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SHAFT79, USER'S MANUAL

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SHAFT79 USER'S MANUAL

by

Karsten Pruess and Ron C. Schroeder

Introduction

SHAFT79 (Simultaneous Heat And Fluid Transport) is an integrated finite difference program for computing two-phase non-isothermal flow in porous media. The principal application for which SHAFT79 is designed is in geothermal reservoir simulation. SHAFT79 solves the same equations as an earlier version, called SHAFT78, but uses much more efficient mathematical and numerical methods. The physical model employed in both SHAFT78 and SHAFT79 is discussed in Pruess et al., 1979 a, b. Some pre- and post-processor programs used with SHAFT78 and SHAFT79 are described in the SHAFT78 user's manual (Pruess et al., 1979a). The present SHAFT79 user's manual gives a brief account of equations and numerical methods and then describes in detail how to set up input decks for running the program. The application of SHAFT79 is illustrated by means of a few sample problems; further examples of application are provided in Pruess et al., 1979c, and Pruess and Schroeder, 1979.

Equations and Numerical Methods

1. Governing Equations

SHAFT79 solves coupled mass- and energy-balance equations of the following form:

$$\frac{\partial \phi \rho}{\partial t} = - \operatorname{div} \underset{\sim}{F} + q \tag{1}$$

$$\frac{\partial U}{\partial t} = - \operatorname{div} \underset{\sim}{G} + Q \tag{2}$$

Here ϕ is porosity (void fraction), ρ is fluid density, $\underset{\sim}{F}$ is mass flux, q is a source term for mass generation, U is the volumetric internal energy of the rock/fluid mixture, $\underset{\sim}{G}$ is energy flux, and Q is an energy source term.

Mass flux is given by Darcy's Law:

$$\underset{\sim}{F} = \sum_{\substack{\alpha = \text{vapor,} \\ \text{liquid}}} \underset{\sim}{F}_\alpha = - \sum_\alpha \frac{kk_\alpha}{\mu_\alpha} \rho_\alpha (\nabla p - \rho_\alpha \underset{\sim}{g}) \tag{3}$$

where k, k_α are absolute and relative permeability, respectively, μ_α is viscosity, p is pressure and $\underset{\sim}{g}$ is gravitational acceleration.

Energy flux contains conductive and convective terms:

$$\underset{\sim}{G} = - K \nabla T + \sum_\alpha h_\alpha \underset{\sim}{F}_\alpha \tag{4}$$

where K is thermal conductivity of the rock/fluid mixture, T is temperature, and h_α is specific enthalpy of vapor ($\alpha = v$) or liquid ($\alpha = \ell$).

The volumetric internal energy is:

$$U = \phi u \rho + (1 - \phi)\, \rho_R C_R T \tag{5}$$

with u the specific internal energy of the (two-phase) fluid, ρ_R the rock density, and C_R the specific heat of the rock.

The main assumptions made in the above formulation are as follows: (1) The physical systems described by SHAFT79 are approximated as systems of porous rock saturated with one-component fluid in liquid and vapor form. (2) Except for porosity which can vary with pressure and temperature all other rock properties---density, specific heat, thermal conductivity, absolute permeability---are independent of temperature, pressure, or vapor saturation. (3) Liquid, vapor, and rock matrix are in local thermodynamic equilibrium, i.e., at the same temperature and pressure, at all times. (4) Capillary pressure is neglected.

2. Equation of State

The governing equations, above, need to be complemented with a description of the equilibrium thermodynamic properties of the fluid filling the void space. In SHAFT79 this description consists of a "fluid table," which gives all required quantities---temperature T, pressure P, vapor saturation S, heat conductivity K, liquid and vapor viscosities μ_ℓ, μ_v, densities ρ_ℓ, ρ_v, specific internal energies u_ℓ, u_v,---as functions of the

two principal dependent variables, which are fluid density ρ and fluid specific internal energy u. All thermodynamic information, including all derivatives, is obtained by means of bivariate interpolation from the fluid table. Such a table can be specified for any one-component fluid, and hence SHAFT79 is capable of modeling the flow of any one-component fluid in porous rock.

We have applied SHAFT79 only for systems of water and rock. For water, the fluid table is generated by executing two FORTRAN-programs, called WATER and PROPER. WATER computes and tabulates the steam table equations as given by the International Formulation Committee (IFC, 1967). PROPER numerically inverts these tables into functions of (u, ρ) and appends parameters other than T, p, S. The tabulation is done in such a way that interpolation does not occur across the saturation line, where derivatives change in discontinuous fashion.

Numerical methods used in WATER and PROPER and the preparation of input decks for these programs are described in the SHAFT78 user's manual (Pruess et al., 1979a).

A fluid table called FLUTAB3, which covers most of the equation of state of water substance in the temperature range 5° C $< T < 400^{\circ}$ C and the pressure range 0.5 bar $< p <$ 220 bar, is available as part of the SHAFT79 program package. FLUTAB3 should provide adequate range and accuracy for most any geothermal problem.

3. Numerical Methods

Space discretization of equations (1), (2) is achieved with the integrated finite difference method. This method allows a very flexible geometric description, because it does not distinguish between one-, two-, or three-dimensional regular or irregular geometries. Time is discretized fully implicitly as a first-order finite difference, resulting in the following finite difference equations:

$$D_n(\underset{\sim}{X}^{k+1}) \equiv \phi_n^{k+1}\rho_n^{k+1} - \phi_n^k\rho_n^k - \frac{\Delta t}{V_n}\left\{\sum_m F_{nm}^{k+1} + V_n q_n^{k+1}\right\} = 0 \tag{6}$$

$$E_n(\underset{\sim}{X}^{k+1}) \equiv \phi_n^{k+1}\rho_n^{k+1}u_n^{k+1} - \phi_n^k\rho_n^k u_n^k + \left[(1-\phi_n)\rho_R\right] C_R\,(T_n^{k+1} - T_n^k) - \frac{\Delta t}{V_n}\left\{\sum_m G_{nm}^{k+1} + V_n Q_n^{k+1}\right\} = 0 \tag{7}$$

Here, n, m label the volume elements, and k labels the time step. $\underset{\sim}{X}^{k+1} = (\rho_1^{k+1}, \ldots \rho_N^{k+1}, u_1^{k+1}, \ldots u_N^{k+1})$ is the vector of the 2N unknowns for a system with N elements. Δt is the time step, $\Delta t = t^{k+1} - t^k$, V_n is the volume of element n, and

$$F_{nm} = A_{nm} \sum_{\alpha} k_{(nm)} \left(\frac{k_\alpha}{\mu_\alpha}\right)_{(nm)} (\rho_\alpha)_{(nm)} \left(\frac{P_m - P_n}{d_{nm}} - (\rho_\alpha)_{(nm)} g_{(nm)}\right) \qquad (8)$$

is the mass flow from element m into element n, with interface area A_{nm} over a distance d_{nm}. An analogous definition holds for the energy flow G_{nm}. Whereas ϕ_n can vary with time, the apparent rock density $(1-\phi_n)\rho_R$ is constant. Different weighting procedures can be selected for the various "interface quantities," labeled with subscript (nm) (harmonic weighting, spatial interpolation, upstream weighting).

The non-linear finite difference equations, above, are solved with the Newton/Raphson method. The set of linear equations arising at each iteration step is solved with an efficient direct solver, employing sparse storage techniques (Duff, 1977).

4. Overview of Program Execution

Figure 1 summarizes the computational procedure as executed by SHAFT79. The program is initialized in a flexible user-oriented way. Most of the data required for a simulation are supplied from disk files, which can be either directly provided by the user, or which will be generated by SHAFT79 from data cards provided as part of the input deck. The initialization stage can generate simple regular geometric grids in one, two, or three dimensions. Also, initial conditions can be converted from the user-oriented variables temperature, pressure, and vapor saturation to the internal program variables energy and density. At the beginning of a simulation, volume-, mass-, and energy-balances and averages will be computed for the various reservoir

domains (subroutine BALLA). The program then proceeds to compute the first time step. The iterative sequence for a time step begins with computing sinks and sources (subroutine QQQ), then proceeds to flow terms, transductances (i.e., derivatives of flow terms), and accumulation terms (subroutine TRANS). Then the "residuals," i.e., the left hand sides, of equations (6) and (7) are computed for the latest iterated values of (u,ρ). Convergence ocurs if the maximum residual is less than some value specified by the user. If no convergence has been achieved yet, the linear equations for Newton/Raphson iteration, derived from equations (6) and (7), will be solved (subroutine SIMMA). All parameters are updated for the latest (u,ρ), and the next iteration is started. If anything goes wrong---failure in solving the linear equations, failure in computing thermodynamic parameters, failure to converge within a given number of iterations---the time step will be repeated with time increment cut in half.

The simulation proceeds until it terminates for one of several termination criteria (number of time steps; machine time; physical time). At the termination, a disk file called SAVE is written which allows to restart the problem in a simple way (see below).

The Input Structure

5. Data Blocks

The types of data needed to characterize a system are summarized

in Table 1. The input of SHAFT79 is organized in "blocks," each of which corresponds to one of the data groups as given in Table 1. In addition there is a data block with computation parameters. There is no special data block for boundary conditions; these have to be specified through appropriately chosen elements, interfaces, initial conditions, and sinks/sources. An overview of the most general input structure is given in Table 2. In addition to the data blocks, SHAFT79 requires an equation of state in tabular form to be provided through a disk file called TABLE.

The first data card must be the TITLE-card. The last data card must be the ENDCY-card, with ENDCY punched in columns 1-5. However, if only file processing is desired, the ENDCY-card is to be replaced by ENDFI. The data blocks between TITLE and ENDCY can be provided in arbitrary order, except that block ELEME must precede block CONNE. The blocks ELEME and CONNE must either be both provided through data cards, or both through a disk file called MESH. The block GENER will be omitted if there are no sinks or sources in the problem. If block START is present, consisting of one data card with START punched in columns 1-5, the block INCON can be incomplete, with elements in arbitrary order, or it can be absent altogether. Elements for which no initial conditions are specified in INCON will then be assigned default initial conditions as given in block PARAM, and default porosity as given in block ROCKS. If START is not present, INCON must have information for all elements, in exactly the same order as they are given in block ELEME. However, element names which have not been defined in ELEME may appear in CONNE, GENER, and INCON.

Such items will be ignored and a diagnostic will be printed.

The format for data blocks ELEME, CONNE, GENER, and INCON is the same when provided as disk files as when provided as part of the input deck. However, some convenient features are available in the latter case. A sequence of identical items can be specified on a single data card. Also, the indices needed for cross-referencing elements, interfaces, and sources will be generated by SHAFT79 rather than having them provided by the user. Usually these features will be desirable to initiate a new simulation problem.

During initialization, SHAFT79 writes the following disk files from information provided through input data blocks:

- a file MFSH, consisting of blocks ELEME and CONNE;
- a file GENER, consisting of the block GENER;
- a file INCON, consisting of the block INCON.

At the completion of a run, the results needed for a subsequent continuation of the problem are written onto a file SAVE. This file is compatible with INCON, and can be provided for a subsequent run either as a disk file, or as part of the data deck. The files MESH, GENER, INCON, and SAVE are in "normal" form; i.e., they contain one card image per item with no sequential items; the elements appear in INCON and SAVE in the same order as in MESH; and cross-referencing indices are provided for interfaces and sources.

We expect the user to initiate a problem with ELEME, CONNE, GENER, and INCON as part of the input deck, using the START-option for flexibility and convenience. Typically, the user will want to run only a

few time steps initially, examine the results and then continue on with time steps chosen so as to give an optimum compromise between accuracy and efficiency. It is recommended that the user save the files MESH and GENER, and provide them as disk files rather than as part of the input deck for restarting the problem. The file SAVE of a completed run must be provided as file INCON for a continuation run. It is also possible to merge MESH, GENER and SAVE (as INCON) into an input deck and use that for restarting. This will require somewhat more computing time for initialization.

6. SHAFT79 - Input Formats

The input data to be provided for a SHAFT79-simulation is summarized in Figure 2. The blocks ROCKS, ELEME, CONNE, GENER, and INCON can have a variable number of cards, depending upon how many items the user wishes to specify. The end of these variable-length blocks is indicated with a blank card. (For CONNE, GENER, and INCON it is possible to have, instead of the blank card, a card with "+++" punched in columns 1-3, followed by some element and source cross-referencing information in the case of CONNE and GENER, and followed by restart-information in the case of INCON; see below.)

We shall now explain the cards and variables in detail. Clarifying examples will be given in Section 8.

All input and output of SHAFT79 is in standard metric units.

TITLE is the first card of the deck, containing a header of up to 80 characters, to be printed on every page of output. This can be used to identify a problem. If no header is desired, leave this card blank.

ROCKS introduces material parameters for the various reservoir domains.

Card ROCKS.1

Format (A5, I5, 7E10.4)
MAT, NAD, DM, POR, (PER (I), I = 1,3), CM, CH

MAT material name (rock type).

NAD if zero or blank, porosity will remain constant; otherwise will read another data card with compressibility and expansivity.

DM rock density (kg/m^3).

POR default porosity (void fraction) for all elements belonging to domain "MAT" for which no other porosity has been specified in block INCON.

PER(I), I = 1,3 absolute permeabilities along the three principal axes, as specified by ISOT in block CONNE.

CM rock heat conductivity (W/m^oC).

CH rock specific heat (J/kg^oC). Domains with CH > 10^4 J/kg^oC will not be included in material balances. Flows entering or leaving domains with CH > 10^4 J/kg^oC will always be 100% upstream weighted. This provision is useful for boundary nodes, which are given very large volumes so that their T, p, S remain constant.

Card ROCKS.1.1 (optional, NAD ≠ 0 only)

Format (2E10.4)
COM, EXPAN

COM compressibility (m^2/N), $\frac{1}{\phi}\left(\frac{\partial\phi}{\partial p}\right)_T$

EXPAN expansivity ($1/^oC$), $\frac{1}{\phi}\left(\frac{\partial\phi}{\partial T}\right)_p$.

Repeat cards 1 and 1.1 for up to seven reservoir domains.

Card ROCKS.2 A blank card closes the ROCKS data block.

START (optional)

A card with START punched in columns 1-5, allows a more flexible assignment of initial conditions. As explained in Section 5, this option will usually be convenient to initiate a new simulation problem.

PARAM introduces computation parameters.

Card PARAM.1

Format (2I2, 3I4, 14I1, 5XI2, I3, 4E10.4)

NOITE, KDATA, MCYC, MSEC, MCYPR, (MOP(I), I = 1, 14), MODE, IREL, (REL(I), I = 1,4)

NOITE specifies the maximum number of iterations per time step (default value is 8).

KDATA specifies amount of printout (default = 1).

0: print only dependent variables and some parameters for each element.

1: print also fluxes.

2: print also transductances.

3: full printout.

If the above values for KDATA are increased by 10, printout will occur after each iteration (not just after convergence).

MCYC maximum number of time steps to be performed.

MSEC maximum duration, in machine seconds, of the simulation (default is infinite).

MCYPR printout will occur for every multiple of MCYPR steps (default is 1).

MOP(I), allows choice of various options
I = 1,14

MOP(1) if unequal 0, short printout for non-convergent iterations will be suppressed.

MOP(2) through MOP(6) generate additional printout in various subroutines, if set ≠ 0. The amount of printout increases with MOP(I).

MOP(2) CYCIT (main subroutine).

MOP(3) TRANS (flow- and accumulation- terms).

MOP(4) QQQ (sinks/sources).

MOP(5) GETEM (equation of state).

MOP(6) SIMMA (linear equations).

Calculational choices are as follows:

MOP(9) determines the composition of produced fluid. The relative amounts of liquid and vapor are determined:

0: according to relative mobilities in the source element.

1: source fluid has the same steam quality as the producing element.

2: only vapor is produced.

3: only liquid is produced.

MOP(11) determines evaluation of mobilities at interfaces.

0: mobilities are upstream weighted with WUP (default is WUP = 1.).

1: mobilities are spatially interpolated between adjacent elements.

MOP(13) if unequal zero, an iterative procedure will be used for a more accurate equation of state in the liquid domain.

MODE 0: equation of state table is read from binary tape.

1: equation of state table is read from formatted tape.

IREL 0: relative permeabilities are assumed to be included in equation of state table.

1: relative permeabilities are computed from Corey's equation.

2: relative permeabilities are interpolated from array REL2, specified in subroutine RELP.

3: relative permeabilities are linear functions of vapor saturation.

REL(1) residual immobile water saturation, corresponding to a steam saturation of 1-REL(1). (IREL = 1 or 3 only).

REL(2) residual immobile steam saturation. (IREL = 1 or 3 only).

REL(3) perfectly mobile steam saturation (default is 1; IREL = 3 only).

Card PARAM. 2

Format (4E10.4, A5)
TSTART, TIMAX, DELTEN, SCALE, ELST

TSTART starting time of simulation in seconds.

TIMAX time in seconds at which simulation should stop (default is infinite).

DELTEN length of time steps in seconds. If DELTEN is a negative integer, DELTEN = -NDLT, the program will proceed to read NDLT cards with time step information.

SCALE scale factor to change the size of the mesh (default = 1.0).

ELST set equal to the name of one element to obtain a short printout after each time step.

Card PARAM. 2.1, 2.2, etc.

Format (8E10.4)
(DLT(I), I = 1, 100)

DLT(I) length (in seconds) of time step I.

This set of cards is optional for DELTEN = -NDLT, a negative integer: Up to 13 cards can be read, each containing 8 time step sizes. If the number of simulated time steps exceeds the number of DLT(I), the simulation will continue with time steps equal to the last non-zero DLT(I) encountered.

Card PARAM. 3

Format (8E10.4)
RESEM, RESDM, FOR, WUP, WNR, DELE, DELD

RESEM convergence criterion for energy equations (default = 1.).

RESDM convergence criterion for density equations (default is 1.E-4).

FOR — weighting factor for time differencing (use only default value = 1., i.e., fully implicit).

WUP — upstream weighting factor for mobilities and enthalpies at interfaces (default = 1.0).

WNR — weighting factor for increments in Newton/Raphson - iteration (default = 1.0).

DELE — energy increment for computing derivatives (default = 1.E-2).

DELD — density increment for computing derivatives (default = 1.E-6).

Card PARAM.4

Format (2E10.4, 10X, E10.4)
EONE, DONE, GF

EONE — with option "START" only;
fluid specific internal energy (J/kg) to be used as initial value at any element for which no other value is specified in deck "INCON." If EONE < 1000, EONE is taken to mean temperature TX (in ^{o}C) rather than energy.

DONE — with option "START" only;
fluid density (kg/m^3) to be used as initial value at any element for which no other value is specified in deck "INCON." If EONE < 1000, meaning temperature, DONE is taken to mean pressure PX for DONE > 1 (in N/m^2, one-phase case); it is taken to mean volumetric vapor saturation SX for DONE < 1 (two-phase case).

GF — magnitude (m/sec^2) of the gravitational acceleration vector. Blank or zero gives "no gravity" calculation.

ELEME — introduces element information.

Card ELEME.1

Format (A3, I2, 2I5, A3, A2, E10.4)
EL, NE, NSEQ, NADD, MA1, MA2, VOLX

EL, NE — 5-character code name of an element. The first three characters are arbitrary, the last two characters must be numbers.

NSEQ — number of additional elements having the same volume and belonging to the same reservoir domain.

NADD increment between the code numbers of two successive elements. (Note: the maximum permissible code number NE + NSEQ * NADD is < 99.)

MA1, MA2 a five character material identifier corresponding to one of the reservoir domains as specified in block ROCKS. If the first three characters are blanks, the last two characters must be numbers and then indicate the sequence numer of the domain as entered in ROCKS.

VOLX element volume (m^3).

Repeat card ELEME.1 for up to 501 elements.

Card ELEME.2 A blank card closes the ELEME data block.

CONNE introduces information for the connections (interfaces) between elements.

Card CONNE.1

Format (A3, I2, A3, I2, 4I5, 4E10.4)
EL1, NE1, EL2, NE2, NSEQ, NAD1, NAD2, ISOT, D1, D2, AREAX, BETAX

EL1, NE1 code name of the first element.

EL2, NE2 code name of the second element.

NSEQ number of additional connections in the sequence.

NAD1 increment of the code number of the first element between two successive connections.

NAD2 increment of the code number of the second element between two successive connections.

ISOT set equal to 1, 2, or 3; specifies absolute permeability to be PER(ISOT) for the materials in elements (EL1, NE1) and (EL2, NE2), where PER is read in block ROCKS. This allows assignment of different permeabilities, e.g., in the horizontal and vertical direction.

D1, D2 distance (m) from center of first and second element, respectively, to their common interface.

AREAX interface area (m^2)

BETAX cosine of the angle between the gravitational acceleration vector and the line between the two elements. GF x BETAX > 0 (<0) corresponds to first element being above (below) the second element.

Repeat card CONNE.1 for up to 1501 connections.

Card CONNE.2 a blank card closes the CONNE data block. (For an alternative, see note at the end of Chapter 6).

GENER introduces sinks and/or sources.

Card GENER.1

Format (A3, I2, A3, I2, 4I5, 5XA4, 1X2E10.4)
EL, NE, SL, NS, NSEQ, NADD, NADS, LTAB, TYPE, GX, EX

EL,NE code name of the element containing the sink/source.

SL,NS code name of the sink/source. The first three characters are arbitrary, the last two characters must be numbers.

NSEQ number of additional sinks/source with the same injection/production rate.

NADD increment between the code numbers of two successive elements with identical sink/source.

NADS increment between the code numbers of two successive sinks/sources.

LTAB number of points in table of generation rate versus time (must not exceed 300). Set 0 or 1 for constant generation rate.

TYPE MASS - mass sink/source,
HEAT - heat sink/source.
default (blank) is HEAT.

GX constant generation rate; positive for injection, negative for production; GX is mass (kg/sec) for a MASS sink/source, and energy (J/kg) for a HEAT sink/source.

EX fixed specific enthalpy (J/kg) of the fluid for mass injection (GX>0).

Card GENER.1.1 (optional, LTAB>1 only)

Format (4E14.7)
F1(L),L = 1, LTAB

F1 generation times

Card GENER.1.2 (optional, LTAB>1 only)

Format (4E14.7)
F2(L), L=1, LTAB

F2 generation rates

Repeat cards GENER.1, 1.1, 1.2 for up to 20 sinks/ sources.

Card Gener.2 a blank card closes the GENER data block. (For an alternative, see note at the end of Chapter 6.)

INCON introduces initial conditions.

Card INCON.1

Format (A3,I2,2I5,5X2G10.4, E20.14)
EL,NE, NSEQ, NADD, EX, DX, PORX

EL,NE code name of element

NSEQ number of additional elements with same initial conditions.

NADD increment between the code numbers of two successive elements with identical initial conditions.

EX fluid internal energy (J/kg)

DX fluid density (kg/m^3)

PORX porosity (void fraction); if zero or blank, porosity will be taken as specified in block ROCKS if option START is used.

Note: (EX,DX) can be (T,p) or (T,S), as explained in connection with default initial conditions (card PARAM.4).

Card INCON.2 A blank card closes the INCON data block. (For an alternative, see note at the end of Chapter 6.)

ENDCY closes the SHAFT79 data deck and initiates the simulation.

If ENDCY is replaced by ENDFI, only file processing will occur. SHAFT79 will write the files MESH (blocks ELEME and CONNE), GENER (block GENER), and INCON (block INCON), and will then terminate.

Note on closure of blocks CONNE, GENER, and INCON.

The "ordinary" way to indicate the end of any of the above data blocks is by means of a blank card. There is an alternative available if the user makes up an input deck from the files MESH, GENER, or SAVE, which have been generated by a previous SHAFT79 run. These files are written exactly according to the specifications of data blocks ELEME and CONNE (file MESH), GENER (file GENER), and INCON (file SAVE), except that the blocks CONNE, GENER, and INCON terminate with a card with "+++" in columns 1-3, followed by some cross-referencing information. SHAFT79 will accept this type of input, and in this case there is no blank card at the end of the indicated data blocks. Providing the cross-referencing information explicitly will save some computing time during initialization.

7. Glossary of Output Variables.

We shall describe the meaning of those variables which are not self-explanatory.

TOTAL TIME	simulation time in seconds.
KCYC	total number of time steps.
ITER	iteration number for current time step.
ITERC	cummulative number of iterations for all previous time steps.
KON	convergence flag (1 - no convergence, 2 - convergence).
DDMAX	maximum density change.
DEMAX	maximum internal energy change.
RESD	maximum residual for density equations.
RESE	maximum residual for energy equations.
DELTEX	current time step in seconds.
NEXT DELTEX	next time step.
ELEM	code name of element

INDEX	internal indexing number of element.
E	specific internal energy, J/kg.
D	fluid density, kg/m^3.
DE	change in specific internal energy.
DD	change in fluid density.
DDE	rate of energy change, DE/DELTEX.
DDD	rate of density change, DD/DELTEX.
T	temperature, ^oC.
P	pressure, N/m^2.
S	vapor saturation, volume fraction.
BOIL	rate of boiling (BOIL>0) or condensation (BOIL<0), kg/m^3sec.
ELEM1	code name of first element
ELEM2	code name of second element.
INDEX	internal indexing number of connection.
FLOH	convective part of heat flow, W. (flows are positive when directed from second element of a connection into the first element)
FLOF	fluid flow, kg/sec.
FLOL	liquid flow.
FLOV	vapor flow.
CUMF	cumulative fluid flow across interface since start of run, kg.
CUMH	cumulative convective heat flow across interface since start of run,J.
ENTHALPY	specific enthalpy of fluid crossing interface, J/kg.
TRAN1-TRAN8	derivatives of mass flow (F) and heat flow (G), with respect to densities (ρ_1 ,ρ_2) and energies (u_1, u_2) of connected elements. The sequence is : $\partial F/\partial\rho_1$, $\partial F/\partial\rho_2$, $\partial F/\partial u_1$, $\partial F/\partial u_2$, $\partial G/\partial\rho_1$, $\partial G/\partial\rho_2$, $\partial G/\partial u_1$, $\partial G/\partial u_2$.
ZIPE1,2 / ZIPD1,2	cumulated derivatives for net mass flow and net energy flow with respect to energy and density.

B	liquid mobility, k_ℓ/μ_ℓ, in m^2/Nsec
VB	vapor mobility, k_v/μ_v, in m^2/Nsec
SOURCE	code name of sink/source
INDEX	internal indexing number of sink/source
GENERATION RATE	kg/sec for mass sink/source, W for heat sink/source.
ENTHALPY	specific enthalpy (J/kg) for produced or injected fluid (mass generation only).
DENSITY	density (kg/m^3) of generated fluid (mass generation only).
SATURATION	vapor saturation (volume fraction) of generated fluid (mass generation only).
DNDQ	ratio of net mass flow into element and produced mass (mass generation only). For a steady flow, DNDQ = -1.

If ELST is specified (card PARAM.2) a short printout will occur after convergence, giving the element name in ELST, followed by (KCYC, ITER). Then follow ST ≡ TOTAL TIME, and DT ≡ DELTEX.

The printout generated by BALLA (volume, mass, and energy balances) is self-explanatory. The user should be cautioned that the quantities pertaining to the liquid phase are obtained as differences between fluid and vapor. This may generate spurious non-zero numbers if no liquid is present, because of the finite number of digits provided by the computer.

A "no convergence" printout occurs as long as the maximum residuals RESD and RESE exceed the convergence criteria specified in card PARAM.3 (RESDM, RESEM).

There are a number of diagnostic printouts if any part of the computation fails. Examples for these are given in section 9, Figure 12.

Sample Problems

Table 3 gives an overview of the types of systems and processes which have been modeled with SHAFT79. As an introduction into using SHAFT79, we shall now discuss in detail input decks for three typical simulation problems.

8. Depletion of Two-Phase Reservoir; Restarting

We use this simple example to illustrate the typical file handling for restarting a problem. The reservoir is a cube with 1 km side length, divided by 9 interfaces into 10 equal sized elements. The input parameters can be read from the input deck, Figure 3. Although rock properties are constant throughout the reservoir, we have divided the system into an "UPPER" and a "LOWER" domain, to make the volume, mass, and energy balances a little more interesting. The reservoir is produced at the top at a rate of 50 kg/s. Gravity has been neglected, and all boundaries are "no flow".

The files used for running the problem are the tabular equation of state ("DIABLO, FLUTAB3") and a compiled version of the SHAFT79 program ("DIABLO, CYG").

The problem is started with just two time steps. We save the files MESH, GENER, and SAVE which are written by SHAFT79, by copying them (deleting end-of-record marks) onto BMESH, BGENER, and BSAVE, respectively, and declaring the latter files "COMMON". These files are also copied to OUTPUT, and are shown in Figures 4a-c.

File MESH as written by SHAFT79 has one card image per item (element or connection; see Figure 4a). Note that for the elements the material identifier as supplied in the input-deck ("UPPER", "LOWER") has been replaced with a number, which is the index number of the material as

given in the block ROCKS (1 for UPPER, 2 for LOWER). Block CONNE has a card with "+++" after all connections, which indicates that subsequently the cross-reference indices will follow. The elements F1, F2 etc. are internally numbered 1,2, etc.; hence connection F1/F2 corresponds to indices (1,2) etc. The cross-reference indices simply provide these internal numbers--one pair per connection--in the order of the connections. The user never needs to provide this information as input, because SHAFT79 will generate it if it is not supplied. However, the file MESH as shown in Figure 4a can be used as is as input for blocks ELEME and CONNE.

File GENER (Figure 4b) has a similar feature. The number(s) printed after the "+++" card give the internal indexing number(s) of the element(s) in which the sinks/sources reside. Note that LTAB has been changed from +1 to -1, which is the internal way of representing a MASS - sink/source in SHAFT79.

File SAVE (Figure 4c) is written according to the specifications of block INCON. The energy- and density-values are the results as computed after 2 time steps, to be used as initial conditions for restarting the problem (see below). The list of energies and densities for all elements terminates with a "+++" - card, which indiates that restart-information will follow. The next card holds the number of completed time steps (KCYC=2), the total number of iterations performed (ITERC=6), the number of reservoir domains (NM=2), the physical time at which the simulation was started (TSTART = 0.) and the physical time reached (SUMTIM = .22E7 seconds). Then follows one card per reservoir domain, containing initial values of: total fluid mass, total vapor mass, total fluid energy, total vapor energy, and total rock energy. This information is needed for computing total cumulative changes and average rates when restarting a problem.

Figure 5 gives part of the printout after 2 time steps. The header information "after (2,3)-2-DECYCLES" indicates that we are seeing the second time step, after 3 iterations, and that convergence has occured (the "2" printed between dashes is the convergence flag KON). Note that the most rapid changes occur at the producing element F1, and that changes slow down away from F1. Figure 6 shows the balances for UPPER and LOWER reservoir domains as well as for the entire reservoir; this printout should be self-explanatory. The calculation took 4.780 seconds CPU-time on the CDC7600, of which time more than 90% is spent in reading the large array with the equation of state (file TABLE).

Figure 7 shows the input deck used for restarting the problem. Note that MESH, GENER, and INCON are provided as disk files, and that the corresponding data blocks are absent from the input deck. It would have been possible, instead, to merge any or all of these files with the input deck. For large systems, with many elements, connections, and sinks/sources, the initialization through disk files rather than data cards will save a significant amount of computing time.

The restarting executes another two time steps, with results given in Figure 8.

9. Natural Hydrothermal Convection System (NHCS).

This problem involves free thermal convection in a cylindrically symmetric reservoir, as shown in Figure 9. The system includes gravity, a 78.5 MegaWatt heat source, and a constant-temperature constant-pressure boundary condition at the top. A cross section through the 2-dimensional mesh is shown in Figure 10. We have used a pocket calculator to compute the geometrical quantities (volumes, areas, distances) as given in the

input deck, Figure 11. The boundary condition at the top is realized by introducing a very large element AT0 0 (volume 10^{50} m^3). The desired (T,p) = (10^oC, 1 bar) was obtained, after some trial-and-error adjusting of ρ, for (u,ρ) = (41990.5 J/kg, 999.694 kg/m^3). Note that for liquid water, due to extremely small compressibility, small density changes will cause large pressure changes. Hence inputting (T,p) = (10^oC, 1 bar) will, after conversion to (u,ρ) and subsequent interpolation in the equation of state table, yield a somewhat different pressure. The option MOP(13) $\neq$ 0 is available to execute an iterative procedure for obtaining exactly the desired (T,p). As this option slows all computations down considerably, however, we prefer adjusting the last digit in ρ "by hand" to obtain the desired pressure.

For the caprock and main reservoir elements, initial (T,p) is chosen to approximately reflect hydrostatic pressure and natural thermal gradient. The main reservoir initial conditions, corresponding to an average depth of 1400 meters, are assigned by default using option START. We did not bother to start out with a vertical pressure profile, as gravitational pressure equilibration occurs rapidly in a liquid water system.

The upper boundary domain, called ATMOS, is given a specific heat of 10^4 J/kg ^oC. This is used as a flag by SHAFT79 to exclude ATMOS from balances for the reservoir. Inclusion of ATMOS with its huge mass and energy content would make these balances meaningless.

The input deck is set up to execute 2 time steps, which were deliberately chosen as a large $\Delta t = 10^{10}$ sec $\hat{=}$ 317 years. Initially the system is far from steady state, and SHAFT79 cannot handle such large Δt. Figure 12 illustrates the kind of messages that are being printed

as SHAFT79 keeps cutting the time step in half, until all parameters remain within the range provided by the equation of state table, and until convergence can be obtained within the allowable number of iterations (default NOITE = 8). For $\Delta t = 10 \times 10^9$ sec, 5×10^9 sec, 2.5×10^9 sec the first iteration gives rise to (u,ρ) which are outside the tabulated range. Thus, subroutine "GETEM cannot find parameters", and time steps are halved. At $\Delta t = 1.25 \times 10^9$ sec all iterations can be executed. The calculation appears to be on its way towards convergence, when on the 9th iteration the time step gets halved again. Messages indicating pivot failure are for informal purposes only; SHAFT79 automatically executes a new decomposition of the matrix in the linear equations (subroutine SIMMA), and continues the iteration process. Pivot failures occur when some terms in the matrix change their relative magnitude such that the algorithm would lose a certain number of significant digits. For $\Delta t = .625 \times 10^9$ sec convergence occurs after six iterations. Part of the output is shown in Figure 13. Not much has happened yet, with the most significant change being the temprature increase in element R5.

We would like to point out that a prudent choice of time steps is required for an economical calculation. Small time steps will require many time steps and iterations to be executed for a desired span of physical time. However, if time steps are chosen too large, much computational work will be spent cutting them down to a size where convergence can be obtained. A "good" choice of time steps will allow SHAFT79 to converge for the desired time steps in most cases.

Another point worth mentioning is that, as we ran the "natural hydrothermal convection system" further out in time, we found it advantageous to

reduce the increments DELE, DELD (card PARAM.3) somewhat below their default values of 10^{-2} and 10^{-6}, respectively. The reason for this is that, in a free convection system, flow directions can reverse. This will give rise to inaccurate derivatives if the increments DELE, DELD average over a reversal of flow.

10. Garg's Problem (Radial Flow).

Our final example involves production from the center of a large flat cylinder. The problem has been previously studied by Garg, and detailed specifications are given in his paper (Garg, 78). The reservoir is initially filled with liquid water of (T,p) = (300°C, 90 bars), and a boiling front moves out into the reservoir as production proceeds. The input deck, Figure 14, models a 5.625° - sector of the reservoir, the thickness of which was arbitrarily set at 100 meters. SHAFT79 executes seven time steps, which were chosen to allow an efficient calculation. Except for time step KCYC = 5, which is cut in half, all time steps are executed successfully. Results after seven time steps, corresponding to a total time of 16,500 seconds, are shown in Figure 15. Five elements have made phase transition, and the most rapid boiling occurs in the well element, F0. The entire calculation takes 6.9 seconds CPU - time on the CDC 7600, of which 4.5 seconds are spent in reading the equation of state - table. Our results agree well with those published by Garg.

11. References

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Garg, S. K., 1978, Pressure transient analysis for two-phase (liquid water/steam) geothermal reservoirs, paper SPE-7479, presented at the 53rd Annual Fall Technical Conference and Exhibition of the SPE, Houston, Texas, 1978.

Pruess, K., Schroeder, R. C., Witherspoon, P. A., and Zerzan, J. M., 1979a, SHAFT78, a two-phase multidimensional computer program for geothermal reservoir simulation: Lawrence Berkeley Laboratory Report LBL-8264.

Pruess, K., Zerzan, J. M., Schroeder, R. C., and Witherspoon, P. A., 1979b, Description of the three-dimensional two-phase simulator SHAFT78 for use in geothermal reservoir studies: paper SPE-7699, presented at the Fifth Symposium on Reservoir Simulation, Denver, Colorado, 1979.

Pruess, K., Bodvarsson, G., Schroeder, R. C., Witherspoon, P. A., Marconcini, R., Neri, G., and Ruffilli, C., 1979c, Simulation of the depletion of two-phase geothermal reservoirs: paper SPE-8266, presented at the 54th Annual Fall Technical Conference and Exhibitiion of the SPE, Las Vegas, Nevada, 1979.

Pruess, K. and Schroeder, R. C., 1979, Geothermal reservoir simulation with SHAFT79, LBL-10066, paper presented at the 5th Geothermal Reservoir Engineering Workshop, Stanford, California, 1979.

TABLE 1: DATA GROUPS FOR A SIMULATION PROBLEM

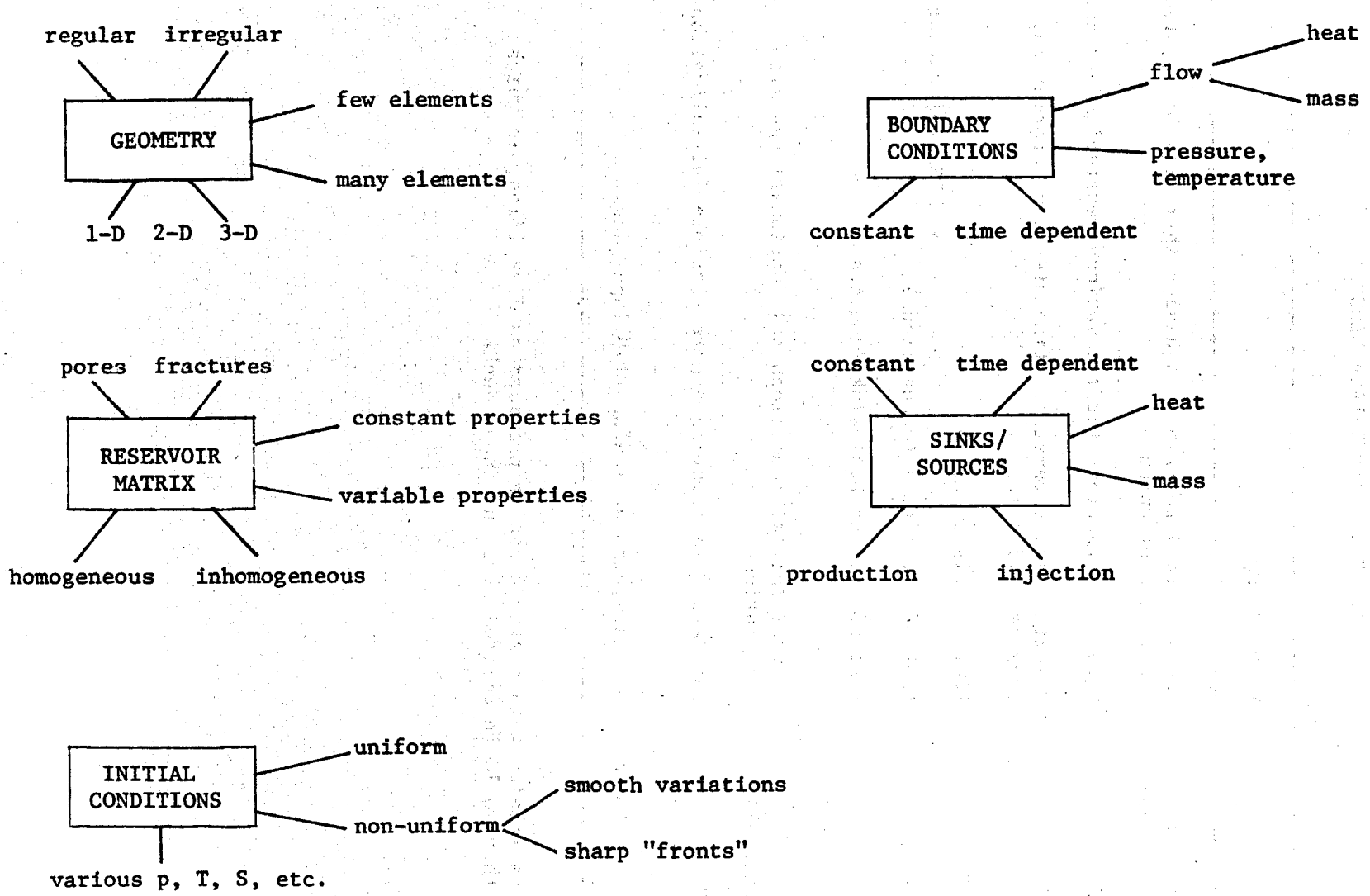

TABLE 2. INPUT DATA BLOCKS[1]

BLOCK	DESCRIPTION	
TITLE (first card)	One data card containing a header that will be printed on every page of output.	
ROCKS	Material parameters for the various reservoir domains.	
PARAM	Computational parameters (time stepping information, program options).	
*ELEME	List of grid elements	MESH - information
*CONNE	List of interfaces (connections)	MESH - information
*GENER (optional)	List of mass or heat sinks/sources	
*INCON (optional)	List of initial conditions and (optional) restart-information.	
START (optional)	One data card allowing a more flexible initialization.	
ENDCY (last card)	One card closing the SHAFT79 input deck.	

[1]Blocks labeled with a star * can be provided as disk files, in which case they would be omitted from the input deck.

TABLE 3: SIMULATION STUDIES WITH SHAFT79.

GEOMETRY	TYPE OF PROBLEM	SIMULATED PROCESSES
1-D, rectangular	depletion of two-phase geothermal reservoirs	various production and injection schemes for reservoirs with uniform initial conditions or with sharp steam/water interfaces.
1-D, cylindrical	two-phase flow near wells	production from two-phase zones; cold water injection into two-phase and superheated steam zones, respectively.
2-D, rectangular	Krafla geothermal reservoir (Iceland)	different space and time patterns of production and injection.
2-D, cylindrical	high level nuclear waste repository	long-term evolution of temperatures and pressures near a powerful heat source (in progress).
3-D, regular	two-phase interference test in Cerro Prieto (Mexico)	(in progress)
3-D, irregular	Serrazzano geothermal reservoir (Italy)	detailed field production from 1960 to 1972.

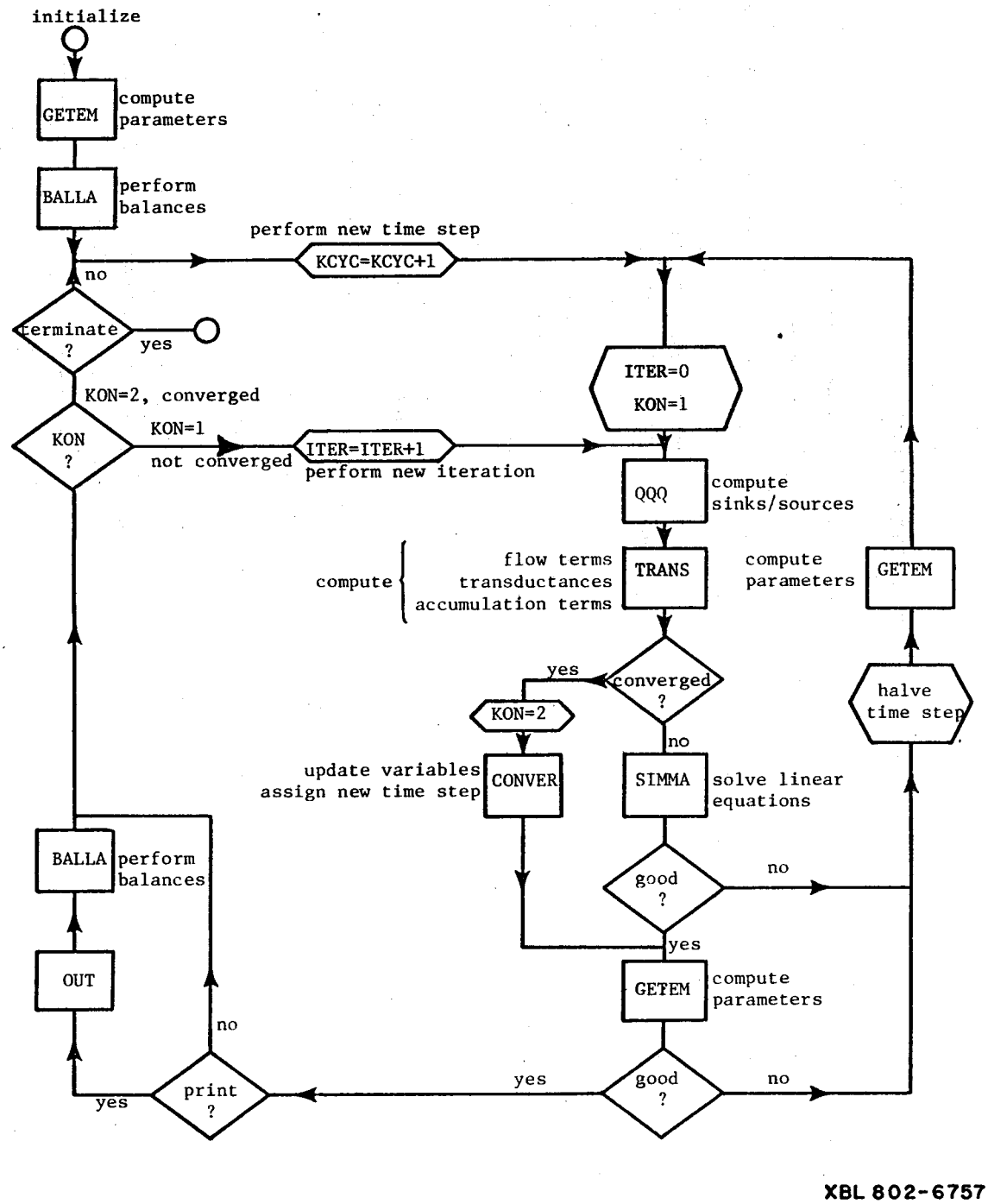

Figure 1. Flow Chart of SHAFT79.

SHAFT 79 - INPUT

Cols. 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80

TITLE

ROCKS

MAT	NAD	DM	POR	PER(1)	PER(2)	PER(3)	CM	CH
COM		EXPAN						

START (optional)

Cols. 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80

PARAM

NOTE / MDATA	MCYC	MSEC	MCYPR	MOP(I), I = 1,14		MXE	IREL	REL(1)	REL(2)	REL(3)	REL(4)
TSTART	TIMAX	DELTEN or -NDLT	SCALE	ELST							
DLT(1)	DLT(2)	DLT(3)	DLT(4)								
									DLT(M) (M≤8×NDLT)		
RESEM	RESDM	FOR	WUP	WNR	DELE	DELD					
EONE	DONE		GF								

Cols. 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80

ELEME

EL	NE	NSEQ	NADD	MA1	MA2	VOLX

CONNE

EL1	NE1	EL2	NE2	NSEQ	NAD1	NAD2	ISOT	D1	D2	AREAX	BETAX

Cols. 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80

GENER

EL	NE	SL	NS	NSEQ	NADD	NADS	LTAB		TYPE	GX	EX
F1(1)		F1(2)		F1(J), J = 1,LTAB							
F2(1)		F2(2)		F2(J), J = 1,LTAB							

Cols. 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80

INCON

EL	NE	NSEQ	NADD		EX	DX	PORX

ENDCY or ENDFI

XBL 803-8964

Figure 2. SHAFT79 Input Formats.

```
BRI2,7,63,30000.467301,PRUESS
*INPUT 6600B 17.29.06  20 MAR 80  VIA KPC0000
*HOLDOUT
FETCHGS,TABLE=PSSBACKUP/DIABLO/FLUTAB3,12605.
FETCHGS,LGO=PSSBACKUP/DIABLO/CYG,12605.
REWIND,LGO.
SFL,170000.
LINK,X,PP=[PL=999999].
COPY,MESH/RB,ORXR,BMESH.
COPY,GENER/RB,ORXR,BGENER.
COPY,SAVE/RB,ORXR,BSAVE.
COMMON,BMESH.
COMMON,BGENER.
COMMON,BSAVE.
COPYSBF,BMESH,OUTPUT.
COPYSBF,BGENER,OUTPUT.
COPYSBF,BSAVE,OUTPUT.
EXIT.
DUMP,0.
FIN.
REWIND,INPUT.
COPYSBF,INPUT,OUTPUT.
```

```
***   TWO-PHASE RESERVOIR DEPLETION   ***   NO GRAVITY   ***
ROCKS
UPPER     2000.     .10          1.E-13                    0.0        1232.
LOWER     2000.     .10          1.E-13                    0.0        1232.

PARAM
 0 1   2 600   100000000000000     1  1 .7
                   -1.                  F   1
       .2E6      .2E7      .2E8

START
ELEMENT INFORMATION
F   1    4    1UPPER     1.0E8
F   6    4    1LOWER     1.0E8

CONNE
F   1F   2    8    1    1    1   50.00    50.00    1000000. 0.

GENER
F   1C01      0    0    0    1    MASS    -  50.0

INCON
F   1    9    1         252.    .5

ENDCYCLES
```

Figure 3. SHAFT79 Input Deck for Two-Phase Reservoir Depletion Problem.

(a) File MESH.

```
ELEME
F   1                1 .1000E+09
F   2                1 .1000E+09
F   3                1 .1000E+09
F   4                1 .1000E+09
F   5                1 .1000E+09
F   6                2 .1000E+09
F   7                2 .1000E+09
F   8                2 .1000E+09
F   9                2 .1000E+09
F  10                2 .1000E+09

CONNE
F   1F   2                     1 .5000E+02 .5000E+02 .1000E+070.
F   2F   3                     1 .5000E+02 .5000E+02 .1000E+070.
F   3F   4                     1 .5000E+02 .5000E+02 .1000E+070.
F   4F   5                     1 .5000E+02 .5000E+02 .1000E+070.
F   5F   6                     1 .5000E+02 .5000E+02 .1000E+070.
F   6F   7                     1 .5000E+02 .5000E+02 .1000E+070.
F   7F   8                     1 .5000E+02 .5000E+02 .1000E+070.
F   8F   9                     1 .5000E+02 .5000E+02 .1000E+070.
F   9F  10                     1 .5000E+02 .5000E+02 .1000E+070.
+++
   1  2  2  3  3  4  4  5  5  6  6  7  7  8  8  9  9  10
```

(b) File GENER.

```
GENER
F   1COI 0                    -1     MASS  -50.00000      -0.
+++
   1
```

(c) File SAVE.

```
INCON  -- INITIAL CONDITIONS FOR   10 ELEMENTS AT TIME    .220000E+07
F   1                1127452.95 401.96747 .10000000000000E+00
F   2                1128142.92 405.76768 .10000000000000E+00
F   3                1128428.20 407.34510 .10000000000000E+00
F   4                1128545.05 407.99223 .10000000000000E+00
F   5                1128592.84 408.25710 .10000000000000E+00
F   6                1128612.39 408.36545 .10000000000000E+00
F   7                1128620.38 408.40975 .10000000000000E+00
F   8                1128623.64 408.42781 .10000000000000E+00
F   9                1128624.94 408.43502 .10000000000000E+00
F  10                1128625.39 408.43755 .10000000000000E+00
+++
   2    6    2-.0                .220000000E+07
 .204220258E+11 .517387978E+09 .230488279E+17 .134569580E+16 .279382736E+18
 .204220258E+11 .517387978E+09 .230488279E+17 .134569580E+16 .279382736E+18
```

Figure 4. Files MESH (a), GENER (b), and SAVE (c) for Two-Phase Reservoir Depletion Problem.

*** TWO-PHASE RESERVOIR DEPLETION *** NO GRAVITY ***

OUTPUT DATA AFTER (2, 3)-2-DECYCLES

TOTAL TIME	KCYC	ITER	ITERC	KON	DDMAX	DEMAX	RESD	RESE	DELTEX	NEXT DELT
.220000E+07	2	3	6	2	.556882E+01	.100978E+04	.245534E-07	.804149E-01	.200000E+07	.200000E+08

ELEM.		INDEX	E	D	DE	DD	DDE	DDD	T	P	S	BOIL
F	1	1	.112745E+07	.401967E+03	-.100978E+04	-.556882E+01	-.504891E-03	-.278441E-05	.251502E+03	.408235E+07	.508642E+00	.282451E-06
F	2	2	.112814E+07	.405768E+03	-.467391E+03	-.258624E+01	-.233695E-03	-.129312E-05	.251776E+03	.410123E+07	.503551E+00	.131211E-06
F	3	3	.112843E+07	.407345E+03	-.196229E+03	-.108712E+01	-.981144E-04	-.543559E-06	.251890E+03	.410907E+07	.501437E+00	.551605E-07
F	4	4	.112855E+07	.407992E+03	-.807353E+02	-.447491E+00	-.403676E-04	-.223746E-06	.251936E+03	.411229E+07	.500570E+00	.227069E-07
F	5	5	.112859E+07	.408257E+03	-.330724E+02	-.183346E+00	-.165362E-04	-.916728E-07	.251955E+03	.411361E+07	.500215E+00	.930361E-08
F	6	6	.112861E+07	.408365E+03	-.135381E+02	-.750583E-01	-.676907E-05	-.375291E-07	.251963E+03	.411414E+07	.500069E+00	.380876E-08
F	7	7	.112862E+07	.408410E+03	-.554820E+01	-.307614E-01	-.277410E-05	-.153807E-07	.251966E+03	.411436E+07	.500010E+00	.156096E-08
F	8	8	.112862E+07	.408428E+03	-.229171E+01	-.127063E-01	-.114586E-05	-.635315E-08	.251968E+03	.411445E+07	.499986E+00	.644772E-09
F	9	9	.112862E+07	.408435E+03	-.990537E+00	-.549202E-02	-.495268E-06	-.274601E-08	.251968E+03	.411449E+07	.499976E+00	.278689E-09
F	10	10	.112863E+07	.408438E+03	-.534499E+00	-.296353E-02	-.267250E-06	-.148177E-08	.251968E+03	.411450E+07	.499973E+00	.150382E-09

*** TWO-PHASE RESERVOIR DEPLETION *** NO GRAVITY ***

KCYC = 2 - ITER = 3 - TIME = .22000E+07

ELEM1		ELEM2		INDEX	FLOH	FLOF	FLOL	FLOV	CUMF	CUMH	ENTHALPY
F	1	F	2	1	.620322E+08	.221559E+02	0.	.221559E+02	.452695E+08	.126746E+15	.279980E+07
F	2	F	3	2	.258269E+08	.922468E+01	0.	.922468E+01	.185411E+08	.519108E+14	.279977E+07
F	3	F	4	3	.106085E+08	.378909E+01	0.	.378909E+01	.758698E+07	.212416E+14	.279975E+07
F	4	F	5	4	.434418E+07	.155164E+01	0.	.155164E+01	.310411E+07	.869073E+13	.279975E+07
F	5	F	6	5	.177758E+07	.634908E+00	0.	.634908E+00	.126990E+07	.355538E+13	.279974E+07
F	6	F	7	6	.726859E+06	.259616E+00	0.	.259616E+00	.519240E+06	.145374E+13	.279974E+07
F	7	F	8	7	.296239E+06	.105809E+00	0.	.105809E+00	.211619E+06	.592479E+12	.279974E+07
F	8	F	9	8	.118367E+06	.422778E-01	0.	.422778E-01	.845556E+05	.236734E+12	.279974E+07
F	9	F	10	9	.414856E+05	.148177E-01	0.	.148177E-01	.296353E+05	.829713E+11	.279974E+07

*** TWO-PHASE RESERVOIR DEPLETION *** NO GRAVITY ***

KCYC = 2 - ITER = 3 - TIME = .22000E+07

ELEMENT		SOURCE	INDEX	GENERATION RATE	ENTHALPY	DENSITY	SATURATION	DNDQ
F	1	COI 0	1	-.500000E+02	.279990E+07	.205298E+02	.100000E+01	-.443118E+00

Figure 5. Output after two Time Steps for Two-Phase Reservoir Depletion Problem.

*** TWO-PHASE RESERVOIR DEPLETION *** NO GRAVITY ***

VOLUME, MASS, AND ENERGY BALANCES - - - - - VOLUME AND MASS AVERAGES

ELAPSED TIME SINCE START OF SIMULATION = .220000E+07 SEC = .697615E-01 YEARS
SINCE START OF RUN = .220000E+07 SEC, SINCE LAST PRINT-OUT = .200000E+07 SEC

- - - - - VOLUME AND MASS IN PLACE - - - - -

DOMAIN	FLUID VOLUME	LIQUID VOLUME	VAPOR SATURATION	FLUID MASS	LIQUID MASS	VAPOR MASS
UPPER	.500000E+08	.248559E+08	.502883E+00	.203133E+11	.197943E+11	.518984E+09
LOWER	.500000E+08	.249999E+08	.500003E+00	.204208E+11	.199033E+11	.517407E+09
RESERVOIR	.100000E+09	.498557E+08	.501443E+00	.407341E+11	.396977E+11	.103639E+10

- - - - - MASS LOSS - - - - -

DOMAIN	MARGINAL	MARGINAL RATE	CUMULATIVE	AVERAGE RATE	FRACTION
UPPER	.987302E+08	.493651E+02	.108730E+09	.494228E+02	.532416E-02
LOWER	.126982E+07	.634908E+00	.126990E+07	.577226E+00	.621827E-04
RESERVOIR	.100000E+09	.500000E+02	.110000E+09	.500000E+02	.269317E-02

- - - - - ENERGY IN PLACE - - - - -

DOMAIN	FLUID	LIQUID	VAPOR	SOLID	MIXTURE
UPPER	.229182E+17	.215683E+17	.134986E+16	.279209E+18	.302127E+18
LOWER	.230473E+17	.217016E+17	.134575E+16	.279381E+18	.302428E+18
RESERVOIR	.459655E+17	.432699E+17	.269561E+16	.558590E+18	.604555E+18

- - - - - MARGINAL ENERGY LOSS - - - - -

DOMAIN	FLUID	LIQUID	VAPOR	SOLID	MIXTURE	RATE
UPPER	.118639E+15	.122421E+15	-.378160E+13	.157795E+15	.276434E+15	.138217E+09
LOWER	.152668E+13	.157592E+13	-.492394E+11	.202848E+13	.355516E+13	.177758E+07
RESERVOIR	.120166E+15	.123997E+15	-.383084E+13	.159824E+15	.279990E+15	.139995E+09

- - - - - CUMULATIVE ENERGY LOSS - - - - -

DOMAIN	FLUID	LIQUID	VAPOR	SOLID	MIXTURE	RATE
UPPER	.130661E+15	.134830E+15	-.416863E+13	.173771E+15	.304432E+15	.138378E+09
LOWER	.152678E+13	.157602E+13	-.492425E+11	.202861E+13	.355539E+13	.161609E+07
RESERVOIR	.132188E+15	.136406E+15	-.421787E+13	.175799E+15	.307987E+15	.139994E+09

- - - - - VOLUME AVERAGES - - - - -

DOMAIN	LIQUID TEMPERATURE	VAPOR TEMPERATURE	LIQUID PRESSURE	VAPOR PRESSURE	FLUID DENSITY	VAPOR DENSITY
UPPER	.251813E+03	.251811E+03	.410378E+07	.410364E+07	.406266E+03	.206403E+02
LOWER	.251967E+03	.251967E+03	.411439E+07	.411439E+07	.408415E+03	.206962E+02
RESERVOIR	.251890E+03	.251889E+03	.410910E+07	.410900E+07	.407341E+03	.206682E+02

Figure 6. Balances and Averages for Two-Phase Reservoir Depletion Problem.

```
BRI2,7,63,30000,467301,PRUESS
*INPUT 6600B 17.36.18  20 MAR 80  VIA KP00000
*HOLDOUT
FETCHGS,TABLE=PSSBACKUP/DIABLO/FLUTAB3,12605.
FETCHGS,LGO=PSSBACKUP/DIABLO/CYG,12605.
REWIND,LGO.
SFL,170000.
COMMON,BMESH.
COMMON,BGENER.
COMMON,BSAVE.
COPY,BMESH/RB,MESH.
COPY,BGENER/RB,GENER.
COPY,BSAVE/RB,INCON.
LINK,X,PP=[PL=999999].
EXIT.
DUMP,0.
FIN.
REWIND,INPUT.
COPYSBF,INPUT,OUTPUT.
```

```
***   TWO-PHASE RESERVOIR DEPLETION   ***   NO GRAVITY   ***
ROCKS
UPPER     2000.     .10          1.E-13                    0.0        1232.
LOWER     2000.     .10          1.E-13                    0.0        1232.

PARAM
 0 1   2 600   100000000000000      1  1 .7
                          .2E8        F   1

ENDCY
```

Figure 7. SHAFT79 Input Deck for restarting Two-Phase Reservoir Depletion Problem.

```
***   TWO-PHASE RESERVOIR DEPLETION   ***   NO GRAVITY   ***

OUTPUT DATA AFTER (   4,   4)-2-DECYCLES
==================================================================================================================

TOTAL TIME   KCYC   ITER   ITERC   KON    DDMAX        DEMAX        RESD         RESE         DELTEX       NEXT DELT
.422000E+08    4      4      14     2   .148121E+02  .237015E+04  .674476E-09  .186372E-02  .200000E+08  .200000E+08

==================================================================================================================

ELEM.  INDEX    E            D            DE           DD           DDE          DDD          T            P            S            BOIL

F   1    1  .112115E+07 .365582E+03-.230675E+04-.148121E+02-.115337E-03-.740605E-06 .248860E+03 .390348E+07 .557089E+00 .749762E-07
F   2    2  .112238E+07 .373453E+03-.237015E+04-.138146E+02-.118507E-03-.690732E-06 .249436E+03 .394122E+07 .546680E+00 .699019E-07
F   3    3  .112337E+07 .379892E+03-.234237E+04-.125926E+02-.117119E-03-.629629E-06 .249906E+03 .397258E+07 .538155E+00 .637123E-07
F   4    4  .112434E+07 .385053E+03-.209776E+04-.113353E+02-.104888E-03-.566763E-06 .250280E+03 .399825E+07 .531265E+00 .574190E-07
F   5    5  .112511E+07 .389196E+03-.185589E+04-.100803E+02-.927947E-04-.504016E-06 .250580E+03 .401885E+07 .525730E+00 .510781E-07
F   6    6  .112571E+07 .392445E+03-.163911E+04-.893803E+01-.819556E-04-.446902E-06 .250815E+03 .403501E+07 .521386E+00 .453011E-07
F   7    7  .112616E+07 .394909E+03-.145858E+04-.797685E+01-.729288E-04-.398842E-06 .250993E+03 .404726E+07 .518090E+00 .404370E-07
F   8    8  .112649E+07 .396678E+03-.132028E+04-.723540E+01-.660139E-04-.361770E-06 .251120E+03 .405605E+07 .515723E+00 .366833E-07
F   9    9  .112670E+07 .397819E+03-.122712E+04-.673371E+01-.613561E-04-.336686E-06 .251203E+03 .406173E+07 .514196E+00 .341427E-07
F  10   10  .112680E+07 .398378E+03-.118034E+04-.648110E+01-.590171E-04-.324055E-06 .251243E+03 .406451E+07 .513448E+00 .328632E-07

==================================================================================================================

***   TWO-PHASE RESERVOIR DEPLETION   ***   NO GRAVITY   ***

                                                                                KCYC =   4  -  ITER =   4  -  TIME =  .42200E+08

ELEM1  ELEM2  INDEX   FLOM         FLOF         FLOL         FLOV         CUMF         CUMH         ENTHALPY

F   1  F   2    1   .119287E+09  .425939E+02 0.            .425939E+02  .163614E+10  .458186E+16  .280055E+07
F   2  F   3    2   .999377E+08  .356866E+02 0.            .356866E+02  .131300E+10  .367677E+16  .280042E+07
F   3  F   4    3   .823018E+08  .293903E+02 0.            .293903E+02  .103847E+10  .290790E+16  .280030E+07
F   4  F   5    4   .664284E+08  .237227E+02 0.            .237227E+02  .809077E+09  .226550E+16  .280020E+07
F   5  F   6    5   .523134E+08  .186826E+02 0.            .186826E+02  .618464E+09  .173172E+16  .280012E+07
F   6  F   7    6   .397988E+08  .142135E+02 0.            .142135E+02  .459259E+09  .128592E+16  .280006E+07
F   7  F   8    7   .286305E+08  .102251E+02 0.            .102251E+02  .324254E+09  .907897E+15  .280002E+07
F   8  F   9    8   .185007E+08  .660741E+01 0.            .660741E+01  .206755E+09  .578900E+15  .279999E+07
F   9  F  10    9   .907348E+07  .324055E+01 0.            .324055E+01  .100594E+09  .281657E+15  .279998E+07

==================================================================================================================

***   TWO-PHASE RESERVOIR DEPLETION   ***   NO GRAVITY   ***

                                                                                KCYC =   4  -  ITER =   4  -  TIME =  .42200E+08

ELEMENT SOURCE INDEX      GENERATION RATE     ENTHALPY     DENSITY     SATURATION     DNDQ

 F   1   COI 0    1          -.500000E+02    .280069E+07  .196041E+02  .100000E+01 -.851879E+00

==================================================================================================================
```

Figure 8. Output after four Time Steps for restarted Two-Phase Reservoir Depletion Problem.

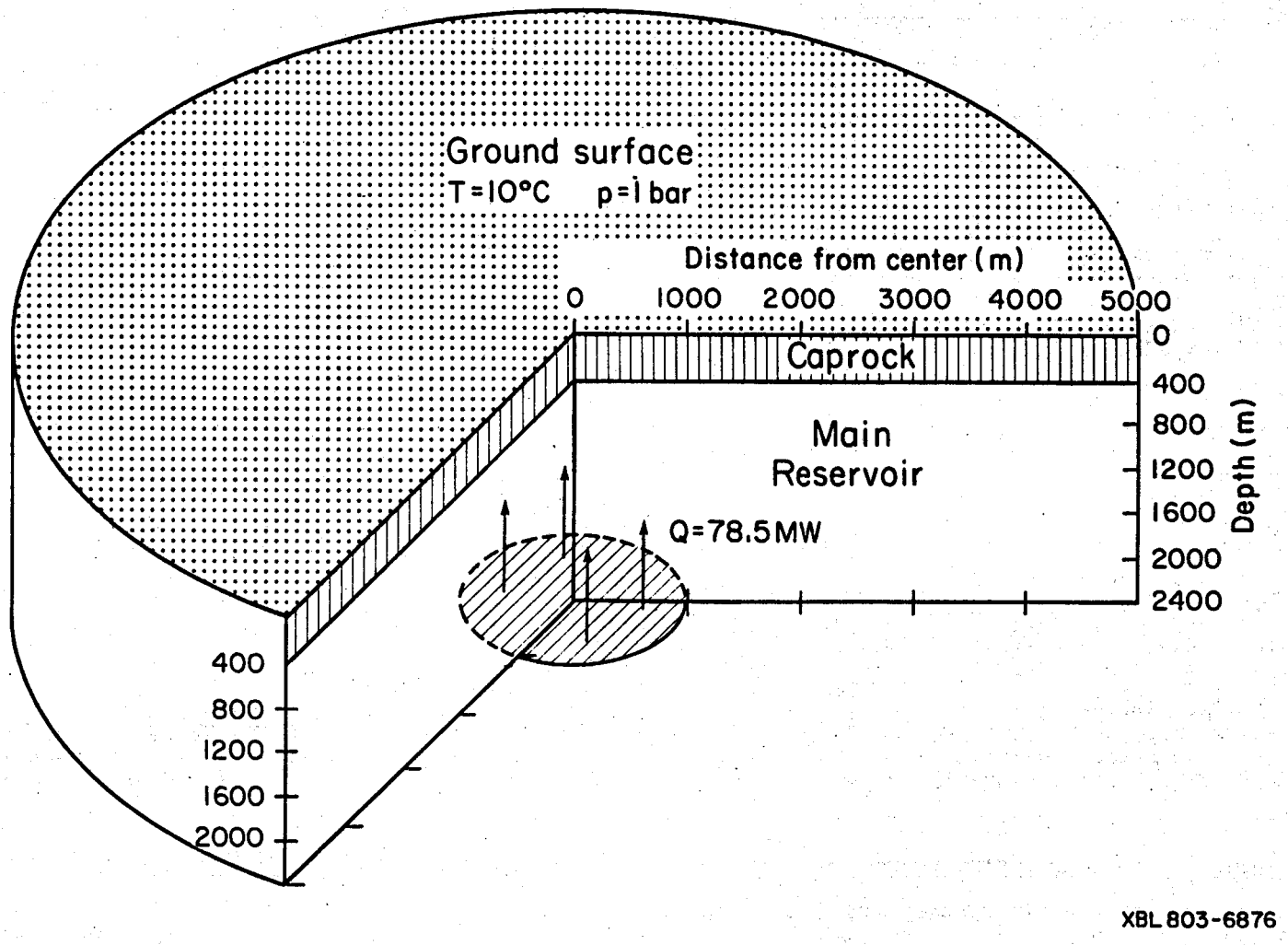

Figure 9. Natural Hydrothermal Convection System (NHCS).

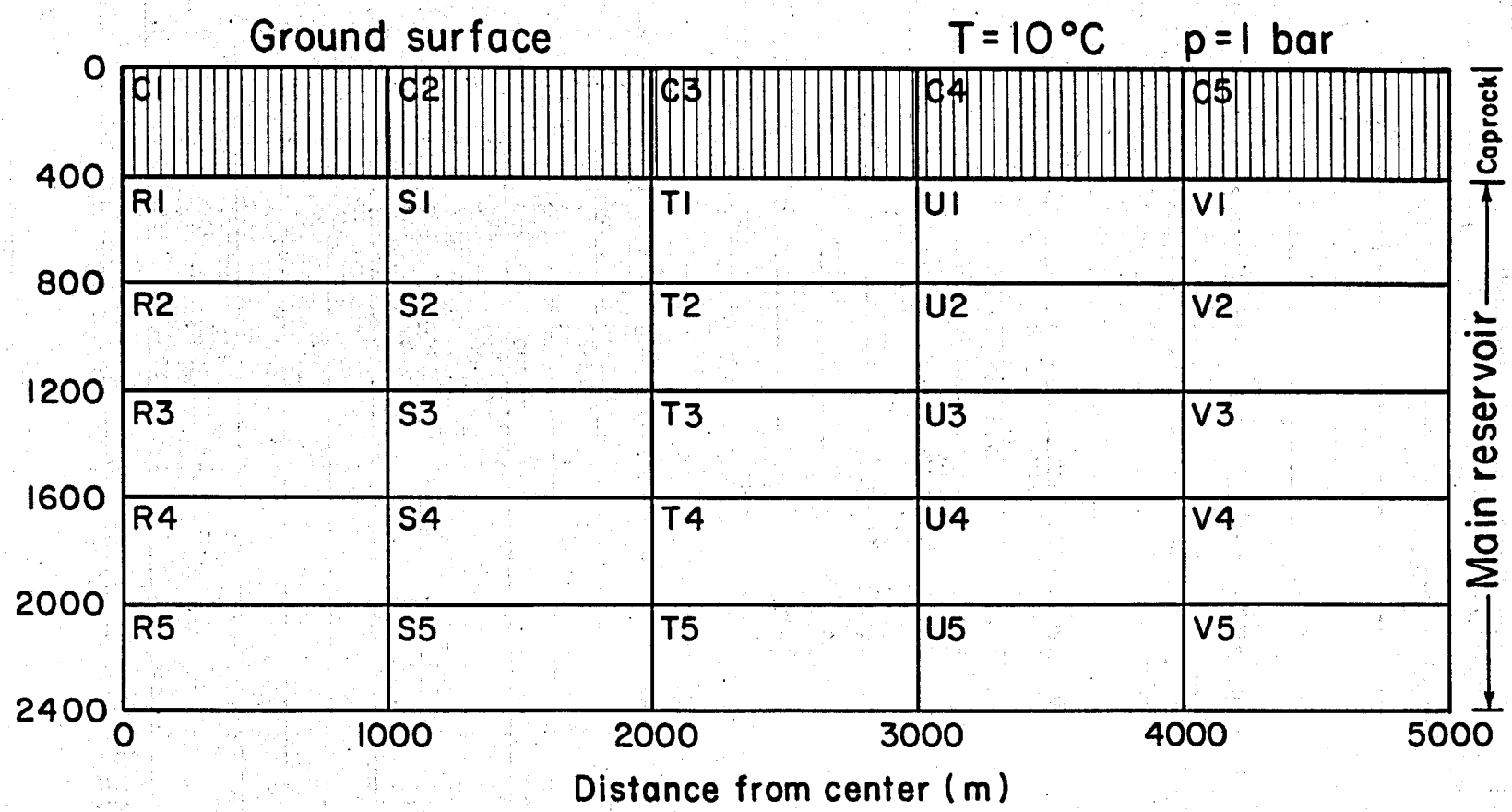

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Figure 10. Vertical Cross Section of NHCS. The center line is on the left, and the space discretization with element names is shown.

```
NHCS,7,63,30000,467301,PRUESS
*INPUT 6600B 10.49.14  24 MAR 80  VIA KP00002
*HOLDOUT
FETCHGS,TABLE=PSSBACKUP/DIABLO/FLUTAB3,12605.
FETCHGS,LGO=PSSBACKUP/DIABLO/CYG,12605.
REWIND,LGO.
SFL,170000.
LINK,X,L=0,PP=(PL=999999).
EXIT.
DUMP,0.
FIN.
REWIND,INPUT.
COPYSBF,INPUT,OUTPUT.

##### NATURAL HYDROTHERMAL CONVECTION SYSTEM #####     5 KM RADIUS     #####
ROCKS
ATMOS     2600.     .10          1.E-13    1.E-13    1.E-13 2.1          1.E4
CAPRO     2600.     .10          1.E-15    1.E-15    1.E-15 2.1     775.
RESER     2600.     .10          1.E-13    1.E-13    1.E-13 2.1     775.

START
PARAM
   1   2 600   100000000000000      1  1 .5
                          10.E9          R   5

55.            140.E5          9.80665
ELEMENT INFORMATION
AT000          ATMOS     1.E50
C   1          CAPRO   1.257E9
C   2          CAPRO   3.770E9
C   3          CAPRO   6.283E9
C   4          CAPRO   8.796E9
C   5          CAPRO   11.31E9
R   1    4    1RESER   1.257E9
S   1    4    1RESER   3.770E9
T   1    4    1RESER   6.283E9
U   1    4    1RESER   8.796E9
V   1    4    1RESER   11.31E9

CONNECTIONS
AT000C   1                    3    1.E-20      200.    3.142E6 1.
AT000C   2                    3    1.E-20      200.    9.425E6 1.
AT000C   3                    3    1.E-20      200.    15.71E6 1.
AT000C   4                    3    1.E-20      200.    21.99E6 1.
AT000C   5                    3    1.E-20      200.    28.27E6 1.
C   1R   1                    3      200.      200.    3.142E6 1.
C   2S   1                    3      200.      200.    9.425E6 1.
C   3T   1                    3      200.      200.    15.71E6 1.
C   4U   1                    3      200.      200.    21.99E6 1.
C   5V   1                    3      200.      200.    28.27E6 1.
R   1R   2    3    1    1     3      200.      200.    3.142E6 1.
S   1S   2    3    1    1     3      200.      200.    9.425E6 1.
T   1T   2    3    1    1     3      200.      200.    15.71E6 1.
U   1U   2    3    1    1     3      200.      200.    21.99E6 1.
V   1V   2    3    1    1     3      200.      200.    28.27E6 1.
C   1C   2                    1      500.      500.    2.513E6 0.
C   2C   3                    1      500.      500.    5.027E6 0.
C   3C   4                    1      500.      500.    7.540E6 0.
C   4C   5                    1      500.      500.    10.05E6 0.
R   1S   1    4    1    1     1      500.      500.    2.513E6 0.
S   1T   1    4    1    1     1      500.      500.    5.027E6 0.
T   1U   1    4    1    1     1      500.      500.    7.540E6 0.
U   1V   1    4    1    1     1      500.      500.    10.05E6 0.

GENERATION
R   5MAG                      1      HEAT     78.5E6

INCON
AT000                   .419905E5 999.694
C   1    4    1     15.            21.E5

ENDCY
```

Figure 11. SHAFT79 Input Deck for NHCS.

```
NO CONVERGENCE AT (   2,  1) --- DELTEX =  .100000E+11   RESD =  .131138E+02   RESE =  .602325E+09  ++++++++++++++++++++++++++++++
///// GETEM CANNOT FIND PARAMETERS ////////////////////  HALVE TIME STEP /////
GETIT AT R   4  E = .558283E+06  D = .953086E+03  NELOK = 17  NDLOK = 82  ISKIP = 4  ISK(I) = 1 1 1 1  IPH = 1  ISAT = 0
++++++++++ HALVE TIME STEP AT (   2,  1) +++++++++++++++   NEW DELT =  .500000E+10
NO CONVERGENCE AT (   2,  1) --- DELTEX =  .500000E+10   RESD =  .655692E+01   RESE =  .301162E+09  ++++++++++++++++++++++++++++++
///// GETEM CANNOT FIND PARAMETERS ////////////////////  HALVE TIME STEP /////
GETIT AT R   5  E = .824959E+06  D = .903534E+03  NELOK = 29  NDLOK = 72  ISKIP = 4  ISK(I) = 1 1 1 1  IPH = 1  ISAT = 0
++++++++++ HALVE TIME STEP AT (   2,  1) +++++++++++++++   NEW DELT =  .250000E+10
NO CONVERGENCE AT (   2,  1) --- DELTEX =  .250000E+10   RESD =  .327846E+01   RESE =  .150581E+09  ++++++++++++++++++++++++++++++
///// GETEM CANNOT FIND PARAMETERS ////////////////////  HALVE TIME STEP /////
GETIT AT R   5  E = .622284E+06  D = .935386E+03  NELOK = 20  NDLOK = 78  ISKIP = 3  ISK(I) = 0 1 1 1  IPH = 1  ISAT = 0
++++++++++ HALVE TIME STEP AT (   2,  1) +++++++++++++++   NEW DELT =  .125000E+10
NO CONVERGENCE AT (   2,  1) --- DELTEX =  .125000E+10   RESD =  .163923E+01   RESE =  .752906E+08  ++++++++++++++++++++++++++++++
NO CONVERGENCE AT (   2,  2) --- DELTEX =  .125000E+10   RESD =  .202377E+05   RESE =  .107167E+11  ++++++++++++++++++++++++++++++
NO CONVERGENCE AT (   2,  3) --- DELTEX =  .125000E+10   RESD =  .602374E+02   RESE =  .192915E+08  ++++++++++++++++++++++++++++++
NO CONVERGENCE AT (   2,  4) --- DELTEX =  .125000E+10   RESD =  .388161E+03   RESE =  .173977E+09  ++++++++++++++++++++++++++++++
VERY SMALL PIVOT IN ROW  15  ---  PERFORM NEW DECOMPOSITION
NO CONVERGENCE AT (   2,  5) --- DELTEX =  .125000E+10   RESD =  .207820E+03   RESE =  .104593E+09  ++++++++++++++++++++++++++++++
VERY SMALL PIVOT IN ROW  21  ---  PERFORM NEW DECOMPOSITION
NO CONVERGENCE AT (   2,  6) --- DELTEX =  .125000E+10   RESD =  .863784E+02   RESE =  .432707E+08  ++++++++++++++++++++++++++++++
NO CONVERGENCE AT (   2,  7) --- DELTEX =  .125000E+10   RESD =  .140221E+03   RESE =  .591212E+08  ++++++++++++++++++++++++++++++
NO CONVERGENCE AT (   2,  8) --- DELTEX =  .125000E+10   RESD =  .300756E+01   RESE =  .142954E+07  ++++++++++++++++++++++++++++++
NO CONVERGENCE AT (   2,  9) --- DELTEX =  .125000E+10   RESD =  .737398E+00   RESE =  .308700E+06  ++++++++++++++++++++++++++++++
++++++++++ HALVE TIME STEP AT (   2,  9) +++++++++++++++   NEW DELT =  .625000E+09
NO CONVERGENCE AT (   2,  1) --- DELTEX =  .625000E+09   RESD =  .819615E+00   RESE =  .376453E+08  ++++++++++++++++++++++++++++++
VERY SMALL PIVOT IN ROW  32  ---  PERFORM NEW DECOMPOSITION
NO CONVERGENCE AT (   2,  2) --- DELTEX =  .625000E+09   RESD =  .233494E+04   RESE =  .107420E+10  ++++++++++++++++++++++++++++++
VERY SMALL PIVOT IN ROW  15  ---  PERFORM NEW DECOMPOSITION
NO CONVERGENCE AT (   2,  3) --- DELTEX =  .625000E+09   RESD =  .441345E+01   RESE =  .264300E+07  ++++++++++++++++++++++++++++++
NO CONVERGENCE AT (   2,  4) --- DELTEX =  .625000E+09   RESD =  .352619E+01   RESE =  .150410E+07  ++++++++++++++++++++++++++++++
NO CONVERGENCE AT (   2,  5) --- DELTEX =  .625000E+09   RESD =  .154931E-03   RESE =  .950988E+02  ++++++++++++++++++++++++++++++
NO CONVERGENCE AT (   2,  6) --- DELTEX =  .625000E+09   RESD =  .237417E-06   RESE =  .133447E+01  ++++++++++++++++++++++++++++++
R   5(   2,  7) ST =  .187500E+10 DT =  .625000E+09 DE =  .686939E+05 DD = -.113067E+02 T = 105.744 P = 21488290. S.= 0.
```

Figure 12. Output Messages for Time Step Reduction.

***** NATURAL HYDROTHERMAL CONVECTION SYSTEM ***** 5 KM RADIUS *****

OUTPUT DATA AFTER (2, 7)-2-DECYCLES

TOTAL TIME	KCYC	ITER	ITERC	KON	DDMAX	DEMAX	RESD	RESE	DELTEX	NEXT DELT
.187500E+10	2	7	29	2	.113067E+02	.686939E+05	.468720E-07	.287279E+00	.625000E+09	.100000E+11

ELEM.	INDEX	E	D	DE	DD	DDE	DDD	T	P	S	BOIL
ATO 0	1	.419905E+05	.999694E+03	.433433E-09	.140776E-39	.693493E-18	.225242E-48	.100030E+02	.998847E+05	0.	0.
C 1	2	.641898E+05	.999953E+03	.432253E+03	-.187732E-01	.691605E-06	-.300372E-10	.153275E+02	.207130E+07	0.	0.
C 2	3	.641723E+05	.999952E+03	.424501E+03	-.190288E-01	.679202E-06	-.304461E-10	.153233E+02	.206816E+07	0.	0.
C 3	4	.641672E+05	.999952E+03	.422269E+03	-.191244E-01	.675631E-06	-.305990E-10	.153221E+02	.206706E+07	0.	0.
C 4	5	.641654E+05	.999952E+03	.421539E+03	-.191458E-01	.674463E-06	-.306333E-10	.153216E+02	.206672E+07	0.	0.
C 5	6	.641647E+05	.999952E+03	.421274E+03	-.191482E-01	.674038E-06	-.306371E-10	.153215E+02	.206662E+07	0.	0.
R 1	7	.227318E+06	.988383E+03	-.539362E+03	.519786E-01	-.862978E-06	.991657E-10	.545653E+02	.597610E+07	0.	0.
R 2	8	.228484E+06	.989845E+03	.153820E+02	-.492554E-02	.246112E-07	-.788987E-11	.549958E+02	.985769E+07	0.	0.
R 3	9	.228227E+06	.991473E+03	.145379E+03	-.199482E-01	.232606E-06	-.319171E-10	.550791E+02	.137474E+08	0.	0.
R 4	10	.235894E+06	.992127E+03	.435859E+04	-.529582E+00	.697375E-05	-.847331E-09	.570762E+02	.176448E+08	0.	0.
R 5	11	.436855E+06	.964015E+03	.686939E+05	-.113067E+02	.109910E-03	-.180908E-07	.105744E+03	.214883E+08	0.	0.
S 1	12	.227295E+06	.988384E+03	-.551054E+03	.626473E-01	-.881686E-06	.100236E-09	.545597E+02	.597126E+07	0.	0.
S 2	13	.228440E+06	.989848E+03	-.498872E+01	-.345128E-02	-.798196E-08	-.552204E-11	.549851E+02	.985113E+07	0.	0.
S 3	14	.227963E+06	.991500E+03	-.483912E+00	-.391140E-02	-.774260E-09	-.625825E-11	.550149E+02	.137367E+08	0.	0.
S 4	15	.227534E+06	.993133E+03	.202277E+02	-.653295E-02	.323643E-07	-.104527E-10	.550494E+02	.176279E+08	0.	0.
S 5	16	.227189E+06	.994756E+03	.609988E+02	-.119076E-01	.975981E-07	-.190522E-10	.551046E+02	.215237E+08	0.	0.
T 1	17	.227295E+06	.988383E+03	-.551110E+03	.624223E-01	-.881776E-06	.998756E-10	.545596E+02	.596965E+07	0.	0.
T 2	18	.228441E+06	.989847E+03	-.462785E+01	-.371607E-02	-.740456E-08	-.594572E-11	.549852E+02	.984957E+07	0.	0.
T 3	19	.227965E+06	.991500E+03	.344408E+00	-.417611E-02	.551052E-09	-.668177E-11	.550154E+02	.137355E+08	0.	0.
T 4	20	.227503E+06	.993136E+03	-.142489E+00	-.405283E-02	-.227982E-09	-.648453E-11	.550419E+02	.176277E+08	0.	0.
T 5	21	.227043E+06	.994775E+03	-.603922E+00	-.397177E-02	-.966275E-09	-.635484E-11	.550692E+02	.215264E+08	0.	0.
U 1	22	.227296E+06	.988383E+03	-.550863E+03	.623308E-01	-.881381E-06	.997293E-10	.545597E+02	.596917E+07	0.	0.
U 2	23	.228442E+06	.989847E+03	-.426924E+01	-.380963E-02	-.683079E-08	-.609541E-11	.549854E+02	.984915E+07	0.	0.
U 3	24	.227967E+06	.991499E+03	.109096E+01	-.429017E-02	.174554E-08	-.686427E-11	.550158E+02	.137352E+08	0.	0.
U 4	25	.227505E+06	.993136E+03	.101214E+01	-.417694E-02	.161943E-08	-.668310E-11	.550425E+02	.176277E+08	0.	0.
U 5	26	.227045E+06	.994775E+03	.608963E+00	-.406030E-02	.974340E-09	-.649648E-11	.550698E+02	.215266E+08	0.	0.
V 1	27	.227296E+06	.988383E+03	-.550626E+03	.622867E-01	-.881001E-06	.996587E-10	.545598E+02	.596902E+07	0.	0.
V 2	28	.228442E+06	.989847E+03	-.415812E+01	-.383533E-02	-.665299E-08	-.613653E-11	.549854E+02	.984902E+07	0.	0.
V 3	29	.227967E+06	.991499E+03	.120795E+01	-.431022E-02	.193271E-08	-.689635E-11	.550158E+02	.137351E+08	0.	0.
V 4	30	.227506E+06	.993136E+03	.119823E+01	-.419800E-02	.191717E-08	-.671679E-11	.550426E+02	.176277E+08	0.	0.
V 5	31	.227046E+06	.994775E+03	.770940E+00	-.407277E-02	.123350E-08	-.651643E-11	.550699E+02	.215266E+08	0.	0.

Figure 13. Output after two Time Steps for NHCS.

```
KPGA,07,63,30000.467301,PRUESS
*HOLDOUT
FETCHGS,LGO=PSSBACKUP/DIABLO/CYG,12605.
FETCHGS,TABLE=PSSBACKUP/DIABLO/FLUTAB3,12605.
REWIND,LGO.
SFL,170000.
LINK,X,L=0,PP=(PL=77777).
EXIT.
DUMP,0.
FIN.
REWIND,INPUT.
COPYSBF,INPUT,OUTPUT.


* GARG'S RADIAL FLOW PROBLEM (CF. PAPER SPE-7479) ******************
ROCKS
RFLOW     2650.     .28          1.E-14                    5.25      1000.

START
PARAM
   1   7        1000000000000000      1  1 .30      .05
                     -1.                    F    0
250.      750.      1000.     2000.     5000.

  300.00        9.E6
ELEMENT INFORMATION
F   0          RFLOW       4.98
F   1          RFLOW      14.73
F   2          RFLOW      24.54
F   3          RFLOW      34.36
F   4          RFLOW      44.18
F   5          RFLOW      54.00
F   6          RFLOW      63.81
F   7          RFLOW      73.63
F   8          RFLOW      83.45
F   9          RFLOW      93.27
F  10          RFLOW     103.08
F  11          RFLOW     136.66
F  12          RFLOW     182.65
F  13          RFLOW     246.05
F  14          RFLOW     334.03
F  15          RFLOW     456.42
F  16          RFLOW     628.01
F  17          RFLOW     869.11
F  18          RFLOW    1209.42
F  19          RFLOW    1690.92
F  20          RFLOW    2373.73
F  21          RFLOW    3346.06
F  22          RFLOW    4730.18
F  23          RFLOW    6706.26
F  24          RFLOW    9531.08
F  25          RFLOW   13573.65
F  26          RFLOW   19365.24
F  27          RFLOW   27667.17
F  28          RFLOW   39578.97
F  29          RFLOW   56680.72
F  30          RFLOW   81244.78
F  31          RFLOW  116539.35
F  32          RFLOW  167274.58
F  33          RFLOW  240224.09
F  34          RFLOW  354144.76
F  35          RFLOW  496069.8
F  36          RFLOW  713221.9
F  37          RFLOW  1025682.
F  38          RFLOW  1475372.
F  39          RFLOW  2122595.
F  40          RFLOW  3054196.
F  41          RFLOW  4395241.
F  42          RFLOW  6325806.
F  43          RFLOW  8863529.
F  44          RFLOW  13349165.
F  45          RFLOW  18867637.
F  46          RFLOW  27162454.
F  47          RFLOW  39105615.
F  48          RFLOW  56301977.
F  49          RFLOW  81062899.
```

Figure 14. SHAFT79 Input Deck for Garg's Problem.

```
CONNE
F    0F    1                    1      .5        .5         9.82
F    1F    2                    1      .5        .5        19.63
F    2F    3                    1      .5        .5        29.45
F    3F    4                    1      .5        .5        39.27
F    4F    5                    1      .5        .5        49.09
F    5F    6                    1      .5        .5        58.90
F    6F    7                    1      .5        .5        68.72
F    7F    8                    1      .5        .5        78.54
F    8F    9                    1      .5        .5        88.36
F    9F   10                    1      .5        .5        98.17
F   10F   11                    1      .5        .6       107.99
F   11F   12                    1      .6        .72      119.77
F   12F   13                    1      .72      .864      133.91
F   13F   14                    1     .864     1.037      150.87
F   14F   15                    1    1.037     1.244      171.24
F   15F   16                    1    1.244     1.493      195.66
F   16F   17                    1    1.493     1.792      224.98
F   17F   18                    1    1.792     2.150      260.15
F   18F   19                    1    2.150     2.580      302.37
F   19F   20                    1    2.580     3.096      353.83
F   20F   21                    1    3.096     3.715      413.81
F   21F   22                    1    3.715     4.458      486.76
F   22F   23                    1    4.458     5.350      574.29
F   23F   24                    1    5.350     6.420      679.33
F   24F   25                    1    6.420     7.703      805.38
F   25F   26                    1    7.703     9.244      956.33
F   26F   27                    1    9.244    11.093     1138.15
F   27F   28                    1   11.093    13.312     1355.96
F   28F   29                    1   13.312    15.974     1617.33
F   29F   30                    1   15.974    19.169     1930.98
F   30F   31                    1   19.169    23.003     2307.36
F   31F   32                    1   23.003    27.603     2759.02
F   32F   33                    1   27.603    33.124     3301.08
F   33F   34                    1   33.124    39.748     3951.38
F   34F   35                    1   39.748    47.698     4731.84
F   35F   36                    1   47.698    57.238     5668.39
F   36F   37                    1   57.238    68.686     6792.25
F   37F   38                    1   68.686    82.223     8140.9
F   38F   39                    1   82.223    98.907     9759.2
F   39F   40                    1   98.907   118.688    11701.3
F   40F   41                    1  118.688   142.226    14031.7
F   41F   42                    1  142.226   170.911    16826.2
F   42F   43                    1  170.911   205.093    20184.1
F   43F   44                    1  205.093   246.112    24112.9
F   44F   45                    1  246.112   295.334    29043.4
F   45F   46                    1  295.334   354.401    34842.1
F   46F   47                    1  354.401   425.281    41801.0
F   47F   48                    1  425.281   510.337    50151.3
F   48F   49                    1  510.337   622.405    60171.8

GENERATION
F    0                          1     MASS    -.21875

ENDCYCLES
```

Figure 14. (continued)

* GARG'S RADIAL FLOW PROBLEM (CF. PAPER SPE-7479) **********************

OUTPUT DATA AFTER (7, 61-2-DECYCLES

TOTAL TIME	KCYC	ITER	ITERC	KON	DDMAX	DEMAX	RESO	RESE	DELTEX	NEXT DELT
.165000E+05	7	6	43	2	.396209E+02	.191839E+05	.391189E-08	.526506E-02	.500000E+04	.500000E+04

ELEM.	INDEX	E	D	DE	DD	DDE	DDD	T	P	S	BOIL
F 0	1	.127853E+07	.531298E+03	-.191839E+05	-.427400E+01	-.383679E+01	-.854800E-03	.204574E+03	.688090E+07	.298519E+00	.302518E-02
F 1	2	.133673E+07	.544922E+03	-.629456E+04	-.132730E+02	-.125891E+01	-.265480E-02	.295863E+03	.811063E+07	.259180E+00	.761089E-03
F 2	3	.134502E+07	.587081E+03	.355016E+04	-.380809E+02	.710031E+00	-.761617E-02	.298829E+03	.846316E+07	.190241E+00	.214868E-03
F 3	4	.133782E+07	.659104E+03	.387824E+04	-.396209E+02	.775648E+00	-.792418E-02	.299591E+03	.855317E+07	.805192E-01	.110442E-03
F 4	5	.133276E+07	.712250E+03	.442019E+02	-.670347E-01	.884038E-02	-.134069E-04	.299942E+03	.859132E+07	.206187E-04	.144959E-06
F 5	6	.133272E+07	.712318E+03	.554682E+02	-.585034E-01	.110936E-01	-.117007E-04	.299949E+03	.862183E+070.		0.
F 6	7	.133267E+07	.712369E+03	.555538E+02	-.584786E-01	.111108E-01	-.116957E-04	.299953E+03	.864723E+070.		0.
F 7	8	.133263E+07	.712413E+03	.554967E+02	-.583864E-01	.110993E-01	-.116773E-04	.299956E+03	.866897E+070.		0.
F 8	9	.133259E+07	.712451E+03	.554097E+02	-.582738E-01	.110819E-01	-.116548E-04	.299958E+03	.868796E+070.		0.
F 9	10	.133256E+07	.712485E+03	.552996E+02	-.581435E-01	.110599E-01	-.116287E-04	.299960E+03	.870482E+070.		0.
F 10	11	.133253E+07	.712515E+03	.551632E+02	-.579941E-01	.110326E-01	-.115988E-04	.299962E+03	.871996E+070.		0.
F 11	12	.133250E+07	.712546E+03	.550044E+02	-.578173E-01	.110009E-01	-.115635E-04	.299964E+03	.873507E+070.		0.
F 12	13	.133247E+07	.712579E+03	.547887E+02	-.575820E-01	.109577E-01	-.115164E-04	.299966E+03	.875137E+070.		0.
F 13	14	.133244E+07	.712614E+03	.544964E+02	-.572676E-01	.108993E-01	-.114535E-04	.299969E+03	.876881E+070.		0.
F 14	15	.133240E+07	.712651E+03	.541CC9E+02	-.568463E-01	.108202E-01	-.113693E-04	.299971E+03	.878729E+070.		0.
F 15	16	.133237E+07	.712690E+03	.535660E+02	-.562798E-01	.107132E-01	-.112560E-04	.299974E+03	.880671E+070.		0.
F 16	17	.133233E+07	.712731E+03	.528431E+02	-.555170E-01	.105686E-01	-.111034E-04	.299976E+03	.882691E+070.		0.
F 17	18	.133229E+07	.712772E+03	.518664E+02	-.544885E-01	.103733E-01	-.108977E-04	.299979E+03	.884774E+070.		0.
F 18	19	.133225E+07	.712815E+03	.505508E+02	-.531048E-01	.101102E-01	-.106210E-04	.299982E+03	.886899E+070.		0.
F 19	20	.133221E+07	.712858E+03	.487890E+02	-.512531E-01	.975781E-02	-.102506E-04	.299985E+03	.889042E+070.		0.
F 20	21	.133217E+07	.712901E+03	.464530E+02	-.487987E-01	.929061E-02	-.975973E-05	.299988E+03	.891175E+070.		0.
F 21	22	.133213E+07	.712943E+03	.434061E+02	-.455977E-01	.868122E-02	-.911955E-05	.299990E+03	.893261E+070.		0.
F 22	23	.133209E+07	.712983E+03	.395265E+02	-.415223E-01	.790530E-02	-.830446E-05	.299993E+03	.895259E+070.		0.
F 23	24	.133205E+07	.713021E+03	.347518E+02	-.365066E-01	.695035E-02	-.730132E-05	.299995E+03	.897121E+070.		0.
F 24	25	.133202E+07	.713055E+03	.291454E+02	-.306173E-01	.582907E-02	-.612345E-05	.299998E+03	.898796E+070.		0.
F 25	26	.133199E+07	.713083E+03	.229644E+02	-.241243E-01	.459288E-02	-.482486E-05	.299999E+03	.900231E+070.		0.
F 26	27	.133197E+07	.713107E+03	.166812E+02	-.175238E-01	.333624E-02	-.350477E-05	.300001E+03	.901387E+070.		0.
F 27	28	.133195E+07	.713124E+03	.109271E+02	-.114791E-01	.218542E-02	-.229582E-05	.300002E+03	.902245E+070.		0.
F 28	29	.133194E+07	.713136E+03	.629225E+01	-.661013E-02	.125845E-02	-.132203E-05	.300003E+03	.902820E+070.		0.
F 29	30	.133194E+07	.713142E+03	.309590E+01	-.325231E-02	.619180E-03	-.650462E-06	.300003E+03	.903158E+070.		0.
F 30	31	.133193E+07	.713146E+03	.126352E+01	-.132736E-02	.252705E-03	-.265472E-06	.300003E+03	.903327E+070.		0.
F 31	32	.133193E+07	.713147E+03	.414952E+00	-.435917E-03	.829905E-04	-.871834E-07	.300004E+03	.903398E+070.		0.
F 32	33	.133193E+07	.713148E+03	.106507E+00	-.111888E-03	.213014E-04	-.223776E-07	.300004E+03	.903421E+070.		0.
F 33	34	.133193E+07	.713148E+03	.207982E-01	-.218490E-04	.415964E-05	-.436980E-08	.300004E+03	.903428E+070.		0.
F 34	35	.133193E+07	.713148E+03	.296416E-02	-.311392E-05	.592831E-06	-.622784E-09	.300004E+03	.903429E+070.		0.
F 35	36	.133193E+07	.713148E+03	.313918E-03	-.329771E-06	.627835E-07	-.659542E-10	.300004E+03	.903429E+070.		0.
F 36	37	.133193E+07	.713148E+03	.238889E-04	-.250841E-07	.477777E-08	-.501682E-11	.300004E+03	.903429E+070.		0.
F 37	38	.133193E+07	.713148E+03	.129799E-05	-.135408E-08	.259599E-09	-.270816E-12	.300004E+03	.903429E+070.		0.
F 38	39	.133193E+07	.713148E+03	.604954E-07	-.517935E-10	.120991E-10	-.103587E-13	.300004E+03	.903429E+070.		0.
F 39	40	.133193E+07	.713148E+03	.706533E-08	-.109482E-11	.141307E-11	-.218964E-15	.300004E+03	.903429E+070.		0.
F 40	41	.133193E+07	.713148E+03	.142681E-07	.143048E-12	.285363E-11	.286096E-16	.300004E+03	.903429E+070.		0.
F 41	42	.133193E+07	.713148E+03	.263411E-08	-.148484E-12	.526822E-12	-.296968E-16	.300004E+03	.903429E+070.		0.
F 42	43	.133193E+07	.713148E+03	.143847E-07	.170686E-13	.287694E-11	.341371E-17	.300004E+03	.903429E+070.		0.
F 43	44	.133193E+07	.713148E+03	.275875E-08	-.357746E-13	.551751E-12	-.715492E-17	.300004E+03	.903429E+070.		0.
F 44	45	.133193E+07	.713148E+03	.525013E-08	.359095E-16	.105003E-11	.718191E-20	.300004E+03	.903429E+070.		0.
F 45	46	.133193E+07	.713148E+03	.208794E-08	.974281E-14	.417507E-12	.114856E-17	.300004E+03	.903429E+070.		0.
F 46	47	.133193E+07	.713148E+03	.208686E-08	.697053E-14	.417372E-12	.139411E-17	.300004E+03	.903429E+070.		0.
F 47	48	.133193E+07	.713148E+03	.103615E-07	-.108940E-13	.207230E-11	-.217880E-17	.300004E+03	.903429E+070.		0.
F 48	49	.133193E+07	.713148E+03	.262084E-08	.101635E-13	.524168E-12	.203270E-17	.300004E+03	.903429E+070.		0.
F 49	50	.133193E+07	.713148E+03	.103594E-07	-.351277E-14	.207189E-11	-.702554E-18	.300004E+03	.903429E+070.		0.

Figure 15. Output after seven Time Steps for Garg's Problem.