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SALTY

**A Hybrid Computer Program for
Three-Dimensional Heat Transfer from
a Discrete Source**

R. S. Stone
O. W. Burke

OAK RIDGE NATIONAL LABORATORY
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INSTRUMENTATION AND CONTROLS DIVISION

SALTY
A HYBRID COMPUTER PROGRAM FOR THREE-DIMENSIONAL
HEAT TRANSFER FROM A DISCRETE SOURCE

R. S. Stone

O. W. Burke

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ABSTRACT

SALTY, a hybrid computer code, has been written for calculation of the temperature distributions in an extended medium with spatially varying properties and one or more discrete energy sources. Such complex, multidimensional, time-dependent simulations constitute one useful application of the parallel computation and continuous integration capabilities of the analog-digital hybrid computer. An application of SALTY to a problem involving nuclear waste disposal in salt is described, and the results are compared to those from the pure digital code HEATING5. SALTY gives much the same results at a lower computer cost. Differences in the results are discussed.

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FOREWORD

This report was prepared by the Instrumentation and Controls Division of the Oak Ridge National Laboratory in cooperation with the Office of Waste Isolation and is a part of the National Waste Terminal Storage Program. The principal objective of this program is to establish facilities in various deep geologic formations at several locations in the United States which will safely dispose of commercial radioactive waste. This report documents the use of a hybrid analog-digital computer to solve heat transfer problems associated with the burial of radioactive waste. As a part of the Thermal Analysis Studies of the Office of Waste Isolation, this report compares cost and results with the digital code HEATING5.

1. INTRODUCTION

Impetus for development of a hybrid heat transfer program came from the long running times required by the digital program HEATING5¹ when calculating transient temperature distributions surrounding buried heat sources. Interest in mine stability and environmental consequences resulting from burial of nuclear fuel cycle wastes has led to a need for detailed calculations of heat transfer in geological media. These calculations involve complex multidimensional, time-dependent equations, and typically require long runs on large digital computing facilities. To determine the extent of possible savings in cost and time, the heat transfer equations were programmed on an analog-digital hybrid computer for a feasibility study. The advantage of an analog machine in such an application is that it provides fast, continuous, simultaneous solutions to a substantial number of coupled differential equations. In many instances this parallel-running capability precludes the need for iterative runs to reach convergence. By making computations simultaneously instead of in series, and by avoiding iteration, the savings in time can sometimes be enormous. Adding a close-coupled digital computer to the analog machine permits "sharing" the analog matrix so as to expand the number of equations which can be addressed. In addition, the digital advantages of memory, preprogramming, and virtually unlimited function generation are provided.

2. STRUCTURE OF THE MODEL

The system which SALT² is set up to handle is a rectangular-coordinate array of 20 heat-conduction nodes, taken 4 in the y-direction and 5 in the x. For the required level of complexity of the nodes this takes most of the available capacity of the analog machine. Figure 1 shows the analog programming. Digital programming is provided to share this x-y matrix among sequential locations in the z dimension. The program listing is provided in Appendix A. The nodes may be spaced as desired with no requirement for equal increments, though it is preferable for the x-y spacings to be the same at every z-level. Each node is a

finite difference representation of one spatial element and contains an analog integrator to provide time integration of the net thermal input; this latter value, divided by the heat capacity, provides a continuously updated temperature reading. Table 1 lists the variables used in the analysis.

Equations used for heat flow are of the form

$$\frac{\partial T}{\partial t} = \frac{k}{\rho c} \sum_s^{x,y,z} \frac{(T_{n-1} - T_n)_s}{\Delta S_{s1} \Delta S_{s2}} + \frac{(T_{n+1} - T_n)_s}{\Delta S_{s1} \Delta S_{s3}} \quad (1)$$

Because the nodes are, in general, not uniformly spaced, ΔS_{s1} (the length of the node in the s direction) is not always the same as ΔS_{s2} and/or ΔS_{s3} (forward and backward distances between nodes along s). As used in the model, $\Delta S_{s1} = 0.5(\Delta S_{s2} + \Delta S_{s3})$.

Temperatures are represented by scaled voltages, and x-y thermal resistance between nodes by digitally set attenuators, or "digital coefficient units" (DCUs). Settings of the DCUs may be functions of geometry, material, and temperature, and are periodically recalculated and updated by the digital computer. In the z direction, since adjacent temperatures are not continuously available as analog inputs, the vertical contribution to the heat transfer integrand is held constant throughout each time step.

Inasmuch as analog integration is continuous rather than stepwise incremental, the term "time step" simply signifies an interval over which the analog coefficients are held constant. For any given step the integration time must be identical for all 20 nodes in the x-y array, but it may be varied for different positions in the z dimension. This option permits longer time steps in those regions where larger spatial steps in z are used, and where the time constants are, therefore, correspondingly greater. The length of the time step may also be varied as a function of time, for example, steps may be shorter for a freshly perturbed system, and longer as equilibrium is approached. This approach helps to minimize run time by limiting the number of digital operations to no greater a number than accuracy and stability require. A few trial runs may be needed to optimize step length as a function of time and location.

The length of the time step is programmed by timer choices available in the logic portion of the analog machine. For example, for the sample 30-year waste isolation problem described later in this report, the analog is scaled at a ratio of 1 sec machine time to 1 yr of simulated time, with time-step choices of 0.0001, 0.0005, 0.001, 0.0025, 0.01, and 1.0 sec (yr), the value used being a function of the elapsed time since the transient began. The time step chosen is determined by digital programming, operating through reevaluations of the control word ITWD. This selection takes place early in the program, as shown on page 38 of the program listing (Appendix A). Here, IT is the sequential number of the time step. As suggested above, the time step is also a function of the z position of the x-y matrix. Where sections are very thin (short time constant), the time steps may be made shorter. This is done by manipulation of the command SETLI (see page 46), by which the timer pattern set in by ITWD is modified. Where sections are very thick (long time constant), the time steps may be made longer and changed less frequently, since the integrand is not changing rapidly. Rather than running 100 times longer, the same smaller time step can be used, but with an integrand 100 times the actual value. The quadratures are then performed only every 100th pass. In the sample problem, this means that in the blocks hundreds of feet thick, such as are used in the areas remote from the thermal perturbation, temperatures and material properties are updated only once a year, while most z levels are updated every 0.01 yr, and the two thinnest sections are reevaluated every 0.001 yr. These operations are shown on page 46, where IZ refers to the z position, with the IZ value representing an ordinal listing of the z nodes from the bottom up. In the sample problem there is a total of 31 IZs, with No. 1 (deep earth) and No. 31 (surface) held at fixed temperatures. Values of IZ that are ≤ 6 and ≥ 25 are updated only once a year.

Time steps from 1 μ sec to 100 sec are available by patching on the analog logic board. There are 16 digital control lines on the analog logic panel, numbered from DGC 0 to DGC 15. In general, the function of these control lines is to alter the time step as desired, to alter geometry as required by certain z levels, and to control the operating mode of the analog machine. These lines are set on or off depending on the

Table 1. List of variables and their definitions.

C	Thermal conductance
c	Heat capacity per unit mass
CP	Heat capacity (reciprocal)
CP1	Heat capacity for special cases (reciprocal)
GDN	Geometry factor in downward direction
GUP	Geometry factor in upward direction
GX	Geometry factor in x direction
GY	Geometry factor in y direction
HAIR	Heat transfer coefficient between air and room surface
HK1	Conductivity in upward direction
HK2	Conductivity in downward direction
IAD	Name of array containing digital coefficient device addresses
IAMP	Name of array containing addresses of analog amplifiers
IAP	Name of array containing addresses of servo-set potentiometers
INIT	Setword argument used to set the bit pattern in control line register
IT	Time step count variable
ITEMPT	Array containing node temperatures as read from analog amplifiers
ITWD	Part of INIT dependent on time-step count, IT
IVD	Array containing digital coefficient device values or settings
IVP	Array containing servo-set potentiometer values or settings
IX	Node index in x direction
IY	Node index in y direction
IZ	Node index in z direction
IZWD	Part of INIT dependent on z level, IZ
NADC	Number of analog-to-digital converter lines used in problem
NAMP	Number of amplifiers used in problem
NDAC	Number of digital coefficient devices used in problem
NPOT	Number of servo-set potentiometers used in problem
PFR	Waste heat generation rate as a function of time after burial, expressed as a fraction of the rate at time of burial
PWR	Heat generated by radioactive decay
q _v	Volumetric rate of power generation
R	Thermal resistance
ΔS_{e1}	Length of node in s direction
ΔS_{s2}	Center-to-center backward distance to adjoining node in s direction
ΔS_{s3}	Center-to-center forward distance to adjoining node in s direction
SFT	Time scale multiplier
SFX	Scale factor for x direction
SFY	Scale factor for y direction
SFZ	Scale factor for z direction
T	Time in years
TEMP	Array containing values of node temperatures for a particular time-step
TEMPER	Array containing temporary values of node temperatures for a particular time-step
TEMPRT	Array containing values of node temperatures to be printed on line printer
V	Volume
XHT	Time rate of change of temperature in x direction
YHT	Time rate of change of temperature in y direction
YPLN	y distance expressed in feet
ZDIST	z distance expressed in feet
ZHT	Time rate of change of temperature in z direction
ZHT1	Contribution to ZHT in upward direction
ZHT2	Contribution to ZHT in downward direction
ρ	Density

makeup of the 5-digit hybrid call SETWD. Table 2 lists the control line numbers, together with the SETWD components which set them high. For example, a SETWD of 8200 ($= 8192 + 8$) would set DGCs 2 and 12. In program SALTY, the call SETWD is broken into two components, IZWD and ITWD. IZWD makes z-level dependent changes in the control lines to implement changes in geometry or materials with depth. Involved are DGCs 2, 3, 4, 5, 8, 9, and 10 (see Figs. 1 and 2). ITWD sets the time-step control lines that depend on the time variable and involves time-step DGCs 0, 11, 12, and 13. The initial-condition control line, DGC 15, is set at the same time. If all five of these time-step dependent lines were set high, ITWD would be set to 32797. The analog logic diagram for the time-step is shown in Fig. 2a. An ITWD value of 29 (i.e., $32797 - 32768$) would set DGCs 11, 12, 13, and 15 high and DGC 0 low, thus selecting the 100- μ sec timing rate. (A timing rate is selected by setting its associated DGC low; see Fig. 2.) An ITWD value of 32793 (i.e., $32797 - 4$) sets all time lines high except DGC 13, thus selecting the 1-msec timing rate. The situation is more complex when $ITWD = 32789$ (or $32797 - 8$) is selected, and DGC 11 goes low. In this situation the time step can be either 0.5 or 2.5 msec, depending on whether DGC 14 is high or low. This decision is z-dependent, and DGC 14 is set independently of SETWD by the SETLI command. Page 46 includes the applicable programming. Also, page 38 contains instructions which determine the ITWD structure at various time intervals after the start of the program.

In the absence of option routines in the program, the timing instructions just discussed must be edited and altered to fit the system under evaluation. The rate of change of the driving function as a function of time and the thermal time constants of the nodes as a function of z will

Table 2. Control lines turned on vs digital components present in SETWD

Control Line No.	0	1	2	3	4	5	6	7
SETWD Component	32768	16384	8192	4096	2048	1024	512	256
Control Line No.	8	9	10	11	12	13	14	15
SETWD Component	128	64	32	16	8	4	2	1

a. Patchable logic diagram for time-step control.

b. Patchable logic diagram for spatial variations.

Fig. 2. Configuration of patchable logic elements.

be the determining factors in the pattern of time steps which is actually chosen. Too many steps lead to longer than necessary running time; too few steps lead to instability and "hunting" in the solution.

For the example program whose listing appears in Appendix A, time steps depend upon both IT and IZ, as shown in Table 3. Qualitatively, steps can be longer where z thicknesses are greater; they must be shorter where z thicknesses are thin or at the start of the run where temperatures are changing most rapidly. Time-dependent relations are called out by ITWD determinations on page 38; z-dependent exceptions to these are determined by SETLI calls introduced on page 46. As an example, the call SETLI (0, 0, 11, 0) indicates that DGC 11 is to be set low, regardless of the value of the corresponding ITWD.

To summarize, the control lines are addressed en masse by SETWD, of which ITWD is a component, or individually by SETLI. For z levels 7-11 and 22-24, there are 514 time steps in the first year's simulation. From that point on, there are 1, 100, 400, or 1000 steps per year, depending on the z level. Because of their low heat capacity and steep thermal gradient, levels 15 and 16 have more time steps. To further smooth the behavior at the z = 16 level (burial chamber floor), the vertical heat transfer value at that level is made equal to the average of the value most recently calculated and the value from the preceding time step. At this same z-level, the equations for convection to air in the room or conduction to salt in the pillar are differentiated by variations in analog programming on an x-dependent basis. Logic programming is shown in Fig. 2b.

Table 3. Length of time step (yr) as function of vertical position and elapsed time

IT Value (No. of time step)	IZ position			
	1-6,25-30	7-11,22-24	12-14,17-21	15,16
0-100	1	0.0001	0.0001	0.0001
101-130	1	0.001	0.001	0.0005
131-514	1	0.0025	0.0025	0.0005
515-3414	1	0.01	0.0025	0.001

On page 39 the elapsed time in years T is determined in terms of the current time-step IT in a number of program algorithms, and the relative source strength PFR is determined as a function of T . On page 40 (reciprocal) heat capacity CP and the temperature-dependent heat transfer coefficients $HK1$ and $HK2$ are selected as functions of spatial position. These variables are problem dependent.

3. DIGITAL COMPUTER CONTRIBUTION

The digital computer portion of the hybrid computer system is assigned the following tasks:

1. Calculate the values to be used to set the analog coefficient devices [coefficients in Eq. (1)].
2. Direct the setting of the analog coefficient devices.
3. Control the operation of the analog computer through the patchable logic elements on the analog console.
4. Read the outputs from the analog amplifiers, store the values, and print them out at the conclusion of the run.

The FORTRAN IV language is used to program the DEC PDP-10 digital computer. FORTRAN callable hybrid computation routines (HCRs) are used to communicate with the analog computer.

3.1 Digital Computer Program

A flow diagram of the digital computer program is shown in Fig. 3, and a listing of the digital program is shown in Appendix A.

The digital program is largely composed of a collection of nested DO loops. The outermost loop, containing the tasks to be done during a particular time step, is the time-step loop having the index "IT." The next loop inside the time-step loop performs the tasks associated with each z level; its index is "IZ." Three loops inside the z -level loop calculate the coefficients for the transient heat conduction equation, Eq. (1), at each of the 20 x - y locations.

To begin the program, the initial values for the variables and the values of the constants used in the problem are read into the digital

computer. Under digital program control the analog computer is interrogated to ensure that all the equipment to be used is operational. The analog computer is placed in the initial condition mode, and the constant-value servo-set potentiometers are set.

The time-step loop is then entered. The program chooses the time-step size for the particular time-step or IT value by setting the arguments in the SETWD call to such a value as to activate the proper logic control lines on the analog machine. The effective time step size varies from 100 μ sec to 1 sec at a scale of 1 sec = 1 yr. The steps are shorter during the rapid temperature changes at the start of the run, and lengthen as equilibrium is approached. The very long time steps (1 yr) are used only for the massive blocks far above and below the source level. The accumulated time in years is continually totaled, and at each time step the appropriately decayed power generation rate is set in as a source factor. The source is constant during each time step.

The program next enters the z-level loop, where the logic control line pattern is set to that appropriate for the current z level. The analog computer is placed in the initial condition mode.

The loop for calculating the coefficients for heat transfer in the z direction is entered next. Most of the heat transfer coefficients are temperature dependent, and, because of changes in material, they are position dependent as well. Since z-direction ΔT 's are fixed during each time step, the ΔT 's are included in the z-direction heat transfer coefficients. The heat transfer loop makes 20 calculations, one for each of the nodes in the x-y plane.

Loops for calculating the coefficients for heat transfers in the x and y directions are also made part of the z-level loop. These loops are similar to the loop for the z-direction calculations, except that ΔT 's in the x and y directions are continuously calculated on the analog machine; they are not constant values from the previous time step as are the driving functions in the z direction. The analog computer is put in the OPERATE mode by a command from the digital computer. The patchable logic on the analog computer places the analog in the HOLD mode at the end of the time-step interval, as determined by a digital clock in the analog machine. The digital computer interrogates the analog logic until

Fig. 3. Digital computer program flow diagram.

it is informed that the analog is in the HOLD mode, at which time it reads the output values of the 20 integrators (temperature generators) and stores the values. This completes the z-level loop; the process is repeated a z-dependent number of times at each z level for every repetition of the time-step loop. For the large z-steps at each end of the vertical range, integration may come as infrequently as once every hundred time steps. The temperature values are stored at 1-yr intervals for final printout. This completes the time-step loop.

The loop is repeated for a sufficient number of time steps to make up the scaled-problem time. At the conclusion of the last time-step loop, the temperature values that have been stored at 1-yr intervals are printed out on the line printer. This concludes the program.

4. ANALOG CIRCUITRY

The analog circuit used is shown in Fig. 1, with the controlling logic patching in Fig. 2. The 4×5 matrix of analog integrators represents the 4×5 matrix of temperature nodes described in Sect. 2. Each integrator with its associated summer and attenuators solves Eq. (1) at one specific node in the system under study. Nodes are closely spaced near sources, but are more widely spaced as their distance from the source increases. Difference amplifiers generate the ΔT between adjacent cells, and digitally set coefficients multiply this ΔT by the appropriate heat transfer, heat capacity, and geometric coefficients. The maximum analog voltage (150 V) is scaled to the maximum expected temperature. In the test case this was the maximum initial temperature in the waste.

In the x-y plane all temperatures are continuously updated, with all 20 in equilibrium with each other at all times. For heat flow in the z-direction, the ΔT 's are not continuously updated, and the values applied during each time step are those measured at the end of the preceding interval, just as would be done for all ΔT 's in an all-digital code. Similarly, the material properties are, in general, temperature-dependent, but are held constant during each time interval and updated at the end of each time step at the same time as the ΔT 's. During the

reading and updating process, the analog machine is switched to the HOLD mode.

The ΔT 's between each individual station and the stations immediately above and below it are fixed during each time step, and are set to the values read at the end of the preceding time step, as stored in the digital memory. Exceptions are made at all air boundaries, where stability considerations make it desirable for ΔT to vary during the time step. Computations start at the level of the source centerline and move upward; the x-y matrix is integrated at successive z-levels until the upward extreme -- a constant temperature boundary condition -- is reached. Having finished all levels from the source centerline to the upward extreme, the program begins again immediately below the source centerline, starting with the centerline at the temperature achieved at the end of the immediately preceding run. This centerline offset in time is necessary so that the central temperature may be reduced by the heat lost in both directions. Starting just below the source centerline, integrations are run for one time step at progressively lower levels. At the lower extreme, as at the upper extreme, there is a constant temperature boundary condition. Completion of the lower leg completes one time step, and the matrix is reprogrammed to start again at the midsource level.

In Fig. 1 auxiliary switching is shown applied to the integrators in various areas of the diagram. This switching has the general function of altering conduction paths between x-y nodes when the z-level reaches a void or other discontinuity. Digital-analog converters (DACs) supply those inputs which remain constant during each time step. These fixed DACs have a choice of 1- or 100-V inputs, depending on the level of the fixed input desired (100 V for an included source or for a high vertical gradient; 1 V for a small vertical gradient). This choice of inputs ensures that the DAC need not be set too low for accuracy when settings are small, or that the DAC will not overrun its range when settings are large. The choice is made following computation of the desired coefficient in the digital computer.

5. SAMPLE PROBLEM

The *hybrid* program SALTY was applied to calculation of a nuclear waste burial problem previously run using the *digital* program HEATING5 so that we could compare the hybrid and digital numerical results and running times.

The model to be described simulates one unit cell in a hypothetical, but typically configured, waste repository in bedded salt. The room and pillar excavation is assumed to lie 2000 ft below the surface, where an infinite array of infinitely long, 18-ft-square rooms are separated along their axes by pillars 60 ft thick. Waste canisters 2×2 ft in cross section and 8 ft long are assumed buried in a vertical position every 17 ft down the centerline of each room. The tops of the canisters lie 10 ft below the floor of the room. Immediately above each canister is a 3-ft airspace, and this is overlain by a 7-ft concrete plug. Figure 4 shows the assumed geometry in the vicinity of the repository room.

The unit cell is a rectangular prism with one vertical edge, the z-axis, running through the centerline of a waste canister and extending from the surface of the earth (2000 ft above the repository floor) to a point 4000 ft down (2000 ft below the repository floor). Figure 4 shows the configuration. The origin of coordinates is at the level of the repository floor. The y-axis runs along the centerline of the floor; in this direction the unit cell extends from the axis of the waste canister to the line of symmetry halfway to the next burial hole, a distance of 8.4 ft. The x-axis is perpendicular to the other two axes; the unit cell extends in this direction from the axis of the waste canister to the centerline of the bounding pillar, a distance of 39 ft. This division slices the waste canister into four longitudinal sections, one of which lies in the unit cell which is simulated.

A change from pure salt (below) to a mixture of salt and shale (above) is assumed to take place at the level of the repository ceiling. Coolant air under forced convection is assumed to flow through the repository, keeping the air temperature in the room at a constant 74°F.

Fig. 4. Repository plan (unit cell).

The x-y matrix described in Sect. 2 is applied to this geometry, with nodes centered at 0, 2, 5, 9, and 39 ft in the x-direction, and at 0, 2, 4, and 8.4 ft in the y-direction. Stations in the z-direction are selected under program control from the digital computer; there are 29 active stations as well as 2 constant-temperature boundary condition stations at the upper and lower extremes. The model grid is shown in Fig. 4, where the vertical levels chosen are identified. The digital program identifies the grid points by numerical designation of the vertical position, as shown in parentheses in Fig. 4, for example, the repository floor is at "Level 16."

There is a steep temperature gradient in the area of the room floor. This is the 2000-ft level, or in the nomenclature of the program, "Level 16." To aid stability, the time steps at Levels 15 and 16 are of shorter duration than those allotted to the adjacent z-levels. Moreover, in calculating the vertical ΔT applied to Level 16, an average of the last two time steps is taken to avoid the temperature "see-sawing" which can develop between time steps in this sensitive area. In addition, exceptions to the program of fixed ΔT 's in the z-direction are provided at the floor and ceiling of the burial room. Since the temperature gradient at these locations makes fixed ΔT 's conducive to instability, and since the air temperature is constant and known, it is relatively easy to introduce the same continuous updating of ΔT in the z-direction as is done for x and y.

Continuously variable ΔT is also provided across the air gap above the canister of waste, where radiative heat transfer occurs from the top of the waste to the bottom of the concrete plug. If this waste-to-concrete radiation is included in the simulation, the relatively large ΔT makes this area a particularly troublesome spot in regard to calculational instability. To avoid this, the hybrid model uses "half-continuous, half-stepwise" ΔT formulation at the air gap. When the rate of change of the temperature at the bottom face of the concrete plug is calculated, the program uses as the radiative ΔT the difference between the instantaneous concrete temperature and a constant set to the last known temperature at the top of the waste. Conversely, when the temperature rate of change at the top level of the waste is calculated, the radiative

ΔT is formed between the instantaneous waste temperature and a constant set to the last known temperature at the bottom of the concrete. This arrangement permits the driving ΔT to instantaneously go down as heat transfer goes up, with no wait for the end of the time step. The resulting negative feedback stabilizes the computation by avoiding temperature overshoot.

A diagram of the waste-concrete air gap is shown in Fig. 5. The view factor from node to node (end to end) is only 3%. An argument can be made, however, for including part of the walls of the cavity in the view factor. In brief, for the hybrid model thermal radiation (solid arrows) incident on the sides of the cavity above the halfway mark is assumed to "belong" to the concrete plug and to transfer its energy to node 13. Radiation incident on the walls below the halfway mark (dotted arrows) is assumed to be a "failed escape" and is ignored in the heat transfer. The net geometry factor is 3% for the end of the cavity (bottom of the concrete) and 2.2% for the top ends of each of the four sides, for a total of 11.8%.²

Radiative heat transfer is governed by the formula

$$\dot{H} = \sigma \epsilon F A (T_1^4 - T_2^4) ,$$

where

$\dot{H}$ = heat transfer from surface 1 to surface 2,

σ = Stefan-Boltzmann constant = 1.713×10^{-9} Btu ft⁻²hr⁻¹°R⁻⁴,

ϵ = emissivity,

F = geometry factor, that is, the fraction of radiation from one surface which is intercepted by the other,

A = area of the emitting surface.

In the present example, $\epsilon = 0.90$, $F = 0.118$, and $A = 1$ ft²; therefore, $\dot{H} = 1.819 \times 10^{-10} (T_{12}^4 - T_{13}^4)$ Btu/hr. Since rates of change are low in the simulation, this equation is rescaled to

$$\dot{H} = 1.594 \times 10^{-6} (T_{12}^4 - T_{13}^4) \text{ Btu/yr} .$$

Because $T_{12}^4 - T_{13}^4$ is to be a continuous function of the analog, there is an apparent need to generate two widely varying analog voltages with consequent scaling problems. This situation is resolved by factoring the temperature term:

$$T_{12}^4 - T_{13}^4 = (T_{12} - T_{13})(T_{12} + T_{13})(T_{12}^2 + T_{13}^2) .$$

In this case, T_{12} (the top-of-the-waste temperature) decreases as T_{13} (the bottom-of-the-concrete temperature) increases. Results of preliminary simulations show that the loss in one temperature is about equal to the gain in the other; consequently, $(T_{12} + T_{13})$ is almost constant, and even the cubic expression $K_T \equiv (T_{12} + T_{13})(T_{12}^2 + T_{13}^2)$ changes by only about 25% over the whole run. The hybrid formulation takes advantage of this, setting K_T constant at an average value of $2 \times 10^9 \text{ }^\circ\text{R}^3$, thus simplifying the radiation equation to

$$\dot{H} \approx 3187 (T_{12} - T_{13}) \text{ Btu/yr} .$$

To convert this to a rate of change of temperature, the equation is divided by heat capacity. The volumetric heat capacity ρc of the waste material is taken to be $37 \text{ Btu } ^\circ\text{F}^{-1} \text{ ft}^{-3}$. Since node 12 contains 2 ft^3 of waste, its total heat capacity is $74 \text{ Btu/}^\circ\text{F}$, and the node 12 equation for temperature change due to radiation is

$$\dot{T}_{12R} = -43.07 (T_{12} - T_{13}) \text{ }^\circ\text{F/yr} .$$

The heat capacity of concrete is taken to be $35.2 \text{ Btu } ^\circ\text{F}^{-1} \text{ ft}^{-3}$. Since node 13 contains 2 ft^3 of concrete, its total heat capacity is $70.4 \text{ Btu/}^\circ\text{F}$, and the node 13 equation for temperature change due to radiation is

$$\dot{T}_{13R} = + 45.29 (T_{12} - T_{13}) \text{ }^\circ\text{F/yr} .$$

Fig. 5. Thermal radiation from waste to concrete plug.

Numerically, the coefficients for both $\dot{T}_{12R}$ and $\dot{T}_{13R}$ are about the same; so, for convenience, a mean value of 44.18 is used for both. The gain of all integrators is programmed to be 1000; therefore, the potentiometer setting must be 0.0442. With reference to Fig. 1, the lower left-hand corner, the coefficients are 032 and 033. Inasmuch as potentiometer 032 must be set to 0.3137 as an input to switch 200A at level 16, potentiometer 033 is set to $0.0442/0.3137 = 0.1409$, and is chosen by switch 020A when the computation reaches levels 12 or 13 in the corner cell and DGC 02 is actuated by the value 8192 included in IZWD. Similar paths can be traced for other changes in geometry or materials of heat transfer.

A model assuming zero heat transfer across the waste-to-concrete gap has also been implemented and run on the hybrid computer for additional insight into the sensitivity of the final temperatures to the model.

In the nodes representing waste, the right side of Eq. (1) is augmented by a heat generation term.

$$\frac{\partial T}{\partial t} = \frac{k}{\rho c} \sum_s^{x,y,z} \left\{ \frac{(T_{n-1} - T_n)_s}{\Delta S_{s1} \Delta S_{s2}} + \frac{(T_{n+1} - T_n)_s}{\Delta S_{s1} \Delta S_{s3}} + q_v V_w / [(\rho c V)_w + (\rho c V)_s] \right\}. \quad (2)$$

Here q_v is the time-dependent volumetric rate of power generation, V_w is the volume of waste, and V_s the volume of salt associated with the node. (A node at a waste-salt interface may consist of part salt and part waste.)

In addition to the heat from the waste, there is a geothermal heat flux, as demonstrated by natural temperature rise in the earth as a function of depth. The geothermal heat flux is included in the calculations by applying a constant-temperature boundary condition of 130°F at the 4000-ft level. As part of the boundary condition, the model assumes a constant heat transfer coefficient of $12,830 \text{ Btu yr}^{-1} \text{ ft}^{-1} \text{ }^\circ\text{F}^{-1}$ for the material lying between the 3000- and 4000-ft levels. Although realistic for some geological materials, this is about half the value for pure salt at the local temperature, and is set at the lower value to force an initial temperature spread close to that used in the comparison run from

HEATING5. The initial temperature at 3000 ft is 105°F, which taken with the 4000-ft boundary conditions yields an initial upward heat flux of 320 Btu yr⁻¹ ft⁻². (This higher than average geothermal value is credible because the thermal conductivity of salt is higher than that of earth and rock.) Should heat from above raise the 3000-ft temperature above 105°F, the geothermal flux will be reduced, as it would in the earth itself. A similar stratagem is used at the upper end of the vertical range. The hybrid model maintains the surface temperature at a fixed (infinite heat capacity) value of 60°F. The next nodes down (at a depth of 1000 ft) will start at initial temperatures equal to their undisturbed equilibrium values, that is, 60°F plus the ΔT to be expected from 320 Btu yr⁻¹ ft⁻² across 1000 ft of mixed salt and shale, or at about 76.4°F. Should the 1000-ft temperature rise above 76.4°F, the heat flux to the surface will rise above the natural geothermal value. If it be desired to calculate conservative values of surface temperature changes, the surface temperature can be allowed to float, with a provision for convective heat transfer to the fixed temperature ground-level air. Inasmuch as there is only a 2.6°F temperature rise at the 1000-ft level in 30 yr, it is questionable whether a change in surface temperature would be measurable.

The model described above was considered the most credible representation of the conditions assumed, and was used for most of the results to be reported. In some minor respects this model does differ from the assumptions of the HEATING5 model used for digital comparison; so for the sake of equal inputs to the compared programs, the hybrid machine was also run using the HEATING5 assumptions. One difference is in the initial conditions shown in Table 4. The right-hand set is that used in the digital run, and its origin is unknown; it was probably taken from published data for change of temperature with depth in the earth. It exhibits a constant thermal gradient of 0.021°F/ft from top to bottom, showing no change in conductivity with temperature and no break in slope at the salt-to-salt-plus-shale interface. The left-hand set of initial conditions is that used for the standard hybrid model; it was chosen to have about the same temperature as the digital version at the repository floor, but above and below that level, it recognizes conductivity changes.

due to temperature and material differences. Because of the low heat flux, differences between the two sets are not large. Another difference is in the radiative heat transfer from the top of the waste to the bottom of the concrete plug. As discussed in connection with Fig. 5, the standard hybrid model has a geometry factor of 11.8% for this heat transfer; the available HEATING5 results assumed a factor of zero. (Initial temperatures are assumed to be same.) The differences in results are small, mainly affecting concrete temperature, and will be discussed in Sect. 6. In addition, neither of the hybrid models included thermal radiation from the repository floor, this having been assumed to be of negligible effect. In actuality, the radiation term does become significant and should be included, as discussed in Sect. 6.

In the model used, the cylinder of waste is transformed into a parallelepiped to accommodate the rectangular coordinates used in the computation. Dimensions of the 10.5-in. radius, quarter cylinder in the unit cell are taken to be 1- × 1- × 8-ft long. This model absorbs all of the shielding and structural material into the waste itself. The initial power output of each whole cylinder is 5 kW, one-fourth of which is channeled into the simulated quarter-unit cell. To match the high level waste conditions in the HEATING5 comparison run, the initial power density is made $533 \text{ Btu hr}^{-1} \text{ ft}^{-3} = 4.676 \times 10^6 \text{ Btu yr}^{-1} \text{ ft}^{-3}$, which is equivalent to 1.25 kW over the 8-ft^3 of buried waste. This decays to 1 kW after 7 yr, and to 0.563 kW after 30 yr. Decay with time is approximated by Eq. (3), where PFR is the coefficient by which initial power is multiplied, and t is time after burial in years. The actual decay curve is a sum of exponentials, but over the 30-yr simulation Eq. (3) is within 1.2% of the tabulated values used in the reference digital calculation. Obviously, Eq. (3) can be altered to reflect the constants of processed vs unprocessed waste or to account for varying decay times before burial. The objective here is not to provide input for making waste isolation decisions but to illustrate the applicability of a hybrid computer to this type of computation. Equation (3) is as follows:

Table 4. Temperatures (°F) at time zero,
taken at the y=zero plane through the waste sample^a

Elev (feet below grade)	From Hybrid Model x distance (ft)					From Digital Model x distance (ft)					
	0.0	2.0	5.0	9.0	39.0	0.0	0.8	2.0	5.0	9.0	34.0
1000	76	76	76	76	76	73	73	73	73	73	73
1978	93	93	93	93	93	92	92	92	92	92	92
1982	93	93	93	93	93	93	93	93	93	93	93
1985	74	74	74	93	93	74	74	74	74	93	93
1988	74	74	74	93	93	74	74	74	74	93	93
1991	74	74	74	93	93	74	74	74	74	93	93
1994	74	74	74	93	93	74	74	74	74	93	93
1997	74	74	74	93	93	74	74	74	74	93	93
2000	98	93	93	93	93	100	99	93	93	93	93
2001	98	93	93	93	93	100	99	93	93	93	93
2003	98	93	93	93	93	100	99	93	93	93	93
2007	98	93	93	93	93	100	98	93	93	93	93
2010	518	93	93	93	93	697	534	93	93	93	93
2014	560	93	93	93	93	700	594	93	93	93	93
2018	310	93	93	93	93	383	325	93	93	93	93
2024	93	93	93	93	93	93	93	93	93	93	93
2040	93	93	93	93	93	94	94	94	94	94	94
3000	105	105	105	105	105	114	114	114	114	114	114

^aRounded to nearest degree.

$$t < .2 \text{ yr:} \quad \text{PFR} = 1 - 0.0415 t, \quad (3a)$$

$$2 \leq t < 15 \text{ yr:} \quad \text{PFR} = 0.960 - 0.0215 t, \quad (3b)$$

$$t \geq 15 \text{ yr:} \quad \text{PFR} = 0.826 - 0.0125 t. \quad (3c)$$

Salt and salt-plus-shale have temperature-dependent thermal conductivities. In the hybrid program these functions are approximated by Eqs. (4) and (5), where HK is the thermal conductivity in $\text{Btu yr}^{-1} \text{ ft}^{-1} \text{ }^{\circ}\text{F}^{-1}$. These relations are linearized fits to the tabulated values used in the reference digital calculation and match those values within a few percent:

Salt

$$T_{av} < 212^{\circ}\text{F:} \quad \text{HK} = 32636 - 53.53 T_{av}, \quad (4a)$$

$$212^{\circ} \leq T_{av} < 392^{\circ}\text{F:} \quad \text{HK} = 27787 - 30.66 T_{av}, \quad (4b)$$

$$T_{av} \geq 392^{\circ}\text{F:} \quad \text{HK} = 21491 - 14.6 T_{av}. \quad (4c)$$

Salt-plus-shale

$$T_{av} < 349^{\circ}\text{F:} \quad \text{HK} = 21150 - 21.17 T_{av}, \quad (5a)$$

$$T_{av} > 349^{\circ}\text{F:} \quad \text{HK} = 17300 - 10.14 T_{av}. \quad (5b)$$

Where nodes include two or more materials, appropriate averages are taken. As an example, one may consider the lower end of the waste container as shown in Fig. 6. At Level 10, the corner node includes (vertically) 2 ft of waste and 3 ft of salt. The general assumption is that heat transfer is taken node point to node point. In this case, where heat generation as well as transmission is involved, the heat transfer is assumed to come from the midpoint of the waste. The heat transfer coefficient k in the waste is given as $1 \text{ Btu hr}^{-1} \text{ ft}^{-1} \text{ }^{\circ}\text{F}^{-1} = 8760 \text{ Btu yr}^{-1} \text{ ft}^{-1} \text{ }^{\circ}\text{F}^{-1}$. That in the salt will be expressed as HK (T_{av}), as shown above. For the corner, the depth of the node in the y-direction is 1 ft. The x-direction thermal resistance for the upper 2 ft of the node is then

$$R_u = \sum \frac{\ell}{kA} = \frac{0.5}{8760(2)} + \frac{1.0}{2 \text{ HK}} = \frac{\text{HK} + 17520}{35040 \text{ HK}}.$$

$$C_u \equiv \frac{1}{R_u} = 35040 \text{ HK}/(\text{HK} + 17520).$$

NOTE: DIMENSIONS IN FEET

Fig. 6. Configuration of node at base of waste.

Heat in the upper 2 ft of the node travels radially from the waste into the salt. Heat in the salt which composes the lower 3 ft of the node derives primarily from the waste; it flows from the bottom face of the waste into the salt, and thence travels both downward and radially into the adjoining nodes. For purposes of quantifying this heat flow in the x-direction, the mean distance from the bottom face of the waste to the vertical boundary with the adjacent node is assumed to be $1.5 \sqrt{2} = 2.12$ ft. The mean cross-sectional area for heat flow is assigned the value of 2.5 ft^2 . Using these values to calculate the thermal resistance across the salt in the lower 3 ft of the node produces

$$C_l = \frac{kA}{l} = HK \times 2.5/2.12 = 1.1785 \text{ HK} .$$

Combining the x-direction conductances for the upper and lower portions of the node gives

$$C_T = C_u + C_l = [35040 \text{ HK}/(\text{HK} + 17520)] + 1.1785 \text{ HK} .$$

The volumetric heat capacity is $37 \text{ Btu ft}^{-3} \text{ }^\circ\text{F}^{-1}$ for the waste and $27 \text{ Btu ft}^{-3} \text{ }^\circ\text{F}^{-1}$ for the salt. The total heat capacity for the node is, therefore, $Vc_v = (2 \times 37) + (3 \times 27) = 155 \text{ Btu }^\circ\text{F}^{-1}$.

The rate of change of temperature due to heat flow in the x-direction is given by

$$\dot{T}_x \approx \frac{C_T \Delta T}{c_v V} = [35040 \text{ HK}/(\text{HK} + 17520) + 1.1785 \text{ HK}] \frac{\Delta T}{155} .$$

To give a numerical example: if $T_{av} = 238^\circ\text{F}$, by Eq. (4b), $HK = 20,490 \text{ Btu yr}^{-1} \text{ ft}^{-1} \text{ }^\circ\text{F}^{-1}$, making $C_T/c_v V = 277.7 \text{ yr}^{-1}$. The programmed time scale capacitors give the integrators an inherent gain of 10^3 , making 0.2777 the correct setting for the appropriate attenuator. The digital portion of the hybrid computer would set this value into coefficient device 245 (Fig. 1), which would then operate on the voltage representing ΔT between T_{11} and T_{21} . As the mean temperature of the salt changed in

this area, local HK would vary, thereby affecting the setting of coefficient 245. Proper material and geometrical properties would be recognized in the setting of each coefficient for all values of x , y , and z .

6. DISCUSSION OF RESULTS

The equilibrium conditions of the repository are upset by two perturbations at the start of the simulation. The first is the burial of hot, power-producing waste along the z -axis between the 2010- and 2018-ft levels. The second is the introduction of a flow of 74°F cooling air into an excavated room in which the floor is 10 ft above the top level of the waste canister. One introduction produces heat, the other removes it, with the result that some initial temperatures will go up and others down. Table 4 lists the initial conditions for SALTY and HEATING5. As mentioned previously, SALTY boundary conditions were so chosen as to make the two sets of initial salt temperatures very close to the same.

The computational node points in HEATING5 are more closely spaced than those in SALTY. Among the nodes included in HEATING5 but omitted in SALTY are those which lie along the waste-salt interface. Thus SALTY generates only one waste temperature at each z -level, and the closest salt temperature measurements are 1 ft from the waste-salt boundary. To compare the outputs of the two programs, it is desirable to start from as close as possible to the same initial conditions. Since each waste node in SALTY must represent both the salt interface and the centerline waste temperatures of HEATING5, each initial condition for a waste node in SALTY is made a weighted average of the centerline and the interface temperatures used for initial conditions in the reference digital calculation.

The greatest differences between the two models are as follows: (1) the finer x - y grid structure in the digital version; and (2) the inclusion of thermal radiation from waste to concrete in the hybrid model; and (3) thermal radiation from the excavation floor to the cavity walls in HEATING5. The results of these differences are intermingled in the temperature discrepancies between the hybrid and digital results.

To largely separate the effects, temperatures can be examined at a location where fine structure is less important and far enough from the excavation floor to make radiation to the room unimportant. The locations chosen lie along a vertical line in the salt at $y = 2$ ft, $x = 0$, picking three points adjacent to the waste burial pit at $z = 2014$ ft (level of the waste midpoint), $z = 2010$ ft (top of the waste), and $z = 2007$ ft (bottom of the concrete plug). These are the points in the "a" boxes shown in Table 5. After two years of simulated heat transfer, SALTY-produced temperatures at these three locations are 288, 226, and 164°F, respectively, while those for HEATING5 are 296, 234, and 163°F. When the hybrid program is rerun without waste-to-concrete radiation, the corresponding temperatures are 293, 234, and 163°F, or virtually the same as for HEATING5. It is clear that the effect of the waste-to-concrete thermal radiation has been isolated, and that at 2 ft from the waste centerline the main effect is to reduce the salt temperature by 7-8°F.

If temperatures in the waste itself are examined, the effects of the thermal radiation are accentuated, but the finer structure of the digital model in this area also has an effect. For $x = 0$, $y = 0$, at 2 yr, and for the same z -locations, the hybrid model with radiation gives temperatures of 537, 449, and 183°F. The digital results are 549, 429, and 165°F. Because of the radiative heat transfer, the concrete plug is 18°F hotter in the hybrid results, but at 429°F the top of the waste is unexpectedly cooler in the digital case. When SALTY is run without waste-to-concrete radiation, the three temperatures are 543, 484, and 159°F. Comparison of the two sets of hybrid results shows a clear effect of including thermal radiation: the temperature at the top of the waste is decreased 35°F, and the bottom of the concrete is increased 24°F. The lower temperatures in the waste nodes of HEATING5 appear to result from the cooling effect of thin salt nodes immediately adjacent to the waste; these are provided in HEATING5, but not in the hybrid simulation. As time passes, these thin salt nodes will be heated to almost the temperature of the waste, and their differential effect should become less.

Table 5. Temperatures (°F) at time 2 yr, and taken at the y = 2 ft plane through the waste sample^a

Elev (feet below grade)	From Hybrid Model x distance (ft)					From Digital Model x distance (ft)					
	0.0	2.0	5.0	9.0	39.0	0.0	0.8	2.0	5.0	9.0	34.0
1000	77	77	77	77	77	74	74	74	74	74	74
1978	82	82	82	84	94	89	89	89	89	89	97
1982	79	79	79	83	96	88	88	88	88	86	99
1985	74	74	74	83	97	74	74	74	74	84	100
1988	74	74	74	84	99	74	74	74	74	83	102
1991	74	74	74	87	100	74	74	74	74	84	104
1994	74	74	74	91	102	74	74	74	74	86	106
1997	74	74	74	96	104	74	74	74	74	90	108
2000	b 108	112	104	104	107	b 96	96	96	95	97	111
2001	114	115	110	108	108	104	104	104	103	103	112
2003	127	126	121	116	110	121	120	120	117	114	113
2007	164	159	146	131	114	163	162	159	148	135	117
2010	a 226	199	166	140	117	a 234	228	209	173	149	119
2014	228	238	185	149	120	296	286	252	195	161	122
2018	233	211	180	153	122	241	237	222	188	163	124
2024	164	162	157	149	124	168	168	167	162	154	126
2040	132	132	131	130	119	133	133	133	133	131	123
3000	105	105	105	105	105	114	114	114	114	114	114

^aRounded to nearest degree.

Table 5 presents 2-yr temperatures for SALTY and for HEATING5, taken at the $y = 2$ ft plane. Temperatures in the area adjacent to the waste deposit have been discussed previously, and their values are compared in the boxes labeled "a." As demonstrated previously, when thermal radiation from the waste is omitted from the hybrid model, SALTY results in this area are almost identical to those from HEATING5. Results diverge in the area of the repository floor, where the hybrid model shows temperatures 12°F higher. These temperatures are compared in the boxes labeled "b." Investigation shows that almost all of this difference is due to omitting the thermal radiation term from the repository floor heat balance in the hybrid model. At zero time the radiation term is indeed negligible. However, as the floor heats up, the fourth-power radiation term can represent a significant fraction of total heat loss to the room, and this vigorous nonlinear feedback limits the temperature difference between the floor and its surroundings. Should the hybrid program be pursued, it would be desirable to include terms for radiation from the repository floor. Because of the limited range of temperatures assumed by the floor, ceiling, and walls, the approximation $(T_1^4 - T_2^4) \approx K_T(T_1 - T_2)$ holds even closer here than it did in the case of waste-to-concrete radiation. The view factor from the floor to the ceiling is 0.3125, and K_T for the temperatures involved is $\sim 2.09 \times 10^8 \text{ }^\circ\text{R}^3$. This yields a floor-to-ceiling heat flux of

$$\dot{H}_c \approx 2845 (T_{\text{floor}} - \bar{T}_{\text{ceiling}}) \text{ Btu yr}^{-1} \text{ ft}^{-2}.$$

The view factor from the floor to the wall is about 0.38, and K_T for those temperatures is $\sim 2.63 \times 10^8 \text{ }^\circ\text{R}^3$. This gives a floor-to-wall heat flux of

$$\dot{H}_w \approx 3574 (T_{\text{floor}} - \bar{T}_{\text{wall}}).$$

To add these relations to the hybrid program in a continuously varying analog fashion would require an additional digital coefficient unit (DCU) for each cavity-abutting node, for a total of 16 DCUs.

The available HEATING5 printout stops at 3 yr, at which time its output has not changed drastically from the 2-yr values. In the hybrid model the bottom of the concrete plug peaks at 184°F at 3 yr, and the repository floor temperature peaks at about 109°F at 4 yr. In the absence of a thermal radiation term, all floor temperatures must be considered to be too high. At 8 yr the peak waste temperature is 480°F; the floor temperature is 108°F. At 15 yr the peak waste temperature is 393°F; the floor temperature is 103°F.

Table 6 shows the outputs of two hybrid runs at 30 yr. The data labeled "Standard Hybrid Results" are from the as-formulated SALTY program described in this report. The "Digital Input Hybrid Results" are from a hybrid run without waste-to-concrete thermal radiation and started from the HEATING5 initial temperatures and boundary conditions. The data in the "a" boxes show that the top of the waste is cooler and the bottom of the concrete is hotter where radiative heat transfer is included, but that these two temperatures are the only ones significantly affected. Floor temperatures in the "b" boxes are almost identical in the two data sets, and, for reasons previously established, can be considered to be a few degrees too high. As indicated, inclusion of a radiation term would be desirable at the repository floor. Differences at the 3000-ft level reflect the inequality of boundary conditions in the two models.

Running time of the hybrid program (for 30-yr simulations) was reduced from 5.5 hr to slightly over 3 hr by judicious manipulation of the time steps. The final schedule of time steps is that shown in Table 3. A reduction of another hour could very likely be achieved by increasing the 0.0025-yr time step to 0.0060 yr after IT = 514, possibly including some step-to-step averaging to increase stability.

SALTY was written as an exploratory test program to determine the usefulness of the hybrid approach to spatially extended heat transfer problems. It was not optimized for minimum running time, nor was it programmed for flexibility in terms of callable options. However, even as it stands, the hybrid program SALTY provides reasonable approximations to HEATING5 results in about 20% of the running time and on a 10

times cheaper machine. (It should be recognized that the sample HEATING5 calculation solved a 7×13 node x-y matrix, SALTY only 4×5 .) Where changes in the model were required, local reprogramming did not prove a difficult task. For problems of the type described, the hybrid approach provides a useful alternative to digital programming.

REFERENCES

1. W. D. Turner, D. C. Elrod, and I. I. Siman-Tov, *HEATING5 - An IBM 360 Heat Conduction Program*, ORNL/CSD/TM-15 (March 1977).
2. W. H. McAdams, *Heat Transmission*, McGraw-Hill, New York, 1954, Figs. 4-10 and 4-11.

Table 6. Temperatures (°F) at time 30 yr, and taken at the $y = 0$ plane through the waste sample^a

Elev (feet below grade)	Standard Hybrid Results x distance (ft)					Digital-Input Hybrid Results x distance (ft)				
	0.0	2.0	5.0	9.0	39.0	0.0	2.0	5.0	9.0	34.0
1000	79	79	79	79	79	76	76	76	76	76
1978	79	79	79	80	89	80	80	80	81	91
1982	77	77	77	80	91	77	78	78	80	93
1985	74	74	74	80	93	74	74	74	81	94
1988	74	74	74	81	94	74	74	74	82	95
1991	74	74	74	83	96	74	74	74	84	97
1994	74	74	74	85	98	74	74	74	86	99
1997	74	74	74	89	100	74	74	74	90	101
2000	b 92	95	93	94	102	b 93	95	94	95	103
2001	98	99	97	97	103	99	99	98	98	104
2003	107	106	104	102	104	107	107	105	103	106
2007	134	126	118	111	108	124	126	120	113	109
2010	a 255	154	131	118	110	a 269	157	133	119	112
2014	291	182	143	124	113	294	184	145	126	115
2018	209	162	142	128	116	212	165	144	131	118
2024	137	136	134	130	119	140	139	136	132	122
2040	129	129	129	128	124	132	132	132	131	127
3000	106	106	106	106	106	116	116	116	116	116

^a Rounded to nearest degree.

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APPENDIX A
DIGITAL LISTING OF SALTY PROGRAM

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Appendix A

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C      PROGRAM SALLY: REVISED 2/22/78 04B
C
      DIMENSION IAD(68),IVD(68),IAP(75),IVP(75),TEMPRT(5,4,31,31)
      ,GUP(31),GDN(31),GX(4),GY(3),IADB(68),ITEMPT(5,4),TEMP(5,4,31)
      ,IVT(33),YPLN(4),ZDIST(40),IVAL(68),IAPB(75),IAMP(80),IAMPB(80)
      ,TEMPER(5,4,31),OZHT(18)
      WRITE(5,10)
10  FORMAT(' IS ANALOG READY? TYPE 1 FOR YES.')
```

C

```

      READ(5,20) IANSW
20  FORMAT(1)
      IF(IANSW-1) 1,2,1
2  CONTINUE
      CALL INITA(0,0)
      OPEN (UNIT=10,DEVICE='DSK0',FILE='ST0R1.DAT')
C      READ DATA FROM DISK0 FILE 'ST0R1.DAT'.
      READ(10,30) NDAC,NPOT,NAUC,NAMP
30  FORMAT(1216)
      READ(10,30)(IAD(JD),IVD(JD),JD=1,NDAC)
      READ(10,30)(IAP(JP),IVP(JP),JP=1,NPOT)
      READ(10,30) IAMP
      READ(10,40) TEMP
40  FORMAT(10F8.2)
      READ(10,150) GUP
150 FORMAT(8F10.5)
      READ(10,150) GDN
      READ(10,150) GX
      READ(10,150) GY
      READ(10,40) YPLN
      READ(10,40) ZDIST
      CLOSE(UNIT=10,DEVICE='DSK0',FILE='ST0R1.DAT')
      DO 200 J=1,NAMP
      CALL ADDR(IAMP(J),IAMPB(J))
      CALL MURPHY(IAMPB(J),M)
      IF(M) 210,200,210
210 WRITE(5,90) IAMP(J)
200 CONTINUE
      CALL ADDR(6220,IADC)
      DO 32 L=1,NDAC
      CALL ADDR(IAD(L),IADB(L))
      CALL MURPHY(IADB(L),M)
      IF(M)110,32,110
110 WRITE(5,90) IAD(L)
90  FORMAT(16,3X,'INVALID')
32  CONTINUE
C      MAKE PROVISION FOR UTILIZING PAUSES IN PROGRAM.
      WRITE(5,1500)
1500 FORMAT(' DO YOU WISH TO SET POTS? TYPE 1 FOR YES.')
```

C

```

      READ(5,20) IPOT
      WRITE(5,50)
50  FORMAT(' TYPE 1 FOR PAUSES, 0 FOR MINIMAL PAUSES')
```

C

```

      READ(5,20) IPAU
C      STORE INITIAL TEMPERATURE VALUES FOR PRINTOUT.
      DO 51 I3=1,31
      DO 51 I2=1,4
      DO 51 I1=1,5
51  TEMPRT(I1,I2,I3,1)=TEMP(I1,I2,I3)
      CALL RUN(0)
C      PUT ANALOG COMPUTER IN INITIAL CONDITION MODE.
      CALL SETWD(0,29)
C      SET FIXED VALUE COEFFICIENT SERV0-POTS.
```



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      IF (IPBT) 1502, 1502, 1501
1501 DO 3 JP=1, NPBT
      CALL ADDR(IAP(JP), IAPB(JP))
      CALL MURPHY(IAPB(JP), M)
      IF (M) 100, 3, 100
      100 WRITE(5, 90) IAP(JP)
      3 CALL STIND(U, IAP(JP), IVP(JP))
1502 HAIR=5519,
      IPRT=1
C      IT IS THE TIME INCREMENT INDEX.
      5 DO 2000 IT=1, 3414
C      SET SETWD ARGUMENT (ITWD) FOR GOING TO I.C. MODE FOR THIS TIME
C      INCREMENT.
      IF (IT.LT, 50) GO TO 7518
      M3=IT-50
      M4=M3/50
      M5=50*M4
      IF (M3-M5)/517, 7517, 7518
7517 WRITE(5, 7519) IT
7519 FORMAT(' IT = ', I5)
7518 CONTINUE
      SFT=1.
      IF (IT.LE, 100) GO TO 8
      IF (IT.GT, 130) GO TO 17
      ITWD=32793
      GO TO 9
      17 IF (IT.GT, 514) GO TO 23
      ITWD=32781
      GO TO 9
      23 ITWD=32789
      GO TO 9
      8 ITWD=29
      9 CONTINUE
C      CALCULATE T (TIME IN YEARS) AND PFR (POWER GENERATION FRACTION).
      IF (IT.LE, 100) GO TO 26
      IF (IT.LE, 130) GO TO 25
      IF (IT.LE, 514) GO TO 24
      IF (IT.LE, 614) GO TO 27
      IF (IT.LE, 1914) GO TO 22
      T=(IT-1914)*.01+15.
      PFR=.826+.0125*T
      GO TO 29
      27 T=(IT-514)*.01+1.
      GO TO 28
      22 T=(IT-614)*.01+2.
      PFR=.960+.0215*T
      GO TO 29
      24 T=(IT-130)*.0025+.04
      GO TO 28
      25 T=(IT-100)*.001+.01
      GO TO 28
      26 T=IT*.0001
      28 PFR=1.-.0415*T
      29 CONTINUE
      IF (IT.LT, 514) GO TO 1135
      MU=IT-514
      M1=MU/100
      M2=100*M1
      MOV=MU-M2
      GO TO 2910

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1135 MOV=1
2910 CONTINUE
C   IZ IS THE Z LEVEL INDEX.
    IZZ=0
    DO 1000 ILEV=1,31
    IF(ILEV.GT.21) GO TO 1001
    IZ=ILEV+10
    IF(IZ.EQ.15) IZCNT=0
    IF(IZ.EQ.12.AND.IT.GT.514) IZCNT=0
    IF(IZ.EQ.17.AND.IT.GT.514) IZCNT=0
    GO TO 1002
1001 IZZ=IZZ+1
    IZ=11-IZZ
1002 CONTINUE
    IZCNT=IZCNT+1
C   MAKE PROVISION FOR SETTING LEVEL DEPENDENT LINES- DGC 05- DGC 14.
    IF(IZ.LE.9.OR.IZ.GE.23) IZWD=2048
    IF(IZ.EQ.10) IZWD=5120
    IF(IZ.EQ.11) IZWD=7168
    IF(IZ.EQ.12) IZWD=9216
    IF(IZ.EQ.13) IZWD=8192
    IF(IZ.EQ.14.OR.IZ.EQ.15) IZWD=6144
    IF(IZ.EQ.16) IZWD=6208
    IF(IZ.GE.17.AND.IZ.LE.21) IZWD=2080
    IF(IZ.EQ.22) IZWD=2176
C   INIT IS THE SETWD ARGUMENT USED TO PUT ANALOG IN I.C. MODE.
    INIT=ITWD+IZWD
C   PUT ANALOG IN I.C. MODE FOR THIS Z LEVEL.
    CALL SETWD(0,INIT)
    IF(IZ.EQ.16.OR.IZ.EQ.17.OR.IZ.EQ.22.OR.IZ.EQ.23) CALL WAIT(25)
    IF(IZ.EQ.12.OR.IZ.EQ.14) CALL WAIT(25)
C   CALCULATE COEFFICIENT FOR HEAT GENERATION AND HEAT TRANSFER IN THE
C   Z DIRECTION AT THIS Z LEVEL FOR EACH X-Y LOCATION.
    INUM=0
    DO 89 IY=1,4
    DO 89 IX=1,5
    INUM=INUM+1
    SFZ=1.
    IF(INUM.NE.1) GO TO 501
    IF(IZ.GE.10.AND.IZ.LE.12) SFZ=.01
501 CONTINUE
    IF(MOV) 502,502,6997
6997 IF(IZ.LE.6.OR.IZ.GE.25) GO TO 1000
    GO TO 503
502 IF(IZ.EQ.1.OR.IZ.EQ.31) GO TO 89
    IF(IZ.LE.6.OR.IZ.GE.25) SFZ=100.
503 TAV1=.5*(TEMP(IX,IY,IZ-1)+TEMP(IX,IY,IZ))
    TAV2=.5*(TEMP(IX,IY,IZ)+TEMP(IX,IY,IZ+1))
    IF(IZ.GT.22) GO TO 11
    IF(IZ.LE.10) GO TO 97
    IF(INUM.EQ.1.AND.IZ.EQ.11) GO TO 82
    IF(INUM.EQ.1.AND.IZ.EQ.12) GO TO 83
    IF(INUM.EQ.1.AND.IZ.EQ.13) GO TO 84
    IF(INUM.EQ.1.AND.IZ.EQ.14) GO TO 85
    IF(INUM.EQ.1.AND.IZ.EQ.15) GO TO 85
97 CH=.037
    IF(IZ.EQ.2) GO TO 213
118 IF(TAV1.LE.212.) GO TO 204
    IF(TAV1.LE.392.) GO TO 203
    HKI=21491.-14.6*TAV1

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      GO TO 205
203 HK1=27787,-30.66*TAV1
      GO TO 205
204 HK1=32636,-53.53*TAV1
      GO TO 205
213 HK1=12830
205 CONTINUE
      IF (IZ.EQ.22) GO TO 211
      IF (TAV2.LE.212.) GO TO 207
      IF (TAV2.LE.392.) GO TO 206
      HK2=21491,-14.6*TAV2
      GO TO 208
206 HK2=27787,-30.66*TAV2
      GO TO 208
207 HK2=32636,-53.53*TAV2
      GO TO 208
      CP=.03356
      IF (TAV1.LE.349.) GO TO 209
      HK1=17300,-10.14*TAV1
      GO TO 211
209 HK1=21150,-21.17*TAV1
211 CONTINUE
      IF (TAV2.LE.349.) GO TO 212
      HK2=17300,-10.14*TAV2
      GO TO 208
212 HK2=21150,-21.17*TAV2
208 CONTINUE
      ZHT1=HK1*GUP(IZ)*(TEMP(IX,IY,IZ-1)-TEMP(IX,IY,IZ))
      IF (INUM.EQ.1.AND.IZ.EQ.10) GO TO 81
      ZHT2=HK2*GDN(IZ)*(TEMP(IX,IY,IZ+1)-TEMP(IX,IY,IZ))
95  ZHT=(ZHT1+ZHT2)*CP*2.*SFZ*SFT
      IZHT=IFIX(ZHT)
      IVU(INUM)=IZHT
      IF (IZ.EQ.16) GO TO 86
      IF (IZ.EQ.22) GO TO 91
      IF (IZ.GE.17.AND.IZ.LE.21) GO TO 92
      GO TO 84
81  PWR=PFR*1.8688E6
      CPI=.03226
      HK2=8760.
      ZHT2=HK2*GDN(IZ)*(TEMP(IX,IY,IZ+1)-TEMP(IX,IY,IZ))
      ZHT=(ZHT1+ZHT2+PWR)*CPI*2.*SFZ*SFT
      GO TO 131
82  PWR=PFR*1.2614E5
      CPI=.027
      HK1=8760.
      HK2=8760.
      GO TO 88
83  PWR=PFR*1.2614E5
      CPI=.027
      HK1=8760.
      ZHT1=HK1*.125*(TEMP(IX,IY,IZ-1)-TEMP(IX,IY,IZ))
      ZHT=(ZHT1+CPI+PWR)*2.*SFZ*SFT
      GO TO 131
84  CPI=.0284
      HK2=13140.
      ZHT2=HK2*.125*(TEMP(IX,IY,IZ+1)-TEMP(IX,IY,IZ))
      ZHT=ZHT2*CPI*2.*SFZ*SFT
      GO TO 131
85  CPI=.0284

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      HK1=13140.
      HK2=13140.
      PWR=0.
      GO TO 86
86  IF (INUM.NE.1) GO TO 87
      CPI=.0284
      ZHT1=26200.*(TEMP(IX,IY,IZ-1)-TEMP(IX,IY,IZ))
      ZHT2=0.
      ZHT=(ZHT1+ZHT2)*CPI*2.*SFZ*SFT
      GO TO 131
88  ZHT1=HK1*GUP(IZ)*(TEMP(IX,IY,IZ-1)-TEMP(IX,IY,IZ))
      ZHT2=HK2*GDN(IZ)*(TEMP(IX,IY,IZ+1)-TEMP(IX,IY,IZ))
      ZHT=((ZHT1+ZHT2)*CPI+PWR)*2.*SFZ*SFT
      GO TO 131
87  IF (IX.EQ.5) GO TO 89
      IF (IX.EQ.4) GO TO 93
      HK2=HAIR*2.
      ZHT2=0.
      ZHT=(ZHT1*4.+ZHT2)*CP*2.*SFZ*SFT
      IF (IT .EQ. 514) GO TO 450
      IF (IT .LT. 514) GO TO 131
      ZHT = 0.5 * (ZHT + 0ZHT(INUM))
450  0ZHT(INUM) = ZHT
      GO TO 131
93  ZHT1=HK1*.5484*(TEMP(IX,IY,IZ-1)-TEMP(IX,IY,IZ))
      HK2=HK2*.1613
      ZHT2=HK2*(TEMP(IX,IY,IZ+1)-TEMP(IX,IY,IZ))+HAIR*.1129*(74.-TEMP(IX
      ,IY,IZ))
      ZHT=(ZHT1+ZHT2)*CP*2.*SFZ*SFT
      GO TO 131
91  IF (IX.EQ.4.OR.IX.EQ.5) GO TO 119
      ZHT2=ZHT2*1.75
      CPI=.03356
      HK1=HAIR*.5
      ZHT1=0.
      ZHT=(ZHT1+ZHT2)*CPI*2.*SFZ*SFT
      GO TO 131
119 IF (IX.EQ.5) GO TO 121
      CPI=.0347
      ZHTA=HAIR*3.5*(74.-TEMP(IX,IY,IZ))
      ZHT1=(HK1*.5.*(TEMP(IX,IY,IZ-1)-TEMP(IX,IY,IZ))+ZHTA)*.0177
      ZHT=(ZHT1+ZHT2*1.053)*CPI*2.*SFZ*SFT
      GO TO 131
121 CPI=.0350
      ZHT=(ZHT1+ZHT2)*CPI*2.*SFZ*SFT
      GO TO 131
92  IF (IX.EQ.4.OR.IX.EQ.5) GO TO 89
      IVD(INUM)=0
      GO TO 89
131 IZHT=IFIX(ZHT)
      IVD(INUM)=IZHT
89  CONTINUE
      ISEN=ITEST(0,0,2)
      ILINE=ITEST(0,0,2)
      IF (IABS(IVD(2)).GT.16000) GO TO 857
      IF (IABS(IVD(3)).GT.16000.OR.IABS(IVD(5)).GT.15000) GO TO 857
      IF (IABS(IVD(7)).GT.16000.OR.IABS(IVD(9)).GT.15000) GO TO 857
      IF (IABS(IVD(11)).GT.16000.OR.IABS(IVD(12)).GT.16000) GO TO 857
      IF (IABS(IVD(13)).GT.16000.OR.IABS(IVD(15)).GT.16000) GO TO 857
      IF (IABS(IVD(17)).GT.16000.OR.IABS(IVD(19)).GT.16000) GO TO 857

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      IVOLT2=0
      IF(ILINE.EQ.0) GO TO 858
      CALL SETLI(0,0,1,0)
      CALL WAIT(25)
      GO TO 858
857 IVOLT2=1
      IF(ILINE.EQ.1) GO TO 859
      CALL SETLI(0,0,1,1)
      CALL WAIT(25)
859 IVD(2)=IVD(2)/100
      IVD(3)=IVD(3)/100
      IVD(6)=IVD(6)/100
      IVD(7)=IVD(7)/100
      IVD(8)=IVD(8)/100
      IVD(11)=IVD(11)/100
      IVD(12)=IVD(12)/100
      IVD(13)=IVD(13)/100
      IVD(16)=IVD(16)/100
      IVD(17)=IVD(17)/100
      IVD(18)=IVD(18)/100
858 CONTINUE
      ISEN=ITEST(0,0,1)
      ILINE=ITEST(0,0,1)
      IF(IABS(IVD(1)).GT.16000) GO TO 871
      IVOLT1=0
      IF(ILINE.EQ.0) GO TO 872
      IF(IZ.EQ.10.OR.IZ.EQ.11.OR.IZ.EQ.12) GO TO 872
      CALL SETLI(0,0,5,0)
      CALL WAIT(25)
      GO TO 872
871 IVOLT1=1
      IF(ILINE.EQ.1) GO TO 873
      CALL SETLI(0,0,5,1)
      CALL WAIT(25)
873 CONTINUE
      IF(IZ.EQ.10.OR.IZ.EQ.11.OR.IZ.EQ.12) GO TO 872
      IVD(1)=IVD(1)/100
872 CONTINUE
      IVD(5)=-IVD(5)/10
      IVD(10)=IVD(10)/10
      IVD(15)=-IVD(15)/10
      IVD(20)=IVD(20)/10
C      ASSIGN VALUES TO I C DACS FOR THIS Z LEVEL.
      INUM=20
      DO 301 IY=1,4
      DO 301 IX=1,5
      INUM=INUM+1
      IF(IZ.GE.17.AND.IZ.LE.21.AND:IX.LE.3) GO TO 181
      VU=TEMP(IX,IY,IZ)*20+.5
      IVD(INUM)=IF(IX(VU)
      GO TO 301
181 IVD(INUM)=1480
301 CONTINUE
C      CALCULATE COEFFICIENT VALUES FOR HEAT TRANSFER IN THE X DIRECTION
C      AT THIS Z LEVEL FOR ALL X-Y LOCATIONS.
      INUM=40
      DO 189 IY=1,4
      DO 189 IX=1,4
      INUM=INUM+1
      SFX=1.

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      IF (IZ.GE.17.AND.IZ.LE.21.AND.IX.LE.2) GO TO 192
      IF (IZ.GE.17.AND.IZ.LE.21.AND.IX.EQ.3) GO TO 193
      TAV = .5*(TEMP(IX,IY,IZ)+TEMP(IX+1,IY,IZ))
      IF (IZ.GT.22) GO TO 111
      IF (IZ.EQ.22.AND.IX.NE.4) GO TO 111
      CP=.037
      IF (TAV.LE.212.) GO TO 304
      IF (TAV.LE.392.) GO TO 303
      HKI=21491.-14.6*TAV
      GO TO 305
303 HKI=27787.-30.66*TAV
      GO TO 305
304 HKI=32636.-53.53*TAV
305 IF (IZ.NE.22) GO TO 307
      HKIT=HKI
111 CP=.03356
      IF (TAV.LE.349.) GO TO 309
      HKI=17300.-10.14*TAV
      GO TO 306
309 HKI=21150.-21.17*TAV
306 IF (IZ.EQ.22.AND.IX.EQ.4) HKI=HKIT*.4236+HKI*.5714
307 CONTINUE
      IF (INUM.EQ.41.AND.IZ.EQ.11) GO TO 182
      IF (INUM.EQ.41.AND.IZ.EQ.12) GO TO 182
      IF (INUM.EQ.41.AND.IZ.EQ.13) GO TO 184
      IF (INUM.EQ.41.AND.IZ.EQ.14) GO TO 184
      IF (INUM.EQ.41.AND.IZ.EQ.15) GO TO 184
      XHT=HKI*GX(IX)*CP*10.*SFX*SFT
      IXHT=IFIX(XHT)
      IVD(INUM)=IXHT
      IF (IZ.EQ.16) GO TO 186
      IF (IZ.EQ.22) GO TO 191
      IF (INUM.EQ.41.AND.IZ.EQ.10) GO TO 481
      GO TO 189
481 XHT=(.1*HKI+600.)*SFX*SFT
      GO TO 188
182 XHT=1./(.00005708+1./HKI)*.27*SFX*SFT
      GO TO 188
187 IF (IX.NE.3) GO TO 189
      XHT=HKI*.00146*10.*SFX*SFT
      GO TO 188
192 IVD(INUM)=0
      GO TO 189
193 CP=.037
      XHT=HAIR*.01214*10.*SFX*SFT
      GO TO 188
184 XHT=1./(.0000761+1./HKI)*.284*SFX*SFT
      GO TO 188
186 IF (INUM.NE.41) GO TO 187
      XHT=1./(.0000761+1./HKI)*.284*SFX*SFT
      GO TO 188
191 IF (IX.NE.3) GO TO 197
      XHT=HKI*.00297*10.*SFX*SFT
      GO TO 188
197 IF (IX.NE.4) GO TO 189
      XHT=HKI*.000078*10.*SFX*SFT
188 IXHT=IFIX(XHT)
      IVD(INUM)=IXHT
189 CONTINUE
C   CALCULATE COEFFICIENT VALUES FOR HEAT TRANSFER IN THE Y DIRECTION

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C   AT THIS Z LEVEL FOR ALL X-Y LOCATIONS.
      INUM=56
      DO 289 IX=1,4
      DO 289 IY=1,3
      INUM=INUM+1
      SFY=1.
      TAV= .5*(TEMP(IX,IY,IZ)+TEMP(IX,IY+1,IZ))
      IF(IZ.EQ.22.AND.IX.NE.4) GO TO 411
      IF(IZ.GT.22) GO TO 411
      CP=.037
      IF(TAV.LE.212.) GO TO 404
      IF(TAV.LE.392.) GO TO 403
      HKI=21491.-14.6*TAV
      GO TO 405
403  HKI=27787.-30.66*TAV
      GO TO 405
404  HKI=32636.-53.53*TAV
405  IF(IZ.NE.22) GO TO 407
      HKT=HKI
411  CP=.03356
      IF(TAV.LE.349.) GO TO 409
      HKI=17300.-10.14*TAV
      GO TO 406
409  HKI=21150.-21.17*TAV
406  IF(IZ.EQ.22.AND.IX.EQ.4) HKT=.6018*HKI+.3982*HKT
407  CONTINUE
      IF(IZ.GE.17.AND.IZ.LE.21) GO TO 292
      IF(INUM.NE.57) GO TO 285
      IF(IZ.EQ.11) GO TO 282
      IF(IZ.EQ.12) GO TO 282
      IF(IZ.GE.13.AND.IZ.LE.16) GO TO 284
285  CONTINUE
      YHT=HKI*GY(IY)*CP*10.*SFY*SFT
      IYHT=IFIX(YHT)
      IVD(INUM)=IYHT
      IF(INUM.EQ.57.AND.IZ.EQ.10) GO TO 281
      IF(IZ.EQ.22) GO TO 291
      GO TO 289
281  YHT=(.1*HKI+600.)*SFY*SFT
      GO TO 288
282  YHT=1./(.00005708+1./HKI)*.27*SFY*SFT
      GO TO 288
284  YHT=1./(.0000761+1./HKI)*.284*SFY*SFT
      GO TO 288
291  IF(IX.NE.4) GO TO 289
      IF(IY.EQ.1) GO TO 243
      IF(IY.EQ.2) GO TO 242
      YHT=HKT*.00248*10.*SFY*SFT
      GO TO 288
242  YHT=HKT*.0087*10.*SFY*SFT
      GO TO 288
243  YHT=HKT*.0174*10.*SFY*SFT
288  IYHT=IFIX(YHT)
      IVD(INUM)=IYHT
      GO TO 289
292  IF(IX.EQ.4) GO TO 289
      IVD(INUM)=0
289  CONTINUE
      IF(IZ.GT.6.AND.IZ.LT.25) GO TO 7/2
      DO 773 IU=2,20

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773 IVD(ID)=0
DO 771 ID=41,68
771 IVD(ID)=0
772 CONTINUE
C RECALCULATE SETTING FOR IVD(68).
IF (IZ.NE.12) GO TO 6161
VD=TEMP(1,1,13)*20.+.5
IVD(68)=FIX(VD)
6161 CONTINUE
IF (IZ.NE.13) GO TO 6162
VD=TEMP(1,1,12)*20.+.5
IVD(68)=FIX(VD)
6162 CONTINUE
IF (IZ.EQ.16.OR.IZ.EQ.22) IVD(68)=1480
CALL SSWTCH(0,ISW)
IF (ISW-1) 1056,1056,1057
1056 IF (IVOLT2.EQ.1) GO TO 861
IOPV2=1
GO TO 862
861 IOPV2=0
862 CONTINUE
IF (IVOLT1.EQ.1) GO TO 866
IOPV1=1
GO TO 867
866 IOPV1=0
867 CONTINUE
WRITE(3,8010) IT,IZ,IVOLT1,IOPV1,IVOLT2,IOPV2,IZCNT
8010 FORMAT(' IT=',I4,', IZ=',I2,', VOLTAGE 1=',I1,'0',I1,
^ ' VOLTS',', VOLTAGE 2=',I1,'0',I1,', VOLTS',', IZCNT=',I3)
WRITE(3,1050) IVD
1050 FORMAT(10I8)
WRITE(3,1055)((TEMP(IX,IY,IZ),IX=1,5),IY=1,4)
1055 FORMAT(5F10.2)
1057 CONTINUE
C PUT TEMPERATURES CALCULATED FOR LAST Z LEVEL IN PERMANENT STORAGE.
IF (IZ.EQ.10.OR.IZ.EQ.11) GO TO 34
IF (IZ.GE.1.AND.IZ.LE.9) GO TO 33
IF (IZ.EQ.12.AND.IT.GT.514) GO TO 551
IF (IZ.EQ.15.AND.IT.GT.100.AND.IT.LE.514) GO TO 361
IF (IZ.EQ.15.AND.IT.GT.514) GO TO 774
IF (IZ.EQ.17.AND.IT.GT.514) GO TO 881
DO 31 IY=1,4
DO 31 IX=1,5
31 TEMP(IX,IY,IZ-1)=ITEMPT(IX,IY)*.05
GO TO 34
361 IF (IZCNT.EQ.1) GO TO 362
IF (IZCNT.EQ.3.AND.IT.LE.130) GO TO 363
IF (IZCNT.GE.3.AND.IZCNT.LE.7.AND.IT.GT.130) GO TO 34
IF (IZCNT.EQ.9) GO TO 363
GO TO 34
362 DO 364 IY=1,4
DO 364 IX=1,5
364 TEMPER(IX,IY,IZ-1)=ITEMPT(IX,IY)*.05
GO TO 34
363 DO 365 IY=1,4
DO 365 IX=1,5
365 TEMP(IX,IY,IZ-1)=TEMPER(IX,IY,IZ-1)
GO TO 34
551 IF (IZCNT.EQ.1) GO TO 552
IF (IZCNT.LT.10) GO TO 34

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      DO 554 IY=1,4
      DO 554 IX=1,5
554  TEMP(IX,IY,IZ-1)=TEMPER(IX,IY,IZ-1)
      GO TO 34
552  DO 555 IY=1,4
      DO 555 IX=1,5
555  TEMP(IX,IY,IZ-1)=ITEMPT(IX,IY)*.05
      GO TO 34
774  IF(IZCNT.EQ.1) GO TO 775
      IF(IZCNT.LT.19) GO TO 34
      DO 776 IY=1,4
      DO 776 IX=1,5
776  TEMP(IX,IY,IZ-1)=TEMPER(IX,IY,IZ-1)
      GO TO 34
775  DO 777 IY=1,4
      DO 777 IX=1,5
777  TEMP(IX,IY,IZ-1)=ITEMPT(IX,IY)*.05
      GO TO 34
881  IF(IZCNT.EQ.1) GO TO 882
      IF(IZCNT.LT.16) GO TO 34
      DO 883 IY=1,4
      DO 883 IX=1,5
883  TEMP(IX,IY,IZ-1)=TEMPER(IX,IY,IZ-1)
      GO TO 34
882  DO 884 IY=1,4
      DO 884 IX=1,5
884  TEMP(IX,IY,IZ-1)=ITEMPT(IX,IY)*.05
      GO TO 34
33  DO 35 IY=1,4
      DO 35 IX=1,5
35  TEMP(IX,IY,IZ+1)=ITEMPT(IX,IY)*.05
34  CONTINUE
C    SET THE DACS FOR THIS Z LEVEL.
      IF(IT.GT.514) GO TO 661
      IF(IZ.EQ.15.AND.IT.GT.100.OR;IZ.EQ.16.AND.IT.GT.100) GO TO 9100
      GO TO 4520
9100 CALL SETLI(0,0,11,0)
      CALL SETLI(0,0,13,1)
      CALL SETLI(0,0,14,1)
      GO TO 4520
661  IF(IZ.LT.12.OR.IZ.GT.21) GO TO 4520
      IF(IZ.LT.15.OR.IZ.GT.16) GO TO 9101
      CALL SETLI(0,0,13,0)
      CALL SETLI(0,0,12,1)
      GO TO 4520
9101 CALL SETLI(0,0,11,0)
      CALL SETLI(0,0,12,1)
      CALL SETLI(0,0,14,0)
4520 CALL STARA(IADB,IVD,NDAC)
      CALL SETIA(3216)
      CALL WAIT(50)
C    PUT ANALOG COMPUTER IN OPERATE MODE.
      CALL SETLI(0,0,15,0)
C    CHECK FOR HOLD MODE.
      IHOLD=ITEST(0,0,3)
3600 IF(ITEST(0,0,3)) 36,36,3/
36  GO TO 3600
37  CONTINUE
C    READ NEWLY CALCULATED TEMPERATURES FROM ADC.
      CALL SCAN(IADC,IVT,NADC)

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      ICNT =2
      DO 41 IY=1,4
      DO 41 IX=1,5
      ICNT=ICNT+1
      ITEMPT(IX,IY)=IVT(ICNT)
      IF(IZ.GT.6.AND.IZ.LT.25) GO TO 41
      IF(ICNT.LT.4) GO TO 41
      ITEMPT(IX,IY)=ITEMPT(1,1)
41  CONTINUE
      IF(MOV.NE.U.AND.IZ.EQ.7) GO TO 1504
      IF(MOV.NE.U.AND.IZ.EQ.24) GO TO 1504
      IF(IZ.GT.1.AND.IZ.LT.31) GO TO 4572
1504 DO 39 IY=1,4
      DO 39 IX=1,5
      39  TEMP(IX,IY,IZ)=ITEMPT(IX,IY)*.05
      GO TO 1000
4572 IF(IT.LE.1000) GO TO 1000
      IF(IT.GT.514) GO TO 4573
      IF(IZ.EQ.15.AND.IZCNT.GT.1) GO TO 653
      IF(IZ.EQ.16) GO TO 461
      GO TO 1000
653  IZ=16
      GO TO 1002
461  IF(IZCNT.EQ.2) GO TO 462
      IF(IZCNT.EQ.4.AND.IT.LE.130) GO TO 467
      IF(IZCNT.LE.8) GO TO 463
467  DO 4670 IY=1,4
      DO 4670 IX=1,5
4670 TEMP(IX,IY,IZ)=TEMPER(IX,IY,IZ)
      GO TO 1000
462  DO 4620 IY=1,4
      DO 4620 IX=1,5
4620 TEMPER(IX,IY,IZ)=TEMP(IX,IY,IZ)
463  DO 4630 IY=1,4
      DO 4630 IX=1,5
4630 TEMP(IX,IY,IZ)=ITEMPT(IX,IY)*.05
      IZ=15
      GO TO 1002
4573 IF(IZ.EQ.12.AND.IZCNT.GT.1) GO TO 786
      IF(IZ.EQ.13.AND.IZCNT.GT.2) GO TO 781
      IF(IZ.EQ.14) GO TO 761
      IF(IZ.EQ.15.AND.IZCNT.GT.1) GO TO 754
      IF(IZ.EQ.16) GO TO 791
      IF(IZ.EQ.17.AND.IZCNT.GT.1) GO TO 755
      IF(IZ.EQ.18.AND.IZCNT.GT.2) GO TO 782
      IF(IZ.EQ.19.AND.IZCNT.GT.3) GO TO 783
      IF(IZ.EQ.20.AND.IZCNT.GT.4) GO TO 784
      IF(IZ.EQ.21) GO TO 731
      GO TO 1000
786  IZ=13
      GO TO 1002
781  IZ=14
      GO TO 1002
754  IZ=16
      GO TO 1002
791  IF(IZCNT.EQ.2) GO TO 792
      IF(IZCNT.LE.18) GO TO 793
      DO 794 IY=1,4
      DO 794 IX=1,5
794  TEMP(IX,IY,IZ)=TEMPER(IX,IY,IZ)

```

```

      GO TO 1000
792  DO 7920 IY=1,4
      DO 7920 IX=1,5
7920  TEMPER(IX,IY,IZ)=TEMP(IX,IY,IZ)
793  DO 7930 IY=1,4
      DO 7930 IX=1,5
7930  TEMP(IX,IY,IZ)=ITEMPT(IX,IY)*.05
      IZ=15
      GO TO 1002
755  IZ=18
      GO TO 1002
782  IZ=19
      GO TO 1002
783  IZ=20
      GO TO 1002
784  IZ=21
      GO TO 1002
761  IF (IZCNT, EQ, 3) GO TO 762
      IF (IZCNT, LE, 9) GO TO 763
      DO 764 IY=1,4
      DO 764 IX=1,5
764  TEMP(IX,IY,IZ)=TEMPER(IX,IY,IZ)
      GO TO 1000
762  DO 7620 IY=1,4
      DO 7620 IX=1,5
7620  TEMPER(IX,IY,IZ)=TEMP(IX,IY,IZ)
763  DO 7630 IY=1,4
      DO 7630 IX=1,5
7630  TEMP(IX,IY,IZ)=ITEMPT(IX,IY)*.05
      IZ=12
      GO TO 1002
731  IF (IZCNT, EQ, 5) GO TO 732
      IF (IZCNT, LE, 15) GO TO 733
      DO 734 IY=1,4
      DO 734 IX=1,5
734  TEMP(IX,IY,IZ)=TEMPER(IX,IY,IZ)
      GO TO 1000
732  DO 7320 IY=1,4
      DO 7320 IX=1,5
7320  TEMPER(IX,IY,IZ)=TEMP(IX,IY,IZ)
733  DO 7330 IY=1,4
      DO 7330 IX=1,5
7330  TEMP(IX,IY,IZ)=ITEMPT(IX,IY)*.05
      IZ=17
      GO TO 1002
1000  CONTINUE
C      STORE TEMPERATURE VALUES AT 1 YEAR INTERVALS FOR PRINTOUT.
      IF (MODV) 72, 72, 2000
72  IPRT=IPRT+1
      DO 73 I3=1,31
      DO 73 I2=1,4
      DO 73 I1=1,5
73  TEMPRT(I1,I2,I3,IPRT)=TEMP(I1,I2,I3)
2000  CONTINUE
C      END OF CALCULATIONS FOR THIS CASE.
C      PRINT OUT RESULTS FOR THIS CASE.
      DO 4000 I=1,31
      IYR=I-1
      DO 4000 IY=1,4
      WRITE(3,220)

```

```

220 FORMAT(1H, 5X, '***** TEMPERATURES EXPRESSED IN DEGREES FAHRENHE
    IT *****')
    WRITE(3,230) IYR
230 FORMAT(1H, 23X, '**** TIME=', 13, ' YEARS ****')
    WRITE(3,240) YPLN(IY)
240 FORMAT(1H, 23X, 'Y PLANE DISTANCE=', F8.1, ' FEET')
    WRITE(3,250)
250 FORMAT(1H, 20X, 'I-----X DISTANCE, FEET-----I
    ')
    WRITE(3,260)
260 FORMAT(24X, '0.0', /X, '2.0', /X, '5.0', 7X, '9.0', 6X, '39.0')
    WRITE(3,270)
270 FORMAT(1H, 3X, 'ELEVATION, FEET')
    WRITE(3,280)
280 FORMAT(3X, 'BELOW GRADE')
    DO 4000 IZED=1,31
        IZ=32-IZED
        WRITE(3,290) ZDIST(IZED), (TEMPRT(IX,IY,IZ,I), IX=1,5)
290 FORMAT(F12.2, F16.2, 4F10.2)
4000 CONTINUE
    END

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APPENDIX B
DATA INCLUDED IN STORI FILE

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Appendix B

Data Included in "STORI" File

<u>Variable</u>	<u>Format</u>	<u>Variable Description</u>
NDAC	I6	Number of digital coefficient units used
NPOT	I6	Number of servo-set potentiometers used
NADC	I6	Number of analog-to-digital conversion channels used
NAMP	I6	Number of analog amplifiers used
IAD(JD), IVD(JD), JD=1, NDAC	I6	Digital coefficient unit address and value
IAP(JP), IVP(JP), JP=1, NPOT	I6	Servo-set potentiometer address and value
IAMP	I6	Analog amplifier address
TEMP	F8.2	Node temperature
GUP	F10.5	Geometry factor in upward Z direction
GDN	F10.5	Geometry factor in downward Z direction
GX	F10.5	Geometry factor in X direction
GY	F10.5	Geometry factor in Y direction
YPLU	F8.2	Y plane number
ZDIST	F8.2	Elevation, in feet

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