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UNDERGROUND DETECTION USING DIFFERENTIAL
HEAT ANALYSIS.

THE OHIO STATE UNIVERSITY, PH.D., 1979

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UNDERGROUND DETECTION USING
DIFFERENTIAL HEAT ANALYSIS

DISSERTATION

Presented in Partial Fulfillment of the Requirements for
the Degree Doctor of Philosophy in the Graduate
School of The Ohio State University

By

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The Ohio State University

1979

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ABSTRACT

Field tests were conducted to determine if an object buried near the surface of the soil could be detected by monitoring the surface temperature. A series of twelve tests using various object depths and thermal diffusivities was made with a portable infrared thermometer. In addition, a three-dimensional, implicit computer simulation was used to model and normalize the data. The method of underground detection investigated appears to have limited effectiveness in locating a buried object and also in estimating its thermal diffusivity. Furthermore, some idea of object shape and depth can be obtained.

Three field runs were made with nothing buried in the test area in order to obtain the temperature history at the soil surface and at a depth of four inches over a 24-hour period. The surface temperature was measured with Mikron 15 infrared thermometer mounted on a two-dimensional scanner. After the homogeneous runs, four tests with bricks buried at depths of 0, 2, 3.5, and 6 inches were run to find the correlation between object depth and the magnitude of the surface temperature anomaly. The anomaly became apparent just after sunset and ranged from 1 to 4°F. In each case the anomaly reached a maximum soon after sunset and decreased as the dawn approached. Next, two tests were made with objects buried at two-inch depths and with thermal diffusivities less than that of the soil. The history of

the anomaly magnitudes was opposite in sign (negative at night) to that for the brick which has a diffusivity greater than the soil. Three additional runs were conducted with varying conditions such as object shape and weather. A computer program was used to simulate and normalize the experimental results. The values of the program parameters (soil characteristics) were chosen to give a good fit of the field data and still remain comparable to literature values. For the normalization all the computer models were run with the same conditions so the results could be compared.

The anomaly magnitudes were strongly dependent on incident solar radiation and, to a lesser degree, on the heat transfer coefficient from the soil to the air. The technique for underground detection is restricted by the depth to which it is effective (six inches for climates similar to Ohio) but need be used only once after sunset to obtain a general survey of the subsurface.

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NOMENCLATURE

A, A_{cs} - cross-sectional area
 A_{1m} - logarithmic mean average for cross-sectional area
 a_1 - constants for the implicit alternating-direction equations 24a, b, and c
 b_1 - coefficients for the polynomial equation 25
 C_p - heat capacity
 FLX - total radiant heat flux
 G - generation term, W/m^2
 H - sum of all radiant fluxes to and from the ground
 h - heat transfer coefficient
 I - radial direction
 J - vertical direction
 K - horizontal or circular direction
 k - thermal conductivity
 k_{eff} - effective thermal conductivity
 L - maximum increment in the I direction
 M - maximum increment in the J direction
 N - maximum increment in the K direction
 Q_1 - heat rate
 ΔQ_1 - difference between Q_{in} and Q_{out}
 r - radius
 $\partial r, dr, \Delta r$ - change in the radius
 R_A - radiation from the atmosphere, W/m^2
 R_G - radiation from the ground, W/m^2
 R_S - solar radiation, W/m^2
 ρ - reflectance of the ground in Figure 3
 T - temperature
 T_G - temperature of the ground
 T^* - temperature at time $t + \Delta t$
 T^*, T^{**} - intermediate temperature in equations 24a, b, and c
 $dT, \Delta T$ - change in temperature
 $\Delta T_a = T_{air} - T_G$
 t - time
 Δt - change in time
 V - volume
 $dx, \Delta x$ - change in the vertical direction

Greek letters

α - thermal diffusivity
 ϵ_G - emissivity of the ground
 ζ - adjustment factor for $\Delta r_1 = \zeta r_1$
 ν - absorptivity of the ground

NOMENCLATURE (continued)

Greek letters (continued)

- π - 3.14159
- ρ - density
- σ - Stefan-Boltzmann constant
- θ - fraction of the circle, $1/N$

INTRODUCTION

The most common method of underground detection of objects in use today is test trenching; however, it is laborious and painstaking and can result in the destruction of archeological evidence. If the archeologist could visualize what lies beneath the surface, the choice of dig sites could be made with a greater degree of accuracy and with less destruction. In the case of street systems and village lay-outs, the need for excavation might be eliminated altogether.

Of the newly developed scientific aids for prospecting, the magnetometer appears to be the most promising. The magnetometer is a device that measures the intensity of the earth's magnetic field at a point. Archeological objects, especially those that have been burned or fired, cause magnetic changes called anomalies. These anomalies are very small when compared to the earth's magnetic field, and until recently, a magnetometer of sufficient sensitivity was unavailable. However, the new rubidium and cesium magnetometers can detect objects up to seven meters below the surface. One of the drawbacks of this device is that it can only detect objects that are large or fired. Unfired objects, like walls, are difficult to detect. Furthermore, ground that is magnetically susceptible will blot out anomalies due to underlying objects. Another disadvantage is that point readings are obtained, and therefore the task of mapping an area can be time-consuming. Furthermore, it takes a trained eye to distinguish

archeological features from geological features and trash objects.

Probably the second most promising scientific prospecting tool is the soil resistivity meter. There are drawbacks which restrict its use. Soil which is too wet, too dry, rocky or has non-archeological obstructions will mask or confuse the resistivity readings. Sandy soil does not retain moisture; thus the high resistance of the soil will conceal underlying objects. In rocky soil or boulder clay, one has difficulty in properly spacing and inserting the probes. If this is not accomplished correctly, the readings are inaccurate.

Another prospecting technique is aerial photography. By photographing the ground during certain times of the day or the year, underground features may be observed. Crops and other plants often grow at different rates or not at all when planted in soil covering buried objects. Frost may melt quickly in certain areas due to the heat retained by underground features. Of course, the choice of the time for photographing is very indefinite and depends to a great extent on luck.

The underground detection technique investigated here depends upon different heat retention properties of different materials. Such a buried object will have a different temperature history than the surrounding soil. This could produce a cold or hot spot on the surface depending on the depth and diffusivity of the object. By measuring surface temperature differences, underlying objects could be outlined and their depths estimated. The heat in this study was supplied by the sun and by convection from the air; but, remote heating devices could be used if a greater temperature was desired.

To test the idea, the effects on the surface temperature of objects at varying depths and of different diffusivity and shape must be determined.

This dissertation is an extension of the work started in the master's thesis, An Engineering Approach to Underground Detection by the author.¹ In the M.S. thesis, computer simulations were used to prove that an object buried near the surface would produce a daily surface temperature anomaly. A temperature anomaly is a difference between the surface temperature of an area and an average temperature. Once the feasibility had been shown, it was decided to substantiate the computer results with field data. And basically, this is the purpose of the present work.

The main premise for the research is that an object, buried near the surface of the soil and with a thermal diffusivity different from that of the soil, would affect the surface temperature. The object would store and transmit the heat of the sun at a rate different from that of the soil around it. And by monitoring the surface temperature anomaly produced by this difference, it may be possible to determine certain aspects of the object. The aspects which were investigated in the master of science work were relative thermal diffusivity, depth, and shape. These same aspects are the subject of this work with greater emphasis on the first two parameters.

It was determined in the previous research that theoretically there was a correlation between the depth of the object and the time at which the maximum temperature deviation would occur (the greater the depth, the later the anomaly would peak, see Figure 1). It was

SURFACE TEMP. DIFFERENCES FOR VARYING DEPTHS
(MASTER OF SCIENCE PROGRAM)¹

FIGURE 1

hoped that by determining the time at which this maximum occurred the object depth could be estimated. Also, in the earlier work, the object thermal diffusivity, relative to the soil diffusivity, would determine the magnitude of the temperature anomaly (the greater the relative difference; the greater the absolute magnitude, see Figure 2). Object diffusivities greater than that of the soil would produce negative anomalies during the day and positive ones at night. This was exactly opposite for diffusivities smaller than that of the soil. Again, it was hoped that the sign and magnitude of the anomaly would indicate the relative diffusivity of the object. Size did not appear to be a major factor. The present work was to prove or disprove these results.

The experimental procedure used in this research can be divided into two parts: field data and computer simulation. The gathering of actual field data was the major purpose of this research. As was mentioned earlier, data were needed to support or disprove the master of science results. The surface temperature of a cleared area (8 1/2 by 6 feet) of ground was measured by an infrared thermometer over a 24-hour period. A series of these tests was made under various conditions. In order to estimate some of the thermal characteristics (emissivity, absorptivity, etc.) of the soil, the first three runs were done without a buried object in the site. Four runs were then made with a block of bricks buried at depths of 0, 2, 3.5, and 6 inches. The results from these tests would relate surface temperature difference to object depth. The other major area of investigation was object thermal diffusivity, and two tests were

SURFACE TEMP. DIFFERENCES FOR VARYING DIFFUSIVITIES
(MASTER OF SCIENCE PROGRAM)¹

FIGURE 2

made with wood objects at the depth of two inches. The results from these two runs could be compared to the brick results at two inches. The data would then give a correlation between surface temperature difference and object thermal diffusivity. Three additional runs were made to investigate the effects of object shape and solar radiation. One of the three tests was done using three blocks of wood placed a foot apart and at the depths of 0, 1.5, and 3 inches. The results from this test would give an indication of the effect of more than one buried object. The test procedure was designed to examine in a field situation the effect of a buried object of varying depth, diffusivity, and shape on the surface temperature of the soil.

The simulation part was secondary to the field testing and consisted of computer modeling the test results in order to normalize the data. The computer program was done in three-dimensional cylindrical coordinates and used an implicit alternating-direction method of solution. In the simulation the major parameters were object and soil thermal diffusivity, soil emissivity and absorptivity, the heat transfer coefficient, and the matrix size. The values of the parameters were chosen to give a good fit of the field data and still remain comparable to literature values. Since the test conditions (such as sunlight and air temperature) varied from run to run, the results from the tests could not be compared unless they were put on a common basis (normalized). The theoretical program fits for the various runs were repeated using a set of conditions referred to as ideal. These conditions were the soil emissivity and absorptivity, the incident solar radiation, the heat transfer coefficient, and the

air temperature. Once the runs were normalized in this manner, the data could be more easily interpreted. The procedure used in both the field tests and the computer simulation is covered in greater detail in the procedure and results sections.

As to the application of the methods developed and the results obtained, they can be used in situations involving heat transfer in a large mass containing an object of different diffusivity. Of course in this case, the situation was the detection of objects buried near the surface of the soil and the heat transfer produced by the diurnal cycle. This particular case has applications in archeology where a quick method of surveying can be used to pinpoint areas of interest or to obtain a general layout.

THEORY

This section will deal almost exclusively with the computer simulation program, with some mention also being made about the data analysis program. The computer simulation is a three-dimensional, implicit alternating direction, unsteady state, finite difference model. It differs from the master of science program in that it is in three-dimensions and in cylindrical coordinates. Since the earlier program was thoroughly tested, it was used as a check on the results from this simulation.

Computer Simulation

The basic equation used in developing the program was

$$\text{In} + \text{Generation} = \text{Out} + \text{Accumulation}$$

or

$$\text{In} - \text{Out} = \text{Accum.} - \text{Gen.} \quad (1)$$

The In. and Out terms are the rates (Watts) of heat entering and leaving a finite section. For most of the program, a section looks like this:

$$V = \theta \pi (r_3^2 - r_2^2) \Delta x$$

9

where θ is the fraction of a total circle, r is the radius, and Δx is the change in the vertical direction. The three directions are I in the radial, J in the vertical, and K in the horizontal. Using point "3" as the center, the equation for the heat flux in the radial (or I) direction is

$$Q/A = -k\partial T/\partial r \quad (2)$$

where Q is the heat rate, A is the cross-sectional area (and in this case equal to $2\pi\theta r\Delta x$), k is the thermal conductivity, T is temperature, and r is radius. Substituting in the area term and rearranging, the following is obtained:

$$Q/dr/r = -k2\pi\theta\Delta x/dT \quad (3)$$

The limits of integration are for r : $r_2 - \Delta r/2$ to $r_3 - \Delta r/2$ and for T : $T(2,J,K)$ to $T(3,J,K)$. The equation for heat input is

$$Q_{in} = k2\pi\theta\Delta x\Delta T_{in}/\ln[(r_3+r_2)/(3r_2-r_3)] \quad (4)$$

where $\Delta T_{in} = T(2,J,K) - T(3,J,K)$. A similar equation is obtained for the output, but ΔT_{out} equals $T(3,J,K) - T(4,J,K)$, and the argument of the natural logarithm term is $(3r_3-r_2)/(r_3+r_2)$. Subtracting output from input and dividing through by the density (ρ), heat capacity (C_p), and volume (V), the following equation is obtained:

$$(Q_{in}-Q_{out})/\rho C_p V = CI(3)[\alpha\Delta T_{in}/CII(3) - \alpha\Delta T_{out}/CIO(3)] \quad (5)$$

where $CI(2) = 2/(r_3^2 - r_2^2)$, $CII(3)$ is the $\ln$ term for input, $CIO(3)$ is the $\ln$ term for output, and α is the thermal diffusivity.

In the vertical direction (J), the equation is simpler since the cross-sectional area is constant. The area term is $\theta\pi(r_3^2 - r_2^2)$. The

heat flow for input is

$$Q_{in} = -kA\partial T/\partial x \quad (6)$$

where ∂x is the change in the vertical direction. Changing to finite differences and substituting in the area term, the equation becomes

$$Q_{in} = k\theta\pi(r_3^2 - r_2^2)\Delta T_{in}/\Delta x \quad (7)$$

where $\Delta T_{in} = T(I,2,K) - T(I,3,K)$. The J direction is numbered down so that the surface is 1. The output term is the same except that ΔT_{out} equals $T(I,3,K) - T(I,4,K)$. Again dividing through by $\rho C_p V$ and subtracting output from input, this equation is obtained:

$$(Q_{in} - Q_{out})/\rho C_p V = (\alpha \Delta T_{in} - \alpha \Delta T_{out})/(\Delta x)^2 \quad (8)$$

In the horizontal or circular direction (K), the cross-sectional area is again constant and is $\Delta r \Delta x$. The distance in the K direction that the heat flow must cover is $2\pi\theta(r_2 + \Delta r/2)$ or, knowing $\Delta r = r_3 - r_2$, $\pi\theta(r_3 + r_2)$. The expression for the heat flow in is

$$Q_{in} = k\Delta r \Delta x \Delta T_{in}/(\pi\theta)(r_3 + r_2) \quad (9)$$

where $\Delta T_{in} = T(I,J,2) - T(I,J,3)$. Following the same procedure as shown earlier, the following expression is obtained:

$$(Q_{in} - Q_{out})/\rho C_p V = CK(3)(\alpha \Delta T_{in} - \alpha \Delta T_{out}) \quad (10)$$

where $CK(3) = [(\pi\theta)^2(r_3 + r_2)^2]^{-1}$.

Now, the input minus the output terms in each direction are added together and set equal to the accumulation term (no generation):

$$(\Delta Q_I + \Delta Q_J + \Delta Q_K)/\rho C_p V = (T'_3 - T_3)/\Delta t \quad (11)$$

where Δt is the incremental time, T_3 is the temperature at time t , and T'_3 is at $t = t + \Delta t$.

Center Section

For the center section, the expressions are considerably different. The volume (V) equals $\pi r_1^2 \Delta x$ (volume for a cylinder). It was assumed the cross-sectional area was constant in the I

direction. Obviously, this is not true since the area goes from zero to $2\pi\theta(r_1 + \Delta r/2)\Delta x$, but the assumption worked reasonably well with certain modifications. The area was taken to be $2\pi\theta r_1 \Delta x$. The heat flow into one section from the center is

$$Q_I = k(2\pi\theta r_1 \Delta x) \Delta T / \Delta r_1 \quad (12)$$

where $\Delta T = T(1, J, 1) - T(2, J, K)$ and $r_1 = \zeta \Delta r$ with ζ as an adjustment factor. It was assumed earlier that the cross-sectional area in the I direction was constant. This assumption would cause the center temperature to be appreciably different from the other surface temperatures until ζ was set at 0.50. For the total heat flow into all the sections adjacent to the center in the I direction, the individual flows are summed:

$$\Sigma (Q_I / \rho C_p V) = \Sigma \theta \alpha \Delta T / r_1^2 \quad (13)$$

For the J direction (center section), the cross-sectional area is constant at πr_1^2 , and the expression for the flow is the same as that obtained for a non-center section:

$$\Delta Q_J / \rho C_p V = (\alpha \Delta T_{in} - \alpha \Delta T_{out}) / \Delta x^2$$

which is identical to Equation (8). The center section is also different in that a generation term may be added. This is to allow

for studies using a heat generator. The area utilized by the generator is the total surface area of the disk or $2\pi r_1(r_1 + \Delta x)$. The final equation is

$$(-\Sigma Q_I + \Delta Q_J) / \rho C_p V = (T'_1 - T_1) / \Delta t + 2G(r_1 + \Delta x) / \rho C_p r_1 \Delta x \quad (14)$$

where G is the generation term.

Surface Conditions

The surface is the most important section of the simulation. Here all three types of heat transfer exist. There is radiant heat transfer from the sun and the atmosphere to the ground and from the ground to the sky. There is convection from the ground to the air. And, there is conduction away from or to the surface. A half section was used for the surface so that the temperature node would be on the surface. This made the volume one half that used in the earlier derivation or $\theta\pi(r_3^2 - r_2^2)\Delta x/2$. For the heat flow in the J direction, the heat input from the air by convection is

$$Q_{in} = h\theta\pi(r_3^2 - r_2^2)\Delta T_a \quad (15)$$

where h is the heat transfer coefficient and ΔT_a is $T_{air} - T(I, l, K)$.

The air temperature was approximated as a sine wave using a fit from data obtained in the field tests. In addition to the convection term, there is radiant heat transfer into the section. The radiant energy consists of three terms as mentioned above. Figure 3 gives a general idea of the magnitudes of these radiant energies. The solar flux is read into the program from data taken during the field runs and then multiplied by the absorptivity(α) of the soil. The radiant heat from the ground is the Stefan-Boltzmann law:

$$R_G = \epsilon G \sigma T_G \quad (16)$$

TYPICAL RADIANT FLUXES⁵

FIGURE 3

where R_G is the radiant heat transfer, ϵ_G is the emissivity of the ground, σ is the Stefan-Boltzmann constant ($5.67 \times 10^{-8} \text{ W/m}^2 \text{ K}^4$), and T_G is the temperature of the ground in absolute degrees. The sky at night was assumed to be at absolute zero. A single value of T_G was used across the entire surface since an anomaly of a few degrees would have almost no effect on the R_G term. Since R_G is radiating away from the ground, it is opposite in sign from the radiant energy to the ground from the sun and atmosphere. The last term is the radiation from the atmosphere (R_A). The expression used in the program was obtained from the article by Gates⁵:

$$R_A = 1.561 \times 10^{-14} T_{\text{air}}^6 \quad (17)$$

where R_A is in W/m^2 , and T_{air} is in $^{\circ}\text{R}$. All three terms are combined to arrive at the total radiant heat transfer term:

$$\text{FLX} = \nu R_S + R_A - R_G \quad (18)$$

where FLX is the total radiant flux, and R_S is the solar flux. This term is then multiplied by the cross-sectional area or $\theta \pi (r_3^2 - r_2^2)$. The conduction terms in the I and K direction are the same as that for the main body since the cross-sectional area and the volume are halved. The final equation for the surface is the same as equation (11) except that

$$\Delta Q_J / \rho C_p V = 2h\Delta T_a / \rho C_p \Delta x + 2\text{FLX} / \rho C_p \Delta x - 2\alpha \Delta T_{\text{out}} / (\Delta x)^2 \quad (19)$$

For the center surface section, the expression is the same as that derived for the normal center section except that the convection and radiant terms are include. A list of all the major equations are shown in Table 1.

TABLE 1

List of Major Equations

For the I direction

$$(Q_{in}-Q_{out})/\rho C_p V = CI(3)[\alpha \Delta T_{in}/CII(3)-\alpha \Delta T_{out}/CIO(3)] \quad (5)$$

where $CI(3) = 2/(r_3^2 - r_2^2)$, $CII(3) = \ln[(r_3 + r_2)/(3r_2 + r_3)]$, and
 $CIO(3) = \ln[(3r_3 - r_2)/(r_3 + r_2)]$

For the J direction

$$(Q_{in}-Q_{out})/\rho C_p V = (\alpha \Delta T_{in} - \alpha \Delta T_{out})/(\Delta x)^2 \quad (8)$$

For the K direction

$$(Q_{in}-Q_{out})/\rho C_p V = CK(3)(\alpha \Delta T_{in} - \alpha \Delta T_{out}) \quad (10)$$

where $CK(3) = [(\pi \phi)^2 (r_3 + r_2)^2]^{-1}$.

For the total heat flow

$$(\Delta Q_I + \Delta Q_J + \Delta Q_K)/\rho C_p V = (T'_3 - T_3)/\Delta t \quad (11)$$

For the center section

$$(-\Sigma Q_I + \Delta Q_J)/\rho C_p V = (T'_1 - T_1)/\Delta t + 2G(r_1 + \Delta x)/\rho C_p r_1 \Delta x \quad (14)$$

For the surface in the J direction

$$Q_J/\rho C_p V = 2h\Delta T_a/\rho C_p \Delta x + 2FLX/\rho C_p \Delta x - 2\alpha \Delta T_{out}/(\Delta x)^2 \quad (19)$$

Boundary Conditions

The boundaries in the I and J direction were assumed to be insulated. This was accomplished by setting the temperature just beyond the boundary (L+1 or M+1) equal to the temperature just before the boundary (L-1 or M-1). In the I direction, L was made large enough to make the assumption valid (L was set at 13). But in the J direction, it was found that by varying M, the average temperature at various depths could be increased or decreased. So, M became a parameter in the simulation.

Effective Thermal Conductivity

Next, the effective thermal conductivities (k_{eff}) had to be computed for sections with different k's (nonhomogeneous case). Since the temperature node is located in the center of a section, the heat would flow half its total distance in its initial section and the other half in a different section. In the J direction the equation for resistances in series is

$$\Delta x / k_{eff} A_{cs} = \Delta x / 2k_1 A_{cs} + \Delta x / 2k_2 A_{cs} \quad (20)$$

The cross-sectional area (A_{cs}) is constant and can be cancelled out along with Δx . The equation for k_{eff} reduces to

$$k_{eff} = 2 / (1/k_1 + 1/k_2) \quad (21)$$

In the K direction the equation for k_{eff} is the same since the cross-sectional area is constant. In the I direction, the area is

I direction

not constant, and the equation is more complicated:

$$\Delta r/k_{eff}A_{1m} = \Delta r/2k_1A_{1m_1} + \Delta r/2k_2A_{1m_2} \quad (22)$$

where A_{1m} is the logarithm mean average for the cross-sectional area.

After various manipulations with Δr 's the final expression becomes

$$k_{eff} = \ln C_1 / (\ln C_2/k_1 + \ln C_3/k_2) \quad (23)$$

where $C_1 = (r_1 + \Delta r/2)/(r_1 - \Delta r/2)$, $C_2 = r_1/(r_1 - \Delta r/2)$, and $C_3 = (r_1 + \Delta r/2)/r$.

Once calculated, the values of k_{eff} were divided by ρC_p to obtain the effective thermal diffusivity.

Solution of Equations

To derive the temperature for each node in the time dimension, the implicit alternating-direction method shown in Carnahan et al.² is used. This method utilizes a half-time increment with intermediate values. The equations are

$$(T^* - T) / \Delta t / 2 = a_I T^* + a_J T_n + a_K T \quad (a)$$

$$(T^{**} - T) / \Delta t / 2 = a_I T^* + a_J T^{**} + a_K T \quad (b) \quad (24)$$

$$(T' - T^{**}) \Delta t / 2 = a_I T^* + a_J T^{**} + a_K T' \quad (c)$$

where a_I , a_J , and a_K are the constants for the I, J, and K directions, T^* and T^{**} are intermediate values of temperature, and T' is the temperature at time plus Δt . The procedure in the program is to solve for T^* in the I direction, which would produce L (where L is the number of increments in the I direction) number of equations and L unknowns. This set of equations would be solved for each T^* using the Thomas algorithm³. The equations can be written in the form

$$\begin{aligned}
B_1 \cdot T_1^* + C_1 \cdot T_2^* &= D_1 \\
F_1 \cdot T_{i-1}^* + B_i \cdot T_i^* + C_i \cdot T_{i+1}^* &= D_i \\
2 \leq i \leq L-1 \\
F_L \cdot T_{L-1}^* + B_L \cdot T_L^* &= D_L
\end{aligned} \tag{25}$$

To solve these equations the method developed by L.H. Thomas is used.

This consisted of using the following equations:

$$\begin{aligned}
w_1 &= B_1 \\
w_i &= B_i - F_i \cdot C_{i-1} / w_{i-1} \quad 2 \leq i \leq L \\
g_1 &= D_1 / w_1 \\
g_i &= D_i - F_i \cdot g_{i-1} / w_i
\end{aligned} \tag{26}$$

The values of T are then found by the following:

$$\begin{aligned}
T_L^* &= g_L \\
T_i^* &= g_i - C_i \cdot T_{i+1}^* / w_i \quad 1 \leq i \leq L-1
\end{aligned} \tag{27}$$

The values of w and g are found in increasing i 's; whereas, the T^* 's are found in decreasing i 's. The new value for T^* is then used for temperatures in the I direction in Equations 24(b) and (c). The values for T^{**} are solved for in the same manner and used in Equation 24(c). For the K direction a program called DIAGON is used to solve the augmented matrix in Equation 24(c). This subprogram was developed by Dr. Harry Hershey at The Ohio State University. The values obtained for T' are then printed out. The half time increment used in the program was 1800 seconds. The master's program had to be run for sixteen days of simulation time in order to allow any instability to steady out (Figure 4), but this program proves very stable after only four simulation days.

TEMPERATURE STABILIZATION TEST ¹

FIGURE 4

Once the program had been debugged, the results were compared to the data from the master's program. For the homogeneous case, the surface temperatures at various times and the temperatures at various depths were within a half of a degree F of the master's values which are shown in Figures 5 and 6. The program worked well and reproduced the data quite closely, as will be shown in the results section.

Data Analysis Program

In the data analysis program, the data were smoothed with a second-order polynomial. The data were fed into the program as a matrix with a x, y, and time coordinate. The time spread between the last point and first point in the matrix was approximately 48 minutes. In order to compare the various points, they had to be converted to a uniform time. This was done using a polynomial fit of seven points. Each point in the matrix had a x and y coordinate which remained the same through time. The temperatures of one point at seven times were used to find the coefficients (b) for the polynomial:

$$T = b_0 + b_1 t + b_2 t^2 \quad (28)$$

The method for calculating b_0 , b_1 , and b_2 are shown in a number of math books and will not be shown here. Once the coefficients were determined, the temperature was recalculated at the time of the last point in the matrix, so that, all the data in the matrix would be at one time. The conversion was done on the fourth temperature of the seven. In other words, if the temperatures 16 through 22 are used, the temperature at time 19 would be recalculated. The fit would then move to encompass the times 17 through 22 with 20 being converted.

HOMOGENEOUS: DEPTH PROFILE¹

FIGURE 5

FIGURE 6

The first and last four temperatures in the time dimension were calculated using a fit for the first and last seven times. Other than at the beginning and the end, only one temperature was affected. This process has the dual purpose of smoothing the data and converting it to uniform times.

Limitations

The major limitation of the computer program was the use of parameters of constant value through the 24-hour simulation. There were six main variables for fitting the data: object thermal diffusivity, soil emissivity, absorptivity, and diffusivity, heat transfer coefficient, and matrix size. The diffusivity terms would be essentially constant, though there is some slight change due to temperature, and the object and soil diffusivities could be reasonably estimated since literature values are available. The matrix size was constant and was not related to any field parameters, being only a program variable. The soil emissivity and absorptivity are functions of temperature, but over the temperature range encountered in this project (100°F maximum), the assumption of these values remaining constant through the 24-hour period was valid. Where the assumption breaks down is when the heat transfer coefficient is assumed constant.

The coefficient is a strong function of many factors including wind velocity and temperature. For example, if the wind speed changes from 2 to 30 m.p.h., the coefficient would increase from 2 to 29 $W/^{\circ}C-m^2$. The surface wind was continually changing speed and direction. The surface temperature varied from about 130 to 50°F and the air temperature from about 90 to 50°F. Though it was possible to take more measurements and obtain a value for the heat transfer coefficient as a function of time of day, it was decided that a constant value for the coefficient would be adequate for the simulation. When the runs were normalized, the same coefficient value was used in each run. Similarly, the diffusivities, emissivity, and absorptivity could have been determined experimentally, but the outlay of time was not necessary due to the degree accuracy required from the program and the approximate values available in the literature. The incident solar flux and air temperature were measured on site and directly fed into the program, so they were not parameters.

Parameter Evaluation

There are three ways of determining the values of the parameters: 1) use the literature values, 2) take enough data in the field to calculate the values, or 3) use the values that give a good fit of the field data and still are comparable to literature values. The last method was used to evaluate the parameters.

Within the limitations cited above, the field data were simulated by manipulating the parameters. These six variables (soil emissivity, absorptivity, and thermal diffusivity, object diffusivity, heat transfer coefficient, and matrix size) affected the

computer results in different ways though the effects did overlap. For example, the value of the soil absorptivity greatly affected the surface temperature during the day and, to a lesser degree, the surface temperature at night. The emissivity value was the major variable determining the surface temperature at night and would also influence the surface temperature during the day. The soil thermal diffusivity was the most important parameter since it would influence the temperature throughout the matrix. But by studying the phase data at a depth of four inches, the soil diffusivity could be estimated. For the nonhomogeneous simulations, the object thermal diffusivity was the major variable determining the magnitude of the surface temperature anomaly. But, the heat transfer coefficient also affected the anomaly magnitude, especially at night. The coefficient was estimated from the anomaly phase data. The matrix size (called M in the J direction) was used to adjust the temperature near the bottom of the matrix. As mentioned earlier, the values for all the parameters were kept within an order of magnitude of the literature values and in the case of emissivity and absorptivity much closer.

EQUIPMENT AND PROCEDURE

This section deals with the equipment and procedure used to collect the field data. The equipment can be broken down into three groups: 1) monitoring devices - infrared thermometer, solar radiometer, and thermocouple; 2) recording devices - thermocouple switcher and two-pen strip chart recorder; and 3) two-dimensional scanner with accessory equipment. The first group is the main topic covered in this section. Mention will also be made of the equipment used to process the raw data.

Sensor

The main monitoring device was the Mikron 15 portable infrared thermometer. This sensor measures a target's spectral emission in the 7-20 μ m range (0-140°F) and outputs a proportional voltage of 0-10mv. The voltage can then be converted to a temperature. The sensor was placed ten feet above the ground and used to scan an area of cleared soil (the site). The Mikron output was continuous across the site, and each point on the strip chart represented a four-inch diameter circle of surface (target).

A major area of difficulty involved the calibration of the sensor. This was accomplished by varying either the sensor's or the target's temperature and recording the millivolt output of the Mikron. A thermocouple was attached to the sensor, and a plastic bag was used to enclose the unit. A plastic tube was connected from an air outlet to

a copper coil and from the coil to the plastic bag. The coil was placed in a water bath where the temperature could be varied or kept constant. In this way the air surrounding the sensor could be carefully controlled. The target consisted of a copper plate painted flat black with a thermocouple soldered to the back. Another air hose, attached in the same manner as that for the sensor, was placed so as to blow across the target. The target temperature could also be controlled. The sensor was placed on a tripod ten feet from the target. The thermocouples from the sensor and target and the millivolt output from the Mikron were connected to a PDP 15, which converted the thermocouple voltage to temperatures. The response time between a change in the temperature around the sensor and the sensor output was measured and found to be 1.25 minutes. Initially, tests were made varying the ambient temperature (temperature around the sensor) and holding the target temperature constant; but, because of the long response time, this did not work well. So the target temperature was varied, and the ambient was held constant. Fifteen tests were made at nine different ambient temperatures ranging from 63° to 87°F (Table 2). For each test the sensor millivolt output was plotted against the target temperature, and a straight line was used to approximate the data. The slopes ranged from 15.43 to 20.88°F/V. The intercept (the point at which ambient and target temperature were equal) was also found and ranged from 5.428 to 5.636 mv. The average intercept was 5.537 mv, and the average slope was 17.57°F/mv (but a slope of 17.0°F/mv was used in the calibration). The calibration equation

TABLE 2
Sensor Calibration Results

Run	Ambient Temp., °F	Intercept Volts	Slope °F/V
1	63	5.580	19.53
2	65	5.636	17.92
3	65	5.469	15.43
4	67	5.583	16.44
5	67	5.560	20.88
6	67	5.513	17.09
7	67	5.530	18.48
8	70	5.467	16.95
9	75	5.500	16.13
10	80	5.587	16.42
11	82	5.503	18.52
12	82	5.428	19.80
13	85	5.565	17.24
14	87	5.620	16.13
15	87	5.520	16.53
Average	-	5.537	17.57

used was

$$T_T = 17(V_S - 5.537) + T_{amb} \quad (29)$$

where T_T is the target temperature ($^{\circ}\text{F}$), V_S is the sensor voltage (mv), and T_{amb} is the ambient temperature ($^{\circ}\text{F}$). Seventy values were used to test the calibration, and the standard deviation was 0.965°F . This was the calibration used to interpret the raw data.

In addition to the calibration tests, another test was run to determine whether the sensor would be affected by reflected sunlight. The target plate from the calibration study was set up in the shade, the target thermocouple output was referenced to a thermocouple in an ice bath, and the voltage difference was then fed into the Honeywell recorder. The sensor was placed ten feet away and connected to the recorder. At the start of the test, the thermocouple read 45% on the recorder, and the sensor 24%. The target was then bathed in sunlight, and cool air was blown across it in order to keep the temperature constant. A thermometer was also placed near the sensor to make sure the sensor remained unaffected by ambient temperature. This temperature remained constant throughout the test. The target temperature was brought back down to 45%, and correspondingly, the sensor output came down to 23% which was within experimental error. The test indicated that the sensor is sensitive to temperature only and not to reflected sunlight. It also demonstrated how responsive the sensor was to temperature changes (response time: one second for 95% of the final value).

Additional Equipment

A Weather Measure solar radiometer was used to record the sunlight intensity. This device records on a strip chart the difference in the expansion of four plates (two painted black and two white). The difference was digitized from the strip chart, converted to a solar flux, and read into the simulation program. Five thermocouples (four chromel-alumel and one copper-constantan) were employed to monitor the surface (2), 10cm depth, air and sensor temperatures. The two thermocouples on the surface were covered lightly with soil so as not to absorb sunlight, and the air thermocouple was one inch off the surface and shaded from the sun. All five thermocouples were referenced to thermocouples in an ice bath (H in Figure 7). The ice bath was buried in the ground to reduce the heat transfer into the bath. The voltage differences were fed into a thermocouple switch. The switch output would alternate among the five thermocouples and a reference voltage with the output going to the recorder. A Honeywell, two-pen, strip-chart recorder (J) was used to register the voltage from the sensor and from the thermocouple switch. The ranges for the two voltages were 5mv and 2mv, respectfully.

Scanner

A two-dimensional scanner device was used to move the sensor across the site. The sensor was mounted in an aluminum block (A in Figure 7) that moved laterally (x direction) along two metal rods (B). A 12-volt d.c. automobile power-window motor (C) and chain (D) were employed to drive the block. Once a lateral run had been completed, the block and rods assembly was rotated (y direction) by another

EXPERIMENTAL SETUP

FIGURE 7

Procedure

The procedure consisted of preparing the site for the test, setting the equipment in place, and running the test. Initially an area 8 1/2 by 6 feet was cleared of grass, and the ground was made as level as possible. For the first two runs, the ground was left undisturbed in order to obtain its temperature history. In the following runs the ground was turned over across the entire site, and the object of interest (bricks, wood, etc.) was buried at the desired depth. The soil was then packed down and leveled off. The control box and power source were attached to the scanner assembly, and the sensor and thermocouples were plugged into the recorder. The ice bath was filled with ice, and the solar radiometer was set up. The ice had to be replaced halfway through the run. The sensor had to be aimed at a specific point at the beginning of a test so that the rows would be consistent from run to run. Between runs the motor and rods assembly was covered with plastic and left in the field. The tests were usually started around 8:00 a.m. and continued for 24 hours. It was important to monitor the surface temperature and solar radiation during the day since the surface response at night was so strongly dependent on the daylight factors. The raw data consisted of about 120 feet of strip chart paper.

Data Digitization

To utilize the data, they had to be digitized. This was done with a Bendix Datagrid Digitizer, which converts continuous data to

digital. The digitizer is located at The Ohio State University computer center. The thermocouple data were printed on cards and read into either the data analysis or the simulation program. The sensor data were transferred to magnetic tape due to the large number of points (approximately 7,000). Depending on the run, either seven or eight of the eleven rows were digitized with 34 points per row. The distance between points was 1.75 inches.

Error Analysis

The precision of the data varied from the homogeneous to the nonhomogeneous runs, since the former data were taken exclusively with thermocouples and the later were taken with the sensor and a thermocouple. Using a temperature range of 100°F, the error in the thermocouple readings can be assumed to be about 1°F, which is a little high, and in the Honeywell recorder at 1°F. The digitizer was very precise, and the error would not be greater than 1/2°F. For the surface the thermocouples can be assumed to contain no error in depth, and for the four-inch depth an error of 1/4 inch would be reasonable. A 1/4 inch error in the depth at four inches would affect the temperature only slightly, maybe 1°F, as can be seen in Figure 5. Thus for the homogeneous runs, the surface temperature and four-inch temperature would have errors of about 2°F. This error is reasonable when dealing with field data.

The nonhomogeneous error is more complicated to compute since the data underwent extensive analysis. As mentioned previously, the sensor precision was about 1°F. The temperatures were curve fitted by the data analysis program, and the error can be estimated at about 1°F.

So the total measurement error from the sensor, thermocouple, recorder, digitizer, and analysis program comes to about 2°F . This error should be increased when the temperatures were subtracted to obtain differences, but the data were taken continuously and under almost identical conditions (especially at night) for each set of surface temperature readings. Under these conditions, the error would be increased somewhat but not greater than $1/4^{\circ}\text{F}$ for a temperature range of 5°F . The largest error is in the physical setup. The brick and wood blocks were buried at a depth of two inches, and an error of $1/4$ inch or about 12 1/2% was possible. The surface temperature differences were not sensitive enough to be thrown off by 12 1/2% if the object depth was a $1/4$ inch wrong, as was observed in comparing results at varying depths (i.e., 2 and 3.5 inches). But it would not be unreasonable to expect the overall error to be between $1/4$ and $1/2^{\circ}\text{F}$ of temperature difference.

DISCUSSION OF RESULTS

The following discussion of results is presented in two parts:

(1) experimental results from each of the field tests and the computer simulation of the results, and (2) the computer normalization of the runs. Table 3 shows the experimental conditions for field runs. The normalizations in Part 2 are referred to in the text as ideal runs, since the best atmospheric conditions (sunlight, air temperature, etc.) were used in the computer program. These conditions will be explained in more detail later in the discussion. In this section a time scale based on a 24-hour clock with 1.00 hrs. as 1:00 a.m. and 23.00 hrs. as 11:00 p.m. is used, thus 17.50 hrs. is 5:30 p.m., and 0.00 is midnight.

Experimental Results and Simulations

Run #1 (no figure number) - 6/14/78

This run was a preliminary test of the equipment, even though it did not start out that way. The ground was cleared of sod and leveled, but otherwise undisturbed. Two thermocouples were placed on the surface, one in the air, one at a six-inch depth, and one on the sensor. This arrangement of thermocouples remained the same for all the runs except that the depth was changed to four inches instead of six. The run started at 7.50 hrs. and ended at 3.50 hrs. the following day, due to a recorder malfunction. The thermocouple data were converted

TABLE 3
Experimental Conditions

Figure no.	Run no.	Mat'l	Depth, inches	Size, inches
-	1	Soil	-	-
8	2	Soil	-	-
9	3	Soil turned over		-
11	5	Brick	0	$16\frac{1}{2} \times 11\frac{1}{2} \times 7\frac{1}{2}$
14	6	Brick	2	Same
19	9	Brick	3.5	Same
23	8	Brick	6	Same
27	7	Wood	2	$16\frac{1}{2} \times 11\frac{1}{2} \times 5\frac{1}{2}$
30	10	Wood box	2	$12 \times 10\frac{1}{2} \times 9$
33	12	Wood	$0, 1\frac{1}{2}, 3$	$16\frac{1}{2} \times 3\frac{1}{2} \times 5\frac{1}{2}$ (each)
36	4	Brick	0	$16\frac{1}{2} \times 11\frac{1}{2} \times 7\frac{1}{2}$ Cloudy
-	11	Brick	2	- $3\frac{1}{2} \times 7\frac{1}{2}$ Hexagon

to temperatures, but the sensor data were not analyzed. Because of the incompleteness of the run and the fact it rained during the night, the results were only used as a check on Run #2.

Run #2 (Figure 8) - 6/22/78

This run was a repeat of Run #1, and the conditions were the same except for the change in one thermocouple. The run began at 7.50 hrs. and ended at 7.75 hrs. the next morning. For the surface, the maximum was 120°F at 16.50 hrs. (point A on Figure 8), and the minimum was 55°F at 6.50 hrs. (B). For the four-inch depth, the extremes were 88°F at 18.00 hrs. (C) and 66°F at 8.00 hrs. (D).

In the simulation (or theoretical) part, it was decided to model Run #3 before attempting the same on Run #2. This was because the soil in Run #3 was more homogeneous. A number of attempts were made to reproduce the results of Run #2. But when a fit could not be made, the parameters from Run #3 were used for Run #2 (see Table 4). The only exception was the emissivity of soil which was 0.80 instead of 0.88. The average air temperature (TAM) used in the simulation was 69°F, and the air temperature difference (TDF) was 20°F. This means that the air temperature in the sine function varied from 49°F to 89°F. Also, the solar radiometer data were fed into the program. The parameters for the program are discussed in the section on Run #3.

The surface temperature fit was very good, but the temperature at four inches differed by about 5°F. The discrepancy can be attributed to the nonhomogeneity of the soil. When the soil was turned over, a number of large rocks were taken from the ground, and there was a layer of very hard dirt underlying the area. Both these factors, as

TABLE 4

Parameters for Simulation

Run	Object Diff. m^2/s	ϵ_G	ν	h $\text{W}/^\circ\text{C}-\text{m}^2$	TAM* $^\circ\text{F}$	TDF** $^\circ\text{F}$	M	Δx m
2	-	0.80	0.46	6.5	69	20	8	0.10
3	-	0.88	0.46	6.5	86.5	14.5	8	0.10
6	$14.\text{X}10^{-7}$	0.80	0.70	25	72.5	20.5	11	0.102
Ideal	$14.\text{X}10^{-7}$	0.80	0.70	25	79	19	11	0.102
7	$2.6\text{X}10^{-7}$	0.90	0.70	2	79	19	11	0.102
Ideal	$2.6\text{X}10^{-7}$	0.80	0.70	25	79	19	11	0.102
8	$14.\text{X}10^{-7}$	0.80	0.90	25	88	12	7	0.305
Ideal	$14.\text{X}10^{-7}$	0.80	0.70	25	79	19	5	0.305
9	$14.\text{X}10^{-7}$	0.80	0.70	25	81	15	7	0.178
Ideal	$14.\text{X}10^{-7}$	0.80	0.70	25	79	19	7	0.178
10	$3.1\text{X}10^{-7}$	0.80	0.70	5	85	15	11	0.102
Ideal	$14.\text{X}10^{-7}$	0.80	0.70	25	79	19	11	0.102

* Average air temperature

** Air temperature difference

Both air temperature values were determined experimently

well as any residual moisture, contribute to the ground's nonuniformity.

Run #3 (Figures 9 and 10) - 6/28/78

In preparation for Run #3, the ground was turned over to a depth of one foot across the entire site. This had the dual purpose of drying out the soil and making the soil more homogeneous. Also, any large rocks were removed from the site. The area was covered with plastic on rainy days and left exposed on sunny days. The soil dried out considerably after a few days and turned powdery.

The test began at 8.00 hrs. and continued until 10.00 hrs. the next morning. Between 12.00 hrs. and 15.00 hrs., the recording pen for the surface thermocouple went off scale, and the missing values were estimated with the previous runs and the theoretical fit (see A on Figure 9). The variations of the surface and the four-inch temperature are shown in Figure 9. Figure 10 is a contour map of the surface temperature differences in degrees Fahrenheit. The difference is calculated by subtracting the temperature from an average temperature, which was obtained by adding the temperatures of the 34 points in the row $y = 20.5$ inches to the 34 points in the row $y = 87.0$ inches and dividing by 68. The contour shows the distribution for 24.20 hours. This was done to show the end effects of the site. As can be seen on the graph, the center area from $y = 30.0$ to 87.0 inches is relatively constant with rapid decreases near the right (A), left (B), and top edges (C). The left and right disturbances were caused by the nearness to the grass boundaries. The anomaly in the row $y = 20.5$ inches was probably caused by the shadow of the equipment during the day. These edge effects could not be eliminated but were

TEMPERATURE FOR DISTURBED HOMOGENEOUS

FIGURE 9

SURFACE TEMPERATURE DIFF. CONTOUR FOR DISTURBED HOMOGENEOUS

FIGURE 10

taken into account when making the theoretical models. The center area was relatively constant in temperature difference ranging from 0.49 to 1.78°F. Thus the center area was where all the test objects were buried, and their anomalies can be readily discerned from the edge effects.

For the simulation there were five parameters: the absorptivity, emissivity, and thermal diffusivity of the soil, the initial temperature of the model, and the heat transfer coefficient (again see Table 4). The temperature of the matrix was initialized at the estimated final values. This helped reduce the time the program had to run before steadying out. The only initial value varied was the temperature of the last point (called M) in the vertical or J direction. By lowering this value, the average temperature at the surface would be decreased slightly, while the average at four inches would be affected more noticeably. Since this value could be easily estimated from the field data, the temperature of 41°F was chosen after a few trial and errors. The effect of the heat transfer coefficient would be greatest during the day when the difference between the surface and the air temperature was greatest. It was decided to leave the heat transfer coefficient at $6.5 \text{ W/}^\circ\text{C-m}^2$ which was the value used in the master of science program. The absorptivity of the soil like the heat transfer coefficient had its greatest effect during the day. By increasing the absorptivity, the surface temperature would increase considerably during the day and slightly at night. A value of 0.46 was used in the final

simulation. When the nonhomogeneous runs were made, the values for the absorptivity and heat transfer coefficient were increased (see Table 4) in order to fit the data. The emissivity of the soil had essentially uniform effect day or night since absolute temperature was used in calculating the ground radiation. It played an important part in adjusting the surface temperature at night. The emissivity was set at 0.88 for this run, and the value compares reasonably well with similar materials (the emissivity of brick is 0.75^6). By far the most important parameter in the test was the soil thermal diffusivity. A decrease in diffusivity would increase the surface temperature (especially during the day) and at four inches, would delay the peak time, increase the difference between the maximum and minimum temperature, and slightly decrease the average temperature. Since the peak time was clearly defined by the field data at 18.00 hrs. (B in Figure 9), the spread in diffusivity values could be narrowed and was eventually set at $4.69 \times 10^{-7} \text{ m}^2/\text{s}$. This value fits nicely between the diffusivities for coarse earth (1.39×10^{-7}) and clay (10.1×10^{-7})⁴. This parameter was determined before any of the other four variables were found. The average air temperature (TAM) and the air temperature difference (TDF) were set at 86.5°F and 14.5°F from the field data. The final fit was very good as shown by Figure 9. A comparison of the field data from Runs #2 and #3 will show that by turning the soil over, the maximum temperature at four inches was increased in relation to the maximum surface temperature. This was probably due more to the drier nature of the soil in Run #3 than to the lack of homogeneity in Run #2. Also, as mentioned above,

the soil emissivity appeared to be reduced in Run #2. This could have been due to atmospheric conditions and not necessarily to ground disturbance.

Run #5 (Figures 11, 12, and 13) 7/6/78

A number of difficulties was encountered in this run, but the desired information was obtained. A total of nine red bricks was buried in the center of the plot so as to be flush with the surface. The entire site was dug up so any anomaly would be due to the bricks and not to the disturbance of the soil. This was done in all subsequent runs. The bricks formed a rectangular prism with a length (y direction) of 16 1/2 inches, a width (x direction) of 11 1/2 inches, and a depth of 7 1/4 inches (see point A in Figure 13). The top surface of the bricks was covered lightly with dirt to keep its absorptivity and emissivity the same as the rest of the site. The bricks were situated with the row $y = 58.5$ inches through the center. At the start of the test, there were three wet spots on the site, and even though they were small, they could have affected the results. So the soil was turned over across the site, and the wet soil dispersed. As a result, the run began at 11.75 hrs.. The incident solar radiation is shown in Figure 12. The dips in the solar curve (point A in Figure 12) are due to passing clouds. At about midnight (0.00 hrs.), the sensor batteries failed, and the run was terminated.

Rows $y = 30.0$ through 87.0 inches were digitized from the chart data. As mentioned earlier, the first and last rows were summed and averaged in order to obtain an average temperature. The point

SURFACE TEMP. DIFFERENCE FOR BRICK. 0 IN.

FIGURE 11

SOLAR DATA FOR BRICK, 0 IN.

FIGURE 12

used in Figure 11 was directly above the buried bricks. The figure shows a large temperature anomaly at the start of the run and immediately after sunset (19.00 hrs. at point A). During the day, the surface temperature can vary by 20°F over a short distance with no apparent cause. A temperature profile of the surface resembles a silhouette of the Rocky Mountains, so that any anomaly due to a subsurface object would be almost completely masked. This was true of all the runs. But at night, the surface temperature profile leveled out considerably. This is when the anomalies became readily visible. For this run, the temperature disturbance due to the bricks was very prominent as the sun set. Figure 13 shows a surface temperature difference contour, and the anomaly can be seen quite clearly. This proved that a buried object affects the surface temperature which is the basic premise of this study. The magnitude of the disturbance decreased as the night continued. This was due to convective heat transfer to the air; more will be said about this in the discussion of Run #6. Lastly, no simulation was attempted on this run, because the program cannot model an object that comes flush with the surface. The object has to be at a minimum depth of about two inches. The overall results were very promising.

Run #6 (Figure 14, 15, 16, and 17) - 7/11/78

This was the second of four tests using buried bricks. In the run the bricks were buried at a depth of two inches, and the dimensions were the same as Run #5. The test began at 9.50 hrs. and ended at 10.00 hrs. the next morning. Rows $y = 20.5$ through 87.0 inches were digitized. Figure 14 shows the negative surface temperature difference

FIGURE 13

SURFACE TEMP. DIFFERENCE FOR BRICK, 2 IN.

FIGURE 14

SOLAR DATA FOR BRICK, 2 IN.

FIGURE 15

FIGURE 16

during the day and the positive difference at night which was predicted by the master's thesis. This indicated a thermal diffusivity greater than that of the ground. The anomaly became visible soon after sunset, reaching a peak at around 0.00 hrs. and tapering off slowly for the rest of the night. A typical profile is shown in Figure 17, where the object width is 11 1/2 inches (point A). Though the anomaly was visible on the strip chart, it was not as prominent as was expected, and the surface temperature difference contour (Figure 16) does not show the disturbance as clearly as Run #5 or subsequent runs. This may have been due to the scattered cloud cover during the day, and the large irregularities caused by the edge effects.

In the simulation some of the parameters had to be readjusted in order to fit the data. The two main variables were the heat transfer coefficient and the thermal diffusivity of the buried object. The TAM and TDF were 72.5°F and 20.5°F, respectfully. Δx was set at four inches (0.102 m), which placed the object at two inches ($\Delta x/2$). The parameters are summerized in Table 4. The procedure that follows was originally used on the results from Run #9, since the data were the better of the two runs; but, it will be described here for the sake of clarity. First the heat transfer coefficient was varied to achieve a peak time approximating that of the field data. Figure 18 shows how the heat transfer coefficient can affect the surface temperature difference. As the heat transfer coefficient increases, the surface temperature difference and the peak time decreases. A heat transfer coefficient value of $25\text{W}/^\circ\text{C}-\text{m}^2$ was finally chosen in order to obtain a peak time close to 0.00 hrs.. This value was used in Runs #8 and #9

SURFACE TEMPERATURE PROFILE. BRICK AT 2 IN.

FIGURE 17

SURFACE TEMP. DIFFERENCES FOR VARYING H.T.C. (IDEAL)

FIGURE 18

and in the ideal tests. Once the heat transfer coefficient was set, the absorptivity and emissivity of the soil had to be adjusted so as to bring the surface temperature in line with the field data. The emissivity was left at 0.80 from Run #2, but the absorptivity was raised to 0.70. Now the magnitude of the anomaly had to be approximated, and this was done by adjusting the thermal diffusivity of the buried object. To obtain a true picture of the magnitude, a profile was plotted (Figure 17), and by studying the profile, the anomaly could be more easily evaluated. After a number of trials, the object thermal diffusivity was set at $14.07 \times 10^{-7} \text{ m}^2/\text{s}$ (300% of ground diffusivity), which closely approximates that of stone ($\approx 12.0 \times 10^{-7} \text{ m}^2/\text{s}$)⁴. Also, in Figure 17 the theoretical results are shown with the actual data. This was done to show how closely the widths of the anomalies agree. It was an indication that the program was functioning properly, since the width and length of the actual and the theoretical bricks were almost identical.

Run #9 (Figure 19, 20, 21, and 22) - 7/28/78

In this run and subsequent runs the analysis and simulation were essentially the same except for the variation of one or two parameters. For Run #9, the bricks were at a depth of 3.5 inches, and rows $y = 39.5$ through 96.5 inches were digitized. Since the day was clear (Figure 20), the surface temperature difference history (Figure 19) and the contour data (Figure 21) shows a very distinct anomaly with the maximum at about 0.40 hrs. (A in Figure 19). In both figures (21 and 22) the anomaly covers more area than the test at two inches. The profile from Run #6 (Figure 17) can be used as a comparison.

SURFACE TEMP. DIFFERENCE FOR BRICK. 3.5 IN.

FIGURE 19

INCIDENT RADIATION, W/M²

SOLAR DATA FOR BRICK, 3.5 IN.

FIGURE 20

FIGURE 21

FIGURE 22

This dispersal of heat was expected since as the heat travels the greater distance vertically, it also travels more laterally.

For the simulation, the only parameters different from Run #6 were: TAM at 81°F, TDF at 15°F, Δx at seven inches (giving a depth of 3.5 inches), and M at 7. The maximum J coordinate (M) was changed from 11 to 7 in order to maintain approximately the same vertical temperature distribution as previous runs, since the temperature at point M was initially set at a value different from the rest of the matrix as mentioned earlier. The modeling results can be seen in Figures 19 and 22, and the parameters are tabulated in Table 4.

Run #8 (Figure 23, 24, 25, and 26) - 7/20/78

In Run #8 the bricks were buried at six inches on row $y = 49.0$ inches, and rows $y = 11.0$ through 77.5 inches were digitized. Because of its dispersal, the anomaly is not as distinct (Figures 25 and 26) as in Run #9 and cannot be clearly seen on the profile graph. The edge effects tended to enhance the magnitude, because, as was shown in Figure 10, the edges tend to be cooler than the center area. The anomaly appeared to reach a peak soon after sunset then remain essentially constant through the remainder of the night. During the day, there was no noticeable effect.

In the simulation TAM was 88°F, TDF was 12°F, M was 7, Δx was 12 inches, and soil absorptivity was 0.90 (see Table 4). The results are shown in Figures 23 and 26, and as can be seen in Figure 23, the fit was not very good. Though a variety of parameters were adjusted, the theoretical data could not be made to fit the actual data for the early evening hours (approximately 19.00 to 23.00 hrs., point A).

SURFACE TEMP. DIFFERENCE FOR BRICK, 6 IN.

FIGURE 23

SOLAR DATA FOR BRICK, 6 IN.

FIGURE 24

FIGURE 25

SURFACE TEMPERATURE PROFILE, BRICK AT 6 IN.

FIGURE 26

But the fit was good from 23.00 hrs. until the run's end at 8.00 hrs.. M was left at 7, which changed the vertical temperature distribution, but it seemed to improve the model. The same can be said for the change in soil absorptivity. For the ideal run, M was set at 5 to bring it in line with the other runs.

Run #7 (Figure 27, 28, and 29) - 7/17/78

In this run the thermal diffusivity of the object was varied instead of its depth. Nine wooden blocks placed so as to form a rectangular prism ($16 \frac{3}{4} \times 11 \frac{1}{2} \times 5 \frac{1}{4}$ inches) were buried at a depth of two inches. The size and depth of the block were chosen to correspond to Run #6, which was the size used in ideal runs (Figures 40-45). The block was situated on row $y = 68.0$ inches, and rows $y = 30.0$ through 96.5 inches were digitized. Run #7 was an excellent run due to clear weather (Figure 28), and the anomaly was very distinct and large (Figure 29). The anomaly was most prominent just after sunset (19.00 hrs.), thus the use of the time 21.20 hrs. for the contour. Upon looking at the surface temperature difference history (Figure 27), it will be readily noticed that the curve is positive during the day and negative at night, which is exactly opposite to Figures 14, 19, and 23. From the master's work, this indicates a diffusivity less than that of the ground.

For the simulation, Δx , M, and soil absorptivity were set at the same values used in Run #6; four inches, 11, and 0.70, respectfully. TAM was 79°F, and TDF was 19°F (Table 4). This left three parameters to be adjusted according to the fit, and these were the soil emissivity, object thermal diffusivity, and the heat transfer

SURFACE TEMP. DIFFERENCE FOR WOOD, 2 IN.

FIGURE 27

SOLAR DATA FOR WOOD, 2 IN.

FIGURE 28

coefficient. The diffusivity only affects the magnitude of the anomaly and not the phase of the surface temperature difference curve; so, the diffusivity was the last parameter set. The soil emissivity was used to maintain the surface temperature close to that of the experimental data. This left the heat transfer coefficient as the major parameter, and as shown in Figure 18, it can be used to adjust the phase or peak time. After a number of trials, the heat transfer coefficient was set at $2\text{W}/^\circ\text{C}\cdot\text{m}^2$, which was less than one tenth that used in previous tests. Though this seems to be too radical of a change, it did bring the theoretical results in line with the actual data (Figure 27). The change may have been due to a lack of wind or some other climatic condition. The air temperature was much higher on this run and Run #10 than any of the other runs (except Run #8). Once the heat transfer coefficient was chosen, the emissivity was set at 0.90. To find the diffusivity of the object, the anomaly profile was plotted so as to obtain an accurate estimate of the anomaly's magnitude. This was also done on Run #10, but neither graph is shown. The thermal diffusivity of the object was chosen as 57% of ground diffusivity or $2.57 \times 10^{-7} \text{m}^2/\text{s}$, which is about twice that listed⁴ for pine (radially) at $1.24 \times 10^{-7} \text{m}^2/\text{s}$. This was reasonable since the heat transfer was not radial, and the values were relative.

The fit was not good in the hours soon after sunset (19.00-1.00 hrs.) and at dawn (7.00 hrs.). The former was close enough to allow for experimental error, but the latter was probably due to the starting times of the two sets of data. The field data began at about 8.50 hrs., and the theoretical at 6.00 hrs.. This meant the actual

data for the earlier morning hours was a result of the following day's conditions and not 7/17/78, which was used exclusively for the theoretical run. But, overall the patterns are similar and exhibit the same peak during the day and gradual anomaly increase at night. The change during the night in the anomaly was not as radical as indicated by the graph.

Run #10 (Figures 30, 31, and 32) - 8/1/78

This run was similar to Run #7 in that an object of lesser diffusivity was used. In this case it was a hollow wooden box (12 X 10 1/2 X 9 inches) with sides of one-inch thick plywood. The box was buried at a depth of two inches in row y = 77.5 inches, and rows y = 30.0 through 96.5 inches were digitized. The day was partly cloudy (Figure 31); and so the run was not as effective. But, an anomaly is still quite visible after sunset at 19.00 hrs. (Figure 32), and the surface temperature difference history (Figure 30) follows the pattern of Run #7.

The theoretical part was done in the same manner as Run #7. A_x , M and soil absorptivity were the same. TAM was 85°F, and TDF was 15°F (Table 4). The soil emissivity, heat transfer coefficient, and object diffusivity used in the final theoretical run were 0.80, $5W/°C-m^2$, and $3.05 \times 10^{-7} m^2/s$ (65% of ground diffusivity). Since this value for the diffusivity is so close to that for wood, the hollow space seemed to play a secondary role to the wood surrounding it. Air has a diffusivity of about $3.0 \times 10^{-5} m^2/s$ or 6000% that of the soil.⁴ Obviously, the air pocket was not the controlling factor.

SURFACE TEMP. DIFFERENCE FOR AIR, 2 IN.

FIGURE 30

INCIDENT RADIATION, W/CM²

SOLAR DATA FOR AIR: 2 IN.

TIME OF DAY

FIGURE 31

FIGURE 32

Run #12 (Figure 33, 34, and 35) - 9/4/78

This run was designed to determine the effects of three conditions: size, depth, and shape. The wood blocks used in Run #7 were divided into three groups each $3 \frac{3}{4}$ inches wide, $16 \frac{3}{4}$ inches long, and $5 \frac{1}{4}$ inches thick. This made each group exactly one third the width of the wood object used in Run #7. One group (far left, point A) was buried at a depth of three inches, another (middle, point B) at $1 \frac{1}{2}$ inches, and the last (far right, point C) on the surface or zero inches. The groups were placed one foot apart with the long edges parallel and with overlapping rows. The first group was covered by rows $y = 49.0$ and 58.5 inches, the middle group by rows $y = 58.5$ and 68.0 inches, and the last group by rows $y = 68.0$ and 77.5 inches. Rows $y = 30.0$ through 96.5 inches were digitized.

By looking at Figure 35, it can be seen that the group buried at $1 \frac{1}{2}$ inches and the surface group produce noticable anomalies with the surface one being much greater. But, the object at three inches had no apparent effect on the surface temperature difference. It can also be seen that the anomalies are longer than they are wide, giving an indication of their shape, and there appeared to be no interaction between the groups. Figure 33 shows that the magnitude of the anomaly decreased with an increase in depth. As with earlier runs, the peak times were not distinct for each depth, but the response was faster for the zero depth than the other depths. In addition, when the surface temperature difference results are compared to those from Run #7, the anomaly magnitude seemed to be less for the smaller volume. The middle group was a half inch closer to the surface, but its

SURFACE TEMP. DIFFERENCE FOR VARIABLE RUN

FIGURE 33

INCIDENT RADIATION, W/M²

TIME OF DAY

SOLAR DATA FOR VARIABLE RUN

FIGURE 34

FIGURE 35

surface temperature difference was less than that for the larger volume. This correlation was supported by the results from Run #11. No simulation was done on this run.

Run #4 (Figures 36, 37, and 38) - 7/5/78

This run was done under the same conditions as Run #5 (bricks at zero depth). The only change was that the day was cloudy (Figure 37) with a minimum of solar radiation. The anomaly magnitude was much less than that for Run #5, and this can be clearly seen when the contour maps (Figures 13 and 38) are compared. The incident solar radiation is very important in determining the effect of the buried object on the surface temperature.

Run #11 (no figures) - 8/21/78

As in Run #12, this run was an attempt to determine the effect of shape. The bricks were arranged in a hexagon at a depth of two inches. The hexagon wall was one brick ($3 \frac{3}{4}$ inches) thick and extended $7 \frac{1}{4}$ inches down. After the run was finished and the strip chart checked, there was no sign of an anomaly. This would seem to indicate that there is a minimum size under which an object would have no effect on the surface temperature. The minimum thickness for bricks at a depth of two inches lies between $11 \frac{1}{2}$ and $3 \frac{3}{4}$ inches.

Another run was attempted using bricks buried at two inches but with wet soil instead of dry. A complete break down in the scanner brought the run, as well as the field testing, to a halt.

SURFACE TEMP. DIFFERENCE FOR CLOUDY DAY

FIGURE 36

SOLAR DATA FOR CLOUDY DAY

FIGURE 37.

FIGURE 38

FIGURE 38

Normalized (Ideal) Runs

In order to compare the various experimental results, the runs would have had to be conducted under identical atmospheric conditions. As can be seen in Table 4 and the solar data figures, the conditions in the different runs were far from identical. So once the experimental data had been simulated with the computer program, the theoretical runs were repeated using what is called ideal conditions. These conditions were the same (except for the maximum vertical dimension, M) for all the ideal runs so the results could be compared. Figure 39 shows the solar data used in the ideal runs. The other ideal parameters were $25 \text{ W/}^\circ\text{C-m}^2$ for the heat transfer coefficient, 0.80 and 0.70 for the soil emissivity and absorptivity, 79°F for the average air temperature (TAM), and 19°F for the air temperature difference (TDF).

Figures 40 and 41

Figure 40 is a graph of the actual data for Runs #5, #6, #9, and #8. These were the runs with bricks buried at various depths. Little can be determined from the graph except that the buried object has a diffusivity less than the surrounding soil. The individual curves are discussed in greater detail above.

In Figure 41 the theoretical profiles from Runs #6, #9, and #8 are shown. Even though the anomaly magnitudes are different, some idea of the spreading effect caused by increased depth can be obtained. Using the center point of the anomaly as point 1, the object ends halfway between points 3 and 4 in either direction. The distance between each point is 2.3 inches. If the temperature difference at

SOLAR DATA FOR IDEAL DAY

FIGURE 39

SURFACE TEMP. DIFFERENCES FOR VARYING DEPTHS

FIGURE 40

SURFACE TEMP. DIFFERENCE PROFILES FOR VARYING DEPTH (THEOR. I)

FIGURE 41

point 1 is taken as 100%, the changes between points 3 and 4 for the 2, 3.5, and 6 inch depths are 87.7%, 77.1% and 76.5%, respectfully. If point 3 is used as 100%, the percent change from 3 to 4 is 86.0%, 72.5%, and 70.3%. As can be seen from these figures, the greater the depth the smaller the percent change in temperature. And this temperature dispersal can be seen on the contour maps. The dispersal would seem to suggest a possible method of determining depth. But, the profiles of the actual data were not distinct enough to make the method reliable.

Figure 42

The theoretical simulations of Runs #6 (2 inches), #9 (3.5 inches), and #8 (6 inches) were repeated using the ideal conditions mentioned earlier. The only difference was in the M values, and they were 11, 7, and 5, respectfully. As can be seen from the graph, the magnitude of the anomaly decreases with an increase in depth. The peak time would appear to be another method of determining depth; but, as discussed earlier, the anomaly is hard to detect and analyze during the day, and at night the heat transfer coefficient has a very strong affect on peak time. So as with the earlier method, the peak time does not seem to be a reliable indication of depth.

Figure 43

This is a graph of the surface temperature differences from Runs #6, #7, and #10. In all these runs, the buried object was at a depth of two inches, but the buried objects were of different diffusivities: brick, wood, and air (in reality wood). As can be clearly seen in Figure 43, the object with a thermal diffusivity greater than the soil

SURFACE TEMP. DIFFERENCES FOR VARYING DEPTHS (IDEAL)

FIGURE 42

SURFACE TEMP DIFFERENCES FOR VARYING DIFFUSIVITIES

FIGURE 43

is the inverse of the two with smaller diffusivities. This supported the results (Figure 2) of the master's thesis. From the surface temperature difference history, the relative diffusivity (and therefore the actual diffusivity) can be estimated.

Figure 44

Figure 44 is the graph of the ideal theoretical results for Runs #6, #7, and #10. The M valued used in all three runs was 11 since Δx was the same for each. This graph shows essentially the same results as in Figure 43. It does show the effect of a small change in relative diffusivity (65% for air and 57% for wood). Obviously as the relative diffusivity approaches 100% (the same diffusivity as the soil), the magnitude of the anomaly decreases.

Figure 45

In Figure 45, the data were generated by running the ideal simulation on bricks at two inches with varying soil diffusivities. The brick diffusivity was kept constant. So, as the soil diffusivity was increased, its heat transfer ability would be increased, but the buried object's relative diffusivity would decrease. The opposite would be true for a decrease in soil diffusivity. As can be seen from the graph, the two effects cancel each other out. Also, there is no shift in peak time, but this may be due to the heat transfer coefficient. For an object with a relative diffusivity less than the soil, a decrease in soil diffusivity would have the effect of reducing the anomaly, and inversely an increase would greatly increase the anomaly. The best case would be an object of low diffusivity buried in soil with a high diffusivity. The effective depth would be greatest for this case.

SURFACE TEMP. DIFFERENCE FOR VARYING DIFFUSIVITIES (IDEAL)

FIGURE 44

SURFACE TEMP. DIFFERENCES FOR VARYING GRO. DIFFUSIVITY

FIGURE 45

SUMMARY

From the results described in the previous section, this underground detection technique works, at least under the conditions experienced during the tests. As mentioned in the introduction, the basic objective was to determine if an object, buried near the surface and with a diffusivity sufficiently different from the soil, would affect the surface temperature enough to be detectable. This was clearly shown by the results. But as to the extent to which the buried object can be described, the data were not as conclusive.

Initially, the object had to be located, and in all the runs the surface temperature anomalies were most distinct in the first few hours after sunset. The surveying technique used in this study would not be practical on site, since it was designed to cover a small area. An infrared scanner that can register the temperatures over an entire surface (instead of point readings) with a link up to a small computer would be much faster and efficient. This type of system is currently available, but the high price made its use in this study prohibitive.

Once located, the anomaly will give a vague idea of the object shape. In the nonhomogeneous runs the buried object widths and lengths were not sufficiently different to produce anything but roughly circular anomalies. The only exception being in Run #12

where the width was only about a quarter the size of the length. Here the anomaly was oval shaped. Obviously, a clear outline of the buried object cannot be determined unless the object is flush with the surface, but a general outline can be obtained for the shallower depths and especially for walls.

By monitoring the surface temperature difference over a 24-hour period, the relative thermal diffusivity can be estimated. The results showed that the surface temperature difference history would indicate whether the object diffusivity is greater or less than the soil. And, as was done in the data analysis, a profile of the anomaly could be used to narrow the diffusivity down even further. Of course on site there would be a general idea of the objects likely to be found in the area.

The last area of interest would be the depth; not only in estimating the object depth but also the depth to which this technique would be effective. It was hard to estimate object depth from the results, since the peak time method did not work. As mentioned earlier, the peak time was too hard to distinguish during the day and a function of the heat transfer coefficient at night. The anomaly profile and contour would give some indication, but an accurate value for the depth would be hard to obtain. This would not be too essential since once the object is located, it would be a simple matter to determine its depth.

The effective depth is a function of several factors: soil diffusivity and moisture content; object diffusivity, size, and depth; solar intensity and frequency; and heat transfer coefficient. These

factors would be unique to each site, and thus the effective depth would be unique. For this study the bricks could still be detected at six inches, but this was near the limit of effectiveness. The type of site would be the determining factor in the use of this technique.

Two areas not investigated in this study were moisture content and heat generation. The soil moisture content could be either a help or a hinderance. If the soil is very wet, the heat will not penetrate the surface due to evaporative heat loss, but if the soil is only slightly wet, the moisture may accentuate the difference between object and soil. A heat generator placed in the soil could be used to help pinpoint an object once the area had been narrowed down. As with solar heat, the object would show a transient response different from that of the soil. This technique would not be effective over a large area.

CONCLUSION

1. This method of underground detection is effective only at shallow depths (about six inches) and therefore has limited use. From the results it was found that the anomaly was most distinct just after sunset (19 to 24 hrs.). By surveying the surface temperature of a site once in the early evening, it may be possible to obtain a general layout of the subsurface, depending on the conditions of the test area. A sophisticated infrared camera would greatly facilitate data gathering and analysis.
2. The two most influential parameters of this method are the object depth and relative thermal diffusivity (relative to the ground). The effects of the two parameters are inversely related.
3. The effectiveness of the technique heavily depends on the magnitude and duration of the sunlight incident on the site and, to a lesser degree, on the heat transfer coefficient between the surface and the air.
4. The 24-hour history of the anomaly magnitude will give an indication of the object relative thermal diffusivity.
5. The anomaly gives a general idea of the object shape and depth.

RECOMMENDATIONS

1. This method of underground detection should be tested on an archeological or other suitable site, preferably where the objects of interest are of stone, wood, or metal.
2. The equipment and procedure used in this study for data gathering should not be used on site. There are better (and more expensive) methods of recording temperatures over large areas and of data analysis.
3. The use of a heat generator should be investigated for localized surveys.
4. The effect of water on the effectiveness of this technique should be checked.

COMPUTER PROGRAM

1	//SMB300 JOB 'XXXXXXXXXXXXXXXXX', 'BERNER, STEVE',	JOB 4952
	// TIME=(0,40), REGION=192K	
	***JCBPAM LINES=3033, CARDS=500, DISKIO=1300	
2	//STEPA EXEC PG1=IGL FORT, PARM='LINECH=60, MAP', TIME=(0,10)	JCLB 02
	*** STEP A IS COMPILE STEP	JCLB 03
3	//SYSLIN DD UNIT=SYSCA, SPACE=(CYL,(2,2)), DISP=(MCD,PASS),	JCLB 04
	// DCB=(RECFM=FB, LRECL=80, BLKSIZE=400)	JCLB 05
4	//SYS PRINT DD SYSOUT=A	JCLB 06
5	//SYS PUNCH DD SYSOUT=B	JCLB 07
6	//SYS IN DD *	JCLB 08
7	//STEPB EXEC PG4=LOADER, PARM='MAP', TIME=(0,30)	JCLB 11
	*** STEP B IS LOAD AND GO (LOAD PROGRAM PLUS SUBMIT (YES AND EXECUTE)	JCLB 12
8	//SYSLIN DD DSN=SYS1.SYSLIB, DISP=(GLD,DELETE)	JCLB 13
9	//SYSLIB DD DSN=SYS1.FORTLIB, DISP=SHR	JCLB 14
10	// DD DSN=FEA680.CHEMFGR, DISP=SHR	JCLB 15
11	// DD DSN=SYS2.FORTSSP, DISP=SHR	JCLB 16
12	//SYSCUT DD SYSOUT=A	JCLB 17
13	//FTCSF001 DD DDNAME=SYSIN	JCLB 19
14	//FTCF001 DD SYSOUT=A	JCLB 20
15	//FTCF001 DD SYSOUT=B	JCLB 21
16	//SYSIN DD *	JCLB 22
	//	0

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0001      DIMENSION R(22,12,11),T(22,12,11),S(22,12,11),AL(44,24,11)
0002      DIMENSION RA(25),A(25),E(25),C(25),D(25),W(25),G(25)
0003      DIMENSION C1(25),CK(25),C11(25),C10(25),GEN(25),XGEN(25)
0004      DIMENSION B(18,18),NZ(18)
0005      DIMENSION E1(125),E(125),Z(28)
0006      DIMENSION SDAT(70),REF(9),SPAN(9),OUT(9)
0007      DIMENSION TEMP(20),SRAD(70)
0008      REAL*8 B
0009      C      COMPUTER SIMULATION OF 3-DIMENSIONAL, CYLINDRICAL COORD.
0010      IDAT=0
0011      PI=3.14159
0012      ISK=1
0013      ATE=J.
0014      IXZ=1
0015      C      BOLTZMANN CONST., BOL
0016      BOL=5.4C7E-09
0017      LT=23
0018      C      CR IS THE RADIUS INCREMENT IN M
0019      CR=0.05R4
0020      ZET=0.50
0021      RA(1)=ZET*CR
0022      C      DX IS THE DEPTH INCREMENT IN M
0023      DX=0.102
0024      C      THE IS THE FRACTION OF CIRCLE
0025      N IS THE MAX. DIMENSION IN THE CIRCULAR DIRECTION(K)
0026      N=7
0027      THE=1./N
0028      NO=N+1
0029      C      L IS THE MAX. DIMENSION IN THE RADIAL DIRECTION(I)
0030      L=16
0031      LO=L+1
0032      C      M IS THE MAX. DIMENSION IN THE VERTICAL DIRECTION(J)
0033      M=11
0034      MO=M+1
0035      MM=M-1
0036      C      DIMENSION SIZES FOR THERMAL DIFFUSIVITIES(AL)
0037      IA=2*L
0038      JA=2*M
0039      C      DT1 IS THE HALF-TIME INCREMENT IN SEC
0040      DT1=9JD.
0041      TIME=0.0
0042      C      DAYS IS THE LENGTH OF RUN IN DAYS.
0043      LDAYS=5
0044      DAYS=LDAYS
0045      TMAX=DAYS*3600.*24.
0046      LHR=2
0047      C      RCAP IS THE DENSITY TIMES THE CAPACITY IN W-S/C*M**3
0048      RCAP=1.279E+C6
0049      RCPB=RCAP
0050      C      THERMAL CONDUCTIVITY IN W/C*M (TK*)
0051      TKC=J.6JD
0052      TKB=TKC*3.0
0053      INDM=1
0054      WALP=TKB/RCPB
0055      WALG=TKG/RCAP
0056      PAL=(WALB/WALG)*100.
0057      WRITE(6,518) PAL,WALG
0058      518 FORMAT(1X,'PERCENT OF GROUND DIFFUSIVITY =',F6.1,3X,'GROUND DIFFUS

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CIVITY = 'E11.4,/)
C      TH IS THE HEAT TRANSFER COEF. IN W/C*M**2
JJ46      TH=25.
0047      XTH=2.*TH/(PCAP*DX)
C      SRAD IS THE SOLAR RADIATION IN W/M**2
0048      READ(5,11)(SRAD(15),IS=1,16)
0049      11 FORMAT(16F5.1)
JJ50      READ(5,13)(SRAD(15),IS=17,30)
0051      13 FORMAT(14F5.1)
0052      WRITE(6,16) (SRAD(KC),KC=1,30)
0053      16 FORMAT(1X,14(F5.0,2X),7,14(F5.0,2X),/)
C      GEN IS THE GENERATION TERM FOR THE CENTER IN W/M**2
0054      DO 5 J=2,M
0055      GEN(J)=0.0
0056      5 XGEN(J)=GEN(J)=2.*(TRAT(J)*DX)/(RCAP*RA(I)*DX)
C      INITIALIZING THE MATRIX
0057      TINT=5.0
0058      DO 6 I=1,IA
0059      DO 7 J=1,JA
0060      DO 8 K=1,KO
0061      8 AL(I,J,K)=TKG/RCAP
0062      7 CONTINUE
0063      6 CONTINUE
0064      T1=30.
0065      DO 12 J1=1,MH
0066      IF(J1,GE,4) T1=T1-3.0
0067      R(1,J1,1)=T1
0068      DO 14 I1=2,LO
0069      DO 19 K1=1,KO
0070      R(I1,J1,K1)=T1
0071      R(I1,M,K1)=TINT
0072      R(I1,MO,K1)=T1
0073      19 CONTINUE
0074      14 CONTINUE
0075      12 CONTINUE
0076      R(1,M,1)=TINT
0077      DO 10 I1=2,LO
0078      KI=I1-1
0079      RAT(I1)=RAT(KI)+DR
0080      CI(I1)=2./(RA(I1)**2-RA(KI)**2)
0081      CK(I1)=1./((PI*THE)**2)*(RA(I1)+RA(KI))**2)
0082      10 CIO(I1)=ALOG((3.*RA(I1)-RA(KI))/(RA(I1)+RA(KI)))
0083      DO 15 I1=2,L
0084      15 CII(I1+1)=ALOG((RA(I1+1)+RA(I1))/(3.*RA(I1)-RA(I1+1)))
0085      CII(2)=2.0000
C      NON-HOMOGENEOUS
C      COORDINATES OF BLOCK
0086      KB=4
0087      JB=2
0088      JAZ=2
0089      DEPTH=(JB-1)*DX/0.3048-DX/0.6096
0090      IR=9
0091      CTCB=(18-2)*CR+RA(1)
0092      FCTC=CTCB/0.3048
0093      WRITE(6,519) DEPTH,FCTC
0094      519 FORMAT(2X,'DEPTH = ',F8.4,' FT',3X,'CENT TO CENT = ',F8.4,' FT',/)
0095      JDX=1
0096      JDR=5

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0097		FDX=JDX*DX/O.3048		
0098		EDR=JDR*DR/O.3048		
0099		WD=FC*(C*2.*PI/N		
0100		DO 527 JNC=1. JDX		
0101		J4=JH0*JBZ-1		
0102		DO 526 IND=1. JOR		
0103		IB=IND*6		
0104		TKF=2./(1./TKB+1./TKG)		
0105		II=IB*2-1		
0106		IO=IO*2-1		
0107		IK=IR*2-2		
0108		JK=JB*2-1		
0109		JI=JB*2-2		
0110		JO=JB*2		
0111		AL(IK,JK,KB-1)=TKE/RCAP		
0112		AL(IK,JK,KB)=TKE/RCAP		
0113		ALB=TKB/RCAP		
0114		ALB=TKB/RCAP		
0115		IF(JDX-1) 621,621,622		
0116	622	CONTINUE		
0117		JVX=JDX*JBZ-1		
0118		AL(IK,JI,KB)=ALB		
0119		AL(IK,JJ,KB)=ALB		
0120		IF(JB-EQ. JBZ) AL(IK,JI,KB)=ALE		
0121		IF(JB-EQ. JVB) AL(IK,JO,KB)=ALE		
0122		GO TO 623		
0123	621	CONTINUE		
0124		AL(IK,JO,KB)=ALE		
0125		AL(IK,JI,KB)=ALE		
0126	623	CONTINUE		
0127		DR2=DP/2.		
0128		R1=PA(1)+(18-2)*CR		
0129		R2=PA(1)+(18-1)*DR		
0130		TK1=ALOG(R1/DR2)/(R1-DR2)		
0131		TK11=ALOG(R1/DR2)/(R1-DR2)		
0132		TK12=ALOG(R1/DR2)/(R1-DR2)		
0133		TK2=ALOG(R2/DR2)/(R2-DR2)		
0134		TK21=ALOG(R2/DR2)/(R2-DR2)		
0135		TK22=ALOG(R2/DR2)/(R2-DR2)		
0136		IF(JDR-1) 631,631,632		
0137	631	CONTINUE		
0138		TK11=TK11*TKB/TKG		
0139		TK22=TK22*TKB/TKG		
0140		GO TO 633		
0141	632	CONTINUE		
0142		IF(18-EQ.7) TK11=TK11*TKB/TKG		
0143		IF(18-EQ.11) TK22=TK22*TKB/TKG		
0144	633	CONTINUE		
0145		TK1=TK1/(TK11+TK12)		
0146		TK2=TK2/(TK21+TK22)		
0147		AL(II,JK,KB)=TKI/RCAP		
0148		AL(II,JK,KB)=TKO/RCAP		
0149	526	CONTINUE		
0150	527	CONTINUE		
0151		WRITE(6,524) FDR,WD,FOX		
0152	524	FORMAT(1X,'BLOCK DIMENSIONS',/,1X,'LENGTH=',F8.6,' FT',2X,'WIDTH=',F8.6,' FT',2X,'THICKNESS=',F8.6,' FT',///)		
0153		FOR=DR/3.3348		


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0154      IB=9
0155      400 TIME=TIME+DTI*2.
           C FOR 1 DIRECTION
           C PLACE TIME INCREMENT CHANGE HERE
0156      LD=TIME/(3600.*24.)
0157      LT=(TIME-LD*3600.*24.)/3600.
0158      LTT=(TIME-LD*3600.*24.-LT*3600.)/760.
           C TAF IS THE AIR TEMPERATURE IN DEG. F
0159      TAM=79.
0160      TDF=19.
0161      TAF=TAM+TDF*5*IN(TIME*PI/43200.-PI/4.)
0162      IF(LT.EQ.21) ATE=C.
0163      IF(LT.GE.15.AND.LT.LT.17) ATE=ATE+2.
0164      IF(LT.GE.17.AND.LT.LT.21) ATE=ATE-1.
0165      TAF=TAF-ATE
0166      IF(LT.GT.21.OR.LT.EQ.0) TAF=TAM-TDF
0167      IF(LT.EQ.1.AND.LTT.EQ.0) TAF=(TAF+TAM-TDF)/2.
0168      TAC=(TAF-32.)/1.8
           C RATH IS THE RADIATION FROM THE ATM. IN W/M**2
0169      RATH=1.561E-14*((TAF+460.)*61)
           C RGRD IS THE RADIATION FROM THE GRD. IN W/M**2
0170      RGRD=BUL*((R(1,1,1)+273.)*1.8)**4
0171      RGRD=RGRD*.80
0172      ISR=ISR+1
0173      IF(ISR-30) 17,17,18
0174      SRAD(ISR)=0.0
0175      IF(ISR.EQ.48) ISR=0
0176      17 CONTINUE
0177      SOLAR=SRAD(ISR)*0.70
0178      LIDAY=LIDAYS-1
0179      IF(LD-LT.LIDAY) SOLAR=SOLAR*.75
           C SFLX IS THE TOTAL RADIATION FLUX IN W/M**2
0180      SFLX=SOLAR+RATH-RGRD
0181      XFLX=.7.*SFLX/(RCAP*DX)
0182      CJ=1./(DX**2)
0183      CZ=4.*ZET/(2.*ZET+1.)
0184      THE=THE*CZ
           C IMPLICIT IN THE I-DIRECTION
           C SURFACE(J=1)
0185      J=1
0186      I=1
0187      ZI=1./(AL(1,1,2)*CZ/RA(1)**2+1./DTI)
0188      SUMR=0.0
0189      DO 20 K=2,ND
0190      SUMR=SUMR+R(2,1,K)
0191      20 S(1,1,1)=ZI*(THE*AL(1,1,2)*SUMR/RA(1)**2+XTH*(TAC-R(1,1,1))*2.*AL
           C (1,1,2)*(R(1,2,1)-R(1,1,1))/DX**2+R(1,1,1)/DTI+XFLX)
0192      WJ=S(1,1,1)
0193      DO 24 K=2,NO
0194      24 DO 25 I=2,L
0195      II=2.*I-3.
0196      IO=2.*I-1.
0197      JK=2.*J-1.
0198      IK=2.*J-2.
0199      JI=2.*J-2.
0200      JO=2.*J
0201      A(1)=-C(1,1)*AL(11,JK,K)/CII(1)
0202      F(1)=C(1,1)*(AL(11,JK,K)/CII(1)+AL(10,JK,K)/CIO(1))*1./DTI

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0203 C(I)=-C(I)+AL(10,J,K)/C(10,I)
0204 NJ=XTH*(TAC-R(I,J,K))+2*CG*AL(I,K)+J*(R(I,J,K)-R(I,J,K))
0205 DK=CX(I)*AC(I,K)+J*(R(I,J,K)-R(I,J,K))+AL(I,K)*R(I,J,K)
0206 CK(I)=R(I,J,K)+J*(R(I,J,K)-R(I,J,K))+XFLX
0207 D(I)=DJ+DK+R(I,J,K)/DTI+XFLX
0208 C(I)=0.0
0209 D(2)=D(2)-A(2)*R(1,1,1)
0210 G(10)=J
0211 SILDT(J,K)=SIL-1,J,K)
0212 C(1)=0.0
0213 DO 26 J=2,M
0214 SUMR=0.0
0215 DO 27 K=2,ND
0216 SIL(SUMR+R(2,J,K)
0217 C(J)=
0218 DO 29 K=2,ND
0219 DT 29 I=2,L
0220 I=2,M-1
0221 I=2,M-1
0222 JK=2,M-1
0223 JK=2,M-1
0224 JI=2,M-2
0225 JO=2,M
0226 A(I)=-C(I)+AL(I,J,K)/C(10,I)+AL(10,J,K)/C(10,I)+L/DTI
0227 E(I)=C(I)+AL(I,J,K)/C(10,I)+AL(10,J,K)/C(10,I)
0228 C(I)=-C(I)+AL(I,J,K)/C(10,I)+AL(10,J,K)/C(10,I)
0229 DK=CK(I)+AL(I,K)+J*(R(I,J,K)-R(I,J,K))+AL(I,K)*R(I,J,K)
0230 DJ=CJ+AL(I,K)+J*(R(I,J,K)-R(I,J,K))+AL(I,K)*R(I,J,K)-
0231 C(I)+J*(K))
0232 D(I)=DJ+DK+R(I,J,K)/DTI
0233 C(I)=0.0
0234 D(2)=D(2)-A(2)*R(1,1,1)
0235 G(10)=J
0236 SILC(J,K)=SIL-1,J,K)
0237 110 CONTINUE
0238 CONTINUE
0239 DO 125 J=1,M
0240 DO 123 K=2,ND
0241 SIL(J,K)=SIL,J,K)
0242 125 CONTINUE
0243 I=1
0244 J=1
0245 C CENTER SECTION
0246 SUMR=0.0
0247 DO 32 K=2,ND
0248 SUMR=SUMR+SIL(2,1,K)
0249 A(I)=0
0250 F(I)=XTH+2*ACJ*AL(I,J,2)+L-/DTI
0251 C(I)=-2*CG*AL(I,J,2)
0252 D(I)=AL(1,J,2)*TH*SUMR-SIL(1,1,1)/RA(1)+2
0253 D(1)=D(1)+XTH*TAC+R(1,1,1)/DTI+XFLX
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0253 DO 33 J=2,M
0254 A(J)=CJ*AL(I,J)=I+2
0255 F(J)=CJ*AL(I,J)=I+2+AL(I,J,2)*I./DTI
0256 C(J)=CJ*AL(I,J,2)
0257 SUMR=0.0
0258 DO 34 K=2,MC
0259 SUMR=SUMR+S(2,J,K)
0260 DI=AL(I,J,2)*I*HE*SUMR-S(I,J,1)/RA(I)*2
0261 D(J)=DI+R(I,J,1)/DTI+XGEN(J)
0262 A(I)=A(M)+C(M)
0263 C(M)=0.0
0264 K=1
0265 GO TO 203
0266 T(L,MC,1)=I+M-1,1
0267 WY=I(1,1,1)
C
0268 DO 35 I=2,L
0269 DO 36 K=2,NO
0270 J=I
0271 I=2.*I-3.
0272 I=2.*I-1.
0273 JK=2.*J-1.
0274 JK=2.*J-2.
0275 JI=2.*J-2.
0276 JD=2.*J
0277 A(I)=0.
0278 F(I)=XTHF2=CJ*AL(IK,JO,K)+I./DTI
0279 C(I)=-2.*CJ*AL(IK,JO,K)
0280 DI=C(I)*AL(I,J,K)*S(I-1,J,K)-S(I,J,K)/CII(I)+AL(IO,JK,K)*S
C(I+1,J,K)-S(I,J,K)/CIO(I)
0281 DK=C(K)*AL(IK,JK,K-1)*R(I,J,K-1)+AL(IK,JK,K)*R(I,J,
C(K+1)-R(I,J,K))
0282 D(I)=DI+DK+XTHETAC+K(I,J,K)/DTI+XFLX
0283 DJ 37 J=2,M
0284 I=2.*I-3.
0285 I=2.*I-1.
0286 JK=2.*J-1.
0287 JK=2.*J-2.
0288 JI=2.*J-2.
0289 JD=2.*J
0290 A(J)=CJ*AL(IK,JI,K)
0291 F(J)=CJ*AL(IK,JI,K)+AL(IK,JO,K)+I./DTI
0292 C(J)=CJ*AL(IK,JO,K)
0293 DI=C(I)*AL(I,J,K)*S(I-1,J,K)-S(I,J,K)/CII(I)+AL(IO,JK,K)*S
C(I+1,J,K)-S(I,J,K)/CIO(I)
0294 DK=C(K)*AL(IK,JK,K-1)*R(I,J,K-1)+AL(IK,JK,K)*R(I,J,
C(K+1)-R(I,J,K))
0295 37 D(J)=DI+DK+R(I,J,K)/DTI
0296 C(I)=0.0
0297 GO TO 200
0298 T(I,40,K)=I+M-1,K
0299 36 CONTINUE
0300 35 CONTINUE
0301 DO 42 J=1,40
0302 DO 44 I=2,L
0303 DO 46 K=2,NO
0304 46 R(I,J,K)=I(I,J,K)
0305

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0326 44 CONTINUE
0327 42 RU J=1,10,1,1
C
C CENTER SECTION
C
0308 J=1
0309 SUMR=0
0310 DO 52 K=2,NO
0311 52 SUMR=SUMR+S(2,J,K)
0312 I(1,1)=0
0313 C(1,1)=2-CJ*AL(1,2,2)*(R(1,2,1)-R(1,1,1))/RA(1,1)*2*XT*(TAC-R(1,1,1))
0314 MV=I(1,1,1)
0315 DO 53 J=2,M
0316 SUMR=0
0317 DO 54 K=2,NO
0318 54 SUMR=SUMR+S(2,J,K)
0319 53 I(1,J,1)=DTI*(AL(1,J,2)-R(1,J,1))/RA(1,1)*2+CJ*(AL(1,J,1)-R(1,J,1))*XGEN(J)
C(1,1)=R(1,1,1)
C
C MAIN BODY-SURFACE
C
0320 J=1
0321 DO 55 I=2,1
0322 DO 56 K=2,NO
0323 I1=2*I-1
0324 I0=2*I-1
0325 JK=2*I-1
0326 IK=2*I-1
0327 J1=2*I-2
0328 J0=2*I-2
0329 A(K)=C(K,1)*AL(IK,JK,K-1)
0330 F(K)=C(K,1)*AL(IK,JK,K)
0331 C(K)=C(K,1)*AL(IK,JK,K)*(S(I1-J,K)-S(I0-J,K))/C(I0,1)
0332 C(I1+J,K)=TAC-K(I,J,K)+2*CJ*AL(IK,JK,K)*(R(I1,J+1,K)-R(I1,J,K))
0333 DJ=XTH*(TAC-K(I,J,K)+2*CJ*AL(IK,JK,K)*(R(I1,J+1,K)-R(I1,J,K))
0334 56 DK=DI+DJ*R(I1,J,K)/DTI+XFLX
0335 GO TO 300
0336 302 CONTINUE
0337 C
C MAIN BODY
0338 DO 57 J=2,M
0339 DO 58 I=2,1
0340 DO 59 K=2,NO
0341 I1=2*I-1
0342 I0=2*I-1
0343 JK=2*I-1
0344 IK=2*I-1
0345 J1=2*I-2
0346 J0=2*I-2
0347 A(K)=C(K,1)*AL(IK,JK,K-1)
0348 F(K)=C(K,1)*AL(IK,JK,K)
0349 C(K)=C(K,1)*AL(IK,JK,K)*(S(I1-J,K)-S(I0-J,K))/C(I0,1)
0350 C(I1+J,K)=TAC-K(I,J,K)+2*CJ*AL(IK,JK,K)*(R(I1,J+1,K)-R(I1,J,K))
0351 DJ=XTH*(TAC-K(I,J,K)+2*CJ*AL(IK,JK,K)*(R(I1,J+1,K)-R(I1,J,K))
0352 59 DK=DI+DJ*R(I1,J,K)/DTI
0353 GO TO 333

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0354      310 CONTINUE
0355      58 CONTINUE
0356      57 CONTINUE
0357      GO TO 503
0358      SCI CONTINUE
0359      DO 64 J=1,M
0360      DO 64 I=2,L
0361      R(I,J,1)=T(I,J,10)
0362      R(I,J,NO+1)=T(I,J,2)
0363      DO 66 K=2,NG
0364      R(I,J,K)=T(I,J,K)
0365      R(I,J,K)=T(I,J,K)
0366      R(I,J,K)=T(I,J,K)
0367      R(I,MC,K)=T(I,M-L,K)
0368      64 CONTINUE
0369      62 R(I,J,1)=T(I,J,1)
0370      GO TO 400
0371      100 W(2)=F(2)
0372      DO 101 IO=3,L
0373      W(IO)=F(IO)
0374      W(IO)=F(IO)+A(IO)*C(ID-1)/W(ID-1)
0375      101 S(L,J,K)=G(L)
0376      LI=L-2
0377      DO 102 IO=1,LI
0378      IS=L-IO
0379      S(IS,J,K)=G(IS)-C(IS)*S(IS+1,J,K)/W(IS)
0380      IF(J-1) 105,105,110
0381      W(1)=F(1)
0382      G(1)=D(1)/W(1)
0383      DO 201 JO=2,M
0384      W(JO)=F(JO)+A(JO)*C(JO-1)/W(JO-1)
0385      G(JO)=D(JO)-A(JO)*G(JO-1)/W(JO)
0386      T(1,2,K)=G(M)
0387      M=L-1
0388      DO 202 JO=1,M1
0389      JT=4-JO
0390      T(1,JT,K)=G(JT)-C(JT)*T(1,JT+1,K)/W(JT)
0391      IF(J-1) 205,205,210
0392      201 ACOL=4
0393      ACOL=NO
0394      ACOL=18
0395      NO=14
0396      DO 303 IY=1,NO
0397      DO 304 IX=1,N
0398      B(IX,IY)=0.0
0399      303 CURR=1
0400      304 CURR=1
0401      401 4(1,1)=F(2)
0402      4(1,2)=C(2)
0403      B(1,NO)=A(2)
0404      403 4(1,1)=1
0405      DO 307 IR=2,N1
0406      4(1,IR)=A(IR+1)
0407      B(1,IR)=F(IR+1)
0408      B(1,IR+1)=C(IR+1)
0409      307 B(1,NO)=C(IR+1)
0410      B(1,NO)=A(NO)
0411

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0412      B(H,H)=F(HOI)
0413      B(N,1)=C(INO)
0414      B(N,N)=D(INO)
0415      CALL OIACON(B,NZ,NROW,NCOL,ARDIM,NCDIM,C9876)
0416      DO 308 IR=1,N
0417      308      IF(J-1) 305,305,311
0418      305      IF(J-1) 305,305,311
0419      305      IF(J-1) 305,305,311
0420      305      IF(J-1) 305,305,311
0421      IF(LD,LI-LIDAY) GO TO 521
0422      LI=(TIME-LD*3600)*24.773600
0423      LTI=(TIME-LD*3600)*24.-LI*3600./60.
0424      LTTI=(TIME-LD*3600)*24.-LI*3600.-LTI*60.
0425      IDAT=IDAT+1
0426      SDAT(IDAT)=(IIB,I,K8)-Y(L-1,I,K8*21)*1.8
0427      WRITE(6,905) IIB,I,K81,I(L-1,I,K81),T(L-1,I,K8*21),SDAT(IDAT)
0428      905      FORMAT(1X,2F10.2,' DIFF = ',F10.2)
0429      IF(LH*EQ.2) GO TO 605
0430      LK=LH*2
0431      IF(TMAX-GE-TIME) GO TO 501
0432      IF(IHCH-1) 606,9878,606
0433      LI=0.0
0434      ENV=3.0
0435      NM=60
0436      NL=60
0437      L3=1.3
0438      YI=(L-1)*OR
0439      YD=2*(L-1)*OR/NW
0440      YN=YI+YD/2.
0441      RY=NL+1
0442      DO 831 LY=1,NY
0443      YN=YI
0444      YN=YI-YD
0445      NM2=NM+2
0446      DO 802 JL=1,NW2
0447      802      E1(JL)=100.
0448      DO 803 I=1,L
0449      803      RAD=(1-I)*OR
0450      DO 804 K=2,ND
0451      804      NDEG=(K-2)*36./N
0452      RD=NDEG*PI/180.
0453      Y=RADECOS(RD)
0454      IF(Y,LI,YU,AND,Y,GT,YN) GO TO 830
0455      GO TO 840
0456      830      X=RAD*51N(RD)*NW/(2.*YI)+3.5
0457      JX=X
0458      JL=(NM/2)+1+JX
0459      F1(JL)=T(I,1,K)-T(I,1,8)
0460      840      CONTINUE
0461      804      CONTINUE
0462      803      CONTINUE
0463      CALL INSTPL(L1,NW,L3,E1,NL,ENV)
0464      ENV=ENV+YD
0465      L1=L1+1
0466      L3=L3+1
0467      IF(L3-EQ.11) L3=1
0468      801      CONTINUE

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0525      DO 711 IW=1,8
0526      SPAN(IW)=XMAX-XMIN
0527      REFT(IW)=XMIN
0528      711 OUT(IW)=SPAN(IW)+XMAX
0529      TME=6.0
0530      WRITE(6,720)
0531      720 FORMAT(18X,'-10 F',5X,'-8 F',6X,'-6 F',6X,'-4 F',6X,'-2 F',7X,'0 F',
0532      6',7X,'2 F',7X,'4 F',7X,'6 F',7X,'8 F',6X,'1C F',/)
0533      DO 712 KW=1,ICAT
0534      OUT(I)=SDAT(KW)
0535      CALL PLOTH(SPAN,REF,OUT,TME)
0536      TME=TME+DT1*2.73600
0537      IF(TME-GT.24.75) TME=1.0
0538      712 CONTINUE
0539      888 FORMAT(1X,'IXZ = ',14)
0540      999 CONTINUE
0541      STOP
0542      END

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FORTRAN IV G1 RELEASE 2.0		PLOT8	DATE = 78362	15/26/41	PAGE 0001
0001		SUBROUTINE PLOT8(SPAN,REF,OUT,TME)		00000100	
	C	PLCT8 SIMULATES AN 8CHANNEL STRIP CHART RECORDER		00000110	
0002		DIMENSION SPAN(8),REF(8),OUT(8),IOUT(8),CODE(8),SPACE(101)		00000120	
	C	DEFINE HOLLERITH CONSTANTS		00000130	
0003		DATA CODE/1H1,1H2,1H3,1H4,1H5,1H6,1H7,1H8/		00000140	
0004		DATA BLANK/1H /,ASTRSK/1H*/.S/1H5/		00000150	
	C	CALCULATE POSITION ACROSS PAGE FOR EACH CHANNEL		00000160	
0005		DO 1 I=1,8		00000170	
0006		DEL=OUT(I)-REF(I)		00000180	
0007		IOUT(I)=(DEL/SPAN(I))*100.0+1.5		00000190	
0008		IF(IOUT(I).GT.101)IOUT(I)=101		00000200	
0009		IF(IOUT(I).LT.1)IOUT(I)=1		00000210	
0010		1 CONTINUE		00000220	
	C	CLEAR LINE TO ALL BLANKS		00000230	
0011		DO 2 I=1,101		00000240	
0012		2 SPACE(I)=BLANK		00000250	
	C	MARK EACH TEN PLACES WITH AN ASTERISK (*)		00000260	
0013		DO 3 I=1,101,10		00000270	
0014		3 SPACE(I)=ASTRSK		00000280	
	C	CONSIDER EACH SPACE IN TURN		00000290	
0015		DO 4 I=1,101		00000300	
0016		ICTR=0		00000310	
	C	CHECK EACH CHANNEL		00000320	
0017		DO 5 J=1,8		00000330	
0018		IF(IOUT(J).NE.1)GO TO 5		00000340	
0019		SPACE(I)=CODE(J)		00000350	
0020		ICTR=ICTR+1		00000360	
0021		5 CONTINUE		00000370	
	C	PRINT AN S IF TWO OR MORE CHANNELS COINCIDE		00000380	
0022		IF(ICTR.GT.1)SPACE(I)=S		00000390	
0023		4 CONTINUE		00000400	
	C	OUTPUT THE LINE AND RETURN		00000410	
0024		WRITE(6,100)TME,(SPACE(K),K=1,101)		00000420	
0025		100 FORMAT(1H ,F8.2,1CX,101A1)		00000430	
0026		RETURN		00000440	
0027		END		00000450	


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0059      IF(E1(JL).LE.-0.9.AND.E1(JL).GT.-1.1) E(JL)=Z(22)
0060      IF(E1(JL).LE.-1.1.AND.E1(JL).GT.-1.5) E(JL)=Z(23)
0061      IF(E1(JL).LE.-1.5.AND.E1(JL).GT.-2.0) E(JL)=Z(24)
0062      IF(E1(JL).LE.-2.0.AND.E1(JL).GT.-2.5) E(JL)=Z(25)
0063      IF(E1(JL).LE.-2.5.AND.E1(JL).GT.-10.) E(JL)=Z(26)
0064      705 CONTINUE
0065      WRITE(6,706) ENV,(E(JL),JL=1,NW1)
0066      706 FORMAT(F9.2,123A1)
0067      NL1=NL+1
0068      IF(L1.NE.NL) GO TO 799
0069      JC=0
0070      DO 9 JL=1,NW3
0071      E(JL)=Z(11)
0072      L2=(JC+10)+1
0073      IF(JL.EQ.L2) E(JL)=Z(12)
0074      9 IF(JL.EQ.L2) JC=JC+1
0075      WRITE(6,700)(E(JL),JL=1,NW1)
0076      799 CONTINUE
0077      RETURN
0078      END

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