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Full Name of Author — Nom complet de l'auteur

ALLAN DAVID HIEBERT

Date of Birth — Date de naissance	Country of Birth — Lieu de naissance
JUNE 11, 1958	CANADA

Permanent Address — Résidence fixe

11308-55 AVE
EDMONTON, ALBERTA
CANADA, T6H 0X2

Title of Thesis — Titre de la thèse

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COMPUTER SIMULATION OF IN SITU, LOW FREQUENCY, ELECTRICAL HEATING OF OIL SAND FORMATIONS

by

© ALLAN DAVID HIEBERT

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE

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TITLE OF THESIS COMPUTER SIMULATION OF IN SITU, LOW FREQUENCY, ELECTRICAL HEATING OF OIL SAND FORMATIONS

DEGREE FOR WHICH THESIS WAS PRESENTED MASTER OF SCIENCE

YEAR THIS DEGREE GRANTED SPRING, 1981

(SIGNED) Allan Hiebert

PERMANENT ADDRESS:

11308 - 55 Ave.

Edmonton, Alberta, Canada

T6H 0X2

DATED January 19, 1981

THE UNIVERSITY OF ALBERTA

FACULTY OF GRADUATE STUDIES AND RESEARCH

The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research, for acceptance, a thesis entitled "Computer Simulation of In Situ, Low Frequency, Electrical Heating of Oil Sand Formations" submitted by Allan David Hiebert in partial fulfilment of the requirements for the degree of Master of Science.

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Supervisor

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Date.. Jan. 19. 1981

Abstract

The mathematical modeling of electrical and thermal phenomena that occur during in situ, low frequency, electrical heating of oil sand, or other materials with similar electrical properties, is studied. Particular attention was directed toward the modeling of the electrical field at an interface between two media of different electrical conductivities. The finite difference method is used to develop a computer program to simulate, in two dimensions, the mathematical model that was developed.

This computer program is used to study the role of various parameters in determining the final temperature profile after a fixed time period and fixed rate of heating. The parameters studied include the position of the electrodes relative to the overlying and underlying formations, the spacing between the electrodes, and the ratio of the conductivity of the oil sand formation to the conductivity of the surrounding formations.

Acknowledgement

I would like to thank my supervisors, Dr. C.E. Capjack, Dr. F.S. Chute and Dr. F.E. Vermeulen, for their very helpful assistance during all stages of my study.

I would also like to thank Dr. M. Cervenan for his help, and J. Fearn and A. Vogan for their efforts in setting up and performing the physical scale model runs that provided data that could be compared to the results from the computer program.

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Nomenclature

A_{ij}	Coefficent of the (i,j) term of the difference equation.
$\bar{B}$	Magnetic flux density vector.
C_{ij}	Coefficent of the (i-1,j) term of the difference equation.
$\bar{D}$	Electrical displacement vector.
$\bar{E}$	Electrical field vector.
E_E	Electrical energy input.
E_H	Total heat generated.
E_T	Thermal energy stored in the formation.
F_{ij}	Coefficent of the (i,j-1) term of the difference equation.
$\bar{H}$	Magnetic field vector.
I^n	Total electrical current during the nth time step.
$\bar{J}$	Electrical current density vector.
M	Volumetric heat capacity.
$\dot{Q}$	Instantaneous heating rate.
$\dot{Q}_{AV}$	Average heating rate.
R_{ij}	Coefficent of the (i,j+1) term of the difference equation.
S_{ij}	Coefficent of the (i+1,j) term of the difference equation.
T	Temperature
T_o	Initial temperature of the formation.
V^n	Voltage between the electrodes during the nth time step.

d	Distance between the electrodes.
j	Square root of -1.
k_h	Thermal conductivity.
t	Time.
Δt	Length of time step.
V_{ij}	Volume of the (i,j) grid block.
α	Temperature dependence of electrical conductivity.
ε	Electrical permittivity.
φ	Electrical potential.
ρ	Electrical charge density.
ρ_s	Electrical surface charge density.
σ	Electrical conductivity.
σ_{24}	Electrical conductivity at 24°C.
ω	Frequency in radians per second.

1. Introduction

1.1 Electrical Preheat In Situ Method

In northern Alberta there exist large deposits of petroleum in the form of oil sand.[1] The oil in these deposits is too viscous to recover by conventional methods. Commercial developments to date have mined the oil sand in open pit mines, then separated out the petroleum (in the form of bitumen) in large extraction plants. The bitumen is upgraded to "synthetic crude", then piped to a refinery.

As the thickness of the earth, or overburden, above the oil sand formation increases, open pit mining becomes uneconomical. Only about ten percent of the oil sand reserves are recoverable by surface mining.[2] Thus, there is considerable interest in developing *in situ* (in place) methods of separating out the bitumen. A wide range of possible in situ techniques have been suggested.[3]

One of the proposed in situ techniques is steam flooding. In the steam flood method an array of injection and production wells are drilled, then steam is pumped down the injection wells and oil and water are pumped up the production wells. A major problem with this method is in developing "communication" between the injection and the production wells. The unheated bitumen is so viscous it blocks the steam and heated, mobilized bitumen from traveling from one well to the other. Various methods have been proposed to develop communication. These include

injection of solvents, formation of emulsions and formation fracturing.[17] The first two methods are designed to reduce the viscosity of the bitumen, and the third method produces a direct channel between wells.

The electrical preheat in situ method proposes that the oil sand formation be heated by passing an electrical current through it, and, once the viscosity has been lowered sufficently, steam or some other hot fluid be used to drive out the bitumen. The viscosity of bitumen decreases rapidly with increases in temperature.[4] At natural formation temperatures Athabasca bitumen has a viscosity in the millions of centipoise. If this bitumen is heated to 80°C the viscosity drops to 1000 cp, and if heated to 200°C the viscosity will be about 10 cp. The heat used to raise the temperature of the bitumen is generated right in the oil sand by the electrical current flowing in the connate water. This heating in place overcomes some of the problems usually associated with heating heavy oil formations with steam, such as low thermal conductivity and difficulty directing the applied heat. Electrical heating has seen limited use in secondary recovery of conventional oil fields.[5] Several patents have been issued on the application of electrical heating to oil sand. Petro-Canada Explorations Ltd. is running a pilot plant investigating the electrical preheat method.[4]

1.2 Means of Investigation

Before pilot plant tests or commercial developments of the electrical preheat method are embarked upon it is necessary to develop an idea of the optimal electrode configuration, heating rates, and heating times. Other than pilot plant or field tests, the study of the electric preheat method may be carried out by three means: analytic calculations, laboratory scale models, and numerical simulation. In all three of these means it is necessary that a mathematical model of the important processes be developed.

The electrical conductivity of oil sand is temperature dependent. This couples the governing thermal and electrical equations. The resulting set of partial differential equations is difficult or impossible to solve analytically for all but the simplest one dimensional cases.

Physical scale modeling of in situ recovery methods is discussed by Farouq Ali and Redford,[6] and the physical modeling of electromagnetic heating of oil sand is discussed by Vermeulen, Chute, and Cervenan.[7]

It was decided to use numerical simulation to study some aspects of the electrical preheat method. Two other studies reporting numerical simulation of electrical heating of petroleum reservoirs are by Todd and Howell[8] and El-Feky.[9] Todd and Howell simulate electrically heating oil sand to several hundred degrees Celsius, while cooling the well bore. El-Feky studied electrically heating conventional

oil reservoirs for secondary recovery. Both of these studies and simulators differ in detail and application from this study.

Numerical simulation may be used as a compliment or alternative to physical scale modeling. Numerical simulation allows easy adjustment of parameters and electrode configurations, but is only as good as the mathematical model on which the simulation is based. Comparison of numerical simulation results and physical scale model results can provide insight into the accuracy of a mathematical model. Physical scale modeling of the electrical heating of oil sand is being done by Vermeulen, Chute and Cervenan[7] at the University of Alberta, and some of the results of their group are compared to the results obtained by the numerical simulator which is discussed in this thesis.

1.3 Electrical and Thermal Properties of Oil Sand

The electrical conductivity and relative dielectric constant of reconstituted oil sand were measured by Chute, Vermeulen, Cervenan and McVea[10] and correlated to frequency, moisture content, temperature, and density. Similarly, the heat capacity and thermal conductivity of various grades of oil sand were reported by Cervenan, Vermeulen, and Chute[11]. The applicable results of these two papers are summarized in Table 1.1 and Table 1.2.

Table 1.1 Electrical Properties of Reconstituted Oil Sand at 60 Hz and 24°C.[10]

Material	Water (% wt.)	Conductivity (S/m)	Dielectric Constant
Oil Sand A	5.8	1.5×10^{-2}	$4. \times 10^{4}$
Oil Sand B	3.3	$6. \times 10^{-3}$	$1. \times 10^{4}$
Oil Sand C	1.3	1.2×10^{-3}	$1. \times 10^{3}$

Table 1.2 Thermal Properties of Reconstituted Oil Sand and Other Materials.[11-18]

Material	Water (% wt.)	Conductivity (W/m-K)	Heat Capacity (J/m^3-K)
Oil Sand	4.3	1.80	-
Oil Sand	2.1	1.42	-
Oil Sand	1.3	1.35	-
Oil Sand	1.5	-	1.71×10^{6}
Oil Sand	11.1	-	2.23×10^{6}
Oil Sand	1.4	-	1.83×10^{6}
Sandstone	-	.877	1.59×10^{6}
Limestone	-	1.70	1.86×10^{6}
Shale	-	1.04	1.87×10^{6}

The electrical conductivity was found to increase approximately linearly with temperature dependence up to 90°C. The computer program written in this study incorporates this temperature dependence. The electrical conductivity is expressed by

$$\sigma(T) = \sigma_{24}[1 + \alpha(T - 24)] \qquad (1.1)$$

where T is in degrees Celsius and σ is in Siemens/meter. The constant α has units $°C^{-1}$ and is the temperature dependence of electrical conductivity. A typical measured value of α for oil sand is $2.3 \times 10^{-2}\ °C^{-1}$.

The author knows of no published data on the temperature dependence of conductivity of oil sand at temperatures above 90°C. Chute et.al.[10] report that above 90°C the conductivity tends to level off, and hence the value of α decreases. In an electrical preheat of an oil sand formation the temperature will remain below 90°C in the bulk of the formation. Near the electrodes the temperature may reach 250°C or higher, but the conductivity of the oil sand will probably be affected by the injection of brine into the formation. Due to the lack of published data the author has assumed that the conductivity increases linearly with temperature, even well above 90°C.

While the thermal conductivity and heat capacity of oil sand may have some temperature dependence, there is no detailed study on such temperature dependence reported in the literature. A few measurements by Cervenan et. al.[11]

show no marked temperature dependence for the heat capacity of oil sand samples between 20°C and 70°C. The computer program was written so that the temperature dependences of thermal conductivity and heat capacity could easily be included once these dependences are known.

The effects on the electrical preheat process of changing the ratio of the electrical conductivities of the oil sand and surrounding formations is one of the items studied in this thesis. For the study of the effects of changing this ratio the thermal properties of the surrounding formations are assumed to be the same as those of the oil sand. It is also possible to give the surrounding formations different thermal properties than the oil sand.

1.4 The Computer Program "MEGAERA"

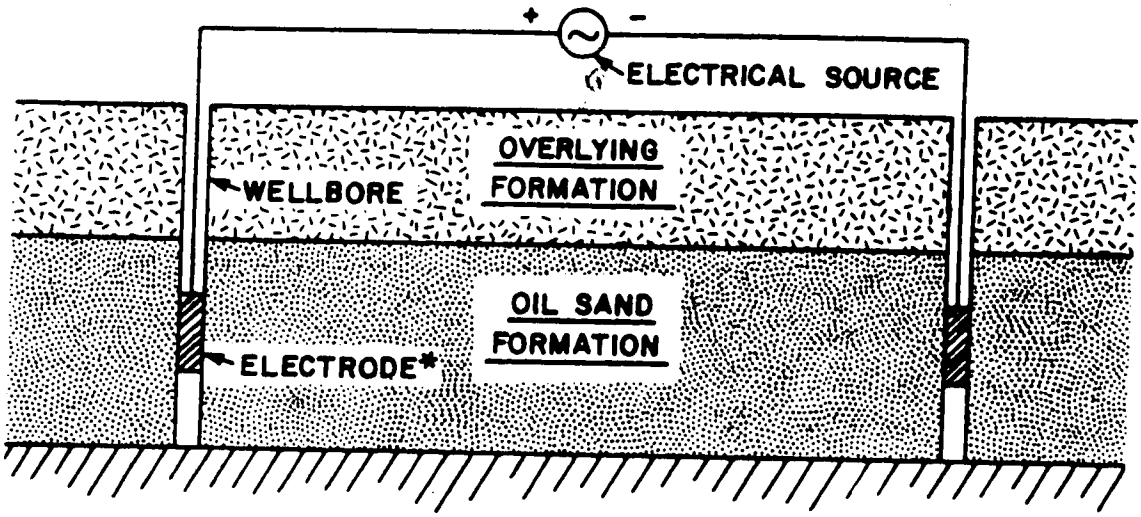
A computer program entitled MEGAERA[16] was written to numerically simulate the electrical conduction heating of oil sands, or other solid materials. The mathematical model and finite difference scheme used in MEGAERA are discussed in detail in the second and third chapters of this thesis. MEGAERA was used to study a variety of electrical heating configurations with different conductivity ratios between the oil sand and the surrounding formations. The results of this study are given in chapter four of this thesis.

Any study, analytic, experimental or numerical, must be limited to some extent. The specification for MEGAERA were based on the type of physical scale modeling being done by

Vermeulen, Chute and Cervenan at the University of Alberta and the experience of the author in writing and using an earlier two dimensional electrical heating simulator.

There were two primary considerations in developing MEGAERA. First, the program had to be able to simulate overburden and underburden of different electrical conductivities than the oil sand. The optimal electrode configuration for heating an oil sand formation is highly dependent on whether the surrounding formations are more or less conductive than the oil sand. Second, the program must be relativly inexpensive to run. For this reason MEGAERA was limited to two dimensions. A typical MEGAERA run takes two to three minutes of C.P.U. time on an Amdahl 470V/7. The time required by a three dimensional program can be conservativly estimated by multiplying the time required by the two dimensional program by the number of grid lines in the third dimension. For a reasonable amount of detail in the third dimension the program would be too expensive to run more than a few times.

While the universe is generally perceived to have three spacial dimensions, it is often convenient and reasonably accurate to model a physical system as two dimensional. In studying electrical heating of oil sand there are two different two dimensional slices of interest. A horizontal (areal) study of the heating pattern in a five spot pattern assumes that the oil sand formation is infinitly thick, but may yield results which are correct for the middle of a



*For clarity the electrodes shown are of the simple cylindrical variety. In actual practise extended electrodes would be used.

Figure 1.1 Typical Vertical Electrode Geometry

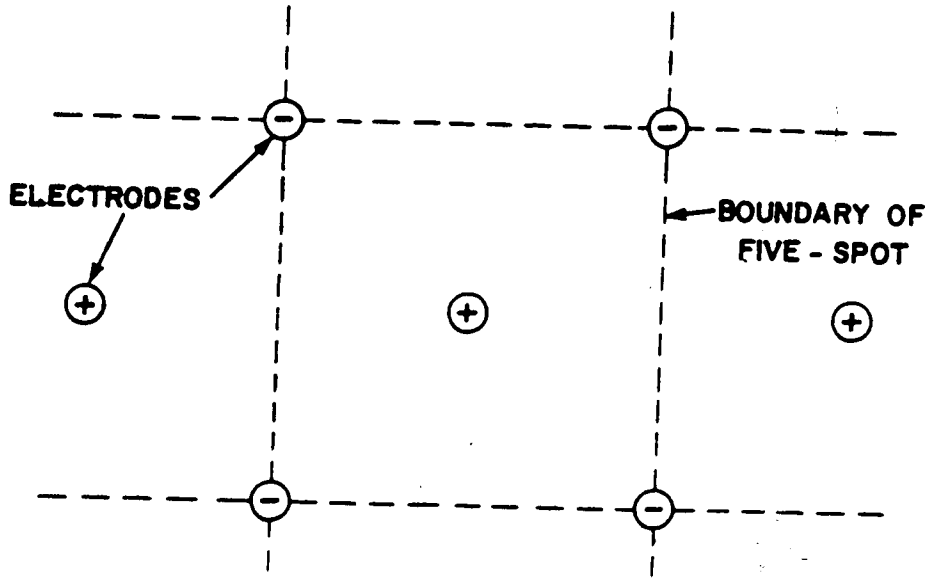


Figure 1.2 Typical Horizonta Electrode Geometry

finite formation. A vertical section studying the heating between two parallel plates allows one to see the effects of changing the conductivity of the surrounding formations. Parallel plates may be approximated in a field test by systems of closely spaced electrodes or by using a more widely spaced system of electrodes in which each electrode has been effectively enlarged by jet cutting the formation with a brine solution.

In modeling configurations with overburden and underburden the energy losses due to electrical current leakage and heat conduction from the oil bearing formation are calculated by MEGAERA. Voltage, current, power and resistance calculation are done at each time step. MEGAERA will automatically scale the applied voltages to produce constant power and constant current heating, if this is desired. A post processor, called MEGAERA.PLOTTER, was written to produce contour and profile plots of the electrical potential, heating rate and temperature at specified times.

2. The Mathematical Model

2.1 Electrical Fields

The basic set of equations of classical electricity and magnetism, first written by Maxwell in 1863, are:[1,2]

$$\nabla \cdot \bar{D} = \rho \qquad (2.1)$$

$$\nabla \cdot \bar{B} = 0 \qquad (2.2)$$

$$\nabla \times \bar{E} = -\frac{\partial \bar{B}}{\partial t} \qquad (2.3)$$

$$\nabla \times \bar{H} = \bar{J} + \frac{\partial \bar{D}}{\partial t} \qquad (2.4)$$

These equations, together with the appropriate boundary conditions, may be used to find the electric field of any electrical heating configuration at any frequency. However, an analytic or numerical solution to Maxwell's equations is difficult, if not impossible, in all but the simplest cases. It is therefore desirable to simplify these equations, dropping terms which are negligible for the frequencies and electrode configurations of interest.

2.1.1 The Quasi-static Approximation

In their paper on physical scale modeling, Vermeulen et.al.[7] discuss the simplification of Maxwell's equations for various types of electrical heating. The discussion in this section (2.1.1) is drawn from the work of their paper

and from Magid.[13]

Consider the displacement current term in equation (2.4). The ratio of conduction current to displacement current is given by $\sigma/\omega\varepsilon$ for time harmonic solutions. For oil sand this ratio is typically greater then one hundred at power frequencies (60 Hz), and does not fall to ten until frequencies of about one megahertz are reached. Thus, for power frequencies the effects of displacement current may be neglected.

The study of the fields of two dimensional, parallel electrode, electrical heating configurations is similar to the calculation of electric fields in lossy parallel plate capacitors. In these types of problems the effects of the time varying magnetic field on the time varying electric field may be neglected if the largest dimension of the problem geometry is much less than a wavelength in the medium. This reduction of Maxwell's equations to the static field equations by neglecting these magnetic and displacement current effects is known as the quasi-static approximation.

The wavelength in oil sand at 60 Hz is between 2000 m and 9000 m,[7] depending on the water content of the oil sand. As the maximum dimension of a typical electrical heating configuration will probably be less then 200 m, the quasi-static approximation should be valid. If the surrounding formations (overburden and underburden) are also to be modeled, the wavelength in these materials must also

be much greater then the maximum problem dimension and the loss tangent must be much greater than one.

When using the quasi-static approximation the geometry of the electric field is calculated from the static electric field equations. While calculating the fields the potential difference between electrodes is fixed at the peak A.C. value. The time varying electric field is then expressed as:

$$\bar{E} = \bar{E}(x,y,z) \sin \omega t \qquad (2.5)$$

where $\bar{E}(x,y,z)$ describes the static field, $\omega = 2\pi f$ where f is the frequency, and t is the time in seconds. The r.m.s. value of the potential difference is used in MEGAERA rather then the peak value. This simplifies the calculation of heating rates and conforms to the practise of stating power line voltages as r.m.s. rather then peak values.

The discussion in the previous paragraph applies to single phase heating. When three phase heating is used the geometry of the electric field of each phase must be calculated separately, using the static field equations and setting the electrodes of the other phases to ground potential. Each of the three electric field geometries thus calculated is then multiplied by the appropriate time variation, which must include the phase differences. Finally, the three fields are added vectorially and the square of the magnitude of the resulting field is averaged over a cycle to get the heating rate. This procedure was not incorporated in MEGAERA, so multiphase heating cannot be

simulated.

2.1.2 Current Continuity Equation

Neglecting the effect of the time varying magnetic field of the electric field yields:

$$\nabla \times \bar{E} = 0 \tag{2.6}$$

Thus, a scalar potential $\psi(x,y,z)$ may be defined

$$\bar{E} = -grad\ \psi \tag{2.7}$$

Droping the displacement current term in equation (2.4) gives

$$\nabla \times \bar{H} = \bar{J} \tag{2.8}$$

Taking the divergence of both sides of equation (2.8) gives

$$div\ \bar{J} = 0 \tag{2.9}$$

which states that the current is continuous. As $\bar{J} = \sigma \bar{E}$, where σ is the electrical conductivity, equa on (2.9) becomes

$$div(\sigma\ grad\ \psi) = 0 \tag{2.10}$$

As the electrical conductivity σ depends on temperature, it will, in general, be a function of of position, and equation (2.10) may not be simplified by moving the conductivity term outside the divergence operator.

2.1.3 Electrical Boundary Conditions

Three different types of electrical boundaries are to be modeled in the electrical conduction heating simulation. They are: electrode - conducting material boundaries, insulator - conducting material boundaries, and boundaries between two conducting materials.

Electrodes are simply modeled as regions of constant voltage. If constant power or constant current heating is requested, MEGAERA first calculates the fields assuming constant voltage, then measures the current and scales the electric field to the appropriate case. Electrode - Oil Sand contact impedances were noted by Chute et. al.[10] when measuring the electrical properties of oil sand. A major cause of contact impedence is poor physical contact between the oil sand and the electrode. In the mathematical model used it is assumed that contact impedance has been made negligible by a suitable technique such as the injection of a saline solution near the electrode.

Insulator - conducting material boundaries are modeled in electrostatics as surfaces at which there is no current flow normal to the surface (a homogeneous Neumann boundary condition). Having no current normal to the surface implies that the normal component of the electric field is zero just inside the conducting material. As well as modeling insulating boundaries, this type of boundary condition may be used to model planes of symmetry. Many of the electrode configurations of interest in electrical conduction heating

of oil sand consist of large arrays of electrodes of alternating polarity. The planes of symmetry in the electric field may be used to divide the large array into many small identical cells. The simulation of the heating in one of these small cells is all that is necessary to find the heating in the entire array.

At a boundary between two media of finite conductivity the electric field boundary conditions are:[15]

$$\bar{n} \times (\bar{E}_2 - \bar{E}_1) = 0 \qquad (2.11)$$

$$\bar{n} \cdot (\bar{D}_2 - \bar{D}_1) = \rho_s \qquad (2.12)$$

where $\bar{E}_1$, $\bar{E}_2$, and $\bar{D}_1$, $\bar{D}_2$, are the fields in the two media, and where ρ_s is the surface charge at the interface in coulombs per square meter and $\bar{n}$ is a unit vector locally normal to the boundary. These are general boundary conditions for Maxwell's equations and are valid for all frequencies. The boundary conditions may be expressed in terms of the normal and tangential components of the electric field.

Starting with Maxwell's equations, take the divergence of equation (2.4) and substitiute in equation (2.1) to get the current continuity equation.

$$\nabla \cdot \bar{J} + \frac{\partial \rho}{\partial t} = 0 \qquad (2.13)$$

Writing this equation in its integral form and applying the divergence theorem gives

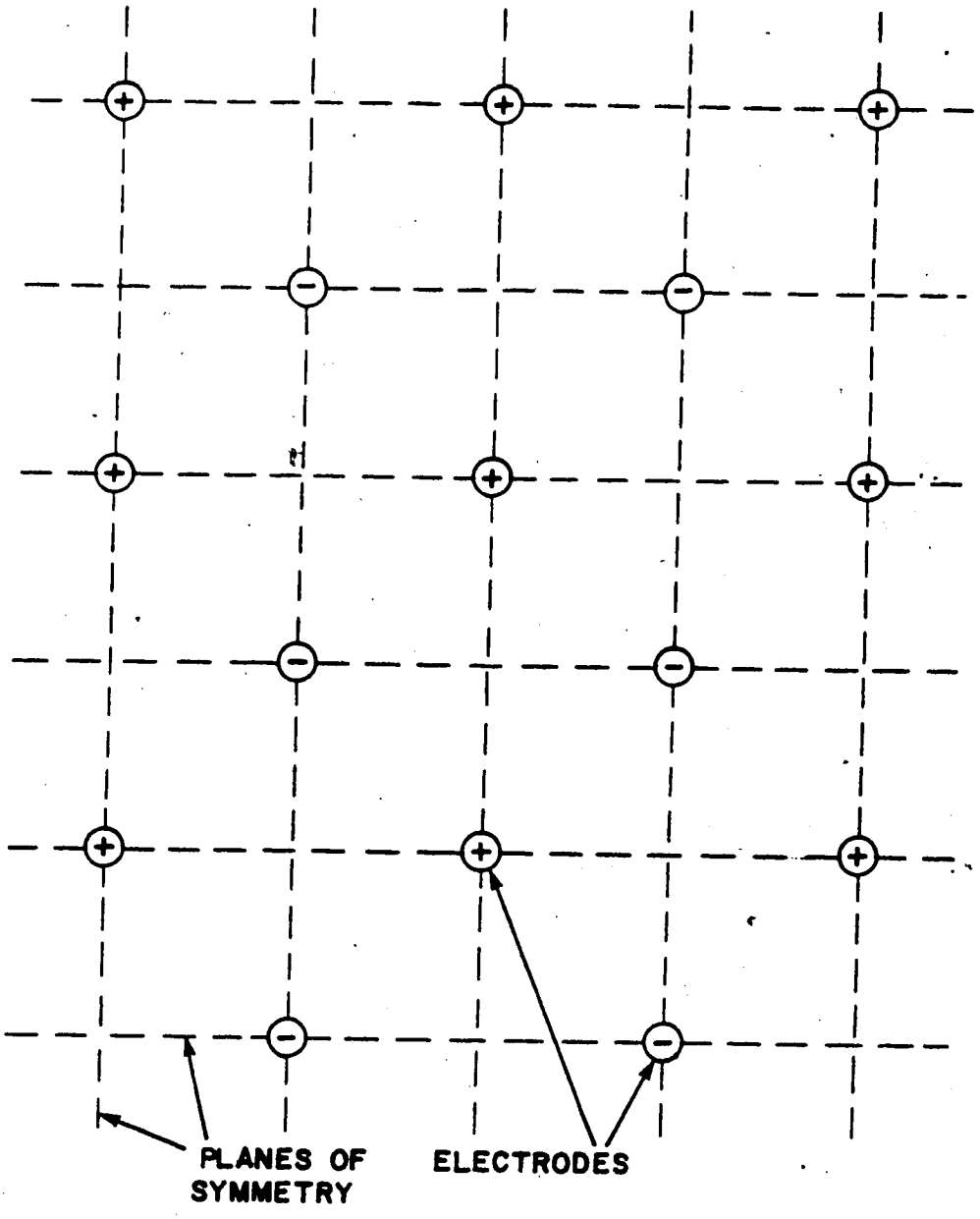


Figure 2.1 Planes of Symmetry in a Five Spot Array

$$\int_S \bar{J} \cdot d\bar{s} = -\int_V \frac{\partial \rho}{\partial t}\, dv \qquad (2.14)$$

To apply equation (2.14) to the boundary between two materials of finite conductivity, consider a small cylindrically shaped volume enclosing a portion of the boundary. One face of the cylinder, denoted S_1, is in material 1 and is parallel to the boundary. The second face, S_2, is in material 2 and is parallel to the boundary. The side of the cylinder, S_3, cuts across the boundary connecting the two faces. Applying equation (2.14) now gives

$$\int_{S_1} \bar{J} \cdot d\bar{s} + \int_{S_2} \bar{J} \cdot d\bar{s} + \int_{S_3} \bar{J} \cdot d\bar{s} = -\int_V \frac{\partial \rho}{\partial t}\, dV \qquad (2.15)$$

Now, let the length of the side of the cylinder shrink toward zero. As both materials 1 and 2 are of finite electrical conductivity, the current density must remain finite, and the integral over S_3 goes to zero. For S_1 and S_2 sufficently small (but an order larger then S_3), equation (2.15) becomes

$$\sigma_1 E_{n1} \Delta S + \sigma_2 E_{n2} \Delta S = -\frac{\partial \rho_s}{\partial t} \Delta S \qquad (2.16)$$

where ΔS is the area of a face of the cylinder, ρ_s is the surface charge density per unit area, and E_{n1} and E_{n2} are the components of the electric field normal to the boundary in materials 1 and 2 respectively. Dividing out the ΔS and assuming a time harmonic field yields

$$\sigma_1 E_{n1} - \sigma_2 E_{n2} = -j\omega \rho_s \qquad (2.17)$$

From equation (2.12) and assuming that the electrical permittivity is uniform and isotropic in each material

$$\varepsilon_1 E_{n1} - \varepsilon_2 E_{n2} = \rho_s \qquad (2.18)$$

Substituting in equation (2.17) gives

$$(\sigma_1 + j\omega\varepsilon_1) E_{n1} = (\sigma_2 + j\omega\varepsilon_2) E_{n2} \qquad (2.19)$$

Recall that for the quasistatic approximation to hold $\sigma/\omega\varepsilon$ must be much greater then one. Thus, when using the quasistatic approximation the normal component of current is continuous across a boundary between two materials of finite electrical conductivity.

Treating the problem as quasistatic and assuming there are no double layers of charge at the interface, the electric potential must be continuous across the boundary. Thus the boundary conditions used are

$$\sigma_1 E_{n1} = \sigma_2 E_{n2} \qquad (2.20)$$

$$\psi_1 = \psi_2 \qquad (2.21)$$

In this discussion of the boundary between two materials of finite conductivity it was assumed that the conductivity was discontinuous at the boundary. In an actual oil sand formation the conductivity may change continuously between the oil sand and the overburden or underburden. The electric fields calculated assuming either a sharp, discontinuous boundary, or assuming a continuous transition

over a short distance will be the same except in the transition region. As no data is available describing how the conductivity changes from the oil sand to the surrounding formations, and as the transition distance is likely small compared to the formation thickness, it is assumed that a sharp, discontinuous change in conductivity occurs at the boundary.

2.2 Heat Generation and Tranfer

The instantaneous heating rate due to electrical conduction is given by

$$\dot{Q} = \sigma \bar{E} \cdot \bar{E} \qquad (2.22)$$

If, when using the quasi-static approximation, the r.m.s. values of the applied voltages are used, then the average heating rate is

$$\dot{Q}_{AV} = \sigma |\bar{E}_{rms}|^2 \qquad (2.23)$$

Of the three major heat transfer mechanisms (radiation, convection, and conduction) only conduction is included in the mathematical model. Radiation is negligible as the radiation from a black body at reservoir temperatures would only penetrate a very short distance into the oil sand. Natural convection due to temperature gradiants is neglected even though its importance as a heat transfer mechanism in oil sand at the temperatures of interest is unclear. The scale modeling factors developed by Vermeulen et. al.[7]

included only conduction in their derivation. By comparing the results of numerical simulations based on this premise with the results of physical scale model runs some grasp on the accuracy of this mathematical model may be obtained. The treatment of forced convection due to fluid injection or pumping is beyond the scope of this study.

Thus, the equation used to model the heat generation and transfer is

$$M\frac{\partial T}{\partial t} = \nabla\cdot(k_h \nabla T) + \sigma|\bar{E}_{rms}|^2 \qquad (2.24)$$

where M is the volumetric heat capacity, K_h is the thermal conductivity, and T is the temperature in Celsius. Note that in the computer program the volumetric heat capacity and thermal conductivity are assumed constant within each formation.

The outer boundaries are assumed to be insulated, no-heat-flow boundaries. If the boundaries are planes of symmetry or actual insulated boundaries this is a good model. However, if the problem to be modeled consists of an oil sand formation surrounded above and below by formations which are much thicker then the oil sand formation (i.e. semi-infinite overburden and underburden) artificial boundaries will have to be introduced to limit the extent of the problem domain. If these boundaries are far enough from the electrodes little current or heat will reach the area near these artificial boundaries.

Different materials in the problem domain may have

different thermal properties. At the boundary between two different materials the temperature and heat flow across the boundary are assumed to be continuous.

3. Numerical Solution of the Model

Finite difference techniques are used to approximate the solution of partial differencial equations in many different fields, including oil reservoir simulation, laser-plasma interaction studies, and water flow problems. Finite difference approximations to derivatives were used by L. Euler (1768) and there are currently several textbooks available which explain the finite difference method in detail.[19] [20] [21] The error, stability and convergence of the approximation and solution techniques are areas of concern and study when using this method to solve partial differential equations. In this chapter the particular methods used in developing MEGAERA are outlined, and an explanation of how boundary conditions, stability and convergence problems were delt with is given.

3.1 Differencing of the Current Continuity Equation

The electrical current continuity equation (equation 2.10) may be rewritten (for two dimensions) as

$$\frac{\partial}{\partial x}\left(\sigma \frac{\partial \varphi}{\partial x}\right) + \frac{\partial}{\partial y}\left(\sigma \frac{\partial \varphi}{\partial y}\right) = 0 \qquad (3.1)$$

The finite difference approximation for the first term of equation (3.1) is given by

$$\frac{\partial}{\partial x}\left(\sigma \frac{\partial \varphi}{\partial x}\right) \cong$$
$$\left(\frac{2}{h_i + h_{i-1}}\right)\left[\left(\frac{\sigma_{i-1} + \sigma_i}{2}\right)\left(\frac{\varphi_{i-1} - \varphi_i}{h_i}\right) - \left(\frac{\sigma_{i-1} + \sigma_i}{2}\right)\left(\frac{\varphi_i - \varphi_{i-1}}{h_{i-1}}\right)\right] \qquad (3.2)$$

See figure 3.1 for details on the grid structuring and labeling.

This approximation (equation 3.2) is "conservative" in that the current flowing out of the left boundary of the grid block (i,j) is equal to the current flowing into the right boundary of the grid block (i+1,j). A symmetric approximation for the second (y direction) term of equation (3.1) is added to equation (3.2) to give an algebraic difference equation at the center of each grid block. Rearranging the terms gives

$$R_{ij}\,\psi_{i,j+1} + S_{ij}\,\psi_{i+1,j} + A_{ij}\,\psi_{ij} + C_{ij}\,\psi_{i-1,j} + F_{ij}\,\psi_{i,j-1} = 0 \qquad (3.3)$$

where

$$R_{ij} = (\sigma_{i,j+1} + \sigma_{ij})/[k_j(k_j + k_{j-1})] \qquad (3.4)$$

$$S_{ij} = (\sigma_{i+1,j} + \sigma_{ij})/[h_i(h_i + h_{i-1})] \qquad (3.5)$$

$$A_{ij} = -R_{ij} - S_{ij} - C_{ij} - F_{ij} \qquad (3.6)$$

$$C_{ij} = (\sigma_{i-1,j} + \sigma_{ij})/[h_{i-1}(h_i + h_{i-1})] \qquad (3.7)$$

$$F_{ij} = (\sigma_{i,j-1} + \sigma_{ij})/[k_{j-1}(k_j + k_{j-1})] \qquad (3.8)$$

The presence of a boundary adjacent to the grid block requires the modification of equations (3.3) to (3.8). If an insulator is in the (i-1,j) grid block, then the boundary condition in the left direction is $\frac{\partial \psi}{\partial n} = 0$. This is

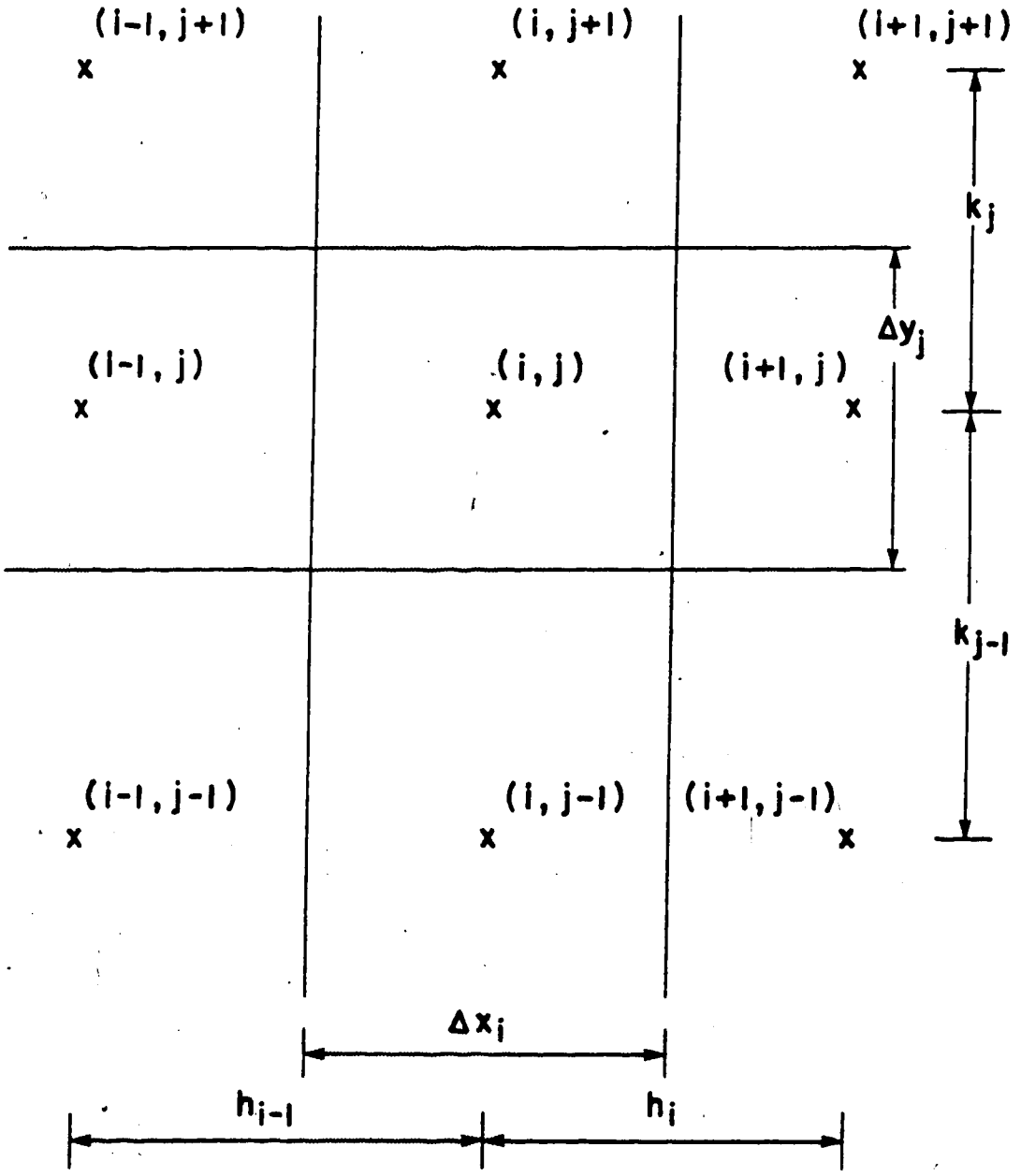


Figure 3.1 Finite difference grid used in MEGAERA showing the locations at which potential, temperature and conductivities are computed.

approximated by setting $\psi_{i-1,j}$ equal to $\psi_{i,j}$. Equation (3.3) becomes

$$R_{ij}\,\psi_{i,j+1} + S_{ij}\,\psi_{i-1,j} + (A_{ij} + C_{ij})\,\psi_{i,j} + F_{ij}\,\psi_{i,j-1} = 0 \qquad (3.9)$$

If the (i-1,j) grid block is part of an electrode then $\psi_{i-1,j}$ is known. The coefficent of $\psi_{i-1,j}$ must be modified to take into account the infinite conductivity of the electrode (which extends up to the grid block boundary). Thus, the difference equations are

$$C'_{ij} = \sigma_{ij}/[\Delta x_i (h_i + h_{i-1})] \qquad (3.10)$$

$$A'_{ij} = -R_{ij} - S_{ij} - C'_{ij} - F_{ij} \qquad (3.11)$$

$$R_{ij}\,\psi_{i,j+1} + S_{ij}\,\psi_{i-1,j} + A'_{ij}\,\psi_{ij} + F_{ij}\,\psi_{i,j-1} = -C'_{ij}\,\psi_{i-1,j} \qquad (3.12)$$

When a medium of different conductivity is in the (i-1,j) grid block the equations (3.3) to (3.8) must be modified to deal explicitly with the conductivity transition. Equations (2.20) and (2.21) give the boundary conditions at the interface. If the electric field is constant between the center of the grid block and the interface, the continuity condition for the electrical potential (Equ. 2.21) yields

$$(\psi_{ij} - \psi_{i-1,j}) = \frac{\partial \psi_{ij}}{\partial x}\left(\frac{\Delta x_i}{2}\right) + \frac{\partial \psi_{i-1,j}}{\partial x}\left(\frac{\Delta x_{i-1}}{2}\right) \qquad (3.13)$$

Figure (3.2) shows a profile of ψ vs X between the grid block centers. Writing equation (2.20) as

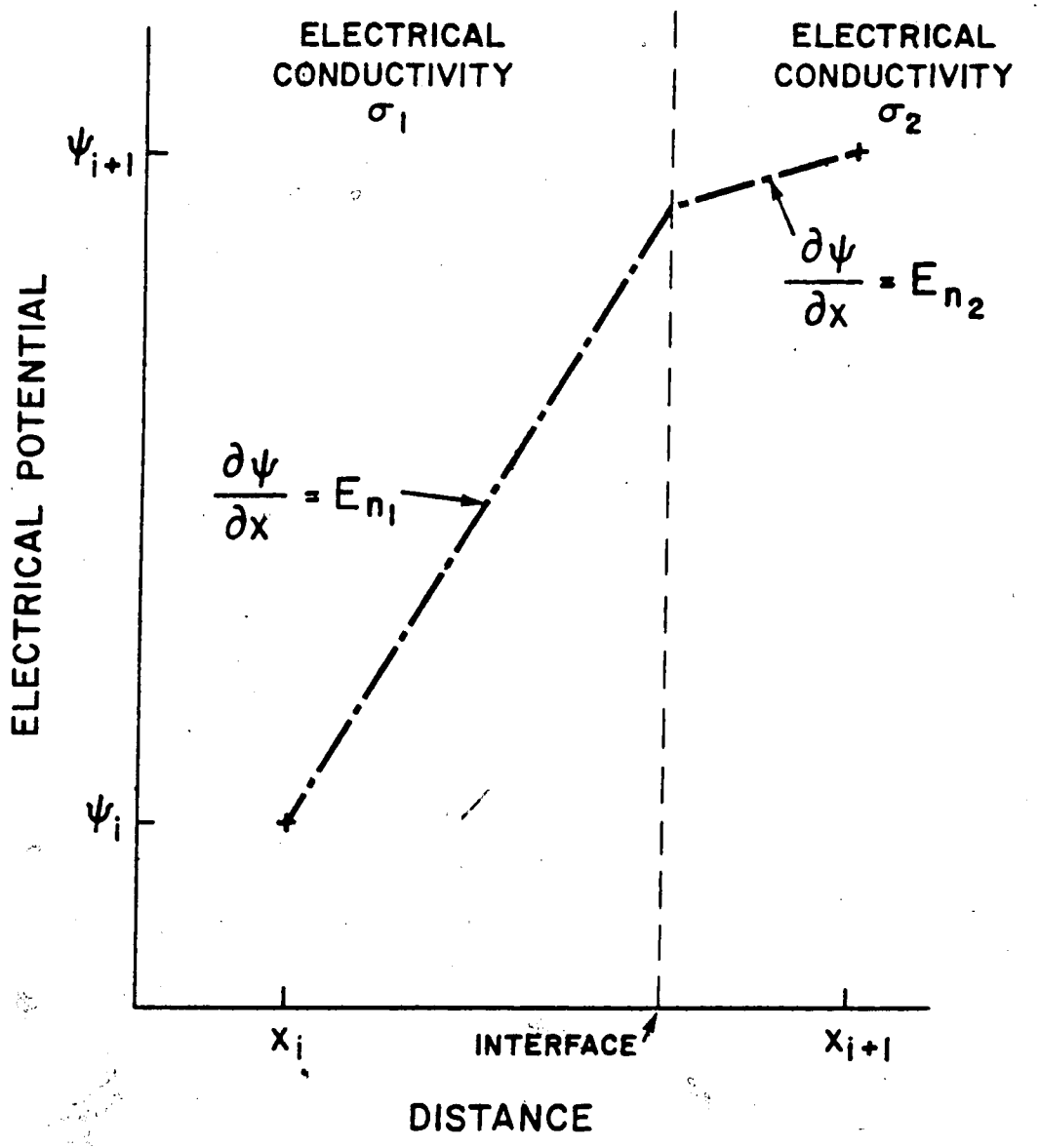


Figure 3.2 Profile of Electrical Potential ψ Across an Conductivity Discontinuity, showing the abrupt change in normal component of the electric field as required for continuity of the normal component of current

$$\sigma_{i,j}\frac{\partial \psi_{i,j}}{\partial x} = \sigma_{i-1,j}\frac{\partial \psi_{i-1,j}}{\partial x} \qquad (3.14)$$

the derivative $\frac{\partial \psi_{i-1,j}}{\partial x}$ in (3.13) may be eliminated.

$$\frac{\partial \psi_{i,j}}{\partial x} = (\psi_{i,j} - \psi_{i-1,j})/\left[\frac{\Delta x_i}{2} + \left(\frac{\sigma_{i,j}}{\sigma_{i-1,j}}\right)\frac{\Delta x_{i-1}}{2}\right] \qquad (3.15)$$

Thus, the coefficents $C_{i,j}$ and $A_{i,j}$ in the finite difference equation (3.3) become

$$C''_{i,j} = 4\sigma_{i,j}/\left[(h_i + h_{i-1})\left(\Delta x_i + \frac{\sigma_{i,j}}{\sigma_{i-1,j}}\Delta x_{i-1,j}\right)\right] \qquad (3.16)$$

$$A''_{i,j} = -R_{i,j} - S_{i,j} - C''_{i,j} - F_{i,j} \qquad (3.17)$$

3.2. Differencing the Thermal Equation

The thermal partial differential equation (2.24) is in many respects analogous to the electrical current continuity equation (2.10). The differencing of the term

$$\frac{\partial}{\partial x}\left(k_h \frac{\partial T}{\partial x}\right) \cong$$

$$\frac{2}{(h_i + h_{i-1})}\left[\left(\frac{k_{h_{i,j}} + k_{h_{i-1,j}}}{2}\right)\left(\frac{T_{i-1,j} - T_{i,j}}{h_i}\right) - \left(\frac{k_{h_{i-1,j}} + k_{h_{i,j}}}{2}\right)\left(\frac{T_{i,j} - T_{i-1,j}}{h_{i-1}}\right)\right] \qquad (3.18)$$

is directly analogous to the differencing of the x term in equation (2.10). The handling of the boundary conditions is also analogous, with constant temperature boundaries corresponding to electrodes and thermal insulators corresponding to electrical insulators.

The time derivative of the thermal equation is approximated by the forward difference

$$M \frac{\partial T}{\partial t} \cong M_{ij} (T_{ij}^{n+1} - T_{ij}^{n}) / \Delta t^{n} \qquad (3.19)$$

where the superscript indicates the number of the timestep. The heating rate term is also calculated and included in the complete difference equation.

3.3 Solution of the Difference Equations

In solving a set of partial differential equations by the finite difference technique it is desirable to reduce the set of equations by eliminating all but one unknown (one unknown being a single variable unknown at all points in the domain). This may be done before or after differencing the equations. In the electrical heating simulation presented in this thesis, the electrical and thermal equations are coupled non-linearly making the elimination of either the potential or the temperature difficult. For this reason the equations were coupled explicitly: first the electric field was found, then the new temperatures were found. This explicit coupling leads to convergence problems which are discussed in the section on program testing.

The procedure followed by MEGAERA for each time step is as follows:

1. The electrical conductivity of each grid block is updated from the temperature of the grid block at the end of the last time step.
2. The coefficents of the electrical difference equation are found for each grid block.

3. This set of electrical difference equations is simultaneous. With one equation per grid block, a matrix of 2500 rows and columns is formed by MEGAERA if the full fifty by fifty grid is used. This matrix is solved by the Alternating Direction Implicit Procedure. This is an iterative relaxation method, which requires an initial guess at the solution. As the potential does not vary greatly from time step to time step, the potential found in the lasf time step is used as the initial guess for the potential of this time step and the new potential is found after only a few iterations.
4. With the potential now known, the volumetric heating rate in each grid block is found. MEGAERA calculates the heating rate directly from the potential and cannot output the electric field. The total current passing through the formation between the electrodes is calculated. If constant current or constant power heating is requested, the heating rates are scaled appropriately.
5. The temperatures at the end of the time step are found by solving the thermal equation using the Alternating Direction Implicit method. Despite the similarity of the names, the ADI method is different then the Alternating Direction Implicit Procedure, the former being used for parabolic equations and the latter for elliptic equations.
6. An energy balance is done for the time step. The energy

input, both for the time step and cumulative, is calculated in three different ways, as will be discussed in section 3.4.1. The energy calculations are done for each region of the domain separately, allowing one to find the percentage of energy input to, for example, the overburden and comparing it to the energy input to the oil sand.

MEGAERA was written to allow variable grid widths. The ratio of maximum width to minimum width should not excede ten in the domain of the problem, with adjacent grid widths being within a factor of two. The program is only two dimensional and the maximum number of grid blocks in each the X and Y directions is fifty. MEGAERA was written in single precision, which on the Amdahl 470 is 32 bit, hexidecimal format floating point arithmetic. Using the full fifty by fifty grid, MEGAERA uses approximately 1.9 seconds of C.P.U. time per time step on an Amdahl 470V/7, and requires about 110 pages of virtual memory. Thus, a typical eighty time step run will require about two and a half minutes of C.P.U. time.

3.4 Testing of MEGAERA

A large simulation code may be tested in several ways. Internal checks, such as energy balance calculations, give one indication of the accuracy of the program. Analytic solution of simple problems may be possible, and the results of simulating these problems may be compared to the analytic

solution. Physical modeling of more complex problems may be possible and numerical simulation results may be compared to physical model results. Finally, one may check that alteration of the problem grid and scale do not significantly affect the results produced by the simulator. All of these methods were used to test M[illegible]RA.

3.4.1 Energy Balance

The cumulative electrical energy input at the electrodes is found from

$$E_E^n = E_E^{n-1} + V^n I^n \Delta t^n \qquad (3.20)$$

where E_E^n denotes the total electrical energy input up till the end of the nth time step, V^n and I^n are the voltage and current respectively during the nth time step, and Δt^n indicates the length in seconds of the nth time step.

The cumulative electrical energy that is converted to heat is found by integrating the volumetric heating rate over the volume and time:

$$E_H^n = E_H^{n-1} + \sum_{ij} \dot{Q}_{AV_{i,j}}^n V_{i,j} \Delta t^n \qquad (3.21)$$

where E_H^n is the cumulative energy converted to heat at the end of the nth time step, $V_{i,j}$ is the volume of (i,j) grid block and $Q_{AV_{i,j}}^n$ is the volumetric heating rate in the grid block during the nth time step.

The total heat energy stored in the temperature rise of the formation is found by summing the product of temperature

rise, volumetric heat capacity and volume of each grid block:

$$E_T^n = \sum_{ij} (T_{ij}^n - T_o) M_{ij} v_{ij} \qquad (3.22)$$

All three calculations of the energy input to the formation should yield the same quantitative result. The computer program calculated E_E, E_H, and E_T for each timestep that was output. Comparing E_E and E_H, the differences between both the cumulative and the incremental values of these quantities were under one percent for all production runs of MEGAERA. The differences were greatest for the first time step, usually about .5 to .7 percent, and decrease as the run progressed. By the eightyth time step both cumulative and incremental differences were below one quarter percent. The difference between E_H and E_T was usually less than 0.1 percent. These figures are taken from production runs (Run No.s 10 - 20), where the electrical conductivity varied from one region to the next by up to a factor of ten.

3.4.2 Comparison with Analytic Results

A number of MEGAERA runs were done for simple one dimensional problems whose solutions could be found analytically. Initially the temperature dependence of electrical conductivity was set equal to zero, uncoupling the electrical equations from the thermal equation. The problem geometry consisted of two materials of different

conductivity in series. The results showed that the potential solver, constant current or power scaling, heating rate calculator, and temperature solver were working properly, at least for one dimensional problems. In these tests the calculated values agreed with the analytic solutions to within .1 percent. The problems were solved using grids of varying grid width and differing overall scale (i.e. maximum dimensions).

It is also possible to analytically solve a one dimensional problem involving electrical conductivity which varies with temperature. If a rectangle of homogeneous material is placed between two parallel plates (and the remaining four sides are insulated) and a constant voltage is applied between the plates, the electric field will remain constant between the plates. As the conductivity rises with temperature so will the heating rate. The temperature at any time may be found by solving the integral equation

$$T = \frac{V^2 \sigma_{ref}}{M d^2} \int_0^t [1 + \alpha (T - 24)]\, dt + T_0 \qquad (3.23)$$

where d is the distance between the plates, and V is the applied voltage (r.m.s. value). This integral equation may be solved by use of a Laplace transform. The solution is[22 23]

$$T(t) = \left[\frac{1}{\alpha} + (T_0 - 24)\right] \exp\left(\frac{V^2 \sigma_{ref} \alpha}{M d^2} t\right) + 24 - \frac{1}{\alpha} \qquad (3.24)$$

Runs was carried out modeling this problem. When the maximum

allowed temperature change per timestep was three percent, the difference between the computer solution and the analytic solution was one half of one percent after a temperature rise of 230°C. If the maximum allowed temperature change per timestep was increased to ten percent, this difference, after a similar temperature rise, was five percent. The former case required roughly three times the C.P.U. usage of the latter case.

The difference between the analytic solution and the computed temperatures is due to the explicit coupling of the electrical and thermal equations. The electrical field and heating rates are held fixed in a time step, resulting in a conservative approximation to the actual heating. As the conductivity increases with temperature, the calculated heating rate will always be less then its actual value. The error induced by this problem is negligible if the maximum allowed temperature change per timestep is five percent or less.

3.4.3 Comparison with Physical Models

MEGAERA was used to simulate a physical model run which was carried out by J. Fearn and A. Vogan of the Applied Electromagnetics group at the University of Alberta. The geometry of the physical model was a scaled down version of figure 4.2. The model consisted of eighteen inches (457 mm) of underlying sand covered by seven and three quarters inches (197 mm) of low conductivity oil sand, which in turn

is covered by six inches (152 mm) of overburden sand. The spacing between the electrodes was thirteen inches (330 mm) and the third dimension of the model, i.e. the thickness of the two-dimensional slice, was four inches (102 mm). The electrodes were constructed of one quarter inch (6 mm) copper plate and were two inches (51 mm) high and their lengthes were equal to the thickness of the two-dimensional slice, i.e. four inches (102 mm). The electrodes were positioned so the right electrode was forty percent in the overburden sand and the left electrode was forty percent in the underlying sand, the remainder of each electrode being in the oil sand.

The underlying and overburden formations in the scale model were modeled using packed sand whose moisture content had been adjusted so the conductivity of the packed sand (density of 1.8 gm/cm^3) was 7.4 X 10^{-3} S/m. The oil sand was modeled with oil sand whose conductivity when packed (density of 2.0 gm/cm^3) was 2.0 X 10^{-3} S/m.

The scale model was heated by passing a constant current of .183 A between the electrodes for 3605 seconds. The initial temperature of the model was 22°C (±.8°). After the run was completed the thermal properties of the sand and oil sand used in the model were measured. The thermal conductivity of the underlying and overlying sand was 1.56 W/K-m and its volumetric heat capacity was 1.37 X 10^6 J/K-m^3. The thermal conductivity of the oil sand was 1.61 W/K-m and its volumetric heat capacity was 1.8 X 10^6 J/K-m^3.

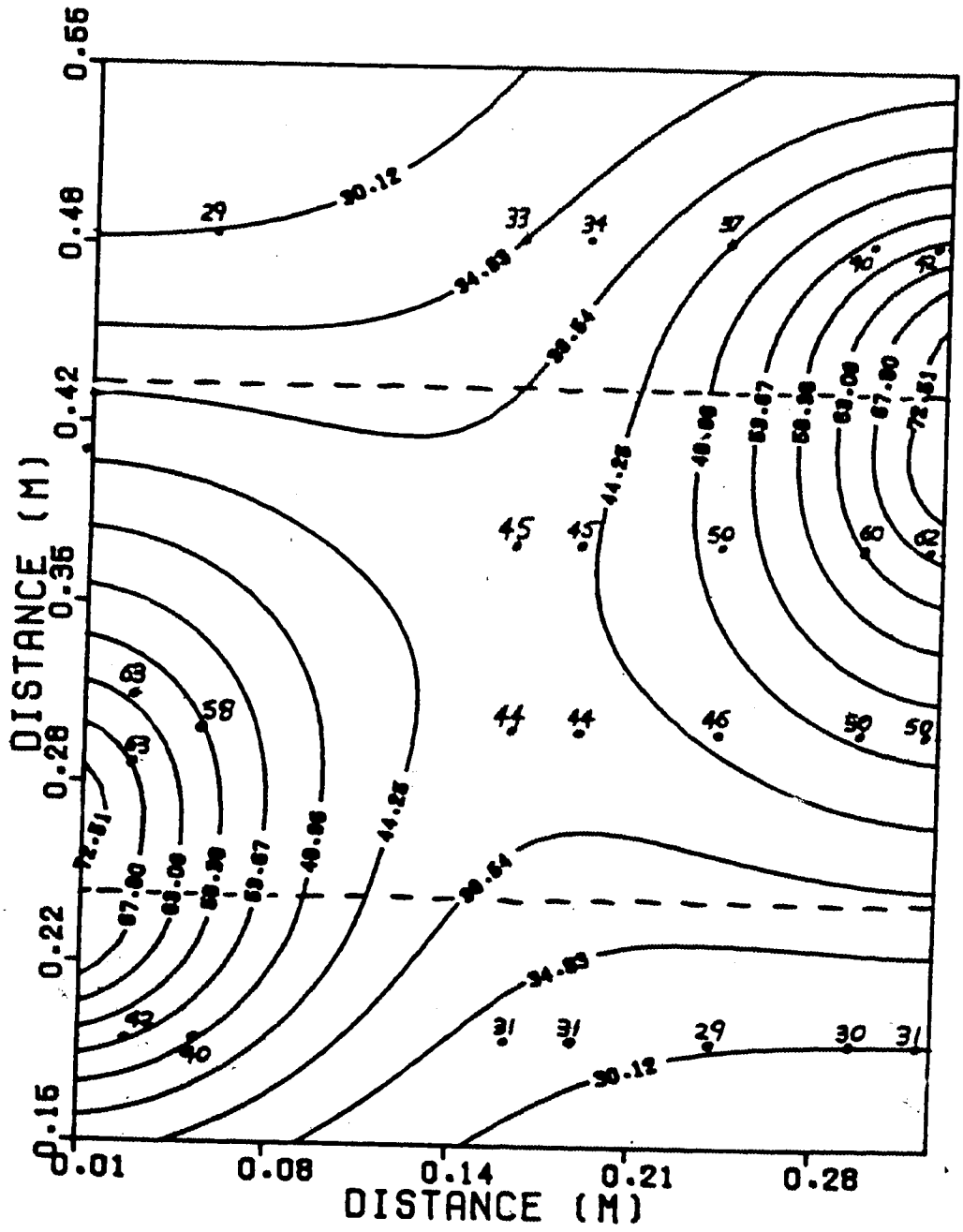


Figure 3.3 Computer calculated and measured temperatures for the physical model run. The contour plots are computer generated and the measured values are written on top.

The simulation was carried out with the thermal conducitity of the electrodes initially set to that of oil sand, and secondly to a value ten times greater. This change caused only a slight change in the final temperature profile in the immediate vicinity of the electrodes.

The geometry, dimensions, sand and oil sand electrical and thermal properties, and the heating type and time were input to MEGAERA. The temperature dependence of electrical conductivity was not measured, but was assumed to be 0.0229 K^{-1}, which is a typical value at low frequencies[7]. A contour plot of the simulation results is given in figure 3.4 with the measured temperatures from the physical model noted where measured. Agreement between the simulation results and the physical model results is excellent, except in the immediate vicinity of the electrodes. The measured and computed resistances were also compared and the percent difference between the two was always less then two percent.

4. Results of MEGAERA Simulation Runs

There are a large number of variables which affect the electrical heating of an oil sand formation. These include the electrical and thermal properties of the oil sand and surrounding formations, the length and thickness of the electrodes, the spacing between electrodes, the thickness of the oil sand, and the rate of heating. In studying the effects of varying one of these variables the other variables must be held fixed.

The initial studies done with MEGAERA were on the effects of different ratios of electrical conductivity of oil sand to that of the surrounding formations, and on the effect of changing the spacing between the electrodes.

4.1 Effects of the Electrical Conductivity Ratio

The author has conducted a series of runs of MEGAERA in which the physical dimensions, thermal properties and heating rates were held fixed, but the electrical conductivities of the oil sand and surrounding formations were varied. The purpose of the series of runs was to determine which of two electrode configurations produces the most favourable temperature distribution for a given ratio between the electrical conductivity of the oil sand and that of the surrounding formations. The problem geometries, labeled configuration A and B, are shown in figures 4.1 and 4.2. In all runs constant power heating of eight kilowatts

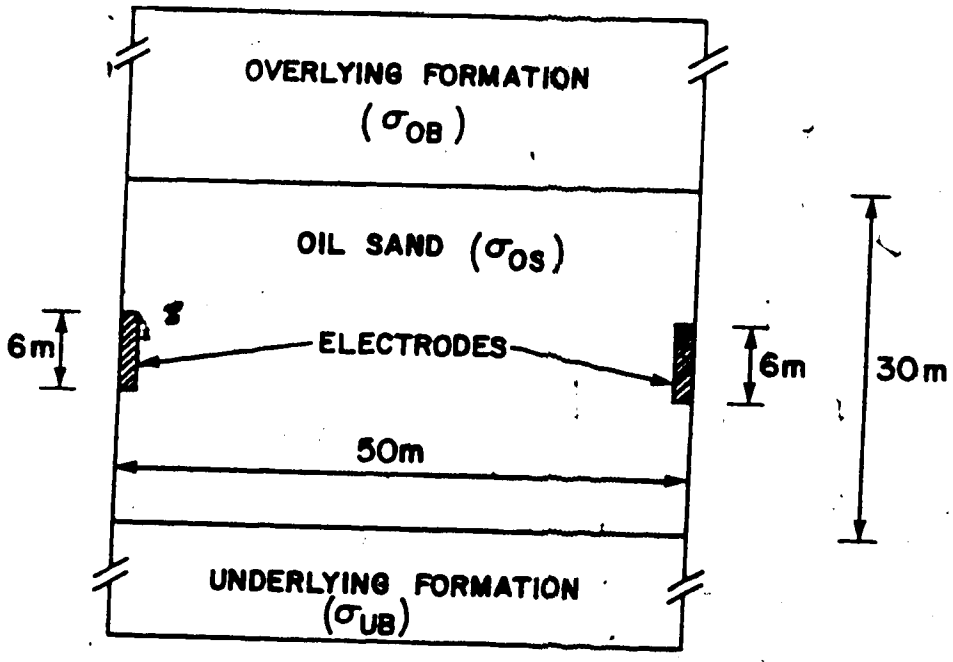


Figure 4.1 Heating Configuration A.

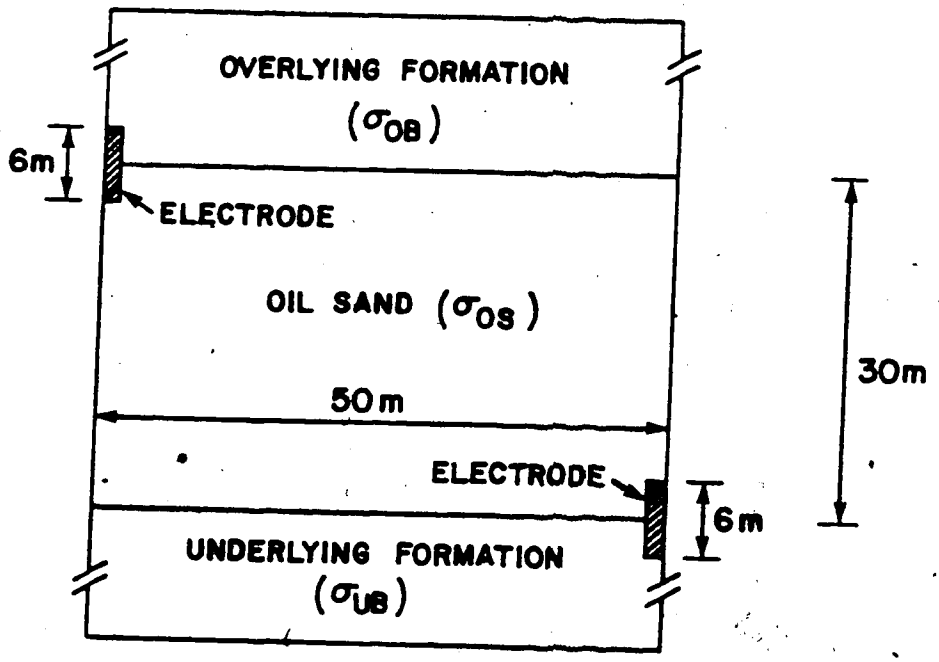


Figure 4.2 Heating Configuration B. The thicknesses of these two dimensional geometries are set to one meter for resistance and power calculations.

per meter length of the parallel plate electrodes was applied for a period of one year. Thus, all the runs had the same heating rate regardless of the actual resistance between the electrodes. The results of this series of runs are summarized in Table 4.1 and the temperature plots at the end of the heating period are given in Figures 4.3 to 4.9.

In configuration A (i.e. the electrodes positioned in the middle of the oil sand formation) the maximum temperature, which occurs near the electrodes, increases linearly with the ratio of the electrical conductivities of the surrounding formations to that of the oil sand. (This ratio, electrical conductivity of overburden and underburden to electrical conductivity of oil sand, shall hereafter be refered to as the conductivity ratio.) The temperature in the formation mid way between the electrodes dropped as the conductivity ratio increased. Configuration B had the opposite trend with the electrode temperature dropping and the mid formation temperature rising with increased conductivity ratio. For conductivity ratios greater than two configuration B had a more desirable temperature profile than configuration A. A graph of temperature vs. conductivity ratio is given in figure 4.10.

When the fraction of the total energy input that is retained in the oil sand formation is computed, configuration A is superior to configuration B even with the conductivity ratio as high as five. With a conductivity ratio of one half, configuration A heating will retain about

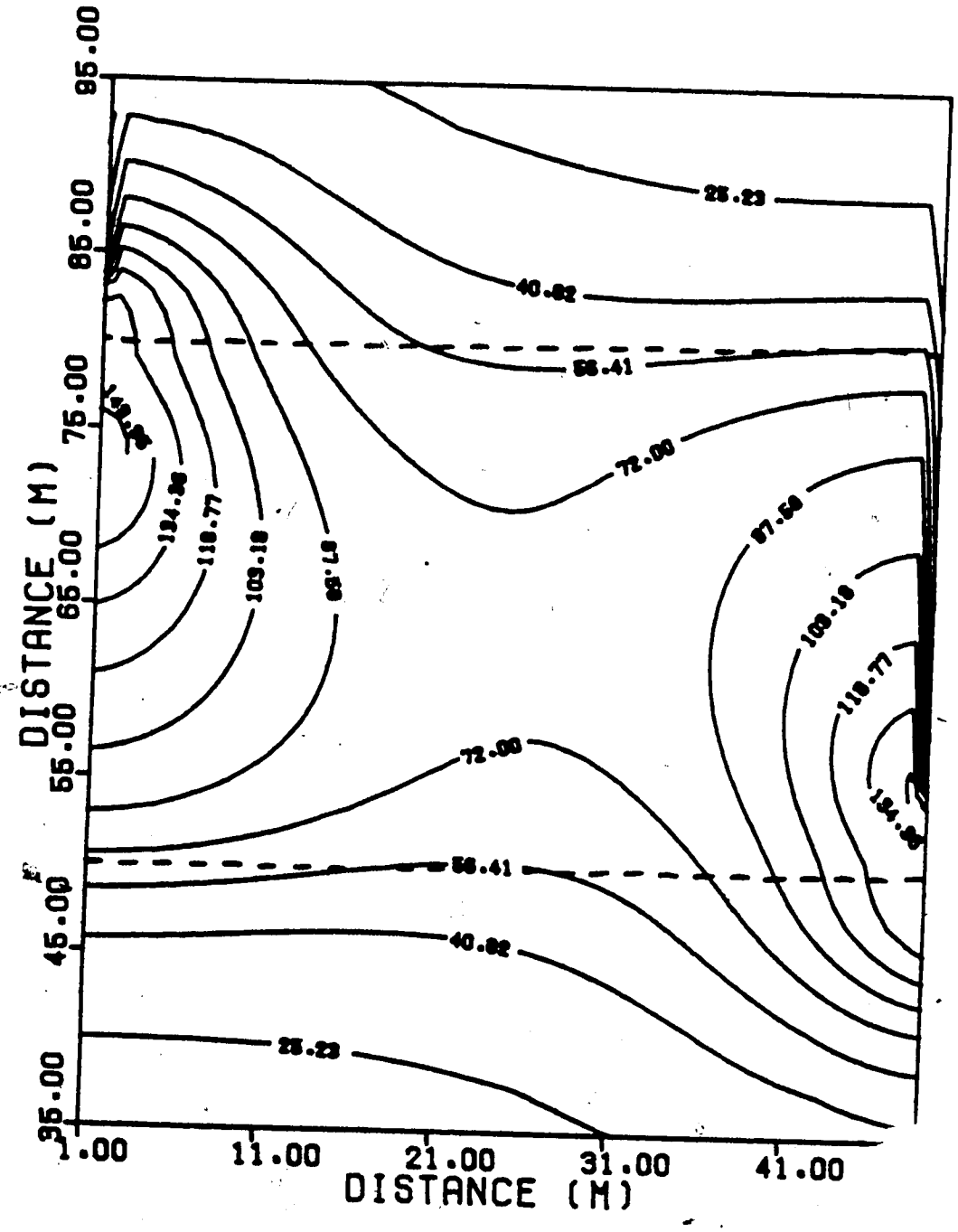


Figure 4.3 Contour plot of temperature in Celsius after one year of heating at 8 kW/m. Run no. 10, configuration B, with an electrical conductivity ratio (overburden, underburden/ oil sand) of 10.

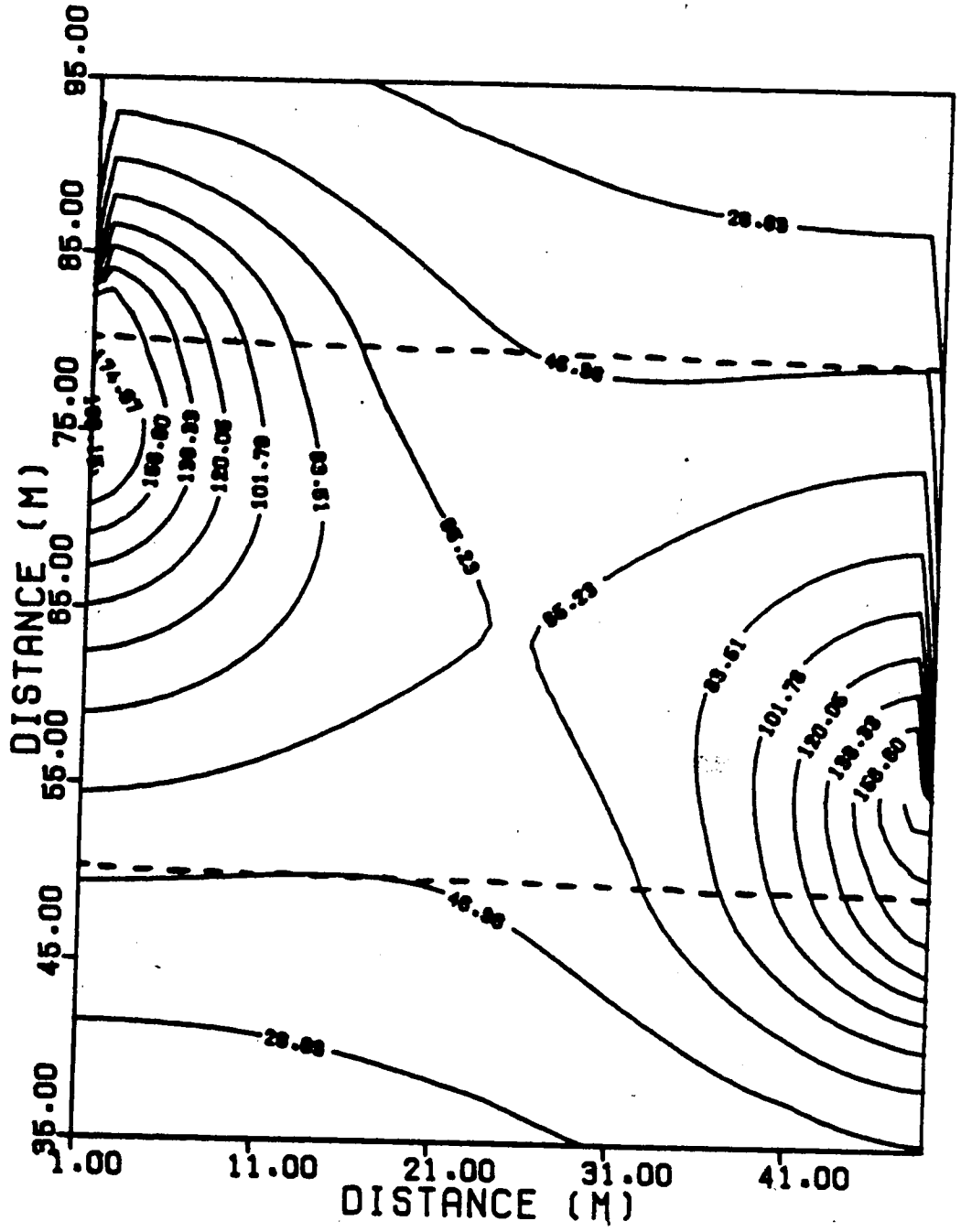


Figure 4.4 Contour plot of temperature in Celsius after one year of heating at 8 kW/m. Run no. 12, configuration B, with an electrical conductivity ratio (overburden, underburden/ oil sand) of 2.

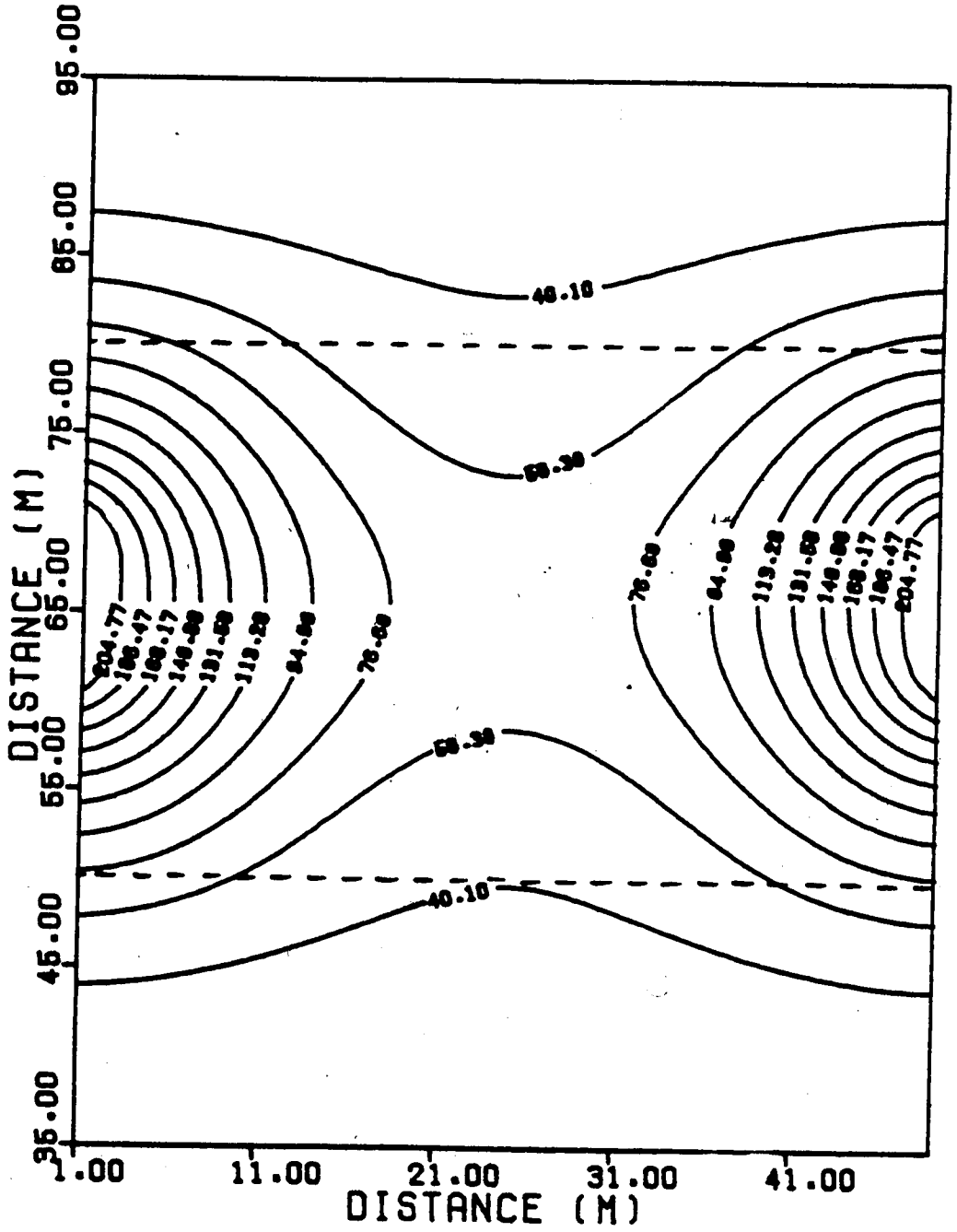


Figure 4.5 Contour plot of temperature in Celsius after one year of heating at 8 kW/m. Run no. 18, configuration A, with an electrical conductivity ratio (overburden, underburden/ oil sand) of 2.

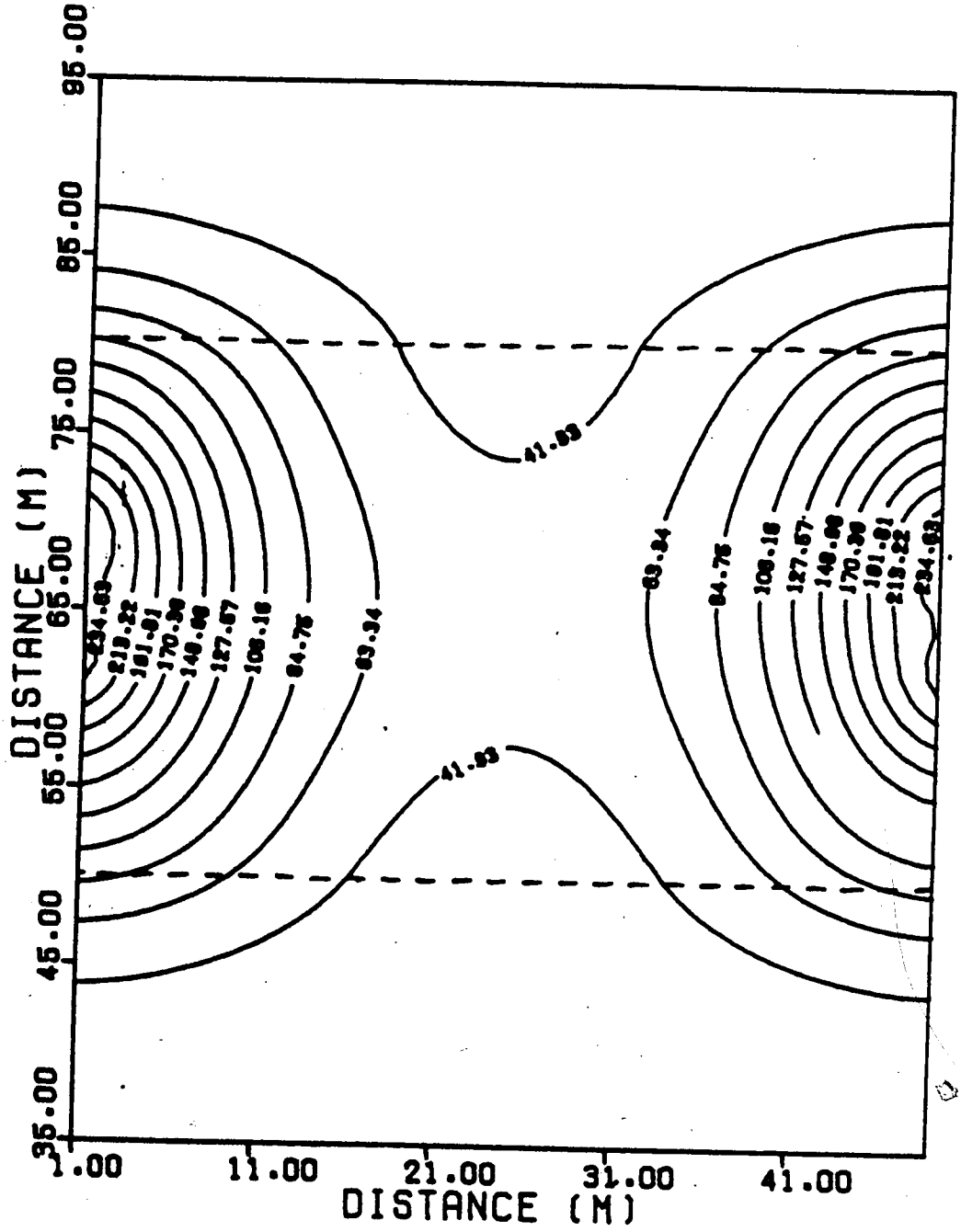


Figure 4.6 Contour plot of temperature in Celsius after one year of heating at 8 kW/m. Run no. 19, configuration A, with an electrical conductivity ratio (overburden, underburden/ oil sand) of 5.

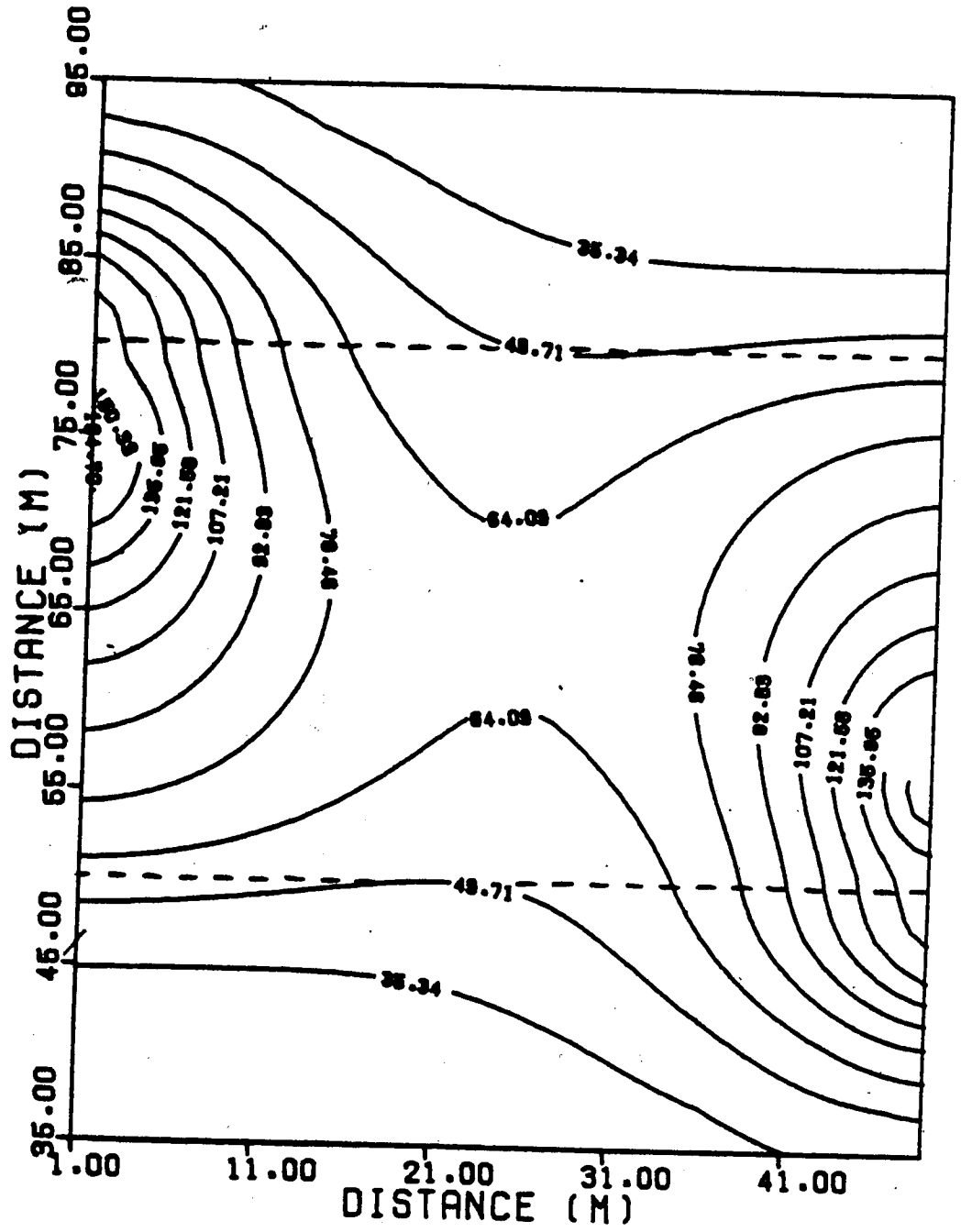


Figure 4.7 Contour plot of temperature in Celsius after one year of heating at 8 kW/m. Run no. 20, configuration B, with an electrical conductivity ratio (overburden, underburden/ oil sand) of 5.

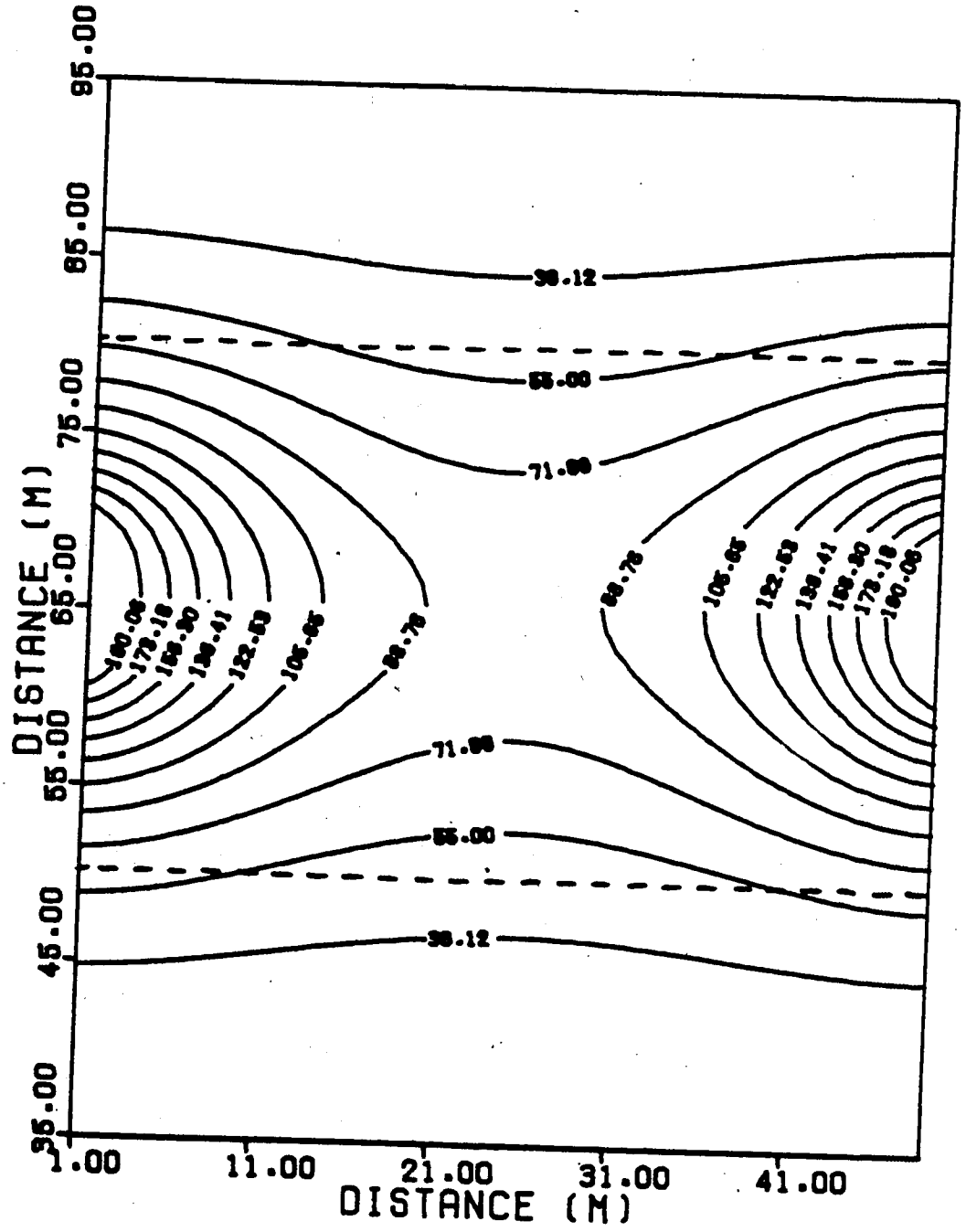


Figure 4.8 Contour plot of temperature in Celsius after one year of heating at 8 kW/m. Run no. 21, configuration A, with an electrical conductivity ratio (overburden, underburden/ oil sand) of 1.

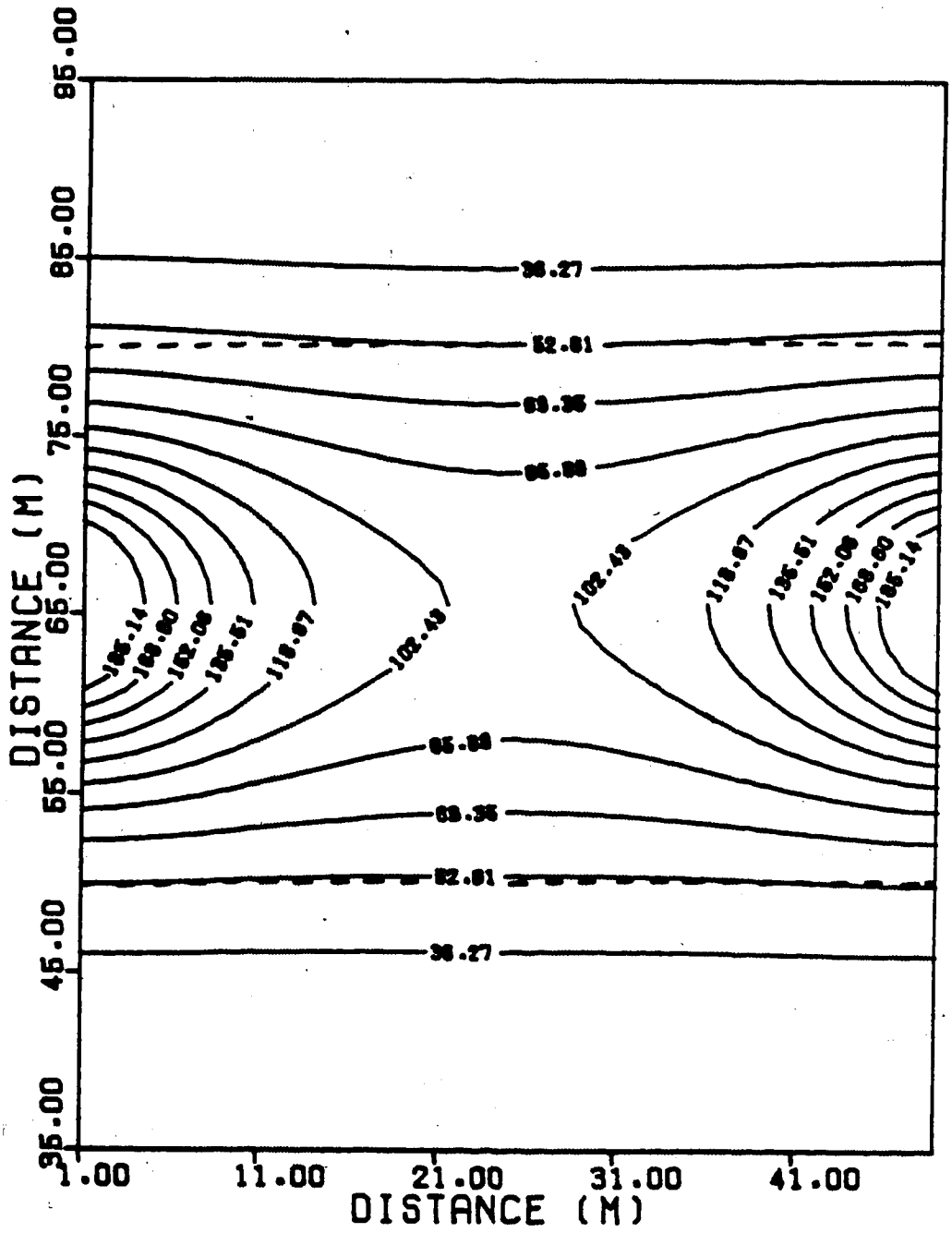


Figure 4.9 Contour plot of temperature in Celsius after one year of heating at 8 kW/m. Run no. 22, configuration A, with an electrical conductivity ratio (overburden, underburden/ oil sand) of .5

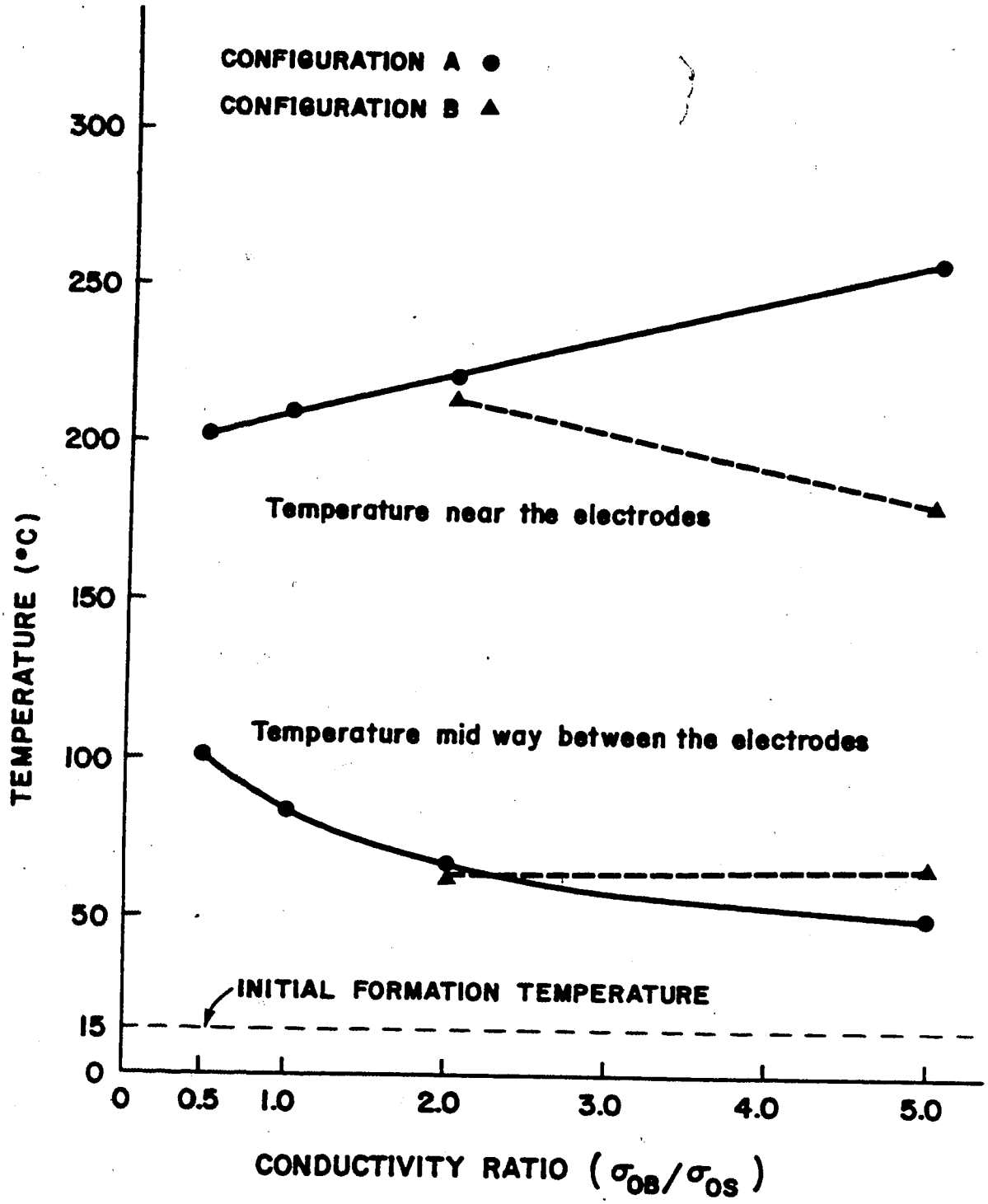


Figure 4.10 Temperature vs. the ratio of the electrical conductivities of the surrounding formations to that of the oil sand.

Table 4.1 Temperature rise and thermal efficency as a function of the relative conductivity of the oil sand and surrounding formations.

The conductivity of the oil sand is 1.0 X 10^{-3} S/m for all runs. Constant power heating of 8 kW per meter was applied for one year. Initial reservoir temperature is 15°C.

1. Run No.	2. Config-uration	3. $\sigma_{o/s}$ S/m x10^{-3}	4. $\sigma_{u/s}$ S/m x10^{-3}	5. Max. Temp. °C	6. Mid Temp. °C	7. Heating in Oil Sand %	8. Energy in Oil Sand %
22	A	0.5	0.5	202	101	88	81
21	A	1.0	1.0	210	85	84	78
18	A	2.0	2.0	220	67	81	75
12	B	2.0	2.0	212	65	65	62
19	A	5.0	5.0	257	50	84	75
20	B	5.0	5.0	180	66	68	65
10	B	10.	10.	177	75	74	69

1. Runs were numbered in chronological order.
2. Dimensions and electrode positions are given in figures 4.1 and 4.2.
3. Conductivity of overlying formation.
4. Conductivity of underlying formation.
5. Maximum temperature near the electrodes.
6. Maximum temperature mid way between the electrodes.
7. Electrical energy dissipated in the oil sand formation as a percentage of the total energy dissipated in the oil sand and surrounding formations.
8. The energy stored in the oil sand formation at the end of one year, as a percentage of the total energy input. The difference between columns 7 and 8 is due to thermal conduction.

eighty percent of the energy in the oil sand after heating for one year. When the conductivity ratio is increased to five, configuration A will retain three quarters of the energy in the oil sand formation, while heating with configuration B will result in only sixty five percent of the energy remaining in the oil sand at the end of the year. In both configurations most of the energy is lost by current passing through (and thus heating) the overlying and underlying formations. Thermal conduction typically accounts for the loss of five to ten percent of the total energy input, or ten to forty percent of the total energy lost to the surrounding formations.

When heating in configuration A, the conductivity ratio determines what fraction of the current enters the surrounding formations. As the conductivity ratio increases more of the current travels most of the distance between the electrodes in the overlying or underlying formations, where relatively low resistance is encountered. As a result the bulk of the voltage drop and the heating is in the oil sand near the electrodes, where the current is travelling from the electrode almost directly into the surrounding formations. This leads to a higher electrode temperature and a lower temperature midway between the electrodes. When heating in configuration B, a high conductivity ratio results in the overlying and underlying formations acting like large extended electrodes. Most of the voltage drop is across the oil sand formation from the overlying formation

to the underlying formation. However, in configuration B most of the current must travel some of the distance between the electrodes through the surrounding formations and this results in a lower fraction of the total heating occuring in the oil sand formation. This explains why, for a conductivity ratio of five, configuration B has a more uniform temperature profile in the oil sand, while configuration A has more of the energy input retained in the oil sand.

The total oil sand volume in both configurations A and B, per meter thick slice of the formation, is 1500 m^3. The chemical energy content of oil sand is of the order of 10^{10} Joules/m^3, so the total chemical energy in the heated formation is about 10^{13} Joules. An electrical preheat of 8 kW/m for one year uses about 2.5 X 10^{11} Joules of electrical energy, which is of the order of one percent of the chemical energy in place.

4.2 Effects of changing the distance between the electrodes

Computer runs were carried out with 75 m and 100 m spacings between the electrodes, with the other dimensions and electrode positions as in configuration A (figure 4.1). The power input was increased to 12 kW/m for the 75 m spacing and to 16 kW/m for the 100 m spacing, but the heating time remained at one year. The results of these runs, and similar runs done with 50 m spacings, are given in table 4.2. The temperature contour plots for the end of the

year of heating are given in figures 4.11 to 4.17.

Even though the power output from the electrodes is increased in proportion to the distance between the electrodes, the maximum temperature near the electrodes remained constant for conductivity ratios of one half and one. For the runs with different electrical conductivities for the overlying and underlying formations, the maximum temperature near the electrodes increased by fifteen percent when the distance between the electrodes was increased from 50 m to 100 m. The temperature midway between the electrodes decreased with an increase in the distance between the electrodes. A graph of the temperature midway between the electrodes vs. the distance between the electrodes is given in figure 4.18. The fraction of the total energy input that is retained in the oil sand formation at the end of the year also declines with an increase in the distance between the electrodes.

As the distance between the electrodes increases, more of the current reaches the surrounding formations, and less desirable temperature profiles and thermal efficencies result. A tradeoff must be made between the cost of the extra electrodes for a closely spaced heating configuration and the extra electrical energy and heating time required to obtain the same temperature profile for a larger spacing. The effect of changing the distance between the electrodes is more pronounced for higher conductivity ratios. The optimal distance between the electrodes will be a function

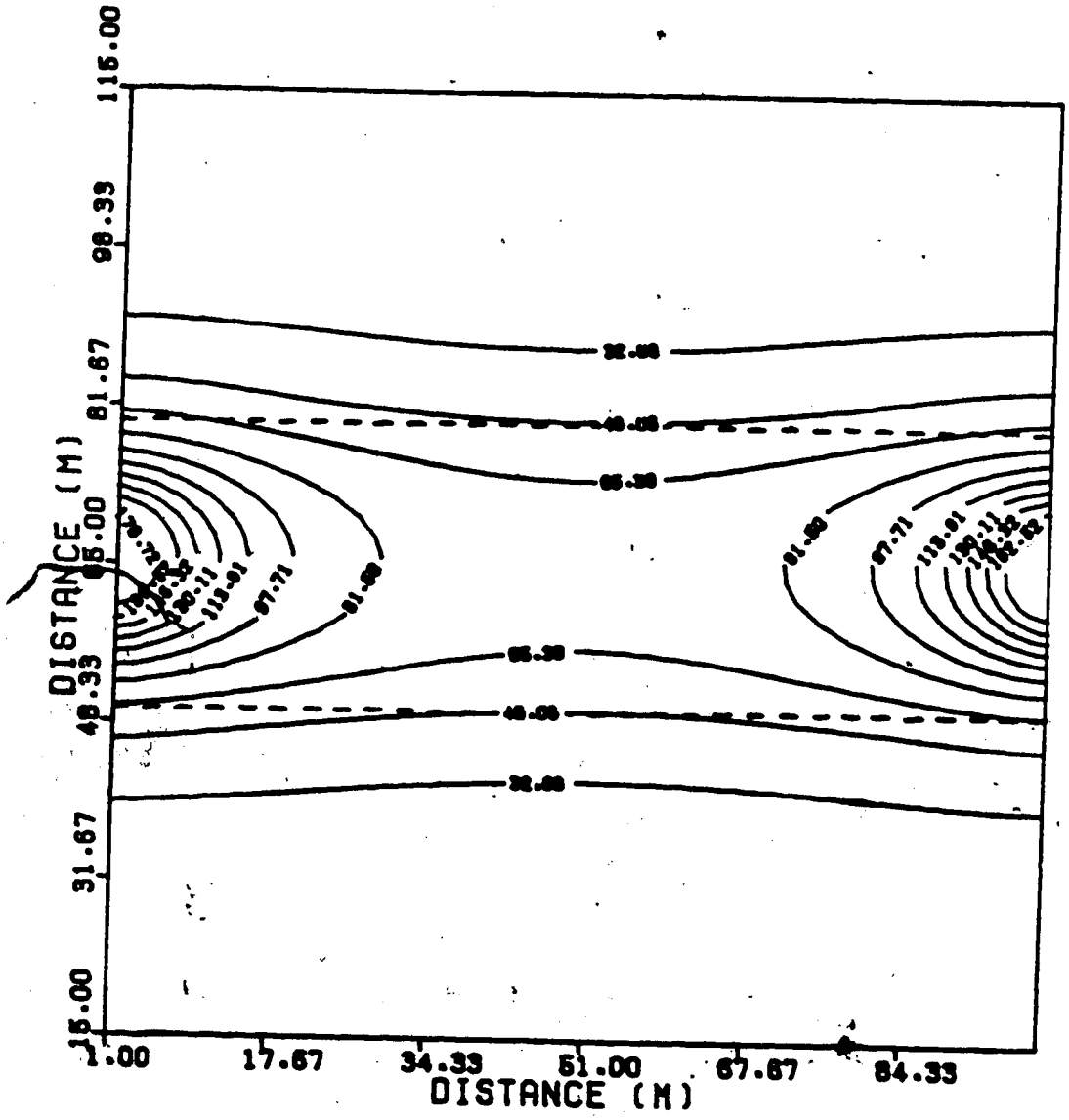


Figure 4.11 Contour plot of temperature in Celsius at the end of heating for one year at 16 kW/m. Run no. 23, configuration A, with a conductivity ratio (overburden, underburden/ oil sand) of .5

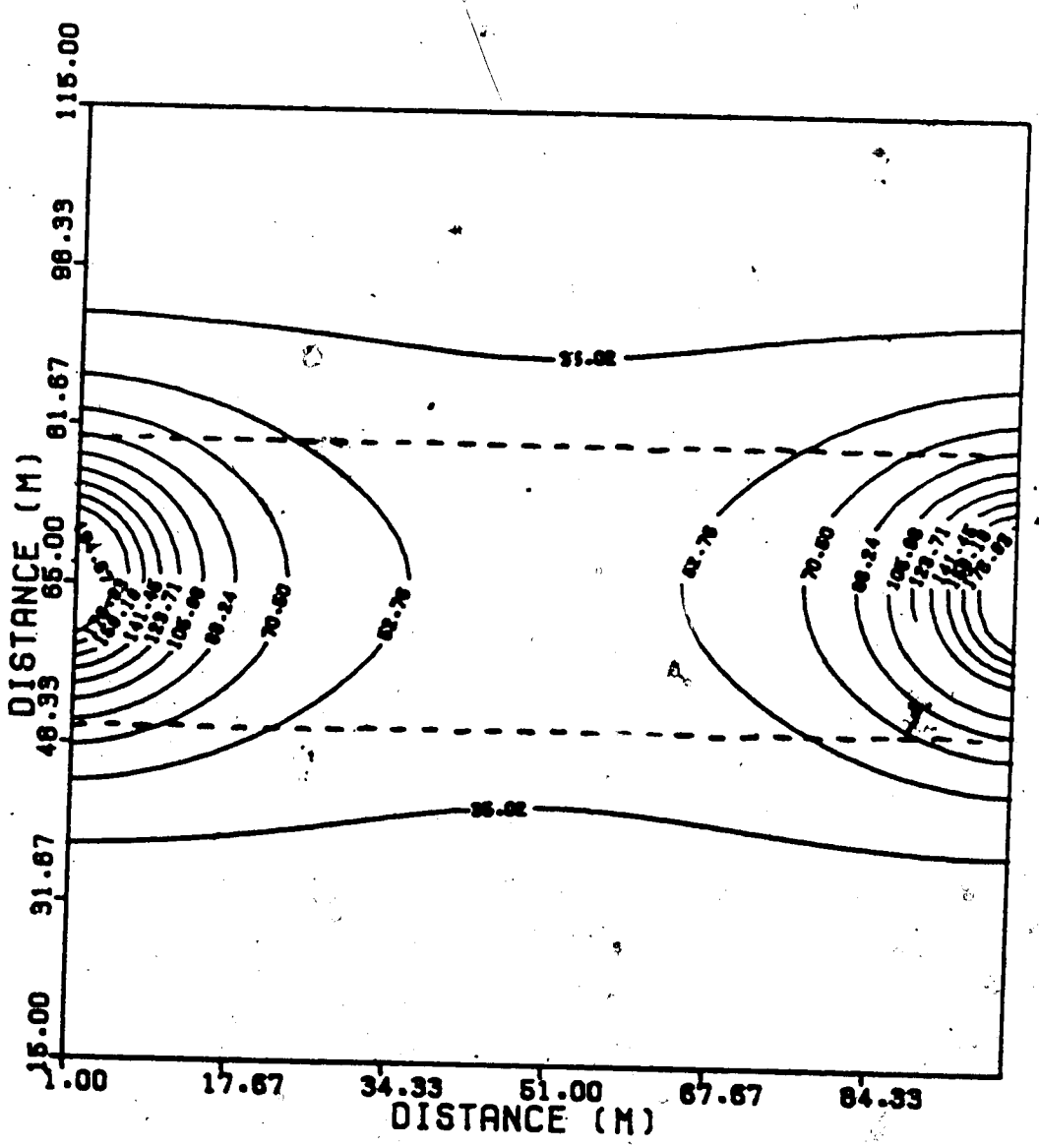


Figure 4.12 Contour plot of temperature in Celsius at the end of heating for one year at 16 kW/m. Run no. 24, configuration A, with a conductivity ratio (overburden, underburden/ oil sand) of 1.

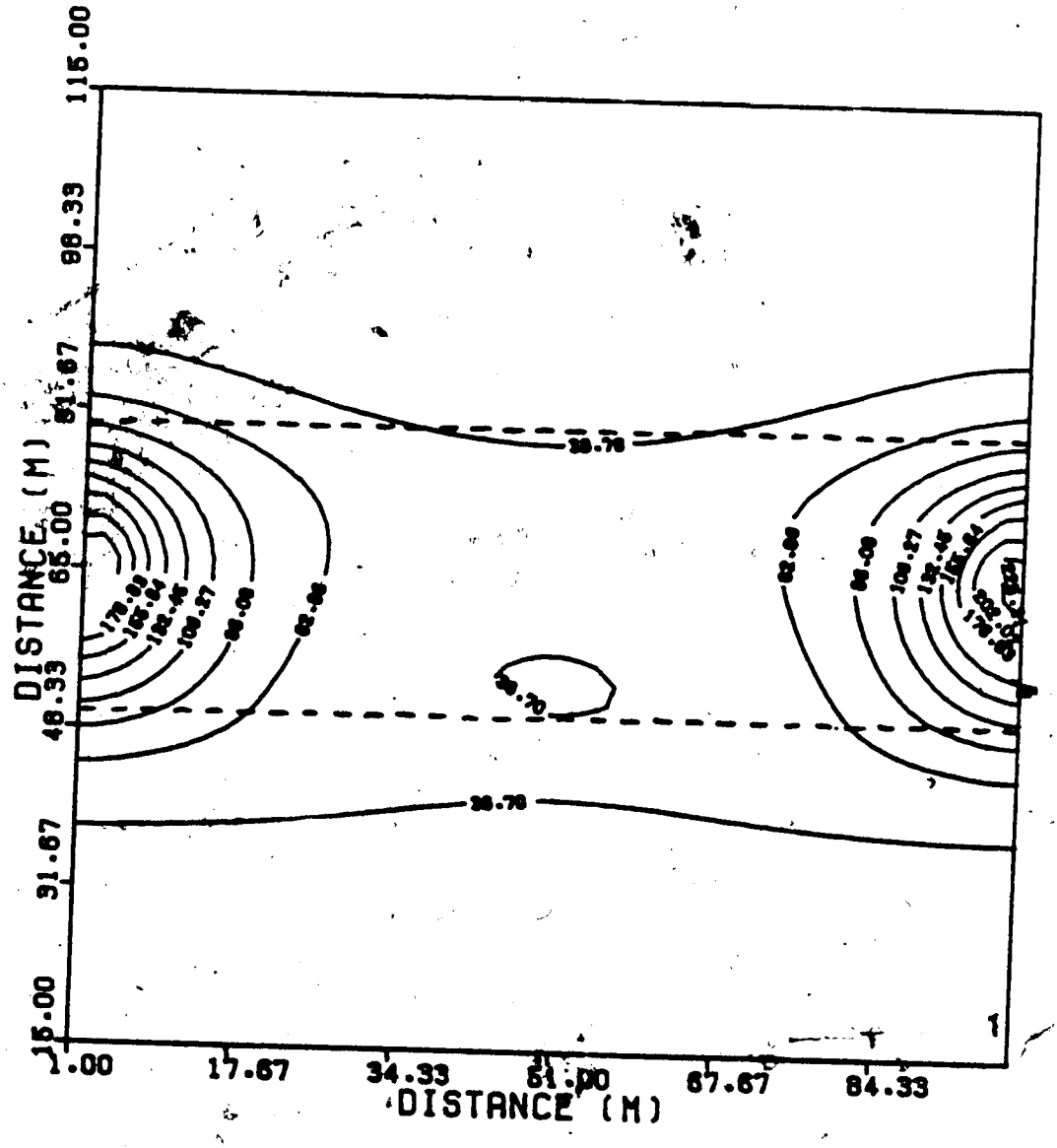


Figure 4.13 Contour plot of temperature in Celsius at the end of heating for one year at 16 kW/m. Run no. 25, overburden half as conductive and underburden twice as conductive as oil sand.

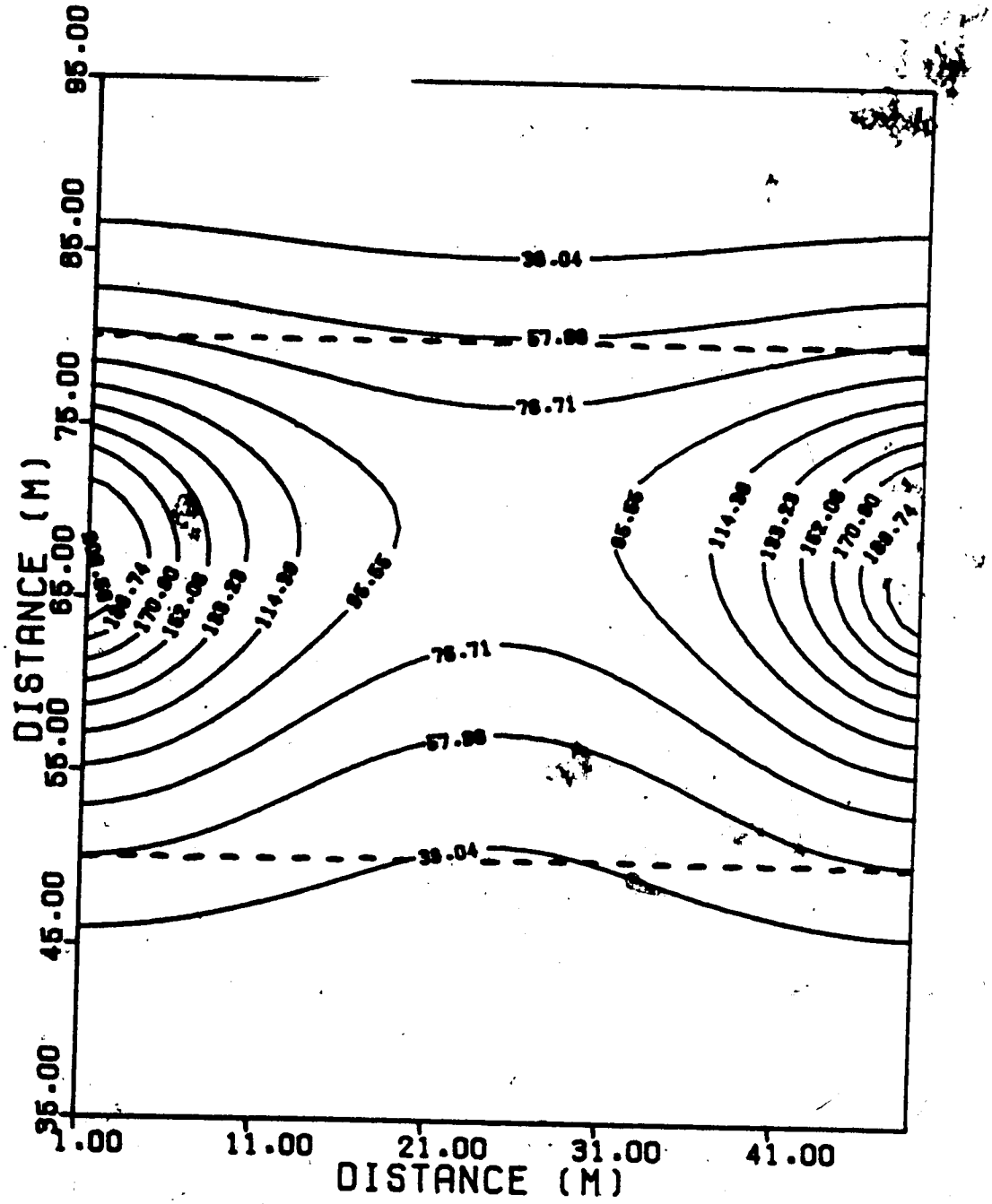


Figure 4.14 Contour plot of temperature in Celsius at the end of heating for one year at 8 kW/m. Run no. 26, overburden half as conductive and underburden twice as conductive as oil sand.

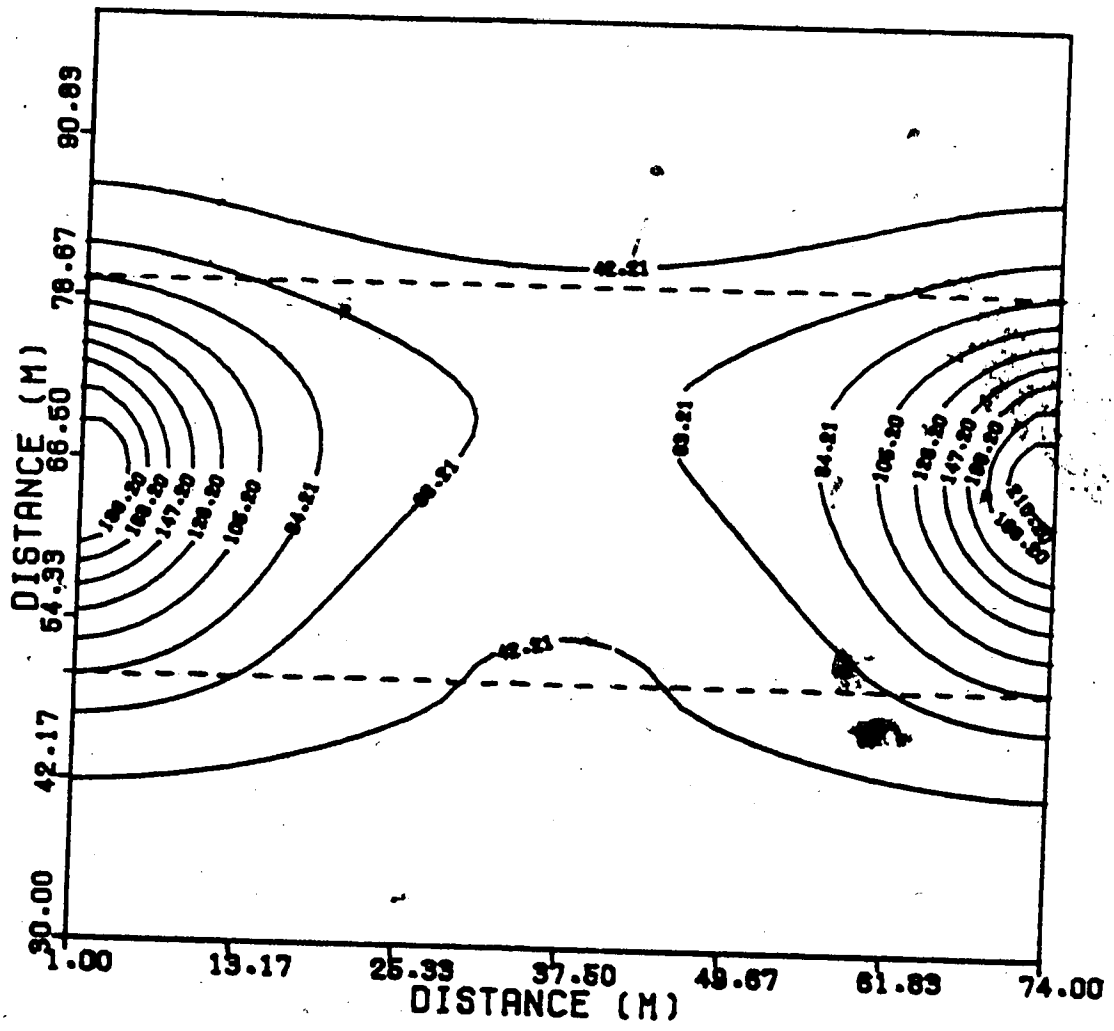


Figure 4.15 Contour plot of temperature in Celsius at the end of heating for one year at 12 kW/m. Run no. 32, overburden half as conductive and underburden twice as conductive as oil sand.

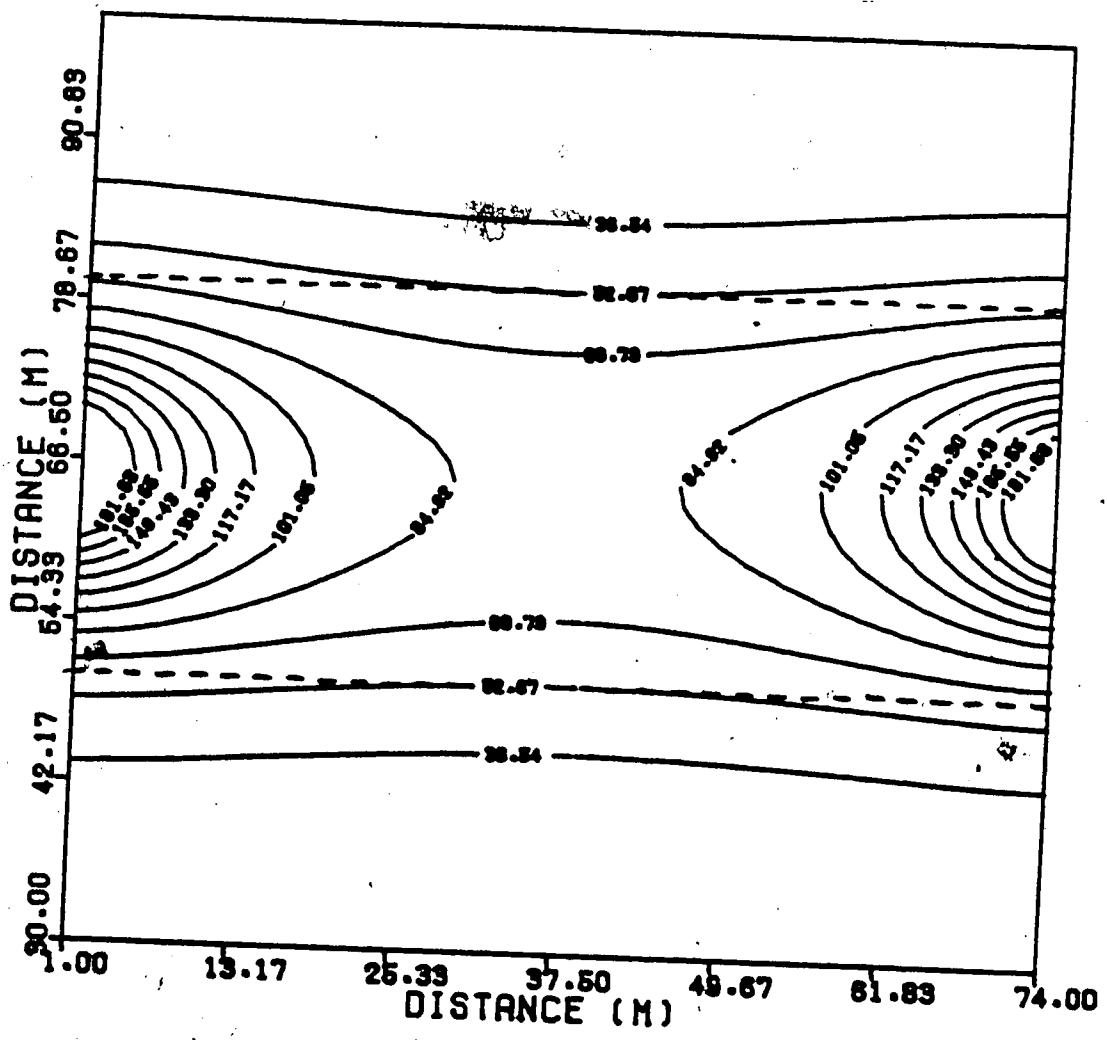


Figure 4.16 Contour plot of temperature in Celsius at the end of heating for one year at 12 kW/m. Run no. 34, configuration A, with a conductivity ratio (overburden, underburden/ oil sand) of .5

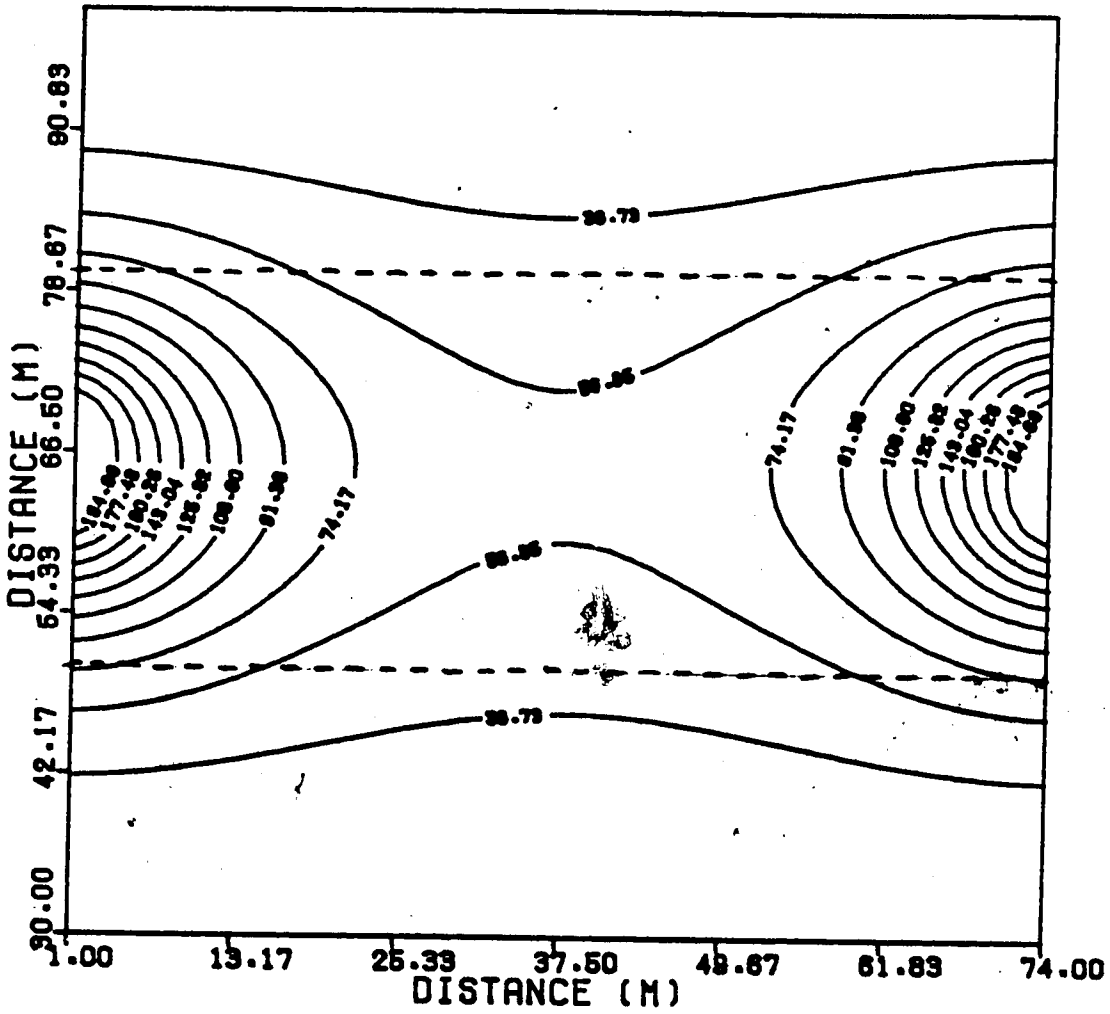
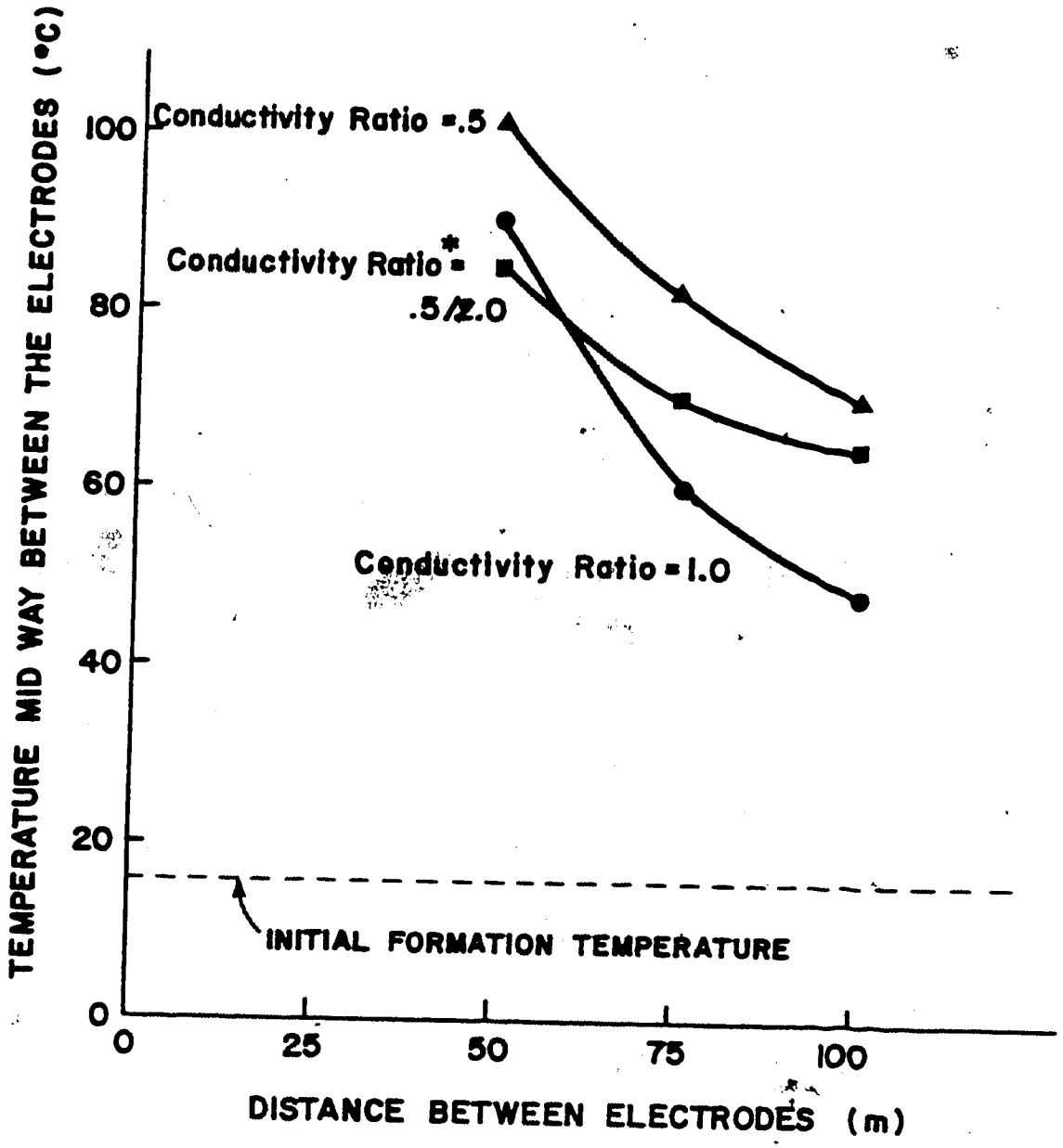


Figure 4.17 Contour plot of temperature in Celsius at the end of heating for one year at 12 kW/m. Run no. 35, configuration A,. with a conductivity ratio (overburden, underburden/ oil sand) of 1.



*Overlying formation is half as conductive as the oil sand and the underlying formation is twice as conductive as the oil sand.

Figure 4.18 Temperature midway between the electrodes vs. the distance between the electrodes. Electrode positions are as in configuration A, except for the mixed conductivity ratio where the electrodes were moved up three meters.

Table 4.2 Temperature rise and thermal efficency as a function of distance between the electrodes.

The conductivity of the oil sand is 1.0 X 10^{-3} S/m for all runs. Constant power heating of 8 kW per meter in the runs with a 50 m spacing, 12 kW per meter in the runs with a 75 m spacing, and 16 kW per meter in the runs with a 100 m spacing was applied for one year. Formation thicknesses and electrode sizes and positions are as in configuration A (Fig. 4.1).

1. Run No.	2. Spacing m	3. σ_{os} S/m x10^{-3}	4. σ_{us} S/m x10^{-3}	5. Max. Temp. °C	6. Mid Temp. °C	7. Heating in Oil Sand %	8. Energy in Oil Sand %
22	50	0.5	0.5	202	101	88	81
34	75	0.5	0.5	196	82	79	73
23	100	0.5	0.5	195	72	72	67
21	50	1.0	1.0	210	85	84	78
35	75	1.0	1.0	210	60	71	66
24	100	1.0	1.0	210	48	62	58
26	50	0.5	2.0	230	90	85	79
32	75	0.5	2.0	258	74	74	68
25	100	0.5	2.0	264	46	65	60

1. Runs were numbered in chronological order.
2. Distance between the electrodes.
3. Conductivity of overlying formation.
4. Conductivity of underlying formation.
5. Maximum temperature near the electrodes.
6. Maximum temperature mid way between the electrodes.
7. Electrical energy dissipated in the oil sand formation as a percentage of the total energy dissipated in the oil sand and surrounding formations.
8. The energy stored in the oil sand formation at the end of one year, as a percentage of the total energy input. The difference between columns 7 and 8 is due to thermal conduction.

of many parameters, with two important factors being the cost of the wells and electrodes and the relative conductivities of the surrounding formations to the oil sand.

5. Conclusions

The results of the full scale simulation runs done using the computer program MEGAERA are encouraging. These results indicate that, by using less than five percent of the chemical energy in place in a typical thickness Athabasca oil sand formation, it is possible to raise the temperature midway between the electrodes to 80°C, with higher temperatures near the electrodes. The viscosity of the bitumen (Athabasca oil sand) would be about 1000 cp midway between the electrodes, and considerably less near the electrodes. This is low enough to allow an efficent steam drive to be conducted.

The comparisons done between the analytic solution and the computer simulation indicate that the finite difference scheme used was correct. The convergence error due to the explicit coupling of the electrical and thermal equations remains, but, if the maximum temperature change per timestep is kept less than five percent, this error will not be significant.

The best test of both the mathematical model and the finite difference scheme that were used is conducted by comparing the simulator results with a physical model run. When this was done the simulator results were in agreement with the measured temperatures from the physical model run, except in the immediate vicinity of the electrodes. Thus, at least for temperatures up to 90°C (above which accurate electrical conductivity data is not available), the

mathematical model used will accurately predict temperatures and resistance for electrical heating of solid materials.

There are several items which should be kept in mind when interpreting the results of the full scale simulator runs. First, the electrical and thermal properties of oil sand have not been reported in the liturature for temperatures above 90°C. In the simulator the therma properties were assumed independent of temperature, and the electrical conductivity was assumed to increas linearly with temperature, up to 250°C. Second, the conduc ity of the oil sand near the electrodes in a field test would be altered by the injection of brine near the electrode. These two factors may result in significant error in the predicted temperatures near the electrodes. Finally, the conductivity of the oil sand was made uniform throughout the formation for the simulation runs. This was by choice and not due to any limitation of the simulator. In an actual oil sand formation there is probably variations in electrical conductivity with height in the formation and due to the presence of shale breaks and clay deposits.

The investigation to date indicates that the electrical preheat method may be developed into an economical method of preparing an oil sand formation for a steam flood or fire flood. Further measurement of the electrical and thermal properties of oil sand need to be performed at formation pressures and temperatures in the range of 100°C to 300°C. The computer simulator should be extended to three

dimensions so that simulation of five spot patterns are possible in addition to the parallel plate electrode (or line drive) geometry which was studied in this thesis. Finally, due to variations in the conductivities of the oil sand and the surrounding formations no one electrode configuration is optimal and each recovery location will have to be investigated individually to determine the optimal electrode size, positioning and spacing.

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Appendix I. - Listing of the Program MEGAERA

```
C
C
C
C
C
C
C
C                                      ********************
C                                      *                  *
C                                      *   M E G A E R A  *
C                                      *                  *
C                                      ********************
C
C                            SIMULATION OF ELECTRICAL CONDUCTION HEATING
C                            -------------------------------------------
C                                OF OILSAND AND OTHER MATERIALS
C                                ------------------------------
C
C
C                                  ALLAN HIEBERT, AUGUST 1980
C
C                                  WRITTEN FOLLOWING THE OLYMPUS
C                                  PROGRAMING SYSTEM DEVELOPED AT
C                                  CULHAM LABORITORIES, ENGLAND.
C
C
C
C
C
C
C
C
C-------------------------------------------------------------------
C
C                                     INDEX OF SUBPROGRAMS
C
C
C                                     MAIN CONTROL.          CLASS 0
C  MAIN      FORTRAN MAIN PROGRAM                                0.0
C  BASIC     INITIALIZE BASIC CONTROL DATA                       0.1
C  MODIFY    MODIFY BASIC DATA IF REQUIRED                       0.2
C  COTROL    CONTROL THE RUN                                     0.3
C  USER      PRINT USER, TIME AND DATE TO DIARY                  0.4
C
C                                     PROLOGUE.              CLASS 1
C  LABRUN    LABEL THE RUN                                       1.1
C  CLEAR     CLEAR VARIABLES AND ARRAYS                          1.2
C  PRESET    SET DEFAULT VALUES                                  1.3
C  DATA      DEFINE DATA SPECIFIC TO RUN                         1.4
C  AUXVAL    SET AUXILIARY VALUES                                1.5
C  INITAL    DEFINE PHYSICAL INITIAL CONDITIONS                  1.6
C  RESUME    RESUME FROM PREVIOUS RECORD                         1.7
C  START     START OR RESTART THE RUN                            1.8
C  EPARAM    CALCULATE ITERATION PARAMETERS FOR A.D.I.P.         1.9
C  TCOEFF    CALCULATE CONSTANTS FOR THE THERMAL EQUATION        1.10
C
C                                     CALCULATION.           CLASS 2
C  STEPON    STEP ON THE CALCULATION                             2.1
```

```
C  ELEPOT    CALCULATE THE ELECTRICAL POTENTIAL                          2.2
C  ELECOF    CALCULATE COEFFICENTS OF DIFFERENCE EQUATION                2.3
C  THOMAS    SOLVE TRIDIAGONAL SYSTEM BY THOMAS ALGORITHM               2.4
C  MAXDIF    FIND THE MAXIMUM DIFFERENCE BETWEEN TEM3, TEM1             2.5
C  QCALC     CALCULATE THE ELECTRICAL CONDUCTIVITY                      2.6
C  TCALC     CALCULATE THE HEATING RATES FOR THE GRID                   2.7
C  ENGBAL    SOLVE THE HEAT DIFFUSION EQUATION                          2.8
C  ELECUR    CALCULATE THE ENERGY BALANCE FOR THE TIMESTEP              2.9
C            CALCULATE THE CURRENT THROUGH A SURFACE                    2.10
C
C                                 OUTPUT                          CLASS 3
C
C  OUTPUT(1) CONTROL THE OUTPUT
C  OUTGRD(1) OUTPUT ONE OF THE GLOBAL VARIABLE ARRAYS                    3.1
C  ALINTP(7) DO A LINEAR INTERPOLATION                                   3.2
C  OUTINT(2) INTERPOLATE AND PRINT A GLOBAL VARIABLE                     3.3
C  OUTR      OUTPUT A LABEL AND A REAL VARIABLE                          3.4
C  OUTI      OUTPUT A LABEL AND AN INTEGER VARIABLE                      3.5
C  OUTH      OUTPUT A LABEL AND A HOLLERITH VARIABLE                     3.6
C  OUTTAP(1) OUTPUT RUN INFORMATION TO MAGNETIC TAPE                     3.7
C                                                                        3.8
C
C                                 EPILOGUE                        CLASS 4
C
C  TESEND    TEST FOR COMPLETION OF RUN                                  4.1
C  ENDRUN    TERMINATE THE RUN                                           4.2
C
C                                DIAGNOSTICS.                     CLASS 5
C
C  REPORT(3) CONTROL THE DIAGNOSTICS
C  CLIST(2)  PRINT COMMON VARIABLES                                      5.1
C  ARRAYS(2) PRINT COMMON ARRAYS                                         5.2
C                                                                        5.3
C
C                                UTILITIES                        CLASS U
C
C  MESAGE(1) PRINT 48-CHARACTER MESSAGE ON OUTPUT CHANNEL                U.1
C  PAGE      FETCH NEW PAGE ON OUTPUT CHANNEL                            U.2
C  BLANKS(1) INSERT BLANK LINES ON OUTPUT CHANNEL                        U.3
C  RVAR(2)   PRINT NAME AND VALUE OF REAL VARIABLE                       U.4
C  IVAR(2)   PRINT NAME AND VALUE OF INTEGER VARIABLE                    U.5
C  HVAR(2)   PRINT NAME AND VALUE OF HOLLERITH VARIABLE                  U.6
C  LVAR(2)   PRINT NAME AND VALUE OF LOGICAL VARIABLE                    U.7
C  RARRAY(3) PRINT NAME AND VALUES OF REAL ARRAY                         U.8
C  IARRAY(3) PRINT NAME AND VALUES OF INTEGER ARRAY                      U.9
C  HARRAY(3) PRINT NAME AND VALUES OF HOLLERITH ARRAY                    U.10
C  REPTHD(3) PRINT HEADING FOR DIAGNOSTIC REPORT                         U.11
C  RUNTIM    UPDATE CPU TIME AND PRINT IT                                U.12
C  DAYTIM    PRINT DATE AND TIME                                         U.13
C  RESETR(3) RESET REAL ARRAY TO SPECIFIED VALUE                         U.14
C  RESETI(3) RESET INTEGER ARRAY TO SPECIFIED VALUE                      U.15
C  RESETH(3) RESET HOLLERITH ARRAY TO SPECIFIED VALUE                    U.16
C  JOBTIM    FETCH ALLOCATED JOBTIME                                     U.17
C  LARRAY(3) PRINT NAME AND VALUES OF LOGICAL ARRAY                      U.18
C  RESETL(3) RESET LOGICAL ARRAY TO SPECIFIED VALUE                      U.19
C  RARAY2    PRINT DOUBLY-SUBSCRIPTED ARRAY                              U.20
C  SCALER(3) SCALE A REAL ARRAY BY A REAL VALUE                          U.21
C  SCALEI(3) SCALE AN INTEGER ARRAY BY AN INTEGER VALUE                  U.22
C  COPYR(5)  COPY ONE REAL MATRIX INTO ANOTHER                           U.23
C  COPYI(5)  COPY ONE INTEGER MATRIX INTO ANOTHER                        U.24
C  SIGNR(2)  CHANGE THE SIGN OF A REAL MATRIX                            U.25
C  SIGNI(2)  CHANGE THE SIGN OF AN INTEGER MATRIX                        U.26
```

```
      DUMCOM(3) DUMP SELECTED COMMON BLOCKS                              U.27

C
CL                                C1.1.    BASIC SYSTEM PARAMETERS
C     VERSION 2B                  14.8.73      KVR/MHH          CULHAM
C      COMMON/COMBAS/
C
C
C  ALTIME       TIME ALLOCATED TO JOB. (MINS)                          R  1.1
C  CPTIME       CPU TIME USED SO FAR ON THIS JOB. (MINS)               R  1.1
C  LABEL1(12) LABEL DESCRIBING THE RUN                                 IA 1.1
C  LABEL2(12) LABEL DESCRIBING THE RUN                                 IA 1.1
C  LABEL3(12) LABEL DESCRIBING THE RUN                                 IA 1.1
C  LABEL4(12) LABEL DESCRIBING THE RUN                                 IA 1.1
C  LABEL5(12) LABEL AVAILABLE TO PROGRAMMER                            IA 1.1
C  LABEL6(12) LABEL AVAILABLE TO PROGRAMMER                            IA 1.1
C  LABEL7(12) LABEL RESERVED FOR SYSTEM USE                            IA 1.1
C  LABEL8(12) LABEL RESERVED FOR SYSTEM USE                            IA 1.1
C  NDIARY       CHANNEL FOR DIARY O                                    I  1.1
C  NIN          CURRENT INPUT CHANNEL                                  I  1.1
C  NLEDGE       CHANNEL FOR RESTART RECORDS                            I  1.1
C  NLEND        .TRUE. IF RUN TO BE TERMINATED                         L  1.1
C  NLRES        .TRUE. IF RUN TO BE RESTARTED                          L  1.1
C  NONLIN       CHANNEL FOR ONLINE INPUT-OUTPUT                        I  1.1
C  NOUT         CURRENT OUTPUT CHANNEL                                 I  1.1
C  NPRINT       CHANNEL FOR PRINTED OUTPUT                             I  1.1
C  NPUNCH       CHANNEL FOR CARD OUTPUT (OR EQUIVALENT)                I  1.1
C  NREAD        CHANNEL FOR CARD INPUT                                 I  1.1
C  NREC         CURRENT RECORD NUMBER                                  I  1.1
C  NRESUM       RESUME FROM RECORD ON THIS CHANNEL                     I  1.1
C  NRUN         MAXIMUM NUMBER OF STEPS                                I  1.1
C  NSTEP        CURRENT STEP NUMBER                                    I  1.1
C  STIME        START TIME. (MINS)                                     R  1.1
C
C
C-----------------------------------------------------------------------
C
C
CL                                1.9.    DEVELOPMENT AND DIAGNOSTIC PARAMETERS
C     VERSION 1B                  14.8.73      KVR/MHH          CULHAM
C      COMMON/COMDDP/
C
C
C
C  MAXDUM       MAXIMUM DIMENSION OF DUMP ARRAYS                       I  1.9
C  MXDUMP       ACTUAL DIMENSION OF DUMP ARRAYS                        I  1.9
C  NADUMP(M)    CODES FOR ARRAY DUMPS                                  IA 1.9
C  NCLASS       MOST RECENT CLASS REPORTED                             I  1.9
C  NLCHED       .TRUE. IF CLASS O REPORT HEADS REQUIRED                L  1.9
C  NLHEAD(9)    .TRUE. IF CLASSES 1-9 REPORT HEADS REQUIRED            LA 1.9
C  NLOMT1(50) CLASS 1 SUBPROGRAM SELECTOR                              LA 1.9
C  NLOMT2(50) CLASS 2 SUBPROGRAM SELECTOR                              LA 1.9
C  NLOMT3(50) CLASS 3 SUBPROGRAM SELECTOR                              LA 1.9
C  NLREPT       .TRUE. IF ANY REPORT REQUIRED                          L  1.9
C  NPDUMP(M)    CODES FOR DUMPING POINTS                               IA 1.9
C  NPOINT       MOST RECENT POINT REPORTED                             I  1.9
C  NSUB         MOST RECENT SUBPROGRAM REPORTED                        I  1.9
C  NVDUMP(M)    CODES FOR DUMPING VARIABLES                            IA 1.9
C
C-----------------------------------------------------------------------
```

```
C
C          1.2     /COMGLO/ - GLOBAL VARIABLES
C
C  DELTAX     WIDTHS OF GRID BLOCKS                                  R  1.2
C  DELTAY     HEIGHT OF GRID BLOCKS                                  R  1.2
C  DTIME      LENGTH OF TIMESTEP ( DELTA TIME)                       R  1.2
C  ELECON     ELECTRICAL CONDUCTIVITY                                R  1.2
C  ELEGEO     ELECTRICAL GEOMETRY                                    R  1.2
C               NEGATIVE - DOMAIN POINT
C               ZERO     - NOT IN DOMAIN
C               POSITIVE - ELECTRODE
C  QTHERM     HEAT GENERATED BY ELECTRIC FIELD                       R  1.2
C  POTENT     ELECTRICAL POTENTIAL                                   R  1.2
C  TEMP       TEMPERATURE                                            R  1.2
C  THICK      THICKNESS OF TWO DIMENSIONAL SLICE                     R  1.2
C  THMGEO     THERMAL GEOMETRY                                       R  1.2
C  TIME       CURRENT VALUE OF THE TIME                              R  1.2
C  XCOORD     X COORDINATES OF GRIDPOINTS                            R  1.2
C  YCOORD     Y COORDINATES OF GRIDPOINTS                            R  1.2
C           ORIGIN AT LOWER LEFT CORNER OF (1,1) BLOCK
C  XMIN       MINIMUM X FOR INTERPOLATED PRINTOUT                    R  1.2
C  XMAX       MAXIMUM X  FOR INTERPOLATED PRINTOUT                   R  1.2
C  YMIN       MINIMUM Y  FOR INTERPOLATED PRINTOUT                   R  1.2
C  YMAX       MAXIMUM Y  FOR INTERPOLATED PRINTOUT                   R  1.2
C
C-----------------------------------------------------------------------
C
C          1.3     /COMELE/ - ELECTRICAL COEFFICENTS
C
C  ECXM       COEFFICENT OF FINITE DIFFERENCE EQU.                   R  1.3
C  ECXP       COEFFICENT IN POSITIVE X DIRECTION                     R  1.3
C  ECYM         "    "    NEGATIVE Y    "                           R  1.3
C  ECYP         "    "    POSITIVE Y DIRECTION                     R  1.3
C  EXMXP      SUM OF THE TWO X DIRECTION COEFFICENTS                 R  1.3
C  EYMYP      SUM OF THE TWO Y DIRECTION COEFFICENTS                 R  1.3
C  ERHS       RIGHT HAND SIDE OF DIFFERENCE EQU.                     R  1.3
C  ELEVOL     VOLTAGES OF DIFFERENT ELECTRODES                       R  1.3
C  ELEALP     COEFFICENTS FOR CONDUCTIVITY CALC.                     R  1.3
C    "    ELEBET      "    "    "    "                              R  1.3
C  ELEPAR     ITERATION PARAMETERS FOR A.D.I.P.                      R  1.3
C  EPSELE     CONVERGENCE CRITERIA FOR POTENTIAL                     R  1.3
C
C-----------------------------------------------------------------------
C
C          1.4     /COMTHM/ - THERMAL CONDUCTIVITY AND CAPACITY
C
C  THMCON     THERMAL CONDUCTIVITIES                                 R  1.4
C  THMCAP     VOLUMETRIC HEAT CAPACITY                               R  1.4
C  THMTEM     VECTOR OF CONSTANT TEMPERATURES                        R  1.4
C  TCYP       COEFFICENT OF THE THERMAL EQU. ( Y POS. )              R  1.4
C  TCXP         "    "    "    "    "    ( X POS. )                 R  1.4
C  TCXM         "    "    "    "    "    ( X NEG. )                 R  1.4
C  TCYM         "    "    "    "    "    ( Y NEG. )                 R  1.4
C  TCX        SUM OF X COEFFICENTS                                   R  1.4
C  TCY        SUM OF Y COEFFICENTS                                   R  1.4
C  TCRHS      TERMS ON CONSTANT TEMPERATURE BOUNDARY                 R  1.4
C
C-----------------------------------------------------------------------
C
C          1.5     /COMTEM/ - TEMPERARY ARRAYS
```

```
241     C
242     C  TEM1        TWO DIMENSION ARRAY FOR A.D.I.                    R  1.5
243     C  TEM2                                                          R  1.5
244     C  TEM3                                                          R  1.5
245     C  T1          ONE DIMENSION ARRAY FOR THOMAS ALGOR.             R  1.5
246     C  T2                                                            R  1.5
247     C  T3                                                            R  1.5
248     C  T4                                                            R  1.5
249     C  T5                                                            R  1.5
250     C                                                                R  1.5
251     C-----------------------------------------------------------------
252     C
253     C              1.6  /COMDIM/ - INTEGER COMMON BLOCK
254     C
255     C  NX          ACTUAL NUMBER OF GRID BLOCKS IN X DIR.            I  1.6
256     C  NY          ACTUAL NUMBER OF GRID BLOCKS IN Y DIR.            I  1.6
257     C  NDX         ACTUAL DIMENSION OF ARRAYS                        I  1.6
258     C  NDY         ACTUAL DIMENSION OF ARRAYS                        I  1.6
259     C  NEQU        NUMBER OF EQUATION FOR THOMAS ALGOR.              I  1.6
260     C  NALPHA      NUMBER OF ITERATION PARAMETERS USED               I  1.6
261     C  MITER       CURRENT ITERATION COUNTER FOR POTENTIAL           I  1.6
262     C  MMAX        MAXIMUM ALLOWED VALUE FOR MITER                   I  1.6
263     C  NREG        NUMBER OF DIFFERENT REGIONS IN PROBLEM            I  1.6
264     C  NGEO        0 IF IN VERTICAL MODE, 1 IN HORIZONTAL            I  1.6
265     C  NERROR      ERROR RETURN CODE FROM TIMESTEP ROUTINES          I  1.6
266     C  NTYPE       INDICATES TYPE OF HEATING                         I  1.6
267     C                  1- CONSTANT VOLTAGE
268     C                  2- CONSTANT CURRENT
269     C                  3- CONSTANT POWER
270     C                  4- NO HEATING
271     C  NSPO        NUMBER OF TIME STEPS PER OUTPUT                   I  1.6
272     C  NSTO        NUMBER OF TIMESTEPS BETWEEN TAPE STORES           I  1.6
273     C  NPX         NUMBER OF X INTERVALS FOR INTERPOLATION           I  1.6
274     C  NPY         NUMBER OF Y INTERVALS FOR INTERPOLATION           I  1.6
275     C  NIJ         INDICATES IF SURFACE OF CURRENT INTEGERAL
276     C              IS PERPENDICULAR TO X OR Y                        I  1.6
277     C  NCI         INDICE OF GRIDLINE WHICH INTEGRAL IS ALONG        I  1.6
278     C
279     C-----------------------------------------------------------------
280     C
281     C
282     C              1.7   /COMCON/ - HEATING CONTROL VARIABLES
283     C  HTIME       TOTAL TIME OF HEATING                             R  1.7
284     C  CTIME       TOTOL TIME OF COOLING                             R  1.7
285     C  CCUR        CONSTANT VALUE OF CURRENT                         R  1.7
286     C  CPOW        CONSTANT VALUE OF CURRENT                         R  1.7
287     C  DTEMP       MAXIMUM RELATIVE CHANGE IN TEMPERATURE            R  1.7
288     C  DELT        ACTUAL CHANGE IN TEMPERATURE FOR TIMESTEP         R  1.7
289     C  CUR         CURRENT CALCULATED FORM CURRENT INTEGRAL          R  1.7
290     C  VOLTS       ACTUAL VOLTAGE ACROSS ELECTRODES                  R  1.7
291     C  CVOL        VOLTAGE USED IN PROBLEM DEFINITION                R  1.7
292     C  RESIST      RESISTANCE BETWEEN ELECTRODES                     R  1.7
293     C  POWER       ELECTRICAL POWER INPUT DURING TIMESTEP            R  1.7
294     C  TINIT       INITIAL TEMPERATURE OF THE FORMATION              R  1.7
295     C  DEENG       ELECTRICAL ENERGY INPUT FOR THE TIMESTEP          R  1.7
296     C  TEENG       TOTAL ELECTRICAL ENERGY INPUT FOR THE RUN         R  1.7
297     C  DQENG       HEAT PRODUCED FOR THE TIMESTEP                    R  1.7
298     C  TQENG       TOTAL HEAT PRODUCED IN THE RUN                    R  1.7
299     C  QENG        VECTOR OF HEATING IN EACH REGION                  R  1.7
300     C  TTENG       ENERGY IN THE TEMPERATURE CHANGE                  R  1.7
```

```
C  TENG      VECTOR OF ENERGY OF TEMP. CHANGE BY REGION  R  1.7
C  SCALE     SCALE FACTOR FOR CONSTANT CURRENT AND POWER R  1.7
C
C-----------------------------------------------------------------
C
C
C O.O  FORTRAN MAIN PROGRAM
C
C
C/ INSERT COMBAS
C
C     TIME ALLOCATED TO JOB
        CALL JOBTIM(ALTIME)
C
C     SET UP THE BASIC CONTROL DATA
        CALL BASIC
C
C     PRINT DATE AND TIME
        CALL PAGE
        CALL DAYTIM
C
C     CONTROL THE RUN
        CALL CONTROL
C
        STOP
        END
C
C
C-----------------------------------------------------------------
C
      SUBROUTINE BASIC
C
C O.1  INITIALIZE BASIC DATA
C
C
C/ INSERT COMBAS
C/ INSERT COMDDP
      DATA        IBLANK/4H    /
CL                1.          GENERAL OLYMPUS DATA
C
CL                   1.1      BASIC SYSTEM PARAMETERS
C     CPU - TIME USED SO FAR
        CPTIME=0.0
C
C     CLEAR ALL 8 LABEL ARRAYS
        IL = 8 * 12
        CALL RESETH(LABEL,IL,IBLANK)
C
C     INPUT-OUTPUT CHANNELS
        NLEDGE = 30
        NONLIN = 1
        NPUNCH=7
        NPRINT=6
        NREAD=5
        NDIARY=NPRINT
        NIN=NREAD
        NOUT=NPRINT
C
C     TIMESTEP CONTROL
        NRUN = 1
```

```
361                NSTEP=0
362      C
363      C     RESTART CONTROL
364                NREC = 1
365                NRESUM = NLEDGE
366      C
367      C     LOGICAL SWITCHES
368                NLEND=.FALSE.
369                NLRES=.FALSE.
370      C
371      CL                1.9       DIAGNOSTIC AND DEVELOPMENT PARAMETERS
372                MAXDUM = 20
373      C     MAXIMUM DIMENSIONS OF DUMP ARRAYS
374                MXDUMP = 10
375      C     RESET DUMP ARRAYS
376                CALL RESETI(NADUMP,MAXDUM,0)
377                CALL RESETI(NPDUMP,MAXDUM,0)
378                CALL RESETI(NVDUMP,MAXDUM,0)
379      C     TRACER VARIABLES
380                NCLASS = 9
381                NSUB = 9
382                NPOINT = 9
383      C     LOGICAL SWITCHES
384                NLCHED = .FALSE.
385                NLREPT = .FALSE.
386      C     REPORT HEADS FOR CLASSES 1-9
387                CALL RESETL(NLHEAD,9,.FALSE.)
388      C     RESET CLASS 1,2,3 SUBPROGRAM SELECTOR ARRAY
389                CALL RESETL(NLOMT1,50,.FALSE.)
390                CALL RESETL(NLOMT2,50,.FALSE.)
391                CALL RESETL(NLOMT3,50,.FALSE.)
392      C
393      C     USER INTERFACE
394                CALL MODIFY
395      C
396                RETURN
397                END
398      C
399      C-----------------------------------------------------------------
400      C
401                SUBROUTINE MODIFY
402      C
403      C O.S.  MODIFY BASIC DATA IF REQUIRED
404      C
405      C/ INSERT COMBAS
406      C/ INSERT COMODP
407      C
408           NAMELIST/INMOD/NONLIN,NRUN,NREC,NRESUM,NLRES
409      C
410      C     PRINT USER, TIME AND DATE TO DIARY FILE.
411                CALL USER
412      C
413      C     SET DEFAULT VALUE FOR NRESUM
414                NRESUM=2
415      C
416      C     INPUT NAMELIST TO MODIFY BASIC DATA
417                READ(NREAD,INMOD)
418                IF(.NOT.NLRES) NREC=1
419                RETURN
420                END
```

```
      C
      C-----------------------------------------------------------------
      C
                SUBROUTINE COTROL
      C
      C 0.3  CONTROL THE RUN
      C
      C     VERSION 2B              17/12/73       KVR/MHH          CULHAM
      C
      C/ INSERT COMBAS
      C/ INSERT COMDDP
      CL                  1.          PROLOGUE
      C
                IF(NLRES) GO TO 170
      C
      C                     A.          NEW RUN
      C
      CL                          1.1       LABEL THE RUN
        110     CALL LABRUN
      C
      CL                          1.2       CLEAR VARIABLES AND ARRAYS
        120     CALL CLEAR
      C
      CL                          1.3       SET DEFAULT VALUES
        130     CALL PRESET
      C
      CL                          1.4       DEFINE DATA SPECIFIC TO RUN
        140     CALL DATA
      C
      CL                          1.5       SET AUXILIARY VALUES
        150     CALL AUXVAL
      C
      CL                          1.6       DEFINE PHYSICAL INITIAL CONDITIONS
        160     CALL INITAL
                GO TO 180
      C
      C                     B.          RESUME A PREVIOUS RUN
      C
      CL                          1.7       PICK UP RECORD, MODIFY REQUIRED PARAMETERS
        170   CONTINUE
      C     LABEL THE CONTINUATION RUN
              CALL LABRUN
      C     CLEAR VARIABLES AND ARRAYS
              CALL CLEAR
      C     PICK UP RECORD AND PRINT DETAILS
              CALL RESUME
      C     READ ANY NEW DATA NEEDED
              CALL DATA
      C     MODIFY AUXILIARY VARIABLES AS REQUIRED
              CALL AUXVAL
      C
      C                     C.          PRELIMINARY OPERATIONS
      C
      CL                          1.8       START OR RESTART THE RUN
        180   CALL START
      C     INITIAL OUTPUT
              CALL OUTPUT(1)
      C
      C
      CL                  2.          CALCULATION
```

```
481      C
482      CL
483        210     CALL STEPON          2.1      STEP ON THE CALCULATION
484      C
485      CL                    3.               OUTPUT
486      C
487      CL                                3.1   PERIODIC PRODUCTION OF OUTPUT
488        310     CALL OUTPUT(2)
489      C
490      CL                    4.               EPILOGUE
491      C
492      CL                                4.1   TEST FOR COMPLETION OF RUN
493        410     CALL TESEND
494                IF(.NOT.NLEND) GO TO 210
495      C
496      C       FINAL OUTPUT
497                CALL OUTPUT(3)
498      C
499      CL                                4.2   TERMINATE THE RUN
500        420     CALL ENDRUN
501      C
502                RETURN
503                END
504      C
505      C-----------------------------------------------------------------
506      C
507                SUBROUTINE USER
508      C
509      C  0.4  LOG USER CSID, TIME AND DATE TO DIARY FILE
510      C
511            INTEGER*4 INAME, ITIME(2), IDATE(3)
512                CALL GUINFO('SIGNONID',INAME)
513                CALL TIME(4,0,ITIME)
514                CALL TIME(5,0,IDATE)
515                CALL FTNCMD('ASSIGN 18=HADI:ULOG',19)
516                WRITE(18,20) INAME,ITIME(1),ITIME(2),(IDATE(J),J=1,3)
517       20       FORMAT(' MEGAERA',5X,A4,5X,A4,5X,3A4)
518                RETURN
519           END
520      C
521      C-----------------------------------------------------------------
522      C
523                SUBROUTINE LABRUN
524      C
525      C 1.1  LABEL THE RUN
526      C
527      C/ INSERT COMBAS
528                NAMELIST/LABELS/LABEL1,LABEL2,LABEL3,LABEL4
529      C
530      C     READ IN LABELS
531                READ(NREAD,LABELS)
532      C
533      C     PRINT PROGRAM HEADING AND LABELS
534                CALL BLINES(3)
535                WRITE(NPRINT,20)
536                WRITE(NPRINT,21)
537                WRITE(NPRINT,22)
538                CALL BLINES(2)
539                CALL MESAGE(LABEL1)
540                CALL MESAGE(LABEL2)
```

```
      CALL MESAGE(LABEL3)
      CALL MESAGE(LABEL4)
      RETURN
C
C
 20   FORMAT(35X,'P R O G R A M   M E G A E R A')
 21   FORMAT(35X,'-------------------------------')
 22   FORMAT('0',34X,'ADH',14X,'AUGUST, 1980')
C
      END
C
C-----------------------------------------------------------------
C
      SUBROUTINE CLEAR
C
C 1.2  CLEAR VARIABLES AND ARRAYS
C
C
C/ INSERT COMGLO
C/ INSERT COMELE
C/ INSERT COMTHM
C/ INSERT COMTEM
C/ INSERT COMCON
C/ INSERT COMDIM
C
      NDX=50
      NDY=50
      NV=NDX
      IF(NDY.GT.NDX) NV=NDY
      NA=NDX*NDY
C
C     CLEAR GLOBAL VARIABLES
        IL=6 * NA + 4 * NV + 7
          CALL RESETR(ELECON,IL,0.0)
C
C     CLEAR ELECTRICAL COMMON BLOCKS
        IL= 7 * NA + 3 * 10 + 1 * NV
          CALL RESETR(ECXP,IL,0.0)
C
C     CLEAR THERMAL COMMON BLOCK
        IL= 3 * 10 + 7 * NA
          CALL RESETR(THMCON,IL,0.0)
C
C     CLEAR TEMPERARY ARRAYS
        IL= 3 * NA + 5 * NV
          CALL RESETR(TEM1,IL,0.0)
C
C     CLEAR TIMESTEP CONTROL COMMON BLOCK
        IL= 38
          CALL RESETR(HTIME,IL,0.0)
C
C     CLEAR INTEGER VARIABLES
        IL= 18
          CALL RESETI(NX,IL,0)
C
      RETURN
      END
C
C-----------------------------------------------------------------
C
```

```
601                SUBROUTINE PRESET
602       C
603       C 1.3  SET DEFAULT VALUES
604       C
605       C/ INSERT COMDIM
606       C/ INSERT COMELE
607       C/ INSERT COMCON
608       C/ INSERT COMGLO
609       C
610       C     THE ELECTRICAL AND THERMAL GEOMETRY DEFAULTS TO INSULATORS.
611       C     THIS HAS BEEN PRESET BY SETTING THE ARRAYS ELEGEO AND
612       C     THMGEO TO ZERO ( AS DONE IN SUBROUTINE CLEAR ).
613       C
614              NDX=50
615              NDY=50
616              EPSELE=1.E+6
617              SCALE=1.0
618              THICK=1.0
619              MMAX=200
620              NSPO=1
621              NERROR=0
622              NPX=20
623              NPY=20
624              NIJ=1
625              NCI=0
626              NSTO=1000
627       C
628               RETURN
629               END
630       C
631       C-----------------------------------------------------------------
632       C
633                SUBROUTINE DATA
634       C
635       C 1.4  DEFINE DATA SPECIFIC TO RUN
636       C
637       C/ INSERT COMGLO
638       C/ INSERT COMELE
639       C/ INSERT COMTHM
640       C/ INSERT COMDIM
641       C/ INSERT COMBAS
642       C/ INSERT COMCON
643       C
644             DATA HHOR,HVER/'HORI','VERT'/,HELE,HINS/'ELEC',
645            #      'INSU'/,HCTE/'CTEM'/
646       C
647       C     NAMELISTS
648             NAMELIST /INPUT1/
649            #          NX,NY,DELTAX,DELTAY,THICK,GEOMET,NREG
650             NAMELIST /REGION/
651            #          MINI,MAXI,MINJ,MAXJ,EALPHA,EBETA,THMK,
652            #          THMRC,ETYPE,TTYPE,VOLTS,TEMPER
653             NAMELIST /INPUT2/
654            #          XMIN,XMAX,YMIN,YMAX,NSPO,NSTO,NPX,NPY
655             NAMELIST /INPUT3/
656            #          TINIT,DTIME,HTIME,NTYPE,CCUR,CPOW,CTIME,
657            #          DTEMP,NIJ,NCI,CVOL,EPSELE,MMAX
658       C
659       C     RESUMING AN OLD RUN?
660             IF(NLRES) GOTO 10
```

```
      C
      C     READ IN FIRST NAMELIST
            GEOMET=HVER
            READ(NREAD,INPUT1,END=900)
                NALPHA=MAX(NX,NY)
                CALL BLINES(2)
                CALL OUTR('THICKNESS OF 2D SLICE (THICK)      ',THICK)
                CALL OUTH('GEOMETRY OF PROBLEM                ',GEOMET)
                CALL OUTI('NUMBER OF REGIONS (NREG)           ',NREG)
                IF(NREG.GT.9) GOTO 901
                NGEO=0
                IF(GEOMET.EQ.HHOR) NGEO=1
      C
      C     READ IN AND OVERLAY DIFFERENT REGIONS
            DO 1 K=1,NREG
                READ(NREAD,REGION,END=900)
                CALL BLINES(2)
                CALL OUTI('REGION NUMBER                      ',K)
      C
      C     FIND ELECTRICAL AND THERMAL REGION TYPES
                IET=-K
                IF(ETYPE.EQ.HELE) IET=K
                IF(ETYPE.EQ.HINS) IET=0
                ITT=-K
                IF(TTYPE.EQ.HINS) ITT=0
                IF(TTYPE.EQ.HCTE) ITT=K
      C
      C     OVERLAY ELECTRICAL AND THERMAL GEOMETRIES
                DO 2 I=MINI,MAXI
                    DO 3 J=MINJ,MAXJ
                        ELEGEO(I,J)=IET
                        THMGEO(I,J)=ITT
      3             CONTINUE
      2         CONTINUE
      C
      C     STORE ELECTRICAL AND THERMAL PROPERTIES OF THE REGION
                CALL OUTH('ELECTRICAL TYPE                    ',ETYPE)
                IF(IET.GE.0) GOTO 4
                  ELEALP(K)=EALPHA
                  ELEBET(K)=EBETA
                  CALL OUTR('TEMP. DEPENDENCE OF CONDUCTIVITY',
     #                      EALPHA)
                  CALL OUTR('CONDUCTIVITY AT 24 CELSIUS       ',EBETA)
      4         IF(IET.GT.0) ELEVOL(K)=VOLTS
                IF(IET.GT.0)
     #          CALL OUTR('VOLTAGE ( BEFORE SCALING )         ',VOLTS)
                CALL OUTH('THERMAL REGION TYPE                ',TTYPE)
                IF(ITT.GE.0) GOTO 5
                  THMCON(K)=THMK
                  THMCAP(K)=THMRC
                  CALL OUTR('THERMAL CONDUCTIVITY
     #                       THMK)
                  CALL OUTR('THERMAL HEAT CAPACITY
     #                       THMRC)
      5         IF(ITT.GT.0) THMTEM(K)=TEMPER
                IF(ITT.GT.0)
     #          CALL OUTR('CONSTANT TEMPERATURE               ',TEMPER)
      C
      1     CONTINUE
            XCOORD(1)=DELTAX(1)/2.
```

```
      YCOORD(1)=DELTAY(1)/2.
         DO 6 I=2,NX
    6       XCOORD(I)=XCOORD(I-1)+(DELTAX(I-1)+DELTAX(I))/2.
         DO 7 J=2,NY
    7       YCOORD(J)=YCOORD(J-1)+(DELTAY(J-1)+DELTAY(J))/2.
      XMIN=XCOORD(1)
      XMAX=XCOORD(NX)
      YMIN=YCOORD(1)
      YMAX=YCOORD(NY)
C
C     INPUT OUTPUT CONTROL VARIABLES
      READ(NREAD,INPUT2)
         CALL BLINES(2)
         CALL OUTI('NO. OF STEPS PER PRINTED OUTPUT   ',NSPO)
         CALL OUTI('NO. OF STEPS PER TAPE STORAGE     ',NSTO)
         CALL OUTI('NO. OF INTERPOLATION POINTS IN X  ',NPX)
         CALL OUTI('NO. OF INTERPOLATION POINTS IN Y  ',NPY)
         CALL OUTR('X MINIMUM FOR INTERPOLATION       ',XMIN)
         CALL OUTR('X MAXIMUM FOR INTERPOLATION       ',XMAX)
         CALL OUTR('Y MINIMUM FOR INTERPOLATION       ',YMIN)
         CALL OUTR('Y MAXIMUM FOR INTERPOLATION       ',YMAX)
C
C     INPUT HEATING INFORMATION
   10 READ(NREAD,INPUT3)
         IF(EPSELE.GT.1.E+4) EPSELE=CVOL/1.E+5
         DELT=DTEMP
         IF(NCI.EQ.0) GOTO 902
         CALL BLINES(3)
         CALL OUTR('INITIAL TEMPERATURE IN CELSIUS   ',TINIT)
         CALL OUTR('TOTAL HEATING TIME IN SECONDS    ',HTIME)
         CALL OUTR('INITIAL TIMESTEP SIZE IN SECONDS',DTIME)
         CALL OUTI('GRIDLINE FOR CURRENT INTEGRAL  ',NCI)
         IF(NTYPE.EQ.1)
     #      CALL OUTR('CONSTANT VOLTAGE                  ',CVOL)
         IF(NTYPE.EQ.2)
     #      CALL OUTR('CONSTANT CURRENT  ( AMPERES )     ',CCUR)
         IF(NTYPE.EQ.3)
     #      CALL OUTR('CONSTANT POWER  ( WATTS )         ',CPOW)
         CALL OUTR('CHANGE IN TEMPERATURE / TIMESTEP ',DTEMP)
         CALL OUTI('MAXIMUM NO. OF ITERATIONS (MMAX)',MMAX)
         CALL OUTR('ELECTRICAL CONVERGENCE CRITERIA ',EPSELE)
         CALL OUTI('NUMBER OF ITERATION PARAMETERS  ',NALPHA)
      RETURN
C
C     ERROR MESSAGES
  900 CALLMESAGE(48H  ***  NAMELIST WAS NOT FOUND DURING DATA INPUT  )
         CALL ENDRUN
         STOP
  901 CALLMESAGE(48H  ***  ONLY NINE REGIONS MAY BE SPECIFIED        )
         CALL ENDRUN
         STOP
  902 CALLMESAGE(48H  ***  NO SURFACE FOR CURRENT INTEGRAL IS GIVEN  )
         CALL ENDRUN
         STOP
      END
C
C-----------------------------------------------------------------
C
      SUBROUTINE AUXVAL
C
```

```
781      C 1.5  SET AUXILIARY VALUES
782      C
783                CALL EPARAM
784                CALL TCOEFF
785      C
786              RETURN
787              END
788      C
789      C-------------------------------------------------------------
790      C
791              SUBROUTINE INITAL
792      C
793      C 1.6  DEFINE PHYSICAL INITIAL CONDITIONS
794      C
795      C/ INSERT COMGLO
796      C/ INSERT COMDIM
797      C/ INSERT COMCON
798      C/ INSERT COMTHM
799      C
800      C      SET INTIAL TEMPERATURE
801                DO 1 J=1,NY
802                     DO 1 I=1,NX
803                          TEMP(I,J)=TINIT
804                          K=THMGEO(I,J)
805                          IF(K.GT.0) TEMP(I,J)=THMTEM(K)
806       1          CONTINUE
807      C
808              RETURN
809              END
810      C
811      C-------------------------------------------------------------
812      C
813              SUBROUTINE RESUME
814      C
815      C 1.7  RESUME FROM PREVIOUS RECORD
816      C
817      C/ INSERT COMBAS
818      C/ INSERT COMGLO
819      C/ INSERT COMELE
820      C/ INSERT COMTHM
821      C/ INSERT COMCON
822      C/ INSERT COMDIM
823      C
824      C      SET DEFAULT VALUES
825                NDX=50
826                NDY=50
827                SCALE=1.0
828                NERROR=0
829      C
830      C      INPUT RECORD OF RUN GEOMETRY AND MATERIAL PROPERTY DATA
831       1     READ(NRESUM,END=900)ELEGEO,THMGEO,DELTAX,DELTAY,THICK,
832            #                    XCOORD,YCOORD,XMIN,XMAX,YMIN,YMAX,ELEVOL,
833            #                    ELEALP,ELEBET,EPSELE,THMCON,THMCAP,THMTEM,
834            #                    TINIT,NX,NY,NALPHA,MMAX,NREG,NGEO,NSPO,
835            #                    NSTO,NPX,NPY,NIJ,NCI
836      C
837      C      READ UNTIL SPECIFIED RECORD IS INPUT
838       2     READ(NRESUM,END=900)NSTEP,TIME,POTENT,QTHERM,TEMP,TEENG,TENG,
839            #                    TQENG,QENG,NR,DTIME
840                IF(NR.LT.NREC) GOTO 2
```

```
841                IF(NR.GT.NREC) GOTO 900
842                RETURN
843      C
844      C     RECORD NOT FOUND
845       900  CALLMESAGE(48H    ***    SPECIFIED RECORD NOT FOUND IN RESUME    )
846            CALL ENDRUN
847            STOP
848               END
849      C
850      C-------------------------------------------------------------
851      C
852                SUBROUTINE START
853      C
854      C 1.8  START OR RESTART THE RUN
855      C
856      C
857                RETURN
858                END
859      C
860      C-------------------------------------------------------------
861      C
862                 SUBROUTINE EPARAM
863      C
864      C  1.9  CALCULATE ITERATION PARAMETERS FOR ELECTRICAL A.D.I.P.
865      C
866      C/ INSERT COMELE
867      C/ INSERT COMDIM
868      C
869             DO 3 K=1,NALPHA
870                  ELEPAR(K)=(SIN(K*3.141528/(2.*NALPHA)))**2
871       3     CONTINUE
872      C
873            RETURN
874            END
875      C
876      C-------------------------------------------------------------
877      C
878                 SUBROUTINE TCOEFF
879      C
880      C  1.10  CALCULATE THE COEFFICENTS FOR THE HEAT EQUATION
881      C
882      C/ INSERT COMGLO
883      C/ INSERT COMDIM
884      C/ INSERT COMTHM
885      C
886      C     COVER THE GRID
887            DO 1 J=1,NY
888                 JP=J+1
889                 JM=J-1
890                 DY=DELTAY(J)
891                 DO 2 I=1,NX
892                      IP=I+1
893                      IM=I-1
894      C
895      C     CHECK IF THE BLOCK IS IN THE THERMAL DOMAIN
896                      K=THMGEO(I,J)
897                      IF(K.GE.0) GOTO 2
898      C
899      C     FIND THE THERMAL CONDUCTIVITY AND CLEAR VARIABLES
900                      TC=THMCON(-K)
```

```
                    DX=DELTAX(I)
                    TCRHS(I,J)=0.
                    TCX(I,J)=0.
                    TCY(I,J)=0.
C
C     FIND COEFFICENTS IN THE X DIRECTION
C     CHECK SURROUNDING BLOCKS
                KP=0
                IF(I.LT.NX) KP=THMGEO(IP,J)
                KM=0
                IF(I.GT.1)  KM=THMGEO(IM,J)
                TCP=TC
                IF(KP.LT.0) TCP=THMCON(-KP)
                TCM=TC
                IF(KM.LT.0) TCM=THMCON(-KM)
                RP=TC/TCP
                RM=TC/TCM
C
C     DECIDE WHICH CASE THIS GRID BLOCK IS
C     1. NORMAL BLOCK SURROUNDED BY DOMAIN
                IF(KP.GE.0.OR.KM.GE.0) GOTO 3
                   H=(DX+DELTAX(IP))/2.
                   HM=(DX+DELTAX(IM))/2.
                   TCXP(I,J)=(TC+TCP)/(H*(H+HM))
                   TCXM(I,J)=(TC+TCM)/(HM*(H+HM))
C     CHECK FOR CONDUCTIVITY DISCONTINUITIES
                   IF(KP.NE.K)
     #                TCXP(I,J)=TC/(.25*(H+HM)*(DX+RP*DELTAX(IP)))
                   IF(KM.NE.K)
     #                TCXM(I,J)=TC/(.25*(H+HM)*(DX+RM*DELTAX(IM)))
                   TCX(I,J)=TCXM(I,J)+TCXP(I,J)
                   GOTO 10
C
C     2. CONSTANT TEMPERATURE BOUNDARY IN ONE DIRECTION
 3              IF(KP.EQ.0.OR.KM.EQ.0) GOTO 4
                   H=(DX+DELTAX(IP))/2.
                   HM=(DX+DELTAX(IM))/2.
                   IF(KP.GT.0) H=DX/2.
                   IF(KM.GT.0) HM=DX/2.
                   TCXP(I,J)=(TC+TCP)/(H*(H+HM))
                   TCXM(I,J)=(TC+TCM)/(HM*(H+HM))
                   TCX(I,J)=TCXP(I,J)+TCXM(I,J)
                   IF(KP.GT.0) TCRHS(I,J)=TCRHS(I,J)+
     #                                    TCXP(I,J)*THMTEM(KP)
                   IF(KP.GT.0) TCXP(I,J)=0.
                   IF(KM.GT.0) TCRHS(I,J)=TCRHS(I,J)+
     #                                    TCXM(I,J)*THMTEM(KM)
                   IF(KM.GT.0) TCXM(I,J)=0.
                   GOTO 10
C
C     3. BOUNDARY IN ONE DIRECTION
 4              IF(KP.GE.0.AND.KM.GE.0) GOTO 900
                   TCXM(I,J)=0.
                   TCXP(I,J)=0.
                   IF(KP.LT.0) TCXP(I,J)=
     #                         (TC+TCP)/(.5*((DX+DELTAX(IP))**2))
                   IF(KM.LT.0) TCXM(I,J)=
     #                         (TC+TCM)/(.5*((DX+DELTAX(IM))**2))
                   TCX(I,J)=TCXM(I,J)+TCXP(I,J)
C
```

```
      C     .CALCULATE COEFFICENTS IN Y DIRECTION
   10             KP=0
                  IF(J.LT.NY) KP=THMGEO(I,JP)
                  KM=0
                  IF(J.GT.1)  KM=THMGEO(I,JM)
                  TCP=TC
                  IF(KP.LT.0) TCP=THMCON(-KP)
                  TCM=TC
                  IF(KM.LT.0) TCM=THMCON(-KM)
                  RP=TC/TCP
                  RM=TC/TCM
      C
      C     DECIDE WHICH CASE THIS GRID BLOCK IS
      C     1. NORMAL BLOCK SURROUNDED BY DOMAIN
                IF(KP.GE.0.OR.KM.GE.0) GOTO 5
                  H=(DY+DELTAY(JP))/2.
                  HM=(DY+DELTAY(JM))/2.
                  TCYP(I,J)=(TC+TCP)/(H*(H+HM))
                  TCYM(I,J)=(TC+TCM)/(HM*(H+HM))
      C     CHECK FOR CONDUCTIVITY DISCONTINUITIES
                  IF(KP.NE.K)
     #              TCYP(I,J)=TC/(.25*(H+HM)*(DY+DELTAY(JP)*RP))
                  IF(KM.NE.K)
     #              TCYM(I,J)=TC/(.25*(H+HM)*(DY+DELTAY(JM)*RM))
                  TCY(I,J)=TCYM(I,J)+TCYP(I,J)
                  GOTO 2
      C
      C     2. CONSTANT TEMPERATURE BOUNDARY
    5           IF(KP.EQ.0.OR.KM.EQ.0) GOTO 6
                  H=(DY+DELTAY(JP))/2.
                  HM=(DY+DELTAY(JM))/2.
                  IF(KP.GT.0) H=DY/2.
                  IF(KM.GT.0) HM=DY/2.
                  TCYP(I,J)=(TC+TCP)/(H*(H+HM))
                  TCYM(I,J)=(TC+TCM)/(HM*(H+HM))
                  TCY(I,J)=TCYM(I,J)+TCYP(I,J)
                  IF(KP.GT.0) TCRHS(I,J)=TCRHS(I,J)+
     #                                    TCYP(I,J)*THMTEM(KP)
                  IF(KP.GT.0) TCYP(I,J)=0.
                  IF(KM.GT.0) TCRHS(I,J)=TCRHS(I,J)+
     #                                    TCYM(I,J)*THMTEM(KM)
                  IF(KM.GT.0) TCYM(I,J)=0.
                  GOTO 2
      C
      C     3. BOUNDARY IN ONE DIRECTION
    6           IF(KP.GE.0.AND.KM.GE.0) GOTO 900
                  TCYP(I,J)=0.
                  TCYM(I,J)=0.
                  IF(KP.LT.0) TCYP(I,J)=
     #                        (TC+TCP)/(.5*((DY+DELTAY(JP))**2))
                  IF(KM.LT.0) TCYM(I,J)=
     #                        (TC+TCM)/(.5*((DY+DELTAY(JM))**2))
                  TCY(I,J)=TCYM(I,J)+TCYP(I,J)
      C
      C
    2           CONTINUE
    1         CONTINUE
              RETURN
      C
      C     ERROR RETURN
```

```
 900  CALLMESAGE(48H    ***    ERROR RETURN FROM ROUTINE TCOEF          )
         CALL ENDRUN
         RETURN
      END
C
C-----------------------------------------------------------------
C
         SUBROUTINE STEPON
C
C 2.1  STEP ON THE CALCULATION
C
C/ INSERT COMBAS
C/ INSERT COMGLO
C/ INSERT COMCON
C/ INSERT COMDIM
          NSTEP=NSTEP+1
C
C
C     IF END OF HEATING PERIOD, RESET ELECTRICAL VARIABLES
          IF(ABS(TIME-HTIME).GT.1.) GOTO 1
               NTYPE=4
               CALL RESETR(POTENT,NDX*NDY,0.0)
               CALL RESETR(QTHERM,NDX*NDY,0.0)
               VOLTS=0.
               POWER=0.
               CUR  =0.
               RESIST=0.
C
C     IF NO HEATING, SKIP E-FIELD AND Q CALCULATIONS
   1       IF(NTYPE.EQ.4) GOTO 14
C
C     CALCULATE ELECTRICAL CONDUCTIVITY
               CALL ECOND
               IF(NERROR.NE.0) RETURN
C
C     DESCALE POTENTIAL AND FIND NEW POTENTIAL
               S=1./SCALE
               CALL SCALER(POTENT,NDX*NDY,S)
               CALL ELEPOT
               IF(NERROR.NE.0) RETURN
C
C     SCALE THE POTENTIAL IF CONSTANT CURRENT OR POWER
               CALL ELECUR
               RESIST=CVOL/CUR
               GOTO (10,11,12),NTYPE
C
C     CONSTANT VOLTAGE
  10           VOLTS=CVOL
               POWER=VOLTS*CUR
               GOTO 13
C
C     CONSTANT CURRENT
  11           SCALE=CCUR/CUR
               VOLTS=CVOL*SCALE
               CALL SCALER(POTENT,NDX*NDY,SCALE)
               POWER=CCUR*VOLTS
               CUR=CCUR
               GOTO 13
C
C     CONSTANT POWER
```

```
 12                SCALE=SQRT(CPOW/(CUR*CVOL))
                   VOLTS=SCALE*CVOL
                   POWER=CPOW
                   CUR=CUR*SCALE
                   CALL SCALER(POTENT,NDX*NDY,SCALE)
C
C     CALCULATE THE HEATING RATES
 13          CALL QCALC
             IF(NERROR.NE.0) RETURN
C
C     FIND THE TIMESTEP SIZE FOR THE NEXT HEATING STEP
 14       DTIME=DTIME*DTEMP/DELT
          IF(NTYPE.LE.3.AND.(DTIME+TIME).GT.(HTIME-1.E-2))
     #       DTIME=HTIME-TIME
          IF(NTYPE.EQ.4.AND.(DTIME+TIME).GT.(HTIME+CTIME))
     #       DTIME=HTIME+CTIME-TIME
C
C     FIND THE NEW TEMPERATURE
           CALL TCALC
              IF(NERROR.NE.0) RETURN
C
C     CHECK THE ENERGY BALANCE
            CALL ENGBAL
            TIME=TIME+DTIME
         RETURN
         END
C
C-----------------------------------------------------------------
C
            SUBROUTINE ELEPOT
C
C  2.2  CALCULATE THE ELECTRICAL POTENTIAL FROM THE
C       FINITE DIFFERENCE EQUATION, USING THE
C       ALTERNATING DIRECTION IMPLICIT PROCEDURE.
C
C/ INSERT COMGLO
C/ INSERT COMELE
C/ INSERT COMTEM
C/ INSERT COMDIM
C
C     FIRST, CALCULATE THE COEFFICENTS FOR THIS TIME STEP
           CALL ELECOF
               IF(NERROR.NE.0) RETURN
C
C     USE THE POTENTIAL OF THE LAST STEP AS THE FIRST GUESS
           CALL COPYR(POTENT,1,TEM1,1,NDX*NDY)
C
C     RESET THE ITERATION COUNTER
           MITER=0
C
C  ***  START OF ITERATION LOOP FOR A.D.I.P.  ***
 1         MITER=MITER+1
C
C     CHECK IF THE MAXIMUM NUMBER OF ITERATIONS IS REACHED
           IF(MITER.GT.MMAX) GOTO 900
C
C     CHOOSE THE ITERATION PARAMETER
           L=MITER-(MITER/NALPHA)*NALPHA
           IF(L.EQ.0) L=NALPHA
           ALPHA=ELEPAR(L)
```

```
1141      C
1142      C     FIRST STAGE, IMPLICIT IN X.
1143            DO 2 J=1,NY
1144                 JM=J-1
1145                 IF(J.EQ.1) JM=1
1146                 JP=J+1
1147                 IF(J.EQ.NY) JP=NY
1148                 NEQU=0
1149                 DO 3 I=1,NX
1150      C
1151      C     IF THE BLOCK IS AN ELECTRODE, OR NOT IN THE DOMAIN,
1152      C          SKIP TO THE NEXT BLOCK.
1153                      K=ELEGEO(I,J)
1154                      IF(K.GE.0) GOTO 3
1155      C
1156      C     CALCULATE AND ASSIGN TRIDIAGONAL COEFFICENTS
1157                      NEQU=NEQU+1
1158                      ECSUM=EXMXP(I,J)+EYMYP(I,J)
1159                      T1(NEQU)=ECXM(I,J)
1160                      T2(NEQU)=-(EXMXP(I,J)+ALPHA*ECSUM)
1161                      T3(NEQU)=ECXP(I,J)
1162                      T4(NEQU)=-(ECYM(I,J)*TEM1(I,JM)+ECYP(I,J)*TEM1(I,JP))
1163           #                  +(EYMYP(I,J)-ALPHA*ECSUM)*TEM1(I,J)
1164           #                  -ERHS(I,J)
1165       3          CONTINUE
1166      C
1167      C     SOLVE THE TRIDIAGONAL SYSTEM
1168                 CALL THOMAS
1169      C
1170      C     PLACE RESULTS IN TEM2
1171                 NEQU=0
1172                 DO 5 I=1,NX
1173                      TEM2(I,J)=0.
1174                      K=ELEGEO(I,J)
1175                      IF(K.GE.0) GOTO 5
1176                      NEQU=NEQU+1
1177                      TEM2(I,J)=T5(NEQU)
1178       5          CONTINUE
1179      C
1180       2     CONTINUE
1181      C
1182      C     START OF SECOND STAGE
1183            DO 6 I=1,NX
1184                 IM=I-1
1185                 IF(I.EQ.1) IM=I
1186                 IP=I+1
1187                 IF(I.EQ.NX) IP=I
1188                 NEQU=0
1189                 DO 7 J=1,NY
1190      C
1191      C     IF NOT IN DOMAIN, SKIP TO NEXT POINT
1192                      K=ELEGEO(I,J)
1193                      IF(K.GE.0) GOTO 7
1194      C
1195      C     CALCULATE AND ASSIGN TRIDIAGONAL COEFFICENTS
1196                      NEQU=NEQU+1
1197                      ECSUM=EXMXP(I,J)+EYMYP(I,J)
1198                      T1(NEQU)=ECYM(I,J)
1199                      T2(NEQU)=-(EYMYP(I,J)+ALPHA*ECSUM)
1200                      T3(NEQU)=ECYP(I,J)
```

```
1201                    T4(NEQU)=-(ECXM(I,J)*TEM2(IM,J)+ECXP(I,J)*TEM2(IP,J))
1202          #                        +(EXMXP(I,J)-ALPHA*ECSUM)*TEM2(I,J)
1203          #                        -ERHS(I,J)
1204       7          CONTINUE
1205       C
1206       C      SOLVE TRIDIAGONAL SYSTEM
1207                  CALL THOMAS
1208       C
1209       C      PLACE RESULTS IN TEM3
1210                  NEQU=0
1211                  DO 9 J=1,NY
1212                       TEM3(I,J)=0.
1213                       K=ELEGEO(I,J)
1214                       IF(K.GT.0) TEM3(I,J)=ELEVOL(K)
1215                       IF(K.GE.0) GOTO 9
1216                       NEQU=NEQU+1
1217                       TEM3(I,J)=T5(NEQU)
1218       9          CONTINUE
1219       C
1220        6     CONTINUE
1221       C
1222       C      CHECK FOR CONVERGENCE
1223                  CALL MAXDIF(1,EPS)
1224                        IF(EPS.LT.EPSELE) GOTO 10
1225       C
1226       C      NO CONVERGENCE, TRANSFERE TEM3 TO TEM1
1227                  CALL COPYR(TEM3,1,TEM1,1,NDX*NDY)
1228       C
1229       C      LOOP BACK TO START NEXT ITERATION
1230                  GOTO 1
1231       C
1232       C  ***  END OF ITERATION LOOP  ***
1233       C
1234       C      TRANSFERE FINAL SOLUTION TO POTENT
1235        10        CALL COPYR(TEM3,1,POTENT,1,NDX*NDY)
1236             RETURN
1237       C
1238       C      ERROR MESSAGE - SOLUTION FAILED TO CONVERGE
1239        900       NERROR=1
1240                  CALL COPYR(TEM3,1,POTENT,1,NDX*NDY)
1241                  RETURN
1242             END
1243       C
1244       C-------------------------------------------------------------
1245       C
1246                 SUBROUTINE ELECOF
1247       C
1248       C  2.3  CALCULATION OF COEFFICENTS OF ELECTRICAL DIFFERENCE EQU.
1249       C
1250       C/ INSERT COMGLO
1251       C/ INSERT COMELE
1252       C/ INSERT COMDIM
1253       C
1254       C      FOR EACH GRID BLOCK, CALCULATE THE FOUR COEFFICENTS
1255                DO 1 J=1,NY
1256                  DY=DELTAY(J)
1257                  DO 2 I=1,NX
1258       C      IF BLOCK NOT IN DOMAIN, THEN SKIP TO NEXT BLOCK
1259                       K=ELEGEO(I,J)
1260                       IF(K.GE.0) GOTO 2
```

```
1261      C
1262                        ERHS(I,J)=0.
1263                        EXMXP(I,J)=0.
1264                        EYMYP(I,J)=0.
1265                        DX=DELTAX(I)
1266                        S=ELECON(I,J)
1267      C
1268      C     CALCULATE COEFFICENTS FOR X DIRECTION
1269      C     CHECK SURROUNDING BLOCKS
1270                  KP=0
1271                  IF(I.LT.NX) KP=ELEGEO(I+1,J)
1272                  KM=0
1273                  IF(I.GT.1)  KM=ELEGEO(I-1,J)
1274                  SP=S
1275                  IF(KP.LT.0)  SP=ELECON(I+1,J)
1276                  SM=S
1277                  IF(KM.LT.0)  SM=ELECON(I-1,J)
1278                  RP=S/SP
1279                  RM=S/SM
1280      C
1281      C     DECIDE WHICH CASE THIS GRID BLOCK IS
1282      C     1. NORMAL BLOCK SURROUNDED BY DOMAIN
1283                  IF(KP.GE.0.OR.KM.GE.0) GOTO 3
1284                     H=(DX+DELTAX(I+1))/2.
1285                     HM=(DX+DELTAX(I-1))/2.
1286                     ECXP(I,J)=(S+SP)/(H*(H+HM))
1287                     ECXM(I,J)=(S+SM)/(HM*(H+HM))
1288      C     CHECK FOR CONDUCTIVITY DISCONTINUITIES
1289                     IF(KP.NE.K)
1290           #            ECXP(I,J)=S/(.25*(H+HM)*(DX+RP*DELTAX(I+1)))
1291                     IF(KM.NE.K)
1292           #            ECXM(I,J)=S/(.25*(H+HM)*(DX+RM*DELTAX(I-1)))
1293                     EXMXP(I,J)=ECXM(I,J)+ECXP(I,J)
1294                     GOTO 10
1295      C
1296      C     2. ELECTRODE IN ONE DIRECTION
1297       3           IF(KP.EQ.0.OR.KM.EQ.0) GOTO 4
1298                     H=(DX+DELTAX(I+1))/2.
1299                     HM=(DX+DELTAX(I-1))/2.
1300                     IF(KP.GT.0) H=DX/2.
1301                     IF(KM.GT.0) HM=DX/2.
1302                     ECXP(I,J)=(S+SP)/(H*(H+HM))
1303                     ECXM(I,J)=(S+SM)/(HM*(H+HM))
1304                     EXMXP(I,J)=ECXM(I,J)+ECXP(I,J)
1305                     IF(KP.GT.0) ERHS(I,J)=ERHS(I,J)+
1306           #                                 ECXP(I,J)*ELEVOL(KP)
1307                     IF(KP.GT.0) ECXP(I,J)=0.
1308                     IF(KM.GT.0) ERHS(I,J)=ERHS(I,J)+
1309           #                                 ECXM(I,J)*ELEVOL(KM)
1310                     IF(KM.GT.0) ECXM(I,J)=0.
1311                     GOTO 10
1312      C
1313      C     3. BOUNDARY IN ONE DIRECTION
1314       4           IF(KP.GE.0.AND.KM.GE.0) GOTO 900
1315                     ECXM(I,J)=0.
1316                     ECXP(I,J)=0.
1317                     IF(KP.LT.0) ECXP(I,J)=
1318           #                       (S+SP)/(.5*((DX+DELTAX(I+1))**2))
1319                     IF(KM.LT.0) ECXM(I,J)=
1320           #                       (S+SM)/(.5*((DX+DELTAX(I-1))**2))
```

```
1321                        EXMXP(I,J)=ECXM(I,J)+ECXP(I,J)
1322      C
1323      C     CALCULATE COEFFICENTS IN THE Y DIRECTION
1324       10             KP=0
1325                      IF(J.LT.NY) KP=ELEGEO(I,J+1)
1326                      KM=0
1327                      IF(J.GT.1)  KM=ELEGEO(I,J-1)
1328                      SP=S
1329                      IF(KP.LT.0) SP=ELECON(I,J+1)
1330                      SM=S
1331                      IF(KM.LT.0) SM=ELECON(I,J-1)
1332                      RP=S/SP
1333                      RM=S/SM
1334      C
1335      C     DECIDE WHICH CASE THIS GRID BLOCK IS
1336      C     1. NORMAL BLOCK SURROUNDED BY DOMAIN
1337                      IF(KP.GE.0.OR.KM.GE.0) GOTO 5
1338                         H=(DY+DELTAY(J+1))/2.
1339                         HM=(DY+DELTAY(J-1))/2.
1340                         ECYP(I,J)=(S+SP)/(H*(H+HM))
1341                         ECYM(I,J)=(S+SM)/(HM*(H+HM))
1342      C     CHECK FOR CONDUCTIVITY DISCONTINUITIES
1343                         IF(KP.NE.K)
1344           #                ECYP(I,J)=S/(.25*(H+HM)*(DY+RP*DELTAY(J+1)))
1345                         IF(KM.NE.K)
1346           #                ECYM(I,J)=S/(.25*(H+HM)*(DY+RM*DELTAY(J-1)))
1347                         EYMYP(I,J)=ECYM(I,J)+ECYP(I,J)
1348                         GOTO 2
1349      C
1350      C     2. ELECTRODE IN ONE DIRECTION
1351       5              IF(KP.EQ.0.OR.KM.EQ.0) GOTO 6
1352                         H=(DY+DELTAY(J+1))/2.
1353                         HM=(DY+DELTAY(J-1))/2.
1354                         IF(KP.GT.0) H=DY/2.
1355                         IF(KM.GT.0) HM=DY/2.
1356                         ECYP(I,J)=(S+SP)/(H*(H+HM))
1357                         ECYM(I,J)=(S+SM)/(HM*(H+HM))
1358                         EYMYP(I,J)=ECYM(I,J)+ECYP(I,J)
1359                         IF(KP.GT.0) ERHS(I,J)=ERHS(I,J)+
1360           #                                   ECYP(I,J)*ELEVOL(KP)
1361                         IF(KP.GT.0) ECYP(I,J)=0.
1362                         IF(KM.GT.0) ERHS(I,J)=ERHS(I,J)+
1363           #                                   ECYM(I,J)*ELEVOL(KM)
1364                         IF(KM.GT.0) ECYM(I,J)=0.
1365                         GOTO 2
1366      C
1367      C     3. BOUNDARY IN ONE DIRECTION
1368       6              IF(KP.GE.0.AND.KM.GE.0) GOTO 900
1369                         ECYM(I,J)=0.
1370                         ECYP(I,J)=0.
1371                         IF(KP.LT.0) ECYP(I,J)=
1372           #                           (S+SP)/(.5*((DY+DELTAY(J+1))**2))
1373                         IF(KM.LT.0) ECYM(I,J)=
1374           #                           (S+SM)/(.5*((DY+DELTAY(J-1))**2))
1375                         EYMYP(I,J)=ECYM(I,J)+ECYP(I,J)
1376      C
1377      C
1378       2          CONTINUE
1379       1        CONTINUE
1380              RETURN
```

```
1381      C
1382      C      ERROR RETURN
1383       900     NERROR=4
1384               RETURN
1385               END
1386      C
1387      C-----------------------------------------------------------------
1388      C
1389                  SUBROUTINE THOMAS
1390      C
1391      C  2.4  SOLVE A TRIDIAGONAL SYSTEM BY THOMAS'S ALGORITHM
1392      C
1393      C/ INSERT COMTEM
1394      C/ INSERT COMDIM
1395      C
1396                DIMENSION W(50),G(50)
1397      C
1398                 W(1)=T3(1)/T2(1)
1399                 G(1)=T4(1)/T2(1)
1400      C
1401                 DO 1 I=2,NEQU
1402                      IM=I-1
1403                      DENOM=T2(I)-T1(I)*W(IM)
1404                      W(I)=T3(I)/DENOM
1405                      G(I)=(T4(I)-T1(I)*G(IM))/DENOM
1406       1         CONTINUE
1407      C
1408                 T5(NEQU)=G(NEQU)
1409                 DO 2 I=2,NEQU
1410                      I1=NEQU+1-I
1411                      IP=I1+1
1412                      T5(I1)=G(I1)-W(I1)*T5(IP)
1413       2         CONTINUE
1414      C
1415               RETURN
1416              END
1417      C
1418      C-------------  ---------------------------------------
1419      C
1420                  SUBROUTINE MAXDIF(ICODE,EPS)
1421      C
1422      C  2.5  FIND THE MAXIMUM DIFFERENCE BETWEEN TEM3, TEM1
1423      C
1424      C/ INSERT COMTEM
1425      C/ INSERT COMDIM
1426      C/ INSERT COMGLO
1427      C
1428      C
1429             EPS=0.
1430             DO 1 J=1,NY
1431                  DO 2 I=1,NX
1432                       IF(ICODE.EQ.1) K=ELEGEO(I,J)
1433                       IF(ICODE.EQ.2) K=THMGEO(I,J)
1434                            IF(K.GE.0) GOTO 2
1435                       DIF=ABS(TEM3(I,J)-TEM1(I,J))
1436                       IF(ICODE.EQ.2)
1437            #          DIF=DIF/ABS(TEM1(I,J))
1438                       EPS=AMAX1(DIF,EPS)
1439       2          CONTINUE
1440       1     CONTINUE
```

```
1441            RETURN
1442            END
1443      C
1444      C-----------------------------------------------------------------
1445      C
1446                  SUBROUTINE ECOND
1447      C
1448      C  2.6  CALCULATE THE ELECTRICAL CONDUCTIVITY
1449      C
1450      C     THE ELECTRICAL CONDUCTIVITY IS ASSUMED TO BE TEMPERATURE
1451      C     DEPENDENT. ACCORDING TO THE FORMULA:
1452      C
1453      C               SIGMA(T)=BETA(1+ALPHA(T-24))
1454      C
1455      C     WHERE T IS IN DEGREES CELCIUS.
1456      C
1457      C/ INSERT COMGLO
1458      C/ INSERT COMELE
1459      C/ INSERT COMDIM
1460      C
1461      C
1462            DO 1 J=1,NY
1463                 DO 2 I=1,NX
1464                      K=ELEGEO(I,J)
1465                      IF(K.GE.0) GOTO 2
1466      C
1467      C     FIND THE COEFFICENTS FOR THE CONDUCTIVITY
1468                      K=-K
1469                      ALPHA=ELEALP(K)
1470                      BETA=ELEBET(K)
1471                      T=TEMP(I,J)
1472      C
1473                      ELECON(I,J)=BETA*(1.+ALPHA*(T-24.))
1474      C
1475       2          CONTINUE
1476       1     CONTINUE
1477             RETURN
1478             END
1479      C
1480      C-----------------------------------------------------------------
1481      C
1482                  SUBROUTINE QCALC
1483      C
1484      C  2.7  CALCULATE THE HEATING RATE AT EACH GRIDPOINT.
1485      C
1486      C/ INSERT COMDIM
1487      C/ INSERT COMGLO
1488      C
1489      C     FOR EACH GRID POINT
1490            DO 80 J=1,NY
1491                 JP=J+1
1492                 JM=J-1
1493                DO 81 I=1,NX
1494                      IM=I-1
1495                      IP=I+1
1496                      QTHERM(I,J)=0.
1497      C
1498      C     CHECK IF THIS GRIDBLOCK IS IN THE DOMAIN
1499                      K=ELEGEO(I,J)
1500                      IF(K.GE.0) GOTO 81
```

```
      C
      C     CHECK BLOCKS IN THE X DIRECTION
                  KP=0
                  IF(I.LT.NX) KP=ELEGEO(IP,J)
                  KM=0
                  IF(I.GT.1)  KM=ELEGEO(IM,J)
      C
      C     CALCULATION WHEN SURROUNDING BLOCKS ARE DOMAIN BLOCKS
                  IF(KP.EQ.0.OR.KM.EQ.0.OR.(KP.NE.K.AND.KM.EQ.K.AND
     #            .KP.LT.0).OR.(KM.NE.K.AND.KP.EQ.K.AND.KM.LT.0))GOTO 2
                      H=(DELTAX(I)+DELTAX(IP))/2.
                      HM=(DELTAX(I)+DELTAX(IM))/2.
                      IF(KP.GT.0) H=DELTAX(I)/2.
                      IF(KM.GT.0) HM=DELTAX(I)/2.
                      HS=H**2
                      HMS=HM**2
                      EX=(POTENT(IP,J)*HMS+(HS-HMS)*POTENT(I,J)
     #                    -POTENT(IM,J)*HS)/(H*HM*(H+HM))
                  GOTO 3
      C
      C     SPECIAL CASES
       2          IF(KP.GE.0.AND.KM.GE.0) GOTO 900
                  IF((KP.EQ.0.AND.KM.LT.0).OR.KM.EQ.K)
     #    EX=(2./(DELTAX(I)+DELTAX(IM)))*(POTENT(I,J)-POTENT(IM,J))
                  IF((KP.LT.0.AND.KM.EQ.0).OR.KP.EQ.K)
     #    EX=(2./(DELTAX(I)+DELTAX(IP)))*(POTENT(IP,J)-POTENT(I,J))
      C
       3          CONTINUE
      C
      C     CHECK BLOCKS IN THE Y DIRECTION
                  KP=0
                  IF(J.LT.NY) KP=ELEGEO(I,JP)
                  KM=0
                  IF(J.GT.1)  KM=ELEGEO(I,JM)
      C
      C     CALCULATION WHEN SURROUNDED BY DOMAIN BLOCKS
                  IF(KP.EQ.0.OR.KM.EQ.0.OR.(KP.NE.K.AND.KM.EQ.K.AND
     #            .KP.LT.0).OR.(KM.NE.K.AND.KP.EQ.K.AND.KM.LT.0))GOTO 4
                      H=(DELTAY(J)+DELTAY(JP))/2.
                      HM=(DELTAY(J)+DELTAY(JM))/2.
                      IF(KP.GT.0) H=DELTAY(J)/2.
                      IF(KM.GT.0) HM=DELTAY(J)/2.
                      HS=H**2
                      HMS=HM**2
                      EY=(POTENT(I,JP)*HMS+(HS-HMS)*POTENT(I,J)
     #                    -POTENT(I,JM)*HS)/(H*HM*(H+HM))
                  GOTO 5
      C
      C     SPECIAL CASES
       4          IF(KP.GE.0.AND.KM.GE.0) GOTO 900
                  IF((KP.EQ.0.AND.KM.LT.0).OR.KM.EQ.K)
     #    EY=(2./(DELTAY(J)+DELTAY(JM)))*(POTENT(I,J)-POTENT(I,JM))
                  IF((KP.LT.0.AND.KM.EQ.0).OR.KP.EQ.K)
     #    EY=(2./(DELTAY(J)+DELTAY(JP)))*(POTENT(I,JP)-POTENT(I,J))
      C
       5          CONTINUE
      C
      C     CALCULATE HEATING
                  QTHERM(I,J)=ELECON(I,J)*(EX**2+EY**2)
      C
```

```
      81            CONTINUE
      80         CONTINUE
               RETURN
C
C      ERROR RETURN
900            NERROR=2
               RETURN
               END
C
C-----------------------------------------------------------------
C
               SUBROUTINE TCALC
C
C  2.8  SOLVE THE TEMPERATURE EQUATION
C
C/ INSERT COMGLO
C/ INSERT COMTHM
C/ INSERT COMTEM
C/ INSERT COMCON
C/ INSERT COMDIM
C
C      COPY THE TEMPERATURE INTO TEM1
               CALL COPYR(TEMP,1,TEM1,1,NDX*NDY)
C
               M=0
 8             M=M+1
C
C      START OF FIRST STAGE
               DO 1 J=1,NY
                    JM=J-1
                    IF(J.EQ.1) JM=1
                    JP=J+1
                    IF(J.EQ.NY) JP=NY
                    NEQU=0
                    DO 2 I=1,NX
C
C      IF BLOCK IS NOT IN DOMAIN, SKIP TO NEXT BLOCK
                         K=THMGEO(I,J)
                         IF(K.GE.0) GOTO 2
                         F1=THMCAP(I,J)*(1-K)/(DTIME/2.)
C
C      ASSIGN TRIDIAGONAL COEFFICENTS
                         NEQU=NEQU+1
                         T1(NEQU)=TCXM(I,J)
                         T2(NEQU)=-(TCX(I,J)+F1)
                         T3(NEQU)=TCXP(I,J)
                         T4(NEQU)=-(TCYM(I,J)*TEM1(I,JM)+TCYP(I,J)*TEM1(I,JP))
     #                           +(TCY(I,J)-F1)*TEM1(I,J)-TCRHS(I,J)
     #                           -QTHERM(I,J)
 2             CONTINUE
C
C      SOLVE TRIDIAGONAL SYSTEM
               CALL THOMAS
C
C      PLACE RESULTS IN TEM2
               NEQU=0
               DO 3 I=1,NX
                    TEM2(I,J)=0.
                    K=THMGEO(I,J)
                    IF(K.GE.0) GOTO 3
```

```
1621                    NEQU=NEQU+1
1622                    TEM2(I,J)=T5(NEQU)
1623     3          CONTINUE
1624     C
1625      1       CONTINUE
1626     C
1627     C       START OF SECOND STAGE
1628             DO 4 I=1,NX
1629                  IP=I+1
1630                  IF(I.EQ.NX) IP=NX
1631                  IM=I-1
1632                  IF(I.EQ.1)  IM=I
1633                  NEQU=0
1634                  DO 5 J=1,NY
1635     C
1636     C       IF BLOCK NOT IN DOMAIN, SKIP TO NEXT BLOCK
1637                       K=THMGEO(I,J)
1638                       IF(K.GE.0) GOTO 5
1639     C
1640     C       ASSIGN TRIDIAGONAL COEFFICENTS
1641                       F1=THMCAP(-K)/(DTIME/2.)
1642                       NEQU=NEQU+1
1643                       T1(NEQU)=TCYM(I,J)
1644                       T2(NEQU)=-(TCY(I,J)+F1)
1645                       T3(NEQU)=TCYP(I,J)
1646                       T4(NEQU)=-(TCXM(I,J)*TEM2(IM,J)+TCXP(I,J)*TEM2(IP,J))
1647            #                  +(TCX(I,J)-F1)*TEM2(I,J)-TCRHS(I,J)
1648            #                  -QTHERM(I,J)
1649      5          CONTINUE
1650     C
1651     C       SOLVE THE TRIDIAGONAL SYSTEM
1652                  CALL THOMAS
1653     C
1654     C       PLACE THE RESULTS IN TEM3
1655                  NEQU=0
1656                  DO 6 J=1,NY
1657                       TEM3(I,J)=0.
1658                       K=THMGEO(I,J)
1659                       IF(K.GT.0) TEM3(I,J)=THMTEM(K)
1660                       IF(K.GE.0) GOTO 6
1661                       NEQU=NEQU+1
1662                       TEM3(I,J)=T5(NEQU)
1663      6          CONTINUE
1664     C
1665      4       CONTINUE
1666     C
1667     C       FIND THE MAXIMUM RELATIVE CHANGE IN TEMPERATURE
1668                  CALL MAXDIF(2,DELT)
1669     C
1670     C       IF CHANGE LESS THEN TOLERANCE EXIT OUT
1671                  IF(DELT.LE.DTEMP) GOTO 7
1672     C
1673     C       CHANGE TOO BIG, CHANGE DTIME
1674                  IF(M.GT.5) GOTO 900
1675                  DTIME=DTIME*DTEMP/DELT
1676                  DTIME=DTIME-DTIME*.01
1677                  GOTO 8
1678     C
1679     C       COPY NEW TEMPERATURE TO TEMP
1680      7           CALL COPYR(TEM3,1,TEMP,1,NDX*NDY)
```

```
1681      C
1682            RETURN
1683      C
1684      C     ERROR RETURN
1685       900    NERROR=3
1686              RETURN
1687            END
1688      C
1689      C-----------------------------------------------------------------
1690      C
1691                  SUBROUTINE ENGBAL
1692      C
1693      C  2.9  CALCULATE THE ENERGY BALANCE FOR THE TIMESTEP
1694      C
1695      C     THREE METHODS ARE USED TO CALCULATE THE ENERGY INPUT
1696      C           1.  ELECTRICAL POWER * TIME
1697      C           2.  HEATING RATE * VOLUME * TIME - HEAT FLOW OUT
1698      C           3.  TEMPERATURE RISE * VOLUME * HEAT CAPACITY
1699      C
1700      C     THE LAST TWO METHODS ARE CALCULATED SEPERATELY FOR EACH REGION.
1701      C
1702      C/ INSERT COMGLO
1703      C/ INSERT COMTHM
1704      C/ INSERT COMCON
1705      C/ INSERT COMDIM
1706      C
1707      C     CALCULATE ELECTRICAL ENERGY
1708                DEENG=POWER * DTIME
1709                TEENG=TEENG + DEENG
1710      C
1711      C     CALCULATE HEATING ENERGY AND TEMPERATURE RISE ENERGY
1712                DQENG=0.
1713                TTENG=0.
1714                DO 111 K=1,10
1715       111              TENG(K)=0.
1716           DO 1 J=1,NY
1717                DY=DELTAY(J)
1718                DO 2 I=1,NX
1719                     V=DY*DELTAX(I)*THICK
1720      C
1721      C     CHECK IF BLOCK IN TEMPERATURE DOMAIN
1722                     K=THMGEO(I,J)
1723                     IF(K.GE.0) GOTO 2
1724      C
1725      C     CALCULATE HEAT PRODUCED MINUS HEAT FLOW OUT TO CONSTANT
1726      C     TEMPERATURE BOUNDARIES.
1727                   DQ=QTHERM(I,J)*V*DTIME
1728                   IF(I.EQ.NX) GOTO 3
1729                     KP=THMGEO(I+1,J)
1730                     IF(KP.LE.0) GOTO 3
1731                       DQ1=(TEMP(I,J)-THMTEM(KP))*THMCON(K)*DTIME*
1732           #                 2.*DY*THICK/DELTAX(I)
1733                       DQ=DQ-DQ1
1734       3           IF(I.EQ.1) GOTO 4
1735                     KM=THMGEO(I-1,J)
1736                     IF(KM.LE.0) GOTO 4
1737                       DQ1=(TEMP(I,J)-THMTEM(KM))*THMCON(K)*DTIME*
1738           #                 2.*DY*THICK/DELTAX(I)
1739                       DQ=DQ-DQ1
1740       4           IF(J.EQ.NY) GOTO 5
```

```
1741                        KP=THMGEO(I,J+1)
1742                        IF(KP.LE.0) GOTO 5
1743                          DQ1=(TEMP(I,J)-THMTEM(KP))*THMCON(K)*DTIME*
1744          #                    2.*DELTAX(I)*THICK/DY
1745                          DQ=DQ-DQ1
1746       5                IF(J.EQ.1) GOTO 6
1747                          KM=THMGEO(I,J-1)
1748                          IF(KM.LE.0) GOTO 6
1749                            DQ1=(TEMP(I,J)-THMTEM(KM))*THMCON(K)*DTIME*
1750          #                    2.*DELTAX(I)*THICK/DY
1751                            DQ=DQ-DQ1
1752       6                CONTINUE
1753                        DQENG=DQENG+DQ
1754                        QENG(-K)=QENG(-K)+DQ
1755      C
1756      C       CALCULATE ENERGY INDICATED BY TEMPERATURE RISE.
1757                        DT=(TEMP(I,J)-TINIT)*V*THMCAP(-K)
1758                        TTENG=TTENG+DT
1759                        TENG(-K)=TENG(-K)+DT
1760      C
1761        2           CONTINUE
1762        1       CONTINUE
1763                    TQENG=TQENG+DQENG
1764                RETURN
1765                END
1766      C
1767      C-------------------------------------------------------------
1768      C
1769                    SUBROUTINE ELECUR
1770      C
1771      C   2.10   FIND THE CURRENT THROUGH A SURFACE PERPENDICULAR TO
1772      C          THE X OR Y DIRECTION
1773      C
1774      C       IF NIJ=1, THE SURFACE IS PERPENDICULAR TO X, ALONG THE
1775      C                 GRIDLINE I=NCI.
1776      C       OTHERWISE, THE INTEGRAL IS PERPENDICULAR TO Y, ALONG THE
1777      C                  GRIDLINE J=NCI.
1778      C
1779      C/ INSERT COMGLO
1780      C/ INSERT COMDIM
1781      C/ INSERT COMCON
1782      C
1783      C       CHECK ORIENTATION OF INTEGRAL.
1784                    IF(NIJ.NE.1) GOTO 10
1785      C
1786      C       PERPENDICULAR TO X
1787                    H=(DELTAX(NCI)+DELTAX(NCI+1))/2.
1788                    HM=(DELTAX(NCI)+DELTAX(NCI-1))/2.
1789                    HS=H**2
1790                    HMS=HM**2
1791                    CUR=0.
1792                    DO 1 J=1,NY
1793                        S=ELECON(NCI,J)
1794                        E=(HMS*POTENT(NCI+1,J) + (HS-HMS)*POTENT(NCI,J)
1795          #                - HS*POTENT(NCI-1,J))/(H*HM*(H+HM))
1796                        CUR=CUR+E*S*DELTAY(J)
1797        1           CONTINUE
1798                    CUR=ABS(CUR*THICK)
1799                    RETURN
1800      C
```

```
1801      C     PERPENDICULAR TO Y
1802       10         H=(DELTAY(NCI)+DELTAY(NCI+1))/2.
1803                  HM=(DELTAY(NCI)+DELTAY(NCI-1))/2.
1804                  HS=H**2
1805                  HMS=HM**2
1806                  CUR=0.
1807                  DO 2 I=1,NX
1808                       S=ELECON(I,NCI)
1809                       E=( HMS*POTENT(I,NCI+1) + (HS-HMS)*POTENT(I,NCI)
1810                  #        - HS*POTENT(I,NCI-1))/(H*HM*(H+HM))
1811                       CUR=CUR+E*S*DELTAX(I)
1812       2          CONTINUE
1813                  CUR=ABS(CUR*THICK)
1814                  RETURN
1815                END
1816      C
1817      C-------------------------------------------------------------------
1818                SUBROUTINE OUTPUT(ICODE)
1819      C
1820      C 3.1  CONTROL THE OUTPUT
1821      C
1822      C/ INSERT COMBAS
1823      C/ INSERT COMDIM
1824      C/ INSERT COMGLO
1825      C/ INSERT COMCON
1826      C
1827      C     BRANCH TO INITIAL, MIDDLE, AND FINAL OUPUT ROUTINES
1828                GOTO (1,2,3),ICODE
1829      C
1830      C     INITIAL OUTPUT
1831       1          IF(NLRES) RETURN
1832                  CALL PAGE
1833      C     OUTPUT ELECTRICAL GRID STRUCTURE
1834                  CALL OUTGRD(1)
1835                  CALL PAGE
1836      C     OUTPUT THERMAL GRID STRUCTURE
1837                  CALL OUTGRD(2)
1838      C     IF TAPE STORAGE IS REQUESTED, STORE GRID ETC. ON TAPE
1839                  IF(NSTO.LT.200) CALL OUTTAP(1)
1840              RETURN
1841      C
1842      C
1843      C     PERIODIC OUTPUT
1844      C     CHECK IF PRINTED OUTPUT THIS  TIMESTEP
1845       2          IF(MOD(NSTEP,NSPO).NE.0.AND.NSTEP.NE.1) GOTO 5
1846       4            CALL PAGE
1847                    CALL OUTI('TIMESTEP NUMBER                    ',NSTEP)
1848                    IF(NSTO.LE.200)
1849                  #  CALL OUTI('CURRENT RECORD NUMBER              ',NREC)
1850                    CALL BLINES(1)
1851                    CALL OUTR('TIME AT END OF STEP                ',TIME)
1852                    CALL OUTR('SIZE OF TIMESTEP                   ',DTIME)
1853                    CALL BLINES(1)
1854                    IF(NTYPE.EQ.4) GOTO 6
1855                      CALL OUTI('NO. OF ITERATIONS OF A.D.I.P.    ',MITER)
1856                      CALL OUTR('VOLTAGE BETWEEN ELECTRODES       ',VOLTS)
1857                      CALL OUTR('POWER INPUT TO DOMAIN            ',POWER)
1858                      CALL OUTR('CURRENT BETWEEN ELECTRODES       ',CUR)
1859                      CALL OUTR('RESISTANCE BETWEEN ELECTRODES    ',RESIST)
1860                      CALL BLINES(1)
```

```
1861      6           WRITE(NPRINT,20)
1862                  WRITE(NPRINT,22) DEENG,DQENG
1863                  WRITE(NPRINT,21) TEENG,TQENG,TTENG
1864                  DO 100 K=1,NREG
1865                        WRITE(NPRINT,23) K,QENG(K),TENG(K)
1866      100         CONTINUE
1867                  CALL BLINES(1)
1868                  IF(NTYPE.EQ.4) GOTO 7
1869                       CALL OUTINT(4,1)
1870                       IF((25+NPY).GT.45) CALL PAGE
1871                       CALL OUTINT(5,1)
1872                       IF((25+2*NPY).GT.50) CALL PAGE
1873       7          CALL OUTINT(3,1)
1874      C
1875      C     PERIODIC TAPE OUTPUT
1876       5          IF(NSTO.LE.200.AND.(MOD(NSTEP,NSTO).EQ.0.OR.ICODE.EQ.3))
1877      #               CALL OUTTAP(2)
1878            RETURN
1879      C
1880      C
1881       20     FORMAT(4X,'ENERGY BALANCE      ( JOULES )')
1882       21     FORMAT(4X,'CUMULATIVE:  ELECTRICAL ENERGY =',1PE12.4,
1883      #          5X,'HEAT GENERATED =',1PE12.4,5X,
1884      #          'TEMP. RISE ENERGY =',1PE12.4)
1885       22    FORMAT(4X,'TIMESTEP   :  ELECTRICAL ENERGY =',1PE12.4,5X,
1886      #        'HEAT PRODUCED =',1PE12.4)
1887       23    FORMAT(8X,'REGION =',I3,5X,'HEAT GENERATED =',1PE12.4,5X,
1888      #            'TEMP. RISE ENERGY =',1PE12.4)
1889      C
1890      C     FINAL OUTPUT
1891       3          IF(MOD(NSTEP,NSPO).NE.0.AND.NSTEP.NE.1) GOTO 4
1892                  IF(MOD(NSTEP,NSTO).NE.0) GOTO 5
1893             RETURN
1894             END
1895      C
1896      C-----------------------------------------------------------------
1897      C
1898            SUBROUTINE OUTGRD(ICODE)
1899      C
1900      C  3.2   OUTPUT ONE OF THE GLOBAL VARIABLE ARRAYS
1901      C
1902      C    ICODE INDICATES WHICH ARRAY IS TO BE OUTPUT
1903      C          1 - ELEGEO, THE ELECTRICAL GEOMETRY
1904      C          2 - THMGEO, THE THERMAL GEOMETRY
1905      C          3 - TEMP  , THE TEMPERATURE
1906      C          4 - POTENT, THE ELECTRICAL POTENTIAL
1907      C          5 - QTHERM, THE HEATING
1908      C          6 - ELECON, THE ELECTRICAL CONDUCTIVITY
1909      C
1910      C/ INSERT COMBAS
1911      C/ INSERT COMDIM
1912      C/ INSERT COMGLO
1913      C
1914      C     PRINT OUT HEADING
1915            IF(ICODE.EQ.1) WRITE(NPRINT,20)
1916            IF(ICODE.EQ.2) WRITE(NPRINT,21)
1917            IF(ICODE.EQ.3) WRITE(NPRINT,22)
1918            IF(ICODE.EQ.4) WRITE(NPRINT,23)
1919            IF(ICODE.EQ.5) WRITE(NPRINT,24)
1920            IF(ICODE.EQ.6) WRITE(NPRINT,25)
```

```
1921                      IF(ICODE.LT.3) GOTO 4
1922      C
1923      C     FORMAT STATEMENTS
1924       20       FORMAT('O',10X,'ELECTRICAL REGIONS OF THE GRID (NOT TO SCALE)')
1925       21       FORMAT('O',10X,'THERMAL REGIONS OF THE GRID  (NOT TO SCALE)')
1926       22       FORMAT('O',10X,'TEMPERATURE IN DEGREES CELSIUS')
1927       23       FORMAT('O',10X,'ELECTRICAL POTENTIAL IN VOLTS')
1928       24       FORMAT('O',10X,'HEATING RATE IN JOULES/SECOND-METER**3')
1929       25       FORMAT('O',10X,'ELECTRICAL CONDUCTIVITY IN MHOS/METER')
1930       26       FORMAT('O    COLUMN ',10(8X,I2))
1931       27       FORMAT('         X    ',10(3X,F7.3))
1932       28       FORMAT(' ROW     Y    ')
1933       29       FORMAT(' ',I3,1X,F7.3,10(3X,F7.2))
1934       30       FORMAT(' ',I3,1X,F7.3,10(3X,F7.0))
1935       31       FORMAT(' ',I3,1X,F7.3,10(3X,F7.4))
1936       32       FORMAT('O')
1937.      33       FORMAT(' ',I2,5X,50(I2))
1938       34       FORMAT('OCOLUMN ',50(I2))
1939       35       FORMAT('OROW')
1940      C
1941                     DO 1 I1=1,NX,10
1942                          IT=MINO(I1+9,NX)
1943                               DO 2 J2=1,NY,50
1944                                    JI=MINO(J2+49,NY)
1945      C      PRINT PAGE HEADING
1946                               WRITE(NPRINT,26) (I,I=I1,IT)
1947                               WRITE(NPRINT,27) (XCOORD(I),I=I1,IT)
1948                               WRITE(NPRINT,28)
1949      C      PRINT EACH ROW
1950                                    DO 3 JM=J2,JI
1951                                         J=NY+1-JM
1952                                              IF(ICODE.EQ.3)
1953            #                    WRITE(NPRINT,29) J,YCOORD(J),(TEMP(I,J),I=I1,IT)
1954                                              IF(ICODE.EQ.4)
1955            #                    WRITE(NPRINT,29) J,YCOORD(J),(POTENT(I,J),I=I1,IT)
1956                                              IF(ICODE.EQ.5)
1957            #                    WRITE(NPRINT,30) J,YCOORD(J),(QTHERM(I,J),I=I1,IT)
1958                                              IF(ICODE.EQ.6)
1959            #                    WRITE(NPRINT,31) J,YCOORD(J),(ELECON(I,J),I=I1,IT)
1960       3                             CONTINUE
1961                                     WRITE(NPRINT,32)
1962       2                        CONTINUE
1963       1                    CONTINUE
1964                          RETURN
1965      C
1966      C     OUTPUT THE GEOM[illegible] DEFINING ARRAYS
1967       4                   WRITE(NP[illegible] 35)
1968                          DO 5 J=1,N
1969                               JM=NY+[illegible] J
1970                               IF(ICODE[illegible] EQ.1)
1971            #                     WRITE([illegible]PRINT,[illegible] JM,(ELEGEO(I,JM),I=1,NX)
1972                               IF(ICODE.EQ.2)
1973            #                     WRITE([illegible]PRINT,[illegible] JM,(THMGEO(I,JM),I=1,NX)
1974       5                   CONTINUE
1975                          WRITE(NPRINT,34) (I,I=1,NX)
1976                     RETURN
1977                     END
1978      C
1979      C-------------------------------------------------------------------
1980      C
```

```
1981            FUNCTION ALINTP(X,Y,Z,Z1,Z2,M,N)
1982      C
1983      C  3.3  INTERPOLATE VALUES FROM GRID
1984      C
1985      C     THIS FUNCTION INTERPOLATES A VALUE AT THE POINT (X,Y) FROM
1986      C     THE MATRIX Z. THE INTERPOLATION IS LINEAR.
1987      C
1988            DIMENSION Z(50,50),Z1(50),Z2(50)
1989      C
1990      C     FIND FIRST X CO-ORDINATE NOT LESS THAN X
1991      C
1992               DO 1 II=2,M
1993            I=II-1
1994            IF(X-Z1(II))3,1,1
1995      C     ************
1996          1 CONTINUE
1997          3    XL=X-Z1(I)
1998               XR=Z1(I+1)-X
1999               XBASE=XR+XL
2000      C
2001      C     FIND FIRST Y CO-ORDINATE NOT LESS THAN Y
2002      C
2003               DO 2 JJ=2,N
2004            J=JJ-1
2005            IF(Y-Z2(JJ))4,2,2
2006      C     ************
2007          2 CONTINUE
2008          4    YL=Y-Z2(J)
2009               YR=Z2(J+1)-Y
2010               YBASE=YR+YL
2011      C
2012      C     BILINEAR INTERPOLATION
2013      C
2014               ALINTP=(YL*(XR*Z(I,J+1)+XL*Z(I+1,J+1))
2015           #   +YR*(XR*Z(I,J)+XL*Z(I+1,J)))/(XBASE*YBASE)
2016            RETURN
2017            END
2018      C
2019      C-------------------------------------------------------------
2020      C
2021                  SUBROUTINE OUTINT(ICODE,IP)
2022      C
2023      C  3.4  INTERPOLATE ONE OF THE GLOBAL VARIABLES
2024      C
2025      C     ICODE - DETERMINES WHICH VARIABLE IS INTERPOLATED ( SEE OUTGRD )
2026      C     IP    = 1, IF PRINTING DESIRED.
2027      C               RESULTS OF ITERPOLATION STORED IN TEM3
2028      C
2029      C/ INSERT COMGLO
2030      C/ INSERT COMTEM
2031      C/ INSERT COMDIM
2032      C/ INSERT COMBAS
2033      C/ INSERT COMELE
2034      C/ INSERT COMTHM
2035      C
2036      C
2037                  TX=XMAX-XMIN
2038                  TY=YMAX-YMIN
2039                  SX=TX/(NPX-1.)
2040                  SY=TY/(NPY-1.)
```

```
      C
      C     COPY APPROPRIATE ARRAY TO TEM1
            IF(ICODE.EQ.3) CALL COPYR(TEMP,1,TEM1,1,NDX*NDY)
            IF(ICODE.EQ.4) CALL COPYR(POTENT,1,TEM1,1,NDX*NDY)
            IF(ICODE.EQ.5) CALL COPYR(QTHERM,1,TEM1,1,NDX*NDY)
            IF(ICODE.EQ.6) CALL COPYR(ELECON,1,TEM1,1,NDX*NDY)
      C
      C     DO INTERPOLATION
      C     RESULTS STORED IN TEM3, X COORDINATES IN T1, Y COORDINATES IN T2
            DO 1 J=1,NPY
                 Y=YMIN+(J-1)*SY
                 T2(J)=Y
                 DO 2 I=1,NPX
                      X=XMIN+(I-1)*SX
                      T1(I)=X
                      TEM3(I,J)=ALINTP(X,Y,TEM1,XCOORD,YCOORD,NX,NY)
       2         CONTINUE
       1    CONTINUE
      C
      C     IF NO PRINTING IS DESIRED, RETURN
                 IF(IP.NE.1) RETURN
      C
      C     PRINT OUT ARRAY
      C     PRINT OUT HEADING
                IF(ICODE.EQ.3) WRITE(NPRINT,22)
                IF(ICODE.EQ.4) WRITE(NPRINT,23)
                IF(ICODE.EQ.5) WRITE(NPRINT,24)
                IF(ICODE.EQ.6) WRITE(NPRINT,25)
      C
      C     FORMAT STATEMENTS
        22       FORMAT('O',10X,'TEMPERATURE IN DEGREES CELSIUS')
        23       FORMAT('O',10X,'ELECTRICAL POTENTIAL IN VOLTS')
        24       FORMAT('O',10X,'HEATING RATE IN JOULES/SECOND-METER**3')
        25       FORMAT('O',10X,'ELECTRICAL CONDUCTIVITY IN MHOS/METER')
        26       FORMAT('O    COLUMN ',10(8X,I2))
        27       FORMAT('O       X (M)',10(3X,F7.3))
        28       FORMAT('    Y (M)')
        29       FORMAT(' ',F7.3,5X,10(2X,F8.1))
      C
                    DO 6 I1=1,NPX,10
                         IT=MINO(I1+9,NPX)
                              DO 7 J2=1,NPY,50
                                 JI=MINO(J2+49,NPY)
      C     PRINT PAGE HEADING
                         WRITE(NPRINT,27) (T1(I),I=I1,IT)
                         WRITE(NPRINT,28)
      C     PRINT EACH ROW
                                   DO 8 JM=J2,JI
                                      J=NPY+1-JM
                           WRITE(NPRINT,29) T2(J),(TEM3(I,J),I=I1,IT)
        8                        CONTINUE
        7                   CONTINUE
        6                CONTINUE
                 RETURN
                 END
      C
      C-----------------------------------------------------------------
      C
                 SUBROUTINE OUTR(A,B)
      C
```

```
2101      C  3.5  OUTPUT A REAL VARIABLE WITH A LABEL
2102      C
2103      C/ INSERT COMBAS
2104                 REAL A(8),B
2105                 WRITE(NPRINT,20) (A(I),I=1,8),B
2106       20      FORMAT(4X,8A4,' =',1PE12.4)
2107                 RETURN
2108               END
2109      C
2110      C-------------------------------------------------------------
2111      C
2112                 SUBROUTINE OUTI(A,B)
2113      C
2114      C  3.6  OUTPUT A LABEL AND AN INTEGER VARIABLE
2115      C
2116      C/ INSERT COMBAS
2117                 REAL A(8)
2118                 INTEGER B
2119                 WRITE(NPRINT,20) (A(I),I=1,8),B
2120       20     FORMAT(4X,8A4,' =',I12)
2121                 RETURN
2122               END
2123      C
2124      C-------------------------------------------------------------
2125      C
2126                 SUBROUTINE OUTH(A,B)
2127      C
2128      C  3.7  OUTPUT A LABEL AND A HOLLERITH VARABLE.
2129      C
2130      C/ INSERT COMBAS
2131                 REAL A(8)
2132                 REAL B
2133                 WRITE(NPRINT,20) (A(I),I=1,8),B
2134       20      FORMAT(4X,8A4,' =',8X,A4)
2135                 RETURN
2136                 END
2137      C
2138      C-------------------------------------------------------------
2139      C
2140                 SUBROUTINE OUTTAP(ICODE)
2141      C
2142      C  3.8  OUTPUT RUN INFORMATION TO MAGNETIC TAPE
2143      C
2144      C/ INSERT COMBAS
2145      C/ INSERT COMGLO
2146      C/ INSERT COMELE
2147      C/ INSERT COMTHM
2148      C/ INSERT COMCON
2149      C/ INSERT COMDIM
2150      C
2151                 GOTO (1,2) , ICODE
2152      C
2153      C      INITIAL STORAGE
2154       1         WRITE(NONLIN) ELEGEO,THMGEO,DELTAX,DELTAY,THICK,
2155            #                  XCOORD,YCOORD,XMIN,XMAX,YMIN,YMAX,ELEVOL,
2156            #                  ELEALP,ELEBET,EPSELE,THMCON,THMCAP,THMTEM,
2157            #                  TINIT,NX,NY,NALPHA,MMAX,NREG,NGEO,NSPO,
2158            #                  NSTO,NPX,NPY,NIJ,NCI
2159                 NREC=NREC+1
2160                 RETURN
```

```
2161      C
2162      C      PERIODIC STORAGE
2163       2        WRITE(NONLIN) NSTEP,TIME,POTENT,QTHERM,TEMP,TEENG,TENG,
2164            #                TOENG,QENG,NREC,DTIME
2165              NREC=NREC+1
2166              RETURN
2167             END
2168      C
2169      C-----------------------------------------------------------------
2170      C
2171                SUBROUTINE TESEND
2172      C
2173      C 4.1  TEST FOR COMPLETION OF RUN
2174      C
2175      C/ INSERT COMBAS
2176      C/ INSERT COMGLO
2177      C/ INSERT COMCON
2178      C/ INSERT COMDIM
2179      C
2180                 IF(NERROR.NE.0) CALL ENDRUN
2181                 IF(NSTEP.GE.NRUN) NLEND = .TRUE.
2182                 IF(TIME.GE.(HTIME+CTIME)) NLEND = .TRUE.
2183               RETURN
2184               END
2185      C
2186      C-----------------------------------------------------------------
2187      C
2188                SUBROUTINE ENDRUN
2189      C
2190      C 4.2  TERMINATE THE RUN
2191      C
2192      C/ INSERT COMBAS
2193      C/ INSERT COMDDP
2194      C/ INSERT COMDIM
2195      C
2196      C      CHECK IF A NORMAL TERMINATION
2197             IF(.NOT.NLEND) GO TO 100
2198                CALL BLINES(2)
2199                CALLMESAGE(48H   4.2 TERMINATE THE RUN                    )
2200                WRITE(18,20)
2201       20       FORMAT('+',50X,'*** NORMAL EXIT')
2202                CALL BLINES(2)
2203                CALL DAYTIM
2204                CALL RUNTIM
2205                CALL PAGE
2206                STOP
2207      C
2208      C      ERROR WAS FOUND SOMEWHERE, ABNORMAL TERMINATION
2209        100 CONTINUE
2210            CALL BLINES(3)
2211            CALLMESAGE(48H   4.2 ABNORMAL EXIT                          )
2212                 IF(NERROR.EQ.1)
2213           # CALLMESAGE(48H  ***  SOLUTION FAILED TO CONVERGE IN ELEPOT    )
2214                 IF(NERROR.EQ.2)
2215           # CALLMESAGE(48H  ***  GEOMETRIC ERROR DETECTED IN ROUTINE QCALC)
2216                 IF(NERROR.EQ.3)
2217           # CALLMESAGE(48H  ***  ERROR RETURN FROM ROUTINE TCALC         )
2218                IF(NERROR.EQ.4)
2219           # CALLMESAGE(48H   ***   ERROR RETURN FROM SUBROUTINE ELECOF    )
2220                 CALL OUTGRD(4)
```

```
2221                  CALL OUTGRD(5)
2222                  CALL OUTGRD(3)
2223      C
2224      C       PRINT THE FINAL TIMES
2225                  CALL BLINES(2)
2226                  CALL DAYTIM
2227                  CALL RUNTIM
2228                  CALL PAGE
2229      C
2230                  STOP  2230
2231                  END
2232      C
2233      C-------------------------------------------------------------
2234      C
2235                  SUBROUTINE MESAGE(KMESS)
2236      C
2237      C U.1  PRINT 48-CHARACTER MESSAGE ON OUTPUT CHANNEL
2238      C
2239      C       VERSION 1B              17/12/73        KVR/MHH         CULHAM
2240      C
2241      C/ INSERT COMBAS
2242                  DIMENSION KMESS(12)
2243      C
2244                  WRITE(NOUT,9900) (KMESS(J),J=1,12)
2245      C
2246                  RETURN
2247       9900       FORMAT(4X,12A4)
2248                  END
2249      C
2250      C-------------------------------------------------------------
2251      C
2252                  SUBROUTINE PAGE
2253      C
2254      C U.2  FETCH NEW PAGE ON OUTPUT CHANNEL
2255      C
2256      C       VERSION 1B              17/12/73        KVR/MHH         CULHAM
2257      C
2258      C/ INSERT COMBAS
2259                  WRITE(NOUT,9900)
2260      C
2261                  RETURN
2262       9900       FORMAT(1H1)
2263                  END
2264      C
2265      C-------------------------------------------------------------
2266      C
2267                  SUBROUTINE BLINES(K)
2268      C
2269      C U.3  INSERT BLANK LINES ON OUTPUT CHANNEL
2270      C
2271      C       VERSION 1B              17/12/73        KVR/MHH         CULHAM
2272      C
2273      C/ INSERT COMBAS
2274      C
2275                  DO 100 J=1,K
2276         100      WRITE(NOUT,9900)
2277      C
2278                  RETURN
2279       9900       FORMAT(1H )
2280                  END
```

```
2281      C
2282      C-------------------------  ------------------------------------
2283      C
2284                SUBROUTINE RUNTIM
2285      C
2286      C U.12 UPDATE CPU TIME (MINS) AND PRINT IT
2287      C
2288      C      VERSION 2B            17/12/73       KVR/MHH          CULHAM
2289      C
2290      C/ INSERT COMBAS
2291      C
2292      C      TIME(1,0,ICPUT) IS A MTS LIBRARY FUNCTION GIVING THE CPU-TIME
2293      C      USED SO FAR (ICPUT IN MSECS)
2294                 CALL TIME(1,0,ICPUT)
2295                ISEC = ICPUT/1000
2296                MIN = ISEC/60
2297                ISEC = ISEC - 60*MIN
2298                SEC = ISEC
2299                CPTIME = MIN + SEC/60.
2300               WRITE(NOUT,9900) MIN,ISEC
2301     C
2302               RETURN
2303       9900    FORMAT(5X,22HCPU TIME USED SO FAR =,I4,5H MINS,I4,5H SECS)
2304               END
2305     C
2306     C-------------------------------------------------------------------
2307     C
2308               SUBROUTINE DAYTIM
2309     C
2310     C U.13 PRINT DATE AND TIME
2311     C
2312     C      VERSION 2B            17/12/73       KVR/MHH          CULHAM
2313     C
2314     C/ INSERT COMBAS
2315     C      TIME IS AN MTS LIBRARY ROUTINE WHICH RETURNS THE DATE AND TIME
2316                DIMENSION DATE(4),TIIME(2)
2317                CALL TIME(21,0,DATE)
2318                CALL TIME(4,0,TIIME)
2319     C
2320                WRITE(NOUT,9900) DATE,TIIME
2321               RETURN
2322       9900     FORMAT(5X,4A4,5X,2A4)
2323               END
2324     C
2325     C-------------------------------------------------------------
2326     C
2327               SUBROUTINE RESETR(PA,KDIM,PVALUE)
2328     C
2329     C U.14 RESET REAL ARRAY TO SPECIFIED VALUE
2330     C
2331     C      VERSION 1B            17/12/73       KVR/MHH          CULHAM
2332     C
2333            DIMENSION   PA(KDIM)
2334     C
2335              DO 100 J=1,KDIM
2336              PA(J) = PVALUE
2337       100    CONTINUE
2338     C
2339               RETURN
2340               END
```

```
      C
      C-----------------------------------------------------------------
      C
                SUBROUTINE RESETI(KA,KDIM,KVALUE)
      C
      C U.15 RESET INTEGER ARRAY TO SPECIFIED VALUE
      C
      C       VERSION 1B              17/12/73        KVR/MHH         CULHAM
      C
               DIMENSION    KA(KDIM)
                 DO 100 J=1,KDIM
                 KA(J) = KVALUE
          100    CONTINUE
      C
                 RETURN
                 END
      C
      C-----------------------------------------------------------------
      C
                SUBROUTINE RESETH(KA,KDIM,KVALUE)
      C
      C U.16 RESET HOLLERITH ARRAY TO SPECIFIED VALUE
      C
      C       VERSION 1B              17/12/73        KVR/MHH         CULHAM
      C
            DIMENSION    KA(KDIM), KVALUE(1)
      C
                 DO 100 J=1,KDIM
                 KA(J) = KVALUE(1)
          100    CONTINUE
      C
                 RETURN
                 END
      C
      C-----------------------------------------------------------------
      C
                SUBROUTINE JOBTIM(PTIME)
      C
      C U.17 FETCH ALLOCATED JOBTIME (MINS)
      C
      C       VERSION 2B              17/12/73        KVR/MHH         CULHAM
      C
      C        SET CPU TIME COUNTER TO 0.
                  CALL TIME(0,0,JUNK)
      C
      C       GUINFO(78,INFO1) IS AN MTS LIBRARY FUNCTION WHICH GIVES THE GLOBAL
      C       TIME REMAINING
      C       GUINFO(86,INFO2) IS AN MTS LIBRARY FUNCTION WHICH GIVES THE LOCAL
      C       TIME REMAINING
      C       INFO1 AND INFO2 ARE IN CPU TIME UNITS.  ONE TIME UNIT
      C        EQUALS 13.0208333333 MICROSECS.  CPTIME IS IN MINS.
                  CALL GUINFO(78,INFO1)
                  CALL GUINFO(86,INFO2)
                  INFO = MINO(INFO1,INFO2)
                  PTIME = 2.1701389*INFO
      C
                 RETURN
                 END
      C
      C-----------------------------------------------------------------
```

```
      C
            SUBROUTINE RESETL(KLA,KDIM,KLVAL)
      C
      C U.19 RESET LOGICAL ARRAY TO SPECIFIED VALUE
      C
      C     VERSION 1B            17/12/73      KVR/MHH         CULHAM
      C
            LOGICAL     KLA,      KLVAL
            DIMENSION   KLA(KDIM)
              DO 100 J=1,KDIM
              KLA(J) = KLVAL
        100   CONTINUE
      C
              RETURN
              END
      C
      C-----------------------------------------------------------------
      C
            SUBROUTINE SCALER(PA,KDIM,PC)
      C
      C U.21 SCALE A REAL ARRAY BY A REAL VALUE
      C
      C     VERSION 1B            17/12/73      KVR/MHH         CULHAM
      C
            DIMENSION PA(KDIM)
      C
              DO 100 J=1,KDIM
              PA(J) = PA(J) * PC
        100   CONTINUE
      C
              RETURN
              END
      C
      C---------------------------------------------------------------
      C
            SUBROUTINE COPYR(PA1,K1,PA2,K2,KDIM)
      C
      C U.23 COPY ONE REAL ARRAY INTO ANOTHER
      C
      C     VERSION 1B            17/12/73      KVR/MHH         CULHAM
      C
            DIMENSION   PA1(KDIM),PA2(KDIM)
      C
              DO 100 J=1,KDIM
              I1 = K1 + J - 1
              I2 = K2 + J - 1
              PA2(I2) = PA1(I1)
        100   CONTINUE
      C
              RETURN
              END
END OF FILE
      C/ MODULE COMBAS
      C
      C  1.1          BASIC SYSTEM PARAMETERS
           COMMON /COMBAS/
          R     ALTIME,     CPTIME,     STIME,
          I     LABEL1,     LABEL2,     LABEL3,     LABEL4,
          I     LABEL5,     LABEL6,     LABEL7,     LABEL8,
          I     NDIARY,        NIN,     NLEDGE,     NONLIN,
```

```
      I        NOUT,      NPRINT,      NPUNCH,      NREAD,
      I        NREC,      NRESUM,        NRUN,      NSTEP,
      L      NLEND,       NLRES
C
       LOGICAL NLEND,NLRES
C
       INTEGER*4  LABEL1(12),LABEL2(12),LABEL3(12),LABEL4(12),
     I            LABEL5(12),LABEL6(12),LABEL7(12),LABEL8(12)
C/ MODULE COMDDP
C
C  1.9          DEVELOPMENT AND DIAGNOSTIC PARAMETERS
       COMMON /COMDDP/
      I      MAXDUM,      MXDUMP,      NADUMP,       NCLASS,
      I      NPDUMP,      NPOINT,        NSUB,       NVDUMP,
      L      NLCHED,      NLHEAD,      NLOMT1,       NLOMT2,
      L      NLOMT3,      NLREPT
C
       LOGICAL  NLCHED,NLHEAD(9),NLOMT1(50),NLOMT2(50),NLOMT3(50),
     L          NLREPT
C
       INTEGER*4  NADUMP(20),NPDUMP(20),NVDUMP(20)
C/ MODULE COMGLO
C
C  1.2  GLOBAL VARIABLES
         COMMON /COMGLO/
     #          ELECON,QTHERM,POTENT,TEMP,
     #          DELTAX,DELTAY,THICK,DTIME,TIME,
     #          XCOORD,YCOORD,XMIN,XMAX,YMIN,YMAX,
     #          ELEGEO,THMGEO
C
          REAL ELECON(50,50),QTHERM(50,50),DELTAX(50),
     #          POTENT(50,50),TEMP(50,50),DELTAY(50),
     #          XCOORD(50),YCOORD(50)
         INTEGER*4 ELEGEO(50,50),THMGEO(50,50)
C/ MODULE COMELE
C
C  1.3  ELECTRICAL CONDUCTIVITY AND DIFFERENCE EQU. COEFFICENTS
         COMMON /COMELE/
     #          ECXP,ECXM,ECYP,ECYM,ERHS,EXMXP,EYMYP,
     #          ELEVOL,ELEALP,ELEBET,ELEPAR,EPSELE
C
          REAL ECXP(50,50),ECXM(50,50),ECYP(50,50),ECYM(50,50),
     #          ELEVOL(10),ELEALP(10),ELEBET(10),ELEPAR(50),
     #          ERHS(50,50),EXMXP(50,50),EYMYP(50,50)
C/ MODULE COMTHM
C
C  1.4  THERMAL CONDUCTIVITY AND HEAT CAPACITY
         COMMON /COMTHM/
     #          THMCON,THMCAP,THMTEM,TCXP,TCXM,TCYP,TCYM,
     #          TCX,TCY,TCRHS
C
          REAL THMCON(10),THMCAP(10),THMTEM(10)
          REAL TCXP(50,50),TCXM(50,50),TCYP(50,50),TCYM(50,50)
          REAL TCX(50,50),TCY(50,50),TCRHS(50,50)
C/ MODULE COMTEM
C
C  1.5  TEMPERARY ARRAYS
         COMMON /COMTEM/
     #          TEM1,TEM2,TEM3,T1,T2,T3,T4,T5
C
```

```
      REAL TEM1(50,50),TEM2(50,50),TEM3(50,50),T1(50),
     #     T2(50),T3(50),T4(50),T5(50)
C/ MODULE COMDIM
C
C  1.6  DIMENSION AND COUNTER VARIABLES
          COMMON /COMDIM/
     #    NX,NY,NEQU,NALPHA,MITER,MMAX,NREG,NGEO,NERROR,NTYPE,
     #    NSPO,NPX,NPY,NIJ,NCI,NDX,NDY,NSTO
C
          INTEGER*4 NX,NY,NDX,NDY,NEQU,NALPHA,MITER,MMAX
          INTEGER*4 NREG,NGEO,NERROR,NTYPE,NSPO,NPX,NPY
          INTEGER*4 NIJ,NCI,NSTO
C/ MODULE COMCON
C
C  1.7  CONTROL THE HEATING
           COMMON /COMCON/
     #          HTIME,CTIME,CCUR,CPOW,DTEMP,DELT,CUR,
     #          VOLTS,RESIST,POWER,CVOL,TINIT,DEENG,TEENG,
     #          DQENG,QENG,TQENG,TTENG,TENG,SCALE
C
           REAL QENG(10),TENG(10)
END OF FILE
```

Appendix II - Sample Output from MEGAERA

```
 1    &INMOD NRUN=100 &END
 2    &LABELS
 3      LABEL1='MEGAERA RUN NO. 35     PARALLEL ELECTRODES',
 4      LABEL2='OVERBURDEN CONDUCTIVITY RATIO   OS/OB = 1.0',
 5      LABEL4='GEOMETRY SET UP AND ENTERED BY ALLAN HIEBERT',
 6    &END
 7    &INPUT1      NX=50,NY=50,
 8      DELTAX=50*1.5,DELTAY=8*5.0,2.5,3*2.0,1.5,25*1.2,
 9      1.5,3*2.0,2.5,6*5.0,10.0,NREG=5,
10    &END
11    &REGION    MINI=1,MAXI=50,MINJ=14,MAXJ=38,
12        ETYPE='DOMA',EALPHA=2.29E-2,EBETA=1.E-3,
13        TTYPE='COND',THMRC=1.6E6,THMK=1.8,
14    &END
15    &REGION    MINI=1,MAXI=50,MINJ=1,MAXJ=13,
16        ETYPE='DOMA',EALPHA=2.29E-2,EBETA=1.0E-3,
17        TTYPE='COND',THMRC=1.6E6,THMK=1.8,
18    &END
19    &REGION    MINI=1,MAXI=50,MINJ=39,MAXJ=50,
20        ETYPE='DOMA',EALPHA=2.29E-2,EBETA=1.0E-3,
21        TTYPE='COND',THMRC=1.6E6,THMK=1.8,
22    &END
23    &REGION    MINI=1,MAXI=1,MINJ=24,MAXJ=29,
24        ETYPE='ELEC',VOLTS=1000.,
25        TTYPE='COND',THMRC=1.E6,THMK=3.0,
26    &END
27    &REGION    MINI=50,MAXI=50,MINJ=24,MAXJ=29,
28        ETYPE='ELEC',VOLTS=0.,
29        TTYPE='COND',THMRC=1.E6,THMK=3.0,
30    &END
31    &INPUT2
32       NSPO=10,XMIN=1.0,XMAX=49.0,NPX=17,
33       YMIN=40,YMAX=85,NPY=10,
34    &END
35    &INPUT3
36       TINIT=15.,DTIME=1.E5,HTIME=3.154E7,NTYPE=3,
37       CPOW=12.E3,CVOL=1000.,DTEMP=.05,NCI=20,
38       MMAX=350,EPSELE=.02,
39    &END
40    &INPLOT
41       LABEL1='PARALLEL PLATE RUN NO. 35     80/11/25',NLAB1=38,
42       LABEL2='CONDUCTIVITY RATIO    OB/OS = 1.0/ 1.0',NLAB2=38,
43       NCPLTS=1,CPTIME=3.15E7,NCCODE=3,
44       CXMIN=1.0,CXMAX=74.0,CYMIN=30.,CYMAX=100.,
45       NPPLTS=1,PPTIME=3.15E7,NPCODE=7,
46       PXMIN=1.0,PXMAX=99.0,PYMIN=15.,PYMAX=115.,
47    &END
```

PROGRAM MEGAERA

ADH AUGUST, 1980

MEGAERA RUN NO. 35 PARALLEL ELECTRODES
OVERBURDEN CONDUCTIVITY RATIO OS/OB = 1.0

GEOMETRY SET UP AND ENTERED BY ALLAN HIEBERT

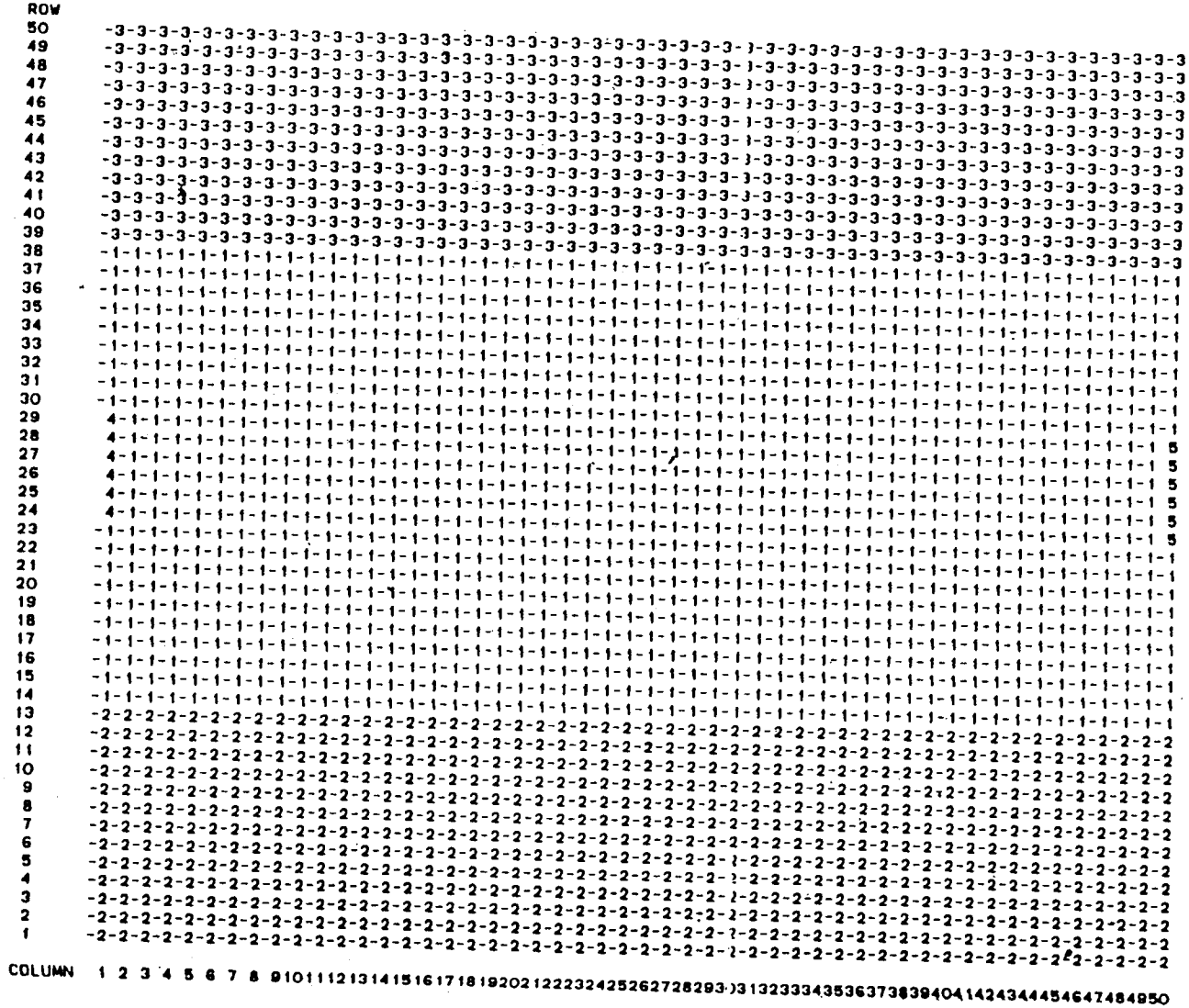
THICKNESS OF 2D SLICE (THICK)	=	1.0000E+00
GEOMETRY OF PROBLEM	=	VERT
NUMBER OF REGIONS (NREG)	=	5
REGION NUMBER	=	1
ELECTRICAL TYPE	=	DOMA
TEMP. DEPENDENCE OF CONDUCTIVITY	=	2.2900E-02
CONDUCTIVITY AT 24 CELSIUS	=	1.0000E-03
THERMAL REGION TYPE	=	COND
THERMAL CONDUCTIVITY	=	1.8000E+00
THERMAL HEAT CAPACITY	=	1.6000E+06
REGION NUMBER	=	2
ELECTRICAL TYPE	=	DOMA
TEMP. DEPENDENCE OF CONDUCTIVITY	=	2.2900E-02
CONDUCTIVITY AT 24 CELSIUS	=	1.0000E-03
THERMAL REGION TYPE	=	COND
THERMAL CONDUCTIVITY	=	1.8000E+00
THERMAL HEAT CAPACITY	=	1.6000E+06
REGION NUMBER	=	3
ELECTRICAL TYPE	=	DOMA
TEMP. DEPENDENCE OF CONDUCTIVITY	=	2.2900E-02
CONDUCTIVITY AT 24 CELSIUS	=	1.0000E-03
THERMAL REGION TYPE	=	COND
THERMAL CONDUCTIVITY	=	1.8000E+00
THERMAL HEAT CAPACITY	=	1.6000E+06
REGION NUMBER	=	4
ELECTRICAL TYPE	=	ELEC
VOLTAGE (BEFORE SCALING)	=	1.0000E+03
THERMAL REGION TYPE	=	COND
THERMAL CONDUCTIVITY	=	3.0000E+00
THERMAL HEAT CAPACITY	=	1.0000E+06
REGION NUMBER	=	5
ELECTRICAL TYPE	=	ELEC
VOLTAGE (BEFORE SCALING)	=	0.0

THERMAL REGION TYPE	=	COND
THERMAL CONDUCTIVITY	=	3.0000E+00
THERMAL HEAT CAPACITY	=	1.0000E+06

NO. OF STEPS PER PRINTED OUTPUT	=	10
NO. OF STEPS PER TAPE STORAGE	=	1000
NO. OF INTERPOLATION POINTS IN X	=	17
NO. OF INTERPOLATION POINTS IN Y	=	10
X MINIMUM FOR INTERPOLATION	=	1.0000E+00
X MAXIMUM FOR INTERPOLATION	=	4.9000E+01
Y MINIMUM FOR INTERPOLATION	=	4.0000E+01
Y MAXIMUM FOR INTERPOLATION	=	8.5000E+01

INITIAL TEMPERATURE IN CELSIUS	=	1.5000E+01
TOTAL HEATING TIME IN SECONDS	=	3.1540E+07
INITIAL TIMESTEP SIZE IN SECONDS	=	1.0000E+05
GRIDLINE FOR CURRENT INTEGRAL	=	20
CONSTANT POWER (WATTS)	=	1.2000E+04
CHANGE IN TEMPERATURE / TIMESTEP	=	5.0000E-02
MAXIMUM NO. OF ITERATIONS (MMAX)	=	350
ELECTRICAL CONVERGENCE CRITERIA	=	2.0000E-02
NUMBER OF ITERATION PARAMETERS	=	50

ELECTRICAL REGIONS OF THE GRID (NOT TO SCALE)



THERMAL REGIONS OF 4HE GRID (NOT TO SCALE)

ROW	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50
50	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3
49	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3
48	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3
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8	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2
7	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2
6	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2
5	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2
4	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2
3	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2
2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2
1	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2	-2
COLUMN	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50

TIMESTEP NUMBER = 1

TIME AT END OF STEP = 1.3055E+04
SIZE OF TIMESTEP = 1.3055E+04

NO. OF ITERATIONS OF A.D.I.P. = 226
VOLTAGE BETWEEN ELECTRODES = 5.2318E+03
POWER INPUT TO DOMAIN = 1.2000E+04
CURRENT BETWEEN ELECTRODES = 2.2937E+00
RESISTANCE BETWEEN ELECTRODES = 2.2810E+03

ENERGY BALANCE (JOULES)
TIMESTEP : ELECTRICAL ENERGY = 1.5666E+08 HEAT PRODUCED = 1.5809E+08
CUMULATIVE: ELECTRICAL ENERGY = 1.5666E+08 HEAT GENERATED = 1.5809E+08 TEMP. RISE ENERGY = 1.5801E+08
REGION = 1 HEAT GENERATED = 1.2496E+08 TEMP. RISE ENERGY = 1.2484E+08
REGION = 2 HEAT GENERATED = 1.5665E+07 TEMP. RISE ENERGY = 1.5634E+07
REGION = 3 HEAT GENERATED = 1.7467E+07 TEMP. RISE ENERGY = 1.7437E+07
REGION = 4 HEAT GENERATED = 0.0 TEMP. RISE ENERGY = 4.8345E+04
REGION = 5 HEAT GENERATED = 0.0 TEMP. RISE ENERGY = 5.4437E+04

ELECTRICAL POTENTIAL IN VOLTS

Y (M) \ X (M)	1.000	4.000	7.000	10.000	13.000	16.000	19.000	22.000	25.000	28.000
85.000	3578.0	3557.6	3515.4	3456.1	3384.8	3305.7	3222.0	3135.6	3047.9	2959.6
80.000	3826.4	3790.1	3719.3	3627.0	3524.0	3417.0	3309.5	3203.2	3098.7	2995.9
75.000	4207.6	4121.0	3979.5	3824.1	3671.7	3527.6	3392.3	3264.8	3143.7	3027.5
70.000	4963.0	4578.8	4259.0	4004.3	3793.2	3612.3	3452.6	3308.2	3174.7	3048.9
65.000	5207.7	4780.2	4370.0	4069.4	3834.3	3639.6	3471.6	3321.6	3184.2	3055.5
60.000	4709.5	4463.1	4197.7	3967.5	3769.5	3596.3	3441.6	3300.5	3169.4	3045.5
55.000	4097.4	4030.0	3912.3	3775.8	3637.1	3502.5	3374.1	3251.8	3134.6	3021.6
50.000	3757.9	3726.9	3665.3	3583.1	3489.3	3390.0	3288.9	3187.9	3087.7	2988.7
45.000	3529.8	3511.6	3473.7	3419.8	3354.3	3280.8	3202.1	3120.4	3036.9	2952.3
40.000	3365.9	3353.7	3327.6	3289.4	3241.2	3185.3	3123.5	3057.4	2988.2	2917.0

Y (M) \ X (M)	31.000	34.000	37.000	40.000	43.000	46.000	49.000
85.000	2871.1	2782.4	2693.5	2604.4	2514.9	2425.0	2334.9
80.000	2894.6	2794.1	2694.1	2593.7	2492.6	2390.0	2285.5
75.000	2914.8	2804.3	2694.7	2584.9	2473.7	2359.9	2242.2
70.000	2928.4	2811.1	2695.2	2579.2	2461.3	2339.8	2212.8
65.000	2932.6	2813.3	2695.6	2577.8	2457.9	2334.2	2204.4
60.000	2926.5	2810.5	2695.9	2581.1	2464.5	2344.5	2219.3
55.000	2911.5	2803.4	2696.0	2588.5	2479.6	2368.4	2253.8
50.000	2890.6	2793.2	2696.1	2598.6	2500.5	2401.2	2300.3
45.000	2867.2	2781.8	2696.1	2610.2	2524.0	2437.6	2351.3
40.000	2844.3	2770.6	2696.4	2621.9	2547.6	2473.7	2400.7

HEATING RATE IN JOULES/SECOND-METER**3

Y (M) \ X (M)	1.000	4.000	7.000	10.000	13.000	16.000	19.000	22.000	25.000	28.000
85.000	1.4	1.3	1.3	1.1	1.0	1.0	0.9	0.8	0.8	
80.000	3.0	2.7	2.3	2.0	1.7	1.4	1.3	1.1	1.0	
75.000	8.2	6.4	4.6	3.4	2.6	2.1	1.7	1.5	1	
70.000	67.1	18.3	8.9	5.3	3.6	2.6	2.1	1.7	5	3
65.000	4.7	20.9	10.8	6.2	4.0	2.9	2.2	1.8	1.6	1.4
60.000	32.4	14.1	7.8	4.9	3.4	2.5	2.0	1.7	1.5	1.3

55.000	6.1	5.1	3.9	3.0	2.3	1.9	1.6	1.4	1.2	1.1
50.000	2.4	2.3	2.0	1.7	1.5	1.3	1.1	1.0	1.0	0.9
45.000	1.2	1.2	1.1	1.0	0.8	0.8	0.8	0.7	0.7	0.7
40.000	0.7	0.7	0.6	0.6	0.6	0.6	0.5	0.5	0.5	0.5

X (M) / Y (M)	31.000	34.000	37.000	40.000	43.000	46.000	49.000
85.000	0.7	0.7	0.7	0.7	0.7	0.8	0.8
80.000	0.9	0.9	0.9	0.9	0.9	1.0	1.1
75.000	1.1	1.1	1.1	1.1	1.1	1.2	1.3
70.000	1.2	1.2	1.2	1.2	1.3	1.4	1.5
65.000	1.3	1.2	1.2	1.2	1.3	1.4	1.6
60.000	1.2	1.2	1.2	1.2	1.2	1.3	1.5
55.000	1.1	1.0	1.0	1.0	1.1	1.1	1.3
50.000	0.9	0.8	0.8	0.8	0.9	0.9	1.0
45.000	0.7	0.7	0.7	0.7	0.7	0.7	0.7
40.000	0.5	0.5	0.5	0.5	0.5	0.5	0.5

TEMPERATURE IN DEGREES CELSIUS

X (M) / Y (M)	1.000	4.000	7.000	10.000	13.000	16.000	19.000	22.000	25.000	28.000
85.000	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0
80.000	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0
75.000	15.1	15.1	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0
70.000	15.5	15.1	15.1	15.0	15.0	15.0	15.0	15.0	15.0	15.0
65.000	15.0	15.2	15.1	15.1	15.0	15.0	15.0	15.0	15.0	15.0
60.000	15.3	15.1	15.1	15.0	15.0	15.0	15.0	15.0	15.0	15.0
55.000	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0
50.000	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0
45.000	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0
40.000	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0

X (M) / Y (M)	31.000	34.000	37.000	40.000	43.000	46.000	49.000
85.000	15.0	15.0	15.0	15.0	15.0	15.0	15.0
80.000	15.0	15.0	15.0	15.0	15.0	15.0	15.0
75.000	15.0	15.0	15.0	15.0	15.0	15.0	15.0
70.000	15.0	15.0	15.0	15.0	15.0	15.0	15.0
65.000	15.0	15.0	15.0	15.0	15.0	15.0	15.0
60.000	15.0	15.0	15.0	15.0	15.0	15.0	15.0
55.000	15.0	15.0	15.0	15.0	15.0	15.0	15.0
50.000	15.0	15.0	15.0	15.0	15.0	15.0	15.0
45.000	15.0	15.0	15.0	15.0	15.0	15.0	15.0
40.000	15.0	15.0	15.0	15.0	15.0	15.0	15.0

TIMESTEP NUMBER = 79

TIME AT END OF STEP = 3.1540E+07
SIZE OF TIMESTEP = 1.5970E+06

NO. OF ITERATIONS OF A.D.I.P. = 18
VOLTAGE BETWEEN ELECTRODES = 3.0009E+03
POWER INPUT TO DOMAIN = 1.2000E+04
CURRENT BETWEEN ELECTRODES = 3.9988E+00
RESISTANCE BETWEEN ELECTRODES = 7.5046E+02

ENERGY BALANCE (JOULES)
TIMESTEP : ELECTRICAL ENERGY = 1.9164E+10 HEAT PRODUCED = 1.9173E+10
CUMULATIVE: ELECTRICAL ENERGY = 3.7848E+11 HEAT GENERATED = 3.7824E+11 TEMP. RISE ENERGY = 3.7819E+11

REGION = 1	HEAT GENERATED = 2.6882E+11	TEMP. RISE ENERGY = 2.5076E+11
REGION = 2	HEAT GENERATED = 5.1464E+10	TEMP. RISE ENERGY = 5.8573E+10
REGION = 3	HEAT GENERATED = 5.6879E+10	TEMP. RISE ENERGY = 6.4705E+10
REGION = 4	HEAT GENERATED = 0.0	TEMP. RISE ENERGY = 2.0873E+09
REGION = 5	HEAT GENERATED = 0.0	TEMP. RISE ENERGY = 2.0876E+09

ELECTRICAL POTENTIAL IN VOLTS

Y (M) \ X (M)	1.000	4.000	7.000	10.000	13.000	16.000	19.000	22.000	25.000	28.000
85.000	2382.3	2366.1	2331.8	2281.9	2219.3	2146.9	2067.1	1981.8	1892.6	1800.7
80.000	2529.3	2506.8	2460.7	2396.4	2318.7	2231.4	2137.6	2039.1	1937.7	1834.2
75.000	2695.4	2657.6	2589.3	2503.8	2407.7	2304.7	2197.2	2086.8	1974.7	1861.5
70.000	2927.9	2812.6	2697.5	2584.5	2470.4	2354.5	2236.8	2117.9	1998.6	1879.0
65.000	2994.1	2870.4	2734.4	2610.3	2489.8	2369.4	2248.5	2127.1	2005.5	1884.1
60.000	2857.1	2777.0	2675.5	2569.0	2458.7	2345.3	2229.5	2112.3	1994.2	1875.8
55.000	2652.4	2620.0	2558.8	2479.2	2387.8	2288.6	2184.3	2076.5	1966.7	1855.6
50.000	2491.9	2471.4	2428.8	2368.5	2294.8	2211.3	2121.0	2025.7	1927.2	1826.4
45.000	2347.9	2332.7	2300.6	2253.6	2194.3	2125.3	2048.9	1966.9	1880.8	1791.9
40.000	2218.9	2207.2	2182.1	2144.7	2096.8	2040.1	1976.2	1906.7	1832.9	1755.8

Y (M) \ X (M)	31.000	34.000	37.000	40.000	43.000	46.000	49.000
85.000	1706.9	1612.0	1516.4	1420.8	1325.6	1231.3	1138.7
80.000	1729.4	1624.0	1518.1	1412.2	1306.6	1201.5	1097.6
75.000	1747.7	1633.7	1519.5	1405.3	1291.2	1177.3	1063.9
70.000	1759.4	1639.8	1520.4	1400.9	1281.4	1161.8	1042.2
65.000	1762.7	1641.6	1520.6	1399.6	1278.5	1157.3	1035.9
60.000	1757.3	1638.7	1520.2	1401.7	1283.1	1164.6	1046.1
55.000	1743.8	1631.6	1519.2	1406.8	1294.5	1182.5	1071.1
50.000	1724.2	1621.2	1517.7	1414.2	1310.9	1208.4	1107.1
45.000	1700.9	1608.8	1516.0	1423.0	1330.6	1239.2	1149.5
40.000	1676.5	1595.7	1514.1	1432.4	1351.3	1271.4	1193.5

HEATING RATE IN JOULES/SECOND-METER**3

Y (M) \ X (M)	1.000	4.000	7.000	10.000	13.000	16.000	19.000	22.000	25.000	28.000
85.000	1.3	1.3	1.3	1.3	1.4	1.4	1.4	1.4	1.4	1.3
80.000	2.3	2.2	2.2	2.1	2.1	2.1	2.0	2.0	1.9	1.9
75.000	5.0	4.3	3.8	3.4	3.1	2.9	2.8	2.6	2.5	2.5
70.000	32.9	10.4	6.4	5.0	4.2	3.8	3.4	3.2	3.0	2.9
65.000	2.4	11.6	7.5	5.6	4.6	4.1	3.7	3.4	3.2	3.0
60.000	16.4	8.3	5.8	4.6	4.0	3.6	3.3	3.1	2.9	2.8

55.000	4.0	3.6	3.3	3.1	2.9	2.7	2.6	2.5	2.4	2.3
50.000	2.0	1.9	1.9	1.9	1.9	1.9	1.8	1.8	1.8	1.7
45.000	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2
40.000	0.7	0.7	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8

X (M) / Y (M)	31.000	34.000	37.000	40.000	43.000	46.000	49.000
85.000	1.3	1.3	1.3	1.3	1.3	1.3	1.4
80.000	1.9	1.8	1.8	1.8	1.8	1.9	1.9
75.000	2.4	2.4	2.3	2.3	2.4	2.4	2.5
70.000	2.8	2.8	2.7	2.7	2.8	2.9	3.0
65.000	2.9	2.9	2.9	2.9	2.9	3.0	3.1
60.000	2.7	2.7	2.7	2.7	2.7	2.8	2.9
55.000	2.3	2.2	2.2	2.2	2.3	2.3	2.4
50.000	1.7	1.7	1.7	1.7	1.7	1.7	1.8
45.000	1.2	1.2	1.2	1.2	1.2	1.2	1.2
40.000	0.9	0.9	0.9	0.9	0.9	0.9	0.8

TEMPERATURE IN DEGREES CELSIUS

X (M) / Y (M)	1.000	4.000	7.000	10.000	13.000	16.000	19.000	22.000	25.000	28.000
85.000	54.0	53.1	51.4	49.2	47.1	45.1	43.4	42.0	40.9	40.1
80.000	83.7	80.7	75.5	69.5	63.9	59.1	55.2	52.2	50.0	48.3
75.000	136.3	126.6	111.8	97.3	85.0	75.5	68.3	63.0	59.2	56.5
70.000	209.2	182.4	150.9	124.4	104.1	89.4	78.9	71.4	66.2	62.5
65.000	207.5	197.0	164.4	134.0	110.8	94.1	82.3	74.1	68.4	64.4
60.000	194.0	170.7	143.0	119.0	100.4	86.7	76.8	69.8	64.8	61.4
55.000	121.5	114.1	102.4	90.3	79.9	71.6	65.3	60.5	57.0	54.6
50.000	75.3	73.0	68.9	64.1	59.5	55.5	52.2	49.7	47.7	46.2
45.000	49.4	48.7	47.4	45.7	44.0	42.4	41.0	39.8	38.9	38.2
40.000	35.4	35.2	34.8	34.3	33.7	33.2	32.7	32.3	31.9	31.6

X (M) / Y (M)	31.000	34.000	37.000	40.000	43.000	46.000	49.000
85.000	39.5	39.1	39.0	39.0	39.3	39.8	40.6
80.000	47.1	46.4	46.2	46.3	46.8	47.8	49.3
75.000	54.6	53.5	53.1	53.3	54.2	55.8	58.2
70.000	60.1	58.7	58.1	58.4	59.5	61.6	64.8
65.000	61.8	60.3	59.7	60.0	61.2	63.4	66.9
60.000	59.1	57.7	57.2	57.4	58.5	60.5	63.5
55.000	52.9	51.9	51.5	51.7	52.5	53.9	56.1
50.000	45.2	44.6	44.3	44.4	44.9	45.8	47.1
45.000	37.7	37.4	37.2	37.3	37.5	38.0	38.6
40.000	31.4	31.3	31.3	31.3	31.4	31.6	31.8

4.2 TERMINATE THE RUN

MON DEC 15/80 09:27:08
CPU TIME USED SO FAR = 2 MINS 37 SECS