0.2480911486D+03	0.2418320329D+03	0.2377382648D+03
0.2352438086D+03	0.2339173148D+03	0.2335033907D+03		
0.2686575763D+03	0.2680358136D+03	0.2661168184D+03	0.2527836781D+03	0.2580277704D+03
0.2522710062D+03	0.2466360086D+03	0.2418826581D+03	0.2382610833D+03	0.2357159216D+03
0.2340754086D+03	0.2331693676D+03	0.2328806388D+03		
0.2592284691D+03	0.2587335427D+03	0.2572355214D+03	0.2547246041D+03	0.2512992417D+03
0.2472948110D+03	0.2433014875D+03	0.2397979473D+03	0.2370173478D+03	0.2349909110D+03
0.2336478611D+03	0.2328910018D+03	0.2326478393D+03		

^aTemperatures in °F. Conversion factor: °C = (°F - 32)/1.8.TABLE VIII. Features Defined by Data in Table VII^a

TOTAL VOLUME UNDERNEATH THE SURFACE= 0.74356E+05		
ISOTHERM TEMPERATURE	AREA INSIDE THE ISOTHERM	INTEGRATED VOLUME
232.6	0.2750E+03	0.1038E+05
240.5	0.1810E+03	0.8685E+04
248.4	0.1470E+03	0.7388E+04
256.2	0.1290E+03	0.6310E+04
264.1	0.9900E+02	0.5447E+04
272.0	0.8300E+02	0.4743E+04
279.8	0.7900E+02	0.4117E+04
287.7	0.6900E+02	0.3550E+04
295.6	0.6500E+02	0.3027E+04
303.4	0.5100E+02	0.2594E+04
311.3	0.4700E+02	0.2197E+04
319.2	0.4500E+02	0.1838E+04
327.0	0.4100E+02	0.1495E+04
334.9	0.4100E+02	0.1172E+04
342.8	0.3700E+02	0.8535E+03
350.6	0.3100E+02	0.5966E+03
358.5	0.2100E+02	0.3939E+03
366.4	0.1700E+02	0.2374E+03
374.2	0.1500E+02	0.1116E+03
382.1	0.7000E+01	0.2226E+02

^aTemperatures are in °F. Conversion factor: °C = (°F - 32)/1.8.

Fig. 18

A Three-dimensional Surface-temperature Plot Using Data in Table VII. Temperatures in °F. Conversion factor. °C = (°F - 32)/1.8. ANL Neg. No. 306-80-130.

Fig. 19

A Three-dimensional Plot of the Cavity Configuration Reconstructed from the Temperature Data in Fig. 18. ANL Neg. No. 306-80-134.

SURFACE ISOTHERM CONTOURS:

LEGEND:

SYMBOL	ISOTHERM BAND WIDTH (DEG.F)	
A	200.0 TO	207.4
B	219.0 TO	228.5
C	233.1 TO	247.5
D	257.1 TO	266.6
E	276.2 TO	285.6
F	295.2 TO	304.7
G	314.3 TO	323.7
H	333.3 TO	342.8
I	352.4 TO	361.8
J	371.4 TO	380.9
K	390.5 TO	400.0

NOTE: ALTHOUGH ELEVEN SYMBOLS ARE USED TO REPRESENT ISOTHERM BANDS IN THE LEGEND, THE TEMPERATURE RANGES FOR THESE SYMBOLS HAVE BEEN SELECTED SUCH THAT TWENTY ONE BANDS CAN BE READ OFF FROM THE ISOTHERM MAP. NOTE THAT THE TEMPERATURE RANGES IN THE LEGEND ARE DISCONTINUOUS, SIGNIFYING THAT A WHITE BAND EXISTS IN BETWEEN THE NEIGHBORING LETTERED BANDS; THE TEMPERATURE RANGE FOR THE WHITE BAND IS BRIDGED IN BETWEEN THOSE OF THE NEIGHBORING BANDS.

```

*****
CCC DDDDD CCC
CCC DDD DDD CCC
C E FFFFF E C
CC F H III H F CC
C DE J J ED C
CC DE ED CC
C DE J J ED C
CC F H III H F CC
C E FFFFF E C
CCC DDD DDD CCC
CCC DDDDD CCC
*****

```

Fig. 20. A Surface Isotherm Map for Data in Table VII

Fig. 21

Plot of Areas Enclosed inside Isotherm
Loops (Table VIII) vs Temperature.
Conversion factor: $^{\circ}\text{C} = (^{\circ}\text{F} - 32)/1.8$.
ANL Neg. No. 306-80-154.

Fig. 22

Integrated Energy Equivalents from
Table VIII vs Temperature. Con-
version factor: $^{\circ}\text{C} = (^{\circ}\text{F} - 32)/1.8$.
ANL Neg. No. 306-80-151.

Table VII gives the surface temperatures (in $^{\circ}\text{F}$) for the test conditions given at the top of the table. The temperatures are listed according to the following computer instruction:

DO 29 K = 1, NK

29 WRITE(6.30) (TNEW(NII, J, K), J = 1, NJ)

Hence, the first temperature in the data array represents the hotspot, the last the cold spot. This temperature array was also used to reconstruct the total temperature field and was plotted in three dimensions as shown in Fig. 18. In the three-dimensional plot, the spatial coordinates are indexed with numerals. They can be converted to actual coordinates using the mesh size given in the legend of Table VII. A reconstruction of the cavity configuration was also attempted, as shown in Fig. 19. The top flat surface in the plot represents the inside refractory surface.

Figure 20 presents an isotherm map; the legend at the top of the figure lists the temperature ranges for the bands coded in the map. A short paragraph of explanation is also provided in the figure to clarify how the isotherm map can be used to read additional bands not coded in the map.

Features extracted from the temperature data in Table VII are listed in Table VIII. The integrated-volume (also called energy-equivalent) data refer to the volume lying underneath a temperature surface, but contained above a specified temperature level. The area and volume data in Table VIII are plotted in Figs. 21 and 22, respectively. The integrated energy-equivalent curve (Fig. 22) appears to be smoother than the area curve (Fig. 21).

To study the effect of cavity-depth changes on surface temperatures, temperature data for three cavity configurations are presented in a composite diagram (Fig. 23). The figure shows clearly that a deepening of the cavity, while the cavity cross section remains constant, not only increases the volume lying underneath the temperature surface, but also raises the maximum and minimum temperature readings measured on the surface. In a like fashion, if the cavity cross section is increased while the cavity depth remains constant, both the volume and the temperature readings again increase (see Fig. 24). As a further attempt to quantify these observations, features were extracted from these temperature data and replotted in Figs. 25 and 26. The legs of the integrated energy-equivalent curves in Fig. 25 shift rapidly toward the right when the cavity is deepened. However, only a slight shift of the curves is noted if the cavity cross section is enlarged (see Fig. 26).

The method given above is probably adequate to predict the cavity configuration if the temperature data can be used for detailed analysis. The method is still too complicated for practical purposes, and simplification is desirable. This was done by picking two features for comparison. Among those features that are easily extractable from the scanned data are (a) the total volume lying underneath the temperature surface, (b) the maximum temperature reading on the surface, and (c) the minimum temperature reading on the surface. A calculation of these three features for a wide range of cavity configurations is shown in Table IX. Of the three, total volume and maximum temperature (columns 5 and 6, respectively) are the most sensitive to cavity configuration; minimum temperature (last column) shows a spread of only 9.5°F (5.3°C) for the wide range of cavities tested, illustrating well the insensitivity of this feature to the presence of flaws.

In Fig. 27, total volume is plotted against maximum surface temperature for each output line of Table IX. To facilitate interpretation of Fig. 27, solid curves have been fitted to all points that have identical cavity cross sections; dashed curves have been fitted to all points sharing identical cavity depths. Obviously, fitting the solid curves by means of a linear function yields satisfactory results; however, data scattering is evident with respect to the dashed curves, particularly for large cavities.

A close examination of Fig. 27 reveals that the data points tend to converge if they share the same cavity cross section and if their cavity widths have similar aspect ratios. For example, points 48 and 50 with cross sections of 60° x 150 mm and 90° x 100 mm, respectively, and therefore a common product of 9000°·mm, converge. This trend is also seen from pairs 3 and 5, 12 and 14, 21 and 23, 30 and 32, and 39 and 41. However, such a trend is not found if the cavity width is disproportionately expanded in one direction. For example, points 47 and 52, with cross sections of 60° x 100 mm and 120° x 50 mm, respectively, fall far apart in the chart, although they share a product of 6000°·mm. Other pairs of points showing the same behavior include 2 and 7, 11 and 16, 20 and 25, 29 and 34, and 38 and 43. In practice, the one nearest-neighbor rule in pattern-recognition theory²⁷ can be used, together with the chart, to predict erosive wear.

Cavity Size: 12.7 mm x 120° x 304.8 mm; 25.4 mm x 120° x 304.8 mm; 38.1 mm x 120° x 304.8 mm

Fig. 23. Effect of Cavity Depth on Temperature. Top row: reconstructions of three cavity configurations. Bottom row: three-dimensional surface-temperature plots. Temperatures in °F. Conversion factor: $^{\circ}\text{C} = (^{\circ}\text{F} - 32)/1.8$. ANL Neg. No. 306-77-398.

Cavity Size: 25.4 mm x 120° x 101.6 mm; 25.4 mm x 180° x 203.2 mm; 25.4 mm x 240° x 304.8 mm

Fig. 24. Effect of Cavity Width on Temperature. Top row: reconstructions of three cavity configurations. Bottom row: three-dimensional surface-temperature plots. Temperatures in °F. Conversion factor: $^{\circ}\text{C} = (^{\circ}\text{F} - 32)/1.8$. ANL Neg. No. 306-77-399.

AREA ENCLOSED INSIDE ISOTHERM LOOPS

INTEGRATED ENERGY EQUIVALENT

Fig. 25. Feature Curves for Cases in Fig. 23. Temperatures in °F. Conversion factor: °C = (°F - 32)/1.8. ANL Neg. No. 306-77-397.

AREA ENCLOSED INSIDE ISOTHERM LOOPS

INTEGRATED ENERGY EQUIVALENT

Fig. 26. Feature Curves for Cases in Fig. 24. Temperatures in °F. Conversion factor: $^{\circ}\text{C} = (^{\circ}\text{F} - 32)/1.8$. ANL Neg. No. 306-77-400.

TABLE IX. Computer Data Used for Prediction of Cavity Configuration

NO	DEPTH ^a	WIDTH ^b	HEIGHT ^a	TOTAL V (ENERGY EQUIVALENT)	MAX T ^c	MIN T ^c
1	0.50	60.0	2.0	44039.3	171.1	158.1
2	0.50	60.0	4.0	44406.4	173.6	158.1
3	0.50	60.0	6.0	44792.6	174.5	158.2
4	0.50	90.0	2.0	44273.1	171.6	158.2
5	0.50	90.0	4.0	44790.3	174.3	158.3
6	0.50	90.0	6.0	45360.2	175.3	158.7
7	0.50	120.0	2.0	44512.8	171.7	158.3
8	0.50	120.0	4.0	45209.8	174.5	158.8
9	0.50	120.0	6.0	45941.2	175.6	159.7
10	0.75	60.0	2.0	44444.8	180.2	158.1
11	0.75	60.0	4.0	45062.4	184.1	158.2
12	0.75	60.0	6.0	45712.2	185.5	158.3
13	0.75	90.0	2.0	44838.4	180.9	158.2
14	0.75	90.0	4.0	45729.3	185.1	158.5
15	0.75	90.0	6.0	46639.1	186.6	159.0
16	0.75	120.0	2.0	45268.0	181.2	158.6
17	0.75	120.0	4.0	46412.1	185.4	159.3
18	0.75	120.0	6.0	47638.7	187.1	160.9
19	1.00	60.0	2.0	44951.6	191.7	158.2
20	1.00	60.0	4.0	45875.9	197.1	158.2
21	1.00	60.0	6.0	46874.0	199.2	158.5
22	1.00	90.0	2.0	45543.4	192.6	158.3
23	1.00	90.0	4.0	46860.1	198.4	158.7
24	1.00	90.0	6.0	48243.0	200.6	159.4
25	1.00	120.0	2.0	46176.2	192.9	158.8
26	1.00	120.0	4.0	47892.8	198.9	159.9
27	1.00	120.0	6.0	49717.8	201.2	162.2
28	1.25	60.0	2.0	45585.6	206.3	158.2
29	1.25	60.0	4.0	46892.5	213.6	158.3
30	1.25	60.0	6.0	48291.2	216.3	158.6
31	1.25	90.0	2.0	46454.0	207.5	158.5
32	1.25	90.0	4.0	48300.3	215.3	159.0
33	1.25	90.0	6.0	50236.9	218.1	160.0
34	1.25	120.0	2.0	47342.2	207.9	159.1
35	1.25	120.0	4.0	49739.2	215.8	160.5
36	1.25	120.0	6.0	52301.0	218.8	163.7
37	1.50	60.0	2.0	46394.8	225.4	158.2
38	1.50	60.0	4.0	48212.5	235.1	158.5
39	1.50	60.0	6.0	50095.7	238.4	158.8
40	1.50	90.0	2.0	47585.7	226.9	158.6
41	1.50	90.0	4.0	50104.2	237.0	159.2
42	1.50	90.0	6.0	52803.5	240.8	160.6
43	1.50	120.0	2.0	48862.6	227.3	159.3
44	1.50	120.0	4.0	52118.5	237.7	161.4
45	1.50	120.0	6.0	55611.0	241.6	165.5
46	1.75	60.0	2.0	47454.3	251.3	158.2
47	1.75	60.0	4.0	49917.9	263.9	158.5
48	1.75	60.0	6.0	52494.9	268.3	159.0
49	1.75	90.0	2.0	49080.1	253.2	158.7
50	1.75	90.0	4.0	52524.1	266.4	159.6
51	1.75	90.0	6.0	56152.7	271.1	161.2
52	1.75	120.0	2.0	50758.6	253.7	159.7
53	1.75	120.0	4.0	55228.0	267.1	162.3
54	1.75	120.0	6.0	59965.5	272.1	167.6

^aIn inches. Conversion factor: 1 in. = 25.4 mm^bHalf the angular span of the cavity, in degrees^cIn °F. Conversion factor: °C = (°F - 32)/1.8

Fig. 27

Chart for Predicting Cavity Configurations.
 Conversion factor: °C = (°F - 32)/1.8.
 ANL Neg. No. 306-80-156.

D. Prediction of Surface Temperatures for a Three-dimensional Model with a Dual-component Wall Lining

Surface temperatures were also calculated using the three-dimensional heat-transfer model with a dual-layered refractory lining. The materials used in the analysis are those of the CO₂ Acceptor Plant test section, shown schematically in Fig. 28. The computer program developed for this case is included as Appendix F. Again, for illustrative purposes, results for only two conditions will be presented. Table X and Fig. 29 provide outputs for a 12.7-mm (0.5-in.)-deep cavity. The case of a 38.1-mm (1.5-in.)-deep cavity was also calculated, and the results are shown in Table XI and Fig. 30. Input

Fig. 28

Schematic Diagram Showing Construction of a Transfer Line with Double-layered Refractory Lining. ANL Neg. No. 306-80-143.

TABLE X Surface-temperature Data for System Shown in Fig. 28 with a 0.5-in. (12.7-mm)-deep Cavity

DIMENSION: ID= 4.00 IN., OD= 10.50 IN., (TOTAL) HEIGHT= 20.00 IN. REFRACTORY THICKNESS: (INNER)= 2.00 IN., (OUTER)= 1.00 IN. SHELL THICKNESS= 0.25 IN. CAVITY SIZE: DEPTH= 0.50 IN., (HALF) ANGLE= 90.00 DEG. (HALF) HEIGHT= 4.00 IN. MESH SIZE: RADIAL= 0.250 IN., ANGULAR= 15.00 DEG., AXIAL= 2.00 IN. TEMPERATURES: INSIDE SURFACE= 1200.00 DEG., AMBIENT= 80.00 DEG. PROPERTIES: K FOR REF.: (INNER)= 16.00 (OUTER)= 2.00 K FOR SHELL= 324.00 BTU IN./HR FT**2 F H= 10.00 BTU/HR FT**2 F ITERATION ERROR: E= 0.10 DEG.				
0.2344004052D+03	0.2343496408D+03	0.2341918733D+03	0.2339046360D+03	0.2334525790D+03
0.2327945772D+03	0.2319125788D+03	0.2308720245D+03	0.2298774226D+03	0.2290620924D+03
0.2284727543D+03	0.2281142554D+03	0.2279897870D+03		
0.2339900265D+03	0.2339351663D+03	0.2337695602D+03	0.2334746831D+03	0.2330225376D+03
0.2323921945D+03	0.2315925393D+03	0.2306918663D+03	0.2298125749D+03	0.2290597439D+03
0.2284889604D+03	0.2281223387D+03	0.2279785988D+03		
0.2326638216D+03	0.2326178762D+03	0.2324790738D+03	0.2322327243D+03	0.2318599764D+03
0.2313480106D+03	0.2307095293D+03	0.2299976418D+03	0.2293012508D+03	0.2286979777D+03
0.2282340698D+03	0.2279303610D+03	0.2278089449D+03		
0.2303888084D+03	0.2303614936D+03	0.2302734781D+03	0.2301180827D+03	0.2298882864D+03
0.2295835439D+03	0.2292150326D+03	0.2288119915D+03	0.2284154084D+03	0.2280649763D+03
0.2277880215D+03	0.2276031617D+03	0.2275287375D+03		
0.2289194931D+03	0.2289049331D+03	0.2288535036D+03	0.2287611798D+03	0.2286270870D+03
0.2284532890D+03	0.2282484436D+03	0.2280269602D+03	0.2278086363D+03	0.2276122806D+03
0.2274542312D+03	0.2273466711D+03	0.2273033087D+03		
0.2284467183D+03	0.2284338973D+03	0.2283922041D+03	0.2283195492D+03	0.2282149825D+03
0.2280813651D+03	0.2279248865D+03	0.2277569424D+03	0.2275910646D+03	0.2274419984D+03
0.2273220074D+03	0.2272424620D+03	0.2272130095D+03		

THREE-DIMENSIONAL SURFACE TEMPERATURE PLOT

RECONSTRUCTION OF CAVITY CONFIGURATION

AREA ENCLOSED INSIDE ISOTHERM LOOPS

INTEGRATED ENERGY EQUIVALENT

Fig. 29. Feature Data for Case in Table X. Temperatures in °F. Conversion factor:
 $^{\circ}\text{C} = (^{\circ}\text{F} - 32)/1.8$. ANL Neg. No. 306-80-139.

RECONSTRUCTION OF CAVITY CONFIGURATION

THREE-DIMENSIONAL SURFACE TEMPERATURE PLOT

AREA ENCLOSED INSIDE ISOTHERM LOOPS

INTEGRATED ENERGY EQUIVALENT

Fig. 30. Feature Data for Case in Table XI. ANL Neg. No. 306-80-136.

TABLE XI. Surface-temperature Data for System Shown in
Fig. 28 with a 1.5-in. (38.1-mm)-deep Cavity

DIMENSION: ID= 4.00 IN., OD= 10.50 IN., (TOTAL) HEIGHT= 20.00 IN. REFRACTORY THICKNESS: (INNER)= 2.00 IN., (OUTER)= 1.00 IN. SHELL THICKNESS= 0.25 IN.				
CAVITY SIZE: DEPTH= 1.50 IN., (HALF) ANGLE= 90.00 DEG. (HALF) HEIGHT= 4.00 IN.				
MESH SIZE: RADIAL= 0.250 IN., ANGULAR= 15.00 DEG., AXIAL= 2.00 IN.				
TEMPERATURES: INSIDE SURFACE= 1200.00 DEG., AMBIENT= 80.00 DEG.				
PROPERTIES: K FOR REF.: (INNER)= 16.00 (OUTER)= 2.00 K FOR SHELL= 324.00 BTU IN./HR FT**2 F H= 10.00 BTU/HR FT**2 F				
ITERATION ERROR: E= 0.10 DEG.				
0.2505967254D+03	0.2504884606D+03	0.2501463323D+03	0.2495030506D+03	0.2484354027D+03
0.2467453387D+03	0.2441479166D+03	0.2404704732D+03	0.2370035863D+03	0.2342594590D+03
0.2323274744D+03	0.2311742841D+03	0.2307790918D+03		
0.2495683584D+03	0.2494480167D+03	0.2490764909D+03	0.2483809348D+03	0.2472334398D+03
0.2454761341D+03	0.2429990871D+03	0.2399389806D+03	0.2368930301D+03	0.2343174728D+03
0.2324064448D+03	0.2312074518D+03	0.2307514478D+03		
0.2459558378D+03	0.2458470420D+03	0.2455147556D+03	0.2448979397D+03	0.2438957278D+03
0.2423908624D+03	0.2403255967D+03	0.2378390916D+03	0.2353606603D+03	0.2332410167D+03
0.2316495321D+03	0.2306365588D+03	0.2302446070D+03		
0.2383591293D+03	0.2382830960D+03	0.2380501016D+03	0.2376331562D+03	0.2369905732D+03
0.2360881905D+03	0.2349294842D+03	0.2335998433D+03	0.2322674317D+03	0.2310936756D+03
0.2301817021D+03	0.2295887242D+03	0.2293608117D+03		
0.2336310841D+03	0.2335825479D+03	0.2334324736D+03	0.2331692600D+03	0.2327818752D+03
0.2322650092D+03	0.23163478.01D+03	0.2309347785D+03	0.2302357746D+03	0.2296088448D+03
0.2291117341D+03	0.2287838122D+03	0.2286594913D+03		
0.2321501970D+03	0.2321108297D+03	0.2319887500D+03	0.2317786593D+03	0.2314740137D+03
0.2310768321D+03	0.2306008304D+03	0.2300796840D+03	0.2295602485D+03	0.2290938615D+03
0.2287229159D+03	0.2284816220D+03	0.2283950279D+03		

data for the runs are listed at the tops of the tables. In each table, the first and last temperature in the output array represent the hot spot and cold spot, respectively.

For a cavity depth of 12.7 mm (0.5 in.), because of the presence of an insulation layer between the inner refractory and the steel shell, the hot-spot temperature at the steel surface is only 4°C (7°F) higher than the cold-spot temperature (see Table X). This temperature difference is raised to 12°C (22°F) if the cavity is deepened to 38.1 mm (1.5 in.) (see Table XI). A thin layer of insulation is thus seen to markedly diminish the temperature gradient on the surface. The shift of curves in the feature plots is also drastically reduced (compare Figs. 29 and 30). Both of these findings point to the fact that in dual-layered systems, the insulation layer might render infrared scanning useless for erosion detection.

E. Prediction of Surface Temperatures for a Three-dimensional Model with Contact Resistances

In the previous calculations, no consideration was given to contact resistance between the steel shell and the refractory lining. This resistance will be considered here, and the computer programs given in Appendix G will be used to examine the effect of contact resistance on surface-temperature distributions.

For a uniform contact resistance between the refractory lining and the steel shell, the resistance plays the role of the second insulation layer studied previously. Figure 31 is a composite diagram comparing the effects of various

Fig. 31. Comparison of Three-dimensional Surface-temperature Plots Obtained with Indicated Values (in h-deg/Btu) of Uniform Interfacial Contact Resistance. Note the different ordinate scale in (a), the no-resistance case. Temperatures in °F. Conversion factor: $^{\circ}\text{C} = (^{\circ}\text{F} - 32)/1.8$. ANL Neg. No. 306-80-137.

uniform contact resistances. The test conditions are summarized in Table XII. From Figs. 31b-31f, the resistance increases ninefold; the difference between the calculated peak and minimum temperatures in Fig. 31b is 11°C (20°F), in contrast to only 4°C (8°F) in Fig. 31f. Figure 31a is a no-resistance case included for comparison.

TABLE XII. Test Conditions for Data Presented in Fig. 31

DIMENSION:	ID= 4.00 IN., OD= 10.50 IN., (TOTAL) HEIGHT= 20.00 IN.
	REFRACTORY THICKNESS= 3.00 IN., SHELL THICKNESS= 0.25 IN.
CAVITY SIZE:	DEPTH= 0.50 IN., (HALF) ANGLE= 120.00 DEG.
	(HALF) HEIGHT= 6.00 IN.
MESH SIZE:	RADIAL= 0.250 IN., ANGULAR= 15.00 DEG., AXIAL= 2.00 IN.
TEMPERATURES:	INSIDE SURFACE= 1500.00 DEG., AMBIENT= 80.00 DEG.
PROPERTIES:	K FOR REF.= 4.60, K FOR SHELL= 324.00 BTU IN./HR FT**2 F
	H= 10.00 BTU/HR FT**2 F
ITERATION ERROR:	E= 0.10 DEG.

In a similar manner, the effect of a nonuniform contact resistance at the interface is examined as shown in Fig. 32. Test conditions are summarized in Table XIII. The contact-resistance function used in the modeling has been given as Eq. 32. The test conditions given here represent a deep-cavity case, which, in the no-resistance condition, has the temperature distribution shown in Fig. 32a. Because of the resistance, the temperature distribution becomes distorted. In the last plot (Fig. 32f), the temperature distribution is so distorted that one might suspect that the pipe has a ringlike cavity because of the dip of the center temperature. As a means of checking what resistance values have been used for tests at the interface, a plot of contact resistance is also shown in Fig. 33.

F. Study of Distortions of Infrared Images

In this section, the sample output for the three-dimensional model study (Table VII) will be used to illustrate image distortions. With reference to Fig. 8, it is assumed that the transfer line [$r_0 = 0.1333$ m (5.25 in.)] is located at a distance $D = 1.524$ m (60 in.) from the camera. For this test setup, Fig. 9 can be used to study the spatial distortions of the image, and Figs. 14 and 15 to study thermal distortions.

For convenience, only the isotherm contour in the first quadrant is presented in Fig. 34. Curve a refers to the isotherm contour for $T = 157.2^\circ\text{C}$ (315°F) as predicted by the model. The coordinates used for this plot are z versus polar angle. Because of the spatial distortion, the actual infrared image observed on the oscilloscope screen will not be what curve a predicts: The actual image observed is curve b. This isotherm contour is viewed in a z -versus-view-angle coordinate system and is obtained using Fig. 9 for correction. Here a displacement of the contour is clearly noted in the angular direction.

(a) 0

(b) 1.25

(c) 1.75

(d) 2.25

(e) 2.75

(f) 3.25

Fig. 32. Comparison of Three-dimensional Surface-temperature Plots Obtained with Various Nonuniform Interfacial Contact Resistances. The peak resistance parameter f for each plot is indicated. Note the different ordinate scale in (a), the ∞ -resistance case. Temperatures in $^{\circ}\text{F}$. Conversion factor: $^{\circ}\text{C} = (^{\circ}\text{F} - 32)/1.8$. ANL Neg. No. 306-80-138.

(a)

(b)

(c)

(d)

(e)

Fig. 33. Three-dimensional Plots of Variable Interfacial Resistances
Used to Generate Temperature Plots Presented in Fig. 32.
ANL Neg. No. 306-80-135.

TABLE XIII. Test Conditions for Data Presented in Fig. 32

DIMENSION:	ID= 4.00 IN.,	OD= 10.50 IN.,	(TOTAL) HEIGHT= 20.00 IN.
	REFRACTORY THICKNESS= 3.00 IN.,	SHELL THICKNESS= 0.25 IN.	
CAVITY SIZE:	DEPTH= 1.50 IN.,	(HALF) ANGLE= 120.00 DEG.	
	(HALF) HEIGHT= 6.00 IN.		
MESH SIZE:	RADIAL= 0.250 IN.,	ANGULAR= 15.00 DEG.,	AXIAL= 2.00 IN.
TEMPERATURES:	INSIDE SURFACE= 1500.00 DEG.,	AMBIENT= 80.00 DEG.	
PROPERTIES:	K FOR REF.= 4.60,	K FOR SHELL= 324.00 BTU IN./HR FT**2 F	
	H= 10.00 BTU/HR FT**2 F		
ITERATION ERROR:	E= 0.10 DEG.

Fig. 34

Distortion of Infrared Images. ANL
Neg. No. 306-78-525.

Depending on the surface material, one could anticipate another distortion resulting from surface-emissivity effects. If the surface has optical constants given as $n = 4$, $k = 0$, then Fig. 15 can be used for correction, yielding curve c of Fig. 34. In this correction, the data predicted in Table VII were multiplied by $\epsilon^{1/4}$, which is a function of the view angle. Of course, this method can also be applied to correct for emissivity effects if the surface is made of metal with, say, $n = 4$, $k = 10$. For the latter case, Fig. 14 would have been used. As it turns out, the small emissivities of metals make the corrected temperatures so low that even the hot-spot temperature [predicted value 198.86° (389.95°F)] in Table VII drops to 119°C (234°F). Toward the edge of the pipe, where the emissivity increases (peak value ≈ 0.24), a multiplication correction factor of about 0.7 is necessary, but the temperature there has also declined to such a level that the resulting temperature is too low to be presented in the image without readjusting the infrared camera settings.

If the isotherm on the camera is selected to be initially located near the center of the view field, the spatial correction will be very small because of the linearity between polar and view angles. However, the temperature distortion will still be present, unless the body is painted black.

VII. CONCLUSIONS AND RECOMMENDATIONS

This analytical study has shown that a quantitative erosive-wear determination through the use of infrared scanning cameras, which are sensitive only to surface-temperature distributions, is extremely difficult. Although three-dimensional heat-transfer models can be established, variables that are unknown to the individual conducting the test can lead to erroneous conclusions in a quantitative sense. One such variable is the thermal-contact resistance. However, if the investigator can be assured that thermal-contact resistance is minimal or at least uniform, then refractory linings up to 200 mm thick on steel piping up to 12 mm thick can be examined. Thicker steel boundaries conduct the heat so rapidly that up to 50% of the thickness of the refractory wall must be eroded before temperature gradients can be sensed.

This study has shown that similar surface-temperature profiles are obtained for cavities (eroded sections) that are reasonably shallow with a large cross section, and cavities that are reasonably deep with small cross sections. These can be discriminated only if the images are analyzed further to determine, for example, the area inside isotherms and the integrated energy (volume) equivalent. Additionally, scanning of round objects produces thermal-image distortion owing to surface-emissivity direction effects.

It is therefore the conclusion of this analysis that erosive wear cannot be determined quantitatively and the cavity geometry cannot be defined without the risk of large errors.

APPENDIX A

Computer Program for a Two-dimensional System

A computer program for evaluating the surface temperature in a two-dimensional system has been developed and is shown in Fig. A.1. Input variables used in the program are defined in Table A.1. The algorithm for the program is given as follows:

1. Lines 6-8 convert SPACEI and SPACEJ to integer constants that are used later to generate a wide range of cavity sizes for tests in the program.

2. Lines 9-14, 17-21, and 30-33 calculate the nodal locations that are used later in various DO loops as index parameters. (See Fig. A.2 for these nodal locations.)

3. Lines 15 and 16 calculate the index parameters for the largest cavity size tested in the program. MIL and MJL represent maximum values that L and M may assume in the DO statements appearing on lines 28 and 29.

4. Lines 22-27 define and compute additional parameters that are later used in the temperature equation. These parameters are defined as follows:

Line 22	DLIS	= $(\Delta r)^2$
Line 23	DLJV	= $1/(\pi\Delta\theta/180)^2$
Line 24	DLIH	= $\Delta r/2$
Line 25	CON1R	= $k_1/(\Delta r)^2$
Line 26	CON2R	= $k_2/(\Delta r)^2$
Line 27	CON12	= $k_1 + k_2$

5. Lines 34-36 initialize all nodal temperatures to $(T_i + T_\infty)/2$.

6. Lines 37-43 set the temperatures at the refractory surface and inside the cavity as T_i , which is unchanged in the course of iteration. This assignment is made by using two DO loops in the program.

7. Starting on line 44 and ending on line 95, the program calculates temperatures (TNEW) at each point in the system. Before the calculation is made, a series of cards placed before the TNEW statements computes the parameters that are later used in the TNEW equation. (For example, lines 47-50 calculate parameters C1, C2, C3, and C4, which appear in the TNEW equation on line 51.) In all instances, these parameters are radially dependent.

```

0001      DOUBLE PRECISION DLI,DLIS,DLJV,DLIH,CON1R,CON2R,CON12,RIR,RI,C1,
      / C2,C3,C4,RII,C1I,C2I,C3I,C4I,RIS,C1S,C2S,C3S,C4S,T(15,15),
      / TNEW(15,15)
0002      READ (5,1) RINS,ROUT,TR,DPMIN,DPMAX,ACHIN,ACHAX,DELR,DLJ,
      / SPACEI,SPACEJ
0003      1 FORMAT (11F6.2)
0004      READ (5,41) TT,TA,H,CON1,CON2,EPS
0005      41 FORMAT (6F8.2)
0006      DLI=1./DELR
0007      INCRI=SPACEI/DLI
0008      INCRJ=SPACEJ/DLJ
0009      NII=(ROUT-RINS)/DLI+1.
0010      KNII=NII
0011      NJ=180./DLJ+1.
0012      LJ=NJ-1
0013      MIN=DPMIN/DLI+1.
0014      MJN=ACHIN/DIJ+1.
0015      MIL=1.+(DPMAX-DMIN)/SPACEI
0016      MJL=1.+(ACHAX-ACHIN)/SPACEJ
0017      NI=TR/DLI+1.
0018      KNI=NI
0019      LI=NI-1
0020      KII=NI+1
0021      LII=NII-1
0022      DIIS=DII**2
0023      DLJV=1./((3.14159*DLJ/180.))**2)
0024      DLIH=DII/2.
0025      CON1R=CON1/DLIS
0026      CON2R=CON2/DLIS
0027      CON12=CON1+CON2
0028      DO 50 L=1,MIL
0029      DO 50 M=1,MJL
0030      MI=MIN+(L-1)*INCRI
0031      MJ=MJN+(M-1)*INCRJ
0032      KI=MI+1
0033      KJ=MJ+1
0034      DO 2 I=1,NII
0035      DO 2 J=1,NJ
0036      2 T(I,J)=.5*(TT+TA)
0037      DO 3 J=1,NJ
0038      TNEW(1,J)=TT
0039      3 T(1,J)=TT
0040      DO 4 I=2,NI
0041      DO 4 J=1,MJ
0042      TNEW(I,J)=TT
0043      4 T(I,J)=TT
0044      80 DO 5 I=KI,LI
0045      RIR=I-1
0046      RI=RIR*DLI+RINS
0047      C1=(RI-DLIH)/DLIS
0048      C2=(RI+DLIH)/DLIS
0049      C3=DLJV/RI
0050      C4=2.*(RI/DLIS+C3)
0051      5 TNEW(I,1)=(C1*T(I-1,1)+C2*T(I+1,1)+2.*C3*T(I,2))/C4
0052      DO 6 I=2,LI

```

Fig. A.1. Computer Program for Evaluating Surface Temperature in a Two-dimensional System

```

0053      RIR=I-1
0054      RI=RIR*DLI+RINS
0055      C1=(RI-DLIH)/DLIS
0056      C2=(RI+DLIH)/DLIS
0057      C3=DLJV/PI
0058      C4=2.*(RI/DLIS+C3)
0059 6 TNEW(I,NJ)=(C1*T(I-1,NJ)+C2*T(I+1,NJ)+2.*C3*T(I,LJ))/C4
0060 DO 7 I=2,MI
0061 DO 7 J=KJ,LJ
0062      RIR=I-1
0063      RI=RIR*DLI+RINS
0064      C1=(RI-DLIH)/DLIS
0065      C2=(RI+DLIH)/DLIS
0066      C3=DLJV/PI
0067      C4=2.*(RI/DLIS+C3)
0068 7 TNEW(I,J)=(C1*T(I-1,J)+C2*T(I+1,J)+C3*(T(I,J-1)+T(I,J+1)))/C4
0069 DO 8 I=KI,II
0070 DO 8 J=2,IJ
0071      RIR=I-1
0072      RI=RIR*DLI+RINS
0073      C1=(RI-DLIH)/DLIS
0074      C2=(RI+DLIH)/DLIS
0075      C3=DLJV/PI
0076      C4=2.*(RI/DLIS+C3)
0077 8 TNEW(I,J)=(C1*T(I-1,J)+C2*T(I+1,J)+C3*(T(I,J-1)+T(I,J+1)))/C4
0078      RII=(XNI-1.)*DLI+RINS
0079      C1I=CON1R*(RII-DLIH)
0080      C2I=CON2R*(RII+DLIH)
0081      C3I=.5*CON12*DLJV/RII
0082      C4I=C1I+C2I+2.*C3I
0083      TNEW(NI,1)=(C1I*T(NI-1,1)+C2I*T(NI+1,1)+2.*C3I*T(NJ,2))/C4I
0084      TNEW(NI,NJ)=(C1I*T(NI-1,NJ)+C2I*T(NJ+1,NJ)+2.*C3I*T(NI,NJ-1))/C4I
0085 DO 9 J=2,IJ
0086 9 TNEW(NI,J)=(C1I*T(NI-1,J)+C2I*T(NI+1,J)+C3I*(T(NI,J-1)+
/ T(NI,J+1)))/C4I
0087      RIS=(XNII-1.)*DLI+RINS
0088      C1S=CON2R*(RIS-DLIH)
0089      C2S=H*RIS/DLI
0090      C3S=.5*CON2*DLJV/RIS
0091      C4S=C1S+C2S+2.*C3S
0092      TNEW(NII,1)=(C1S*T(NII-1,1)+C2S*TA+2.*C3S*T(NII,2))/C4S
0093      TNEW(NII,NJ)=(C1S*T(NII-1,NJ)+C2S*TA+2.*C3S*T(NII,NJ-1))/C4S
0094 DO 10 J=2,LJ
0095 10 TNEW(NII,J)=(C1S*T(NII-1,J)+C2S*TA+C3S*(T(NII,J-1)+T(NII,J+1)))/
/ C4S
0096 DO 85 I=2,MI
0097 DO 85 J=KJ,NJ
0098 IF (DABS(T(I,J)-TNEW(I,J))-EPS) 95,85,40
0099 85 CONTINUE
0100 DO 27 I=KI,NII
0101 DO 27 J=1,NJ
0102 IF (DABS(T(I,J)-TNEW(I,J))-EPS) 27,27,40
0103 27 CONTINUE
0104 GO TO 90
0105 40 DO 31 I=2,MI

```

Fig. A.1 (Contd.)

```

0106      DO 31 J=KJ,NJ
0107      31 T(I,J)=TNPW(I,J)
0108      DO 32 I=KT,NII
0109      DO 32 J=1,NJ
0110      32 T(I,J)=TNBW(I,J)
0111      GO TO 80
0112      50 WRITE (6,30) (TNBW(NII,J),J=1,NJ)
0113      30 FORMAT (5D20.10)
0114      50 CONTINUE
0115      STOP
0116      END

```

Fig. A.1 (Contd.)

TABLE A.1. Definitions of Input Variables for Program in Fig. A.1

Variable Name	Definition	Unit
ACMAX	Maximum (half) angular span of the cavity to be tested in the program	Degree
ACMIN	Minimum (half) angular span of the cavity to be tested in the program	Degree
CON1	Thermal conductivity of refractory	Btu/h·ft ² ·°F/in.
CON2	Thermal conductivity of steel shell	Btu/h·ft ² ·°F/in.
DELR	Number of divisions per inch in the radial direction--a parameter to determine mesh size, $1/\Delta r$	1/in.
DLJ	Mesh size in the angular direction, $\Delta\theta$	Degree
DPMAX	Maximum depth of the cavity to be tested in the program	in.
DPMIN	Minimum depth of the cavity to be tested in the program	in.
EPS	Epsilon--convergence criterion	F
H	Convective heat-transfer coefficient	Btu/h·ft ² ·°F
RINS	Inside radius of the transfer line	in.
ROUT	Outside radius of the transfer line	in.
SPACEI	Increment of the cavity depth used in a series of tests of cavity sizes	in.
SPACEJ	Increment of the cavity (angular) span used in a series of tests of cavity sizes	Degree
TA	Ambient temperature, T_∞	F
TR	Thickness of the refractory	in.
TT	Refractory (inner) surface temperature, T_i	F

Fig. A.2

Schematic Diagram Showing Nodal Locations in a Two-dimensional System.
ANL Neg. No. 306-80-147.

Hence, they must be recalculated every time the I index is varied. This makes them reappear in nearly all DO loops in this part of the program. Of course, if desired, the set of statements between lines 45 and 50 could be written as a subprogram. But this would be done at the expense of the simplicity of other parts of the program.

8. Starting on line 96 and ending on line 103, two DO loops are used to check the convergence of the temperature data. If the convergence is not met, the program branches to statement 40 to assign the new temperature (TNEW) data to T, again using two DO loops. The GO TO statement on line 111 causes the computer to transfer control to statement 80 (line 44) to reinitiate iteration. This process is repeated until the convergence is realized. Then a normal exit from the DO loop (line 103) advances the computer control to line 104, where another GO TO statement instructs the computer to write the surface-temperature data according to the desired format.

To improve accuracy, all computations are carried out in double precision.

APPENDIX B

Computer Program for a Three-dimensional System

A computer program for evaluating the surface temperature in a three-dimensional system is shown in Fig. B.1. The method for indexing the nodal points in a three-dimensional system follows that of the two-dimensional system (Fig. A.2), except that a third coordinate is added along the axial direction (see Fig. B.2). Additional variables required for computer inputs are defined in Table B.1. Since the three-dimensional system represents a general case, the computer program was written with sufficient generality to perform the following functions:

1. Evaluate and tabulate the surface temperature on the steel shell.
2. Plot the surface temperature in three dimensions.
3. Plot the configuration of the cavity in three dimensions.
4. Construct an isotherm map for the surface-temperature distribution, with alphabets in the map to label various isotherm bands.
5. Calculate the total volume lying under the three-dimensional temperature surface that was previously plotted in item 2 above.
6. Tabulate the areas enclosed inside isotherm loops and the volumes lying under the temperature surface, with both evaluated as functions of temperature.
7. Use punched cards to record output data that include the depth, angular span and height of the tested cavity, the data for item 5 above, and the highest and lowest temperature readings observed on the surface of the steel shell.
8. Plot the data given in item 6 above for graphical presentation.

In the development of the computer program, provisions were made to use the computer to scan the output data so that all axes in the plots were drawn with proper lengths and scales. The figures were plotted by means of Argonne's DISSPLA routines. A combination of these features, built into the program, enables the user to run a wide range of test conditions without modification of the program. This capability can be seen from the algorithm as delineated below:

1. Lines 10-16 in the program (Fig. B.1) convert SPACEI, SPACEJ, and SPACEK to integer constants that are used later to generate a wide range of cavity sizes for tests in the program.
2. Lines 17-20, 27 and 28, and 43-50 calculate the index parameters for nodal locations shown in Figs. A.2 and B.2.

```

0001      DIMENSION WORKSP(76),WORKSQ(76),TEXP(25,11),CVPT(25,11),
0002      / G(25),SYMBOL(22),TFXP(25,11),TGXP(25,11),B(21),A(21),V(21)
      DOUBLE PRECISION DLIV,DLJV,DLKV,DLIKV,DLKVC,DLKVD,RI,C1,C2,
      / C3,C4,RII,C1I,C2I,C12I,C5,C6,RISU,C1S,C2S,C7,C8,T(15,15,10),
      / TNEW(15,15,10)
0003      READ (5,1) BINS,ROUT,TR,HIGHT,DPMIN,DPHAX,ACHIN,ACHAX,TLMIN,
      /TLMAX,DELR,DLJ, DELZ,SPACEI,SPACEJ,SPACEK
0004      1 FORMAT (10F6.2)
0005      READ (5,41) TT,TA,H,CON1,CON2,EPS
0006      41 FORMAT (6F8.2)
0007      READ (5,200) (SYMBOL(I),I=1,21),ASTSK
0008      200 FORMAT (22A1)
0009      DLI=1./DELR
0010      INCRI=SPACEI/DLI
0011      DLK=1./DELZ
0012      INCRK=SPACEK/DLK
0013      WIDTH=3.14159*(RINS+ROUT)/2.
0014      DEA=WIDTH*DLJ/180.
0015      INCRJ=SPACEJ/DLJ
0016      NII=(ROUT-RINS)/DLI+1.
0017      XNII=NII
0018      NJ=WIDTH/DEA+1.
0019      NK=HIGHT/DLK+1.
0020      MIM=DPMIN/DLI+1.
0021      MJM=ACHIN/DLJ+1.
0022      MKM=TLMIN/DLK+1.
0023      MIL=1.+(DPHAX-DPMIN)/SPACEI
0024      MJL=1.+(ACHAX-ACHIN)/SPACEJ
0025      MKL=1.+(TLMAX-TLMIN)/SPACEK
0026      NI=TR/DLI+1.
0027      XNI=NI
0028      DLIV=1.
0029      DLIS=DLI**2
0030      DLJV=1./((3.14159*DLJ/180.))**2)
0031      DLKV=(DLI**2)/(DLK**2)
0032      DLIKV=1.+DLKV
0033      CON12=CON1+CON2
0034      DLKVC=CON12*DLKV/2.
0035      DLKVD=0.5*CON2*DLIS/(DLK**2)
0036      DO 50 L=1,MIL
0037      DO 50 M=1,MJL
0038      DO 50 N=1,MKL
0039      MI=MIM+(L-1)*INCI
0040      MJ=MJM+(M-1)*INCRJ
0041      MK=MKM+(N-1)*INCRK
0042      KI=MI+1
0043      LI=NI-1
0044      KII=NI+1
0045      LII=NII-1
0046      KJ=MJ+1
0047      LJ=NJ-1
0048      KK=MK+1
0049      LK=NK-1
0050      DO 2 I=1,NII
0051      DO 2 J=1,NJ

```

Fig. B.1. Computer Program for Evaluating Surface Temperature in a Three-dimensional System


```

0052      DO 2 K=1,NK
0053      2 T(I,J,K)=.5*(TT+TA)
0054      DO 3 J=1,NJ
0055      DO 3 K=1,NK
0056      TNEW(I,J,K)=TT
0057      3 T(I,J,K)=TT
0058      DO 4 I=2,MI
0059      DO 4 J=1,NJ
0060      DO 4 K=1,NK
0061      TNEW(I,J,K)=TT
0062      4 T(I,J,K)=TT
0063      80 DO 5 I=KI,LI
0064      RIR=I-1
0065      RI=RIR*DLI+RINS
0066      C1=1.-DLI/(2.*RI)
0067      C2=1.+DLI/(2.*RI)
0068      C3=DLIS*DLJV/(RI**2)
0069      C4=2.*(DLKV+C3)
0070      5 TNEW(I,1,1)=(DLIV*(C1*T(I-1,1,1)+C2*T(I+1,1,1))+C3*2.*T(I,2,1)+
      DLKV*2.*T(I,1,2))/C4
0071      DO 6 I=2,LI
0072      RIR=I-1
0073      RI=RIR*DLI+RINS
0074      C1=1.-DLI/(2.*RI)
0075      C2=1.+DLI/(2.*RI)
0076      C3=DLIS*DLJV/(RI**2)
0077      C4=2.*(DLKV+C3)
0078      TNEW(I,NJ,1)=(DLIV*(C1*T(I-1,NJ,1)+C2*T(I+1,NJ,1))+C3*2.*
      / T(I,NJ-1,1)+DLKV*2.*T(I,NJ,2))/C4
0079      TNEW(I,1,NK)=(DLIV*(C1*T(I-1,1,NK)+C2*T(I+1,1,NK))+C3*2.*
      / T(I,2,NK)+DLKV*2.*T(I,1,NK-1))/C4
0080      6 TNEW(I,NJ,NK)=(DLIV*(C1*T(I-1,NJ,NK)+C2*T(I+1,NJ,NK))+C3*2.*
      / T(I,NJ-1,NK)+DLKV*2.*T(I,NJ,NK-1))/C4
0081      DO 7 I=2,MI
0082      DO 7 J=KJ,LJ
0083      RIR=I-1
0084      RI=RIR*DLI+RINS
0085      C1=1.-DLI/(2.*RI)
0086      C2=1.+DLI/(2.*RI)
0087      C3=DLIS*DLJV/(RI**2)
0088      C4=2.*(DLKV+C3)
0089      7 TNEW(I,J,1)=(DLIV*(C1*T(I-1,J,1)+C2*T(I+1,J,1))+C3*(T(I,J-1,1)+
      / T(I,J+1,1))+DLKV*2.*T(I,J,2))/C4
0090      DO 8 I=KI,LI
0091      DO 8 J=2,LJ
0092      RIR=I-1
0093      RI=RIR*DLI+RINS
0094      C1=1.-DLI/(2.*RI)
0095      C2=1.+DLI/(2.*RI)
0096      C3=DLIS*DLJV/(RI**2)
0097      C4=2.*(DLKV+C3)
0098      8 TNEW(I,J,1)=(DLIV*(C1*T(I-1,J,1)+C2*T(I+1,J,1))+C3*(T(I,J-1,1)+
      / T(I,J+1,1))+DLKV*2.*T(I,J,2))/C4
0099      DO 9 I=KI,LI
0100      DO 9 K=2,LK

```

Fig. B.1 (Contd.)

```

0101      RIR=I-1
0102      RI=RIR*DLI+RINS
0103      C1=1.-DLI/(2.*RI)
0104      C2=1.+DLI/(2.*RI)
0105      C3=DLIS*DLJV/(RI**2)
0106      C4=2.*(DLIKV+C3)
0107      9 TNEW(I,1,K)=(DLIV*(C1*T(I-1,1,K)+C2*T(I+1,1,K))+C3*2.*T(I,2,K)+
/ DLKV*(T(I,1,K-1)+T(I,1,K+1)))/C4
0108      DO 10 I=2,MI
0109      DO 10 K=KK,LK
0110      RIR=I-1
0111      RI=RIR*DLI+RINS
0112      C1=1.-DLI/(2.*RI)
0113      C2=1.+DLI/(2.*RI)
0114      C3=DLIS*DLJV/(RI**2)
0115      C4=2.*(DLIKV+C3)
0116      10 TNEW(I,1,K)=(DLIV*(C1*T(I-1,1,K)+C2*T(I+1,1,K))+C3*2.*T(I,2,K)+
/ DLKV*(T(I,1,K-1)+T(I,1,K+1)))/C4
0117      DO 11 I=2,LI
0118      DO 11 K=2,LK
0119      RIR=I-1
0120      RI=RIR*DLI+RINS
0121      C1=1.-DLI/(2.*RI)
0122      C2=1.+DLI/(2.*RI)
0123      C3=DLIS*DLJV/(RI**2)
0124      C4=2.*(DLIKV+C3)
0125      11 TNEW(I,NJ,K)=(DLIV*(C1*T(I-1,NJ,K)+C2*T(I+1,NJ,K))+C3*2.*
/ T(I,NJ-1,K)+DLKV*(T(I,NJ,K-1)+T(I,NJ,K+1)))/C4
0126      DO 12 I=2,LI
0127      DO 12 J=2,LJ
0128      RIR=I-1
0129      RI=RIR*DLI+RINS
0130      C1=1.-DLI/(2.*RI)
0131      C2=1.+DLI/(2.*RI)
0132      C3=DLIS*DLJV/(RI**2)
0133      C4=2.*(DLIKV+C3)
0134      12 TNEW(I,J,NK)=(DLIV*(C1*T(I-1,J,NK)+C2*T(I+1,J,NK))+C3*
/ (T(I,J-1,NK)+T(I,J+1,NK))+DLKV*2.*T(I,J,NK-1))/C4
0135      DO 13 I=KI,LI
0136      DO 13 J=2,MJ
0137      DO 13 K=2,MK
0138      RIR=I-1
0139      RI=RIR*DLI+RINS
0140      C1=1.-DLI/(2.*RI)
0141      C2=1.+DLI/(2.*RI)
0142      C3=DLIS*DLJV/(RI**2)
0143      C4=2.*(DLIKV+C3)
0144      13 TNEW(I,J,K)=(DLIV*(C1*T(I-1,J,K)+C2*T(I+1,J,K))+C3*(T(I,J-1,K)+
/ T(I,J+1,K))+DLKV*(T(I,J,K-1)+T(I,J,K+1)))/C4
0145      DO 14 I=2,LI
0146      DO 14 J=KJ,LJ
0147      DO 14 K=2,MK
0148      RIR=I-1
0149      RI=RIR*DLI+RINS
0150      C1=1.-DLI/(2.*RI)

```

Fig. B.1 (Contd.)

```

0151      C2=1.+DLI/(2.*RI)
0152      C3=DLIS*DLJV/(RI**2)
0153      C4=2.*(DLKV+C3)
0154 14 TNEW(I,J,K)=(DLIV*(C1*T(I-1,J,K)+C2*T(I+1,J,K))+C3*(T(I,J-1,K)+
/ T(I,J+1,K))+DLKV*(T(I,J,K-1)+T(I,J,K+1)))/C4
0155      DO 15 I=2,LJ
0156      DO 15 J=2,LJ
0157      DO 15 K=KK,LK
0158      RIR=I-1
0159      RI=RIR*DLI+RINS
0160      C1=1.-DLI/(2.*RI)
0161      C2=1.+DLI/(2.*RI)
0162      C3=DLIS*DLJV/(RI**2)
0163      C4=2.*(DLKV+C3)
0164 15 TNEW(I,J,K)=(DLIV*(C1*T(I-1,J,K)+C2*T(I+1,J,K))+C3*(T(I,J-1,K)+
/ T(I,J+1,K))+DLKV*(T(I,J,K-1)+T(I,J,K+1)))/C4
0165      RII=(XNI-1.)*DLI+RINS
0166      C1I=CON1*(1.-DLI/(2.*RII))
0167      C2I=CON2*(1.+DLI/(2.*RII))
0168      C12I=0.5*(C1I+C2I)
0169      C5=CON12*DLIS*DLJV/(RII**2*2.)
0170      C6=2.*(C12I+C5+DLKVC)
0171      TNEW(NI,1,1)=(DLIV*(C1I*T(NI-1,1,1)+C2I*T(NI+1,1,1))+C5*2.*
/ T(NI,2,1)+DLKVC*2.*T(NI,1,2))/C6
0172      TNEW(NI,NJ,1)=(DLIV*(C1I*T(NI-1,NJ,1)+C2I*T(NI+1,NJ,1))+C5*2.*
/ T(NI,NJ-1,1)+DLKVC*2.*T(NI,NJ,2))/C6
0173      TNEW(NI,1,NK)=(DLIV*(C1I*T(NI-1,1,NK)+C2I*T(NI+1,1,NK))+C5*2.*
/ T(NI,2,NK)+DLKVC*2.*T(NI,1,NK-1))/C6
0174      TNEW(NI,NJ,NK)=(DLIV*(C1I*T(NI-1,NJ,NK)+C2I*T(NI+1,NJ,NK))+C5*
/ 2.*T(NI,NJ-1,NK)+DLKVC*2.*T(NI,NJ,NK-1))/C6
0175      DO 16 J=2,LJ
0176      TNEW(NI,J,1)=(DLIV*(C1I*T(NI-1,J,1)+C2I*T(NI+1,J,1))+C5*
/ (T(NI,J-1,1)+T(NI,J+1,1))+DLKVC*2.*T(NI,J,2))/C6
0177 16 TNEW(NI,J,NK)=(DLIV*(C1I*T(NI-1,J,NK)+C2I*T(NI+1,J,NK))+C5*
/ (T(NI,J-1,NK)+T(NI,J+1,NK))+DLKVC*2.*T(NI,J,NK-1))/C6
0178      DO 17 K=2,LK
0179      TNEW(NI,1,K)=(DLIV*(C1I*T(NI-1,1,K)+C2I*T(NI+1,1,K))+C5*2.*
/ T(NI,2,K)+DLKVC*(T(NI,1,K-1)+T(NI,1,K+1)))/C6
0180 17 TNEW(NI,NJ,K)=(DLIV*(C1I*T(NI-1,NJ,K)+C2I*T(NI+1,NJ,K))+C5*2.*
/ T(NI,NJ-1,K)+DLKVC*(T(NI,NJ,K-1)+T(NI,NJ,K+1)))/C6
0181      DO 18 J=2,LJ
0182      DO 18 K=2,LK
0183 18 TNEW(NI,J,K)=(DLIV*(C1I*T(NI-1,J,K)+C2I*T(NI+1,J,K))+C5*
/ (T(NI,J-1,K)+T(NI,J+1,K))+DLKVC*(T(NI,J,K-1)+T(NI,J,K+1)))/C6
0184      IF (KII-LII) 60,60,70
0185 60 DO 19 I=KII,LII
0186      RIR=I-1
0187      RI=RIR*DLI+RINS
0188      C1=1.-DLI/(2.*RI)
0189      C2=1.+DLI/(2.*RI)
0190      C3=DLIS*DLJV/(RI**2)
0191      C4=2.*(DLKV+C3)
0192      TNEW(I,1,1)=(DLIV*(C1*T(I-1,1,1)+C2*T(I+1,1,1))+C3*2.*T(I,2,1)+
/ DLKV*2.*T(I,1,2))/C4
0193      TNEW(I,NJ,1)=(DLIV*(C1*T(I-1,NJ,1)+C2*T(I+1,NJ,1))+C3*2.*

```

Fig. B.1 (Contd.)

```

/ T(I,NJ-1,1)+DLKV*2.*T(I,NJ,2))/C4
0194 TNEW(I,1,NK)=(DLIV*(C1*T(I-1,1,NK)+C2*T(I+1,1,NK))+C3*2.*
/ T(I,2,NK)+DLKV*2.*T(I,1,NK-1))/C4
0195 19 TNEW(I,NJ,NK)=(DLIV*(C1*T(I-1,NJ,NK)+C2*T(I+1,NJ,NK))+C3*2.*
/ T(I,NJ-1,NK)+DLKV*2.*T(I,NJ,NK-1))/C4
0196 DO 20 I=KII,LII
0197 DO 20 J=7,LJ
0198 RIR=I-1
0199 RI=RIR*DLI+RINS
0200 C1=1.-DLI/(2.*RI)
0201 C2=1.+DLI/(2.*RI)
0202 C3=DLIS*DLJV/(RI**2)
0203 C4=2.*(DLIKV+C3)
0204 TNEW(I,J,1)=(DLIV*(C1*T(I-1,J,1)+C2*T(I+1,J,1))+C3*(T(I,J-1,1)+
/ T(I,J+1,1))+DLKV*2.*T(I,J,2))/C4
0205 20 TNEW(I,J,NK)=(DLIV*(C1*T(I-1,J,NK)+C2*T(I+1,J,NK))+C3*
/ (T(I,J-1,NK)+T(I,J+1,NK))+DLKV*2.*T(I,J,NK-1))/C4
0206 DO 21 I=KII,LII
0207 DO 21 K=2,LK
0208 RIR=I-1
0209 RI=RIR*DLI+RINS
0210 C1=1.-DLI/(2.*RI)
0211 C2=1.+DLI/(2.*RI)
0212 C3=DLIS*DLJV/(RI**2)
0213 C4=2.*(DLIKV+C3)
0214 TNEW(I,1,K)=(DLIV*(C1*T(I-1,1,K)+C2*T(I+1,1,K))+C3*2.*T(I,2,K)+
/ DLKV*(T(I,1,K-1)+T(I,1,K+1)))/C4
0215 21 TNEW(I,NJ,K)=(DLIV*(C1*T(I-1,NJ,K)+C2*T(I+1,NJ,K))+C3*2.*
/ T(I,NJ-1,K)+DLKV*(T(I,NJ,K-1)+T(I,NJ,K+1)))/C4
0216 DO 22 I=KII,LII
0217 DO 22 J=7,LJ
0218 DO 22 K=2,LK
0219 RIR=I-1
0220 RI=RIR*DLI+RINS
0221 C1=1.-DLI/(2.*RI)
0222 C2=1.+DLI/(2.*RI)
0223 C3=DLJV/(RI**2)
0224 C4=2.*(DLIKV+C3)
0225 22 TNEW(I,J,K)=(DLIV*(C1*T(I-1,J,K)+C2*T(I+1,J,K))+C3*(T(I,J-1,K)+
/ T(I,J+1,K))+DLKV*(T(I,J,K-1)+T(I,J,K+1)))/C4
0226 70 RISU=(XNII-1.)*DLI+RINS
0227 C1S=CON2*(1.-DLI/(2.*RISU))
0228 C2S=H*DLI
0229 C7=0.5*CON2*DLIS*DLJV/(RISU**2)
0230 C8=(C1S+C2S)+2.*C7+2.*DLKVD
0231 TNEW(NII,1,1)=(DLIV*(C1S*T(NII-1,1,1)+C2S*TA)+C7*2.*T(NII,2,1)
/ +DLKVD*2.*T(NII,1,2))/C8
0232 TNEW(NII,NJ,1)=(DLIV*(C1S*T(NII-1,NJ,1)+C2S*TA)+C7*2.*
/ T(NII,NJ-1,1)+DLKVD*2.*T(NII,NJ,2))/C8
0233 TNEW(NII,1,NK)=(DLIV*(C1S*T(NII-1,1,NK)+C2S*TA)+C7*2.*
/ T(NII,2,NK)+DLKVD*2.*T(NII,1,NK-1))/C8
0234 TNEW(NII,NJ,NK)=(DLIV*(C1S*T(NII-1,NJ,NK)+C2S*TA)+C7*2.*
/ T(NII,NJ-1,NK)+DLKVD*2.*T(NII,NJ,NK-1))/C8
0235 DO 23 J=2,LJ
0236 TNEW(NII,J,1)=(DLIV*(C1S*T(NII-1,J,1)+C2S*TA)+C7*(T(NII,J-1,1)+

```

Fig. B.1 (Contd.)

```

/ T(NII,J+1,1) +DLKVD*2.*T(NII,J,2) )/C8
0237 23 TNEW(NII,J,NK) = (DLIV*(C1S*T(NII-1,J,NK) +C2S*TA) +C7*
/ (T(NII,J-1,NK) +T(NII,J+1,NK) ) +DLKVD*2.*T(NII,J,NK-1) )/C8
0238 DO 24 K=2,LK
0239 TNEW(NII,1,K) = (DLIV*(C1S*T(NII-1,1,K) +C2S*TA) +C7*2.*T(NII,2,K) +
/ DLKVD*(T(NII,1,K-1) +T(NII,1,K+1) ) )/C8
0240 24 TNEW(NII,NJ,K) = (DLIV*(C1S*T(NII-1,NJ,K) +C2S*TA) +C7*2.*
/ T(NII,NJ-1,K) +DLKVD*(T(NII,NJ,K-1) +T(NII,NJ,K+1) ) )/C8
0241 DO 25 J=2,LJ
0242 DO 25 K=2,LK
0243 25 TNEW(NII,J,K) = (DLIV*(C1S*T(NII-1,J,K) +C2S*TA) +C7*(T(NII,J-1,K) +
/ T(NII,J+1,K) ) +DLKVD*(T(NII,J,K-1) +T(NII,J,K+1) ) )/C8
0244 DO 85 I=2,MI
0245 DO 85 J=KJ,NJ
0246 DO 85 K=1,NK
0247 IF (DABS(T(I,J,K) -TNEW(I,J,K)) -EPS) 85,85,40
0248 85 CONTINUE
0249 DO 27 I=2,MI
0250 DO 27 J=1,NJ
0251 DO 27 K=KK,NK
0252 IF (DABS(T(I,J,K) -TNEW(I,J,K)) -EPS) 27,27,40
0253 27 CONTINUE
0254 DO 26 I=KI,NII
0255 DO 26 J=1,NJ
0256 DO 26 K=1,NK
0257 IF (DABS(T(I,J,K) -TNEW(I,J,K)) -EPS) 26,26,40
0258 26 CONTINUE
0259 GO TO 90
0260 40 DO 31 I=2,MI
0261 DO 31 J=KJ,NJ
0262 DO 31 K=1,NK
0263 31 T(I,J,K) =TNEW(I,J,K)
0264 DO 32 I=KI,NII
0265 DO 32 J=1,NJ
0266 DO 32 K=1,NK
0267 32 T(I,J,K) =TNEW(I,J,K)
0268 DO 33 I=2,NII
0269 DO 33 J=1,NJ
0270 DO 33 K=KK,NK
0271 33 T(I,J,K) =TNEW(I,J,K)
0272 GO TO 80
0273 90 XMI=MI
0274 YMJ=MJ
0275 ZMK=MK
0276 DEPTH=DLI*(XMI-1.)
0277 ACROS=DLJ*(YMJ-1.)
0278 HICAV=DLK*(ZMK-1.)
0279 DINS=2.*RINS
0280 DOUT=2.*ROUT
0281 HIGHU=2.*HIGHT
0282 SHTK=ROUT-RINS-TR
0283 WRITE (6,28) DINS,DOUT,HIGHU,TR,SHTK,DEPTH,ACROS,HICAV,DLI,DLJ,
/ DLK,TT,TA,CON1,CON2,H,EPS
0284 28 FORMAT (1H1,20HDIMENSION: ID=F8.2,8H IN.,OD=F8.2,
/ 21H IN., (TOTAL) HEIGHT=F8.2,

```

Fig. B.1 (Contd.)

```

/ 4H IN./18X,21HREFRACTORY THICKNESS=F6.2,
/ 21H IN.,SHELL THICKNESS=F6.2,4H IN./13H CAVITY SIZE:,5X,
/ 6HDEPTH=F6.2,19H IN., (HALF) ANGLE=F7.2,5H DEG./
/ 17X,15H (HALF) HEIGHT=F7.2,4H IN./
/ 11H MESH SIZE:,7X,7H RADIUS=F6.3,13H IN.,ANGULAR=F6.2,
/ 12H DEG.,AXIAL=F6.2,4H IN./
/ 14H TEMPERATURES:,4X,15H INSIDE SURFACE=
/ F10.2,14H DEG.,AMBIENT=F8.2,5H DEG./12H PROPERTIES:,6X,
/ 11HK FOR REF.=F8.2,14H, K FOR SHELL=F8.2,19H BTU IN./HR FT**2 F/
/ 18X,2HH=F8.2,15H BTU/HR FT**2 F/20H ITERATION ERROR: E=
/ F5.2,5H DEG.///)
DO 29 K=1,NK
0285
0286 29 WRITE (6,30) (TNEW(NII,J,K),J=1,NJ)
0287 30 FORMAT (5D20.10)
0288 NJCT=2*NJ-1
0289 NKCT=2*NK-1
0290 NJDT=NJ+1
0291 NKDT=NK+1
0292 NJET=NJ-1
0293 NKET=NK-1
0294 ANJCT=NJCT
0295 ANKCT=NKCT
0296 BNJCT=-(2.*ANJCT)
0297 BNKCT=-(2.*ANKCT)
0298 CNJCT=1.5*ANJCT
0299 MTTT=TNEW(NII,1,1)/100.+1.
0300 VTT=MTTT*100
0301 MTB=TNEW(NII,NJ,NK)/100.
0302 VTB=MTB*100
0303 MTR=ROUT-RINS+1.
0304 RTT=MTR
0305 DO 101 J=1,NK
0306 DO 101 I=1,NJCT
0307 IF (I-NJ) 102,102,103
0308 102 TEXP(I,J)=TNEW(NII,NJDT-I,J)
0309 GO TO 101
0310 103 TEXP(I,J)=TNEW(NII,I-NJET,J)
0311 101 CONTINUE
0312 DO 104 I=1,NJCT
0313 DO 104 J=1,NKCT
0314 IF (J-NK) 105,105,106
0315 105 TFXP(I,J)=TEXP(I,NKDT-J)
0316 GO TO 104
0317 106 TFXP(I,J)=TEXP(I,J-NKET)
0318 104 CONTINUE
0319 ZHI=ROUT-RINS
0320 ZCI=ROUT-RINS-(XMI-1.)*DLI
0321 NJFT=NJ-MJ+1
0322 NKFT=NK-MK+1
0323 NJGT=NJ+MJ-1
0324 NKGT=NK+MK-1
0325 NJHT=NJFT+1
0326 NKHT=NKFT+1
0327 NJIT=NJGT-1
0328 NKIT=NKGT-1

```

Fig. B.1 (Contd.)

```

0329      DO 111 J=1,NKCT
0330      DO 111 I=1,NJFT
0331 111 CVPT(I,J)=ZHI
0332      DO 112 J=1,NKCT
0333      DO 112 I=NJGT,NJCT
0334 112 CVPT(I,J)=ZHI
0335      DO 113 I=NJHT,NJIT
0336      DO 113 J=1,NKFT
0337 113 CVPT(I,J)=ZHI
0338      DO 114 I=NJHT,NJIT
0339      DO 114 J=NKGT,NKCT
0340 114 CVPT(I,J)=ZHI
0341      DO 115 I=NJHT,NJIT
0342      DO 115 J=NKHT,NKIT
0343 115 CVPT(I,J)=ZCI
0344      WRITE (6,35)
0345 35 FORMAT (1H1,43HTHREE DIMENSIONAL SURFACE TEMPERATURE PLOT:)
0346      CALL STRTP
0347      CALL BGNPL(1)
0348      CALL TITL3D('THREE-DIMENSIONAL SURFACE TEMPERATURE PLOT$',-100,
/ 10.,6.)
0349      CALL AXES3D('ANGULAR DIRECTIONS$',100,'AXIAL DIRECTIONS$',100,
/ 'TEMPERATURE$',100,ANJCT,ANKCT,CNJCT)
0350      CALL VUABS(BNJCT,BNKCT,CNJCT)
0351      CALL GRAF3D(1.,4.,ANJCT,1.,2.,ANKCT,100.,50.,500.)
0352      CALL SURMAT(TFXP,1,NJCT,1,NKCT,WORKSP)
0353      CALL ENDPL(1)
0354      WRITE (6,36)
0355 36 FORMAT (1H1,38HRECONSTRUCTION OF CAVITY CONFIGURATION)
0356      CALL BGNPL(1)
0357      CALL TITL3D('RECONSTRUCTION OF CAVITY CONFIGURATIONS$',-100,
/ 10.,6.)
0358      CALL AXES3D('ANGULAR DIRECTIONS$',100,'AXIAL DIRECTIONS$',100,
/ 'RADIAL DIRECTIONS$',100,ANJCT,ANKCT,CNJCT)
0359      CALL VUABS(BNJCT,BNKCT,CNJCT)
0360      CALL GRAF3D(1.,4.,ANJCT,1.,2.,ANKCT,0.,1.,RTT)
0361      CALL SURMAT(CVPT,1,NJCT,1,NKCT,WORKSQ)
0362      CALL ENDPL(2)
0363      TNC=(VTT-VTB)/21.
0364      VTC=VTB+TNC-0.1
0365      VTD=VTB+2.*TNC
0366      VTE=VTD+TNC-0.1
0367      VTF=VTB+4.*TNC
0368      VTG=VTF+TNC-0.1
0369      VTH=VTB+6.*TNC
0370      VTI=VTH+TNC-0.1
0371      VTJ=VTB+8.*TNC
0372      VTK=VTJ+TNC-0.1
0373      VTL=VTB+10.*TNC
0374      VTM=VTL+TNC-0.1
0375      VTN=VTB+12.*TNC
0376      VTO=VTN+TNC-0.1
0377      VTP=VTB+14.*TNC
0378      VTO=VTP+TNC-0.1
0379      VTR=VTB+16.*TNC

```

Fig. B.1 (Contd.)

```

0380      VTS=VTB+TNC-0.1
0381      VTU=VTB+18.*TNC
0382      VTV=VTU+TNC-0.1
0383      VTW=VTB+20.*TNC
0384      WRITE (6,37)
0385      37 FORMAT(1H1,26HSURFACE ISOTHERM CONTOURS:////8H LEGEND:/5X,
/ 36HSYMBOL ISOTHERM BAND WIDTH (DEG.F)/)
0386      WRITE (6,38) VTB,UTC,UTD,UTE,UTF,VTG,VTH,VTI,V TJ,VTK,VIL,VTM,VIN,
/ VTO,UTP,UTO,UTR,UTS,UTU,UTV,UTW,UTT
0387      38 FORMAT (7X,1HA,10X,F7.1,4H TO ,F7.1/
/ 7X,1HB,10X,F7.1,4H TO ,F7.1/
/ 7X,1HC,10X,F7.1,4H TO ,F7.1/
/ 7X,1HD,10X,F7.1,4H TO ,F7.1/
/ 7X,1HE,10X,F7.1,4H TO ,F7.1/
/ 7X,1HF,10X,F7.1,4H TO ,F7.1/
/ 7X,1HG,10X,F7.1,4H TO ,F7.1/
/ 7X,1HH,10X,F7.1,4H TO ,F7.1/
/ 7X,1HI,10X,F7.1,4H TO ,F7.1/
/ 7X,1HJ,10X,F7.1,4H TO ,F7.1/
/ 7X,1HK,10X,F7.1,4H TO ,F7.1//)
0388      WRITE (6,39)
0389      39 FORMAT (1H ,41HNOTE: ALTHOUGH ELEVEN SYMBOLS ARE USED TO
/ 56H REPRESENT ISOTHERM BANDS IN THE LEGEND, THE TEMPERATURE/
/ 54H RANGES FOR THESE SYMBOLS HAVE BEEN SELECTED SUCH THAT
/ 61H TWENTY ONE BANDS CAN BE READ OFF FROM THE ISOTHERM MAP. NOTE/
/ 59H THAT THE TEMPERATURE RANGES IN THE LEGEND ARE DISCONTINUOUS
/ 53H , SIGNIFYING THAT A WHITE BAND EXISTS IN BETWEEN THE/
/ 54H NEIGHBORING LETTERED BANDS; THE TEMPERATURE RANGE FOR
/ 50H THE WHITE BAND IS BRIDGED IN BETWEEN THOSE OF THE/
/ 19H NEIGHBORING BANDS.//)
0390      DO 201 I=1,NJCT
0391      201 G(I)=ASTSK
0392      WRITE (6,202) G
0393      202 FORMAT (1H ,180A1)
0394      J=NKCT
0395      DO 204 I=1,NJCT
0396      K=(TFXP(I,J)-VTB)/TNC+1.
0397      G(I)=SYMBOL(K)
0398      204 CONTINUE
0399      WRITE (6,205) G
0400      205 FORMAT (1H ,180A1)
0401      J=J-1
0402      IF (J.NE.0) GO TO 203
0403      DO 206 I=1,NJCT
0404      206 G(I)=ASTSK
0405      WRITE (6,207) G
0406      207 FORMAT (1H ,180A1)
0407      SCR=(TNEW(NII,1,1)-TNEW(NII,NJ,NK))/20.
0408      DO 301 K=1,20
0409      BK=K
0410      BIAS=(BK-1.)*SCR+TNEW(NII,NJ,NK)
0411      DO 302 J=1,NKCT
0412      DO 302 I=1,NJCT
0413      302 TGXP(I,J)=TFXP(I,J)-BIAS
0414      COUNT=0.

```

Fig. B.1 (Contd.)


```

0415          ACUM=0.
0416          DO 303 J=1,NKCT
0417          DO 303 I=1,NJCT
0418          IF (TGXP(I,J)) 303,304,304
0419          304 COUNT=COUNT+1.
0420          ACUM=ACUM+TGXP(I,J)
0421          303 CONTINUE
0422          B(K)=BIAS
0423          A(K)=COUNT
0424          301 V(K)=ACUM
0425          DO 350 K=1,10
0426          DIV=10.**K
0427          Y=A(2)/DIV
0428          IF (Y-1) 351,351,350
0429          350 CONTINUE
0430          351 EXPA=K
0431          DO 360 K=1,10
0432          DIV=10.**K
0433          Y=V(2)/DIV
0434          IF (Y-1) 361,361,360
0435          360 CONTINUE
0436          361 EXPV=K
0437          CYCLA=8./EXPA
0438          CYCLV=8./EXPV
0439          THVOL=V(1)+TNEW(NII,NJ,NK)*ANJCT*ANKCT
0440          WRITE (6,371) THVOL
0441          371 FORMAT (1H1,36HTOTAL VOLUME UNDERNEATH THE SURFACE=E12.5//)
0442          WRITE (6,372)
0443          372 FORMAT (1H ,2X8HISOTHEPM5X11HAREA INSIDE4X10HINTEGRATED)
0444          WRITE (6,373)
0445          373 FORMAT (1H ,1X11HTEMPERATURE3X12HTHE ISOTHERM5X6HVOLUME)
0446          DO 374 K=1,20
0447          374 WRITE (6,375) B(K),A(K),V(K)
0448          375 FORMAT (1H ,F9.1,E17.4,E14.4)
0449          PUNCH 330, DEPTH,ACROS,HICAV,THVOL,TNEW(NII,1,1),TNEW(NII,NJ,NK)
0450          330 FORMAT (F10.2,5F10.1)
0451          WRITE (6,376)
0452          376 FORMAT (1H1)
0453          CALL BGNPL(1)
0454          CALL TITLE('AREA ENCLOSED INSIDE ISOTHERM LOOPS$',100,
/ 'TEMPERATURE$',100,'AREA$',100,5.,8.)
0455          CALL FRAME
0456          CALL YLOG(10J.,80.,1.,CYCLA)
0457          CALL GRID(2,2)
0458          CALL CURVE(B,A,20,1)
0459          CALL ENDPL(3)
0460          CALL TITLE('INTEGRATED ENERGY EQUIVALENT$',100,
/ 'TEMPERATURE$',100,'INTEGRATED ENERPGY EQUIVALENT$',100,5.,8.)
0461          CALL FRAME
0462          CALL YLOG(100.,80.,1.,CYCLV)
0463          CALL GRID(2,2)
0464          CALL CURVE(B,V,20,1)
0465          CALL ENDPL(4)
0466          50 CONTINUE
0467          CALL DONEPL

```

Fig. B.1 (Contd.)

FORTRAN IV G1 RELEASE 2.0

0468 STOP
0469 END

Fig. B.1 (Contd.)

Fig. B.2

Schematic Diagram Showing Nodal Locations in the Axial Direction in a Three-dimensional System

TABLE B.1. Definitions of Additional Input Variables for Program in Fig. B.1^a

Variable Name	Definition	Unit
DELZ	Number of divisions per inch in the axial direction--a parameter to determine mesh size, $1/\Delta z$	1/in.
HIGHT	Half-height (length) of the transfer line	in.
SPACEK	Increment of the cavity height used in a series of tests of cavity sizes	in.
TLMAX	Maximum (half) height of the cavity to be tested in the program	in.
TLMIN	Minimum (half) height of the cavity to be tested in the program	in.

^aThis table is to be used together with Table A.1 for definitions of all input variables.

3. Lines 21-29 calculate the minimum and maximum indexes for the cavity sizes in three coordinates. MIL, MJL, and MKL are subsequently used as index parameters for DO loop 50 (lines 37-39); MIM, MJM, and MKM are used to specify the cavity boundary on lines 40-42.

4. Lines 30-36 define and compute parameters that are later used in the temperature equations. These parameters are related to physical quantities as follows:

Line 30 DLIS = $(\Delta r)^2$
 Line 31 DLJV = $1/(\pi \Delta \theta / 180)^2$
 Line 32 DLKV = $(\Delta r / \Delta z)^2$
 Line 33 DLIKV = $1 + (\Delta r / \Delta z)^2$
 Line 34 CON12 = $k_1 + k_2$
 Line 35 DLKVC = $(k_1 + k_2)(\Delta r / \Delta z)^2 / 2$
 Line 36 DLKVD = $k_2(\Delta r / \Delta z)^2 / 2$

5. Lines 51-54 initialize all nodal temperatures using $(T_i + T_\infty)/2$.

6. Lines 55-63 set the temperatures at the refractory surface and inside the cavity as T_i , which is unchanged in the course of iteration.

7. Lines 64-244 calculate nodal temperatures. Again, preceding each temperature-calculation step, a series of computations is made of parameters that appear in the TNEW equation. Right after the computation of temperatures at the refractory/steel interface, a transfer of control is built into the program (line 185). This is done to account for the fact that the program takes the thickness of steel shell as one of the inputs. In some instances, the selected mesh sizes are large while the steel shell is so thin that mesh points are no longer present inside the steel shell. Under these circumstances, $KII = NII$, $NI = LII$, and $LII < KII$. The built-in logic (line 185) enables the computer to bypass lines 186-226 and proceed directly to compute TNEW at the steel surface once the interfacial nodal temperatures have been found.

8. Lines 245-259 check the convergence of the calculated temperature. If the convergence is not realized, the program redirects the control to statement 40 (line 261), where three DO loops (lines 261-271) are used to reassign TNEW values to T at each nodal point. The GO TO statement on line 273 causes the computer to return to statement 80 (line 64) and to repeat iteration.

Eventually, the convergence criterion is met, and a series of normal exits from DO loops 85, 27, and 26 is sequentially effected to advance the computer control to line 274 via the GO TO statement on line 260.

9. Lines 274-285 compute and write those quantities that are later used in the legend in the temperature tabulations. This tabulation is made possible by lines 286-288.

10. Lines 289-363 are used to plot the surface temperature and the cavity configuration, both in three dimensions. Before Argonne's DISSPLA graphic routines are called, some preparations are made in the program.

Because only one quadrant of the total system was used in the analysis, the calculated temperature data only cover one-fourth of the total surface. Arrangements must therefore be made to extend the temperature data to the other three-quarters using planes of symmetry. The reconstruction of the temperature field is carried out in the computer program as follows. First, lines 289-294 are used to calculate the indexing parameters for DO loops, as well as other indexes to extend the temperature array. This is followed by lines 295-299 to calculate parameters that are later used in the computer graphics. Since the temperature axis must be properly labeled to show temperature scales in the succeeding three-dimensional plot, the end-point temperature readings on the axis must be determined from the minimum and the maximum temperature data. Physically, these temperatures are, respectively, $TNEW(NII, NJ, NK)$ and $TNEW(NII, 1, 1)$. Hence, the end-point temperatures can be determined by using lines 300-303. In a similar manner, the end points of the radial axis in the cavity configuration plot (discussed later) are also estimated using lines 304 and 305. Finally, two DO loops (lines 306-319) are used to reconstruct the total temperature field.

The next set of statements (lines 320-344) is used to identify the cavity contours. The thickness (ZHI) of the transfer line is computed via line 320, and the position of the cavity bottom (ZCI) is determined via line 321. Again, eight statements (lines 322-329) are used to compute indexing parameters that appear in the succeeding DO loops (lines 330-344) and thus to reconstruct the cavity configuration in three dimensions.

The preparation for three-dimensional plots is now complete. The surface temperature is plotted using lines 345-354; the cavity configuration is plotted using lines 355-363. The computer graphics used in these plots are based on Argonne's DISSPLA routines. Procedures used to develop this part of the program are given in Ref. 28.

11. Lines 364-408 are used to make an isotherm map. The legend of the map is dealt with first. The program divides the temperature span (VTB to VTT) into 21 bands (line 364). Then the temperature ranges represented by these bands are calculated using lines 365-384. Starting from line 385, the program prepares the legend of the map. Alphabets A-K are used to denote bands in the legend. To explain why 11 alphabets can be used to represent 21 bands, a short statement is injected and written (lines 389 and 390) as part of the output.

Lines 391-408 spell out how the isotherm map is constructed. The map is marked with asterisks for upper and lower boundaries (lines 391-394 and 405-408). Then the temperature data are examined point by point, coded with proper alphabets, and printed sequentially on the map (lines 395-403).

12. Lines 409-426 are used to calculate the areas enclosed inside isotherm loops and the volumes contained under the temperature surface, but lying above a given temperature level. Both of these data are calculated as a function of temperature.

The algorithm for this part of the program starts with the division of the total temperature range [TNEW(NII, NJ, NK) to TNEW(NII, 1, 1)] into 20 equal intervals (line 409). Then a bias temperature is calculated (line 412) inside a DO loop (DO 301). By calculating TGXP (line 415) and using the IF statement on line 420, we can compute the area enclosed inside an isotherm (i.e., COUNT) and the volume contained below the temperature surface (i.e., ACUM). These calculated data are stored together with the BLAS value into A, V and B arrays.

13. The A and V data calculated above may span several orders of magnitude for the range of the bias temperature tested. To plot these A and V curves requires the use of semilog coordinates with the log scale used for A and V axes. The values of A and V at two ends of the log axis must be predetermined before plotting. This is accomplished by inclusion of lines 427-440 in the program.

A typical computation to evaluate the number of cycles required to plot the A data is given in lines 427-432. The exponent thus determined is stored as EXPA on line 432. A similar procedure is followed in lines 433-438 to determine the number of cycles for V. Then, lines 439 and 440 are used to convert EXPA and EXPV to parameters CYCLA and CYCLV, which are later used in the graphics routines.

14. The program is also designed to calculate the "total" volume lying under the temperature surface (see line 441). This piece of data is written together with the calculated A and V data as a part of data output (lines 442-450). To facilitate use of these data for analysis, the program also reproduces outputs on punched cards (line 451). Here the data punched are: cavity depth, cavity angular span, cavity height, the total volume lying under the temperature surface, and the highest and lowest temperature readings observed in the surface-temperature array.

15. Lines 453-467 are used to plot the area enclosed inside isotherm loops and the integrated energy-equivalent curves, using A and V data. For simplicity,⁹ the title "integrated energy equivalent" is used. Again, the portion of the program developed for computer graphics is based on Argonne's DISSPLA routines.²⁹

APPENDIX C

Computer Program for Evaluating Emissivity Effects

A computer program for correction of surface emissivity effects is presented in this appendix (Fig. C.1). The program takes the following as inputs:

- D Distance from camera to the center of the transfer line.
- ROUT Outside radius of the transfer line.
- CN Optical constant n in the complex index of refraction ($n - ik$).
- CK Optical constant k in the complex index of refraction.

The computer program is able to produce the following as outputs:

1. Tabulations of polar angle (θ), view angle (β), and emission angle (α).
2. Tabulation of emissivity.
3. Plot of polar- to view-angle conversion curve.
4. Plot of polar- to emission-angle conversion curve.
5. Plot of directional emissivity curve.

A DO loop (line 2) was invoked in the program to make runs for four test conditions. This loop may be removed if desired.

```

0001    DIMENSION ANGLE(51),THETAN(51),BETAN(51),EMS(51)
0002    DO 21 IREP=1,4
0003    READ (5,1) D,ROUT,CN,CK
0004    1 FORMAT (4F10.4)
0005    ANGLE(1)=0.
0006    THETAN(1)=0.
0007    BETAN(1)=0.
0008    BMAX=ASIN(ROUT/D)
0009    THEMAX=ACOS(ROUT/D)
0010    EL10=(CN-1.)**2+CK**2
0011    EL11=(CN+1.)**2+CK**2
0012    EMS(1)=1.-EL10/EL11
0013    IC=1
0014    DO 3 IA=1,50
0015    ZIA=IA
0016    BETA=ZIA*BMAX/50.
0017    DO 5 IT=IC,1000
0018    ZIT=IT
0019    THETA=ZIT*THEMAX/1000.
0020    U=(D**2+ROUT**2-2.*D*ROUT*COS(THETA))*SIN(BETA)**2
0021    V=ROUT**2*SIN(THETA)**2
0022    IF (U-V) 4,4,5
0023    5 CONTINUE
0024    4 IC=IT+1
0025    ID=IA+1
0026    ANGLE(ID)=THETA+BETA
0027    THETAN(ID)=THETA
0028    3 BETAN(ID)=BETA
0029    EL2=4.*CN**2*CK**2
0030    DO 20 ID=2,51
0031    EL1=(CN**2-CK**2-SIN(ANGLE(ID))**2)**2
0032    EL3=SQRT(EL1+EL2)
0033    EL4=CN**2-CK**2-SIN(ANGLE(ID))**2
0034    A=SQRT(.5*(EL3+EL4))
0035    B=SQRT(.5*(EL3-EL4))
0036    EL5=2.*A*CCS(ANGLE(ID))
0037    EL6=A**2+B**2
0038    EL7=2.*A*SIN(ANGLE(ID))*TAN(ANGLE(ID))
0039    EL8=(SIN(ANGLE(ID))*TAN(ANGLE(ID))**2
0040    EMPER=2.*EL5/(EL6+EL5+COS(ANGLE(ID))**2)
0041    EL9=1.+(EL6+SIN(ANGLE(ID))**2)/(COS(ANGLE(ID))**2*
    / (EL6+EL7+EL8))
0042    20 EMS(ID)=.5*EMPER*EL9
0043    WRITE(6,2)
0044    2 FORMAT (1H1,21HTABULATION OF ANGLES:////)
0045    WRITE (6,6)
0046    6 FORMAT (2X,12HPOLAR ANGLE:/)
0047    WRITE (6,7) (THETAN(ID),ID=1,51)
0048    7 FORMAT (10F8.4)
0049    WRITE (6,9)
0050    9 FORMAT (//2X,11HVIEW ANGLE:/)
0051    WRITE (6,11) (BETAN(ID),ID=1,51)
0052    11 FORMAT (10F8.4)
0053    WRITE (6,13)
0054    13 FORMAT (//2X,15HEMISSION ANGLE:/)

```

Fig. C.1. Computer Program for Correction of Emissivity Effects


```

0055     WRITE (6,15) (ANGLE(ID),ID=1,51)
0056 15  FORMAT (10F8.4)
0057     WRITE (6,16)
0058 16  FORMAT (////1X,25HTABULATION OF EMISSIVITY:////)
0059     WRITE (6,18) (EMS(ID),ID=1,51)
0060 18  FORMAT (10F8.4)
0061     WRITE (6,22) ROUT,D,CN,CK
0062 22  FORMAT (////1X,28HINPUT DATA FOR THIS RUN ARE://2X,
      / 20HPIPE OUTSIDE RADIUS=F8.4,3X,
      / 36HDISTANCE FROM CAMERA TO PIPE CENTER=F8.4/2X,
      / 23HOPTICAL CONSTANTS:  N=F8.4,3X,2HK=F8.4)
0063     CALL STRTPL
0064     CALL BGNPL(1)
0065     CALL TITLE('POLAR TO VIEW ANGLE CONVERSION$',100,
      / 'POLAR ANGLE$',100,'VIEW ANGLE$',10      8.)
0066     CALL FRAME
0067     CALL GRAPH(0.,.3,0.,.025)
0068     CALL GRID(2,2)
0069     CALL CURVE(THETAN,BETAN,51,1)
0070     CALL ENDPL(1)
0071     CALL TITLE('POLAR TO EMISSION ANGLE CONVERSION$',100,
      / 'POLAR ANGLE$',100,'EMISSION ANGLE$',100,5.,8.)
0072     CALL FRAME
0073     CALL GRAPH(0.,.3,0.,.2)
0074     CALL GRID(2,2)
0075     CALL CURVE(THETAN,ANGLE,51,1)
0076     CALL ENDPL(2)
0077     CALL TITLE('DIRECTIONAL EMISSIVITY CURVES$',100,
      / 'POLAR ANGLE$',100,'EMISSIVITY$',100,5.,8.)
0078     CALL FRAME
0079     CALL GRAPH(0.,.3,0.,.125)
0080     CALL GRID(2,2)
0081     CALL CURVE(THETAN,EMS,51,1)
0082     CALL ENDPL(3)
0083 21  CONTINUE
0084     CALL DONEPL
0085     STCP
0086     END

```

Fig. C.1 (Contd.)

APPENDIX D

Derivation of Equations for Estimating Limiting Temperatures

The simplified problem that will be used to check the numerical solution consists of a cylindrical pipe with a two-layer wall, made of materials with conductivities k_1 and k_2 . There is no contact resistance at the interface between these two materials. Only radial heat flow is considered, and the problem is analyzed under steady-state conditions. The problem can be formulated as follows:

In the inner wall, the governing equation for heat conduction is

$$\frac{\partial}{\partial r} \left(r \frac{\partial T_r}{\partial r} \right) = 0, \quad (D.1)$$

with the boundary condition given as

$$T_r(r_i) = T_i. \quad (D.2)$$

In the outer wall, the governing equation is

$$\frac{\partial}{\partial r} \left(r \frac{\partial T_s}{\partial r} \right) = 0, \quad (D.3)$$

with the boundary condition given as

$$-k_s \frac{\partial T_s(r_0)}{\partial r} = h[T_s(r_0) - T_\infty]. \quad (D.4)$$

At the interface, the following two conditions hold:

$$T_r(r_m) = T_s(r_m); \quad (D.5)$$

$$k_r \frac{\partial T_r(r_m)}{\partial r} = k_s \frac{\partial T_s(r_m)}{\partial r}. \quad (D.6)$$

The exact solution for the above problem is

$$T_s - T_\infty = \frac{T_i - T_\infty}{\frac{k_s}{k_r} \ln \frac{r_i}{r_m} + \ln \frac{r_m}{r_0} - \frac{k_s}{hr_0}} \ln \frac{r}{r_0} - \frac{T_i - T_\infty}{\frac{k_s}{k_r} \ln \frac{r_i}{r_m} + \ln \frac{r_m}{r_0} - \frac{k_s}{hr_0}} \frac{k_s}{hr_0}. \quad (D.7)$$

Hence, the surface temperature can be expressed as

$$T_s(r_0) = T_\infty - \frac{T_i - T_\infty}{\frac{k_s}{k_r} \ln \frac{r_i}{r_m} + \ln \frac{r_m}{r_0} - \frac{k_s}{hr_0}} \frac{k_s}{hr_0}. \quad (D.8)$$

APPENDIX E

Computer Program for a Two-dimensional System
Fitted with a Telltale Rib

The two-dimensional system described in Appendix A was modified by adding a rib to the outer steel shell. The rib, which penetrates into the refractory lining, can presumably help detect the condition of the refractory lining, and therefore represents an improvement in the design of the transfer line. A computer program for studying temperature distribution in this modified system is presented in Fig. E.1.

Obviously, the presence of the telltale rib lengthens the computer program considerably. The program was developed on the assumption that the rib was made of a material of conductivity CON3 (see lines 6 and 7 in the program). There is no contact resistance between the rib and the refractory lining. For convenience of formulation, the rib has a tapered profile (see Fig. 17 of the text). The center of the rib is located at index NQJ; the thickness of the rib is $2(\Delta\theta)$ (lines 29-31 in the program). To test the effect of rib location on the temperature distribution a DO loop (line 28) was written into the program to relocate the rib as desired.


```

0066 C3=DLIS*DLJV/(RI**2)
0067 6 TNEW(I,NJ)=(C1*T(I-1,NJ)+C2*T(I+1,NJ)+C3*2.*T(I,NJ-1))/ 120
    /
    (2.*(1.+C3))
0068 IF (IABS(MJ-NQJ)-1) 120,120,121
0069 WRITE (5,111)
0070 120 FORMAT (1H1,40H RIB IS TOO CLOSE TO THE CAVITY BOUNDARY)
0071 WRITE (6,29) NQJ
0072 GO TO 45
0073 121 IF (MJ-NQJ) 123,120,124
0074 122 DO 7 I=2,MI
0075 DO 7 J=KJ,LJ
0076 RIR=I-1
0077 RI=RIR*DLI+RINS
0078 C1=1.-DLI/(2.*RI)
0079 C2=1.+DLI/(2.*RI)
0080 C3=DLIS*DLJV/(RI**2)
0081 7 TNEW(I,J)=(C1*T(I-1,J)+C2*T(I+1,J)+C3*(T(I,J-1)+T(I,J+1)))/
    /
    (2.*(1.+C3))
0082 DO 8 I=KI,LI
0083 DO 8 J=2,NTJ
0084 RIR=I-1
0085 RI=RIR*DLI+RINS
0086 C1=1.-DLI/(2.*RI)
0087 C2=1.+DLI/(2.*RI)
0088 C3=DLIS*DLJV/(RI**2)
0089 8 TNEW(I,J)=(C1*T(I-1,J)+C2*T(I+1,J)+C3*(T(I,J-1)+T(I,J+1)))/
    /
    (2.*(1.+C3))
0090 DO 9 I=KI,LI
0091 RIR=I-1
0092 RI=RIR*DLI+RINS
0093 C1=1.-DLI/(2.*RI)
0094 C2=1.+DLI/(2.*RI)
0095 C3=DLIS*DLJV/(RI**2)
0096 C31=CON1*C3
0097 C33=CON3*C3
0098 C9=CON13*C1/2.
0099 C10=CON13*C2/2.
0100 C11=C9+C10+C31+C33
0101 TNEW(I,NPJ)=(C9*T(I-1,NPJ)+C10*T(I+1,NPJ)+C31*T(I,NTJ)+C33*T(I,NQJ)
    /
    (C11))
0102 TNEW(I,NQJ)=(C1*T(I-1,NQJ)+C2*T(I+1,NQJ)+C3*(T(I,NPJ)+T(I,NRJ)))
    /
    ((1.+C3)*2.)
0103 81 TNEW(I,NRJ)=(C9*T(I-1,NRJ)+C10*T(I+1,NRJ)+C33*T(I,NQJ)+C31*T(I,NQJ)
    /
    (C11))
0104 DO 92 I=KI,LI
0105 DO 92 J=NUJ,LJ
0106 RIR=I-1
0107 RI=RIR*DLI+RINS
0108 C1=1.-DLI/(2.*RI)
0109 C2=1.+DLI/(2.*RI)
0110 C3=DLIS*DLJV/(RI**2)
0111 82 TNEW(I,J)=(C1*T(I-1,J)+C2*T(I+1,J)+C3*(T(I,J-1)+T(I,J+1)))/
    /
    (2.*(1.+C3))
0112 RII=(XNI-1)*DLI+RINS
0113 C11=CON1*(1.-DLI/(2.*RII))
0114 C21=CON2*(1.+DLI/(2.*RII))
0115 C121=0.5*(C11+C21)
0116 C5=CON12*DLIS*DLJV/((RII**2)*2.)
0117 C6=2.*(C121+C5)
0118 TNEW(NI,1)=(C11*T(NI-1,1)+C21*T(NI+1,1)+2.*C5*T(NI,2))/C6
0119 TNEW(NI,NJ)=(C11*T(NI-1,NJ)+C21*T(NI+1,NJ)+2.*C5*T(NI,NJ-1))/C6
0120 DO 9 J=2,NTJ
0121 9 TNEW(NI,J)=(C11*T(NI-1,J)+C21*T(NI+1,J)+C5*(T(NI,J-1)+T(NI,J+1))
    /
    (C6))
0122 C31=DLIS*DLJV/(RII**2)
0123 C1=1.-DLI/(2.*RII)
0124 C9=CON13*C1/2.
0125 C3T=CON23*C3T/2.
0126 C7T=C9+C21+C5+C3T
0127 TNEW(NI,NPJ)=(C9*T(LI,NPJ)+C21*T(KII,NPJ)+C5*T(NI,NTJ)+C3T*
    /
    T(NI,NQJ))/C7T
0128 C1T=CON3*C1I
0129 CST=CON13*C3I
0130 C6T=C1T+C2T+2.*CST
0131 TNEW(NI,NQJ)=(C1T*T(LI,NQJ)+C21*T(KII,NQJ)+C5T*(T(NI,NPJ)
    /
    +T(NI,NRJ)))/C6T
0132 TNEW(NI,NRJ)=(C9*T(LI,NRJ)+C21*T(KII,NRJ)+C3T*T(NI,NQJ)+C5*
    /
    T(NI,NQJ))/C7T

```

Fig. E.1 (Contd.)

```

0133      DO 91 J=NUJ,LJ
0134      91 TNEW(NI,J)=(C1I*T(NI-1,J)+C2I*T(NI+1,J)+C5*(T(NI,J-1)+T(NI,J+1)))/
      /C6
0135      GO TO 125
0136      123 DO 84 J=AI,LI
0137      DO 84 J=2,MJ
0138      RIR=I-1
0139      RI=RIR*DLI+RINS
0140      C1=1.-DLI/(2.*RI)
0141      C2=1.-DLI/(2.*RI)
0142      C3=DLIS*DLJV/(RI**2)
0143      84 TNEW(I,J)=(C1*T(I-1,J)+C2*T(I+1,J)+C3*(T(I,J-1)+T(I,J+1)))/
      /C6
0144      DO 86 I=2,LI
0145      DO 86 J=MJ,1,NTJ
0146      RIR=I-1
0147      RI=RIR*DLI+RINS
0148      C1=1.-DLI/(2.*RI)
0149      C2=1.-DLI/(2.*RI)
0150      C3=DLIS*DLJV/(RI**2)
0151      86 TNEW(I,J)=(C1*T(I-1,J)+C2*T(I+1,J)+C3*(T(I,J-1)+T(I,J+1)))/
      /C6
0152      DO 87 I=2,LI
0153      RIR=I-1
0154      RI=RIR*DLI+RINS
0155      C1=1.-DLI/(2.*RI)
0156      C2=1.-DLI/(2.*RI)
0157      C3=DLIS*DLJV/(RI**2)
0158      C31=CON13*C3
0159      C33=CON13*C3
0160      C9=CON13*C1/2.
0161      C10=CON13*C2/2.
0162      C11=C9+C10+C31+C33
0163      TNEW(I,NPJ)=(C9*T(I-1,NPJ)+C10*T(I+1,NPJ)+C31*T(I,NTJ)+C33*T(I,NQJ)
      /C11
0164      TNEW(I,NQJ)=(C1*T(I-1,NQJ)+C2*T(I+1,NQJ)+C3*(T(I,NPJ)+T(I,NRJ)))/
      /C6
0165      87 TNEW(I,NRJ)=(C9*T(I-1,NRJ)+C10*T(I+1,NRJ)+C33*T(I,NQJ)+C31*T(I,NUJ)
      /C11
0166      DO 88 I=2,LI
0167      DO 88 J=NUJ,LJ
0168      RIR=I-1
0169      RI=RIR*DLI+RINS
0170      C1=1.-DLI/(2.*RI)
0171      C2=1.-DLI/(2.*RI)
0172      C3=DLIS*DLJV/(RI**2)
0173      88 TNEW(I,J)=(C1*T(I-1,J)+C2*T(I+1,J)+C3*(T(I,J-1)+T(I,J+1)))/
      /C6
0174      RI=(XNI-1)*DLI+RINS
0175      C11=CON13*C1
0176      C21=CON23*(1.-DLI/(2.*RI))
0177      C121=0.5*(C11+C21)
0178      C5=CON12*DLIS*DLJV/(RI**2)*2.)
0179      C5=2.*(C121+C5)
0180      TNEW(NI,1)=(C1I*T(NI-1,1)+C2I*T(NI+1,1)+2.*C5*T(NI,2))/C6
0181      TNEW(NI,NJ)=(C1I*T(NI-1,NJ)+C2I*T(NI+1,NJ)+2.*C5*T(NI,NJ-1))/C6
0182      DO 95 J=2,NTJ
0183      95 TNEW(NI,J)=(C1I*T(NI-1,J)+C2I*T(NI+1,J)+C5*(T(NI,J-1)+T(NI,J+1)))/
      /C6
0184      C3I=DLIS*DLJV/(RI**2)
0185      C1=1.-DLI/(2.*RI)
0186      C9=CON13*C1/2.
0187      C3T=C3N23*C3I/2.
0188      C7T=C9+C2I+C5+C3T
0189      TNEW(NI,NPJ)=(C9*T(LI,NPJ)+C2I*T(KII,NPJ)+C5*T(NI,NTJ)+C3T*
      T(NI,NQJ))/C7T
0190      C1T=CON13*C1I
0191      C5T=CON13*C3I
0192      C5T=C1T+C2T+2.*C5T
0193      TNEW(NI,NQJ)=(C1T*T(LI,NQJ)+C2I*T(KII,NQJ)+C5T*(T(NI,NPJ)
      +T(NI,NRJ)))/C6T
0194      TNEW(NI,NRJ)=(C9*T(LI,NRJ)+C2I*T(KII,NRJ)+C3T*T(NI,NQJ)+C5*
      T(NI,NUJ))/C7T
0195      DO 96 J=NUJ,LJ
0196      96 TNEW(NI,J)=(C1I*T(NI-1,J)+C2I*T(NI+1,J)+C5*(T(NI,J-1)+T(NI,J+1)))/
      /C6
0197      125 IF (KII-LII) 60,60,70
0198      50 DO 19 I=KII,LII

```

Fig. E.1 (Contd.)

Fig. E.1 (Contd.)

APPENDIX F

Computer Program for a Three-dimensional System with
a Double-layered Refractory Lining

The program given in Fig. B.1 was modified to account for the situation when the transfer line has a double-layered refractory lining. For this case, additional input variables are needed to describe the system. CON1 and CON2 in Table A.1 are to be redefined as follows:

CON1 - Thermal conductivity of the inner refractory.

CON2 - Thermal conductivity of the outer refractory (or insulation) that is sandwiched between the inner refractory and the steel shell.

In addition, the following three new variables are introduced:

CON3 - Thermal conductivity of the steel shell.

TR1 - Thickness of the inner refractory layer.

TR2 - Thickness of the outer refractory (or insulation) layer.

The computer program for the modified system is presented in Fig. F.1. In the program, the added refractory layer is handled separately. The index parameters used to identify this added layer in the radial direction are shown in Fig. F.2. The presence of a second refractory layer only complicates the solution in the radial direction. Hence, the index parameters in the angular and axial directions remain unchanged from before (refer to Figs. A.2 and B.2).

REQUESTED OR NOTERM,OPT=2

OPTIONS IN 8 NAME(MAIN) OPTIMIZE(2) LINECOUNT(60) SIZE(MAX) AUTODBL(NCNE)
SOURCE EBCDIC NOLIST NODECK OBJECT MAP NOFORMAT GOSTMT NOXREF NOAL

```

ISN 0002      DIMENSION WORKSP(76),TEXP(25,11),CVPT(25,11),
/ G(25),SYMBOL(22),TFXP(25,11),TGXP(25,11),B(21),A(21),V(21)
ISN 0003      DOUBLE PRECISION DLIV,DLJV,DLKV,DLKVC,DLKVD,R?,C1,C2,
/ C3,C4,R11,C11,C21,C121,C5,C6,RISU,C1S,C2S,C7,C8,T(25,15,10),
/ TNEW(25,15,10),DLKWC,DLKWD,DLIS
ISN 0004      READ (5,1) RINS,ROUT,TR1,HIGHT,DPMIN,DPMAX,ACMIN,ACMAX,TLMIN,
/TLMAX,DELR,DLJ, DELZ,SPACEI,SPACEJ,SPACEK,TR2
ISN 0005      1 FORMAT (10F6.2)
ISN 0006      READ (5,41) TT,TA,H,CON1,CON2,CON3,EPS
ISN 0007      41 FORMAT (7F8.2)
ISN 0008      READ (5,200) (SYMBOL(I),I=1,21),ASTSK
ISN 0009      200 FORMAT (22A1)
ISN 0010      DLI=1./DELR
ISN 0011      INCR1=SPACEI/DLI
ISN 0012      DLK=1./DELZ
ISN 0013      INCRK=SPACEK/DLK
ISN 0014      WIDTH=3.14159*(RINS+ROUT)/2.
ISN 0015      DEA=WIDTH*DLJ/180.
ISN 0016      INCRJ=SPACEJ/DLJ
ISN 0017      N1I=(ROUT-RINS)/DLI+1.
ISN 0018      XN1I=N1I
ISN 0019      NJ=WIDTH/DEA+1.
ISN 0020      NK=HIGHT/DLK+1.
ISN 0021      M1M=DPMIN/DLI+1.
ISN 0022      M1J=ACMIN/DLJ+1.
ISN 0023      MKM=TLMIN/DLK+1.
ISN 0024      M1L=1.+(DPMAX-DPMIN)/SPACEI
ISN 0025      M1JL=1.+(ACMAX-ACMIN)/SPACEJ
ISN 0026      MKL=1.+(TLMAX-TLMIN)/SPACEK
ISN 0027      N1=TR1/DLI+1.
ISN 0028      XN1=N1
ISN 0029      N2=(TR1+TR2)/DLI+1.
ISN 0030      XN2=N2
ISN 0031      L1=N1-1
ISN 0032      K1I=N1+1
ISN 0033      M1I=N2-1
ISN 0034      K12=N2+1
ISN 0035      L1I=N1I-1
ISN 0036      DLIV=1.
ISN 0037      DLIS=DLI**2
ISN 0038      DLJV=1./((3.14159*DLJ/180. )**2)
ISN 0039      DLKV=(DLI**2)/(DLK**2)
ISN 0040      DLKVC=1.+DLKV
ISN 0041      CON12=CON1+CON2
ISN 0042      DLKVC=CON12*DLKV/2.
ISN 0043      DLKVD=0.5*CON2*DLIS/(DLK**2)
ISN 0044      CON23=CON2+CON3
ISN 0045      DLKWC=CON23*DLKV/2.
ISN 0046      DLKWD=0.5*CON3*DLIS/(DLK**2)
ISN 0047      DO 50 L=1,M1L
ISN 0048      DO 50 M=1,M1JL
ISN 0049      DO 50 N=1,MKL
ISN 0050      M1=M1M+(L-1)*INCR1

```

Fig. F.1. Computer Program for Evaluating Surface Temperature in a Three-dimensional System Constructed with a Double-layered Refractory Lining

```

ISN 0051      MJ=MJM+(M-1)*INCRJ
ISN 0052      MK=MKM+(N-1)*INCRK
ISN 0053      KI=MI+1
ISN 0054      KJ=MJ+1
ISN 0055      LJ=NJ-1
ISN 0056      KK=MK+1
ISN 0057      LK=NK-1
ISN 0058      DO 2 I=1,NII
ISN 0059      DO 2 J=1,NJ
ISN 0060      DO 2 K=1,NK
ISN 0061      2 T(I,J,K)=.5*(TT+TA)
ISN 0062      DO 3 J=1,NJ
ISN 0063      DO 3 K=1,NK
ISN 0064      TNEW(I,J,K)=TT
ISN 0065      3 T(I,J,K)=TT
ISN 0066      DO 4 I=2,MI
ISN 0067      DO 4 J=1,MJ
ISN 0068      DO 4 K=1,MK
ISN 0069      TNEW(I,J,K)=TT
ISN 0070      4 T(I,J,K)=TT
ISN 0071      80 DO 5 I=KI,LI
ISN 0072      RIR=I-1
ISN 0073      RI=RIR*DLI+RINS
ISN 0074      C1=1.-DLI/(2.*RI)
ISN 0075      C2=1.+DLI/(2.*RI)
ISN 0076      C3=DLIS*DLJV/(RI**2)
ISN 0077      C4=2.*(DLIKV+C3)
ISN 0078      5 TNEW(I,1,1)=(DLIV*(C1*T(I-1,1,1)+C2*T(I+1,1,1))+C3*2.*T(I,2,1)+
/ DLKV*2.*T(I,1,2))/C4
ISN 0079      DO 6 I=2,LI
ISN 0080      RIR=I-1
ISN 0081      RI=RIR*DLI+RINS
ISN 0082      C1=1.-DLI/(2.*RI)
ISN 0083      C2=1.+DLI/(2.*RI)
ISN 0084      C3=DLIS*DLJV/(RI**2)
ISN 0085      C4=2.*(DLIKV+C3)
ISN 0086      TNEW(I,NJ,1)=(DLIV*(C1*T(I-1,NJ,1)+C2*T(I+1,NJ,1))+C3*2.*
/ T(I,NJ-1,1)+DLKV*2.*T(I,NJ,2))/C4
ISN 0087      TNEW(I,1,NK)=(DLIV*(C1*T(I-1,1,NK)+C2*T(I+1,1,NK))+C3*2.*
/ T(I,2,NK)+DLKV*2.*T(I,1,NK-1))/C4
ISN 0088      6 TNEW(I,NJ,NK)=(DLIV*(C1*T(I-1,NJ,NK)+C2*T(I+1,NJ,NK))+C3*2.*
/ T(I,NJ-1,NK)+DLKV*2.*T(I,NJ,NK-1))/C4
ISN 0089      DO 7 I=2,MI
ISN 0090      DO 7 J=KJ,LJ
ISN 0091      RIR=I-1
ISN 0092      RI=RIR*DLI+RINS
ISN 0093      C1=1.-DLI/(2.*RI)
ISN 0094      C2=1.+DLI/(2.*RI)
ISN 0095      C3=DLIS*DLJV/(RI**2)
ISN 0096      C4=2.*(DLIKV+C3)
ISN 0097      7 TNEW(I,J,1)=(DLIV*(C1*T(I-1,J,1)+C2*T(I+1,J,1))+C3*(T(I,J-1,1)+
/ T(I,J+1,1))+DLKV*2.*T(I,J,2))/C4
ISN 0098      DO 8 I=KI,LI
ISN 0099      DO 8 J=2,LJ
ISN 0100      RIR=I-1
ISN 0101      RI=RIR*DLI+RINS
ISN 0102      C1=1.-DLI/(2.*RI)
ISN 0103      C2=1.+DLI/(2.*RI)

```

Fig. F.1 (Contd.)

```

ISN 0104      C3=DLIS*DLJV/(RI**2)
ISN 0105      C4=2.*(DLIKV+C3)
ISN 0106      8 TNEW(I,J,1)=(DLIV*(C1*T(I-1,J,1)+C2*T(I+1,J,1))+C3*(T(I,J-1,1)+
/ T(I,J+1,1))+DLKV*2.*T(I,J,2))/C4
ISN 0107      DO 9 I=KI,LI
ISN 0108      DO 9 K=2,LK
ISN 0109      RIR=I-1
ISN 0110      RI=RIR*DLI+RINS
ISN 0111      C1=1.-DLI/(2.*RI)
ISN 0112      C2=1.+DLI/(2.*RI)
ISN 0113      C3=DLIS*DLJV/(RI**2)
ISN 0114      C4=2.*(DLIKV+C3)
ISN 0115      9 TNEW(I,1,K)=(DLIV*(C1*T(I-1,1,K)+C2*T(I+1,1,K))+C3*2.*T(I,2,K)+
/ DLKV*(T(I,1,K-1)+T(I,1,K+1)))/C4
ISN 0116      DO 10 I=2,MI
ISN 0117      DO 10 K=KK,LK
ISN 0118      RIR=I-1
ISN 0119      RI=RIR*DLI+RINS
ISN 0120      C1=1.-DLI/(2.*RI)
ISN 0121      C2=1.+DLI/(2.*RI)
ISN 0122      C3=DLIS*DLJV/(RI**2)
ISN 0123      C4=2.*(DLIKV+C3)
ISN 0124      10 TNEW(I,1,K)=(DLIV*(C1*T(I-1,1,K)+C2*T(I+1,1,K))+C3*2.*T(I,2,K)+
/ DLKV*(T(I,1,K-1)+T(I,1,K+1)))/C4
ISN 0125      DO 11 I=2,LI
ISN 0126      DO 11 K=2,LK
ISN 0127      RIR=I-1
ISN 0128      RI=RIR*DLI+RINS
ISN 0129      C1=1.-DLI/(2.*RI)
ISN 0130      C2=1.+DLI/(2.*RI)
ISN 0131      C3=DLIS*DLJV/(RI**2)
ISN 0132      C4=2.*(DLIKV+C3)
ISN 0133      11 TNEW(I,NJ,K)=(DLIV*(C1*T(I-1,NJ,K)+C2*T(I+1,NJ,K))+C3*2.*
/ T(I,NJ-1,K)+DLKV*(T(I,NJ,K-1)+T(I,NJ,K+1)))/C4
ISN 0134      DO 12 I=2,LI
ISN 0135      DO 12 J=2,LJ
ISN 0136      RIR=I-1
ISN 0137      RI=RIR*DLI+RINS
ISN 0138      C1=1.-DLI/(2.*RI)
ISN 0139      C2=1.+DLI/(2.*RI)
ISN 0140      C3=DLIS*DLJV/(RI**2)
ISN 0141      C4=2.*(DLIKV+C3)
ISN 0142      12 TNEW(I,J,NK)=(DLIV*(C1*T(I-1,J,NK)+C2*T(I+1,J,NK))+C3*
/ (T(I,J-1,NK)+T(I,J+1,NK))+DLKV*2.*T(I,J,NK-1))/C4
ISN 0143      DO 13 I=KI,LI
ISN 0144      DO 13 J=2,MJ
ISN 0145      DO 13 K=2,MK
ISN 0146      RIR=I-1
ISN 0147      RI=RIR*DLI+RINS
ISN 0148      C1=1.-DLI/(2.*RI)
ISN 0149      C2=1.+DLI/(2.*RI)
ISN 0150      C3=DLIS*DLJV/(RI**2)
ISN 0151      C4=2.*(DLIKV+C3)
ISN 0152      13 TNEW(I,J,K)=(DLIV*(C1*T(I-1,J,K)+C2*T(I+1,J,K))+C3*(T(I,J-1,K)+
/ T(I,J+1,K))+DLKV*(T(I,J,K-1)+T(I,J,K+1)))/C4
ISN 0153      DO 14 I=2,LI
ISN 0154      DO 14 J=KJ,LJ
ISN 0155      DO 14 K=2,MK

```

Fig. F.1 (Contd.)

```

ISN 0156      RIR=I-1
ISN 0157      RI=RIR*DLI+RINS
ISN 0158      C1=1.-DLI/(2.*RI)
ISN 0159      C2=1.+DLI/(2.*RI)
ISN 0160      C3=DLIS*DLJV/(RI**2)
ISN 0161      C4=2.*(DLIKV+C3)
ISN 0162      14 TNEW(I,J,K)=(DLIV*(C1*T(I-1,J,K)+C2*T(I+1,J,K))+C3*(T(I,J-1,K)+
/ T(I,J+1,K))+DLKVC*(T(I,J,K-1)+T(I,J,K+1)))/C4
ISN 0163      DO 15 I=2,L1
ISN 0164      DO 15 J=2,LJ
ISN 0165      DO 15 K=KK,LK
ISN 0166      RIR=I-1
ISN 0167      RI=RIR*DLI+RINS
ISN 0168      C1=1.-DLI/(2.*RI)
ISN 0169      C2=1.+DLI/(2.*RI)
ISN 0170      C3=DLIS*DLJV/(RI**2)
ISN 0171      C4=2.*(DLIKV+C3)
ISN 0172      15 TNEW(I,J,K)=(DLIV*(C1*T(I-1,J,K)+C2*T(I+1,J,K))+C3*(T(I,J-1,K)+
/ T(I,J+1,K))+DLKVC*(T(I,J,K-1)+T(I,J,K+1)))/C4
ISN 0173      RII=(XNI-1.)*DLI+RINS
ISN 0174      C1I=CON1*(1.-DLI/(2.*RII))
ISN 0175      C2I=CON2*(1.+DLI/(2.*RII))
ISN 0176      C12I=0.5*(C1I+C2I)
ISN 0177      C5=CON12*DLIS*DLJV/(RII**2*2.)
ISN 0178      C6=2.*(C12I+C5+DLKVC)
ISN 0179      TNEW(NI,1,1)=(DLIV*(C1I*T(NI-1,1,1)+C2I*T(NI+1,1,1))+C5*2.*
/ T(NI,2,1)+DLKVC*2.*T(NI,1,2))/C6
ISN 0180      TNEW(NI,NJ,1)=(DLIV*(C1I*T(NI-1,NJ,1)+C2I*T(NI+1,NJ,1))+C5*2.*
/ T(NI,NJ-1,1)+DLKVC*2.*T(NI,NJ,2))/C6
ISN 0181      TNEW(NI,1,NK)=(DLIV*(C1I*T(NI-1,1,NK)+C2I*T(NI+1,1,NK))+C5*2.*
/ T(NI,2,NK)+DLKVC*2.*T(NI,1,NK-1))/C6
ISN 0182      TNEW(NI,NJ,NK)=(DLIV*(C1I*T(NI-1,NJ,NK)+C2I*T(NI+1,NJ,NK))+C5*
/ 2.*T(NI,NJ-1,NK)+DLKVC*2.*T(NI,NJ,NK-1))/C6
ISN 0183      DO 16 J=2,LJ
ISN 0184      TNEW(NI,J,1)=(DLIV*(C1I*T(NI-1,J,1)+C2I*T(NI+1,J,1))+C5*
/ (T(NI,J-1,1)+T(NI,J+1,1))+DLKVC*2.*T(NI,J,2))/C6
ISN 0185      16 TNEW(NI,J,NK)=(DLIV*(C1I*T(NI-1,J,NK)+C2I*T(NI+1,J,NK))+C5*
/ (T(NI,J-1,NK)+T(NI,J+1,NK))+DLKVC*2.*T(NI,J,NK-1))/C6
ISN 0186      DO 17 K=2,LK
ISN 0187      TNEW(NI,1,K)=(DLIV*(C1I*T(NI-1,1,K)+C2I*T(NI+1,1,K))+C5*2.*
/ T(NI,2,K)+DLKVC*(T(NI,1,K-1)+T(NI,1,K+1)))/C6
ISN 0188      17 TNEW(NI,NJ,K)=(DLIV*(C1I*T(NI-1,NJ,K)+C2I*T(NI+1,NJ,K))+C5*2.*
/ T(NI,NJ-1,K)+DLKVC*(T(NI,NJ,K-1)+T(NI,NJ,K+1)))/C6
ISN 0189      DO 18 J=2,LJ
ISN 0190      DO 18 K=2,LK
ISN 0191      18 TNEW(NI,J,K)=(DLIV*(C1I*T(NI-1,J,K)+C2I*T(NI+1,J,K))+C5*
/ (T(NI,J-1,K)+T(NI,J+1,K))+DLKVC*(T(NI,J,K-1)+T(NI,J,K+1)))/C6
ISN 0192      DO 19 I=KI,MI
ISN 0193      RIR=I-1
ISN 0194      RI=RIR*DLI+RINS
ISN 0195      C1=1.-DLI/(2.*RI)
ISN 0196      C2=1.+DLI/(2.*RI)
ISN 0197      C3=DLIS*DLJV/(RI**2)
ISN 0198      C4=2.*(DLIKV+C3)
ISN 0199      TNEW(I,1,1)=(DLIV*(C1*T(I-1,1,1)+C2*T(I+1,1,1))+C3*2.*T(I,2,1)+
/ DLKVC*2.*T(I,1,2))/C4
ISN 0200      TNEW(I,NJ,1)=(DLIV*(C1*T(I-1,NJ,1)+C2*T(I+1,NJ,1))+C3*2.*
/ T(I,NJ-1,1)+DLKVC*2.*T(I,NJ,2))/C4

```

Fig. F.1 (Contd.)

```

[SN 0201      TNEW(I,1,NK)=(DLIV*(C1*T(I-1,1,NK)+C2*T(I+1,1,NK))+C3*2.*
/ T(I,2,NK)+DLKV*2.*T(I,1,NK-1))/C4
[SN 0202 19 TNEW(I,NJ,NK)=(DLIV*(C1*T(I-1,NJ,NK)+C2*T(I+1,NJ,NK))+C3*2.*
/ T(I,NJ-1,NK)+DLKV*2.*T(I,NJ,NK-1))/C4
[SN 0203      DO 20 I=KII,MI
[SN 0204      DO 20 J=2,LJ
[SN 0205      RIR=I-1
[SN 0206      RI=RIR*DLI+RINS
[SN 0207      C1=1.-DLI/(2.*RI)
[SN 0208      C2=1.+DLI/(2.*RI)
[SN 0209      C3=DLIS*DLJV/(RI**2)
[SN 0210      C4=2.*(DLIKV+C3)
[SN 0211      TNEW(I,J,1)=(DLIV*(C1*T(I-1,J,1)+C2*T(I+1,J,1))+C3*(T(I,J-1,1)+
/ T(I,J+1,1))+DLKV*2.*T(I,J,2))/C4
[SN 0212 20 TNEW(I,J,NK)=(DLIV*(C1*T(I-1,J,NK)+C2*T(I+1,J,NK))+C3*
/ (T(I,J-1,NK)+T(I,J+1,NK))+DLKV*2.*T(I,J,NK-1))/C4
[SN 0213      DO 21 I=KII,MI
[SN 0214      DO 21 K=2,LK
[SN 0215      RIR=I-1
[SN 0216      RI=RIR*DLI+RINS
[SN 0217      C1=1.-DLI/(2.*RI)
[SN 0218      C2=1.+DLI/(2.*RI)
[SN 0219      C3=DLIS*DLJV/(RI**2)
[SN 0220      C4=2.*(DLIKV+C3)
[SN 0221      TNEW(I,1,K)=(DLIV*(C1*T(I-1,1,K)+C2*T(I+1,1,K))+C3*2.*T(I,2,K)+
/ DLKV*(T(I,1,K-1)+T(I,1,K+1))/C4
[SN 0222 21 TNEW(I,NJ,K)=(DLIV*(C1*T(I-1,NJ,K)+C2*T(I+1,NJ,K))+C3*2.*
/ T(I,NJ-1,K)+DLKV*(T(I,NJ,K-1)+T(I,NJ,K+1))/C4
[SN 0223      DO 22 I=KII,MI
[SN 0224      DO 22 J=2,LJ
[SN 0225      DO 22 K=2,LK
[SN 0226      RIR=I-1
[SN 0227      RI=RIR*DLI+RINS
[SN 0228      C1=1.-DLI/(2.*RI)
[SN 0229      C2=1.+DLI/(2.*RI)
[SN 0230      C3=DLJV/(RI**2)
[SN 0231      C4=2.*(DLIKV+C3)
[SN 0232 22 TNEW(I,J,K)=(DLIV*(C1*T(I-1,J,K)+C2*T(I+1,J,K))+C3*(T(I,J-1,K)+
/ T(I,J+1,K))+DLKV*(T(I,J,K-1)+T(I,J,K+1))/C4
[SN 0233      RI=(XN2-1.)*DLI+RINS
[SN 0234      C1I=CON2*(1.-DLI/(2.*RI))
[SN 0235      C2I=CON3*(1.+DLI/(2.*RI))
[SN 0236      C12I=0.5*(C1I+C2I)
[SN 0237      C5=CON23*DLIS*DLJV/(RI**2*2.)
[SN 0238      C6=2.*(C12I+C5*DLKWC)
[SN 0239      TNEW(N2,1,1)=(DLIV*(C1I*T(N2-1,1,1)+C2I*T(N2+1,1,1))+C5*2.*
/ T(N2,2,1)+DLKWC*2.*T(N2,1,2))/C6
[SN 0240      TNEW(N2,NJ,1)=(DLIV*(C1I*T(N2-1,NJ,1)+C2I*T(N2+1,NJ,1))+C5*2.*
/ T(N2,NJ-1,1)+DLKWC*2.*T(N2,NJ,2))/C6
[SN 0241      TNEW(N2,1,NK)=(DLIV*(C1I*T(N2-1,1,NK)+C2I*T(N2+1,1,NK))+C5*2.*
/ T(N2,2,NK)+DLKWC*2.*T(N2,1,NK-1))/C6
[SN 0242      TNEW(N2,NJ,NK)=(DLIV*(C1I*T(N2-1,NJ,NK)+C2I*(T(N2+1,NJ,NK)+C5*
/ 2.*T(N2,NJ-1,NK)+DLKWC*2.*T(N2,NJ,NK-1))/C6
[SN 0243      DO 516 J=2,LJ
[SN 0244      TNEW(N2,J,1)=(DLIV*(C1I*T(N2-1,J,1)+C2I*T(N2+1,J,1))+C5*
/ (T(N2,J-1,1)+T(N2,J+1,1))+DLKWC*2.*T(N2,J,2))/C6
[SN 0245 516 TNEW(N2,J,NK)=(DLIV*(C1I*T(N2-1,J,NK)+C2I*T(N2+1,J,NK))+C5*
/ (T(N2,J-1,NK)+T(N2,J+1,NK))+DLKWC*2.*T(N2,J,NK-1))/C6

```

Fig. F.1 (Contd.)

```

ISN 0246      DO 517 K=2,LK
ISN 0247      TNEW(N2,1,K)=(DLIV*(C1*T(N2-1,1,K)+C2*T(N2+1,1,K))+C5*2.*
/ T(N2,2,K)+DLKWC*(T(N2,1,K-1)+T(N2,1,K+1)))/C6
ISN 0248 517 TNEW(N2,NJ,K)=(DLIV*(C1*T(N2-1,NJ,K)+C2*T(N2+1,NJ,K))+C5*2.*
/ T(N2,NJ-1,K)+DLKWC*(T(N2,NJ,K-1)+T(N2,NJ,K+1)))/C6
ISN 0249      DO 518 J=2,LJ
ISN 0250      DO 518 K=2,LK
ISN 0251 518 TNEW(N2,J,K)=(DLIV*(C1*T(N2-1,J,K)+C2*T(N2+1,J,K))+C5*
/ (T(N2,J-1,K)+T(N2,J+1,K))+DLKWC*(T(N2,J,K-1)+T(N2,J,K+1)))/C6
ISN 0252      IF (KI2-LII) 560,560,70
ISN 0253 560 DO 519 I=KI2,LII
ISN 0254      RIR=I-1
ISN 0255      RI=RIR*DLI+RINS
ISN 0256      C1=1.-DLI/(2.*RI)
ISN 0257      C2=1.+DLI/(2.*RI)
ISN 0258      C3=DLIS*DLJV/(RI**2)
ISN 0259      C4=2.*(DLIKV+C3)
ISN 0260      TNEW(I,1,1)=(DLIV*(C1*T(I-1,1,1)+C2*T(I+1,1,1))+C3*2.*T(I,2,1)+
/ DLKV*2.*T(I,1,2))/C4
ISN 0261      TNEW(I,NJ,1)=(DLIV*(C1*T(I-1,NJ,1)+C2*T(I+1,NJ,1))+C3*2.*
/ T(I,NJ-1,1)+DLKV*2.*T(I,NJ,2))/C4
ISN 0262      TNEW(I,1,NK)=(DLIV*(C1*T(I-1,1,NK)+C2*T(I+1,1,NK))+C3*2.*
/ T(I,2,NK)+DLKV*2.*T(I,1,NK-1))/C4
ISN 0263 519 TNEW(I,NJ,NK)=(DLIV*(C1*T(I-1,NJ,NK)+C2*T(I+1,NJ,NK))+C3*2.*
/ T(I,NJ-1,NK)+DLKV*2.*T(I,NJ,NK-1))/C4
ISN 0264      DO 520 I=KI2,LII
ISN 0265      DO 520 J=2,LJ
ISN 0266      RIR=I-1
ISN 0267      RI=RIR*DLI+RINS
ISN 0268      C1=1.-DLI/(2.*RI)
ISN 0269      C2=1.+DLI/(2.*RI)
ISN 0270      C3=DLIS*DLJV/(RI**2)
ISN 0271      C4=2.*(DLIKV+C3)
ISN 0272      TNEW(I,J,1)=(DLIV*(C1*T(I-1,J,1)+C2*T(I+1,J,1))+C3*(T(I,J-1,1)+
/ T(I,J+1,1))+DLKV*2.*T(I,J,2))/C4
ISN 0273 520 TNEW(I,J,NK)=(DLIV*(C1*T(I-1,J,NK)+C2*T(I+1,J,NK))+C3*
/ (T(I,J-1,NK)+T(I,J+1,NK))+DLKV*2.*T(I,J,NK-1))/C4
ISN 0274      DO 521 I=KI2,LII
ISN 0275      DO 521 K=2,LK
ISN 0276      RIR=I-1
ISN 0277      RI=RIR*DLI+RINS
ISN 0278      C1=1.-DLI/(2.*RI)
ISN 0279      C2=1.+DLI/(2.*RI)
ISN 0280      C3=DLIS*DLJV/(RI**2)
ISN 0281      C4=2.*(DLIKV+C3)
ISN 0282      TNEW(I,1,K)=(DLIV*(C1*T(I-1,1,K)+C2*T(I+1,1,K))+C3*2.*T(I,2,K)+
/ DLKV*(T(I,1,K-1)+T(I,1,K+1)))/C4
ISN 0283 521 TNEW(I,NJ,K)=(DLIV*(C1*T(I-1,NJ,K)+C2*T(I+1,NJ,K))+C3*2.*
/ T(I,NJ-1,K)+DLKV*(T(I,NJ,K-1)+T(I,NJ,K+1)))/C4
ISN 0284      DO 522 I=KI2,LII
ISN 0285      DO 522 J=2,LJ
ISN 0286      DO 522 K=2,LK
ISN 0287      RIR=I-1
ISN 0288      RI=RIR*DLI+RINS
ISN 0289      C1=1.-DLI/(2.*RI)
ISN 0290      C2=1.+DLI/(2.*RI)
ISN 0291      C3=DLJV/(RI**2)
ISN 0292      C4=2.*(DLIKV+C3)

```

Fig. F.1 (Contd.)

```

ISN 0293 522 TNEW(I,J,K)=(DLIV*(C1*T(I-1,J,K)+C2*T(I+1,J,K))+C3*(T(I,J-1,K)+
/ T(I,J+1,K))+DLKV*(T(I,J,K-1)+T(I,J,K+1)))/C4
ISN 0294 70 RISU=(XNII-1.)*DLI+RINS
ISN 0295 C1S=CON3*(1.-DLI/(2.*RISU))
ISN 0296 C2S=H*DLI
ISN 0297 C7=0.5*CON3*DLIS*DLJV/(RISU**2)
ISN 0298 C8=(C1S+C2S)+2.*C7+2.*DLKWD
ISN 0299 TNEW(NII,1,1)=(DLIV*(C1S*T(NII-1,1,1)+C2S*TA)+C7*2.*T(NII,2,1)
/ +DLKWD*2.*T(NII,1,2))/C8
ISN 0300 TNEW(NII,NJ,1)=(DLIV*(C1S*T(NII-1,NJ,1)+C2S*TA)+C7*2.*
/ T(NII,NJ-1,1)+DLKWD*2.*T(NII,NJ,2))/C8
ISN 0301 TNEW(NII,1,NK)=(DLIV*(C1S*T(NII-1,1,NK)+C2S*TA)+C7*2.*
/ T(NII,2,NK)+DLKWD*2.*T(NII,1,NK-1))/C8
ISN 0302 TNEW(NII,NJ,NK)=(DLIV*(C1S*T(NII-1,NJ,NK)+C2S*TA)+C7*2.*
/ T(NII,NJ-1,NK)+DLKWD*2.*T(NII,NJ,NK-1))/C8
ISN 0303 DO 23 J=2,LJ
ISN 0304 TNEW(NII,J,1)=(DLIV*(C1S*T(NII-1,J,1)+C2S*TA)+C7*(T(NII,J-1,1)+
/ T(NII,J+1,1))+DLKWD*2.*T(NII,J,2))/C8
ISN 0305 23 TNEW(NII,J,NK)=(DLIV*(C1S*T(NII-1,J,NK)+C2S*TA)+C7*
/ (T(NII,J-1,NK)+T(NII,J+1,NK))+DLKWD*2.*T(NII,J,NK-1))/C8
ISN 0306 DO 24 K=2,LK
ISN 0307 TNEW(NII,1,K)=(DLIV*(C1S*T(NII-1,1,K)+C2S*TA)+C7*2.*T(NII,2,K)+
/ DLKWD*(T(NII,1,K-1)+T(NII,1,K+1)))/C8
ISN 0308 24 TNEW(NII,NJ,K)=(DLIV*(C1S*T(NII-1,NJ,K)+C2S*TA)+C7*2.*
/ T(NII,NJ-1,K)+DLKWD*(T(NII,NJ,K-1)+T(NII,NJ,K+1)))/C8
ISN 0309 DO 25 J=2,LJ
ISN 0310 DO 25 K=2,LK
ISN 0311 25 TNEW(NII,J,K)=(DLIV*(C1S*T(NII-1,J,K)+C2S*TA)+C7*(T(NII,J-1,K)+
/ T(NII,J+1,K))+DLKWD*(T(NII,J,K-1)+T(NII,J,K+1)))/C8
ISN 0312 DO 85 I=2,MI
ISN 0313 DO 85 J=KJ,NJ
ISN 0314 DO 85 K=1,MK
ISN 0315 IF (DABS(T(I,J,K)-TNEW(I,J,K))-EPS) 85,85,40
ISN 0316 85 CONTINUE
ISN 0317 DO 27 I=2,MI
ISN 0318 DO 27 J=1,NJ
ISN 0319 DO 27 K=KK,NK
ISN 0320 IF (DABS(T(I,J,K)-TNEW(I,J,K))-EPS) 27,27,40
ISN 0321 27 CONTINUE
ISN 0322 DO 26 I=KI,NII
ISN 0323 DO 26 J=1,NJ
ISN 0324 DO 26 K=1,NK
ISN 0325 IF (DABS(T(I,J,K)-TNEW(I,J,K))-EPS) 26,26,40
ISN 0326 26 CONTINUE
ISN 0327 GO TO 90
ISN 0328 40 DO 31 I=2,MI
ISN 0329 DO 31 J=KJ,NJ
ISN 0330 DO 31 K=1,MK
ISN 0331 31 T(I,J,K)=TNEW(I,J,K)
ISN 0332 DO 32 I=KI,NII
ISN 0333 DO 32 J=1,NJ
ISN 0334 DO 32 K=1,MK
ISN 0335 32 T(I,J,K)=TNEW(I,J,K)
ISN 0336 DO 33 I=2,NII
ISN 0337 DO 33 J=1,NJ
ISN 0338 DO 33 K=KK,NK
ISN 0339 33 T(I,J,K)=TNEW(I,J,K)
ISN 0340 GO TO 80

```

Fig. F.1 (Contd.)

```

ISN 0341 90 XMI=MI
ISN 0342    YMJ=MJ
ISN 0343    ZMK=MK
ISN 0344    DEPTH=DLI*(XMI-1.)
ISN 0345    ACROS=DLJ*(YMJ-1.)
ISN 0346    HICAV=DLK*(ZMK-1.)
ISN 0347    DINS=2.*RINS
ISN 0348    DOUT=2.*ROUT
ISN 0349    HIGHU=2.*HIGHT
ISN 0350    SHTK=ROUT-RINS-TR1-TR2
ISN 0351    WRITE (6,28) DINS,DOUT,HIGHU,TR1,TR2,SHTK,DEPTH,ACROS,HICAV,DLI,
/ DLJ,DLK,TT,TA,CON1,CON2,CON3,H,EPS
ISN 0352 28 FORMAT (1H1,20HDIMENSION: ID=F8.2,8H IN.,OO=F8.2,
/ 21H IN., (TOTAL) HEIGHT=F8.2,
/ 4H IN./18X,21HREFRACTORY THICKNESS:,12H (INNER)=F6.2,
/ 17H IN., (OUTER)=F6.2,4H IN./18X,
/ 16HSHELL THICKNESS=F6.2,4H IN./13H CAVITY SIZE:,5X,
/ 6HDEPTH=F6.2,19H IN., (HALF) ANGLE=F7.2,5H DEG./
/ 17X,15H (HALF) HEIGHT=F7.2,4H IN./
/ 11H MESH SIZE:,7X,7HRAIDIAL=F6.3,13H IN.,ANGULAR=F6.2,
/ 12H DEG.,AXIAL=F6.2,4H IN./
/ 14H TEMPERATURES:,4X,15HINSIDE SURFACE=
/ F10.2,14H DEG.,AMBIENT=F8.2,5H DEG./12H PROPERTIES:,6X,
/ 22HK FOR REF.: (INNER)=F8.2,11H (OUTER)=F8.2/
/ 18X,12HK FOR SHELL=F8.2,19H BTU IN./HR FT**2 F/
/ 18X,2HH=F8.2,15H BTU/HR FT**2 F/20H ITERATION ERROR: E=
/ F5.2,5H DEG.//))
ISN 0353    DO 29 K=1,NK
ISN 0354 29 WRITE (6,30) (TNEW(NII,J,K),J=1,NJ)
ISN 0355 30 FORMAT (5D20.10)
ISN 0356    NJCT=2*NJ-1
ISN 0357    NKCT=2*NK-1
ISN 0358    NJDT=NJ+1
ISN 0359    NKDT=NK+1
ISN 0360    NJET=NJ-1
ISN 0361    NKET=NK-1
ISN 0362    ANJCT=NJCT
ISN 0363    ANKCT=NKCT
ISN 0364    BNJCT=-(2.*ANJCT)
ISN 0365    BNKCT=-(2.*ANKCT)
ISN 0366    CNJCT=1.5*ANJCT
ISN 0367    MTTT=TNEW(NII,1,1)/100.+1.
ISN 0368    VTT=MTTT*100
ISN 0369    MTTB=TNEW(NII,NJ,NK)/100.
ISN 0370    VTB=MTTB*100
ISN 0371    MTTR=ROUT-RINS+1.
ISN 0372    RTT=MTTR
ISN 0373    DO 101 J=1,NK
ISN 0374    DO 101 I=1,NJCT
ISN 0375    IF (I-NJ) 102,102,103
ISN 0376 102 TEXP(I,J)=TNEW(NII,NJDT-I,J)
ISN 0377    GO TO 101
ISN 0378 103 TEXP(I,J)=TNEW(NII,I-NJET,J)
ISN 0379 101 CONTINUE
ISN 0380    DO 104 I=1,NJCT
ISN 0381    DO 104 J=1,NKCT
ISN 0382    IF (J-NK) 105,105,106
ISN 0383 105 TFXP(I,J)=TEXP(I,NKDT-J)

```

Fig. F.1 (Contd.)


```

ISN 0384      GO TO 104
ISN 0385 106  TFXP(I,J)=TEXP(I,J-NKET)
ISN 0386 104  CONTINUE
ISN 0387      ZHI=ROUT-RINS
ISN 0388      ZCI=ROUT-RINS-(XMI-1.)*DLI
ISN 0389      NJFT=NJ-MJ+1
ISN 0390      NKFT=NK-MK+1
ISN 0391      NJGT=NJ+MJ-1
ISN 0392      NKGT=NK+MK-1
ISN 0393      NJHT=NJFT+1
ISN 0394      NKHT=NKFT+1
ISN 0395      NJIT=NJGT-1
ISN 0396      NKIT=NKGT-1
ISN 0397      DO 111 J=1,NKCT
ISN 0398      DO 111 I=1,NJFT
ISN 0399 111  CVPT(I,J)=ZHI
ISN 0400      DO 112 J=1,NKCT
ISN 0401      DO 112 I=NJGT,NJCT
ISN 0402 112  CVPT(I,J)=ZHI
ISN 0403      DO 113 I=NJHT,NJIT
ISN 0404      DO 113 J=1,NKFT
ISN 0405 113  CVPT(I,J)=ZHI
ISN 0406      DO 114 I=NJHT,NJIT
ISN 0407      DO 114 J=NKGT,NKCT
ISN 0408 114  CVPT(I,J)=ZHI
ISN 0409      DO 115 I=NJHT,NJIT
ISN 0410      DO 115 J=NKHT,NKIT
ISN 0411 115  CVPT(I,J)=ZCI
ISN 0412      WRITE (6,35)
ISN 0413 35  FORMAT (1H1,43HTHREE DIMENSIONAL SURFACE TEMPERATURE PLOT:)
ISN 0414      CALL STRTPL
ISN 0415      CALL BGNPL(1)
ISN 0416      CALL TITL3D('THREE-DIMENSIONAL SURFACE TEMPERATURE PLOTS',-100,
/ 10.,6.)
ISN 0417      CALL AXES3D('ANGULAR DIRECTIONS',100,'AXIAL DIRECTIONS',100,
/ 'TEMPERATURES',100,ANJCT,ANKCT,CNJCT)
ISN 0418      CALL VUABS(BNJCT,BNKCT,CNJCT)
ISN 0419      CALL GRAF3D(1.,4.,ANJCT,1.,2.,ANKCT,100.,50.,500.)
ISN 0420      CALL SURMAT(TFXP,1,NJCT,1,NKCT,WORKSP)
ISN 0421      CALL ENDPL(1)
ISN 0422      WRITE (6,36)
ISN 0423 36  FORMAT (1H1,38HRECONSTRUCTION OF CAVITY CONFIGURATION)
ISN 0424      CALL BGNPL(1)
ISN 0425      CALL TITL3D('RECONSTRUCTION OF CAVITY CONFIGURATIONS',-100,
/ 10.,6.)
ISN 0426      CALL AXES3D('ANGULAR DIRECTIONS',100,'AXIAL DIRECTIONS',100,
/ 'RADIAL DIRECTIONS',100,ANJCT,ANKCT,CNJCT)
ISN 0427      CALL VUABS(BNJCT,BNKCT,CNJCT)
ISN 0428      CALL GRAF3D(1.,4.,ANJCT,1.,2.,ANKCT,0.,1.,RTT)
ISN 0429      CALL SURMAT(CVPT,1,NJCT,1,NKCT,WORKSP)
ISN 0430      CALL ENDPL(2)
ISN 0431      TNC=(VTI-VTB)/21.
ISN 0432      VTC=VTB+TNC-0.1
ISN 0433      VTD=VTB+2.*TNC
ISN 0434      VTE=VTD+TNC-0.1
ISN 0435      VTF=VTB+4.*TNC
ISN 0436      VTG=VTF+TNC-0.1
ISN 0437      VTH=VTB+6.*TNC

```

Fig. F.1 (Contd.)

```

ISN 0438      VTI=VTH+TNC-0.1
ISN 0439      VTJ=VTB+8.*TNC
ISN 0440      VTK=VTJ+TNC-0.1
ISN 0441      VTL=VTB+10.*TNC
ISN 0442      VTM=VTL+TNC-0.1
ISN 0443      VTN=VTB+12.*TNC
ISN 0444      VTO=VTN+TNC-0.1
ISN 0445      VTP=VTB+14.*TNC
ISN 0446      VTQ=VTP+TNC-0.1
ISN 0447      VTR=VTB+16.*TNC
ISN 0448      VTS=VTR+TNC-0.1
ISN 0449      VTU=VTB+18.*TNC
ISN 0450      VTV=VTU+TNC-0.1
ISN 0451      VTM=VTB+20.*TNC
ISN 0452      WRITE (6,37)
ISN 0453      37 FORMAT(1H1,26HSURFACE ISOTHERM CONTOURS:///8H LEGEND:/5X,
/ 36HSYMBOL ISOTHERM BAND WIDTH (DEG.F)/)
ISN 0454      WRITE (6,38) VT8,VTC,VTD,VTE,VTF,VTG,VTI,VTJ,VTK,VTL,VTM,VTN,
/ VTO,VTP,VTQ,VTR,VTS,VTU,VTV,VTM,VTI
ISN 0455      38 FORMAT (7X,1HA,10X,F7.1,4H TO ,F7.1/
/ 7X,1HB,10X,F7.1,4H TO ,F7.1/
/ 7X,1HC,10X,F7.1,4H TO ,F7.1/
/ 7X,1HD,10X,F7.1,4H TO ,F7.1/
/ 7X,1HE,10X,F7.1,4H TO ,F7.1/
/ 7X,1HF,10X,F7.1,4H TO ,F7.1/
/ 7X,1HG,10X,F7.1,4H TO ,F7.1/
/ 7X,1HH,10X,F7.1,4H TO ,F7.1/
/ 7X,1HI,10X,F7.1,4H TO ,F7.1/
/ 7X,1HJ,10X,F7.1,4H TO ,F7.1/
/ 7X,1HK,10X,F7.1,4H TO ,F7.1//)
ISN 0456      WRITE (6,39)
ISN 0457      39 FORMAT (1H ,41HNOTE: ALTHOUGH ELEVEN SYMBOLS ARE USED TO
/ 56H REPRESENT ISOTHERM BANDS IN THE LEGEND, THE TEMPERATURE
/ 54H RANGES FOR THESE SYMBOLS HAVE BEEN SELECTED SUCH THAT
/ 61H TWENTY ONE BANDS CAN BE READ OFF FROM THE ISOTHERM MAP. NOTE
/ 59H THAT THE TEMPERATURE RANGES IN THE LEGEND ARE DISCONTINUOUS
/ 53H , SIGNIFYING THAT A WHITE BAND EXISTS IN BETWEEN THE/
/ 54H NEIGHBORING LETTERED BANDS; THE TEMPERATURE RANGE FOR
/ 50H THE WHITE BAND IS BRIDGED IN BETWEEN THOSE OF THE/
/ 19H NEIGHBORING BANDS.//)
ISN 0458      DO 201 I=1,NJCT
ISN 0459 201 G(I)=ASTSK
ISN 0460      WRITE (6,202) G
ISN 0461 202 FORMAT (1H ,180A1)
ISN 0462      J=NKCT
ISN 0463 203 DO 204 I=1,NJCT
ISN 0464      K=(TFXP(I,J)-VTB)/TNC+1.
ISN 0465      G(I)=SYMBOL(K)
ISN 0466 204 CONTINUE
ISN 0467      WRITE (6,205) G
ISN 0468 205 FORMAT (1H ,180A1)
ISN 0469      J=J-1
ISN 0470      IF (J.NE.0) GO TO 203
ISN 0472      DO 206 I=1,NJCT
ISN 0473 206 G(I)=ASTSK
ISN 0474      WRITE (6,207) G
ISN 0475 207 FORMAT (1H ,180A1)
ISN 0476      SCR=(TNEW(NI I,1,1)-TNEW(NI I,NJ,NK))/20.

```

Fig. F.1 (Contd.)

```

ISN 0477      DO 301 K=1,20
ISN 0478      BK=K
ISN 0479      BIAS=(BK-1.)*SCR+TNEW(NII,NJ,NK)
ISN 0480      DO 302 J=1,NKCT
ISN 0481      DO 302 I=1,NJCT
ISN 0482 302  TGXP(I,J)=TFXP(I,J)-BIAS
ISN 0483      COUNT=0.
ISN 0484      ACUM=0.
ISN 0485      DO 303 J=1,NKCT
ISN 0486      DO 303 I=1,NJCT
ISN 0487      IF (TGXP(I,J)) 303,304,304
ISN 0488 304  COUNT=COUNT+1.
ISN 0489      ACUM=ACUM+TGXP(I,J)
ISN 0490 303  CONTINUE
ISN 0491      B(K)=BIAS
ISN 0492      A(K)=COUNT
ISN 0493 301  V(K)=ACUM
ISN 0494      DO 350 K=1,10
ISN 0495      DIV=10.**K
ISN 0496      Y=A(2)/DIV
ISN 0497      IF (Y-1) 351,351,350
ISN 0498 350  CONTINUE
ISN 0499 351  EXPA=K
ISN 0500      DO 360 K=1,10
ISN 0501      DIV=10.**K
ISN 0502      Y=V(2)/DIV
ISN 0503      IF (Y-1) 361,361,360
ISN 0504 360  CONTINUE
ISN 0505 361  EXPV=K
ISN 0506      CYCLA=8./EXPA
ISN 0507      CYCLV=8./EXPV
ISN 0508      THVOL=V(1)+TNEW(NII,NJ,NK)*ANJCT*ANKCT
ISN 0509      WRITE (6,371) THVOL
ISN 0510 371  FORMAT (1H1,36HTOTAL VOLUME UNDERNEATH THE SURFACE=E12.5//)
ISN 0511      WRITE (6,372)
ISN 0512 372  FORMAT (1H ,2X8HISOTHERMSX11HAREA INSIDE4X10HINTEGRATED)
ISN 0513      WRITE (6,373)
ISN 0514 373  FORMAT (1H ,1X11HTEMPERATURE3X12HTHE ISOTHERMSX6HVOLUME)
ISN 0515      DO 374 K=1,20
ISN 0516 374  WRITE (6,375) B(K),A(K),V(K)
ISN 0517 375  FORMAT (1H ,F9.1,E17.4,E14.4)
ISN 0518      PUNCH 330, DEPTH,ACROS,HICAV,THVOL,TNEW(NII,1,1),TNEW(NII,NJ,NK)
ISN 0519 330  FORMAT (F10.2,5F10.1)
ISN 0520      WRITE (6,376)
ISN 0521 376  FORMAT (1H1)
ISN 0522      CALL BGNPL(1)
ISN 0523      CALL TITLE('AREA ENCLOSED INSIDE ISOTHERM LOOPS',100,
/ 'TEMPERATURES',100,'AREAS',100,5.,8.)
ISN 0524      CALL FRAME
ISN 0525      CALL YLOG(100.,80.,1.,CYCLA)
ISN 0526      CALL GRID(2,2)
ISN 0527      CALL CURVE(8,A,20,1)
ISN 0528      CALL ENDPL(3)
ISN 0529      CALL TITLE('INTEGRATED ENERGY EQUIVALENTS',100,
/ 'TEMPERATURES',100,'INTEGRATED ENERGY EQUIVALENTS',100,5.,8.)
ISN 0530      CALL FRAME
ISN 0531      CALL YLOG(100.,80.,1.,CYCLV)
ISN 0532      CALL GRID(2,2)

```

Fig. F.1 (Contd.)

```

ISN 0533  CALL CURVE(8,V,20,1)
ISN 0534  CALL ENDPL(4)
ISN 0535  50 CONTINUE
ISN 0536  CALL DONEPL
ISN 0537  STOP
ISN 0538  END

```

Fig. F.1 (Contd.)

Fig. F.2

Schematic Diagram Showing Nodal Locations in Radial Direction in a Modified Three-dimensional System

APPENDIX G

Computer Program for a Three-dimensional System
with Interfacial Contact Resistance

Figure G.1 shows a computer program for a three-dimensional system with constant contact resistance occurring at the refractory/steel interface. Another program for a similar system, but with variable contact resistance, is presented in Fig. G.2. In both programs, the system under study has only one refractory layer. To generate a wide range of resistance values for tests, additional DO loops have been inserted in each program. Slight modifications have also been made in the resistance expressions used in the interfacial nodal equations. These modifications are rather straightforward in the case of constant contact resistance. For a variable contact resistance, a subprogram is introduced to calculate the resistance parameter at each mesh point on the interface. In addition, since the contact-resistance value, not the resistance parameter, is of practical interest, the program is also designed to calculate these resistance values and tabulate them as additional outputs.

```

0001      DIMENSION WORKSP(76),WCRKSO(76),TEXP(25,11),CVPT(25,11),
/ G(25),SYMBOL(22),TPXP(25,11),T3XP(25,11),B(21),A(21),V(21),
/ STOR*(25,11)
0002      DOUBLE PRECISION DLIV,DLJV,DLKV,DLIVV,DLKVC,DLKVD,PI,C1,C2,
/ C3,C4,R1I,C1I,C2I,C12I,C5,C6,RISU,C1S,C2S,C7,CR,T(15,15,11),
/ TNEW(15,15,10)
0003      READ (5,1) RINS,ROUT,TP,HIGHT,DPMIN,DPMAX,ACHIN,ACMAX,TLMIN,
/ TINAI,DELR,DLJ, DELZ,SPACEI,SPACEJ,SPACEK
0004      1 FORMAT (10F6.2)
0005      READ (5,41) TI,TA,H,CON1,CON2,EPS
0006      41 FORMAT (6F8.2)
0007      READ (5,200) (SYMBOL(I),I=1,21),ASTSK
0008      200 FORMAT (22A1)
0009      DLI=1./DELR
0010      INCR1=SPACEI/DLI
0011      DLK=1./DELZ
0012      INCRK=SPACEK/DLK
0013      WIDTH=3.14159*(RINS+ROUT)/2.
0014      DEA=WIDTH*DLJ/180.
0015      INCRJ=SPACEJ/DLJ
0016      NII=(ROUT-RINS)/DLI+1.
0017      NII=NII
0018      NJ=WIDTH/DEA+1.
0019      NK=HIGHT/DLK+1.
0020      NI=DPMIN/DLI+1.
0021      NJ=ACHIN/DLJ+1.
0022      NK=TLMIN/DLK+1.
0023      NIL=1.+(DPMAX-DPMIN)/SPACEI
0024      MJL=1.+(ACMAX-ACHIN)/SPACEJ
0025      NKL=1.+(TLMAX-TLMIN)/SPACEK
0026      NI=TP/DLI+1.
0027      INI=NT
0028      DLIV=1.
0029      DLIS=DLI**2
0030      DLJV=1./((3.14159*DLJ/180.)**2)
0031      DLKV=(DLI**2)/(DLK**2)
0032      DIKV=1.+DLKV
0033      CON12=CON1+CON2
0034      DLKVC=CON12*DLKV/2.
0035      DLKVD=.5*CON2*DIIS/(DLK**2)
0036      DO 400 ICR=1,10
0037      VCR=ICR
0038      VRES=(VCP-1.)*.25+1.25
0039      DO 50 L=1,NIL
0040      DO 50 I=1,MJL
0041      DO 50 N=1,NKL
0042      MI=MIN+(L-1)*INCR1
0043      MJ=MJM+(I-1)*INCRJ
0044      NK=MKM+(N-1)*INCRK
0045      KI=MI+1
0046      LI=NI-1
0047      KII=NI+1
0048      LII=NI-1
0049      KJ=MJ+1
0050      IJ=NJ-1

```

Fig. G.1. Computer Program for Evaluating Surface Temperature in a Three-dimensional System with Constant Contact Resistance

```

0051      KK=KK+1
0052      IK=KK-1
0053      DO 2 I=1, NII
0054      DO 2 J=1, NJ
0055      DO 2 K=1, NK
0056      2 T(I,J,K) = .5*(TT+TA)
0057      DO 3 J=1, NJ
0058      DO 3 K=1, NK
0059      TNEW(I,J,K) = TT
0060      3 T(I,J,K) = TT
0061      DO 4 I=2, NI
0062      DO 4 J=1, NJ
0063      DO 4 K=1, NK
0064      TNEW(I,J,K) = TT
0065      4 T(I,J,K) = TT
0066      80 DO 5 I=KI, LI
0067      RIR=I-1
0068      RI=RIR*DLI+RINS
0069      C1=1.-DLJ/(2.*RI)
0070      C2=1.+DLJ/(2.*RI)
0071      C3=DLIS*DLJV/(RI**2)
0072      C4=2.*(DLKV+C3)
0073      5 TNEW(I,1,1) = (DLIV*(C1*T(I-1,1,1)+C2*T(I+1,1,1))+C3*2.*T(I,2,1) +
/ DLKV*2.*T(I,1,2))/C4
0074      DO 6 I=2, LI
0075      RIR=I-1
0076      RI=RIR*DLI+RINS
0077      C1=1.-DLJ/(2.*RI)
0078      C2=1.+DLJ/(2.*RI)
0079      C3=DLIS*DLJV/(RI**2)
0080      C4=2.*(DLKV+C3)
0081      TNEW(I,NJ,1) = (DLIV*(C1*T(I-1,NJ,1)+C2*T(I+1,NJ,1))+C3*2.*
/ T(I,NJ-1,1)+DLKV*2.*T(I,NJ,2))/C4
0082      TNEW(I,1,NK) = (DLIV*(C1*T(I-1,1,NK)+C2*T(I+1,1,NK))+C3*2.*
/ T(I,2,NK)+DLKV*2.*T(I,1,NK-1))/C4
0083      6 TNEW(I,NJ,NK) = (DLJV*(C1*T(I-1,NJ,NK)+C2*T(I+1,NJ,NK))+C3*2.*
/ T(I,NJ-1,NK)+DLKV*2.*T(I,NJ,NK-1))/C4
0084      DO 7 I=2, NI
0085      DO 7 J=KJ, LJ
0086      RIR=I-1
0087      RI=RIR*DLI+RINS
0088      C1=1.-DLJ/(2.*RI)
0089      C2=1.+DLJ/(2.*RI)
0090      C3=DLIS*DLJV/(RI**2)
0091      C4=2.*(DLKV+C3)
0092      7 TNEW(I,J,1) = (DLIV*(C1*T(I-1,J,1)+C2*T(I+1,J,1))+C3*(T(I,J-1,1) +
/ T(I,J+1,1))+DLKV*2.*T(I,J,2))/C4
0093      DO 8 I=KI, LI
0094      DO 8 J=2, LJ
0095      RIR=I-1
0096      RI=RIR*DLI+RINS
0097      C1=1.-DLJ/(2.*RI)
0098      C2=1.+DLJ/(2.*RI)
0099      C3=DLIS*DLJV/(RI**2)
0100      C4=2.*(DLKV+C3)

```

Fig. G.1 (Contd.)

```

0101      8 TNEW(I,J,1) = (DLIV*(C1*T(I-1,J,1)+C2*T(I+1,J,1))+C3*(T(I,J-1,1)+
0102      / T(I,J+1,1))+DLKV*2.*T(I,J,2))/C4
0103      DO 9 I=KI,LI
0104      DO 9 K=2,LK
0105      RIR=I-1
0106      RI=RIR*DLI+BINS
0107      C1=1.-DLI/(2.*RI)
0108      C2=1.+DLI/(2.*RI)
0109      C3=DLIS*DLJV/(RI**2)
0110      C4=2.*(DLIKV+C3)
0111      9 TNEW(I,1,K) = (DLIV*(C1*T(I-1,1,K)+C2*T(I+1,1,K))+C3*2.*T(I,2,K)+
0112      / DLKV*(T(I,1,K-1)+T(I,1,K+1)))/C4
0113      DO 10 I=2,MI
0114      DO 10 K=KK,LK
0115      RIR=I-1
0116      RI=RIR*DLI+BINS
0117      C1=1.-DLI/(2.*RI)
0118      C2=1.+DLI/(2.*RI)
0119      C3=DLIS*DLJV/(RI**2)
0120      C4=2.*(DLIKV+C3)
0121      10 TNEW(I,1,K) = (DLIV*(C1*T(I-1,1,K)+C2*T(I+1,1,K))+C3*2.*T(I,2,K)+
0122      / DLKV*(T(I,1,K-1)+T(I,1,K+1)))/C4
0123      DO 11 I=2,LI
0124      DO 11 K=2,LK
0125      RIR=I-1
0126      RI=RIR*DLI+BINS
0127      C1=1.-DLI/(2.*RI)
0128      C2=1.+DLI/(2.*RI)
0129      C3=DLIS*DLJV/(RI**2)
0130      C4=2.*(DLIKV+C3)
0131      11 TNEW(I,NJ,K) = (DLJV*(C1*T(I-1,NJ,K)+C2*T(I+1,NJ,K))+C3*2.*
0132      / T(I,NJ-1,K)+DLKV*(T(I,NJ,K-1)+T(I,NJ,K+1)))/C4
0133      DO 12 I=2,LI
0134      DO 12 J=2,LJ
0135      RIR=I-1
0136      RI=RIR*DLI+BINS
0137      C1=1.-DLI/(2.*RI)
0138      C2=1.+DLI/(2.*RI)
0139      C3=DLIS*DLJV/(RI**2)
0140      C4=2.*(DLIKV+C3)
0141      12 TNEW(I,J,NK) = (DLIV*(C1*T(I-1,J,NK)+C2*T(I+1,J,NK))+C3*
0142      / (T(I,J-1,NK)+T(I,J+1,NK))+DLKV*2.*T(I,J,NK-1))/C4
0143      DO 13 I=KI,LI
0144      DO 13 J=2,MJ
0145      DO 13 K=2,MK
0146      RIR=I-1
0147      RI=PIR*DLI+BINS
0148      C1=1.-DLI/(2.*RI)
0149      C2=1.+DLI/(2.*RI)
0150      C3=DLIS*DLJV/(RI**2)
0151      C4=2.*(DLIKV+C3)
0152      13 TNEW(I,J,K) = (DLIV*(C1*T(I-1,J,K)+C2*T(I+1,J,K))+C3*(T(I,J-1,K)+
0153      / T(I,J+1,K))+DLKV*(T(I,J,K-1)+T(I,J,K+1)))/C4
0154      DO 14 I=2,LI
0155      DO 14 J=KJ,LJ

```

Fig. G.1 (Contd.)


```

0150      DO 14 K=2, NK
0151      RIR=I-1
0152      RI=RIR*DLI+RINS
0153      C1=1.-DLI/(2.*RI)
0154      C2=1.+DLI/(2.*RI)
0155      C3=DLIS*DLJV/(RI**2)
0156      C4=2.*(DLKVC+C3)
0157 14 TNEW(I,J,K)=(DLIV*(C1*T(I-1,J,K)+C2*T(I+1,J,K))+C3*(T(I,J-1,K)+
/ T(I,J+1,K))+DLKVC*(T(I,J,K-1)+T(I,J,K+1)))/C4
0158      DO 15 I=2, LI
0159      DO 15 J=2, LJ
0160      DO 15 K=KK, LK
0161      RIR=I-1
0162      RI=RIR*DLI+RINS
0163      C1=1.-DLI/(2.*RI)
0164      C2=1.+DLI/(2.*RI)
0165      C3=DLIS*DLJV/(RI**2)
0166      C4=2.*(DLKVC+C3)
0167 15 TNEW(I,J,K)=(DLIV*(C1*T(I-1,J,K)+C2*T(I+1,J,K))+C3*(T(I,J-1,K)+
/ T(I,J+1,K))+DLKVC*(T(I,J,K-1)+T(I,J,K+1)))/C4
0168      RII=(XNI-1.)*DLI+RINS
0169      C1Z=CON1*(1.-DLI/(2.*PII))
0170      C1I=C1Z/VRMS
0171      C2I=CON2*(1.+DLI/(2.*PII))
0172      C12I=0.5*(C1I+C2I)
0173      C5=CON12*DLIS*DLJV/(RII**2*2.)
0174      C6=2.*(C12I+C5+DLKVC)
0175      TNEW(NI,1,1)=(DLIV*(C1I*T(NI-1,1,1)+C2I*T(NI+1,1,1))+C5*2.*
/ T(NI,2,1)+DLKVC*2.*T(NI,1,2))/C6
0176      TNEW(NI,NJ,1)=(DLIV*(C1I*T(NI-1,NJ,1)+C2I*T(NI+1,NJ,1))+C5*2.*
/ T(NI,NJ-1,1)+DLKVC*2.*T(NI,NJ,2))/C6
0177      TNEW(NI,1,NK)=(DLIV*(C1I*T(NI-1,1,NK)+C2I*T(NI+1,1,NK))+C5*2.*
/ T(NI,2,NK)+DLKVC*2.*T(NI,1,NK-1))/C6
0178      TNEW(NI,NJ,NK)=(DLIV*(C1I*T(NI-1,NJ,NK)+C2I*T(NI+1,NJ,NK))+C5*
/ 2.*T(NI,NJ-1,NK)+DLKVC*2.*T(NI,NJ,NK-1))/C6
0179      DO 16 J=2, LJ
0180      TNEW(NI,J,1)=(DLIV*(C1I*T(NI-1,J,1)+C2I*T(NI+1,J,1))+C5*
/ (T(NI,J-1,1)+T(NI,J+1,1))+DLKVC*2.*T(NI,J,2))/C6
0181 16 TNEW(NI,J,NK)=(DLIV*(C1I*T(NI-1,J,NK)+C2I*T(NI+1,J,NK))+C5*
/ (T(NI,J-1,NK)+T(NI,J+1,NK))+DLKVC*2.*T(NI,J,NK-1))/C6
0182      DO 17 K=2, LK
0183      TNEW(NI,1,K)=(DLIV*(C1I*T(NI-1,1,K)+C2I*T(NI+1,1,K))+C5*2.*
/ T(NI,2,K)+DLKVC*(T(NI,1,K-1)+T(NI,1,K+1)))/C6
0184      TNEW(NI,NJ,K)=(DLIV*(C1I*T(NI-1,NJ,K)+C2I*T(NI+1,NJ,K))+C5*2.*
/ T(NI,NJ-1,K)+DLKVC*(T(NI,NJ,K-1)+T(NI,NJ,K+1)))/C6
0185      DO 18 J=2, LJ
0186      DO 18 K=2, LK
0187 18 TNEW(NI,J,K)=(DLIV*(C1I*T(NI-1,J,K)+C2I*T(NI+1,J,K))+C5*
/ (T(NI,J-1,K)+T(NI,J+1,K))+DLKVC*(T(NI,J,K-1)+T(NI,J,K+1)))/C6
0188      IF (KII-LII) 60,60,70
0189 60 DO 19 I=KII,LII
0190      RIR=I-1
0191      RI=RIR*DLI+RINS
0192      C1=1.-DLI/(2.*RI)
0193      C2=1.+DLI/(2.*RI)

```

Fig. G.1 (Contd.)

```

0194      C3=DIIS*DLJV/(RI**2)
0195      C4=2.*(DLKV+C3)
0196      TNEW(I,1,1)=(DLIV*(C1*T(I-1,1,1)+C2*T(I+1,1,1))+C3*2.*T(I,2,1)+
/ DLKV*2.*T(I,1,2))/C4
0197      TNEW(I,NJ,1)=(DLIV*(C1*T(I-1,NJ,1)+C2*T(I+1,NJ,1))+C3*2.*
/ T(I,NJ-1,1)+DLKV*2.*T(I,NJ,2))/C4
0198      TNEW(I,1,NK)=(DLIV*(C1*T(I-1,1,NK)+C2*T(I+1,1,NK))+C3*2.*
/ T(I,2,NK)+DLKV*2.*T(I,1,NK-1))/C4
0199      10 TNEW(I,NJ,NK)=(DLIV*(C1*T(I-1,NJ,NK)+C2*T(I+1,NJ,NK))+C3*2.*
/ T(I,NJ-1,NK)+DLKV*2.*T(I,NJ,NK-1))/C4
0200      DO 20 I=KII,LII
0201      DO 20 J=2,LJ
0202      RIR=I-1
0203      RI=RIR*DLI+RINS
0204      C1=1.-DLI/(2.*RI)
0205      C2=1.+DLI/(2.*RI)
0206      C3=DLIS*DLJV/(RI**2)
0207      C4=2.*(DLKV+C3)
0208      TNEW(I,J,1)=(DLIV*(C1*T(I-1,J,1)+C2*T(I+1,J,1))+C3*(T(I,J-1,1)+
/ T(I,J+1,1))+DLKV*2.*T(I,J,2))/C4
0209      20 TNEW(I,J,NK)=(DLIV*(C1*T(I-1,J,NK)+C2*T(I+1,J,NK))+C3*
/ (T(I,J-1,NK)+T(I,J+1,NK))+DLKV*2.*T(I,J,NK-1))/C4
0210      DO 21 I=KII,LII
0211      DO 21 F=2,LK
0212      RIR=I-1
0213      RI=RIR*DLI+RINS
0214      C1=1.-DLI/(2.*RI)
0215      C2=1.+DLI/(2.*RI)
0216      C3=DIIS*DLJV/(RI**2)
0217      C4=2.*(DLKV+C3)
0218      TNEW(I,1,K)=(DLIV*(C1*T(I-1,1,K)+C2*T(I+1,1,K))+C3*2.*T(I,2,K)+
/ DLKV*(T(I,1,K-1)+T(I,1,K+1)))/C4
0219      21 TNEW(I,NJ,K)=(DLIV*(C1*T(I-1,NJ,K)+C2*T(I+1,NJ,K))+C3*2.*
/ T(I,NJ-1,K)+DLKV*(T(I,NJ,K-1)+T(I,NJ,K+1)))/C4
0220      DO 22 I=KII,LII
0221      DO 22 J=2,LJ
0222      DO 22 F=2,LK
0223      RIR=I-1
0224      RI=RIR*DLI+RINS
0225      C1=1.-DLI/(2.*RI)
0226      C2=1.+DLI/(2.*RI)
0227      C3=DLJV/(RI**2)
0228      C4=2.*(DLKV+C3)
0229      22 TNEW(I,J,K)=(DLIV*(C1*T(I-1,J,K)+C2*T(I+1,J,K))+C3*(T(I,J-1,K)+
/ T(I,J+1,K))+DLKV*(T(I,J,K-1)+T(I,J,K+1)))/C4
0230      70 RISU=(XNII-1.)*DLI+RINS
0231      C1S=CON2*(1.-DLI/(2.*RISU))
0232      C2S=R*DLI
0233      C7=0.5*CON2*DLIS*DLJV/(RISU**2)
0234      C8=(C1S+C2S)+2.*C7+2.*DLKVD
0235      TNEW(NII,1,1)=(DLIV*(C1S*T(NII-1,1,1)+C2S*TA)+C7*2.*T(NII,2,1)
/ +DLKVD*2.*T(NII,1,2))/C8
0236      TNEW(NII,NJ,1)=(DLIV*(C1S*T(NII-1,NJ,1)+C2S*TA)+C7*2.*
/ T(NII,NJ-1,1)+DLKVD*2.*T(NII,NJ,2))/C8
0237      TNEW(NII,1,NK)=(DLIV*(C1S*T(NII-1,1,NK)+C2S*TA)+C7*2.*

```

Fig. G.1 (Contd.)

```

0238 / T(NII,2,NK)+DLKVD*2.*T(NII,1,NK-1))/C8
      TNEW(NIJ,NJ,NK)=(DLIV*(C1S*T(NII-1,NJ,NK)+C2S*TA)+C7*2.*
0239 / T(NII,NJ-1,NK)+DLKVD*2.*T(NII,NJ,NK-1))/C8
      DO 23 J=2,LJ
0240 TNEW(NII,J,1)=(DLIV*(C1S*T(NII-1,J,1)+C2S*TA)+C7*(T(NII,J-1,1)+
      / T(NII,J+1,1))+DLKVD*2.*T(NII,J,2))/C8
0241 23 TNEW(NII,J,NK)=(DLIV*(C1S*T(NII-1,J,NK)+C2S*TA)+C7*
      / (T(NII,J-1,NK)+T(NII,J+1,NK))+DLKVD*2.*T(NII,J,NK-1))/C8
0242 DO 24 K=2,IK
0243 TNEW(NII,1,K)=(DLIV*(C1S*T(NII-1,1,K)+C2S*TA)+C7*2.*T(NII,2,K)+
      / DLKVD*(T(NII,1,K-1)+T(NII,1,K+1)))/C8
0244 24 TNEW(NII,NJ,K)=(DLIV*(C1S*T(NII-1,NJ,K)+C2S*TA)+C7*2.*
      / T(NII,NJ-1,K)+DLKVD*(T(NII,NJ,K-1)+T(NII,NJ,K+1)))/C8
0245 DO 25 J=2,LJ
0246 DO 25 K=2,IK
0247 25 TNEW(NII,J,K)=(DLIV*(C1S*T(NII-1,J,K)+C2S*TA)+C7*(T(NII,J-1,K)+
      / T(NII,J+1,K))+DLKVD*(T(NII,J,K-1)+T(NII,J,K+1)))/C8
      DO 85 I=2,MI
0248 DO 85 J=KJ,NJ
0249 DO 85 K=1,NK
0250 IF (DABS(T(I,J,K)-TNEW(I,J,K))-EPS) 85,85,40
0251 85 CONTINUE
0252 DO 27 I=2,MI
0253 DO 27 J=1,NJ
0254 DO 27 K=KK,NK
0255 IF (DABS(T(I,J,K)-TNEW(I,J,K))-EPS) 27,27,40
0256 27 CONTINUE
0257 DO 26 I=KI,NII
0258 DO 26 J=1,NJ
0259 DO 26 K=1,NK
0260 IF (DABS(T(I,J,K)-TNEW(I,J,K))-EPS) 26,26,40
0261 26 CONTINUE
0262 GO TO 90
0263 40 DO 31 I=2,MI
0264 DO 31 J=KJ,NJ
0265 DO 31 K=1,NK
0266 31 T(I,J,K)=TNEW(I,J,K)
0267 DO 32 I=KI,NII
0268 DO 32 J=1,NJ
0269 DO 32 K=1,NK
0270 32 T(I,J,K)=TNEW(I,J,K)
0271 DO 33 I=2,NII
0272 DO 33 J=1,NJ
0273 DO 33 K=KK,NK
0274 33 T(I,J,K)=TNEW(I,J,K)
0275 GO TO 80
0276 90 XMI=MI
0277 YMJ=MJ
0278 ZMK=NK
0279 DEPTH=DLI*(YMI-1.)
0280 ACROS=DLJ*(YMJ-1.)
0281 HICAV=DLK*(ZMK-1.)
0282 DIWS=2.*RINS
0283 DOUT=2.*ROUT
0284 PIGHU=2.*HIGHT
0285

```

Fig. G.1 (Contd.)

```

0286      SHTK=ROUT-BINS-TP
0287      WRITE (6,28) DINS,DOUT,HIGHU,TR,SHTK,DEPTH,ACROS,HICAV,DLI,DLJ,
/      DLK,TT,TA,CON1,CON2,H,EPS
0288      28 FORMAT (1H1,20HDIMENSION:          ID=F8.2,8H IN.,OD=F8.2,
/      21H IN., (TOTAL) HEIGHT=F8.2,
/      4H IN./18X,21HREFFACTORY THICKNESS=F6.2,
/      21H IN.,SHELL THICKNESS=F6.2,4H IN./13H CAVITY SIZE:,5X,
/      6HDEPTH=F6.2,19H IN., (HALF) ANGLE=F7.2,5H DEG./
/      17X,15H (HALF) HEIGHT=F7.2,4H IN./
/      11H MESH SIZE:,7X,7HRADIAL=F6.3,13H IN.,ANGULAR=F6.2,
/      12H DEG.,AXIAL=F6.2,4H IN./
/      14H TEMPERATURES:,4X,15HINSIDE SURFACE=
/      F10.2,14H DEG.,AMBIENT=F8.2,5H DEG./12H PROPERTIES:,6X,
/      11HK FOR REP.=F8.2,14H, K FOR SHELL=F8.2,19H BTU IN./HR FT**2 F/
/      18X,2HH=F8.2,15H BTU/HR FT**2 F/20H ITERATION ERROR: F=
/      F5.2,5H DEG.//)
0289      DO 29 K=1,NK
0290      29 WRITE (6,30) (TNEW(NII,J,K),J=1,NJ)
0291      30 FORMAT (5D20.10)
0292      WRITE (6,401)
0293      401 FORMAT (1H1,23HCONTACT RESISTANCE MAP://)
0294      DO 402 J=1,11
0295      402 13 402 1,25
0296      402 13 402 1,25
0297      DO 403 J=1,11
0298      403 WRITE (6,406) (STORE(J,K),J=1,25)
0299      406 FORMAT (7E14.5)
0300      WRITE (6,404) VRES
0301      404 FORMAT (///45H NOTE: UNIT FOR CONTACT RESISTANCE-HR DEG/FTU/
/      54H CONTACT RESISTANCE VALUES WERE GENERATED USING: VRES=F5.2/

```

5

```

***** 01) IGI0131 SYNTAX
0302      NJCT=2*NJ-1
0303      NKCT=2*NK-1
0304      NJDT=NJ+1
0305      NKDT=NK+1
0306      NJET=NJ-1
0307      NKET=NK-1
0308      ANJCT=NJCT
0309      ANKCT=NKCT
0310      BNJCT=-(2.*ANJCT)
0311      BNKCT=-(2.*ANKCT)
0312      CNJCT=1.5*ANJCT
0313      MTTT=TNEW(NII,1,1)/100.+1.
0314      VTT=MTTT*100
0315      MTB=TNEW(NII,NJ,NK)/100.
0316      VTB=MTB*100
0317      MTR=ROUT-BINS+1.
0318      RTT=MTR
0319      DO 101 J=1,NK
0320      DO 101 I=1,NJCT
0321      IF (I-NJ) 102,102,103
0322      102 TEXP(I,J)=TNEW(NII,NJDT-I,J)
0323      GO TO 101
0324      103 TEXP(I,J)=TNEW(NII,I-NJET,J)

```

Fig. G.1 (Contd.)

```

0325      101 CONTINUE
0326      DO 104 I=1,NJCT
0327      DO 104 J=1,NKCT
0328      IF (J-NK) 105,105,106
0329      105 TFXP(I,J)=TEXP(I,NKDT-J)
0330      GO TO 104
0331      106 TFXP(I,J)=TEXP(I,J-NKET)
0332      104 CONTINUE
0333      ZHI=ROUT-BINS
0334      ZCI=ROUT-BINS-(XHI-1.)*DLI
0335      NJFT=NJ-NJ+1
0336      NKFT=NK-NK+1
0337      NJGT=NJ+NJ-1
0338      NKGT=NK+NK-1
0339      NJHT=NJFT+1
0340      NKHT=NKFT+1
0341      NJIT=NJGT-1
0342      NKIT=NKGT-1
0343      DO 111 J=1,NKCT
0344      DO 111 I=1,NJFT
0345      111 CVPT(I,J)=ZHI
0346      DO 112 J=1,NKCT
0347      DO 112 I=NJGT,NJCT
0348      112 CVPT(I,J)=ZHI
0349      DO 113 I=NJHT,NJIT
0350      DO 113 J=1,NKFT
0351      113 CVPT(I,J)=ZHI
0352      DO 114 I=NJHT,NJIT
0353      DO 114 J=NKGT,NKCT
0354      114 CVPT(I,J)=ZHI
0355      DO 115 I=NJHT,NJIT
0356      DO 115 J=NKHT,NKIT
0357      115 CVPT(I,J)=ZCI
0358      WRITE (6,35)
0359      35 FORMAT ('H1,43HTHREE DIMENSIONAL SURFACE TEMPERATURE PLOT:')
0360      CALL STRTPT
0361      CALL BGNPL(1)
0362      CALL TITL3D('THREE-DIMENSIONAL SURFACE TEMPERATURE PLOTS',-100,
0363      / 10.,6.)
0364      CALL AXES3D('ANGULAR DIRECTIONS',100,'AXIAL DIRECTIONS',100,
0365      / 'TEMPERATURES',100,ANJCT,ANKCT,CNJCT)
0366      CALL VUABS(BNJCT,BNKCT,CNJCT)
0367      CALL GRAP3D(1.,4.,ANJCT,1.,2.,ANKCT,0.,50.,400.)
0368      CALL SURFAT(TFXP,1,NJCT,1,NKCT,WORKSP)
0369      CALL FNDPL(1)
0370      WRITE (6,36)
0371      36 FORMAT ('H1,38HRECONSTRUCTION OF CAVITY CONFIGURATION')
0372      CALL BGNPL(1)
0373      CALL TITL3D('RECONSTRUCTION OF CAVITY CONFIGURATIONS',-100,
0374      / 10.,6.)
0375      CALL AXES3D('ANGULAR DIRECTIONS',100,'AXIAL DIRECTIONS',100,
0376      / 'RADIAL DIRECTIONS',100,ANJCT,ANKCT,CNJCT)
0377      CALL VUARS(BNJCT,BNKCT,CNJCT)
0378      CALL GRAP3D(1.,4.,ANJCT,1.,2.,ANKCT,0.,1.,RTT)
0379      CALL SURFAT(CVPT,1,NJCT,1,NKCT,WORKSQ)

```

Fig. G.1 (Contd.)


```

/ 53H , SIGNIFYING THAT A WHITE BAND EXISTS IN BETWEEN THE/
/ 54H NEIGHBORING LETTERED BANDS; THE TEMPERATURE RANGE FOR
/ 50H THE WHITE BAND IS BRIDGED IN BETWEEN THOSE OF THE/
/ 19H NEIGHBORING BANDS.//)
0413 DO 201 I=1,NJCT
0414 201 G(I)=ASTSK
0415 WRITE (6,202) G
0416 202 FORMAT (1H ,180A1)
0417 J=NKCT
0418 203 DO 204 I=1,NJCT
0419 K=(TFXP(I,J)-VTB)/TNC+1.
0420 G(I)=SYMBOL(K)
0421 204 CONTINUE
0422 WRITE (6,205) G
0423 205 FORMAT (1H ,180A1)
0424 J=J-1
0425 IF (J.NE.0) GO TO 203
0426 DO 206 I=1,NJCT
0427 206 G(I)=ASTSK
0428 WRITE (6,207) G
0429 207 FORMAT (1H ,180A1)
0430 SCR=(TNEW(NII,1,1)-TNEW(NII,NJ,NK))/20.
0431 DO 301 K=1,20
0432 BK=K
0433 BIAS=(BK-1.)*SCR+TNEW(NII,NJ,NK)
0434 DO 302 J=1,NKCT
0435 DO 302 I=1,NJCT
0436 302 TGXP(I,J)=TFXP(I,J)-BIAS
0437 COUNT=0.
0438 ACUM=0.
0439 DO 303 J=1,NKCT
0440 DO 303 I=1,NJCT
0441 IF (TGXP(I,J)) 303,304,304
0442 304 COUNT=COUNT+1.
0443 ACUM=ACUM+TGXP(I,J)
0444 303 CONTINUE
0445 B(K)=BIAS
0446 A(K)=COUNT
0447 301 V(K)=ACUM
0448 DO 350 K=1,10
0449 DIV=10.**K
0450 Y=A(2)/DIV
0451 IF (Y-1) 351,351,350
0452 350 CONTINUE
0453 351 EXPA=K
0454 DO 360 K=1,10
0455 DIV=10.**K
0456 Y=V(2)/DIV
0457 IF (Y-1) 361,361,360
0458 360 CONTINUE
0459 361 EXPV=K
0460 CYCLA=8./EXPA
0461 CYCLV=8./EXPV
0462 THVOL=V(1)+TNEW(NII,NJ,NK)*ANJCT*ANKCT
0463 WRITE (6,371) THVOL

```

Fig. G.1 (Contd.)

```

0464      371 FORMAT (1H1,36HTOTAL VOLUME UNDERNEATH THE SURFACE=E12.5//)
0465      WRITE (6,372)
0466      372 FORMAT (1H ,2X8HISOTHERM5X11HAREA INSIDE4X10HINTEGRATED)
0467      WRITE (6,373)
0468      373 FORMAT (1H ,1X11HTEMPERATURE3X12HTHE ISOTHERM5X6HVOLUME)
0469      DO 374 K=1,20
0470      374 WRITE (6,375) B(K),A(K),V(K)
0471      375 FORMAT (1H ,F9.1,E17.4,E14.4)
0472      PUNCH 330, DEPTH,ACBOS,HICAV,THVOL,TNEW(NIJ,1,1),TNEW(NIJ,NJ,NK)
0473      330 FORMAT (F10.2,5F10.1)
0474      WRITE (6,376)
0475      376 FORMAT (1H1)
0476      CALL BGNPL(1)
0477      CALL TITLE('AREA ENCLOSED INSIDE ISOTHERM LOOPS',100,
/ 'TEMPERATURES',100,'AREAS',100,5.,8.)
0478      CALL FRAME
0479      CALL YLOG(0.,80.,1.,CYCLA)
0480      CALL GRID(2,2)
0481      CALL CURVE(B,A,20,1)
0482      CALL ENDPL(4)
0483      CALL TITLE('INTEGRATED ENERGY EQUIVALENTS',100,
/ 'TEMPERATURES',100,'INTEGRATED ENERGY EQUIVALENTS',100,5.,8.)
0484      CALL FRAME
0485      CALL YLOG(.,80.,1.,CYCLV)
0486      CALL GRID(2,2)
0487      CALL CURVE(B,V,20,1)
0488      CALL ENDPL(5)
0489      50 CONTINUE
0490      400 CONTINUE
0491      CALL DONEPI
0492      STOP
0493      END

```

Fig. G.1 (Contd.)


```

0001      DIMENSION WORKSP(76),WORKSQ(76),TEXP(25,11),CVPT(25,11),
/ G(25),SYMBOL(22),TFXP(25,11),TGXP(25,11),B(21),A(21),V(21),
/ STORE(25,11)
0002      DOUBLE PRECISION DLIV,DLJV,DLKV,DIKVV,DLKVC,DLKVD,RI,C1,C2,
/ C3,C4,BII,C1I,C2I,C12I,C5,C6,BISU,C1S,C2S,C7,C8,T(15,15,10),
/ TNEW(15,15,10)
0003      READ(5,1) RINS,ROUT,TR,HIGHT,DPHIN,D2HAX,ACHIN,ACHAX,TLBIN,
/ TLHAX,DELB,DLJ, DELZ,SPACEI,SPACEJ,SPACEK
0004      1 FORMAT (10F6.2)
0005      READ(5,41) TT,TA,H,CON1,CON2,EPS
0006      41 FORMAT (6F8.2)
0007      READ(5,200) (SYMBOL(I),I=1,21),ASTSK
0008      200 FORMAT (22A1)
0009      DLI=1./DELB
0010      INCR1=SPACEI/DLI
0011      DLK=1./DELB
0012      INCRK=SPACEK/DLK
0013      WIDTH=3.14159*(RINS+ROUT)/2.
0014      DEA=WIDTH*DLJ/180.
0015      INCRJ=SPACEJ/DLJ
0016      NII=(ROUT-RINS)/DLI+1.
0017      XNII=NII
0018      NJ=WIDTH/DEA+1.
0019      NK=HIGHT/DIK+1.
0020      NIH=DPHIN/DLI+1.
0021      NJH=ACHIN/DLJ+1.
0022      NKH=TLBIN/DLK+1.
0023      NIL=1.+(DPHAX-DPHIN)/SPACEI
0024      NJL=1.+(ACHAX-ACHIN)/SPACEJ
0025      NKL=1.+(TLHAX-TLBIN)/SPACEK
0026      NI=TR/DLI+1.
0027      XNI=NI
0028      DLIV=1.
0029      DLIS=DLI**2
0030      DLJV=1./((3.14159*DLJ/180.))**2)
0031      DLKV=(DLI**2)/(DLK**2)
0032      DIKVV=1.+DLKV
0033      CON12=CON1+CON2
0034      DLKVC=CON12*DLKV/2.
0035      DLKVD=0.5*CON2*DLIS/(DIK**2)
0036      DO 400 ICR=1,10
0037      VCR=ICR
0038      VPRES=(VCR-1.)*.25+1.25
0039      DO 50 L=1,NIL
0040      DO 50 M=1,NJL
0041      DO 50 N=1,NKL
0042      RI=RIH+(L-1)*INCR1
0043      RJ=RJH+(M-1)*INCRJ
0044      RK=RKH+(N-1)*INCRK
0045      KI=NI+1
0046      LI=NI-1
0047      KJ=NJ+1
0048      LJ=NJ-1
0049      KJ=NJ+1
0050      LJ=NJ-1

```

Fig. G.2. Computer Program for Evaluating Surface Temperature in a Three-dimensional System with Variable Contact Resistance

```

0051      KK=KK+1
0052      IK=KK-1
0053      DO 2 I=1, NII
0054      DO 2 J=1, NJ
0055      DO 2 K=1, NK
0056      2 T(I,J,K)=.5*(TT+TA)
0057      DO 3 J=1, NJ
0058      DO 3 K=1, NK
0059      TNEW(I,J,K)=TT
0060      3 T(I,J,K)=TT
0061      DO 4 I=2, NI
0062      DO 4 J=1, NJ
0063      DO 4 K=1, NK
0064      TNEW(I,J,K)=TT
0065      4 T(I,J,K)=TT
0066      80 DO 5 I=KI, LI
0067      BIR=I-1
0068      FI=BIP*DI I+RINS
0069      C1=1.-DLI/(2.*BI)
0070      C2=1.+DLI/(2.*BI)
0071      C3=DLIS*DLJV/(BI**2)
0072      C4=2.*(DLKV+C3)
0073      5 TNEW(I,1,1)=(DLIV*(C1*T(I-1,1,1)+C2*T(I+1,1,1))+C3*?.*T(I,2,1)+
/ DLKV*2.*T(I,1,2))/C4
0074      DO 6 I=2, LI
0075      BIR=I-1
0076      FI=BIR*DLI+RINS
0077      C1=1.-DLI/(2.*BI)
0078      C2=1.+DLI/(2.*BI)
0079      C3=DLIS*DLJV/(BI**2)
0080      C4=2.*(DLKV+C3)
0081      TNEW(I,NJ,1)=(DLIV*(C1*T(I-1,NJ,1)+C2*T(I+1,NJ,1))+C3*2.*
/ T(I,NJ-1,1)+DLKV*2.*T(I,NJ,2))/C4
0082      TNEW(I,1,NK)=(DLIV*(C1*T(I-1,1,NK)+C2*T(I+1,1,NK))+C3*2.*
/ T(I,2,NK)+DLKV*2.*T(I,1,NK-1))/C4
0083      6 TNEW(I,NJ,NK)=(DLIV*(C1*T(I-1,NJ,NK)+C2*T(I+1,NJ,NK))+C3*2.*
/ T(I,NJ-1,NK)+DLKV*2.*T(I,NJ,NK-1))/C4
0084      DO 7 I=2, NI
0085      DO 7 J=KJ, LJ
0086      BIR=I-1
0087      FI=BIP*DI I+RINS
0088      C1=1.-DLI/(2.*BI)
0089      C2=1.+DLI/(2.*BI)
0090      C3=DLIS*DLJV/(BI**2)
0091      C4=2.*(DLKV+C3)
0092      7 TNEW(I,J,1)=(DLIV*(C1*T(I-1,J,1)+C2*T(I+1,J,1))+C3*(T(I,J-1,1)+
/ T(I,J+1,1))+DLKV*2.*T(I,J,2))/C4
0093      DO 8 I=KI, LI
0094      DO 8 J=2, LJ
0095      BIR=I-1
0096      FI=BIP*DLI+RTWS
0097      C1=1.-DLI/(2.*BI)
0098      C2=1.+DLI/(2.*BI)
0099      C3=DLIS*DLJV/(BI**2)
0100      C4=2.*(DLKV+C3)

```

Fig. G.2 (Contd.)

```

0101      8 TNEW(I,J,1) = (DLIV*(C1*T(I-1,J,1)+C2*T(I+1,J,1))+C3*(T(I,J-1,1)+
0102      / T(I,J+1,1))+DLKV*2.*T(I,J,2))/C4
0103      DO 9 I=KI,LI
0104      DO 9 K=2,LK
0105      RIR=I-1
0106      RI=RIP*DLI+RINS
0107      C1=1.-DLI/(2.*RI)
0108      C2=1.+DLI/(2.*RI)
0109      C3=DLIS*DLJV/(RI**2)
0110      C4=2.*(DLKV+C3)
0111      9 TNEW(I,1,K) = (DLIV*(C1*T(I-1,1,K)+C2*T(I+1,1,K))+C3*2.*T(I,2,K)+
0112      / DLKV*(T(I,1,K-1)+T(I,1,K+1)))/C4
0113      DO 10 I=2,MI
0114      DO 10 K=KK,LK
0115      RIR=I-1
0116      RI=RIB*DLI+RINS
0117      C1=1.-DLI/(2.*RI)
0118      C2=1.+DLI/(2.*RI)
0119      C3=DLIS*DLJV/(RI**2)
0120      C4=2.*(DLKV+C3)
0121      10 TNEW(I,1,K) = (DLIV*(C1*T(I-1,1,K)+C2*T(I+1,1,K))+C3*2.*T(I,2,K)+
0122      / DLKV*(T(I,1,K-1)+T(I,1,K+1)))/C4
0123      DO 11 I=2,LI
0124      DO 11 K=2,LK
0125      RIR=I-1
0126      RI=RIR*DLI+RINS
0127      C1=1.-DLI/(2.*RI)
0128      C2=1.+DLI/(2.*RI)
0129      C3=DLIS*DLJV/(RI**2)
0130      C4=2.*(DLKV+C3)
0131      11 TNEW(I,NJ,K) = (DLIV*(C1*T(I-1,NJ,K)+C2*T(I+1,NJ,K))+C3*2.*
0132      / T(I,NJ-1,K)+DLKV*(T(I,NJ,K-1)+T(I,NJ,K+1)))/C4
0133      DO 12 I=2,LJ
0134      DO 12 J=2,LJ
0135      RIR=I-1
0136      RI=RIB*DLI+RINS
0137      C1=1.-DLI/(2.*RI)
0138      C2=1.+DLI/(2.*RI)
0139      C3=DLIS*DLJV/(RI**2)
0140      C4=2.*(DLKV+C3)
0141      12 TNEW(I,J,NK) = (DLIV*(C1*T(I-1,J,NK)+C2*T(I+1,J,NK))+C3*
0142      / (T(I,J-1,NK)+T(I,J+1,NK))+DLKV*2.*T(I,J,NK-1))/C4
0143      DO 13 I=KI,LI
0144      DO 13 J=2,NJ
0145      DO 13 K=2,NK
0146      RIR=I-1
0147      RI=RIP*DLI+RINS
0148      C1=1.-DLI/(2.*RI)
0149      C2=1.+DLI/(2.*RI)
0150      C3=DLIS*DLJV/(RI**2)
0151      C4=2.*(DLKV+C3)
0152      13 TNEW(I,J,K) = (DLIV*(C1*T(I-1,J,K)+C2*T(I+1,J,K))+C3*(T(I,J-1,K)+
0153      / T(I,J+1,K))+DLKV*(T(I,J,K-1)+T(I,J,K+1)))/C4
0154      DO 14 I=2,LI
0155      DO 14 J=KJ,LJ

```

Fig. G.2 (Contd.)

```

0150      DO 14 K=2, MK
0151      RIR=I-1
0152      PI=RIR*DI I+BIWS
0153      C1=1.-DLI/(2.*RI)
0154      C2=1.+DLI/(2.*RI)
0155      C3=DLIS*DLJV/(RI**2)
0156      C4=2.*(DLKVC+C3)
0157      14 TNEW(I,J,K) = (DLIV*(C1*T(I-1,J,K)+C2*T(I+1,J,K)) + C3*(T(I,J-1,K) +
/ T(I,J+1,K)) + DLKVC*(T(I,J,K-1)+T(I,J,K+1)))/C4
0158      DO 15 I=2, LI
0159      DO 15 J=2, LJ
0160      DO 15 K=KK, LK
0161      RIR=I-1
0162      RI=RIR*DI I+BIWS
0163      C1=1.-DLI/(2.*RI)
0164      C2=1.+DLI/(2.*RI)
0165      C3=DLIS*DLJV/(RI**2)
0166      C4=2.*(DLKVC+C3)
0167      15 TNEW(I,J,K) = (DLIV*(C1*T(I-1,J,K)+C2*T(I+1,J,K)) + C3*(T(I,J-1,K) +
/ T(I,J+1,K)) + DLKVC*(T(I,J,K-1)+T(I,J,K+1)))/C4
0168      RII=(XNI-1.)*DI+BIWS
0169      C12=CON1*(1.-DLI/(2.*RII))
0170      C1I=C12/PRESIST(VRES,1,1)
0171      C2I=CON2*(1.+DLI/(2.*RII))
0172      C12I=0.5*(C1I+C2I)
0173      C5=CON12*DLIS*DLJV/(RII**2)
0174      C6=2.*(C12I+C5+DLKVC)
0175      TNEW(NI,1,1) = (DLIV*(C1I*T(NI-1,1,1)+C2I*T(NI+1,1,1)) + C5*2.*
/ T(NI,2,1) + DLKVC*2.*T(NI,1,2))/C6
0176      C1I=C12/PRESIST(VRES,NJ,1)
0177      C12I=0.5*(C1I+C2I)
0178      C6=2.*(C12I+C5+DLKVC)
0179      TNEW(NI,NJ,1) = (DLIV*(C1I*T(NI-1,NJ,1)+C2I*T(NI+1,NJ,1)) + C5*2.*
/ T(NI,NJ-1,1) + DLKVC*2.*T(NI,NJ,2))/C6
0180      C1I=C12/PRESIST(VRES,1,NK)
0181      C12I=0.5*(C1I+C2I)
0182      C6=2.*(C12I+C5+DLKVC)
0183      TNEW(NI,1,NK) = (DLIV*(C1I*T(NI-1,1,NK)+C2I*T(NI+1,1,NK)) + C5*2.*
/ T(NI,2,NK) + DLKVC*2.*T(NI,1,NK-1))/C6
0184      C1I=C12/PRESIST(VRES,NJ,NK)
0185      C12I=0.5*(C1I+C2I)
0186      C6=2.*(C12I+C5+DLKVC)
0187      TNEW(NI,NJ,NK) = (DLIV*(C1I*T(NI-1,NJ,NK)+C2I*T(NI+1,NJ,NK)) + C5*
/ 2.*T(NI,NJ-1,NK) + DLKVC*2.*T(NI,NJ,NK-1))/C6
0188      DO 16 J=2, LJ
0189      C1I=C12/PRESIST(VRES,J,1)
0190      C12I=0.5*(C1I+C2I)
0191      C6=2.*(C12I+C5+DLKVC)
0192      TNEW(NI,J,1) = (DLIV*(C1I*T(NI-1,J,1)+C2I*T(NI+1,J,1)) + C5*
/ (T(NI,J-1,1)+T(NI,J+1,1)) + DLKVC*2.*T(NI,J,2))/C6
0193      C1I=C12/PRESIST(VRES,J,NK)
0194      C12I=0.5*(C1I+C2I)
0195      C6=2.*(C12I+C5+DLKVC)
0196      16 TNEW(NI,J,NK) = (DLIV*(C1I*T(NI-1,J,NK)+C2I*T(NI+1,J,NK)) + C5*
/ (T(NI,J-1,NK)+T(NI,J+1,NK)) + DLKVC*2.*T(NI,J,NK-1))/C6

```

Fig. G.2 (Contd.)

```

0197      DO 17 K=2,LK
0198      C1I=C1Z/BESIST(VRES,1,K)
0199      C12I=0.5*(C1I+C2I)
0200      C6=2.*(C12I+C5+DLKVC)
0201      THENW(NI,1,K)=(DLIV*(C1I*T(NI-1,1,K)+C2I*T(NI+1,1,K))+C5*2.*
/ T(NI,2,K)+DLKVC*(T(NI,1,K-1)+T(NI,1,K+1)))/C6
0202      C1I=C1Z/BESIST(VRES,NJ,K)
0203      C12I=0.5*(C1I+C2I)
0204      C6=2.*(C12I+C5+DLKVC)
0205      17 THENW(NI,NJ,K)=(DLIV*(C1I*T(NI-1,NJ,K)+C2I*T(NI+1,NJ,K))+C5*2.*
/ T(NI,NJ-1,K)+DLKVC*(T(NI,NJ,K-1)+T(NI,NJ,K+1)))/C6
0206      DO 18 J=2,LJ
0207      DO 18 K=2,LK
0208      C1I=C1Z/BESIST(VRES,J,K)
0209      C12I=0.5*(C1I+C2I)
0210      C6=2.*(C12I+C5+DLKVC)
0211      18 THENW(NI,J,K)=(DLIV*(C1I*T(NI-1,J,K)+C2I*T(NI+1,J,K))+C5*
/ (T(NI,J-1,K)+T(NI,J+1,K))+DLKVC*(T(NI,J,K-1)+T(NI,J,K+1)))/C6
0212      IF (KII-LIJ) 60,60,70
0213      60 DO 19 I=KII,LII
0214      RIR=I-1
0215      RI=RIR*DLI+RINS
0216      C1=1.-DLI/(2.*RI)
0217      C2=1.+DLI/(2.*RI)
0218      C3=DLIS*DLJV/(RI**2)
0219      C4=2.*(DLKVC+C3)
0220      THENW(I,1,1)=(DLIV*(C1*T(I-1,1,1)+C2*T(I+1,1,1))+C3*2.*T(I,2,1)+
/ DLKVC*2.*T(I,1,2))/C4
0221      THENW(I,NJ,1)=(DLIV*(C1*T(I-1,NJ,1)+C2*T(I+1,NJ,1))+C3*2.*
/ T(I,NJ-1,1)+DLKVC*2.*T(I,NJ,2))/C4
0222      THENW(I,1,NK)=(DLIV*(C1*T(I-1,1,NK)+C2*T(I+1,1,NK))+C3*2.*
/ T(I,2,NK)+DLKVC*2.*T(I,1,NK-1))/C4
0223      19 THENW(I,NJ,NK)=(DLIV*(C1*T(I-1,NJ,NK)+C2*T(I+1,NJ,NK))+C3*2.*
/ T(I,NJ-1,NK)+DLKVC*2.*T(I,NJ,NK-1))/C4
0224      DO 20 I=KII,LII
0225      DO 20 J=2,LJ
0226      RIR=I-1
0227      RI=RIR*DLI+RINS
0228      C1=1.-DLI/(2.*RI)
0229      C2=1.+DLI/(2.*RI)
0230      C3=DLIS*DLJV/(RI**2)
0231      C4=2.*(DLKVC+C3)
0232      THENW(I,J,1)=(DLIV*(C1*T(I-1,J,1)+C2*T(I+1,J,1))+C3*(T(I,J-1,1)+
/ T(I,J+1,1))+DLKVC*2.*T(I,J,2))/C4
0233      20 THENW(I,J,NK)=(DLIV*(C1*T(I-1,J,NK)+C2*T(I+1,J,NK))+C3*
/ (T(I,J-1,NK)+T(I,J+1,NK))+DLKVC*2.*T(I,J,NK-1))/C4
0234      DO 21 I=KII,LII
0235      DO 21 K=2,LK
0236      RIR=I-1
0237      RI=RIR*DLI+RINS
0238      C1=1.-DLI/(2.*RI)
0239      C2=1.+DLI/(2.*RI)
0240      C3=DLIS*DLJV/(RI**2)
0241      C4=2.*(DLKVC+C3)
0242      THENW(I,1,K)=(DLIV*(C1*T(I-1,1,K)+C2*T(I+1,1,K))+C3*2.*T(I,2,K)+

```

Fig. G.2 (Contd.)

```

/ DLKV*(T(I,1,K-1)+T(I,1,K+1))/C4
0243 21 TNEW(I,NJ,K)=(DLIV*(C1*T(I-1,NJ,K)+C2*T(I+1,NJ,K))+C3*2.*
/ T(I,NJ-1,K)+DLKV*(T(I,NJ,K-1)+T(I,NJ,K+1)))/C4
0244 DO 27 I=KI,LJI
0245 DO 22 J=2,LJ
0246 DO 22 K=2,LK
0247 PIR=I-1
0248 RI=PIR*DLI+BINS
0249 C1=1.-DLI/(2.*RI)
0250 C2=1.+DLI/(2.*RI)
0251 C3=DLJV/(RI**2)
0252 C4=2.*(DLKV+C3)
0253 22 TNEW(I,J,K)=(DLIV*(C1*T(I-1,J,K)+C2*T(I+1,J,K))+C3*(T(I,J-1,K)+
/ T(I,J+1,K))+DLKV*(T(I,J,K-1)+T(I,J,K+1)))/C4
0254 70 RISU=(XNII-1.)*DLI+BINS
0255 C1S=CON2*(1.-DLI/(2.*RISU))
0256 C2S=H*DLI
0257 C7=0.5*CON2*DLIS*DLJV/(RISU**2)
0258 C8=(C1S+C2S)+2.*C7+2.*DLKVD
0259 TNEW(NII,1,1)=(DLIV*(C1S*T(NII-1,1,1)+C2S*TA)+C7*2.*T(NII,2,1)
/ +DLKVD*2.*T(NII,1,2))/C8
0260 TNEW(NII,NJ,1)=(DLIV*(C1S*T(NII-1,NJ,1)+C2S*TA)+C7*2.*
/ T(NII,NJ-1,1)+DLKVD*2.*T(NII,NJ,2))/C8
0261 TNEW(NII,1,NK)=(DLIV*(C1S*T(NII-1,1,NK)+C2S*TA)+C7*2.*
/ T(NII,2,NK)+DLKVD*2.*T(NII,1,NK-1))/C8
0262 TNEW(NII,NJ,NK)=(DLIV*(C1S*T(NII-1,NJ,NK)+C2S*TA)+C7*2.*
/ T(NII,NJ-1,NK)+DLKVD*2.*T(NII,NJ,NK-1))/C8
0263 DO 23 J=2,LJ
0264 TNEW(NII,J,1)=(DLIV*(C1S*T(NII-1,J,1)+C2S*TA)+C7*(T(NII,J-1,1)+
/ T(NII,J+1,1))+DLKVD*2.*T(NII,J,2))/C8
0265 23 TNEW(NII,J,NK)=(DLIV*(C1S*T(NII-1,J,NK)+C2S*TA)+C7*
/ (T(NII,J-1,NK)+T(NII,J+1,NK))+DLKVD*2.*T(NII,J,NK-1))/C8
0266 DO 24 K=2,LK
0267 TNEW(NII,1,K)=(DLIV*(C1S*T(NII-1,1,K)+C2S*TA)+C7*2.*T(NII,2,K)+
/ DLKVD*(T(NII,1,K-1)+T(NII,1,K+1)))/C8
0268 24 TNEW(NII,NJ,K)=(DLIV*(C1S*T(NII-1,NJ,K)+C2S*TA)+C7*2.*
/ T(NII,NJ-1,K)+DLKVD*(T(NII,NJ,K-1)+T(NII,NJ,K+1)))/C8
0269 DO 25 J=2,LJ
0270 DO 25 K=2,LK
0271 25 TNEW(NII,J,K)=(DLIV*(C1S*T(NII-1,J,K)+C2S*TA)+C7*(T(NII,J-1,K)+
/ T(NII,J+1,K))+DLKVD*(T(NII,J,K-1)+T(NII,J,K+1)))/C8
0272 DO 85 I=2,NI
0273 DO 85 J=KJ,NJ
0274 DO 85 K=1,NK
0275 IF (DABS(T(I,J,K)-TNEW(I,J,K))-EPS) 85,85,40
0276 85 CONTINUE
0277 DO 27 I=2,NI
0278 DO 27 J=1,NJ
0279 DO 27 K=KK,NK
0280 IF (DABS(T(I,J,K)-TNEW(I,J,K))-EPS) 27,27,40
0281 27 CONTINUE
0282 DO 26 I=KI,NII
0283 DO 26 J=1,NJ
0284 DO 26 K=1,NK
0285 IF (DABS(T(I,J,K)-TNEW(I,J,K))-EPS) 26,26,40

```

Fig. G.2 (Contd.)

```

0286      26 CONTINUE
0287      GO TO 90
0288      40 DO 31 I=2,NI
0289          DO 31 J=KJ,NJ
0290          DO 31 K=1,NK
0291      31 T(I,J,K)=TNEW(I,J,K)
0292          DO 32 I=KI,NI
0293          DO 32 J=1,NJ
0294          DO 32 K=1,NK
0295      32 T(I,J,K)=TNEW(I,J,K)
0296          DO 33 I=2,NI
0297          DO 33 J=1,NJ
0298          DO 33 K=KK,NK
0299      33 T(I,J,K)=TNEW(I,J,K)
0300      GO TO 80
0301      90 XMI=NI
0302          YMJ=NJ
0303          ZMK=NK
0304          DEPTH=DLI*(XMI-1.)
0305          ACROS=DLJ*(YMJ-1.)
0306          HICAV=DLK*(ZMK-1.)
0307          DINS=2.*PINS
0308          DOUT=2.*ROUT
0309          HIGHU=2.*HIGHT
0310          SHTK=ROUT-RINS-TR
0311      WRITE (6,28) DINS,DOUT,HIGHU,TR,SHTK,DEPTH,ACROS,HICAV,DLI,DLJ,
/      DLK,TT,TA,CON1,CON2,H,EPS
0312      28 FORMAT (1H1,20HDIMENSION:          ID=F8.2,4H IN.,OD=F8.2,
/      21H IN., (TOTAL) HEIGHT=F8.2,
/      4H IN./18X,21HBEFFRACTORY THICKNESS=F6.2,
/      21H IN.,SHELL THICKNESS=F6.2,4H IN./13H CAVITY SIZE:,5X,
/      6HDEPTH=F6.2,19H IN., (HALF) ANGLE=F7.2,5H DEG./
/      17X,15H (HALF) HPIGHT=F7.2,4H IN./
/      11H MESH SIZE:,7X,7HRADIAL=F6.3,13H IN.,ANGULAR=F6.2,
/      12H DEG.,AXIAL=F6.2,4H IN./
/      14H TEMPERATURES:,4X,15HINSIDE SURFACE=
/      P10.2,14H DEG.,AMBIENT=F8.2,5H DEG./12H PROPERTIES:,6X,
/      11HK FOR REF.=F8.2,14H, K FOR SHELL=F8.2,19H BTU IN./HR FT**2 F/
/      18X,2HH=F8.2,15H BTU/HR FT**2 F/20H ITERATION ERROR: E=
/      F5.2,5H DEG.///)
0313      DO 29 K=1,NK
0314      29 WRITE (6,30) (TNEW(NII,J,K),J=1,NJ)
0315      30 FORMAT ('5D20.10)
0316          WRITE (6,401)
0317      401 FORMAT (1H1,23HCONTACT RESISTANCE MAP:///)
0318          DO 402 K=1,11
0319          DO 402 J=1,25
0320      402 STORE(J,K)=RESISL(VRFS,DLI,CON1,J,K)
0321          DO 403 K=1,11
0322      403 WRITE (6,406) (STORE(J,K),J=1,25)
0323      406 FORMAT (7E14.5)
0324          WRITE (6,404) VRFS
0325      404 FORMAT (///45H NOTE: UNIT FOR CONTACT RESISTANCE-HR DEG/BTU/
/      54H CONTACT RESISTANCE VALUES WERE GENERATED USING: VRFS=F5.2/
/      60H (REFER TO 'RESISL' EQUATION FOR TESTED RESISTANCE FUNCTION))

```

Fig. G.2 (Contd.)

```

0326      NJCT=2*NJ-1
0327      NKCT=2*NK-1
0328      NJDT=NJ+1
0329      NKDT=NK+1
0330      NJET=NJ-1
0331      NKET=NK-1
0332      ANJCT=NJCT
0333      ANKCT=NKCT
0334      BNJCT=- (2.*ANJCT)
0335      BNKCT=- (2.*ANKCT)
0336      CNJCT=1.5*ANJCT
0337      MTTT=TNEW(NII,1,1)/100.+1.
0338      VTT=MTTT*100
0339      MTTB=TNEW(NII,NJ,NK)/100.
0340      VTB=MTTB*100
0341      MTR=ROUT-RINS+1.
0342      RTT=MTR
0343      DO 101 J=1,NK
0344      DO 101 I=1,NJCT
0345      IF (I-NJ) 102,102,103
0346      102 TEXP(I,J)=TNEW(NJI,NJDT-I,J)
0347      GO TO 101
0348      103 TEXP(I,J)=TNEW(NII,I-NJET,J)
0349      101 CONTINUE
0350      DO 104 I=1,NJCT
0351      DO 104 J=1,NKCT
0352      IF (J-NK) 105,105,106
0353      105 TEXP(I,J)=TEXP(I,NKDT-J)
0354      GO TO 104
0355      106 TEXP(I,J)=TEXP(I,J-NKET)
0356      104 CONTINUE
0357      ZHI=ROUT-RINS
0358      ZCI=ROUT-RINS-(IMI-1.)*DLI
0359      NJFT=NJ-MJ+1
0360      NKFT=NK-MK+1
0361      NJGT=NJ+MJ-1
0362      NKGT=NK+MK-1
0363      NJHT=NJFT+1
0364      NKHT=NKFT+1
0365      NJIT=NJGT-1
0366      NKIT=NKGT-1
0367      DO 111 J=1,NKCT
0368      DO 111 I=1,NJFT
0369      111 CVPT(I,J)=ZHI
0370      DO 112 J=1,NKCT
0371      DO 112 I=NJGT,NJCT
0372      112 CVPT(I,J)=ZHI
0373      DO 113 I=NJHT,NJIT
0374      DO 113 J=1,NKFT
0375      113 CVPT(I,J)=ZHI
0376      DO 114 I=NJHT,NJIT
0377      DO 114 J=NKGT,NKCT
0378      114 CVPT(I,J)=ZHI
0379      DO 115 I=NJHT,NJIT
0380      DO 115 J=NKHT,NKIT

```

Fig. G.2 (Contd.)


```

0381      115 CVPT(I,J)=ZCI
0382      WRITE (6,35)
0383      35 FORMAT (1H1,43HTHREE DIMENSIONAL SURFACE TEMPERATURE PLOT:)
0384      CALL STRTPL
0385      CALL BGNPL(1)
0386      CALL TITL3D('THREE-DIMENSIONAL SURFACE TEMPERATURE PLOTS',-100,
/ 10.,6.)
0387      CALL AXES3D('ANGULAR DIRECTIONS',100,'AXIAL DIRECTIONS',100,
/ 'TEMPERATURES',100,ANJCT,ANKCT,CNJCT)
0388      CALL VUABS(BNJCT,BNKCT,CNJCT)
0389      CALL GRAP3D(1.,4.,ANJCT,1.,2.,ANKCT,0.,50.,400.)
0390      CALL SURMAT(TFPX,1,NJCT,1,NKCT,WORKSP)
0391      CALL ENDPL(1)
0392      WRITE (6,36)
0393      36 FORMAT (1H1,38HRECONSTRUCTION OF CAVITY CONFIGURATION)
0394      CALL BGNPL(1)
0395      CALL TITL3D('RECONSTRUCTION OF CAVITY CONFIGURATIONS',-100,
/ 10.,6.)
0396      CALL AXES3D('ANGULAR DIRECTIONS',100,'AXIAL DIRECTIONS',100,
/ 'RADIAL DIRECTIONS',100,ANJCT,ANKCT,CNJCT)
0397      CALL VUABS(BNJCT,BNKCT,CNJCT)
0398      CALL GRAP3D(1.,4.,ANJCT,1.,2.,ANKCT,0.,1.,PTT)
0399      CALL SURMAT(CVPT,1,NJCT,1,NKCT,WORKSQ)
0400      CALL ENDPL(2)
0401      WRITE (6,405)
0402      405 FORMAT (1H1,46HTHREE DIMENSIONAL PLOT FOR CONTACT RESISTANCE:)
0403      CALL BGNPL(1)
0404      CALL TITL3D ('THREE-DIMENSIONAL PLOT FOR CONTACT RESISTANCES',
/ -100,10.,6.)
0405      CALL AXES3D('ANGULAR DIRECTIONS',100,'AXIAL DIRECTIONS',100,
/ 'CONTACT RESISTANCES',100,ANJCT,ANKCT,CNJCT)
0406      CALL VUABS(BNJCT,BNKCT,CNJCT)
0407      CALL GRAP3D(1.,4.,ANJCT,1.,2.,ANKCT,0.,0.4,1.6)
0408      CALL SURMAT(STORE,1,NJCT,1,NKCT,WORKSQ)
0409      CALL ENDPL(3)
0410      TNC=(VTT-VTB)/21.
0411      VTC=VTB+TNC-0.1
0412      VTD=VTB+2.*TNC
0413      VTE=VTD+TNC-0.1
0414      VTF=VTB+4.*TNC
0415      VTG=VTF+TNC-0.1
0416      VTH=VTB+6.*TNC
0417      VTI=VTH+TNC-0.1
0418      VTJ=VTB+8.*TNC
0419      VTK=VTJ+TNC-0.1
0420      VTL=VTB+10.*TNC
0421      VTH=VTL+TNC-0.1
0422      VTN=VTB+12.*TNC
0423      VTO=VTN+TNC-0.1
0424      VTP=VTB+14.*TNC
0425      VTQ=VTP+TNC-0.1
0426      VTR=VTB+16.*TNC
0427      VTS=VTR+TNC-0.1
0428      VTU=VTB+18.*TNC
0429      VTV=VTU+TNC-0.1

```

Fig. G.2 (Contd.)

```

0430      VTH=VTB+20.*TNC
0431      WRITE (6,37)
0432      37 FORMAT (1H1,26HSURFACE ISOTHERM CONTOURS:////8H LEGEND:/5X,
/ 36HSYMBOL ISOTHERM BAND WIDTH (DEG.F)/)
0433      WRITE (6,38) VTB, VTC, VTD, VTE, VTF, VTG, VTH, VTI, VTJ, VTK, VTL, VTM, VTN,
/ VTO, VTP, VTQ, VTR, VTS, VTU, VTV, VTH, VTT
0434      38 FORMAT (7X,1HA,10X,F7.1,4H TO ,F7.1/
/ 7X,1HB,10X,F7.1,4H TO ,F7.1/
/ 7X,1HC,10X,F7.1,4H TO ,F7.1/
/ 7X,1HD,10X,F7.1,4H TO ,F7.1/
/ 7X,1HE,10X,F7.1,4H TO ,F7.1/
/ 7X,1HF,10X,F7.1,4H TO ,F7.1/
/ 7X,1HG,10X,F7.1,4H TO ,F7.1/
/ 7X,1HH,10X,F7.1,4H TO ,F7.1/
/ 7X,1HI,10X,F7.1,4H TO ,F7.1/
/ 7X,1HJ,10X,F7.1,4H TO ,F7.1/
/ 7X,1HK,10X,F7.1,4H TO ,F7.1//)
0435      WRITE (6,39)
0436      39 FORMAT (1H ,41HNOTE: ALTHOUGH ELEVEN SYMBOLS ARE USED TO
/ 56H REPRESENT ISOTHERM BANDS IN THE LEGEND, THE TEMPERATURE/
/ 54H RANGES FOR THESE SYMBOLS HAVE BEEN SELECTED SUCH THAT
/ 61H TWENTY ONE BANDS CAN BE READ OFF FROM THE ISOTHERM MAP. NOTE/
/ 59H THAT THE TEMPERATURE RANGES IN THE LEGEND ARE DISCONTINUOUS
/ 53H , SIGNIFYING THAT A WHITE BAND EXISTS IN BETWEEN THE/
/ 54H NEIGHBORING LETTERED BANDS; THE TEMPERATURE RANGE FOR
/ 50H THE WHITE BAND IS BRIDGED IN BETWEEN THOSE OF THE/
/ 19H NEIGHBORING BANDS.//)
0437      DO 201 I=1,NJCT
0438      201 G(I)=ASTSK
0439      WRITE (6,202) G
0440      202 FORMAT (1H ,180A1)
0441      J=NKCT
0442      203 DO 204 I=1,NJCT
0443      K=(TFXP(I,J)-VTB)/TNC+1.
0444      G(I)=SYMBOL(K)
0445      204 CONTINUE
0446      WRITE (6,205) G
0447      205 FORMAT (1H ,180A1)
0448      J=J-1
0449      IF (J.NE.0) GO TO 203
0450      DO 206 I=1,NJCT
0451      206 G(I)=ASTSK
0452      WRITE (6,207) G
0453      207 FORMAT (1H ,180A1)
0454      SCR=(TNEW(NII,1,1)-TNEW(NII,NJ,NK))/20.
0455      DO 301 K=1,20
0456      BK=K
0457      BIAS=(BK-1.)*SCR+TNEW(NII,NJ,NK)
0458      DO 302 J=1,NKCT
0459      DO 302 I=1,NJCT
0460      302 TFXP(I,J)=TFXP(I,J)-BIAS
0461      COUNT=0.
0462      ACUM=0.
0463      DO 303 J=1,NKCT
0464      DO 303 I=1,NJCT

```

Fig. G.2 (Contd.)

```

0465      IF (TGXP(I,J)) 303,304,304
0466 304 COUNT=COUNT+1.
0467      ACUM=ACUM+TGXP(I,J)
0468 303 CONTINUE
0469      B(K)=BIAS
0470      A(K)=COUNT
0471 301 V(K)=ACUM
0472      DO 350 K=1,10
0473      DIV=10.**K
0474      Y=A(2)/DIV
0475      IF (Y-1) 351,351,350
0476 350 CONTINUE
0477 351 EXPA=K
0478      DO 360 K=1,10
0479      DIV=10.**K
0480      Y=V(2)/DIV
0481      IF (Y-1) 361,361,360
0482 360 CONTINUE
0483 361 EXPV=K
0484      CYCLA=8./EXPA
0485      CYCLV=8./EXPV
0486      THVOL=V(1)+TNEW(NII,NJ,NK)*ANJCT*ANKCT
0487      WRITE (6,371) THVOL
0488 371 FORMAT (1H1,36HTOTAL VOLUME UNDERNEATH THE SURFACE=E12.5///)
0489      WRITE (6,372)
0490 372 FORMAT (1H ,2X8HISOTHERM5X11HAREA INSIDE4X10HINTEGRATED)
0491      WRITE (6,373)
0492 373 FORMAT (1H ,1X11HTEMPERATURE3X12HTHE ISOTHERM5X6HVOLUME)
0493      DO 374 K=1,20
0494 374 WRITE (6,375) B(K),A(K),V(K)
0495 375 FORMAT (1H ,F9.1,E17.4,E14.4)
0496      PUNCH 330, DEPTH,ACROS,HICAV,THVOL,TNEW(NII,1,1),TNEW(NII,NJ,NK)
0497 330 FORMAT (F10.2,5F10.1)
0498      WRITE (6,376)
0499 376 FORMAT ('H1)
0500      CALL BGNPL(1)
0501      CALL TITLE('AREA ENCLOSED INSIDE ISOTHERM LOOPS$',100,
/ 'TEMPERATURE$',100,'AREAS$',100,5.,8.)
0502      CALL FRAME
0503      CALL YLOG(0.,80.,1.,CYCLA)
0504      CALL GRID(2,2)
0505      CALL CURVE(B,A,20,1)
0506      CALL ENDPL(4)
0507      CALL TITLE('INTEGRATED ENERGY EQUIVALENTS',100,
/ 'TEMPERATURE$',100,'INTEGRATED ENERGY EQUIVALENTS',100,5.,8.)
0508      CALL FRAME
0509      CALL YLOG(0.,80.,1.,CYCLV)
0510      CALL GRID(2,2)
0511      CALL CURVE(B,V,20,1)
0512      CALL ENDPL(5)
0513 50 CONTINUE
0514 400 CONTINUE
0515      CALL DOWPL
0516      STOP
0517      END

```

Fig. G.2 (Contd.)

REFERENCES

1. C. A. Youngdahl and W. A. Ellingson, "Development of Ultrasonic Techniques for Remote Monitoring of Erosive Wear in Coal Conversion Systems," *1978 Ultrasonics Symposium Proceedings*, IEEE Cat #78-CH1344-1SU, pp. 305-310 (1978).
2. C. A. Youngdahl and W. A. Ellingson, "Long Term Erosion Monitoring of Metallic Conduits by Ultrasonic Pulse-echo Techniques," *Proc. 12th Int. Symposium on Nondestructive Evaluation*, San Antonio, TX, pp. 282-291 (1979).
3. N. P. Lapinski, *Gamma Radiography of Refractory-lined Vessels and Components*, ANL-78-43 (Aug 1978).
4. *Materials Science Division Coal Technology Ninth Quarterly Report, October-December 1976*, ANL-77-5 (May 1977).
5. S. H. Birchard and L. M. Rogers, *Industrial Thermography--How Representative of Plant Condition is the Thermal Image Produced by an Infrared Camera*, Brit. J. Nondestr. Test., July 1976, 111-113 (1976).
6. S. H. Birchard and L. M. Rogers, *A Review of Industrial Applications of Thermography*, Brit. J. Nondestr. Test., Jan 1976, 2-11 (1976).
7. E. Sundstrom, *Wide-angle Infrared Camera for Industry and Medicine*, Appl. Opt. 7(9), 1763-1768 (1968).
8. S. Borg, *Thermal Imaging with Real Time Picture Presentation*, Appl. Opt. 7(9), 1697-1704 (1968).
9. R. W. Astheimer and F. Schwarz, *Thermal Imaging Using Pyroelectric Detectors*, Appl. Opt. 7(9), 1687-1696 (1968).
10. C. W. Hurley and K. G. Kreider, *Applications of Thermography for Energy Conservation in Industry*, NBS Technical Note 923 (1976).
11. E. A. Farber, C. K. Hsieh, and M. C. K. Yang, *Space Shuttle Thermal Protection System Condition Assessment by Thermal Radiation Analysis Techniques*, Report TRL-74-B1, Thermal Radiation Laboratory, Mechanical Engineering Department, University of Florida (1974).
12. A. M. Clausing, "Numerical Methods in Heat Transfer," in *Advanced Heat Transfer*, B. T. Chao, Ed., University of Illinois Press, Urbana (1969).
13. C. K. Hsieh and F. E. Davis, *Bibliography on Thermal Contact Conductance*, Air Force Materials Laboratory Report AFML-TR-69-24 (1969).
14. C. K. Hsieh, *On the Nature of Thermal Contact Conductance*, M.S. thesis, Purdue University (1964).
15. C. K. Hsieh and Y. S. Touloukian, "Correlation and Prediction of Thermal Contact Conductance for Nominally Flat Surfaces," *Thermal Conductivity, Proc. Eighth Conference*, Plenum Press, New York, pp. 477-494 (1969).
16. C. K. Hsieh, K. M. Yeddanapudi, and Y. S. Touloukian, "An Analytical Study of Thermal Contact Conductance for Two Rough and Wavy Surfaces Under a Pressure Contact," *9th Conf. on Thermal Conductivity*, Howard R. Shanks, Ed., CONF-691002, pp. 554-570 (1970).
17. R. K. Francis and J. R. Tinklepaugh, *Thermal Conductivity in Ceramic-Metal Laminates*, J. Am. Ceram. Soc. 43(1), 560-563 (1960).

18. R. C. Daniel and I. Cohen, *In-Pile Effective Thermal Conductivity of Oxide Fuel Elements to High Fission Depletions*, WAPP-246, Bettis Atomic Power Laboratory (1964).
19. M. Born and E. Wolf, *Principles of Optics*, Pergamon Press (1970).
20. E. M. Sparrow and R. D. Cess, *Radiation Heat Transfer*, Brooks/Cole (1966).
21. R. Siegel and J. R. Howell, *Thermal Radiation Heat Transfer*, Volume 1, "The Blackbody, Electromagnetic Theory, and Material Properties," NASA SP-164 (1968).
22. M. N. Ozisik, *Radiative Transfer and Interactions with Conduction and Convection*, Wiley-Interscience (1973).
23. H. C. Hottel and A. F. Sarafim, *Radiative Transfer*, McGraw-Hill (1967).
24. C. K. Hsieh and W. A. Ellingson, *A Quantitative Determination of Surface Temperatures Using an Infrared Camera*, J. Soc. Photo-Opt. Instrum. Eng. 124, 228-235 (1977).
25. W. A. Scheffler, *Heat Conduction in Bodies with Small Boundary Perturbations*, J. Heat Transfer 96C(2), 248-249 (1974).
26. C. K. Hsieh and K. C. Su, "A Perturbation Solution of Heat Conduction in a Cavitated Region Subjected to a Convective Boundary Condition," presented at 16th Int. Thermal Conductivity Conf., Chicago (Nov 1979).
27. J. T. Tou and R. C. Gonzalez, *Pattern Recognition Principles*, Addison-Wesley (1974).
28. *DISSPLA Advanced Manual*, Volume II, Integrated Software Systems Corp. (1970).
29. *DISSPLA Beginners and Intermediate Manual*, Volume I, Integrated Software Systems Corp. (1970).

Distribution of ANL-78-82**Internal:**

W. E. Massey	E. M. Stefanski (3)	E. L. Hartig
E. G. Pewitt	W. A. Ellingson (6)	R. B. Poeppel
B. R. T. Frost	K. J. Reimann	W. J. Shack
J. J. Roberts	C. A. Youngdahl	A. B. Krisciunas
R. W. Weeks (6)	A. A. Jonke	ANL Contract File
N. M. O'Fallon	C. R. Kennedy	ANL Libraries (5)
D. Diercks		TIS Files (6)

External:

DOE-TIC, for distribution per UC-90c, -90e, -90h (463)
 Manager, Chicago Operations and Regional Office, USDOE
 Chief, Office of Patent Counsel, DOE-CORO
 President, Argonne Universities Association
 Materials Science Division Review Committee:
 E. A. Aitken, General Electric Co., Sunnyvale
 G. S. Ansell, Rensselaer Polytechnic Inst.
 R. W. Balluffi, Massachusetts Inst. Technology
 R. J. Birgeneau, Massachusetts Inst. Technology
 S. L. Cooper, U. Wisconsin, Madison
 C. Laird, U. Pennsylvania
 M. T. Simnad, General Atomic
 C. T. Tomizuka, U. Arizona
 A. R. C. Westwood, Martin Marietta Laboratories
 E. M. Anderson, The Babcock and Wilcox Company, Lynchburg
 W. G. Bair, Inst. Gas Technology, Chicago
 G. Baker, Grand Forks Energy Technology Center
 R. A. Bradley, Oak Ridge National Lab.
 C. F. Brandenburg, Laramie Energy Technology Center
 G. B. Brenneman, Maxon Corp., Muncie, Ind.
 J. A. Brooks, Amoco Oil Co., Naperville, Ill.
 M. Crowley, Standard Oil of Indiana, Naperville, Ill.
 S. Danyluk, U. Illinois, Chicago Circle
 S. J. Dapkunas, Div. Plans and Technology Assessment, USDOE
 N. F. Fiore, U. Notre Dame
 E. Fox, Stearns-Roger Corp., Homer City, Pa.
 S. M. Gaitonde, Commonwealth Edison Co., Maywood, Ill.
 J. Gardner, Morgantown Energy Technology Center
 D. Glaser, Stearns-Roger Corp., Denver
 W. M. Heher, Grand Forks Energy Technology Center
 H. Heystek, Tuscaloosa Metallurgy Research Center, University, Ala.
 V. Hill, IIT Research Inst.
 L. C. Ianniello, Div. Materials Sciences, USDOE
 R. I. Jaffee, Electric Power Research Institute
 D. L. Keairns, Westinghouse Research Labs., Pittsburgh
 H. Leavenworth, Albany Metallurgy Research Center
 G. R. Leverant, Southwest Research Inst.
 A. V. Levey, Lawrence Berkeley Laboratory
 W. J. Lochman, The Ralph M. Parsons Co., Pasadena

G. Long, Northern Illinois Gas Co., Aurora
R. M. Lundberg, Commonwealth Edison Co., Chicago
M. M. Mamoun, Inst. Gas Technology, Chicago
J. M. O'Donnell, The Lummus Co., Bloomfield, N.J.
K. Pater, Morgantown Energy Technology Center
F. A. Prange, Phillips Petroleum Corp., Bartlesville
S. J. Schneider, National Bureau of Standards (2)
R. Searles, Ashland Synthetic Fuels, Inc., Ashland, Ky.
A. G. Sharkey, Jr., Pittsburgh Energy Technology Center
G. Sorell, Exxon Research and Engineering Co., Florham Park
J. Stevenson, Rolla Metallurgy Research Center
J. Sudbury, Consolidated Coal Co., Library, Pa.
C. Whitten, Peabody Coal Co., Columbia, Tenn.