**VHBORE: A Code to Compute Borehole Fluid Conductivity Profiles
With Pressure Changes in the Borehole**

F.V. Hale and C.F. Tsang

Earth Sciences Division
Lawrence Berkeley Laboratory
University of California
Berkeley, CA 94720

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1. INTRODUCTION

This report describes the code VHBORE which can be used to model fluid electric conductivity profiles in a borehole intersecting fractured rock under conditions of changing pressure in the well bore. Pressure changes may be due to water level variations caused by pumping or fluid density effects as formation fluid is drawn into the borehole. Previous reports describe the method of estimating the hydrologic behavior of fractured rock using a time series of electric conductivity logs (Tsang et al., 1989), and an earlier code, BORE, to generate electric conductivity logs under constant pressure and flow rate conditions (Hale and Tsang, 1988).

The earlier model, BORE, assumed a constant flow rate, q_i , for each inflow into the well bore. In the present code the user supplies the location, constant pressure, h_i , transmissivity, T_i , and storativity, S_i , for each fracture, as well as the initial water level in the well, $h_w(0)$. In addition, the input data contains changes in the water level at later times, $\Delta h_w(t)$, typically caused by turning a pump on or off. The variable density calculation also requires input of the density of each of the inflow fluids, ρ_i , and the initial uniform density of the well bore fluid, $\rho_w(0)$. These parameters are used to compute the flow rate for each inflow point at each time step.

The numerical method of Jacob and Lohman (1952) is used to compute the flow rate into or out of the fractures based on the changes in pressure in the wellbore. A dimensionless function relates flow rate as a function of time in response to an imposed pressure change. The principle of superposition is used to determine the net flow rate from a time series of pressure changes. Additional reading on the relationship between drawdown and flow rate can be found in Earlougher (1977), particularly his Section 4.6, "Constant-Pressure Flow Testing."

The primary difference between variable and constant density applications of the code is that with variable densities the pressure profile is computed at each time step, and when

density variations in the well bore result in a significant pressure change (i.e. equal to a column of water of height equal to one half of the cell height, $pg\Delta x/2$), this is also added to the flow rate calculations. The wellbore is assumed to be vertical for purposes of pressure calculations; however no gravity-driven flow effects are considered in this code.

The electrolyte concentration and the density are not related in the present code. Therefore the code can be considered to model the transport of two independent substances using the same flow field. Only the electrolyte is affected by diffusion in the current code, and only the density affects the pressure profile. The decision to separate the density calculation from the electrolyte concentration was made to permit modeling of conditions where the density effects are due to something other than the electrolyte solutions, such as drilling mud. Full radial mixing is assumed in the cells, and fingering effects are not considered.

2. NUMERICAL AND ANALYTICAL SOLUTIONS

Governing Equation for Borehole Flow with Sources

The differential equation for mass or solute transport in a borehole is:

$$\frac{\partial}{\partial x} \left(K \frac{\partial C}{\partial x} \right) - \frac{\partial}{\partial x} (CV) + S = \frac{\partial C}{\partial t} \quad (1)$$

where

C is the concentration (kg/m^3)

K is the dispersion coefficient (m^2/sec)

S is the source term ($\text{kg/m}^3\text{-sec}$), and

V is the fluid velocity (m/sec)

This partial differential equation is solved numerically using the finite difference method (FDM). The following initial and boundary conditions are also specified:

$$C(x, 0) = C_0(x) \quad (2a)$$

$$C(x > x_{\max}, t) = 0 \quad (2b)$$

$$K = 0 \quad \text{for} \quad x > x_{\max} \quad \text{or} \quad x < x_{\min} \quad (2c)$$

The first condition allows for the specification of initial electrolyte concentrations in the borehole. The second condition implies that there is no electrolyte in the borehole fluid flowing from below the area of interest. If there is a background concentration in the fluid flowing from the borehole bottom, this value should be added to all of the resulting concentrations. The third condition indicates that dispersion does not take place across the specified boundaries of the area of interest. In general, advection will be the dominant process at the boundaries. If dispersion is dominant for a particular problem, the boundaries should be extended in order to prevent improper trapping of electrolyte.

This is the same governing equation used by the constant flow code, BORE. The differences in VHBORE are seen in the source, velocity and, if velocity dependent, dispersion terms. The source term, S_i , is no longer constant, but include the effects of two-way flow between the well bore and the formation as the pressure changes in the borehole. The velocity term, V_i , varies in response to the pressure history of the well, and thus, if the dispersion coefficient, K_i , is velocity dependent, it will also vary continuously with time.

Discretization in Space

In the borehole, uniform, one-dimensional spacing of nodes is used. It is assumed that the borehole has uniform diameter d , and that the region of interest is divided into N equal length cells of length Δx . Position values indicate depth in the borehole; thus x is zero at the surface and increases downward. The flow within the borehole is generally upward, and the cell index i increases downstream (upward, toward the surface). Thus cells 1 and N are located at the bottom and top of the region, respectively, and node x_i is

upstream of and at a greater depth than node x_{i+1} . In general, node i is located at $x_{\max} - (i - 1/2)\Delta x$, with boundaries of $x_{\max} - (i - 1)\Delta x$ upstream (at a depth below the node), and $x_{\max} - (i)\Delta x$ downstream (at a depth above the node). Note that because all cells are assumed to have the same geometry, flow rates are directly proportional to linear velocities.

Each inflow is given a specific location in the input file, and the inflows are then assigned to specific cells. If multiple inflows are assigned to the same cell, their flow rates and mass transfer rates are summed to produce a single source term for the cell. The single source for the cell is assumed to be located at the midpoint of the cell.

The BORE code modeled a fracture as an infinite source of fluid with zero concentration until a specified time, after which time the infinite source provides fluid with a constant concentration. In the codes described here, a set of 50 "buckets" of variable volume and concentration have been set between the borehole and this infinite fluid source of fixed concentration. These buckets represent no particular geometry, but rather just a volume of water with a particular concentration.

As fluid flows from the borehole to the fracture, the buckets are filled, one at each time step. In the code, this is accomplished by storing a volume and concentration in corresponding positions in the matrices VFRAC and CFZ, which are indexed by fracture and bucket. The volume and concentration of the fluid transferred to the fracture depend on the time step, flow rate, and local borehole fluid concentration. If fluid has been flowing into the fracture for some time, and all of the buckets are full (i.e., all elements of the matrices VFRAC and CFZ for the fracture are in use), the oldest ten volumes are combined (i.e., dumped into one bucket, providing nine more empty buckets) by summing the volumes and computing a new concentration based on the total mass.

As fluid flows from the fracture zone to the borehole, the buckets are emptied in the reverse order. If all of the buckets are empty, fluid is drawn from the infinite source of

constant concentration. If a number of buckets are necessary to meet the volume requirements for a single time step, the concentrations are averaged.

The user specifies an initial volume and concentration in the first bucket. There is no longer an initial period of zero concentration, rather fluid transfer between the borehole and the fracture begins immediately. It is possible, however, to specify an initial volume of infiltrated water with a zero concentration.

The concentration of the fluid moving between the borehole and the fracture zone (in either direction) is determined by subroutine CTFRAC which is executed at each time step. Subroutine TSTEP computes the actual mass transfer from the borehole to the fracture zone.

Discretization in Time

Because the flow rates are not constant, a constant time step is not practical. Rather than having the user specify a time step, the subroutines FLOWS, DFLOWS, FLOWSA and TSTEP work together to compute a variable time step based on maximum velocity and mass transfer rates. The time step is initially set by FLOWS or DFLOWS based on flow rates (velocities) in the previous time step, if possible. Then FLOWSA modifies the time step based on the expected flow rates during the present time step. If due to dispersion effects this time step results in mass transfer inconsistencies, the time step is further reduced by subroutine TSTEP.

Methods of Computing the Dispersion Coefficient

Within the code, three methods are available for determining the dispersion coefficient for use at the interface between each pair of cells, $K_{i\pm 1/2}$: constant, velocity scaled, and velocity squared scaled. The first approach is used to model dispersion due to molecular diffusion; the second, velocity dependence, is an approximation for porous medium transport; and the last, velocity-squared dependence, corresponds to Taylor dispersion for flow in a pipe. With each method, the dispersion coefficients at the two

adjacent cells to an interface are computed, then the harmonic mean is used at the interface. Because no dispersion occurs across the region boundaries, $K_{1/2}$ and $K_{N+1/2}$ are defined to be zero.

With the constant method, the input dispersion parameter, K_0 , is used for all the cell interfaces and Equation (1) simplifies to

$$K_0 \frac{\partial^2 C}{\partial x^2} - \frac{\partial}{\partial x}(CV) + S = \frac{\partial C}{\partial t} \quad (3)$$

The velocity scaled methods use a somewhat arbitrary reference dispersion coefficient K_0 defined as the dispersion coefficient at a depth where the flow velocity is equal to the mean velocity or the mean velocity squared,

$$\bar{V}^n = \frac{\min(V_i^n) + \max(V_i^n)}{2} \quad , \quad (4)$$

where V_i^n is the fluid flow velocity at node i raised to the first or second power ($n = 1$ or 2). Then the dispersion coefficient for node i is given by

$$K_i = K_0 \left(\frac{V_i^n}{\bar{V}^n} \right) \quad . \quad (5)$$

Note that since the cells have a uniform volume the velocities are proportional to the flow rates, and the actual calculations are based on q_i rather than v_i (since $q_i = v_i A$, where A is the uniform cross-sectional area).

The dispersion coefficient at the interface between two cells is the harmonic mean:

$$K_{i \pm 1/2} = 1 \left(\frac{1}{K_i} + \frac{1}{K_{i \pm 1}} \right)^{-1} \quad (6)$$

For cells with no flow (e.g., upstream from the first feed point), the dispersion coefficient of the first cell with nonzero flow is used.

The dispersion coefficients are then adjusted for the problem geometry,

$$\gamma_{i+1/2} = \frac{AK_{i+1/2}}{\Delta x} \quad (7)$$

where A is the uniform cross-sectional area.

If the dispersion type is flow rate dependent (ITYPDK is 2 or 3), the dispersion coefficients must be computed during each time step. This is done in subroutine FLOWSA after the current flow rates and velocities have been computed by subroutines FLOWS or DFLOWS.

Calculation of Flow Rates

At a given time the flow rate from a fracture zone to the borehole (or from the borehole to the fracture zone) is a function of the fracture zone hydraulic parameters and the pressure history in the borehole. At each time step the flow rate is computed by a superposition of the effects of individual pressure changes. This calculation is performed in subroutine FLOWS for constant density calculations and by subroutine DFLOWS for variable density calculations.

The effect of a single pressure change, j , for a single inflow, i , is computed using a dimensionless function, q_D , which is defined as follows:

$$q_{i,j}(t) = 2\pi T_i \Delta h_j q_D(t_D(t)) \quad (8)$$

where

$$t_D(t) = \left(\frac{T_i(t - \tau_j)}{S_i r^2} \right) \quad (9)$$

where T_i is the transmissivity of the inflow, S_i is the storativity of the inflow, r is the well bore radius, Δh_j is the drawdown for pressure change j , and τ_j is the time of pressure change j .

In these codes, the terms $2\pi T_i$ and $T_i/S_i r^2$ are calculated in subroutine RDFRAC and stored as QCOEF(I) and TCOEF(I), respectively. The dimensionless function q_D is

computed using linear interpolation on a table for arguments values between 10^{-4} and 10^{12} . The table is from Jacob and Lohman (1952). For dimensionless times (t_D) greater than 10^{12} , Earlougher (1977) suggests using $q_D = 2/(\ln(t_D) + 0.80907)$. For values below 10^{-4} , a somewhat arbitrary constant value of 56.9 is used (this is the value for dimensionless time 10^{-4} given by Jacob and Lohman). Figure 1 shows the graph of the function q_D .

The calculation of flow rates is more complex for variable density cases. As the fluid of different densities enters the well bore, the pressure profile in the well bore changes. The pressure is no longer just a function of the drawdown values specified in the input file, but also of the changing density profile in the well. At any given time, the pressure (in meters of water) can be calculated as:

$$p_i(t) = \frac{1}{\rho_w} \int_{x_w}^{x_i} \rho(x, t) dx \quad (10)$$

where ρ_w is the density of water, g is the acceleration due to gravity, and x_w is the depth of the water surface.

The use of the Jacob-Lohman solution requires that at every time step following a pressure change the effect of the pressure change be computed. In order to provide for some reasonable number of pressure changes to be recorded during the run, the wellbore pressure at each inflow is discretized in time. If a pressure change at an inflow exceeds one half of a cell length, it is considered significant, recorded, and affects all following flow rate calculations. All of this is done in subroutine DFLOWS. The array PHIST stores the pressure history (pressure and time) for each inflow. Stated more concisely, the current criterion for recording a significant pressure change due to density is:

$$|p_i(t_1) - p_i(t_2)| > \Delta x / 2 \quad (11)$$

This condition make the assumption that the water level, x_w , does not change between times t_1 and t_2 .

After the flows between the fracture zones and the borehole have been determined, the flow rates in the remaining cells are computed by subroutine FLOWSA assuming a closed lower boundary and open upper boundary in the borehole, using the discretized version of Equation (1).

Note that if the input value for the initial drawdown and inflow depths and pressure heads results in pressure differences between the input values for the fractures, it is assumed that this pressure change took place at the model starting time (TSTART).

Calculation During Each Time Step

The constant mass injection of BORE has been replaced in the variable pressure codes by possible two-way mass transfer between the borehole and the fractures. At each time step the flow rate (and direction) and fluid concentration for transfer between the borehole and the fracture zones is computed. This has been described above.

The mass transfer within the borehole during time step k is due to flow to or from the feed points (the source of electrolyte), advection, and dispersion. The finite-difference version of Equation (1) may be written in terms of mass transfer (kg/sec) as follows:

$$\begin{aligned}
 (\Delta C_{i,k} / \Delta t)(A\Delta x) = & C_{i,k}^f (q_i^f) \\
 & + C_{i-1,k-1}(q_{i-1/2}) - C_{i,k-1}(q_{i+1/2}) \\
 & + (C_{i-1,k-1} - C_{i,k-1})(\gamma_{i-1/2}) - (C_{i,k-1} - C_{i+1,k-1})(\gamma_{i+1/2})
 \end{aligned} \quad (12)$$

where $C_{i,k}^f$ is the average concentration of electrolyte in the fluid flowing from the feed points into cell i during time step k , and $\gamma_{i\pm 1/2}$ is the dispersion coefficient at the interface between two adjoining cells adjusted for the problem geometry. The first line of the right-hand side is the source term, the second line is the advection term, and the third line is the dispersion term. Upstream weighting is used in the advective terms.

This equation can be rewritten by collecting coefficients of the different cell concentrations as:

$$\begin{aligned}
 (\Delta C_{i,k} / \Delta t)(A\Delta x) = & C_{i,k}^f (q_i^f) \\
 & + C_{i-1,k-1} (q_{i-1/2} + \gamma_{i-1/2}) \\
 & + (C_{i,k-1} (-q_{i+1/2} - \gamma_{i-1/2} - \gamma_{i+1/2})) \\
 & + C_{i+1,k-1} (\gamma_{i+1/2})
 \end{aligned} \tag{13}$$

At each time step k a check is made to verify that the total mass in the cell at the beginning of the time step is greater than or equal to the total mass to be transported out of the cell during the time step. If this condition is not met, an error message is printed and the time step is reduced.

Conservation of mass is verified during each time step and at the end of the problem. Mass may flow into the system from the infinite reservoir in each fracture zone, and mass may flow out of the system at the top of the borehole section. All other boundaries are closed.

Temperature Dependence of Conductivity

All calculations are made assuming a uniform temperature of 20°C throughout the borehole. Generally temperature increases with depth below the land surface, so temperature corrections must be applied to field conductivity data to permit direct comparison with model output.

The effect of temperature on conductivity can be estimated using the following equation from NAGRA (1987):

$$\sigma(20^\circ\text{C}) = \frac{\sigma(T_x)}{1 + S(T_x - 20^\circ\text{C})} \tag{14}$$

where T_x is the temperature (°C) at depth x . The value of S is estimated at 0.022.

Conductivity as a Function of Concentration

Assuming that all of the ions in the borehole fluid can be converted to NaCl equivalents, the conductivity and concentration data in Shedlovsky and Shedlovsky (1971) can be fit fairly well using a quadratic approximation:

$$\sigma = 2,075 C - 45 C^2 \quad (15)$$

where C is the concentration in $\text{kg}/\{\text{m}^3$ and σ is the conductivity in $\mu\text{S}/\text{cm}$ at 25°C . The expression is accurate for a range of C up to $5 \text{ kg}/\text{m}^3$ and σ up to $10,000 \mu\text{S}/\text{cm}$. For even lower C up to $1 \text{ kg}/\{\text{m}^3$ } and σ up to $0.2 \mu\text{S}/\text{cm}$, the second term may be neglected.

Although the experimental values are for 25°C , they may be used at 20°C if multiplied by 0.89 (based on Equation (14) for the temperature dependence of conductivity). Thus the above relationship would be

$$\sigma = 1,850 C - 40 C^2 \quad (16)$$

3. DESCRIPTION OF FORTRAN CODE VHBORE

The main program is little more than a single time step loop and a series of subroutine calls. Before the time step loop begins, a single call to the subroutine INTS is made to initialize all data areas and read the problem descriptions. Within the time step loop, the flow rates are first computed using either constant or variable density approaches (using either subroutine FLOWS or subroutine DFLOWS). Once the flow rates are computed, a time step size is determined, and the mass transfer for the time step is accomplished using subroutine ONESTEP. If the time step was determined to be too large (too much mass was transferred out of a cell), the time step is reduced and the flow rates and mass transfer are preformed again. If the time step was successful, the subroutine GOODSTEP is called to check for output requests. After the ending time has been reached, a single call to the subroutine ENDPROB is made to produce the final messages regarding mass transfer.

Common Blocks

The program has four named common blocks, CORR, FRACS, SEGS and STEP which are defined in a separate source code file, VPCOMMS.F, and included as needed in the main source file. The common block source file uses a set of parameters to specify array sizes, making it easier to change array sizes as need to suit different problems and computing environments.

Common block CORR contains the coefficients for converting electrolyte concentration in kg/m^3 to conductivity in $\mu\text{S/cm}$. These terms are derived from a second degree polynomial fit to experimental data, and are read by subroutine RDCORR.

Common block FRACS contains the arrays describing the fractures, including the fracture flow rates, concentrations, positions, segment locations, transmissivities, storativities, infiltration volumes, fluid densities, etc.

Common block SEGS contains the arrays describing each segment, including the concentration and density at the beginning and end of the time step, the fracture inflow average concentration and density, external flows into and out of the segment, fracture flow into the segment, downstream flow to the next segment, total flow into the segment, the position of the segment and the dispersion coefficient between the segment and the next downstream segment.

Common block STEP contains other variables used during the time steps, including the step duration, number of segments, maximum number of segments allowed, uniform segment volume, cumulative mass and volume out of the system, cumulative mass and volume into the system, time at the beginning and end of the time step, number of fractures, conductivity output unit number, toggle index for the concentration array, etc.

Subroutines and Functions

The first level of subroutines includes INITS, FLOWS, DFLOWS, ONESTEP, GOODSTEP and ENDPROB. These subroutines are called by the main program.

INTTS performs global variable initialization, opens the input and output files, reads the problem definition input file and performs the initial mass balance using subroutine SMASS.

The two main portions of the the time step loop compute the variable flow rates and perform the mass transfer. For a constant density calculation, the variable flow rates are determined by subroutine FLOWS; while for a variable density case, the subroutine DLFLOWS is used. The primary difference between these two routines is that FLOWS using only depth to determine pressure differences (assuming a constant density fluid in the well bore), whereas DFLOWS performs an actual integration of the density of all well bore fluid in order to determine the pressure at some depth. Both subroutines use the function QD to determine individual inflow rates using the Jacob-Lohman solution, and, after the individual inflow rates have been determined, both subroutines also call the subroutine FLOWSA to develop the full flow rate profile, estimate the time step size, and determine any velocity dependent aspects of the calculation.

The mass transfer for a single time step is carried out by subroutine ONESTEP. This subroutine advances the simulation clock, save current state variables in case the time step must be reversed, and calls subroutines CTFRAC and TSTEP. Subroutine CTFRAC determines the average concentration and density of the source terms for the time step based on the inflow rates, the time step, and any storage of fluid in the inflow zones. Subroutine TSTEP performs the actual mass transfer calculation and checks for conservation of mass. If the subroutine TSTEP indicates that an attempt was made to transfer too much mass out of a cell during the time step (due to the combined effects of advection and diffusion), a flag is set and the time step is reduced.

As mentioned above, the subroutine GOODSTEP is called if the time step was successful in order to determine if any output has been requested following the current time step. Actual output of conductivity profiles is produced by subroutine CPRT.

At the end of the computation, the subroutine ENDPROB is called to produce a number of informational messages about the calculation.

4. INPUT AND OUTPUT GUIDE

Input and Output Files

The model uses one input and four output files. The input file contains the problem description consisting of borehole geometry, top and bottom borehole flows, feed point flows, timing parameters, dispersion parameters, and initial concentrations. The output files consist of (1) messages produced by the model, (2) conductivity-depth pairs for each borehole cell at the requested output times, (3) flow rate-depth pairs for each cell at the requested output times, and (4) density-depth pairs for each cell at the requested output times. The following table summarizes the input and output files and indicates their FORTRAN unit numbers.

Table 4-1. Input and Output Files

UNIT NUMBER	INPUT/OUTPUT	DESCRIPTION
5	INPUT	Problem description
6	OUTPUT	Messages
7	OUTPUT	computed conductivity data
8	OUTPUT	Flow rate profile
9	OUTPUT	Density profile

Problem Description

The problem description is entered in free format, with values being separated by spaces or commas. The number of lines in the problem description will be variable depending on the number of feed points, number of times at which conductivity output is

desired, and number of initial concentrations specified. The following table provides a detailed description of each line of the input.

Table 4-2. Input Guide.

LINE	NAME	UNITS	DESCRIPTION
1	XTOP	m	Top of study area, surface is zero and positions increase downward, adjusted if necessary to fit XBOT and DELX
	XBOT	m	Bottom of study area
	DELX	m	Cell length
	DIAM	cm	Borehole diameter (uniform)
	WATLEV	m	Initial water level in well
	TOPD	none	Initial density of well bore fluid normalized by density of water (spec. grav.). TOPD ≤ 0 for constant density calculation
2	IFLIM	none	Number of inflows
2.1	XIN(I)	m	Position of inflow
I=1,IFLIM	CIN(I,1)	kg/m ³	Constant concentration for formation water
	TFRAC(I)	m ² /sec	Inflow transmissivity
	SFRAC(I)		Inflow storativity
	HFRAC(I)	m	Inflow pressure (over p _g)
	VFRAC(I,1)	m ³	Inflow initial volume of infiltrated deionized water
	CFZ(I,1,1)	kg/m ³	Infiltrated water concentration
	CIN(I,2)	none	Density of inflow fluid normalized by density of water (spec. grav.) (only for variable density calculation)

Table 4-2. Continued.

3	IDHLIM	none	Number of water level changes
3.I	DELHT(I)	hr	Time at which water level in borehole changes
I=1,IDHLIM	DELHH(I)	m	Change in water level (positive down)
4	TSTART	hr	Problem start time
	TEND	hr	Problem end time
	TSMAX	min	Maximum time step
	ILPT		Number of print times
4.I	PT(I)	hr	Time to print profile
I=1,ILPT			
5	ITYPDK	none	Type code for dispersion coefficient
			1 means DK is constant over all cells
			2 means DK is the value for the mean velocity,
			$\bar{q} = (\min(q_i) + \max(q_i))/2$, $k_i = DK(q_i \sqrt{q})$
			3 means KD is the value for mean vel. squared,
			$\sqrt{O(q^2_{i,j})} = (\min(q \setminus S(i,2) + \max(q_2)/2, K_i = DK((q_2/q^2)$
	DK	m ² /sec	Dispersion coefficient
6	ICON	none	Number of initial concentrations
6.I	X(I)	m	Position of initial concentration
I=1,ICON	C0(I)	kg/m ³	Initial concentration
	D0(I)	none	Initial density, normalized by density of water (spec. grav.) (only for variable density calculation)
7	OFFSET	μS/cm	constant term for converting concentration in kg/m ³ to conductivity in μS/cm
	COEFA	(μS·m ²)/100	linear coefficient for converting concentration to conductivity
	COEFB	kg (μS·m ⁵)/1000 kg ²	quadratic coefficient for converting concentration to conductivity

The output subroutine CPRT converts concentration to conductivity just prior to output by means of the coefficients in common CORR. If the coefficients 0,1,0 are entered, then the output values are equivalent to the concentrations. The output subroutine CPRT also converts flow rates to liters per minute just prior to output.

5. EXAMPLES

Verification Example: Single inflow, single pressure change

The first example allows verification by comparing with Example 4.4 in Earlougher (1977). A single pressure change is applied to a single inflow. Earlougher's example refers to an inflow zone of length 57.9 meters; this will be represented in two different ways, both as a single inflow and as a set of 58 inflows with a cell length of one meter. The example applies a pressure drop of 703.6 meters (1000 psi). The hydrological characteristics include a permeability of 6.5 millidarcy and a viscosity of 1.35 centipoise, giving a transmissivity of $2.697 \times 10^{-6} \text{ m}^2/\text{sec}$. The porosity-compressibility product is $2.05 \times 10^{-6} \text{ psi}^{-1}$, giving a storativity of 168.7×10^{-6} . The single drawdown occurs at time zero hours.

The input for this example problem with the inflow represented as a single point is shown below.

LINE	DATA
1	000, 2000, 1, 60.96, 0, -1
2	1
2.1	1900. 1.00 2.697e-6 168.7e-6 1899.5 0. 0.
3	1
3.1	0 703.57
4	0,100,15,9
4.1	0.2
4.2	0.5
4.3	1
4.4	2
4.5	5
4.6	10
4.7	20
4.8	50
4.9	100
5	1,0.5e-3
6	0
7	73., 1870., -40.

The input for the case of 58 inflows is identical to that above except for lines 2 and 2.x.

The transmissivity and storativity values have been scaled by 58:

LINE	DATA
2	58
2.1	1900. 1.00 46.495e-9 2.9092e-6 1899.5 0. 0.
2.2	1901. 1.00 46.495e-9 2.9092e-6 1900.5 0. 0.
2.3 to 57	(omitted)
2.58	1957. 1.00 46.495e-9 2.9092e-6 1956.5 0. 0.

The negative value at the end of the first line of the input indicates a constant density calculation. Both approaches to the inflow description result in the same number of simulation time steps (5,415), ranging from 7.8 to 73 seconds.

Figures 2 through 6 illustrate different aspects of the calculation. Figure 2 shows the flow rate as a function of time. The units are Earlougher's oil-field system of barrels per day (one liter per minute is 9.0573 barrels per day). This figure matches Figure 4.13 in Earlougher (1977). The flow rate is the same regardless of which representation of the inflow zone is used.

The flow rate and conductivity profiles for the single point representation are shown in Figures 3 and 4, and Figure 5 and 6 show the same for the 58-cell representation. The different approaches to modeling the inflow section have fairly limited effects. The flow rate shows a ramp for the line source, as opposed to a step for the point source, and there is a slower buildup of saturated concentration levels with the line source.

Variable Density Examples

In order to demonstrate the effect of well bore fluid density on the flow rate, two variations on the above single inflow, single pressure drop case are presented here. In the first, the well bore fluid is twice as dense as the inflow fluid; and, in the second case, the inflow fluid is twice as dense as the well bore fluid. The changes in the input file are shown below:

LINE	DATA
1	1000, 2000, 1, 60.96, 0, 2 [well bore fluid density high]
2	1
2.1	1900. 1.00 2.697e-6 168.7e-6 1899.5 0. 0. 1. 0.

LINE	DATA
1	1000, 2000, 1, 60.96, 0, 1
2	1
2.1	1900. 1.00 2.697e-6 168.7e-6 1899.5 0. 0. 2. 0. [density high]

Figures 7 and 8 show the flow rate as a function time for these two cases. In Figure 7, with the well bore fluid having a higher density, the pressure difference between the inflow and the well bore at the inflow depth is initially reduced, so the flow rate is also reduced. As the less dense fluid flows into the well bore and the denser fluid is pumped out, the pressure difference at the inflow depth increases, until, after about 30 hours the denser fluid initially in the well bore has been flushed out, and the problem converges with the constant density solution.

In Figure 8, with the inflow fluid having a higher density, the flow rate is initially similar to the constant density case. But as the denser fluid flows into the well, driving up the pressure at the inflow depth, the flow rate decreases. Eventually, after a few hundred hours, the flow stops since even with the drawdown of over 700 meters, the denser fluid in the well bore has resulted in equilibrium between the well and the inflow at the inflow depth.

Figure 9 shows the driving pressure differences in meters of water as a function of time for these cases.

Multiple Inflow, Multiple Pressure Change

One more complex example is presented which involves three inflows and two drawdown changes. The problem is a variation of the constant density verification

example at the start of this section. The inflow and drawdown change input is as follows:
shown below:

LINE	DATA
2	3
2.1	1500. 1.00 2.697e-6 168.7e-6 1399.5 0. 0.
2.2	1700. 1.00 2.697e-6 168.7e-6 1799.5 0. 0.
2.3	1900. 1.00 2.697e-6 168.7e-6 1899.5 0. 0.
3	2
3.1	10 703.57
3.1	50 -703.57

Notice that when the water level is at the surface, there is a circulation within the well from 1700 meters to 1500 meters due to inflow pressure head differences. The water level changes approximate turning a pump on at 10 hours and off at 50 hours.

Figure 10 shows the flow rate across the inflow at 1500 meters as a function of time. Note that initially the flow is negative, i.e. water is flowing from the wellbore into the formation. Figure 11 shows the concentration of the water flowing across the inflow.

Figures 12 and 13 show the flow rate and conductivity profiles for the entire wellbore at times before, during and after pumping.

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Figure 1. Dimensionless flow rate as a function of dimensionless time, showing the three solution techniques used in different subdomains.

Figure 2. Flow rate as a function of time for $T=2.697e-6$ m²/m/s, $S=168.7e-6$, drawdown of 703.57 meters. Matches Figure 4.13 in Earlougher (1977) for example of constant-pressure testing in an infinite-acting reservoir (Earlougher's Example 4.4).

Figure 3. Flow rate profile for 1-cell inflow.

Figure 4. Conductivity profile for 1-cell inflow.

Figure 5. Flow rate profile for 58-cell inflow.

Figure 6. Conductivity profile for 58-cell inflow.

Figure 7. Flow rate as a function of time with initial well bore fluid density doubled. Initially, the flow rate is lower than the constant density case; as the higher density wellbore fluid is flushed out, the flow rate converges with the constant density curve.

Figure 8. Flow rate as a function of time with inflow density doubled. Initially, the flow rate is the same as the constant density case, but as the higher density fluid flows into the well bore, the driving pressure difference at the inflow depth decreases until the flow stops after a few hundred hours.

Figure 9. Driving pressure difference (in meters of water) as a function of time. For the constant density calculation, this is simply the drawdown change of 703.6 meters. With higher density initial wellbore fluid, the pressure difference is reduced initially but converges with the constant density solution. With higher inflow density, the difference is initially the same as the constant density case, but decreases to zero as higher density fluid moves into the well bore.

Figure 10. Flow rate as a function of time across the inflow at 1500 m. Notice that the flow is initially negative, from the borehole into the formation. The pump is turned on at 10 hours, and it is turned off at 50 hours.

Figure 11. Fluid electric conductivity as a function of time across the inflow at 1500 m. The most striking feature is the delayed rise in conductivity after the pump starts at 10 hours. This is due to pre-production infiltration of low conductivity fluid from borehole to inflow formation. At late times after pumping, as more of the high conductivity fluid moves out of the wellbore, the concentration gradually drops as the front moves toward 1500m.

Figure 12. Flow rate profile for multiple inflow, multiple drawdown. Before pumping (e.g., 0.2 hr) there is a circulation from 1700m to 1500m. During the pumping period (e.g., 20 hr), the typical inflow pattern is seen. After pumping (e.g., 100 hr), there is a slight inflow at 1700m, a slight outflow at 1900m, and an outflow at 1500m.

Figure 13. Conductivity profile for multiple inflow, multiple drawdown. Flow before pumping (up to 10 hr) is from 1700m to 1500m. During pumping (10 to 50 hr), inflows are seen at 1900m, 1700m and 1500m. After pumping (after 50 hr), flow is again toward 1500m, both from above and below, pulling the high conductivity fronts back toward 1500m.

```

c*** fracture/borehole transient flow model
c*** june 1994
c*** lawrence berkeley laboratory, earth sciences division
c
c      implicit double precision (a-h)
c      implicit double precision (o-z)
c
c      include 'vpcomms.f'
c
c      call inits()
c
c=====
c BEGINNING OF TIME STEP LOOP
c=====
c
c*** compute flow rates and time step
c
c      100 if (ivard.eq.0) then
c          call flows
c      else
c          call dflows
c      endif
c      call onestep
c
c*** if the time step is too big, try again
c
c      if (ifailt.eq.0) goto 200
c      t = tp
c      write(iout,*) 'Reducing time step...'
c      goto 100
c
c*** time step size is good
c
c      200 call goodstep
c      if (t.le.tend) goto 100
c
c=====
c END OF TIME STEP LOOP
c=====
c
c      call endprob
c      stop
c      end
c
c*** subroutine flows
c*** calculate flows through each segment
c*** this subroutine is called at the beginning of each time step
c
c      subroutine flows
c
c      implicit double precision (a-h)
c      implicit double precision (o-z)
c
c      include 'vpcomms.f'
c
c*** maximum time step is minimum time to flush one-tenth
c*** of a segment. note that this time may still be too large
c*** if dispersion is significant
c
c      if (ifailt.eq.0) then
c          if (qtmax.ne.0.) then
c              delt = 0.5 * vol/qtmax
c              if (delt.gt.tamax) delt = tamax
c          else

```

```

              delt = 0.01 * tamax
          endif
      endif
c
c*** initialize segment flows
c
c      do i=1,iflim
c          qfrac(i) = 0.
c      enddo
c
c*** compute flow into segments from fractures
c*** it is possible to have more than one fracture in a single
c*** segment
c
c      do i=1,iflim
c
c*** compute flow rate as a function of pressure drop
c
c          qin(i) = 0.
c
c*** calculate effect of each pressure (drawdown) change
c
c          do idraw=1,idhlim
c              if (t.ge.delht(idraw)) then
c                  qdtid = avgint(t,delht(idraw),tcoef(i),delt)
c                  qin(i) = qin(i) +
c                      (qdtid * qcoef(i) * delhh(idraw))
c              endif
c          enddo
c
c*** calculate effect due to initial conditions
c
c          qinp = hfrac(i)-(xs(ifseg(i))-watley)
c          if (qinp.ne.0. .and. t.ge.tstart) then
c              qdtid = avgint(t,tstart,tcoef(i),delt)
c              qin(i) = qin(i) + qdtid * qcoef(i) * qinp
c          endif
c          qfrac(ifseg(i)) = qfrac(ifseg(i)) + qin(i)
c      enddo
c      call flowsa
c      return
c      end
c
c*** try out a time step
c
c      subroutine onestep()
c
c      implicit double precision (a-h)
c      implicit double precision (o-z)
c
c      include 'vpcomms.f'
c
c      ifailt = 0
c      tp = t
c      t = t + delt
c
c*** save current mass and volume totals
c
c      gtwins = gtwins
c      gtdins = gtdins
c      gtmos = gtmos
c      gtdos = gtdos
c      gtfms = gtfms
c      gtbms = gtbms

```

```

      gtvins = gtvins
      gtvos = gtvos
      gtfbva = gtfbva
      gtfbva = gtfbva
      topas = topa
      topds = topd

c
c*** compute fracture inflows and concentrations to the borehole
c
      call cfrac

c
c*** compute mass transfer for the time step
c
      call tstep
      return
      end

c
c*** complete a time step
c
      subroutine goodstep()

c
      implicit double precision (a-h)
      implicit double precision (o-z)

c
      include 'vpcomms.f'

32 c
      do j=1,ilpt
         if (t.ge.pt(j)) then
            call cprt
            pt(j)=2.*tend
         endif
      enddo

c
      if (delt.le.0.) then
         write(iout,*)'ERROR--time step <= 0!'
         stop
      endif

c
      tsavg = tsavg + delt
      nstep = nstep + 1
      if (delt.lt.tslo) tslo = delt
      if (delt.gt.tshi) tshi = delt

c
c*** write extra output for report plots
c
      cfl = cfrac(ifsegil,1)
      write(80, '(3f12.5)') ((t-delt/2.)/3600,
         (qin(1)*60000.),
         (cfsat + cfl*(coefa + cfl*coefb))
      return
      end

c
c*** initialize constants, etc.
c
      subroutine inits()

c
      implicit double precision (a-h)
      implicit double precision (o-z)

c
      include 'vpcomms.f'

c
c*** input and initialization
c
      do i=1,imax

```

```

         cfrac(i,1)=0.
      enddo
      gtbfa = 0.
      gtbfv = 0.
      gtdina = 0.
      gtdout = 0.
      gtfbm = 0.
      gtfbv = 0.
      gtvina = 0.
      gtvout = 0.
      idout = 9
      iin = 5
      iout = 6
      do i=1,ifmax
         iplim(i) = 0
      enddo
      iprt = 7
      iqout = 8
      itog = 1
      ivard = 0
      pcmax = 0.
      pi = 3.141592654
      qtmx = 0.

c
      open (unit=iin, file='VNB.DAT', status='OLD', form='FORMATTED')
      open (unit=iout, file='VNB.MSG', status='NEW', form='FORMATTED')
      open (unit=iprt, file='VNB.OLT', status='NEW', form='FORMATTED')
      write(iout,*)'Files opened...'

c
c
c*** read borehole parameters
c*** note: set topd <= 0 for constant density
c*** xtop is top of analysis region (m)
c*** xtop may be adjusted during discretization
c*** xbot is bottom of analysis region (m)
c*** note: x increases downward, zero at surface
c*** delx is segment length (m)
c*** diam is borehole diameter (input in cm, converted to m)
c*** area is cross-sectional area of hole (m**2)
c*** vol is segment volume (m**3)
c*** ilin is number of segment over analysis region
c
c*** input stream--one free format record
c*** xtop, xbot, delx, diam
c
      read(iin,*) xtop, xbot, delx, diam, watlev, topd

c
      if (topd.gt.0.) then
         ivard = 1
         write(iout,*)'Variable density model'
      else
         topd = 1.0
         write(iout,*)'Constant density model'
      endif

c
c*** convert diameter in cm to m
c
      diam = diam/100.

c
c*** check geometry
c
      if (xbot.lt.xtop) then

```

```

        write(iout,940)
        stop
    endif
    xdist = xbot-xtop
    xint = xdist/delx
    if (xint.lt.1) then
        write(iout,950)
        stop
    endif
    ilim = xint
    if (ilim.gt.imax) then
        write(iout,960)imax
        stop
    endif
    xtopi = xtop
    xtop = xbot-(ilim*delx)
    deltop = abs(xtop-xtopi)

c
c***  if delta-x does not fit over the interval within 1% of
c***  a delta-x, then make a note
c
    if (deltop.gt.(0.01*delx)) then
        write(iout,960)ilim,delx
        write(iout,970)deltop,xtop
    else
        write(iout,960)ilim,delx
    endif

c
c***  calculate cross-sectional area and volume of a segment
c
    rad = diam/2.
    area = pi*rad*rad
    vol = area*delx
    write(iout,980)diam,area,vol

c
c***  compute segment midpoints
c***  note--sign reversed for graphing
c
    do i=1,ilim
        xs(i) = xbot + (0.5-i)*delx
    enddo

c
c***  read flow from fractures
c***  input stream -- free format
c***  number of fractures
c***  one record for each fracture --
c***  position (m), flow rate (m**3/sec), concentration of
c***  solute (kg/m**3), and solute flow start time (h)
c
c***  read fracture data
c
    read(iin,*)iflim
    if (iflim.gt.ifmax) then
        write(iout,910)ifmax
        stop
    endif
    j=iflim
    do i=1,j
        if (ivard.eq.0) then
            read(iin,*)xin(i),cin(i,1),tfrac(i),sfrac(i),hfrac(i),
            vfrac(i,1),cfz(i,1,1),cin(i,2)
            cin(i,2) = 1.
            cfz(i,1,2) = 1.
        else

```

```

            read(iin,*)xin(i),cin(i,1),tfrac(i),sfrac(i),hfrac(i),
            vfrac(i,1),cfz(i,1,1),cin(i,2),cfz(i,1,2)
        endif
        if (vfrac(i,1).gt.0.) then
            ifznum(i) = 1
        else
            ifznum(i) = 0
        endif
    enddo

c
c***  locate fracture on segments
c
    iskipit = 0
    if ((xin(i).gt.xbot) .or. (xin(i).lt.xtop)) then
        write(iout,930)xin(i)
        iflim = iflim-1
        iskipit = 1
    endif
    if (iskipit.eq.0) then
        ifseg(i) = iconvx(xtop,xbot,delx,xin(i))
        rad = diam/2
        tcoef(i) = tfrac(i) / (sfrac(i)*rad*rad)
        qcoef(i) = 2. * pi * tfrac(i)
    endif
enddo

c
c***  read drawdowns and times
c***  input stream -- free format
c***  number of changes
c***  one record for each change--
c***  time (hrs), drawdown (m)
c
c***  read drawdown data
c
    read(iin,*)idhlim
    if (idhlim.gt.idhmax) then
        write(iout,1910)idhmax
        stop
    endif

c
    j=idhlim

c
    do i=1,j
        read(iin,*)delht(i),delhh(i)
        delht(i) = delht(i) * 3600.
    enddo

c
c***  read time parameters
c***  input stream--
c***  start time (hrs), end time (hrs), number of prints
c***  then, print times (hrs)
c***  note: all times are converted to seconds
c
    read(iin,*)tstart,tend,tmax,ilpt
    tstart = tstart * 3600.
    tend = tend * 3600.
    tmax = tmax * 60.

c
    if (tend.lt.tstart) then
        write(iout,2910)
        stop
    endif
    if (ilpt.gt.ilpt) then
        write(iout,915)ilpt
    endif
enddo

```

```

c
c*** read in print-time parameters
c
read(iin,*) (pt(1),i=1,ilpt)
do i=1,ilpt
  pt(i)=pt(i)*3600.
enddo

c
c*** read dispersion parameter
c*** input stream--(one record)
c*** type code, parameter
c*** at the end of this routine, dka has units m**3/sec
c
read(iin,*) itypdk,dk

c
c*** if itypdk=1, value is constant over all segments
c*** if itypdk=2, value is for mean velocity
c*** if itypdk=3, value is for mean velocity squared
c
dksi = dk * area/delx
do i=1,ilim
  dks(i) = dksi
enddo

c
c*** read initial concentrations and densities
c*** input records:
c*** icon n=number of initial values specified
c*** x, c0 pairs of x values and initial concentrations
c
do i=1,ilim
  cxt(i,1,1)=0.
  cxt(i,1,2)=1.
  cxt(i,2,2)=1.
enddo

c
read(iin,*) icon
if (icon .gt. 0) then
  do i=1,icon
    if (iiverd.eq.0) then
      read(iin,*) x,c0
      d0 = 1.
    else
      read(iin,*) x,c0,d0
    endif
    if ((x.gt.xbot) .or. (x.lt.xtop)) then
      write(iout,900)x
    else
      iseg=iconvx(xtop,xbot,delx,x)
      if (cxt(iseg,1,1).eq.0.) then
        cxt(iseg,1,1)=c0
        cxt(iseg,1,2)=d0
        cxt(iseg,2,2)=d0
      else
        write(iout,3910)x
      endif
    endif
  enddo
endif

c
c*** offset is the background conductivity in S/m
c*** coefa is the linear term for converting concentrations
c*** in kg/m**3 to conductivity in S/m (at 20 C)
c*** coefb is the second degree term for converting
c*** concentrations to conductivity (at 20 C)

```

```

c
read(iin,*) offset,coefa,coefb

c
c*** close input file after reading data
c
close (unit=iin)

c
c*** compute the starting mass and volume in the system
c
write(iout,*) 'Input processed...'
call mass
tmf0 = smf
tdf0 = sdf
tmb0 = smb
tdb0 = sdb
tvm0 = svf
tvb0 = svb
watlev0 = watlev
topv0 = (xtop-watlev)*area
topm0 = cxt(iin,1,1) * topv
topd0 = topd
tshi = 0.
tslo = 1.e30
teavg = 0.
ntstep = 0
t = tstart
delt = 0.001*tmax
topv = topv0

c
return

900 format(' *** NOTE *** initial concentration position',
  ' invalid--ignored'
  ' position is ',f15.5)
910 format(' Maximum number of fractures is ',i4,' -- aborting')
915 format(' Maximum number of print times is ',i4,' -- aborting')
930 format(' *** NOTE *** fracture position outside of region ',f10.4,
  ' -- ignored')
940 format(' Top of region is below bottom of region--aborting')
950 format(' delta-x is greater than region size--aborting')
960 format(' Region has been divided into ',i4,' segments with',
  ' length ',f10.4,' (m)')
970 format(' *** NOTE *** Top of region has been moved by ',
  ' f10.4,' (m) to ',f10.4,' (m)')
980 format(' Each section has diameter ',f12.5,' (m)')
  ' cross-sectional area ',f12.5,' (m**2)'
  ' and volume ',f12.5,' (m**3)')
990 format(' Maximum number of segments is ',i4,' -- aborting')
1910 format(' Maximum number of drawdowns is ',i4,' -- aborting')
2910 format(' End time before start time -- aborting')
3910 format(' *** NOTE *** multiple initial concentrations',
  ' for one segment'
  ' second value ignored--position is ',f15.5)
end

c
c*** function iconvx
c*** convert x position to segment index
c*** segment 1 begins at xbot
c*** segment ilim ends at xtop
c*** this function is used outside of time steps
c
function iconvx(xtop,xbot,delt,x)

c
implicit double precision (x-h)

```

```

implicit double precision (a-z)
c
idrup = (xbot-x) / delx+1.
if (x.eq.xtop) idrup = idrup-1
iconvx = idrup
return
end

c
c*** compute the mass and volume in the system
c
subroutine smass()
c
implicit double precision (a-h)
implicit double precision (o-z)
c
include 'vpcomms.f'
c
smb = 0.
sdb = 0.
c
c*** sum mass in borehole
c
do i=1,ilim
    smb = smb + cxt(i,itog,1)
    sdb = sdb + cxt(i,itog,2)
enddo
smf = smb * vol
sdf = sdb * vol
c
c*** compute volume in borehole
c
svb = ilim * vol
c
c*** sum mass and volume in fractures
c
smf = 0.
sdf = 0.
svf = 0.
do i=1,iflim
    if (ifznum(i).gt.0) then
        do j=1,ifznum(i)
            vij = vfrac(i,j)
            smf = smf + cfz(i,j,1)*vij
            sdf = sdf + cfz(i,j,2)*vij
            svf = svf + vij
        enddo
    endif
enddo
c
return
end

c
c*** subroutine cpvt
c*** print out concentration, flow rate and density arrays
c*** this subroutine is executed whenever concentration arrays
c*** are requested during the time steps, or at the end of the
c*** problem
c*** note: units of output conductivity is S/m
c
subroutine cpvt
c
implicit double precision (a-h)
implicit double precision (o-z)
c

```

```

include 'vpcomms.f'
c
c*** output time in hours and concentrations with ascending
c*** values (note negative increment in loop)
c
c*** output time in hours (convert from seconds)
c
th = t / 3600.
write(iprt, '(f6.2)')th
write(iqout, '(f6.2)')th
write(idout, '(f6.2)')th
c
c*** convert concentrations in kg/m**3 to electric conductivity
c*** in uS/cm using input coefficients
c
do i=1,ilim
    ci = cxt(i,itog,1)
    sigma(i) = ofset + ci*(coefa + ci*coefb)
    qlm(i) = 60000.*qxxt(i)
enddo
c
write(idout, 920)th
write(iprt, '(2f15.5)')(xs(i),sigma(i),i=ilim,1,-1)
write(idout, '(2f15.5)')(xs(i),cxt(i,itog,2),i=ilim,1,-1)
write(iqout, '(2f15.5)')(xs(i),qlm(i),i=ilim,1,-1)
return
c
920 format(' Printing conductivity at time ',e15.5,' (hrs)')
end
c
c*** end of problem
c
subroutine endprob()
c
implicit double precision (a-h)
implicit double precision (o-z)
c
include 'vpcomms.f'
c
c*** check for final print
c
needp = 0
do j=1,ilpt
    if (pt(j).lt.(2.*tend)) needp=1
enddo
if (needp.ne.0) call cpvt
c
c*** end of problem, check mass conservation
c
call smass
c
c*** total system mass
c
smass = smf + smb + topm
edens = sdf + sdb + (topd*topv)
exmass = (tm0 + tmf0 + tope0 + gtdina) - gtdout
exdens = (td0 + tdf0 + (topd0*topv0) + gtdina) - gtdout
perr = 0.
derr = 0.
if (exmass.ne.0.) perr = ((smass-exmass) / exmass) * 100.
if (exdens.ne.0.) derr = ((edens-exdens) / exdens) * 100.
c
c*** fracture mass
c

```

```

exfm = (tmf0 + gtbfm) - gtfbm
exfd = (tdf0 + gtbfd) - gtfbd
pferr = 0.
dferr = 0.
if (exfm.ne.0.) pferr = ((smf-exfm) / exfm) * 100.
if (exfd.ne.0.) dferr = ((sdf-exfd) / exfd) * 100.

c*** total system volume (convert from m**3 to l)
c
if (topv0.gt.topv) then
  gtvout = gtvout + (topv0-topv)
else
  if (topv0.lt.topv) gtvina = gtvina + (topv - topv0)
endif
svf = svf * 1000.
svb = svb * 1000.
topv = topv * 1000.
tv0 = tv0 * 1000.
tvf0 = tvf0 * 1000.
topv0 = topv0 * 1000.
gtvina = gtvina * 1000.
gtvout = gtvout * 1000.
gtbfv = gtbfv * 1000.
gtbfv = gtbfv * 1000.

evol = svf + svb + topv
exvol = (tv0 + tvf0 + topv0 + gtvina) - gtvout
pverr = 0.
if (exvol.ne.0.) pverr = ((evol-exvol) / exvol) * 100.

c*** fracture volume
c
exfv = (tvf0 + gtbfv) - gtfbv
pferr = 0.
if (exfv.ne.0.) pferr = ((svf-exfv) / exfv) * 100.

c
write(iout,*) '
write(iout,*) 'ELECTROLYTE MASS BALANCE:'
write(iout,*) 'Starting mass in system (kg): ',
  (tmf0+tmf0+topm0)
write(iout,*) ' (Borehole (kg):',tmf0,')'
write(iout,*) ' (Fractures (kg):',tmf0,')'
write(iout,*) ' (Top section (kg):',topm0,')'
write(iout,*) 'Mass added to system (kg): ',gtmna
write(iout,*) 'Mass out of system (kg): ',gtmout
write(iout,*) '
write(iout,*) 'Expected ending mass (kg): ',exmass
write(iout,*) '
write(iout,*) 'Actual ending mass (kg): ',amass
write(iout,*) ' (Borehole (kg):',smf,')'
write(iout,*) ' (Fractures (kg):',sdf,')'
write(iout,*) ' (Top section (kg):',topm,')'
write(iout,*) '
write(iout,*) 'Percent error: ',perr

c
write(iout,*) '
write(iout,*) 'FLUID MASS BALANCE (DENSITY BASED):'
write(iout,*) 'Starting mass in system (kg): ',
  (tdf0+tdf0+(topd0*topv0/1000.))
write(iout,*) ' (Borehole (kg):',tdf0,')'
write(iout,*) ' (Fractures (kg):',tdf0,')'
write(iout,*) ' (Top section (kg):',topd0*topv0/1000.,')'
write(iout,*) 'Mass added to system (kg): ',gtdina
write(iout,*) 'Mass out of system (kg): ',gtdout

```

```

write(iout,*) '
write(iout,*) 'Expected ending mass (kg): ',exdms
write(iout,*) '
write(iout,*) 'Actual ending mass (kg): ',edms
write(iout,*) ' (Borehole (kg):',adb,')'
write(iout,*) ' (Fractures (kg):',sdf,')'
write(iout,*) ' (Top section (kg):',topd*topv/1000.,')'
write(iout,*) '
write(iout,*) 'Percent error: ',derr
write(iout,*) '
write(iout,*) 'VOLUME BALANCE:'
write(iout,*) 'Starting vol in system (l): ',(tv0+tvf0+topv0)
write(iout,*) ' (Borehole (l):',tv0,')'
write(iout,*) ' (Fractures (l):',tvf0,')'
write(iout,*) ' (Top section (l):',topv0,')'
write(iout,*) 'Vol added to system (l): ',gtvina
write(iout,*) 'Vol out of system (l): ',gtvout
write(iout,*) '
write(iout,*) 'Expected ending vol (l): ',exvol
write(iout,*) '
write(iout,*) 'Actual ending vol (l): ',evol
write(iout,*) ' (Borehole (l):',svb,')'
write(iout,*) ' (Fractures (l):',svf,')'
write(iout,*) ' (Top section (l):',topv,')'
write(iout,*) '
write(iout,*) 'Percent error: ',pverr
write(iout,*) '
write(iout,*) '
write(iout,*) 'FRACTURE ZONES ELECTROLYTE MASS BALANCE:'
write(iout,*) 'Starting mass in frac (kg): ',tmf0
write(iout,*) 'Mass to frac from bore (kg): ',gtbfb
write(iout,*) 'Mass to bore from frac (kg): ',gtfbm
write(iout,*) '
write(iout,*) 'Expected ending mass (kg): ',exfm
write(iout,*) '
write(iout,*) 'Actual ending mass (kg): ',smf
write(iout,*) '
write(iout,*) 'Percent error: ',pferr
write(iout,*) '
write(iout,*) 'FRACTURE ZONES FLUID MASS BALANCE:'
write(iout,*) 'Starting mass in frac (kg): ',tdf0
write(iout,*) 'Mass to frac from bore (kg): ',gtbfb
write(iout,*) 'Mass to bore from frac (kg): ',gtfbf
write(iout,*) '
write(iout,*) 'Expected ending mass (kg): ',exfd
write(iout,*) '
write(iout,*) 'Actual ending mass (kg): ',sdf
write(iout,*) '
write(iout,*) 'Percent error: ',dferr
write(iout,*) '
write(iout,*) 'FRACTURE ZONES VOLUME BALANCE:'
write(iout,*) 'Starting vol in frac (l): ',tvf0
write(iout,*) 'Vol to frac from bore (l): ',gtbfv
write(iout,*) 'Vol to bore from frac (l): ',gtfbv
write(iout,*) '
write(iout,*) 'Expected ending vol (l): ',exfv
write(iout,*) '
write(iout,*) 'Actual ending vol (l): ',svf
write(iout,*) '
write(iout,*) 'Percent error: ',pferr
write(iout,*) '
write(iout,*) '
write(iout,*) 'Number of time step used: ',ntstep
write(iout,*) 'Minimum time step used (min): ',tsto/60.)

```



```

write(iout,*) 'Average time step used (min):', ((tsavg/60.)/ntstep)
write(iout,*) 'Maximum time step used (min):', (tshi/60.)
write(iout,*) '
write(iout,*) 'Maximum percentage cell mass transfer: ',pcmax
write(iout,*) '
write(iout,*) '
write(iout,*) '*** PROBLEM FINISHED ***'
return
end

c
c*** subroutine tstep
c*** calculate concentrations at next time step
c*** this is the main mass transport time step routine
c*** executed for each time step, and loops over each segment
c
c subroutine tstep
c
c implicit double precision (a-h)
c implicit double precision (o-z)
c
c include 'vpcomms.f'
c
c*** tm1 -- initial mass in segment
c*** tm2 -- final mass in segment
c*** dmal -- rate change in mass due to advection from left (+ = in)
c*** dmar -- rate change in mass due to advection to right (- = out)
c*** dmdl -- rate change in mass due to diffusion with left (+ = in)
c*** dmdr -- rate change in mass due to diffusion with right (- = out)
c*** dmf -- rate change in mass due to fracture inflow (+ = in)
c*** dme -- rate change in mass due to external outflow (- = out)
c*** (occurs at top only)
c
pcmt = 0.
fact = 1.e30
dme = 0.
dqe = 0.
c
c*** loop over each segment
c
itogx = 3-itog
do i=1,ilim
    ipl = i+1
    exti = ext(i,itog,1)
    dxti = ext(i,itog,2)
c
c*** starting mass in the segment
c
    tm1 = exti * vol
    tdl = dxti * vol
c
c*** mass transfer with fracture zone
c
    if (cfrc(i,1).ne.0.) then
        dmf = cfrc(i,1) * qfrac(i)
    else
        dmf = 0.
    endif
    if (cfrc(i,2).ne.0.) then
        ddf = cfrc(i,2) * qfrac(i)
    else
        ddf = 0.
    endif
enddo
c
c*** advection/diffusion with next lower cell

```

```

c
c if (i.gt.1) then
c     iml = i-1
c     dmdl = dmdr
c     dmal = dmar
c     ddel = dder
c else
c     dmal = 0.
c     ddel = 0.
c     dmdl = 0.
c endif
c
c*** advection/diffusion with next upper cell
c
c if (i.lt.ilim) then
c
c note: full upstream weighting is used. without
c*** upstream weighting, these equations would
c*** use (exti+ext(ipl,itog))/2. in place of
c*** exti or ext(ipl,itog)--that is, the
c*** concentration at the interface would be
c*** the average instead of the upstream value
c
c if (qnx(i).gt.0.) then
c     dmar = -exti * qnx(i)
c     dder = -dxti * qnx(i)
c else
c     dmar = -ext(ipl,itog,1) * qnx(i)
c     dder = -ext(ipl,itog,2) * qnx(i)
c endif
c dmdr = (ext(ipl,itog,1)-exti) * dks(i)
c if (qfrac(i).lt.0. .and. i.gt.1) then
c
c if the current cell has an outflow,
c*** advection mass in flows out to outflow (as much as
c*** possible)
c
c if (qnx(i-1).gt.0.) then
c     if (abs(qfrac(i)).ge.qnx(i-1)) then
c         dmf = -dmal
c         ddf = -ddel
c         if (dmdl.gt.0.) dmf = dmf - dmdl
c     else
c         dmf = -(abs(qfrac(i))/qnx(i-1))*dmal
c         ddf = -(abs(qfrac(i))/qnx(i-1))*ddel
c         if (dmdl.gt.0.)
c             dmf = dmf-(abs(qfrac(i))/qnx(i-1))*dmdl
c     endif
c endif
c if (qnx(i).lt.0.) then
c     if (abs(qfrac(i)).ge.abs(qnx(i))) then
c         dmf = dmf - dmar
c         ddf = ddf - dder
c         if (dmdr.gt.0.) dmf = dmf - dmdr
c     else
c         dmf = -(qfrac(i)/qnx(i))*dmar
c         ddf = -(qfrac(i)/qnx(i))*dder
c         if (dmdr.gt.0.)
c             dmf = dmf-(abs(qfrac(i))/qnx(i))*dmdr
c     endif
c endif
c qfnext(i) = -dmf*delt
c qfdens(i) = -ddf*delt
c endif

```

```

      else
        dmar=0.
        ddr=0.
        ddr=0.
c
c*** outflow considered only at top (no mass flow back in at top)
c
      if (qnext(i).gt.0.) then
        dme = -exti * qnext(i)
        dde = -dxti * qnext(i)
      else
        if (qnext(i).lt.0.) then
          dde = -topd * qnext(i)
        endif
      endif
c
c*** check for segment mass limitations
c*** if more mass is being moved out of a segment than is in
c*** the segment, write an error message and stop. This problem
c*** can be fixed by reducing the time step or increasing the
c*** segment length
c
      summo = 0.
      if (dmt.lt.0.) summo = summo - dmt
      if (dme.lt.0.) summo = summo - dme
      if (dml.lt.0.) summo = summo - dml
      if (dmdl.lt.0.) summo = summo - dmdl
      if (dmar.lt.0.) summo = summo - dmar
      if (ddr.lt.0.) summo = summo - ddr
c
c*** attempted to transfer more than 10% mass out of the cell
c*** --time step is too big
c
      if (summo.gt.0.) then
        pcm = 100.*(summo*delt) / tml
        if (pcm.gt.pcm) pcm = pcm
        if (pcm.gt.100) then
          f = 100./pcm
          if (f.lt.fact) fact = f
          ifailt = 1
        endif
      endif
c
c*** compute new mass in segment
c
      tm2 = tml + (dmt+dme+dml+dmdl+dmar+ddr)*delt
      td2 = tml + (ddt+dde+ddl+ddar)*delt
      ext(i,itoqx,1) = tm2/vol
      ext(i,itoqx,2) = td2/vol
c
c
c*** take care of outflows from cell ilim (top)
c
      vout = qnext(ilim)*delt
      amout = -dme*delt
      adout = -dde*delt
      if (dme.lt.0.) then
        gtmout = gtmout + vout*(topm/topv)
        topm = topm - vout*(topm/topv)
        topm = topm + amout
      endif
      if (dde.lt.0.) then
        gtdout = gtdout + vout*topd

```

```

c      write(iout,*)'gtdout=',gtdout
      topd = (adout-(vout*topd)+(topd*topv))/topv
      gtvout = gtvout + vout
c
c***
      if (dde.gt.0.) then
        din = -vout*topd0
        gtdina = gtdina + din
        topd = (adout+din+(topd*topv))/topv
        gtvina = gtvina - vout
      endif
c
c*** end of loop over segments
c
c*** if the mass transfer is good (time step not too big),
c
      if (ifailt.eq.0) then
c
c*** add mass to fracture zone volumes if necessary
c
        do i=1,iflim
          if (qin(i).lt.0) then
            vii = abs(qin(i)*delt)
            cii = qfmax(ifseg(i))/vii
            dii = qfmax(ifseg(i))/vii
            ifznum(i) = ifznum(i)+1
            if (ifznum(i).gt.ifzmax) then
c
c*** if fracture is full, combine the older volumes in order to
c*** accomodate more inflow
c
              do j=1,ifzmax
                if (j.eq.1) then
                  cfz(i,j,1) = cfz(i,j,1)*vfrac(i,j)
                  cfz(i,j,2) = cfz(i,j,2)*vfrac(i,j)
                else
                  if (j.le.10) then
                    cfz(i,1,1) = cfz(i,1,1)
                      + (cfz(i,j,1)*vfrac(i,j))
                    cfz(i,1,2) = cfz(i,1,2)
                      + (cfz(i,j,2)*vfrac(i,j))
                    vfrac(i,1) = vfrac(i,1) + vfrac(i,j)
                  else
                    cfz(i,(j-9),1) = cfz(i,j,1)
                    cfz(i,(j-9),2) = cfz(i,j,2)
                    vfrac(i,(j-9)) = vfrac(i,j)
                  endif
                endif
              enddo
              cfz(i,1,1) = cfz(i,1,1) / vfrac(i,1)
              cfz(i,1,2) = cfz(i,1,2) / vfrac(i,1)
              ifznum(i) = ifzmax+9
            endif
          endif
c
c*** transfer to fracture
c
          vfrac(i,ifznum(i)) = vii
          cfz(i,ifznum(i),1) = cii
          cfz(i,ifznum(i),2) = dii
          gtbfm = gtbfm + vii*cii
          gtbfd = gtbfd + vii*dii
          gtbfv = gtbfv + vii
        enddo
      endif
c

```

```

      if (pcmt.gt.pcmx) pcmx = pcmt
c*** write out flow at top in liters/min
c
      thrs = t / 3600.
      ql = qmxt(111m) * 60000.
      qol = qcvout * 1000.
c
c*** toggle row pointer
c
      itop=itopx
c
c*** amass is expected total mass in system (total in - total out)
c*** gtm is actual total mass in system
c*** if these numbers differ by more than 0.1% of total input mass,
c*** signal a mass conservation error. this requires that the
c*** numerical accuracy of all the discrete mass calculations be
c*** at least three digits (99.9%).
c*** this is executed once each time step
c
      call amass
      gtm = smb + smf + topm
      gtd = sdb + sdf + (topd*topv)
      if (gtm.ne.0.) then
        amass=(tm0 + tmf0 + topm0 + gtdina)-gtmout
        errm=gtm-amass
        errp=(100.*errm)/(tm0 + tmf0 + topm0 + gtdina)
        if (abs(errp).gt.0.1) then
          tm0x = tm0 + tmf0 + topm0
          write(iout,900)errp,gtm,amass,tm0x,gtdina,gtmout,
            smb,smf,topm
          stop
        endif
      endif
      if (gtdina.ne.0.) then
        edens=(td0 + tdf0 + (topd0*topv0) + gtdina)-gtdout
        errd=gtd-edens
        drrp=(100.*errd)/(td0+tdf0+(topd0*topv0)+gtdina)
        if (abs(drrp).gt.0.1) then
          td0x = td0 + tdf0 + (topd0*topv0)
          write(iout,920)drrp,gtd,edens,td0x,gtdina,gtdout,
            sdb,sdf,(topd*topv)
          stop
        endif
      endif
    endif
  else
c*** time step was too big -- cancel mass transfer, reduce delta-t
c
      ot = delt
      delt = 0.5 * (delt * fact)
c
      gtdina = gtdins
      gtdina = gtdins
      gtdout = gtdoes
      gtdout = gtdoes
      gtdfm = gtdfms
      gtdfm = gtdfms
      gtdvina = gtdvins
      gtdvout = gtdvos
      gtdfv = gtdfvs
      gtdfbv = gtdfbv

```

```

c*** restore fracture values if the time step is too big
c
      do i=1,iflim
        n = fsave(i,151)
        ifrmum(i) = n
        if (n.gt.0) then
          do j=1,n
            vfrac(i,j) = fsave(i,j)
            cfx (i,j,1) = fsave(i,j+n1)
            cfs (i,j,2) = fsave(i,j+(2*n))
          enddo
        endif
      enddo
    endif
  endif
  return
c
900 format(' *** NOTE *** mass conservation error ',f10.5,' (%)')
      ' Observed mass in system (kg): ',f20.5//
      ' Expected mass in system (kg): ',f20.5//
      ' Initial mass in system (kg): ',f20.5//
      ' Added mass to system (kg): ',f20.5//
      ' Removed mass of system (kg): ',f20.5//
      ' Mass in borehole (kg): ',f20.5//
      ' Mass in fractures (kg): ',f20.5//
      ' Mass in top (kg): ',f20.5//
910 format(2f15.6)
920 format(' *** NOTE *** dens conservation error ',f10.5,' (%)')
      ' Observed mass in system (kg): ',f20.5//
      ' Expected mass in system (kg): ',f20.5//
      ' Initial mass in system (kg): ',f20.5//
      ' Added mass to system (kg): ',f20.5//
      ' Removed mass of system (kg): ',f20.5//
      ' Mass in borehole (kg): ',f20.5//
      ' Mass in fractures (kg): ',f20.5//
      ' Mass in top (kg): ',f20.5//
    end
c
      subroutine flowsa
c
c*** frac holds the multipliers for schemes 2 and 3
c
      implicit double precision (a-h)
      implicit double precision (o-z)
c
      include 'vpcomms.f'
c
c*** compute flow up to next segment and total flow
c
      do i=1,111m
        if (i.eq.1) then
          qtot(i) = qfrac(i)
          qmxt(i) = qtot(i)
        else
          isgn = qtot(i)*qfrac(i)
          if (isgn.ge.0.) then
            qtot(i) = abs(qmxt(i-1) + qfrac(i))
          else
            if (abs(qfrac(i)).le.abs(qmxt(i-1))) then
              qtot(i) = abs(qmxt(i-1))
            else
              qtot(i) = abs(qfrac(i))
            endif
          endif
        endif
      enddo
    endif
  endif
c

```

```

c*** compute flow to next cell up the hole. qnxt(ilim) is flow
c*** out of (into) the top of the section
c
      qnxt(i) = qnxt(i-1) + qfrac(i)
      endif
    enddo
c
c*** compute maximum time step and Reynold's number
c
      qtnax = qtot(1)
      do i=2,ilim
        if (qtot(i).gt.qtnax) qtnax=qtot(i)
      enddo
      vmax = qtnax/area
      diam = 2.*sqrt(area/3.14159)
      rmaxx = vmax*diam / 0.3e-6
      dtm = delt/60.
c
c*** compute the velocity dependent dispersion coefficients
c*** if dispersion type is 2 or 3
c
      if (itypdk.gt.1) then
        dksl = dk*area/delt
c
c*** find first nonzero, minimum, maximum and mean velocities
c
        qfnz = 0.
        qmin = 1.e20
        qmax = 0.
        if (itypdk.eq.2) then
          do i=1,ilim
            if ((qfnz.eq.0.).and.(qtot(i).ne.0.)) qfnz=qtot(i)
            if (qtot(i).gt.qmax) qmax=qtot(i)
            if (qtot(i).lt.qmin) qmin=qtot(i)
          enddo
        else
          do i=1,ilim
            qtoti2 = qtot(i)*qtot(i)
            if ((qfnz.eq.0.).and.(qtoti2.ne.0.)) qfnz=qtoti2
            if (qtoti2.gt.qmax) qmax=qtoti2
            if (qtoti2.lt.qmin) qmin=qtoti2
          enddo
        endif
        qavg = (qmin+qmax)/2.
        if (qavg.eq.0.) then
          write(iout,910)
          stop
        endif
c
        do i=1,ilim
          if (qtot(i).ne.0.) then
            qtoti = qtot(i)
            if (itypdk.eq.3) qtoti = qtoti*qtoti
c
c*** use first nonzero flow for zero flow area
c
            else
              qtoti = qfnz
            endif
            frac(i) = qtoti/qavg
          enddo
c
c*** compute harmonic mean of scaled dispersion parameter
c

```

```

      j=ilim-1
      do i=1,j
        qx = 2./(1./frac(i) + 1./frac(i+1))
        dks(i) = dksl*qx
      enddo
    endif
    return
c
910 format(/' *** NOTE *** average flow rate is zero -- aborting')
end
c
c*** subroutine cfrac
c*** prepare fracture concentrations for time step
c*** this subroutine is executed during each time step,
c*** and it loops over each fracture
c
      subroutine cfrac
c
      implicit double precision (a-h)
      implicit double precision (o-z)
c
      include 'vpcommon.f'
c
c*** reset values first
c
      do i=1,iflim
        cfrac(ifseg(i),1)=0.
        cfrac(ifseg(i),2)=0.
      enddo
c
c*** save fracture values in case the time step is too big
c
      do i=1,iflim
        n = ifznum(i)
        fsave(i,151)=ifznum(i)
        if (n.gt.0) then
          do j=1,n
            fsave(i,j) = vfrac(i,j)
            fsave(i,(j+n)) = cfx(i,j,1)
            fsave(i,(j+(2*n))) = cfz(i,j,2)
          enddo
        endif
      enddo
c
c*** compute mass inflow during time step
c*** more than one fracture may be in a segment
c
      do i=1,iflim
        is=ifseg(i)
c
c*** compute concentration
c
        if (qini(i).lt.0.) then
          c = ext(is,itog,1)
          d = ext(is,itog,2)
        else
          if (ifznum(i).eq.0.) then
            c = cin(i,1)
            d = cin(i,2)
            gtwina = gtwina + qin(i)*c*delt
            gtdina = gtdina + qin(i)*d*delt
            gtvina = gtvina + qin(i) *delt
          else
            v = qin(i)*delt

```

```

      cm = 0.
      dm = 0.
      vz = 0.
500   iz = ifznum(i)
      v1iz = vfrac(i,iz)
      if (v.gt.(vz+v1iz)) then
        vz = vz + v1iz
        xm = cfx(i,iz,1)*v1iz
        ym = cfx(i,iz,2)*v1iz
        cm = cm + xm
        dm = dm + ym
        gtfbm = gtfbm + xm
        gtfbd = gtfbd + ym
        gtfbv = gtfbv + v1iz
        ifznum(i) = ifznum(i) - 1
      else
        vr = v-vz
        vfrac(i,iz) = vfrac(i,iz)-vr
        cm = cm + cfx(i,iz,1)*vr
        dm = dm + cfx(i,iz,2)*vr
        gtfbm = gtfbm + cfx(i,iz,1)*vr
        gtfbd = gtfbd + cfx(i,iz,2)*vr
        gtfbv = gtfbv + vr
        vz = v
      endif
41   if ((vz.lt.v).and.(ifznum(i).gt.0)) goto 500
      if (va.lt.v) then
        vr = v-vz
        cm = cm + cin(i,1)*vr
        dm = dm + cin(i,2)*vr
        gtmna = gtmna + cin(i,1)*vr
        gtdna = gtdna + cin(i,2)*vr
        gtvna = gtvna + vr
      endif
      if (v.ne.0.) then
        c = cm / v
        d = dm / v
      else
        c = 0.
        d = 0.
      endif
      endif
    endif
  enddo
c*** inflow of mass flow during entire time step (kg/sec)
c
  if (qfrac(is).ne.0.) then
    cfrac(is,1) = cfrac(is,1) + c*cin(i)/qfrac(is)
    cfrac(is,2) = cfrac(is,2) + d*cin(i)/qfrac(is)
  endif
enddo
c
return
end
c
c*** subroutine dflows
c*** calculate flows through each segment
c*** this subroutine is called at the beginning of each time step
c
subroutine dflows
c
implicit double precision (a-h)
implicit double precision (o-z)
c

```

```

include 'vpcomas.f'
c
c*** compute the pressures in each segment
c
wlold = watlev
watlev = watlev0
do idraw=1,ldlim
  if (t.ge.delbt(idraw))
    watlev = watlev + delhh(idraw)
  enddo
  if (watlev.ne.wlold) then
    dv = (wlold - watlev)*area
    if (dv.lt.0.) then
      dm = (dv/topv)*topm
      gtmout = gtmout - dm
      topm = topm + dm
      gtdout = gtdout - (dv*topd)
    else
      topdm = topv * topd
      topd = topdm / (topv + dv)
    endif
    topv = (xtop-watlev)*area
  endif
c
dx2 = delx/2.
press(ilim) = (xtop-watlev)*topd + delx*cxt(ilim,itog,2)
do i=(ilim-1),1,-1
  press(i) = press(i+1) +
    dx2*(cxt((i+1),itog,2)+cxt(i,itog,2))
  if (i.eq.ifseg(1))
    write(90,'(2F20.5)')(t/3600.,press(i))
  enddo
c
c
c*** maximum time step is minimum time to flush one-tenth
c*** of a segment. note that this time may still be too large
c*** if dispersion is significant
c
if (ifvlt.eq.0) then
  if (qtmx.ne.0.) then
    delt = 0.1 * vol/qtmx
    if (delt.gt.tmax) delt = tmax
  else
    delt = 0.01 * tmax
  endif
endif
c
c*** initialize segment flows
c
do i=1,ilim
  qfrac(i) = 0.
enddo
c
c*** compute flow into segments from fractures
c*** it is possible to have more than one fracture in a single
c*** segment
c
do i=1,ilim
c
c*** compute flow rate as a function of pressure drop
c
  qin(i) = 0.
c
c*** calculate effect of each pressure (drawdown) change

```

```

c
  if (iplim(i).eq.0) then
    iplim(i) = 2
    phist(i,1,1) = hfrac(i)
    phist(i,1,2) = -1.e20
    phist(i,2,1) = xs(ifseg(i))-wsklev
    phist(i,2,2) = tstart
  endif
  if (dabs(press(ifseg(i))-phist(i,iplim(i),1))
    .gt. (deltx/2.)) then
    iplim(i) = iplim(i) + 1
    if (iplim(i).gt.npdps) then
      write(iout,*) 'Max iplim is', npdps, '--aborting'
      do iii=1, npdps
        write(iout,*) phist(i,iii,1)
      enddo
      stop
    endif
    phist(i,iplim(i),1) = press(ifseg(i))
    phist(i,iplim(i),2) = t
  endif
c***
c*** note: if pressure change occurs exactly on a
c*** time step boundary, there is no result
c
  do ip=2, iplim(i)
42 c
c*** calculate effect of change between times
c
    if (t.ge.phist(i,ip,3)) then
      qdtd = avgint(t, phist(i,ip,2), tcoef(i), delt)
      qin(i) = qin(i) +
        ( qdtd + qcoef(i) *
          (phist(i,(ip-1),1)-phist(i,ip,1)) )
    endif
    enddo
    qfrac(ifseg(i))=qfrac(ifseg(i))+qin(i)
  enddo
  call flowss
  return
end

c
c*** determine effective dimensionless flow rate for time step
c
  double precision function avgint(t, tp, tcoef, delt)
  implicit double precision (a-h)
  implicit double precision (o-z)
c
  dimension ts(101), qs(101)
c
c*** first check endpoints
c
  write(6,998) (t/3600.), (tp/3600.), delt
c 998 format(' in avgint, t, tp(hr), delt(sec) = ', 3f12.6)
  ts(1) = t - tp
  qs(1) = qd(ts(1)*tcoef)
  ts(2) = ts(1) + delt
  qs(2) = qd(ts(2)*tcoef)
  nvals = 2
  slopen = dabs((qs(2)-qs(1))/(ts(2)-ts(1)))
  write(6,999)slopen,delt
c 999 format(' slope=', e12.3, ' delt(s)=', e12.8)
c
  if (slopen.gt.1.e-2) then
    nvals = 101

```

```

    ts(nvals) = ts(2)
    qs(nvals) = qs(2)
    dt = delt/(nvals-1.)
c write(6,*) 'Integrating qd...'
c write(6,*) ' qs(1) = ', qs(1)
c write(6,*) ' qs(101) = ', qs(nvals)
    do i=2, (nvals-1)
      ts(i) = (t-tp) + (i-1)*dt
      qs(i) = qd(ts(i)*tcoef)
    enddo
  endif
c
  sum = 0.
  do i=1, nvals
    if (i.eq.1 .or. i.eq.nvals) then
      sum = sum + qs(i)/2.
    else
      sum = sum + qs(i)
    endif
  enddo
c write(6,*) ' avg = ', (sum/(nvals-1.))
  avgint = sum / (nvals-1.)
c
  return
end

c
c*** compute dimensionless flow rate as a function of dimensionless
c*** time.
c***
c*** input: dimensionless time, td
c*** output: dimensionless flow rate, qd
c***
c*** error conditions:
c*** if td < 1.e-4, qd is set to first value in table
c***
c*** if an interpolation error is detected,
c*** qd is set to one endpoint value, and
c*** an error message is printed
c***
c*** solution method: table lookup and linear interpolation
c***
c*** range: 1.e-4 <= td <= 1.e12
c***
c*** references: table 1, page S61, of
c*** "Unsteady Flow to a well of constant drawdown in an
c*** extensive aquifer," by C.E. Jacob and S.W. Lohman,
c*** Transactions, American Geophysical Union, v.33, no.4,
c*** August 1952, pp. 559-569.
c***
c*** solution method: direct numerical approximation
c***
c*** range: 1.e12 < td
c***
c*** references: equation 4.41 of
c*** "Advances in Well Test Analysis," by Robert C.
c*** Earlougher, Jr., American Institute of Mining,
c*** Metallurgical, and Petroleum Engineers, Inc., 1977,
c*** p. 40.
c
  double precision function qd(td)
  implicit double precision (a-h)
  implicit double precision (o-z)
  dimension qdtd(145), tds(145)

```

```

      data qdtd /
      . 56.9, 40.4, 33.1, 28.7, 25.7, 23.5, 21.8, 20.4, 19.3,
      . 18.34, 13.11, 10.79, 9.41, 8.47, 7.77, 7.23, 6.79, 6.43,
      . 6.13, 4.47, 3.74, 3.30, 3.00, 2.78, 2.60, 2.46, 2.35,
      . 2.249, 1.716, 1.477, 1.333, 1.234, 1.160, 1.103, 1.057, 1.018,
      . 0.985, 0.803, 0.719, 0.667, 0.630, 0.602, 0.580, 0.562, 0.547,
      . 0.533, 0.461, 0.427, 0.405, 0.389, 0.377, 0.367, 0.359, 0.352,
      . 0.346, 0.311, 0.294, 0.283, 0.274, 0.268, 0.263, 0.258, 0.254,
      . 0.251, 0.232, 0.222, 0.215, 0.210, 0.206, 0.203, 0.200, 0.198,
      . .1964, .1941, .1777, .1733, .1701, .1675, .1654, .1636, .1621,
      . .1608, .1524, .1479, .1449, .1426, .1408, .1393, .1380, .1369,
      . .1360, .1299, .1266, .1244, .1227, .1213, .1202, .1192, .1184,
      . .1177, .1131, .1106, .1089, .1076, .1066, .1057, .1049, .1043,
      . .1037, .1002, .0982, .0968, .0958, .0950, .0943, .0937, .0932,
      . .0927, .0899, .0883, .0872, .0864, .0857, .0851, .0846, .0842,
      . .0838, .0814, .0801, .0792, .0785, .0779, .0774, .0770, .0767,
      . .0764, .0744, .0733, .0726, .0720, .0716, .0712, .0709, .0706, .0704/
      data tds /
      . 1.e-4, 2.e-4, 3.e-4, 4.e-4, 5.e-4, 6.e-4, 7.e-4, 8.e-4, 9.e-4,
      . 1.e-3, 2.e-3, 3.e-3, 4.e-3, 5.e-3, 6.e-3, 7.e-3, 8.e-3, 9.e-3,
      . 1.e-2, 2.e-2, 3.e-2, 4.e-2, 5.e-2, 6.e-2, 7.e-2, 8.e-2, 9.e-2,
      . 1.e-1, 2.e-1, 3.e-1, 4.e-1, 5.e-1, 6.e-1, 7.e-1, 8.e-1, 9.e-1,
      . 1.e0, 2.e0, 3.e0, 4.e0, 5.e0, 6.e0, 7.e0, 8.e0, 9.e0,
      . 1.e1, 2.e1, 3.e1, 4.e1, 5.e1, 6.e1, 7.e1, 8.e1, 9.e1,
      . 1.e2, 2.e2, 3.e2, 4.e2, 5.e2, 6.e2, 7.e2, 8.e2, 9.e2,
      . 1.e3, 2.e3, 3.e3, 4.e3, 5.e3, 6.e3, 7.e3, 8.e3, 9.e3,
      . 1.e4, 2.e4, 3.e4, 4.e4, 5.e4, 6.e4, 7.e4, 8.e4, 9.e4,
      . 1.e5, 2.e5, 3.e5, 4.e5, 5.e5, 6.e5, 7.e5, 8.e5, 9.e5,
      . 1.e6, 2.e6, 3.e6, 4.e6, 5.e6, 6.e6, 7.e6, 8.e6, 9.e6,
      . 1.e7, 2.e7, 3.e7, 4.e7, 5.e7, 6.e7, 7.e7, 8.e7, 9.e7,
      . 1.e8, 2.e8, 3.e8, 4.e8, 5.e8, 6.e8, 7.e8, 8.e8, 9.e8,
      . 1.e9, 2.e9, 3.e9, 4.e9, 5.e9, 6.e9, 7.e9, 8.e9, 9.e9,
      . 1.e10, 2.e10, 3.e10, 4.e10, 5.e10, 6.e10, 7.e10, 8.e10, 9.e10,
      . 1.e11, 2.e11, 3.e11, 4.e11, 5.e11, 6.e11, 7.e11, 8.e11, 9.e11, 1.e12/
      c
      float = 6
      c
      c*** check range of td
      c
      if (td.lt.tds(1)) then
        qdtemp = qdtd(1)
      else
      c
      c*** use analytical solution for large values
      c
      if (td.ge.tds(145)) then
        qdtemp = 2. / (dlog(td) + 0.80907)
      else
      c
      c*** compute indices into table
      c
      tdl = dlog10(td)
      itdm = tdl
      if (tdl.lt.0.d0) itdm = itdm-1
      itdf = td/10.d0**itdm
      if (itdf.eq.10.d0) then
        itdf = 1
        itdm = itdm+1
      endif
      i1 = (itdm+4)*9 + itdf
      if (tds(i1).eq.td) then
        qdtemp = qdtd(i1)
      else

```

```

      c*** interpolate table
      c
      if (td.lt.tds(i1)) i1 = i1-1
      if (td.gt.tds(i1+1)) i1 = i1+1
      if (i1.lt.1) i1 = 1
      if (i1.gt.145) i1 = 145
      if ((td.lt.tds(i1)).or.(td.gt.tds(i1+1))) then
        write(6,*) 'Error--qd interp; tde', td
        qdtemp = qdtd(i1)
      else
        slope = (qdtd(i1+1)-qdtd(i1)) /
          (tds (i1+1)-tds (i1))
        delx = td - tds(i1)
        qdtemp = qdtd(i1) + delx*slope
      endif
      endif
      endif
      c
      qd = qdtemp
      return
      end

```