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EARTH SCIENCES DIVISION

COMPUTER PROGRAM CCC USER'S MANUAL VERSION II

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COMPUTER PROGRAM

CCC

USER'S MANUAL

Version II

(January, 1980)

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COMPUTER PROGRAM CCC--USER'S MANUAL

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1. INTRODUCTION

The Numerical Model CCC (conduction-convection-consolidation), developed at the Lawrence Berkeley Laboratory, solves numerically the heat and mass flow equations for a liquid saturated medium, and computes one-dimensional consolidation of the simulated systems. The model employs the Integrated Finite Difference Method (IFDM) in discretizing the saturated medium and in formulating the governing equations. The sets of equations are solved by an iterative solution technique (Edwards, 1972; Narasimhan and Witherspoon, 1976). The deformation of the medium is calculated using the one-dimensional consolidation theory of Terzaghi. Details of the model are given by Lippmann et al. (1977a) and Mangold et al. (1979).

2. GOVERNING EQUATIONS

The governing equations employed in the model are the basic mass and energy balance laws. The mass flow equation (see Nomenclature at end) can be written in integral form as:

$$\int_V \frac{S_s}{\vec{g}} \frac{\partial P}{\partial t} dV = -\int_A \rho \vec{v}_d \cdot \vec{n} dA + \int_V G_f dV \qquad (1)$$

Equation (1) applies to any control element of volume V and surface area A, containing solids and/or liquid water. The storage coefficient S_s describes the storage capacity of the element, and is related to the total matrix compressibility C_T and the porosity ϕ through the expression:

$$S_s = \phi \rho \vec{g} C_T \qquad (2)$$

The energy equation can similarly be written in integral form as:

$$\frac{D}{Dt}\int_V (\rho c)_M T dV = \int_A K_M \vec{\nabla} T \cdot \vec{n} dA - \int_A \rho c_f \delta T \vec{v}_d \cdot \vec{n} dA + \int_V G_h dV \qquad (3)$$

In equation (3), $(\rho c)_M$ represents the integrated heat capacity of the volume element, i.e.:

$$(\rho c)_M = \phi \rho c_f + (1 - \phi)\, \rho_s c_s \qquad (4)$$

In equation (3), the first term on the right-hand side (RHS) represents heat transfer by conduction as expressed by Fourier's law, K_M being the thermal conductivity of the rock-fluid mixture. The remaining terms on the RHS are the convective term and the source term, respectively. In the convective term, δT denotes the difference between the interface temperature and the temperature of the node.

Equations (1) and (3) are coupled through the pressure- and the temperature-dependent parameters as well as through the convecting term. In the model, the fluxes are calculated using Darcy's law, which can be written as:

$$\vec{v}_d = - \frac{k}{\mu} (\vec{\nabla} P - \rho \vec{g}), \qquad (5)$$

where k is the absolute permeability, μ is the dynamic viscosity of the fluid, and $\vec{g}$ is the acceleration due to gravity.

Equations (1) and (3) are nonlinear with pressure/temperature-dependent parameters ρ, k, μ, K_M, and c. Furthermore, the parameters ϕ, S_s and k are stress-dependent. The equation of state for water, which is used by default in the program, is given in Section 5, under data BLOCK 3 (material properties for the fluid).

Deformation

The model employs the one-dimensional theory of Terzaghi to calculate the deformation of the medium. The basic concept in the theory is the relationship between the effective stress σ' and the pore pressure P. For a saturated medium this expression can be written as:

$$\sigma' = \sigma_N - P, \tag{6}$$

where σ_N denotes the normal stress (overburden). The effective stress can easily be calculated from equation (6) at any time, given that the normal stress σ_N is known and remains constant.

The consolidation behavior of each material is described by the "e - log σ' curves," where e is the void ratio, related to the porosity ϕ by the expression:

$$\phi = e/(1 + e) \tag{7}$$

In practice, consolidation tests are used to obtain the "e - log σ' curves" for each material. In the model this information is given by analytical expressions.

A typical consolidation curve is shown in Figure 1; it consists of a so-called virgin curve and a series of parallel swelling-recompression curves (the model neglects hysteresis between swelling and recompression curves). When the rock is loaded to levels never before attained, the deformation is represented by the virgin curve, but for swelling or load levels below the preconsolidation stress, the deformation is represented by the swelling-recompression curves. In the model, the "e - log σ' curves" are generally approximated by straight lines, one of slope C_c (compression index) for virgin loading, and others of slope C_s (swelling index) for unloading/loading below the preconsolidation stress.

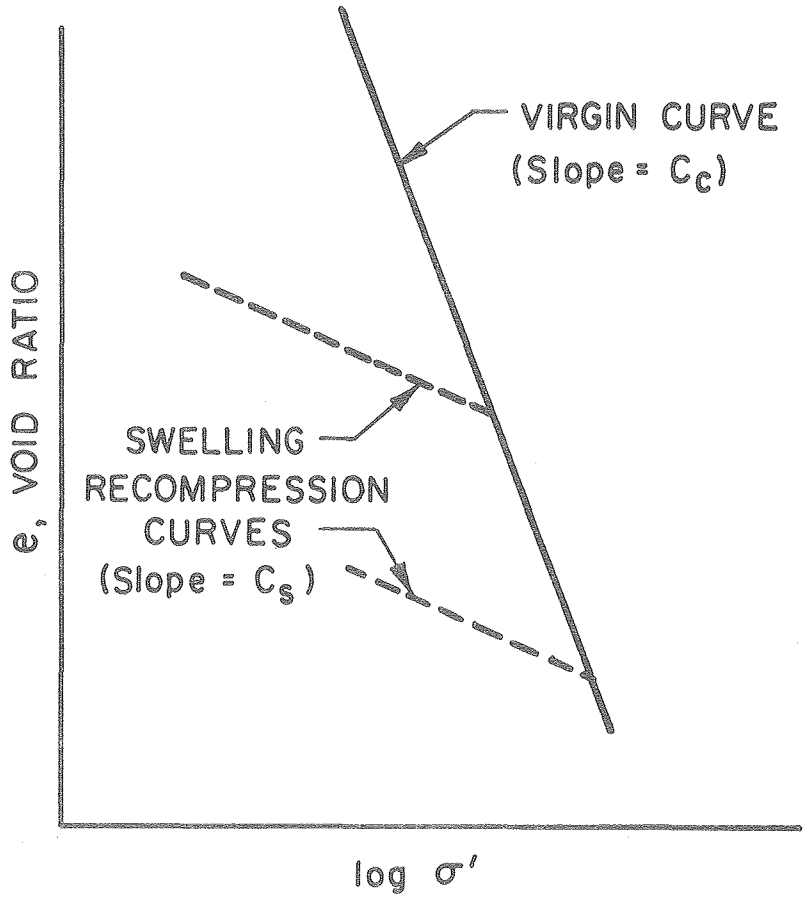

Figure 1. Typical consolidation curve.

The stress-dependent parameters in equations (1) and (3), ϕ, S_s, and k, can easily be calculated if the consolidation curves for each material are given. The porosity is computed using equation (7), and the specific storage S_s can be calculated using the following expression:

$$S_s = \rho g \, [\phi \beta_p + a_v/(1 + e)]. \tag{8}$$

In equation (8) β_p is the fluid compressibility and a_v is the coefficient of compressibility for the matrix, defined as:

$$a_v = - \frac{de}{d\sigma'} = C_c \, / \, (2.303 \, \sigma') \quad . \tag{9}$$

In calculating the permeability k as a function of void ratio, the following empirical relation is used:

$$k = k_o \exp \left[\frac{2.303 \, (e - e_o)}{C_k} \right] . \tag{10}$$

In equation (10), k_o and e_o are arbitrary reference values of the permeability and void ratio, respectively. For a given material, C_k is the slope of the best fitted line of void ratio (e) versus log k.

Assumptions

In the development of the mathematical model used in the computer code, the following primary assumptions have been employed:

1) Darcy's law adequately describes fluid movement through fractured and porous media.
2) The rock and the fluid are in thermal equilibrium at any given time.
3) Energy changes due to the fluid compressibility, acceleration and viscous dissipation are neglected.

These assumptions are generally employed in the numerical modeling of geothermal reservoirs. The chief limitation of the method is that the finite difference gradient approximation is inadequate in evaluating tangential gradients along the interfaces and in handling tensorial properties such as the stress fields which generally rotate with time. Except for the procedure used in evaluating the gradients, the Integrated Finite Difference Method (IFDM) and the modified Galerkin Finite Element Method (with diagonal capacity matrix) are conceptually very similar (Narasimhan and Witherspoon, 1976). Both approaches derive their ability to handle complex geometries from the integral nature of the formulation.

Numerical Formulation

The model employs the Integrated Finite Difference Method (IFDM) to discretize the flow regime and to handle the spatial gradients. The flow regime is divided into arbitrarily-shaped polyhedrons, constructed by drawing perpendicular bisectors to lines connecting nodal points. This permits easy evaluation of the surface integrals in equations (1) and (3). Detailed description of the IFDM are given by Edwards (1972), Sorey (1975), and Narasimhan and Witherspoon (1976).

In numerical notation the governing equations can be written as follows:

mass balance

$$\frac{(S_s V)_n}{g}\frac{\Delta P_n}{\Delta t} = \sum_m \left[\left(\frac{k\rho A}{\mu}\right)_{n,m} \frac{(P_m - P_n)}{D_{n,m}+D_{m,n}} - \left(\frac{k\rho^2 \eta A}{\mu}\right)_{n,m} g\right] + (G_f V)_n \qquad (11)$$

energy balance

$$\left[(\rho c)_M V\right]_n \frac{\Delta T_n}{\Delta t} = \sum_m \left[\frac{(K_M A)_{n,m}}{D_{n,m} + D_{m,n}} (T_m - T_n) + \left(\frac{\rho c_f A k}{\mu} \right)_{n,m} (T_{n,m} - T_n) \left(\frac{P_m - P_n}{D_{n,m} + D_{m,n}} - \eta \rho g \right) \right] + (G_h V)_n \quad . \tag{12}$$

These equations are valid for an arbitrary node n connected to an arbitrary number of nodes m. The nodal point distances to the interface for node n and node m are represented by $D_{n,m}$ and $D_{m,n}$, respectively (see Figure 2). The quantity $\eta = \eta_{n,m}$ is the direction cosine of the angle between the outward normal of node n and g.

Upstream Weighting

To evaluate the interface temperature $T_{n,m}$, the model employs an upstream weighting criterion:

$$T_{n,m} = aT_n + (1 - a) T_m \quad . \tag{13}$$

In equation (13), n is the upstream node and a, the upstream weighting factor, is restricted in value to the range of 0.5 to 1.0 for unconditional stability.

Implicit Formulation

In the model, the equations are solved implicitly to allow for larger time steps to be taken. The implicit formulation is incorporated by means of the following expressions:

$$\begin{aligned} T_n &= T_n^o + \lambda \Delta T_n \\ T_m &= T_m^o + \lambda \Delta T_m \\ P_n &= P_n^o + \lambda \Delta P_n \\ P_m &= P_m^o + \lambda \Delta P_m \quad . \end{aligned} \tag{14}$$

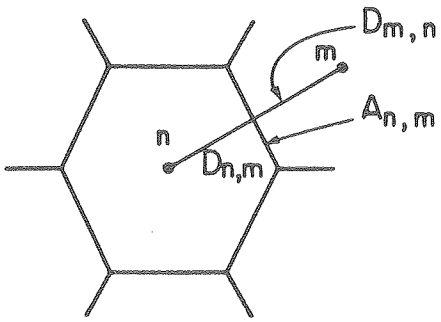

Figure 2. Typical node connection network and nomenclature.

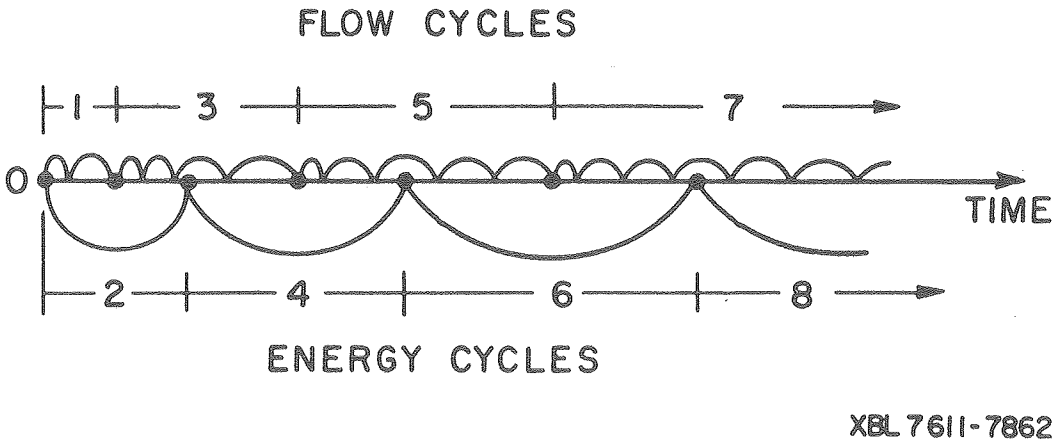

Figure 3. Interlacing of flow and energy calculations.

The weighting factor λ is generally allowed to vary between 0.5 and 1.0 for unconditionally stable solutions, but it may also be specified as a constant. If λ is specified to be 0 during the simulation, a fully explicit solution scheme results (forward differencing) and the time step is restricted below to a critical stable value (see Narasimhan 1975). If $\lambda = 0.5$, the Crank Nicholson Scheme results; for $\lambda = 1.0$, a fully implicit (backward differencing) scheme is employed.

Spatial Gradients

The spatial gradients between nodes are estimated by a linear approximation, i.e.:

$$\vec{\nabla}P = \frac{P_m - P_n}{D_{n,m} + D_{m,n}} \quad . \tag{15}$$

The permeability and thermal conductivity of the matrix and the density of the fluid at the interfaces are evaluated using the harmonic mean as a way to ensure continuity of flux at the interface, as for example:

$$k_{m,n} = k_m k_n \frac{D_{n,m} + D_{m,n}}{k_m D_{n,m} + k_n D_{m,n}} \quad . \tag{16}$$

Solution Technique

The coupled Equations (11) and (12) are solved alternatively by interlacing them in time; this is shown schematically in Figure 3. The flow equation solves for P, $\vec{v}_d$ and e assuming that the temperature dependent properties remain constant. Then the energy equation computes the temperature changes in the nodes (ΔT_n), assuming that $\vec{v}_d$ and pressure-dependent properties remain constant. Since in general the pressure

changes much more rapidly than the temperature, much smaller time steps are used in the flow cycles than in the energy cycles (Figure 3) in order to compute pressure variations accurately. A detailed explanation of the solution technique, called the mixed explicit-implicit iterative scheme, can be found in Narasimhan et al. (1978).

3. CODE DESCRIPTION

Documentation

The code is written in Fortran IV language. The code, its listing, and the user's manual are available upon request from the National Energy Software Center, Argonne National Laboratory, 9700 South Cass Avenue, Argonne, Illinois 60439. For details concerning input and output, see sections 5 and 8, respectively.

Spatial Grid

In the model there is no restriction upon choice of basic node shape or the numbering scheme of the nodes. The geometric configuration of the nodal elements can be arbitrary and the grid may be one-, two-, or three-dimensional, with rectangular, cylindrical, or spherical symmetry. The dimensions of the nodes and the connections between nodes are required input data. For complex problems, the design of the mesh may create the most difficulty in using the program. Auxiliary computer programs for mesh and input data generation have been developed for a number of grid systems, including the case with cylindrical or elliptical rings near a well, which gradually change to rectangular nodes in the far field. This type of mesh is relevant for the simulation of horizontal or inclined fractures intersecting a well (cylindrical or elliptical cross sections) or intersecting other planar fractures within the rock mass (linear cross sections) and similar problems.

Material Properties

At present the code allows specification of up to twelve (12) different materials. For each material the porosity, permeability, specific storage, thermal conductivity, heat capacity, and density of the solid must be specified. These parameters may be constant or may vary with temperature, and/or effective stress. The porosity and specific storage can vary with the effective stress, the permeability with both temperature and effective stress, and the thermal conductivity and heat capacity with temperature only. These relations are specified by tables, interpolated during each time step. Anisotropic permeability (and/or thermal conductivity) can be handled by orienting the nodes parallel to the principal axes of anisotropy.

Fluid Properties

Input parameters are the fluid viscosity, heat capacity, density and compressibility of water. A constant value of the compressibility must be specified; other fluid properties may also be assumed constant. However, the code provides the option of specifying the viscosity and heat capacity as a function of temperature, and density as a function of temperature and pressure. An empirical formula is used for the density function, while the code interpolates input tables for the appropriate value of the viscosity and heat capacity during each time step.

It should be noted that the formulation of the governing equations assumes that the fluid heat capacity is constant. Therefore, employing variable fluid heat capacity may introduce a slight error in the computations. For most practical problems the amount of error should be negligible.

Sources and Sinks

Constant rate mass and energy sources and sinks may be specified for any node.

Initial Conditions

Initial values of pressure, temperature and preconsolidation stress must be specified for each grid block. If the restart option is utilized, the specified initial values must correspond to the final values obtained in the previous run.

Boundary Conditions

In the model, prescribed constant potential or flux boundaries may be used. Finite capacity wells (wellbore storage) as well as a heterogeneous flow regime (fractures) can easily be simulated.

Time Steps

There are several options for selecting the time steps to be taken during the simulation. The maximum and minimum time steps may be specified, or the time steps may be automatically determined based upon the maximum desired pressure and/or temperature changes during a time step. The problem is ended when any one of several criteria is met. These include attainment of steady state, reaching the specified upper or lower limit for temperature and/or pressure, completing the required number of time steps, and reaching the specified maximum simulation time.

Output

Output is provided according to specified times or specified time steps. The pressure, temperature and first and second order derivatives are printed for each node. The fluid and energy fluxes are given for each connection. The mass and the energy balance are also included in the output.

4. SUBROUTINE DESCRIPTIONS

The following is a brief description of the operation of each subroutine for input, calculation and output. Figures 4 and 5 illustrate the calling sequence between subroutines for input and calculation/output, respectively.

Main Program

The main program reads in control cards and intializes control parameters. It maintains the sequence of calls to subroutines for the first time step, and for successive flow and heat cycles.

Subroutine THERM

THERM reads in data BLOCK 2 (material properties for the solid), and BLOCK 4 (node descriptions). It computes the value of the nonconstant physical properties of each node and type of material.

Subroutine FLUID

FLUID reads in data BLOCK 3 (material properties for the fluid). It does calculations for fluid viscosities, expansivities and densities for each node.

Subroutine COMPACT

COMPACT calculates the nodal geometry changes, including changes in volume, fluid content and effective stress dependent permeability. Also, it prints volume changes, stresses, and void ratio for each node.

Subroutine THICK

THICK reads in BLOCK 5 (connections between nodes). It computes temperature changes explicitly for each node.

Subroutine FLICK

FLICK calculates nodal mass capacities (CAC) and computes pressure changes explicitly for each node.

Subroutine TICKLE

TICKLE computes temperature changes implicitly for special nodes. It also computes the corrections for regular nodes connected to special nodes, and checks heat balance convergence.

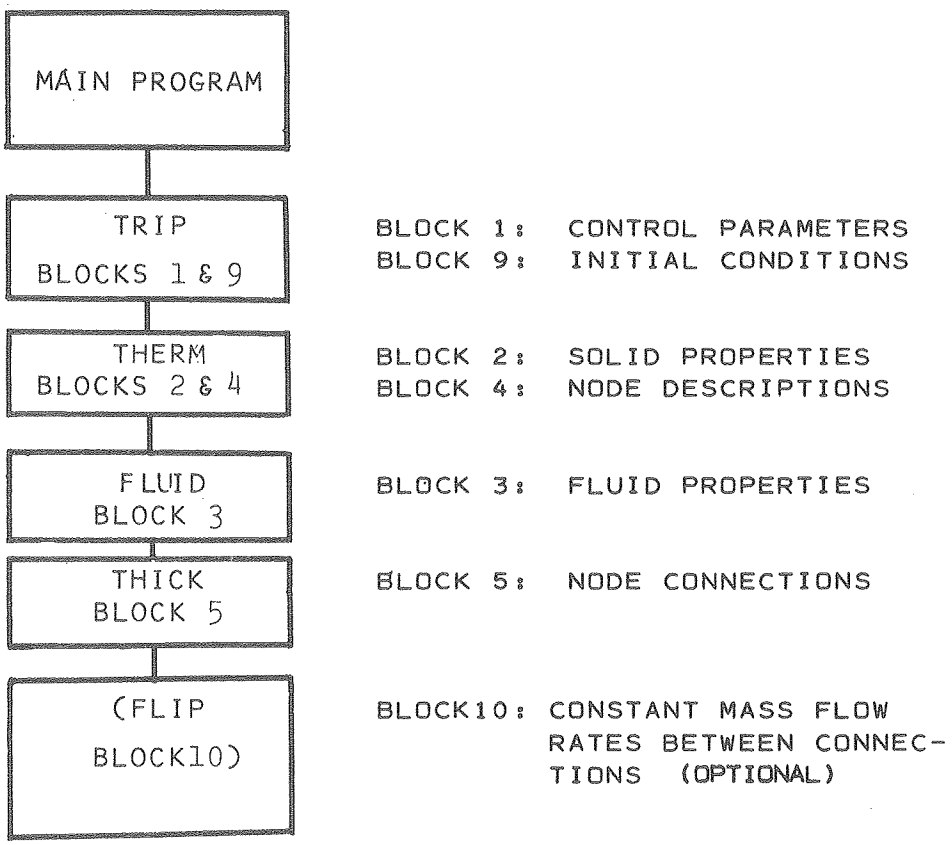

Figure 4. CCC input subroutine calls.

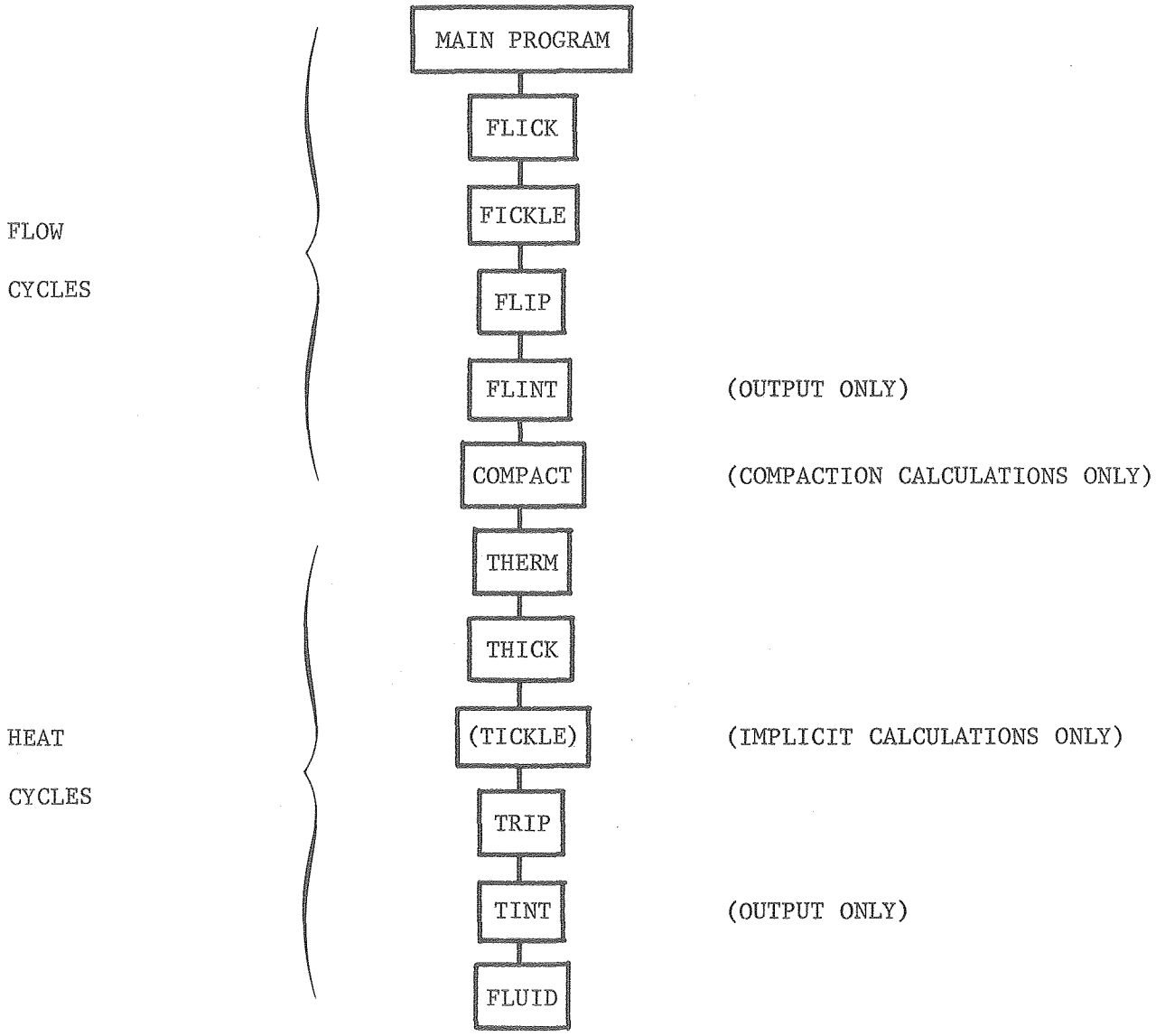

Figure 5. CCC calculation/output subroutine calls.

Subroutine FICKLE

FICKLE calculates pressure changes implicitly for all nodes. It also checks for mass balance convergence.

Subroutine TRIP

TRIP reads in data BLOCK 1 (problem controls, limits and constants), and BLOCK 9 (initial conditions). It controls the time steps in the heat cycles, computes nodal stability limits for heat cycles (SLIM), and changes regular nodes to special nodes if necessary. Also, it tests for certain limits to end the problem, such as thermal steady state, extremes of temperature, and time limits. It prints nodal temperatures, and other information on thermal cycles.

Subroutine FLIP

FLIP reads in data BLOCK10 (constant mass flow rates between connections). It controls the time steps in the flow cycles, and computes nodal stability limits for flow cycles (SLIMF). Also, it tests for pseudo steady-state mass flow in each heat cycle, and extremes of pressures. It generates a punched output at the end of the problem for restart purposes, if specified in BLOCK 1. Also, it prints nodal pressures, and other information on mass flow cycles.

Subroutine TINT

TINT prints summaries of the thermal properties of each node, and energy flow rates for each connection.

Subroutine FLINT

FLINT prints summaries of the hydraulic properties of each node, and mass flow rates for each connection.

Subroutine PATCH

PATCH uses ENCODE and DECODE to check input fields for Hollerith or numerical data.

Subroutine REFER

REFER cross-references nodes, material and connection numbers among data from BLOCKS 2, 4, 5, and 9.

TABLE 1

SUGGESTED UNITS

Basic Units

length : m

mass : kg

time : s

Other Units

compressibility : Pa^{-1}

density : kg/m^3

energy : joule

gravitational acceleration : $9.80665\ m/s^2$

heat capacity : $joule/kg \cdot {}^{o}C$

intrinsic permeability : m^2 ($1\ md = 9.86923 \times 10^{-16}\ m^2$)

pressure : Pa

specific storage : m^{-1}

temperature : ${}^{o}C$

thermal conductivity: $joule/m \cdot s \cdot {}^{o}C$

viscosity : $Pa \cdot s$ ($1\ Pa \cdot s = 10^{-3}$ cp)

5. PREPARATION OF INPUT DATA

The input data deck is organized into seven input blocks. Each block must start with a card with the word "BLOCK" in columns 1 through 5 and "N," the block number, in columns 6 and 7.

Typical units employed are shown in Table 1. Any consistent set of units, such as SI or British engineering, can be used.

See an example of an input deck in Figure 6; for the output example, see section 9.

a. Problem Identification Card, Format (70 A1).

The symbol "*" must be in the first column; any desired problem identification and description, in columns 2 through 70. This identification will be printed out at the top of the page for each data printout.

b. BLOCK 1. Problem Controls, Limits, and Constants (read in Subroutine TRIP)

Card 1. Format (8I5, 4E10.3). General Controls.

cols.	variable	description
1-5	IPRINT	Number of time steps between data output (controlled by KDATA), in addition to output on first and last time steps, and output controlled by TIMEP. IPRINT is not used if negative, zero, or unspecified.
6-10	NUM	Identification number of a node for which temperature, rate of temperature change, pressure, rate of pressure change, and time will be written out after each cycle. NUM will not be used if zero or unspecified.
11-15	KDATA	Controls option on output data, normal amount (0), minimum (-1), or maximum (1) number of parameters printed.
16-20	KSPEC	Node classification and difference-equation control for the HEAT cycles only. Normally zero or unspecified. If zero, regular nodes will be reclassified as special nodes (see variable KS in BLOCK 4) only when necessary to maintain the stability limit above the time step, and the interpolation factor in the heat-balance difference equations may vary in the range 0.57 to 1.0. If negative, no nodes may be reclassified, i.e., explicit formulation, and the steady state criteria will not be used to end the problem. If positive, all nodes will be reclassified as special nodes before the first time step, i.e., implicit formulation. If 2, the interpolation factor will be fixed at 1.0, so that the backward difference method will be used. If 3, the interpolation factor will be fixed at 0.5, so that the

cols.	variable	description
		central difference method will be used. Node classifications may be made individually in BLOCK 4 with KS. DELTO and SMALL must be specified when KSPEC is positive. In the FLOW cycles all nodes are considered to be special nodes (i.e., the interpolation factor is equal to 1.0).
21-25	MCYC	Maximum allowed number of heat cycles. MCYC will not be used if zero or unspecified.
26-30	MSEC	Maximum allowed machine time, in seconds. MSEC will not be used if zero or unspecified. If negative, problem will end after the first heat cycle.
31-35	NPUNCH	If greater than zero, a deck of punched cards in the format of BLOCK 9 is produced when the problem ends normally. If less than zero, decks in the format of BLOCKS 9 and 10 are produced. These decks may be inserted in the input deck, which may then be resubmitted to continue the problem.
36-40	NDOT	If zero, heat and mass flows will be computed. If positive, heat and mass flows will be computed assuming constant fluid density (DONE). In both cases only heat flow computations are allowed after a steady state fluid mass flow has been attained. If negative, only heat flow is computed, density of the fluid is assumed to be constant (DONE), and fixed convection rates must be assigned in BLOCK10.
41-50	TAU	Initial problem time. Will be set to zero if unspecified.
51-60	TIMAX	Maximum allowable problem simulation time. TIMAX will not be used if zero or unspecified. If it is negative, problem will end after the first heat cycle.
61-70	TIMEP	Problem time interval between data output, in addition to output on first and last heat cycles, and output controlled by IPRINT. TIMEP is ignored if negative, zero, or unspecified. Output will be written at exact multiples of TIMEP, if possible, by adjusting the time steps in the range from SMALL to DELTO. The adjustment is also limited to a range from 2/3 to 3/2 of the same step that would otherwise be used.
71-80	SCALE	Scale factor. Set to 1.0 if negative, zero, or unspecified. Will be applied to all geometric input data in BLOCKS 2, 4, and 5 read in following this BLOCK 1. Lengths will be multiplied by SCALE, before computing areas and volumes.

Card 2. Format (2I5, 6E10.3). Symmetry, Units, and Limits.

cols.	variable	description
1-5	KD	Symmetry type indicator: 1 for nonsymmetric (rectangular coordinates), 2 for axisymmetric (cylindrical coordinates), 3 for centrisymmetric (spherical coordinates). Input values of DRAD in BLOCKS 4 and 5 read in after BLOCK 1 will be replaced with DRAD, 2πDRAD, and $4\pi(\text{DRAD})^2$, respectively. KD is set to 1 if unspecified or zero.
6-10	KT	Number of large, constant temperature and/or pressure boundary nodes. This variable affects only the material summary tables.
11-20	DELTO	Maximum allowed time step for the heat cycles. May be used with SMALL to limit range of time step. DELTO is set to 10^{12} if unspecified or not in the range from 10^{-10} to 10^{12}.
21-30	SMALL	Minimum allowed time step for the heat cycles. May be used with DELTO to limit range of time step. Not usually needed. SMALL is set to 10^{-12} if less than 10^{-12} or unspecified.
31-40	TVARY	Desired maximum temperature change in each heat cycle. TVARY is set to 5.0 if unspecified or zero. Controls size of the time step between limits of SMALL and DELTO.
41-50	DELTOF	Maximum allowed time step for the flow cycles. May be used with SMALLF to limit range of time step. DELTOF is set to 10^{12} if unspecified or not in the range from 10^{-10} to 10^{12}.
51-60	SMALLF	Minimum allowed time step for the flow cycles. Not usually needed. SMALLF is set to 10^{-13} if less than 10^{-13} or unspecified.
61-70	RVARY	Desired maximum pressure change in any flow cycle. RVARY is set to 5.0 if unspecified or zero. Controls size of the time step between limits of SMALLF and DELTOF.

Card 3. Format (8E10.3). Default Input Parameters, Acceleration of Gravity and Upstream Weighting Factor.

1-10	TONE	Initial temperature for all nodes for which no TI is specified in BLOCK 9.
11-20	DONE	Initial fluid density for all nodes. Constant fluid density value if NDOT is nonzero.

cols.	variable	description
21-30	PONE	Initial pressure for all nodes for which no PI is specified in BLOCK 9.
31-40	PCONE	Initial preconsolidation pressure for all nodes for which no PCI is specified in BLOCK 9.
41-50	GMONE	Mass injection or production rate for all nodes for which no GI is specified in BLOCK 9 (usually left blank).
51-60	HCONE	Heat content of injected fluid for all nodes for which no HCI is specified in BLOCK 9. (Units: energy/unit mass)
61-70	GF	Acceleration due to gravity. GF is set equal to 9.80665 if unspecified.
71-80	WUP	Upstream weighting parameter. WUP is set equal to 0.7 if unspecified or less than 0.5 or greater than 1.0.

Card 4. Format (4E10.3). Maximum and Minimum Allowable Temperature and Pressure Values.

1-10	TMAX	Maximum allowable problem temperature. Will be set to 300 if unspecified.
11-20	TMIN	Minimum allowable problem temperature. Default value is zero.
21-30	RMAX	Maximum allowable problem pressure. Will be set to 10^8 if unspecified.
31-40	RMIN	Minimum allowable problem pressure. Default value is zero.

c. BLOCK 2 Material Properties for the Solid (read in Subroutine THERM)

NOTE: If some materials are deforming according to Terzaghi's one-dimensional theory (i.e., SS, AV, CC, and CS are all equal to zero) and others are not, use MODE II. That is, MODE I should be employed only when all materials have nonzero specific storage coefficients (SS).

MODE I: If no compaction calculations are required.

Card 1. Format (A5, 4I5, 5X, 5E10.4) Material Description.

cols.	variable	description
1-5	AMAT	Material name. Do not use "SYSTM" as a material name.

cols.	variable	description
6-10	MAT	Material identification number. Must not be zero or left blank.
11-15	LTABC	Number of points listed on specific heat table card or cards (following Card 2), positive if vs. temperature, zero or blank if specific heat is constant (equal to CAPT).
16-20	LTABK	Number of points listed on thermal conductivity table card or cards (following Card 2 and any specific heat table cards), positive if vs. temperature, zero or blank if conductivity is constant (equal to CONDUC(X)).
21-25	LTABP	Number of points listed on intrinsic permeability table card or cards (following Card 2 and any specific heat and/or thermal conductivity table cards), positive if vs. temperature, zero or blank if permeability is constant (equal to PERMEAB(X)).
31-40	DENS	Density of the solid. Set to 10^{-12} if less than 10^{-12} or not specified.
41-50	CAPT	Specific heat of the solid, if constant. Initial value, if variable; set to 10^{-36} if less than 10^{-36} or not specified.
51-60	CONDUC(X)	Thermal conductivity of the fully saturated porous media (solid-liquid mixture) along the X-axis of anisotropy, if constant. Initial value, if variable; set to 10^{-24} if less than 10^{-24} or not specified.
61-70	PERMEAB(X)	Intrinsic permeability of the porous media along the X-axis of anisotropy, if constant. Initial value, if variable, set to 10^{-24} if less than 10^{-24} or not specified.
71-80	SS	Specific storage of the porous media. Must not be zero or left blank.

Card 2. Format (3E10.3) Material Description.

1-10	ANISCON	Anisotropy for thermal conductivity. It is the ratio between the conductivities along the Y and X axes (i.e., CONDUC(Y)/CONDUC(X)). Axes X and Y are arbitrarily fixed in space and are parallel to the principal axes of material anisotropy. Set to 1.0 (isotropic) if zero or not specified.
11-20	ANISPER	Anisotropy for intrinsic permeability. It is the ratio between PERMEAB(Y) and PERMEAB(X). Set to 1.0 (isotropic) if zero or not specified.
21-30	POR	Porosity. Set to 10^{-12} if less than 10^{-12} or not specified.

cols.	variable	description

Card 3A, etc. Format (8E10.3). Specific Heat Table.
(omit if specific heat is constant)

1-10	CAPT(1)	Specific heat.
11-20	TVARC(1)	Temperature corresponding to CAPT(1).
21-30	CAPT(2)	Specific heat.
	(etc.)	

Card 4A, etc. Format (8E10.3). Thermal Conductivity Table.
(omit if thermal conductivity is constant)

1-10	CONT(1)	Thermal conductivity.
11-20	TVARK(1)	Temperature corresponding to CONT(1).
21-30	CONT(2)	Thermal conductivity.
	(etc.)	

Card 5A, etc. Format (8E10.3). Intrinsic Permeability Table.
(omit if intrinsic permeability is constant)

1-10	PERT(1)	Intrinsic permeability.
11-20	TVARP(1)	Temperature corresponding to PERT(1).
21-30	PERT(2)	Intrinsic permeability.
	(etc.)	

Card 6

Repeat card sequence from 1 to 5 for each different material. Following the cards corresponding to the last material, place a blank card.

MODE II. If compaction calculations are required.

Card. 1. Format (A5, 25X, 2E10.4). Average Properties of Overburden and Flow Region

cols.	variable	description
1-5		Punch the word "SYSTM"
31-40	THICK	Elevation of top of overburden above datum level, when multiplied by SCALE (see BLOCKS 1 and 4). The overburden is a hypothetical rock mass above the flow region where no mass flow or heat flow or compaction is computed. However, these quantities are calculated within the flow region.
41-50	DENSBUR	Average density of total system.

Card 2. Format (A5, 4I5, 5X, 5E10.4). Material Description.

Same as Card 1 in MODE I. Set SS equal to zero, or leave columns 71-80 blank.

Card 3. Format (5E10.3). Material Description.

1-10	ANISCON	Same as in MODE I.
11-20	ANISPER	Same as in MODE I.
21-30	AV	Coefficient of compressibility (a_v).
31-40	EZ	Reference void ratio (e_o).
41-50	PZ	Reference effective stress (σ'_o) at which $e = e_o$.

Card 4. Format (5E10.3). Material Description.

1-10	CS	Swelling index (C_s).
11-20	CC	Compression index (C_c).
21-30	CK	Slope of straight line on the e versus log k plot (c_k).
31-40	EK	Reference void ratio (e_k).
41-50	CONZ	Reference intrinsic permeability.

Cards 5A, 6A, 7A, and 8 are equal to Cards 3A, 4A, 5A, and 6 of MODE I, respectively.

d. BLOCK 3. Material Properties for the Fluid (read in Subroutine FLUID).

Card 1. Format (3I5, 5X, 6E10.3). Fluid Properties Description.

cols.	variable	description
1-5	LTABV	Number of points listed on viscosity table card or cards (following Card 2), positive if vs. temperature, zero or blank if viscosity is constant (equal to VIST).
6-10	LTABE	Number of points on fluid compressibility card or cards (following Card 2 and any viscosity table cards), positive if vs. temperature, zero or blank if compressibility is constant (equal to COMPRT).
11-15	LTABF	Number of points on fluid specific heat table card or cards (following Card 2 and any viscosity and/or compressibility table cards), positive if vs. temperature, zero or blank if fluid specific heat is constant (equal to CAPF).
21-30	VIST	Dynamic viscosity of fluid, if constant. Set to 10^{-36} if zero or unspecified.
31-40	COMPRT	Compressibility of fluid, if constant. Set to 10^{-36} if zero or unspecified.
41-50	CAPF	Specific heat of fluid, if constant. Set to 10^{-36} if zero or unspecified.

Card 2. Format (5E10.3). Fluid Properties Description.

1-10	PARAM1	Parameters for the equation of state for the fluid.
11-20	PARAM2	(i.e., density = f(Temperature, Pressure).
21-30	PARAM3	$\rho = P1 + P2 * T + P3 * T^2 + P4 * P + P5 * P^2$
31-40	PARAM4	If PARAM1 is equal to zero or unspecified:
41-50	PARAM5	PARAM1 = 997.091 $kg \cdot m^{-3}$
		PARAM2 = -7.80418×10^{-2} $kg \cdot m^{-3} \cdot {}^{o}C^{-1}$
		PARAM3 = -2.85902×10^{-3} $kg \cdot m^{-3} \cdot {}^{o}C^{-2}$
		PARAM4 = 8.46022×10^{-8} $kg \cdot m^{-3} \cdot Pa^{-1}$
		PARAM5 = 2.04487×10^{-14} $kg \cdot m^{-3} \cdot Pa^{-2}$
		These parameters correspond to pure liquid water (using SI units).

cols.	variable	description

Card 3A, etc. Format (8E10.3) Fluid Viscosity Table.
(omit if viscosity is constant)

1-10	VIST(1)	Dynamic viscosity of fluid.
11-20	TVARV(1)	Temperature corresponding to VIST(1).
21-30	VIST(2)	Dynamic viscosity of fluid.
	(etc.)	

Card 4A, etc. Format (8E10.3). Fluid Compressibility Table.
(omit if compressibility is constant)

1-10	COMPRT(1)	Compressibility of fluid.
11-20	TVARE(1)	Temperature corresponding to COMPRT(1).
21-30	COMPRT(2)	Compressibility of fluid.
	(etc.)	

Card 5A, etc. Format (8E10.3). Fluid Specific Heat Table.
(omit if specific heat is constant)

1-10	CAPF(1)	Specific heat of fluid.
11-20	TVARF(1)	Temperature corresponding to CAPF(1).
21-30	CAPF(2)	Specific heat of fluid.
	(etc.)	

e. BLOCK 4. Node Descriptions (read in Subroutine THERM).

Card 1. Format (5I5, 5X, 5E10.3)

1-5	NODE	Node identification number.
6-10	NSEQ	Number of additional, identically-shaped nodes, or, if DRAD is preceded by a minus sign, nodes with DRAD values incremented by the difference between DRAD for this node and DRAD for the immediately preceding node.

cols.	variable	description
11-15	NADD	Increment between successive values of NODE in the sequence of (NSEQ + 1) nodes generated when NSEQ is used.
16-20	NODMAT	Identification number of the material of which the node is a part.
21-25	KS	Node type indicator. In heat cycles nodes are either regular or special. Regular nodes are those for which only explicit calculations are made. Special nodes are those for which implicit calculations are performed. In flow cycles all nodes are special because only implicit calculations are made. Another category of nodes are those which are assumed to have no mass flow, and therefore only heat calculations are performed. Some regular nodes are reclassified into special nodes in the operation of the mixed explicit-implicit iteration scheme; for details, see Narasimhan et al. (1978), and Edwards (1972). If KSPEC $\leq$ 0 (BLOCK 1) Regular node (KS = 0) Special node (KS > 0) No mass flow node (KS < 0) If KSPEC > 0 (BLOCK 1) Special node (KS $\geq$ 0) No mass flow node (KS < 0)
31-40	DLONG	Geometric factors whose product with $(SCALE)^3$ is equal to the node volume, if KD is 1. For KD values of 2 or 3, the input value of DRAD is replaced with 2πDRAD, or $4\pi(DRAD)^2$, respectively, before calculation of the volume. The program substitutes 10^{-24} if the calculated volume is zero. SCALE and KD are defined in BLOCK 1.
41-50	DWIDE	
51-60	DRAD	
61-70	DELZ	Increment in elevation, when multiplied by SCALE, between successive nodes when NSEQ is used.
71-80	Z	Elevation of nodal point above datum plane when multiplied by SCALE.

cols.	variable	description

Card 2.

Following the card describing the last node, place a blank card.

NOTE: Place the boundary nodes at the end of the sequence. There should be KT of these nodes as specified in BLOCK 1.

f. BLOCK 5. Connections between Nodes (read in Subroutine THICK).

Card 1. Format (2I5, 3I3, I1, 5E10.3, I5)

1-5	NOD1	Identification numbers of the connected nodes.
6-10	NOD2	
11-13	NSEQ	Number of additional identical connections or, if DRAD is preceded by a minus sign, connections with DRAD values incremented by the difference between DRAD for this connection and DRAD for the immediately preceding connection.
14-16	NAD1	Increments between successive values of NOD1 and NOD2, respectively, in the sequence of (NSEQ + 1) connections generated when NSEQ is used.
17-19	NAD2	
20	NZ	Indicates NAD1 and NAD2 are each to be multiplied by 10^{NZ} before use in generating a sequence of connections.
21-30	DEL1	Distance, when multiplied by SCALE, from the nodal points in NOD1 and NOD2 to the connected interface.
31-40	DEL2	
41-50	DLONG	Geometric factors whose product with $(SCALE)^2$ is the area of the connected interface if KD is 1. For KD values of 2 or 3, the input value of DRAD is replaced with 2πDRAD or $4\pi(DRAD)^2$, respectively, before calculating the area.
51-60	DRAD	
61-70	HINT	Heat-transfer coefficient for conduction and convection across the connected interface. If HINT is zero, it is set equal to 10^{-24}. If HINT is not specified, it will be set to 10^{12}.
71-75	NSOTRPY	If nonzero, it is set equal to 1, indicating that this connection is parallel to the Y-axis of anisotropy (see BLOCK 2).

cols.	variable	description

Card 2.

Following the card describing the last connection between nodes, place a blank card.

g. BLOCK 9. Initial Conditions (read in Subroutine TRIP).

Card 1. Format (10X, 2E20.10). Pressure and Stress Correction Card.

11-30	PADD	Value to be added to all pressures read in BLOCK 9.
31-50	PCADD	Value to be added to all preconsolidation stresses read in BLOCK 9.

Card 2. Format (3I5, 5X, 6E10.3). Initial Values.

1-5	NOTE	Node identification number.
6-10	NSEQ	Number of additional nodes with identical initial conditions.
11-15	NADD	Increment between successive node numbers in sequence of (NSEQ + 1) nodes generated when NSEQ is used.
21-30	TI	Initial temperature. TI is set to TONE (BLOCK 1) if not specified.
31-40	PI	Initial pressure. PI is set to PONE (BLOCK 1) if not specified.
41-50	GI	Mass injection or production rate (production: GI < 0). GI is set to GMONE (BLOCK 1) if not specified.
51-60	HCI	Specific heat content of injected fluids (temperature of the injected fluid times fluid specific heat). HCI is set to HCONE (BLOCK 1) if not specified.
61-70	PCI	Initial preconsolidation stress. PCI is set to PCONE (BLOCK 1) if not specified.
71-80	DVOLI	Initial change in nodal volume (volume reduction: DVOLI > 0). DVOLI is set equal to zero if not specified.

Card 3.

Following the card specifying the initial condition of the last node, place a blank card. Note: the order in which the nodes are described in this block may differ from the order followed in BLOCK 4. However, the BLOCK 4 order will be used for printing out the results at the end of each time period.

h. BLOCK10. Constant Mass Flow Rates between Connections (read in Subroutine FLIP).

NOTE: This BLOCK is required only if NDOT = -1 (BLOCK 1) and if connections exist that have nonzero mass flow rates.

Card 1. Format (4(I5, E15.6))

cols.	variable	description
1-5	CONNEC(1)	Connection number (index number assigned in BLOCK 5).
6-20	FLOW(1)	Mass flow rate for CONNEC (1).
21-25	CONNEC(2)	Connection number.
	.	
	.	
	.	
66-80	FLOW(4)	Mass flow rate for CONNEC(4).

NOTE: Specify only connections which have nonzero flow rates. In each card give data for four connections, but the last card may specify less than four connections. By convention, FLOW is considered to be positive when it is from NOD2 toward NOD1 (see BLOCK 5).

Card 2.

Following the last card specifying mass flow rates, place a blank card.

i. Data End Card.

The last card of each data deck must be a Data End card with the word "ENDED" in columns 1 through 5 and either "-1" or "-2" in columns 6 and 7.

j. Final Card.

The last card of the deck must be a Final Card with the word "*SPLIT" in columns 1 through 6. This card stops the program.

6. SUGGESTED INPUT PARAMETERS

The parameters suggested below are to be considered tentative. If oscillations occur, then the parameters should be reduced. These values are inputted in BLOCK 1.

FLOW CYCLE PARAMETERS

$\text{DELTOF} \simeq 10^2\ (\text{SLIMF})\text{min}$

$\text{RVARY} \simeq 10^{-2}\ (\Delta P)\text{max}$

where

(SLIMF)min : Minimum stability limit for nonboundary nodes (for flow calculations).

(ΔP)max : Maximum total pressure change at any node (from t = TAU to t = TIMAX).

HEAT CYCLE PARAMETERS

$\text{DELTO} \simeq 10^2\ (\text{SLIM})\text{min}$

$\text{TVARY} \simeq 10^{-2}\ (\Delta T)\text{max}$

where

(SLIM)min : Minimum stability limit for nonboundary nodes (for heat calculations).

(ΔT)max : Maximum total temperature change at any node (from t = TAU to t = TIMAX).

NOTES:

a. Since the stability limits for the heat calculations (SLIM) are several orders of magnitude larger than the stability limits for the flow calculations (SLIMF) it is convenient to set $\text{DELTO} \simeq 10^2$ DELTOF. Otherwise the computer time limits might be exceeded and the problem might be aborted. (The maximum allowed machine time (MSEC) is checked during the heat calculations but not during the flow calculations).

b. The above-mentioned parameters are adequate for transient calculations. For steady-state calculations it is possible to relax these parameters; for example, let:

$$DELTO \simeq 10^{2} \ (SLIM)min$$

$$DELTOF = 10^{-1} \ (DELTO)$$

$$TVARY = 10^{-1} \ (\Delta T)max$$

$$RVARY \simeq 10^{-2} \ (P)mean$$

where

(P)mean : Mean pressure in the system being modeled.

Otherwise, for better results, it is necessary to run the problem again, using the same parameters as for a transient calculation.

7. BOUNDARY CONDITIONS, SOURCES AND SINKS

Mass Sources

For each node where there is a mass source specify in BLOCK 9 the mass rates (GI>0) and specific heat contents (HCI).

Mass Sinks

For each node where there is a mass sink specify in BLOCK 9 the mass rates (GI<0).

Heat Sources

For each node where there is a heat source specify in BLOCK 9 heat contents (HCI) and very small positive mass rates (e.g., GI = 10^{-20}). The value of HCI should be such that the product of heat content and mass rate should be equal to the energy generation rate at the particular node.

Heat Sinks

Same as in (3) but let HCI be a negative number (GI has to be positive).

Constant Pressure and Temperature Boundaries

Constant pressure and temperature boundaries are modeled by large volume (capacity) nodes which are connected to "internal" nodes of the simulated system. In BLOCK 4, let DRAD, DLONG and DWIDE be such that their volume (i.e., nodal volume) is at least 20 orders of magnitude larger than the volumes of the internal nodes. In BLOCK 5, let the distance from the larger node to the connected surface (DEL1 or DEL2) be a small positive number (e.g., 10^{-5}).

Constant Pressure but Variable Temperature Boundaries

Constant pressure but variable temperature boundaries are modeled by nodes whose materials have large specific storage values (e.g., SS(J) = 10^{10}, in BLOCK 2). This results in nodes with large mass capacities (i.e., CAC(N)) whose pressures are only slightly affected by mass gains or losses.

Constant Temperature but Variable Pressure Boundaries

Constant temperature but variable pressure boundaries are modeled by nodes whose materials have large densities (e.g., DENS(J) = 10^{20}, in BLOCK 2). This results in nodes with large thermal capacities (i.e., CAP(N)) whose temperatures are only slightly affected by energy gains or losses.

Constant Heat Flux Boundaries

The effects of constant heat flux boundaries can be modeled by placing appropriate heat sinks (or sources) within the nodes connected to this type of boundary (see (3) and (4): heat sources and sinks).

Constant Mass Flux Boundaries

The effects of constant mass flux boundaries can be modeled by placing appropriate mass sinks (or sources) within the nodes connected to this type of boundary (see (1) and (2): mass sources and sinks).

8. DESCRIPTION OF OUTPUT DATA

The following is a list of output variables printed during calculations and in final summary tables. The definitions for flow variables are given first, and then those for heat variables, and for compaction. The variable names in parentheses are those used internally in the program.

A descriptive example is given in the next section, illustrated in Figures 7, 8, and 9.

FLOW OUTPUT DATA

SUMMARY HEADING:

PRINTOUT	=	Printout number (NPRINT).
CYCLE	=	Number of time steps (KCYCFC) in the latest flow cycle.
MF	=	Total number of times DPRES or DRMAX has exceeded RVARY in time steps for which DELTF was equal to SMALLF.
MSS	=	Total number of times DPRES or DRMAX were less than RVARY in time steps for which DELTF was equal to DELTMX.
KWIT	=	If larger than zero, indicates reason for end of simulation.
DELTMX	=	Maximum allowable time step. No larger than DELTOF and no smaller than 10^{-10} for flow cycles.
SMALL	=	Minimum allowable time step (SMALLF). No larger than 10^{10} and no smaller than the minimum SLIM (equal to CAC/ZIP), the maximum stable time step for nodes for flow cycles.
RVARY	=	Pressure accuracy control. Time steps adjusted to keep maximum pressure change near RVARY, and no more than 2.0* RVARY. Controls iteration convergence.
PRS	=	Maximum pressure change (DPRES) in time step DELTSF (last time step completed).
DRMAXS	=	Value of DRMAX for time step DELTSF. DRMAX is maximum change in any tabulated property, in equivalent pressure of RVARY*(% change), or 0.025*NUTSF*RVARY, whichever is largest, in time step DELTSF. Time-step control.

NUTS	=	Number of mass-flow balance iterations completed before convergence (NUTSF). NUTMAX is maximum allowable number of iterations (80) of the mass-flow balance equations for interconnected nodes.
TOTAL TIME	=	Total time for flow cycles (OLDTIME).
SUMTIMF	=	Time length of last flow cycle.
FRAC OF DELT	=	SUMTIMF as a fraction of DELT (SUMTIMF/DELT).
TIME STEP	=	Time length of last completed flow step (DELTSF)
TOTAL FLOW	=	Total mass flux (FLUX, sum over FF).
TOTAL MASS	=	Total accumulation of mass (SMASS, sum over DMASS).
NSS	=	Counter for time steps during which pseudo-steady state for flow cycles was reached. Steady state flow field is assumed when NSS = 9.

EACH NODE:

NODE	=	Node identification number (BLOCK 4).
DENSITY	=	Density of fluid in node (D).
PRESSURE	=	Pressure in node (R).
DP	=	Pressure change in the last time step (DR).
DDP	=	Estimated rate of pressure change in the next time step (DDR).
GM	=	Mass generation rate, mass/time (G).
W	=	Total mass content (FLUCT = D*POR*VOL).
NET MASS	=	Change in mass content since the beginning of the problem, at t = TAU (DMASS = CAC*DR).
NET FLUX	=	Net mass transported into the node by internal and external mass flow connections since t = TAU (FF).
TOTAL DP	=	Total pressure change in the node since t = TAU (R - PI).

ITERATIONS :

KCYCF	=	Total number of flow time steps since t = TAU.
TOTAL	=	Total number of iterations (NUTSUMF).
AVERAGE	=	Average number of iterations per time step (NUTAVG = NUTSUMF/KCYCF), using integer division.
MAXIMUM	=	Maximum number of iterations at any time step (NUTXF).
FORF	=	Time step interpolation factor (always equal to one in flow calculations).

INTERNAL CONNECTION DATA:

NOD1, NOD2	=	Identification numbers of nodes being connected (BLOCK 5). Quantities are considered positive if their direction is from NOD2 to NOD1.
VELOCITY	=	Velocity of mass flow [V = FLOW/(AREA*DAV)].
FLOW RATE	=	Rate of mass flow [FLOW = TRAN1*R(NOD1) + TRAN2*R(NOD2) + GPD].
AVG RATE	=	Average mass flow rate for time step (FAV = DFI/DELTSF).
TRAN2	=	Mass transductance for NOD2, and -TRAN2 = TRAN1, mass transductance for NOD1.
GPD	=	Rate of mass flow due to difference in elevation, if gravity is nonzero.

NODE DATA:

NODE	=	Node identification number (BLOCK 4).
MATL	=	Identification number of the material (NOXMAT), (BLOCK 2).
VOLUME	=	Volume of node (VOL).
VISCOSITY	=	Viscosity of fluid in node (VIS).
EXPANSIVITY	=	Expansivity of fluid in node (EXPAN).
ZIP	=	Overall transductance, sum of transductances for the node.

SLIM = Maximum stable time-step for the node for flow cycles (CAC/ZIP).

CAC = Fluid mass capacity of node (VOL*SS/GF).

HEAT OUTPUT DATA

SUMMARY HEADING:

PRINTOUT = Printout number (NPRINT).

CYCLE = Heat cycle number (KCYC).

MF = Total number of times DTEMP or DTMAX has exceeded TVARY in time steps for which DELT = SMALL.

MSS = Total number of times DTEMP or DTMAX were less than TVARY in time steps for which DELT = DELTMX.

KWIT = If larger than zero, indicates reason for end of simulation.

DELTMX = Maximum allowable time step (10^{-10} to 10^{12}). No larger than either DELTO or 2/3 of the smallest value of SLIM(N) for regular nodes, in heat calculations.

SMALL = Minimum allowable time step (in 0.01*DELTMX as long as at least 1/4 of the nodes are regular nodes).

TVARY = Temperature accuracy control. Time steps adjusted to keep maximum temperature change near TVARY, and no more than 2.0*TVARY. Controls iteration convergence and criteria for thermal steady state.

DTEMP = Maximum temperature change in time step DELTS (last time step completed).

DTMAXS = Value of DTMAX for time step DELTS. DTMAX is maximum change in any tabulated property, in equivalent temperature of TVARY*(%change), or NUTMAX*TVARY if NUTMAX iterations were done, or 0.025*NUTS*TVARY, whichever is largest, in time step DELTS. Time-step control.

NUTS = Number of iterations completed before convergence. Will cause next time step to be reduced if more than 40. NUTMAX is maximum allowable number of iterations (80) of the heat balance equations for interconnected special nodes. Number of special node heat-balance iterations.

TOTAL TIME = Total time (SUMTIM).

TIME STEP = Length of last time step (DELT).

HEAT FLOW	=	Net heat flow into the system (FLUX).
TEMP FROM FLUX	=	Resulting average temperature change (TEMPER) of system due to net surface flux.
FLUX RATE	=	Average rate of heat flow (FX) across connections.
TEMP RATE	=	Average rate of temperature change (TX) resulting from heat flow across connections.
AVG TEMP	=	Average system temperature (TEMPAD).
HEAT CAPACITY	=	Total system heat capacity (CAPS).
HEAT CONTENT	=	Heat content of total system (HEAT) at SUMTIM.
NET HEAT INJECTED	=	Total heat injected into the system since t = TAU (initial problem starting time).
NET HEAT FLOW ACROSS BOUNDARIES	=	Total heat coming into the system across the boundaries since t = TAU.

EACH NODE:

NODE	=	Node identification number (BLOCK4).
TEMP	=	Node temperature (T).
DT	=	Temperature change during last time step.
DDT	=	Estimated rate of temperature change for the next time step.
GH	=	Heat generation rate, energy/time.
W	=	Total nodal heat content.
H	=	Change in heat content since t = TAU.
F	=	Net heat transported into the node by internal and external thermal connections since t = TAU.
TOTAL DT	=	Total temperature change in the node since t = TAU.

ITERATIONS:

KCYC	=	Total number of heat cycles (steps).

TOTAL	=	Total number of special node iterations (NUTSUM) used in heat calculations since t = TAU.
AVERAGE	=	Average node iterations per time step (NUTAVG = NUTSUM/KCYC), using integer division.
MAXIMUM	=	Maximum number of iterations in any time step (NUTX).
FOR	=	Time-step interpolation factor.

INTERNAL CONNECTION DATA:

NOD1, NOD2	=	Identification numbers of nodes being connected (BLOCK 5). Quantities are considered positive if their direction is from NOD2 to NOD1.
AVG FLOW	=	Average heat flow rate during last heat cycle (FAV = DFI/DELTS).
TOTAL FLOW	=	Total heat flow since t = TAU (FI).
TOTAL AVG	=	Average heat flow since t = TAU, [FX = FI/(SUMTIM-TAU)].
TRAN1, TRAN2	=	Thermal transductances for nodes NOD1 and NOD2.
ADJ.DEL1	=	Length of DEL1 (BLOCK 5) after upstream weighting, for thermal calculations only (DEL1C).

MATERIAL DATA:

NAME	=	Name of material (BLOCK 2).
MATL	=	Material identification number (BLOCK 2).
TOT CAP	=	Total heat capacity (CAPMS).
TOT HEAT	=	Total heat content (WMS).
AVG TEMP	=	Average temperature (TMS).

NODE DATA:

NODE	=	Nodal identification number (BLOCK 4).
MATL	=	Material identification number (NOXMAT), (BLOCK 2).
NTYPE	=	Node type: regular (0), special (3), reclassified special (4,5).
CAPACITY	=	Heat capacity of the node (CAP).

CONDUCTIVITY	=	Thermal conductivity of the node (CON).
PERMEAB	=	Intrinsic permeability of the node (PER).
FLUID CP	=	Fluid capacity of the node (CPF).
ZIP	=	Overall conductance, sum of conductances for the node.
SLIM	=	Maximum stable time step for a regular node, (CAP/ZIP), for heat cycles.

CONSOLIDATION OUTPUT DATA

NODE	=	Nodal identification number.
E(N)	=	Void ratio of node N.
PC(N)	=	Preconsolidation stress of node N.
ESTRESS(N)	=	Effective stress of node N.
PER(N)	=	Intrinsic permeability of node N.
DELVOL(N)	=	Total nodal pore volume reduction.

Other quantities printed out are self-explanatory. Table 2 summarizes the program messages given by the KWIT variable at the end of the printout.

9. OUTPUT EXAMPLE

A sample input deck is shown in Figure 6 for an example problem. Any number of cards may be placed before the star card (* in column 1) which will then be printed on the output file immediately before the input data summary. Note that two blank cards are used as cards 3 and 4 in BLOCK 1 because default values are assumed for those parameters. The input data is labelled in Figure 7 (2 pages), where the summary of input data is shown which is printed for user verification of data and to preserve a record for future reference. Please refer to section 5 for the explanation of each variable. The material was made anisotropic for this example, even though the mesh is one-dimensional. Note that in the course of calculations node 1 was reclassified to become a special node.

TABLE 2

PROGRAM MESSAGES

Message	What happened	What to do
KWIT (end of printout)		
1 = TIMAX	Problem ended normally at prescribed maximum time (BLOCK 1).	---
2 = TMAX	Maximum temperature (TMAX) exceeded in some node(s).	Check Heat Output Data final summary to find troublesome node(s). Change input values and/or node sizes to solve it.
3 = TMIN	Temperature of some node(s) is less than TMIN.	
4 = S.S.	Steady state was reached in the heat cycle.	The code will automatically end the problem when the change in all nodes is less than 1/100°C in the heat cycle.
5 = RMIN	Pressure of some node(s) is less than RMIN.	Check Flow Output Data final summary to find troublesome node(s). Change input values and/or node sizes to solve it.
6 = RMAX	Maximum pressure (RMAX) exceeded in some node(s).	
7 = MCYC	Problem ended normally at prescribed number of heat cycles.	---
8 = MSEC	Problem ended normally at prescribed number of heat cycles (BLOCK 1).	---
9 = BLK 2, 4 or 5	There was a mistake in specifying the material properties or the geometrical mesh for the problem.	Additional messages are printed by the program to help identify the mistake in the input data for BLOCK 2, 4, or 5. In BLOCK 2, Mode II, THICK or DENSBUR cannot be zero or negative. Also, anisotropy cannot be less than zero.

TABLE 2 (cont'd.)

Message	What happened	What to do
10 = CONVERGENCE FAILURE	The algorithm was unable to iterate successfully to converge to a solution (Number of iterations greater than 80).	Check initial conditions (including generation rates and boundary nodes) for extreme values. Also consider if RVARY or TVARY have been set too small for the problem (BLOCK 1).
11 = PROBLEM SIZE LIMIT	Number of materials permitted was exceeded.	Reduce the number of materials or combine materials which are similar into the same material.
12 = TABLE LENGTH OR ORDER	Tables for property changes were too long or in wrong order.	Reduce the number of entries of fluid viscosity etc. or solid specific heat etc. Make sure order is from lowest temperature to highest temperature.

```
*  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *
*  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *

INJECTION  OF  HOT  WATER  INTO  A  HORIZONTAL  RADIAL  SYSTEM

ONLY  1/6  OF  A  CIRCLE  IS  MODELED  DUE  TO  SYMMETRY

*  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *
*  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *

CONSTANT  FLUID  DENSITY  AND  HEAT  CAPACITY

VISCOSITY  A  FUNCTION  OF  TEMPERATURE

*  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *
*  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *  *


*OUTPUT EXAMPLE* INJECTING 20 DEGREE WATER INTO A ZERO DEGREE SYSTEM
BLOCK 1
                                                 0.       50.
              4.                       1.        1.                 2. E-2

BLOCK 2
SAND      1                   2.7          700.        1.      .01          .001
       .4   .1      .999999999

BLOCK 3
    2                1.         0.       1.
  1.
         1.        0.         .5       20.
BLOCK 4
    1                1               .19634955 1.64        1.64
    2                1               .19634955 9.84        6.56
    3                1               .19634955 28.06       11.66
    4                1               .19634955 60.57       20.85
    5                1               .19634955 128.53      47.11
    6                1               .19634955 257.9       82.26
    7                1               .19634955 532.08      191.92
    8                1               .19634955 1049.       325.
    9                1               .19634955 2142.       768.


BLOCK 5
    1     2         .64        3.28        .39269908 1.64                       1
    2     3         3.28       4.56        .39269908 8.2                        1
    3     4         7.1        8.58        .39269908 19.86                      1
    4     5         12.27      19.09       .39269908 40.71                      1
    5     6         28.02      34.68       .39269908 87.82                      1
    6     7         47.58      77.88       .39269908 170.08                     1
    7     8         114.       136.84      .39269908 362.                       1
    8     9         188.16     313.84      .39269908 687.                       1
BLOCK 9         INITIAL   CONDITIONS   FOR   INJECTION
  PADD
    1                                      3.125E-2        20.

ENDED-1
*SPLIT
333333333.333333333.333333333.333333333.333333333.333333333.333333333.333333333.
333333333.333333333.333333333.333333333.333333333.333333333.333333333.333333333.
333333333.333333333.333333333.333333333.333333333.333333333.333333333.333333333.
333333333.333333333.333333333.333333333.333333333.333333333.333333333.333333333.
1        10        20        30        40        50        60        70        80
```

Figure 6. Sample input deck for output example.

```
CCC OUTPUT DATA                OUTPUT DATE   13.40.26    25 APR 80

*OUTPUT EXAMPLE= INJECTING 20 DEGREE WATER INTO A ZERO DEGREE SYSTEM
DATA BLOCK  1

IPRINT   NUM KDATA KSPEC  MCYC  MSEC NPUNCH NDOT     TAU          TIMAX        TIMEP        SCALE
   -0    -0    -0    -0    -0    -0    -0    -0   0.           .50000E+02 -0.            .10000E+01

  KD   KT    DELTO        SMALL        TVARY        DELTOF       SMALLF       RVARY        GEOM
   1   -0   .40000E+01   .10000E-11   .10000E+01   .10000E+01   .10000E-12   .20000E-01   .10000E+01

    TONE         DONE         PONE         PCONE        GMONE        MCONE        GF           WUP
-0.          -0.          -0.          -0.          -0.          -0.          .98067E+01   .70000E+00

    TMAX         TMIN         RMAX         RMIN
 .30000E+03 -0.          .10000E+09 -0.
DATA BLOCK  2

NAME MATL INDEX LTABC LTABK LTABP    DENSITY     CAPACITY    CONDUC(X)   PERMEAB(X)  SP STORAGE   POROSITY
SAND    1     1    -0    -0    -0   .2700E+01   .7000E+03   .1000E+01   .1000E-01   .1000E-02   .1000E+01

                          ANISOTROPIC MATERIAL(Y/X)   CONDUCTIVITY=    .4000     PERMEABILITY=    .1000
DATA BLOCK  3

LTABV LTABE LTABF   VISCOSITY    FLUID COMPR   FLUID CP     PARAM1       PARAM2       PARAM3       PARAM4       PARAM5
   2    -0    -0   .1000E+01   0.            .1000E+01   .1000E+01 -0.          -0.          -0.          -0.

          VISCOSITY      SLOPE          TVARY
          .100000E+01   -.250000E-01   0.
          .500000E+00   -.250000E-01    .200000E+02
DATA BLOCK  4

  NODE INDEX  MATL NTYPE      DLONG        DWIDE        DRAD         VOLUME          Z
     1     1     1     0   .19635E+00   .16400E+01   .16400E+01   .52810E+00   0.
     2     2     1     0   .19635E+00   .98400E+01   .65600E+01   .12674E+02   0.
     3     3     1     0   .19635E+00   .28060E+02   .11660E+02   .64242E+02   0.
     4     4     1     0   .19635E+00   .60570E+02   .20850E+02   .24797E+03   0.
     5     5     1     0   .19635E+00   .12853E+03   .47110E+02   .11889E+04   0.
     6     6     1     0   .19635E+00   .25790E+03   .82260E+02   .41655E+04   0.
     7     7     1     0   .19635E+00   .53208E+03   .19192E+03   .20051E+05   0.
     8     8     1     0   .19635E+00   .10490E+04   .32500E+03   .66940E+05   0.
     9     9     1     0   .19635E+00   .21420E+04   .76800E+03   .32301E+06   0.
```

Figure 7. Output example: data input summary.

```
DATA BLOCK  5

 NOD1  NOD2 INDEX     DEL1          DEL2          DLONG         DRAD          HINT          AREA          NSDTYPY
    1     2     1  .6400E+00     .3280E+01     .3927E+00     .1640E+01     .1000E+13     .6440E+00        1
    2     3     2  .3280E+01     .4560E+01     .3927E+00     .8200E+01     .1000E+13     .3220E+01        1
    3     4     3  .7100E+01     .8580E+01     .3927E+00     .1986E+02     .1000E+13     .7799E+01        1
    4     5     4  .1227E+02     .1909E+02     .3927E+00     .4071E+02     .1000E+13     .1599E+02        1
    5     6     5  .2802E+02     .3468F+02     .3927E+00     .8782E+02     .1000E+13     .3449E+02        1
    6     7     6  .4758E+C2     .7788F+02     .3927E+00     .1701E+03     .1000E+13     .6679E+02        1
    7     8     7  .1140E+03     .1368E+03     .3927E+00     .3620E+03     .1000E+13     .1422E+03        1
    8     9     8  .1682E+03     .3138E+03     .3927E+00     .6870E+03     .1000E+13     .2698E+03        1

DATA BLOCK  9        INITIAL  CONDITIONS  FOR  INJECTION

  NOTE  INDEX          TI            PI            GI            HCI           PCI           DVOLI
     1     1        -0.           0.          .312500E-01   .200000E+02   0.            0.

DATA ENDED -1

   ELAPSED TIME =    .112 SECONDS

MATERIAL SUMMARY

NAME       MATL NODES    DENSITY       CAPACITY      TOT VOL       TOT POR VOL   TOT MASS      TOT CAP       TOT HEAT      TOT FLUID
SAND          1     9  .27000E+01    .70000E+03    .41568E+06    .41568E+06    .52922E+00    .13137E+01    0.            .52810E+00

SYSTEM TOTAL        9                              .41568E+06    .41568E+06    .52922E+00    .13137E+01    0.            .52810E+00

   CYCLE   12 MADE NODE     1 A SPECIAL NODE
```

Figure 7. (continued).

HEAT OUTPUT DATA

*OUTPUT EXAMPLE= INJECTING 20 DEGREE WATER INTO A ZERO DEGREE SYSTEM

PRINTOUT	CYCLE	MF	MSS	KWIT	DELTMX	SMALL	TVARY	DTEMP	DTMAXS	NUTS
2	20	0	9	1	.40000E+01	.40000E-01	.10000E+01	.31813E-01	.11595E+00	1

TOTAL TIME	TIME STEP	HEAT FLOW	TEMP FROM FLUX	FLUX RATE	TEMP RATE
.50000E+02	.11999E+01	.31141E+02	.74917E-04	.62282E+00	.14983E-05

AVG TEMP	HEAT CAPACITY	HEAT CONTENT
.74917E-04	.41568E+06	.31141E+02

NET HEAT INJECTED= .31250E+02 NET HEAT FLOW ACROSS BOUNDARIES= 0.

NODE	TEMP	DT	DDT	GH	W	W	F	TOTAL DT
1	.8054E+01	.2255E-01	.1857E-01	.6250E+00	.4253E+01	.4253E+01	.4253E+01	.8054E+01
2	.1604E+01	.3181E-01	.2620E-01	0.	.2033E+02	.2033E+02	.2033E+02	.1604E+01
3	.9762E-01	.4795E-02	.3949E-02	0.	.6271E+01	.6271E+01	.6271E+01	.9762E-01
4	.1149E-02	.9516E-04	.7836E-04	0.	.2849E+00	.2849E+00	.2849E+00	.1149E-02
5	.1878E-05	.2246E-06	.1849E-06	0.	.2233E-02	.2233E-02	.2233E-02	.1878E-05
6	.6636E-09	.1051E-09	.8651E-10	0.	.2764E-05	.2764E-05	.2764E-05	.6636E-09
7	.3564E-13	.7118E-14	.5861E-14	0.	.7145E-09	.7145E-09	.7145E-09	.3564E-13
8	.4744E-18	.1159E-18	.9542E-19	0.	.3176E-13	.3176E-13	.3176E-13	.4744E-18
9	.9801E-24	.2863E-24	.2358E-24	0.	.3166E-18	.3166E-18	.3166E-18	.9801E-24

INTERNAL CONNECTION DATA. CHECK CONDUCTANCES (TRAN).
LARGE DIFFERENCES BETWEEN CONNECTIONS MAY BE DUE TO POOR ZONING, AND MAY PRODUCE POOR RESULTS.

NOD1	NOD2	AVG FLOW	TOTAL FLOW	TOTAL AVG	TRAN1	TRAN2	ADJ.DEL1
1	2	-.6147E+00	-.2696E+02	-.5392E+00	-.9692E-01	.6572E-01	.2744E+01
2	3	-.2771E+00	-.6567E+01	-.1313E+00	-.1945E+00	.1643E+00	.5488E+01
3	4	-.1990E-01	-.2873E+00	-.5746E-02	-.2241E+00	.1990E+00	.1098E+02
4	5	-.2229E-03	-.2236E-02	-.4472E-04	-.2152E+00	.2039E+00	.2195E+02
5	6	-.3648E-06	-.2765E-05	-.5530E-07	-.2210E+00	.2200E+00	.4389E+02
6	7	-.1189E-09	-.7146E-09	-.1429E-10	-.2130E+00	.2129E+00	.8782E+02
7	8	-.6465E-14	-.3176E-13	-.6352E-15	-.2267E+00	.2267E+00	.1756E+03
8	9	-.7707E-19	-.3166E-18	-.6332E-20	-.2150E+00	.2150E+00	.3514E+03

MATERIAL DATA

NAME	MATL	TOT CAP	TOT HEAT	AVG TEMP
SAND	1	.4156777E+06	.3114113E+02	.7491652E-04

NODE DATA. CHECK TOTAL CONDUCTANCES (ZIP) AND TIME CONSTANTS (SLIN).
LARGE DIFFERENCES BETWEEN NODES MAY BE DUE TO POOR ZONING, AND MAY PRODUCE POOR RESULTS.

NODE	MATL	NTYPE	CP FLUID	CP SOLID	CONDUCTIX)	CAP	ZIP	SLIN
1	1	4	.1000E+01	.7030E+03	.1000E+01	.5281E+00	.9692E-01	.5449E+01
2	1	0	.1000E+01	.7000E+03	.1000E+01	.1267E+02	.2602E+00	.4871E+02
3	1	0	.1000E+01	.7000E+03	.1000E+01	.6424E+02	.3884E+00	.1654E+03
4	1	0	.1000E+01	.7030E+03	.1000E+01	.2480E+03	.4142E+00	.5987E+03
5	1	0	.1000E+01	.7000E+03	.1000E+01	.1189E+04	.4249E+00	.2798E+04
6	1	0	.1000E+01	.7000E+03	.1000E+01	.4166E+04	.4330E+00	.9621E+04
7	1	0	.1000E+01	.7000E+03	.1000E+01	.2005E+05	.4396E+00	.4561E+05
8	1	0	.1000E+01	.7000E+03	.1000E+01	.6694E+05	.4417E+00	.1516E+06
9	1	0	.1000E+01	.7000E+03	.1000E+01	.3230E+06	.2150E+00	.1503E+07

KCYC = 20, ITERATIONS... TOTAL = 8, AVERAGE = 0, MAXIMUM = 1. FOR = .570 .

Figure 8. Output example: heat output, final summary.

```
 FLOW OUTPUT DATA

 *OUTPUT EXAMPLE= INJECTING 20 DEGREE WATER INTO A ZERO DEGREE SYSTEM
==========================================================================================

 PRINTOUT CYCLE  MF    MSS  KWIT   DELTMX        SMALL         RVARY         PRS.          DRMAXS        NUTS
      2    28 12746     0     1   .10000E+01   .32778E-02   .20000E-01   .11682E-01   .10000E-02      2

  TOTAL TIME      SUMTIMF      FRAC OF DELT      TIME STEP      TOTAL FLOW      TOTAL MASS              NSS
 .50000E+02    .59997E+00     .35555E+15     .14970E-01     .15625E+01     .15625E+01                0

          NET MASS INJECTED=   .15625E+01          NET MASS FLOW ACROSS BOUNDARIES=  0.
==========================================================================================

NODE      DENSITY       PRESSURE        DP          DDP          GM          W          NET MASS     NET FLUX     TOTAL DP
  1     .1000E+01     .3246E+03    .1071E-01    .7153E+00    .3125E-01   .5281E+00    .1748E-01    .1748E-01    .3246E+03
  2     .1000E+01     .1473E+03    .1168E-01    .7804E+00   -0.          .1267E+02    .1903E+00    .1903E+00    .1473E+03
  3     .1000E+01     .7506E+02    .1134E-01    .7575E+00   -0.          .6424E+02    .4917E+00    .4917E+00    .7506E+02
  4     .1000E+01     .2437E+02    .8165E-02    .5454E+00   -0.          .2480E+03    .6163E+00    .6163E+00    .2437E+02
  5     .1000E+01     .1911E+01    .1286E-02    .8593E-01   -0.          .1189E+04    .2317E+00    .2317E+00    .1911E+01
  6     .1000E+01     .3485E-01    .3572E-04    .2386E-02   -0.          .4166E+04    .1480E-01    .1480E-01    .3485E-01
  7     .1000E+01     .9862E-04    .1350E-06    .9021E-05   -0.          .2005E+05    .2016E-03    .2016E-03    .9862E-04
  8     .1000E+01     .7183E-07    .1224E-09    .8176E-08   -0.          .6694E+05    .4903E-06    .4903E-06    .7183E-07
  9     .1000E+01     .8632E-11    .1754E-13    .1172E-11   -0.          .3230E+06    .2843E-09    .2843E-09    .8632E-11
==========================================================================================
 INTERNAL CONNECTION DATA.  CHECK CONDUCTANCES (TRAN).
      LARGE DIFFERENCES BETWEEN CONNECTIONS MAY BE DUE TO POOR ZONING. AND MAY PRODUCE POOR RESULTS.

 NOD1  NOD2    VELOCITY     FLOW RATE     AVG RATE      TRAN2          GPD
   1     2   -.4846E-01   -.3121E-01   -.3122E-01   .1760E-03   0.
   2     3   -.9379E-02   -.3020E-01   -.3020E-01   .4183E-03   0.
   3     4   -.3236E-02   -.2524E-01   -.2521E-01   .4979E-03   0.
   4     5   -.7162E-03   -.1145E-01   -.1138E-01   .5098E-03   0.
   5     6   -.2993E-04   -.1032E-02   -.1019E-02   .5500E-03   0.
   6     7   -.2770E-06   -.1850E-04   -.1814E-04   .5324E-03   0.
   7     8   -.3929E-09   -.5585E-07   -.5440E-07   .5667E-03   0.
   8     9   -.1431E-12   -.3860E-10   -.3735E-10   .5374E-03   0.
==========================================================================================
 NODE DATA.  CHECK TOTAL CONDUCTANCES (ZIP) AND TIME CONSTANTS (SLIMF)
      LARGE DIFFERENCES BETWEEN NODES MAY BE DUE TO POOR ZONING, AND MAY PRODUCE POOR RESULTS.

 NODE  MATL  TYPE      VOLUME      VISCOSITY   COMPRESSIB  PERMEAB(X)      CAC          ZIP          SLIMF
   1     1     0   .5281E+00   .7986E+00   0.          .1000E-01   .5385E-04   .1760E-03   .3060E+00
   2     1     0   .1267E+02   .9599E+00   0.          .1000E-01   .1292E-02   .5943E-03   .2175E+01
   3     1     0   .6424E+02   .9976E+00   0.          .1000E-01   .6551E-02   .9163E-03   .7149E+01
   4     1     0   .2480E+03   .1000E+01   0.          .1000E-01   .2529E-01   .1008E-02   .2509E+02
   5     1     0   .1189E+04   .1000E+01   0.          .1000E-01   .1212E+00   .1060E-02   .1144E+03
   6     1     0   .4166E+04   .1000E+01   0.          .1000E-01   .4248E+00   .1082E-02   .3924E+03
   7     1     0   .2005E+05   .1000E+01   0.          .1000E-01   .2045E+01   .1099E-02   .1860E+04
   8     1     0   .6694E+05   .1000E+01   0.          .1000E-01   .6826E+01   .1104E-02   .6182E+04
   9     1     0   .3230E+06   .1000E+01   0.          .1000E-01   .3294E+02   .5374E-03   .6129E+05
==========================================================================================

 KCYCF = 16748          ITERATIONS...   TOTAL= 19382   AVERAGE =     1   MAXIMUM =     3   FORF =  1.000
==========================================================================================


 ENDED PROB    1     KCYC =    20     KWIT =   1     SUMTIM =    .50000E+02
 KWIT...1=YYMAX, 2=YMAX, 3=YMIN, 4=S.S., 5=RMIN, 6=RMAX, 7=MCYC, 8=MSEC, 9=BLK 2,4 OR 5
      10=CONVERGENCE FAILURE, 11=PROBLEM SIZE LIMIT, 12=TABLE LENGTH OR ORDER.
```

Figure 9. Output example: flow output, final summary.

The final summary outputs for the heat and flow cycles are displayed in Figures 8 and 9, respectively. The explanation for each variable is given in Section 8.

10. VALIDATION

The code "CCC" has been validated against analytical solutions for fluid and heat flow, and against a field experiment for underground storage of hot water. The following is a list of selected problems:

Analytical Solutions (Fluid and Heat Flow)

1. Continuous Line Source: The Theis problem (1935) was solved for both early times (transient flow) and long-term steady radial flow.

2. Cold Water Injection in a Hot Reservoir: Avdonin's (1964) analytical results were matched for early and later times.

3. Doublet Problem: The temperature variations at the production well due to cold water injection were matched against the analytical results of Gringarten and Sauty (1975).

4. Conduction Problem: A one-dimensional conduction problem was solved and compared with the analytical solution given by Carslaw and Jaeger (1959).

5. Two-Node Problem: Transient conduction heat transfer between two nodes was calculated and compared to analytical solutions.

6. Buoyancy Flow: The rate of thermal front tilting when hot water was injected into a cold reservoir was calculated and compared to results by Hellstrom et al. (1979).

Fracture Flow Solutions

1. Vertical Fracture: The pressure response in a well intercepting a finite conductivity vertical fracture was calculated and compared to the semi-analytical solution of Cinco-Ley et al. (1978).

2. Horizontal Fracture: The pressure response in a well intercepting an infinite conductivity horizontal fracture was calculated and compared to the analytical solution of Gringarten (1971).

Auburn University Aquifer Thermal Energy Storage Field Experiment (1979)

Numerical modeling of two cycles of injection, storage and production of hot water in a confined aquifer yielded results that closely matched temperatures, pressures, and energy recovery factors observed in the field (Tsang et al., 1979b).

11. APPLICATIONS

This model has been applied to problems in the fields of geothermal reservoir engineering, aquifer thermal energy storage, well testing, radioactive waste isolation and in situ coal combustion.

Geothermal Reservoir Engineering

1. Simulation and reinjection studies have been done using data from the Cerro Prieto geothermal field (Tsang et al., 1979a; Lippmann and Goyal, 1979; and Lippmann et al., 1980).

2. Generic studies have been made for injection and production in geothermal reservoirs (Lippmann et al., 1977a).

3. Theoretical studies were made of subsidence in geothermal reservoirs due to fluid withdrawal (Lippmann et al., 1976, 1977b).

4. Preliminary studies of flow through fractures in geothermal reservoirs are in progress (Bodvarsson and Lippmann, 1980).

Aquifer Thermal Energy Storage

1. Many generic studies have been performed to demonstrate the feasibility of sensible heat storage in aquifers (Tsang et al., 1976, 1978a, 1978b).

2. The Auburn field experiments in aquifer storage were modeled successfully (Tsang et al., 1979b).

Well Testing

1. Studies of well behavior in a two-layered system with a temperature gradient have been made (Tsang et al., 1979a; Lippmann et al., 1980).

2. The effects of an alternative production-injection scheme on the temperature and pressure response of a geothermal system have been studied (Lippmann et al., 1977a; Tsang et al., 1978c).

3. A study was made of temperature effects in well testing in a single layer system (Mangold et al., 1979).

Radioactive Waste Isolation

1. A study was made to examine the conductive heat transfer near a repository (Chan et al., 1978).

2. Generic studies were performed using porous media, single-fracture and two-fracture models to simulate the fluid flow velocity in a region around a repository. These simulations were for periods of up to 10,000 years (Wang et al., 1980; Wang and Tsang, 1980).

In Situ Coal Combustion

Calculations were performed to investigate the time required for thermal effects to reach the surface from underground combustion of a coal seam (Mangold et al., 1978).

12. REFERENCES

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APPENDIX

NOMENCLATURE

symbol	definition and SI unit
a	upstream weighting factor, dimensionless
A	area, m^2
a_v	coefficient of compressibility for matrix, Pa^{-1}
C_c	slope of virgin curve in "e-log σ' plot," $(\log Pa)^{-1}$
C_k	slope of line in "e-log k" plot, $(\log m^2)^{-1}$
C_s	slope of swelling-recompression curve in "e-log σ' plot," $(\log Pa)^{-1}$
C_T	total compressibility of solid-fluid matrix, Pa^{-1}
c_f	fluid specific heat capacity at constant volume, $J/kg \cdot K$
c_s	solid (rock) specific heat capacity at constant volume, $J/kg \cdot K$
$D_{n,m}$	distance between nodal point n and interface between nodes n and m, m
e	void ratio, dimensionless
G_f	source term--fluid, (heat), kg/s
G_h	source term--heat, J/s
$\vec{g}$	acceleration due to gravity, m/s^2
K_M	thermal conductivity of solid-fluid mixture, $J/m \cdot s \cdot K$
k	intrinsic permeability, m^2
$\vec{n}$	outward unit normal on surface S, dimensionless
P	fluid (pore) pressure, Pa
Q	mass injection rate per unit volume, $kg/m^3 \cdot s$
q	energy injection rate per unit volume, $J/m^3 \cdot s$
S_s	coefficient of specific storage, m^{-1}

symbol	definition and SI unit
T	temperature, K (^oC)
t	time, s
V	volume, m^3
$\vec{v}_d$	Darcy fluid velocity, m/s
β_p	fluid compressibility, Pa^{-1}
δT	difference between the mean temperature within volume element dV and that on surface element dS, K (^oC)
$\eta_{n,m}$	direction cosine of the angle between the outward normal of node n and $\vec{g}$, dimensionless
λ	implicit-explicit interpolation factor, dimensionless
μ	fluid viscosity (dynamic), Pa·s
ρ	fluid density, kg/m^3
ρ_s	solid (rock) density, kg/m^3
$(\rho c)_M$	heat capacity per unit volume of the solid-fluid mixture, $J/m^3 \cdot K$
σ_N	normal stress (overburden), Pa
σ'	effective stress, Pa
ϕ	porosity, dimensionless

subscripts

f	fluid
h	heat
m	at node m
n	at node n
n,m	at interface between nodes n and m
o	reference quantity
s	solid

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